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<td>10:00-11:30 WeA01 Sapphire MN Robotics (RI)</td>
<td>10:00-11:30 WeA02 Sapphire MN Optimization Control and Estimation of Soft Material Systems</td>
<td>10:00-11:30 WeA03 Sapphire MN Advanced Control of Wind Farms and Wind Turbines: Session I: Wind Farm Modeling, Estimation and Control</td>
<td>10:00-11:30 WeA04 Sapphire MN Advanced Control of Wind Farms and Wind Turbines: Session II: Wind Farm Wake Control</td>
<td>10:00-11:30 WeA05 Sapphire MN Identification of Control Systems</td>
<td>10:00-11:30 WeA06 Sapphire MN Nonlinear Systems Optimization Algorithms</td>
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<td>10:00-11:30 WeA10 Aqua 309 Agents-Based Systems</td>
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<td>10:00-11:30 WeA13 Aqua 307 Systems</td>
<td>10:00-11:30 WeA14 Aqua 311A Predictive Control and Planning Methods for Robotic Systems</td>
<td>10:00-11:30 WeA15 Aqua 311B Energy Efficiency in Smart Buildings and Cities</td>
<td>10:00-11:30 WeA16 Aqua 313 Machine Learning and Machine Learning Methods to Accelerate Innovation in Sustainability: A Control Perspective</td>
<td>10:00-11:30 WeA17 Aqua 314 Mechatronics (RI)</td>
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<td>14:00-15:30 WeB05 Sapphire MN Advanced Control of Wind Farms and Wind Turbines: Session III: Wind Farm Modeling, Estimation and Control</td>
<td>14:00-15:30 WeB06 Aqua 303 Nonlinear Systems Identification</td>
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<td>14:00-15:30 WeB08 Aqua 307 Systems Identification and Control of Infinite Dimensional Systems II</td>
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**ACC 2023 Technical Program Thursday June 1, 2023**

08:30-09:30 ThP1

**Why Would We Want a Multi-Agent System Unstable**

08:30-09:30 ThP1

Sapphire CDGHOPKL

Why Would We Want a Multi-Agent System Unstable
## ACC 2023 Technical Program Friday June 2, 2023

**08:30-09:30 FrSP1**
Sapphire OPKL
Towards Flow Control: From Boundary Layers to Wind Farms and Back Again

**08:30-09:30 FrSP2**
Sapphire CDGH
A Journey through Diffusions

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<td>10:00-11:00 FrA02 Sapphire MN Process Control (RI)</td>
<td>10:00-11:00 FrA03 Sapphire MN Robust Control (RI)</td>
<td>10:00-11:00 FrA04 Sapphire MN Statistical Learning</td>
<td>10:00-11:00 FrA05 Sapphire MN Recent Advancement of Human Autonomy Interacti on and Integratio n</td>
<td>10:00-11:00 FrA06 Sapphire MN Advanced Control</td>
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<td>12:30-14:00 FrC01 Sapphire MN Traffic Control (RI)</td>
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**15:30-17:00 FrC01 Sapphire MN Traffic Control (RI) | 15:30-17:00 FrC02 Sapphire MN Advanced Vehicles | 15:30-17:00 FrC03 Sapphire MN EE Control | 15:30-17:00 FrC04 Sapphire MN Advanced Control | 15:30-17:00 FrC05 Sapphire MN Control Systems | 15:30-17:00 FrC06 Sapphire MN Control Systems | 15:30-17:00 FrC07 Sapphire MN Control Systems | 15:30-17:00 FrC08 Sapphire MN Control Systems | 15:30-17:00 FrC09 Sapphire MN Control Systems | 15:30-17:00 FrC10 Sapphire MN Control Systems | 15:30-17:00 FrC11 Sapphire MN Control Systems | 15:30-17:00 FrC12 Sapphire MN Control Systems | 15:30-17:00 FrC13 Sapphire MN Control Systems | 15:30-17:00 FrC14 Sapphire MN Control Systems | 15:30-17:00 FrC15 Sapphire MN Control Systems | 15:30-17:00 FrC16 Sapphire MN Control Systems | 15:30-17:00 FrC17 Sapphire MN Control Systems |
A main challenge in swarm robotics is the unknown mapping between simple agent-level behavior rules and emergent global behaviors. Currently, there is no known swarm control algorithm that maps global behaviors to local control policies. This paper proposes a novel method to circumvent this problem by learning the agent-level controllers of an observed swarm to imitate its emergent behavior. Agent-level controllers are treated as a set of policies that are combined to dictate the agent’s change in velocity. The trajectory data of known swarms is used with linear regression and nonlinear optimization methods to learn the relative weight of each policy. To show our approach’s ability for imitating swarm behavior, we apply this methodology to both simulated and physical swarms (i.e., a school of fish) exhibiting a multitude of distinct emergent behaviors. We found that our pipeline was effective at imitating the simulated behaviors using both accurate and inaccurate assumptions, being able to closely identify not only the policy gains, but also the agent’s radius of communication and their maximum velocity constraint.

We found that our pipeline was effective at imitating the simulated behaviors using both accurate and inaccurate assumptions, being able to closely identify not only the policy gains, but also the agent’s radius of communication and their maximum velocity constraint.

WeA01.2

Imitating Swarm Behaviors by Learning Agent-Level Controllers, pp. 7-13

Musadeequ Rahman Ibrahim

University of Michigan

White, Stanford

University of Mississippi

Crockett, Katelyn

West Virginia University

Gu, Yu

West Virginia University

Abreu Archanjo Dutra, Dimas

West Virginia University

Pereira, Guilherme

West Virginia University

Industrial grippers are generally either electric or pneumatic, with the latter being preferred as their air-based functioning guarantees many advantages such as cost effectiveness and reduced encumbrance. Despite the very large employment, pneumatic grippers do not yet offer performance beyond the open/closed behavior in the majority of cases. Pneumatic grippers mounted on industrial robotic arms are commonly rigid as high forces might be required during the grasping operations. The poorness of the control strategies for the grasping cases. Pneumatic grippers mounted on industrial robotic arms are commonly rigid as high forces might be required during the grasping operations. The poorness of the control strategies for the grasping

A Quadratic-Programming Approach for the Real-Time Control of the Fingers Position in Industrial Pneumatic Grippers, pp. 1-6

Romeo, Rocco Antonio

Istituto Italiano Di Tecnologia

Zocco, Agata

Istituto Italiano Di Tecnologia

Fiorio, Luca

Istituto Italiano Di Tecnologia

Maggiali, Marco

Istituto Italiano Di Tecnologia

This paper presents a chance-constrained formulation for robust trajectory optimization during manipulation. In particular, we present a chance-constrained optimization for Stochastic Discrete-time Linear Complementarity Systems (SDLCS). To solve the optimization problem, we formulate Mixed-Integer Quadratic Programming with Chance Constraints (MIQPC). In our formulation, we explicitly consider joint chance constraints for complementarity as well as states to capture the stochastic evolution of dynamics. We evaluate robustness of our optimized trajectories in simulation on several systems. The proposed approach outperforms some recent approaches for robust trajectory optimization for SDLCS.

Safe Human-Robot Collaborative Transportation Via Trust-Driven Role Adaptation, pp. 22-27

Zheng, Tony

University of California, Berkeley

Bujabararah, Monimoy

UC Berkeley

Borrelli, Francesco

University of California at Berkeley

Stürz, Yvonne R.

UC Berkeley

We study a human-robot collaborative transportation task in presence of obstacles. The task for each agent is to carry a rigid object to a common target position, while safely avoiding obstacles and satisfying the compliance and actuation constraints of the other agent. Human and robot do not share the local view of the environment. The human either assists the robot when they deem the robot actions safe based on their perception of the environment, or actively leads the task.

Using estimated human inputs, the robot plans a trajectory for the transported object by solving a constrained finite time optimal control problem. Sensors on the robot measure the inputs applied by the human. The robot then appropriately applies a weighted combination of the human’s applied and its own planned inputs, where the weights are chosen based on the robot's trust value on its estimates of the human's inputs. This allows for a dynamic leader-follower role adaptation of the robot throughout the task. Furthermore, under a low value of trust, if the robot approaches any obstacle potentially unknown to the human, it triggers a safe stopping policy, maintaining safety of the system and signaling a required change in the human's intent. The robot also uses the sensor feedback to infer obstacles known only by the human and updates its planner to better align with the human's movements. With experimental results, we demonstrate
that our proposed approach increases the success rate of collision-free trials while decreasing the effort required by the human to intervene.

10:16-10:20 WeA01.5
NAPVIG: Local Generalized Voronoi Approximation for Reactive Navigation in Unknown and Dynamic Environments, pp. 28-33
Lissandrini, Nicola University of Padova
Battistella, Luca Department of Information Engineering, University of Padova
Ryll, Markus Technical University Munich
Michieletto, Giulia University of Padova
Cenedese, Angelo University of Padova

In this paper, we propose a novel online approach for reactive local navigation of a robotic agent, based on a fast approximation of the Generalized Voronoi Diagram in a neighborhood of the robot's position. We consider the context of an unknown environment characterized by some narrow passages and a dynamic configuration. Given the uncertainty and unpredictability that affect the scenario, we aim at computing trajectories that are farthest away from every obstacle: this is obtained by following the Voronoi diagram. To ensure full autonomy, the navigation task is performed relying only upon on-board sensor measurement without any a-priori knowledge of the environment. The proposed technique builds upon a smooth free space representation that is spatially continuous and based on some raw measurements. In this way, we ensure an efficient computation of a trajectory that is continuously re-planned according to incoming sensor data. A theoretical proof shows that in ideal conditions the outlined solution exactly computes the local Generalized Voronoi Diagram. Finally, we assess the reactivity and precision of the proposed method with realistic real-time simulations and with real-world experiments.

10:20-10:24 WeA01.6
Invariant Configuration-Space Bubbles for Revolute Serial-Chain Robots, pp. 34-39
Danielson, Claus University of New Mexico

This paper adapts the invariant-set motion planner (ISMP) for robot motion planning. We derive control invariant subsets of configuration-space bubbles lifted into the state-space. The resulting sets guarantee collision avoidance since they are both constraint-admissible and control invariant. We present a command governor that enforces the positive invariance of the constraints in closed-loop. This governor can be used to transform any nominal tracking controller into a constraint enforcing controller. We use these control invariant sets to quantify a relationship between velocity and control authority that enables collision avoidance. We demonstrate our invariant-sets through an illustrative numerical example.

10:24-10:28 WeA01.7
Dynamics Learning-Based Fault Isolation for a Soft Trunk Robot, pp. 40-45
Zhang, Jingting University of Rhode Island
Chen, Xiaotian University of Rhode Island
Jandaghi, Emadodin University of Rhode Island
Zeng, Wei South China University of Technology
Zhou, Mingxi University of Rhode Island
Yuan, Chengzhi University of Rhode Island

In this paper, we investigate the fault isolation (FI) problem of a soft trunk robot and propose a dynamics learning-based FI approach which is generic and applicable to general types of faults. Specifically, an adaptive radial basis function neural network (RBF NN) based dynamics learning scheme is first developed to achieve accurate identification of the robot’s dominant dynamics under different faulty modes, and the learned knowledge is stored and represented by constant RBF NN models. The learned results are then merged by using a novel merging mechanism to construct a bank of global RBF NN models, for capturing the characteristics of the robot’s dynamics under each specific faulty mode. Based on these models, a bank of FI observers are designed to develop an important capability of accurately reconstructing the robot’s dynamics under various faulty modes. The FI scheme is developed using these FI observers, which monitors the robot’s operation status online to provide accurate isolation of faults occurring in the robot. Physical experiments are performed on the soft trunk robot to validate the effectiveness of our proposed approaches.

10:36-10:40 WeA01.10
Masoud, Ahmad A. KFUPM

This paper integrates concepts from the frequency domain control
methods, state space control and robot motion planning to produce a flexible control synthesis approach that is applicable to a wide class of dynamical systems. The method views a system's frequency response as a trajectory in the complex plane that is evolving under the influence of an artificial force to satisfy a geometric stability-performance criterion. A nonlinear subspace approach is used to translate these forces into an equivalent state space dynamical system that governs the dynamics of the parameters of the compensator used to generate the control signal. The design method places no restrictions on the order of the compensator or geometry of the frequency domain criterion. The approach is developed and a proof of its ability to converge, if a solution exists, to the tuning parameters set that satisfies the desired conditions is provided. The paper provides a set of design examples to demonstrate its applicability to different types of linear, nonlinear, SISO and MIMO systems.

WeA02 Sapphire IJ
Machine Learning (RI) (RI Session)
Chair: Lima, Vinicius University of Pennsylvania
Co-Chair: Inoue, Masaki Keio University
10:00-10:04 WeA02.1
Data-Driven Deep Learning Based Feedback Linearization of Systems with Unknown Dynamics, pp. 66-71
Goswami, Rakitm Gautam New York University
Krishnamurthy, Prashanth NYU Tandon School of Engineering
Khorrami, Fanashad NYU Tandon School of Engineering

A methodology is developed to learn a feedback linearization (i.e., nonlinear change of coordinates and input transformation) using a data-driven approach for a single input control-affine nonlinear system with unknown dynamics. We employ deep neural networks to learn the feedback law (input transformation) in conjunction with an extension of invertible neural networks to learn the nonlinear change of coordinates (state transformation). We also learn the matrices A and B of the transformed linear system and define loss terms to ensure controllability of the pair (A, B). The efficacy of our approach is demonstrated by simulations on a nonlinear system. Furthermore, we show that state feedback controllers designed using the feedback linearized system yield expected closed-loop behavior when applied to the original nonlinear system, further demonstrating validity of the learned feedback linearization.

10:04-10:08 WeA02.2
Decentralized Multi-Agent Reinforcement Learning for Continuous-Space Stochastic Games, pp. 72-77
Altaba, Awni Yale University
Yongacoglu, Bora Queen's University
Yuksel, Serdar Queen's University

Stochastic games are a popular framework for studying multi-agent reinforcement learning (MARL). Recent advances in MARL have focused primarily on games with finitely many states. In this work, we study multi-agent learning in stochastic games with general state spaces and an information structure in which agents do not observe each other's actions. In this context, we propose a decentralized MARL algorithm and we establish the near-optimality of its policy updates. Furthermore, we study the global policy-updating dynamics for a general class of best-reply based algorithms and derive a closed-form characterization of convergence probabilities over the joint policy space.

10:08-10:12 WeA02.3
Federated Reinforcement Learning for Generalizable Motion Planning, pp. 78-83
Yuan, Zhenyuan Pennsylvania State University

This paper considers the problem of learning a control policy that generalize well to novel environments given a set of sample environments. We develop a federated learning framework that enables collaborative learning of multiple learners and a centralized server without sharing their raw data. In each iteration, each learner uploads its local control policy and the corresponding estimated normalized arrival time to the server, which then computes the global optimum among the learners and broadcasts the optimal policy to the learners. Each learner then selects between its local control policy and that from the server for next iteration. By leveraging generalization error, our analysis shows that the proposed framework is able to provide generalization guarantees on arrival time and safety as well as consensus at global optimal value in the limiting case. Monte Carlo simulation is conducted to evaluate the proposed framework.

10:12-10:16 WeA02.4
Robust Nonlinear Set-Point Control with Reinforcement Learning, pp. 84-91
Zhang, Ruogu Uppsala University
Mattsson, Per Uppsala University
Wigren, Torbjorn Uppsala University

There has recently been an increased interest in reinforcement learning for nonlinear control problems. However standard reinforcement learning algorithms can often struggle even on seemingly simple set-point control problems. This paper argues that three ideas can improve reinforcement learning methods even for highly nonlinear set-point control problems: 1) Make use of a prior feedback controller to aid amplitude exploration. 2) Use integrated errors. 3) Train on model ensembles. Together these ideas lead to more efficient training, and a trained set-point controller that is more robust to modelling errors and thus can be directly deployed to real-world nonlinear systems. The claim is supported by experiments with a real-world nonlinear cascaded tank process and a simulated strongly nonlinear pH-control system.

10:16-10:20 WeA02.5
Online Learning-Based Predictive Control of Switched Nonlinear Systems with Disturbances, pp. 92-99
Hu, Cheng National University of Singapore,
Wu, Zhe National University of Singapore

This work presents a model predictive control (MPC) scheme using online learning of recurrent neural network (RNN) models to approximate the dynamics of switched nonlinear systems subject to unknown but bounded disturbances, for which the mode transitions follow a prescribed switching schedule. A generalization error bound for online learning RNNs using non-independent and identically distributed (non-i.i.d.) data samples from real-time operation of switched nonlinear systems is first derived. Subsequently, a Lyapunov-based MPC scheme using online learning RNNs is developed to stabilize the switched nonlinear system for each mode and guarantee satisfaction of the scheduled mode transitions, followed by closed-loop stability analysis that accounts for the RNN generalization error. Finally, the effectiveness of the proposed MPC scheme is demonstrated using a chemical process example switched between two modes.

10:20-10:24 WeA02.6
Optimal Control Via Linearizable Deep Learning, pp. 100-105
Lima, Vinicius University of Pennsylvania
Phan, Dzung IBM T.J. Watson Research Center
Nguyen, Lam IBM Research
Kalagnanam, Jayant R. IBM T.J. Watson Research Center

Deep learning models are frequently used to capture relations...
between inputs and outputs and to predict operation costs in dynamical systems. Computing optimal control policies based on the resulting regression models, however, is a challenging task because of the nonlinearity and nonconvexity of deep learning architectures. To address this issue, we propose in this paper a linearizable approach to design optimal control policies based on deep learning models for handling both continuous and discrete action spaces. When using piecewise linear activation functions, one can construct an equivalent representation of recurrent neural networks in terms of a set of mixed-integer linear constraints. That in turn means that the optimal control problem reduces to a mixed-integer linear program (MILP), which can then be solved using off-the-shelf MILP optimization solvers. Numerical experiments on standard reinforcement learning benchmarks attest to the good performance of the proposed approach.

Transfer Learning-Based Modeling and Predictive Control of Nonlinear Processes, pp. 106-112
Xiao, Ming National University of Singapore
Hu, Cheng National University of Singapore
Wu, Zhe National University of Singapore

This work develops a transfer learning (TL) framework for modeling nonlinear dynamic systems using recurrent neural networks (RNNs). The TL-based RNN models are then incorporated into the design of model predictive control (MPC) systems. Specifically, transfer learning uses a pre-trained model developed based on a source domain as the starting point, and adapts the model to a target domain with similar data distribution. The generalization error for TL-based RNNs (TL-RNNs) that depends on model capacity and discrepancy between source and target domains is first derived to demonstrate the generalization capability on target process. Subsequently, the TL-RNN model is utilized as the prediction model in MPC for the target process. Finally, a chemical process example is used to demonstrate the benefits of transfer learning.

Personalization of Control Systems by Policy Update with Improving User Trust, pp. 113-118
Nii, Tomotaka Keio University
Inoue, Masaki Keio University

In this paper, we address the design of personalized control systems, which pursue an individual and private objective defined for each user. To this end, a problem of policy update is formulated where an individual objective function is estimated and the corresponding optimal control law is updated. The novelty of the problem setting is in the presence of a system-user and the policy update driven by his/her rating. The system-user rates on the control system to be updated and the rating is used for estimating his/her objective function. It is assumed that the rating depends not only on his/her private objective but also on his/her trust on the control system. Then, we address the problem of the policy update improving the rating while not impairing the trust. Algorithms of the policy update, which is essentially the objective function estimation, are developed and their convergence analysis is presented. Finally, thorough a numerical experiment, the effectiveness of the algorithms is shown.

Differentiable Safe Controller Design through Control Barrier Functions, pp. 119-124
Yang, Shuo University of Pennsylvania
Chen, Shaoru University of Pennsylvania
Peciało, Victor M. University of Pennsylvania
Mangharam, Rahul University of Pennsylvania

Learning-based controllers, such as neural network (NN) controllers, can show high empirical performance but lack formal safety guarantees. To address this issue, control barrier functions (CBFs) have been applied as a safety filter to monitor and modify the outputs of learning-based controllers in order to guarantee the safety of the closed-loop system. However, such modification can be myopic with unpredictable long-term effects. In this work, we propose a safe-by-construction NN controller which employs differentiable CBF-based safety layers and relies on a set-theoretic parameterization. We compare the performance and computational complexity of the proposed controller and an alternative projection-based safe NN controller in learning-based control. Both methods demonstrate improved closed-loop performance over using CBF as a separate safety filter in numerical experiments.

Dynamic Covariance Prediction Using Variational Wishart Processes with Uncertain Inputs, pp. 125-130
Uzzaman, Nahid Oklahoma State University
Bai, He Oklahoma State University

We consider the problem of forecasting dynamic covariance with uncertain inputs. Various Bayesian approaches, including the variational Wishart process (VWP), were previously used to forecast such covariance with deterministic inputs. However, the VWP framework is insufficient to perform reliable predictions when the input is uncertain. To address this issue, we propose two novel VWP approaches that can model and predict covariance with uncertain inputs. Simulation results show that when the input is uncertain, the proposed novel VWP approaches outperform the original VWP and produce more reliable performance. A comparative discussion between all the approaches is presented based on the simulation results.

Modeling, Control and Estimation of Soft Material Systems (Invited Session)
Chair: Vikas, Vishesh University of Alabama
Co-Chair: Chen, Zheng University of Houston
Organizer: Tan, Xiaobo Michigan State University
Organizer: Vikas, Vishesh University of Alabama

We consider the problem of forecasting dynamic covariance with uncertain inputs. Various Bayesian approaches, including the variational Wishart process (VWP), were previously used to forecast such covariance with deterministic inputs. However, the VWP framework is insufficient to perform reliable predictions when the input is uncertain. To address this issue, we propose two novel VWP approaches that can model and predict covariance with uncertain inputs. Simulation results show that when the input is uncertain, the proposed novel VWP approaches outperform the original VWP and produce more reliable performance. A comparative discussion between all the approaches is presented based on the simulation results.

Physics-Based Modeling of Dielectric Elastomer Enabled Cuff Device (I), pp. 131-136
Kaaya, Theophilus University of Houston
Venkatraman, Rahul University of Houston
Chen, Zheng University of Houston

Venous system disorders such as Orthostatic hypotension, deep vein thrombosis (DVT), and edema affect the lower limbs and are common causes of decreased work performance and quality of life. Solutions such as compression devices, rotation of staff, and regular breaks help improve these problems. Some active compression devices require air compression which needs a pump thus making them bulky. A cuff muscle device that uses a dielectric elastomer as a soft actuator and sensor is proposed to supplement the existing means of reducing the effects of these disorders. A physics-based model of the device is developed by combining the physics of a thin-walled dielectric elastomer vessel with the force interactions between the active vessel and the cylindrical passive elastomer within. The couplings between the two nonlinear elastic models are solved to capture the pressure change experienced by the device under an applied voltage. The model is then validated in the normal frequency range of the device. This model may be used to predict the influence of different model parameters on the performance of the device before the fabrication process reducing the need for multiple prototyping.


Soft robotic actuators have repeatedly demonstrated their utility for underwater manipulation, particularly in the deep sea with delicate biological creatures and fragile artifacts. Up to this point, soft robotic actuators and gripping modules have been limited to relatively small prototypes that are on the same scale as a human hand. Scaling soft robotic grippers to larger sizes is a non-trivial task due to two major challenges: design and manufacturing. In this work, we present a complete and streamlined workflow of modeling, manufacturing, and testing scalable soft actuators that are directly produced using additive manufacturing methods and finite element modeling (FEA). The presented workflow is an iterative approach that uses information gathered from the FEA's simulation to further improve the simplified known initial model. To demonstrate this new workflow, a series of soft actuator designs were modeled, created, and tested. Additionally, a more complex theoretical actuator design that has a non-uniform bending geometry is created and modeled. Once the actuator design matches what is desired, additive manufacturing is used to physically create it. Using this full process, an actuator design is easily scaled to almost three times its original length and is manufactured in under 36 hours. The scaled up actuators are arranged in a custom full gripping array to grasp a cylinder underwater in a predictive manner.

Simultaneous Motion and Stiffness Control for Soft Pneumatic Manipulators Based on a Lagrangian-Based Dynamic Model (I), pp. 145-152
Mei, Yu Michigan State University
Fairchild, Preston Michigan State University
Srivastava, Vaibhav Michigan State University
Cao, Changyong Case Western Reserve University
Tan, Xiaobo Michigan State University

A soft continuum manipulator with tunable stiffness can not only take advantage of high compliance for safe adaptation in unknown environments, but also circumvent the drawbacks of instability and low loading capability. The high nonlinearity of soft manipulators and the strong coupling between actuation and stiffness-tuning make their simultaneous control challenging. In this work, a novel approach to simultaneous control of actuation and stiffness-tuning is proposed for soft pneumatic manipulators. With piecewise-constant curvature assumption, a Lagrangian-based dynamic model with realistic approximation is used for control design, where the dynamics of stiffness-tunable mechanism is incorporated. An extended Kalman filter (EKF) is proposed to estimate unmeasurable states including the stiffness and the velocity. An Nonlinear Model Predictive Control (NMPC) framework is developed first in the configuration space, and then extended to the task space, for simultaneous motion and stiffness control under inflation and vacuum pressure constraints. Simulation results are presented to support the efficacy of the proposed approach.

Controlling the Shape of Soft Robots Using the Koopman Operator (I), pp. 153-158
Singh, Aji Colorado State University
Sun, Jiefei Yale University
Zhao, Jianguo Colorado State University

Abstract— In nature, animals with soft body parts demonstrate remarkable control over their shape, such as an elephant trunk wrapping around a tree branch to pick it up. However, most research on robotic manipulators focuses on controlling the end effector, partly because the manipulator's arm is rigidly articulated. With recent advances in soft robotics research, controlling a soft manipulator into many different shapes will significantly improve the robot's functionality, such as medical robots morphing their shape to navigate the digestive system and deliver drugs to specific locations. However, controlling the shape of soft robots is challenging due to their highly nonlinear dynamics that are computationally intensive. In this paper, we leverage a physics-informed, data-driven approach using the Koopman operator to realize the shape control of soft robots. We simulate the dynamics of a soft manipulator using a physics-based simulator (PyElastica) to generate the input-output data, which is then used to identify an approximated linear model based on the Koopman operator. We then formulate the shape control problem as a convex optimization problem that is computationally efficient. Our linear model is over 12 times faster than the physics-based model in simulating the manipulator's motion. Further, we can control a soft manipulator into different shapes using model predictive control. We envision that the proposed method can be effectively used to control the shapes of soft robots to interact with uncertain environments or enable shape-morphing robots to fulfill diverse tasks. This paper is complemented with a video.
from downstream turbines, increasing the total power produced by the wind farm. Most wake steering methods generate lookup tables offline which map a set of wind farm conditions, such as wind speed, to yaw offset angles for each turbine in a farm. These tables assume all turbines are operational and can be significantly non-optimal when one or more turbines shutdown—as they often do because of low wind speed, routine maintenance, or emergency maintenance. We present a new wake steering method that adapts to turbine shutdown. Using a hybrid model- and learning-based method, differentiable control, we train a neural network to determine yaw offset angles from conditions including turbine status (active/inactive). Unlike the lookup table approach, differentiable control does not solve an optimization problem for each combination of turbine shutdown in a farm; including learning in the method allows it to generalize. We present results for both standard wake steering (all turbines active) and adaptive wake steering (some turbines active). We find that differentiable control has comparable accuracy as and an order of magnitude faster offline compute time than the lookup table approach. Differentiable control enables adaptive wake steering through computationally efficient training and rapid online evaluation.

We present a method to estimate the time-varying free-flow wind speed on a wind farm based on local wind speed measurements taken by a wind turbine inside the wake zone of a turbine array. Our approach relies on a simple modeling of the speed deficit as a 1-D transport equation [1]. We propose to estimate the free-flow wind speed by integrating the error between the local wind measurement and an estimate of it computed with the free-flow estimate. We provide a proof on the estimation error which we formally prove. Finally, we provide numerical simulations to illustrate the interest and the performance of the proposed method.

The power output of a wind farm is influenced by wake effects, a phenomenon in which upstream turbines facing the wind create sub-optimal conditions for turbines located downstream. Yaw misaligning strategies have been shown to increase total production. Yet designing efficient methods of cooperative control to find optimal yaw angles is a challenging task. Classical optimization methods become intractable as the size of the farm grows, do not recover from model inaccuracies and ignore the dynamic propagation of the wind inflow in real conditions. Reinforcement learning methods can provide a model-free alternative, but raise issues of scalability when the control is centralized. Existing decentralized RL methods have been shown to significantly increase power production under dynamic conditions, but relied on tabular methods with state and action space discretization. To accelerate convergence, we employ an actor-critic algorithm with linear function approximation for decentralized cooperative yaw control. We validate our method in dynamic simulators for wind farms with up to 32 turbines, and show empirically that, compared to previous tabular algorithms, our method is faster and scales to larger wind farms.

This paper presents a wind farm control strategy to use wake steering (yaw control) to augment pitch control for tracking a power reference signal. The outer loop controller employs a recently proposed dynamic yaw model with a time-varying graph structure that accounts for changes in the farm power output due to the propagation of wakes and wake interactions from yawing turbines. The inner pitch control loop uses a PI controller combined with a novel power-sharing arrangement that reduces the needed derate at each turbine. A compensation scheme accounts for the slow timescale effects of the yaw control actions within the faster timescale pitch control. The controller is applied to track two power trajectories (typical of secondary frequency regulation signals) using a large-eddy simulation wind farm plant. The results demonstrate that the additional control authority from yaw provides some added benefit in reducing the required turbine derates needed for wind farms to track transient power increases in the proposed setting. However, the benefit decreases and pitch control alone is sufficient when the turbines are derated beyond a certain level. These findings suggest that augmenting pitch control with yaw may provide financial incentives in terms of allowing wind farms to maximize power supply to the bulk power market while still providing regulation services. Further work is needed to analyze the costs and benefits of the additional control complexity versus bandwidth in augmenting pitch control with wake steering in these applications.
strongly convex costs and asymptotic convergence for convex costs. Exponential convergence when the local cost functions are strongly convex is achieved even when the local gradients are only locally Lipschitz. For convex local cost functions, our algorithm guarantees asymptotic convergence to a point in the minimizer set. Through numerical examples, we show that our proposed algorithm delivers a faster convergence compared to existing distributed resource allocation algorithms.

10:15-10:30 WeA05.2

**Accelerated Primal-Dual Scheme for a Class of Stochastic Nonconvex-Concave Saddle Point Problems**, pp. 204-209

Borouن, Morteza

University of Arizona

Alizadeh, Zeinab

University of Arizona

Jalizadeh, Afroz

University of Arizona

Stochastic nonconvex-concave min-max saddle point problems appear in many machine learning and control problems including distributionally robust optimization, generative adversarial networks, and adversarial learning. In this paper, we consider a class of nonconvex saddle point problems where the objective function satisfies the Polyak-Lojasiewicz condition with respect to the minimization variable and it is concave with respect to the maximization variable. The existing methods for solving nonconvex-concave saddle point problems often suffer from slow convergence and/or contain multiple loops. Our main contribution lies in proposing a novel single-loop accelerated primal-dual algorithm with new convergence rate results appearing for the first time in the literature, to the best of our knowledge.

10:30-10:45 WeA05.3


Ozaslan, Ibrahim Kurban

University of Southern California

Jovanovic, Mihailo R.

University of Southern California

We examine global exponential stability of the primal-dual gradient flow dynamics for differentiable convex problems with linear equality constraints. We show that if the set of equilibrium points is affine, then, regardless of the initial conditions, trajectories of the gradient flow move in the direction that is perpendicular to equilibrium set. When the objective function is strongly convex, we utilize this structure to show that the primal-dual dynamics are globally exponentially stable even if the constraint matrix is not full-row rank. We also provide an explicit characterization of the exponential convergence rate in terms of the smallest nonzero singular value of the constraint matrix.

10:45-11:00 WeA05.4

**Accelerated Algorithms for a Class of Optimization Problems with Equality and Box Constraints**, pp. 216-221

Parashar, Anjali

Massachusetts Institute of Technology

Srivastava, Priyank

Massachusetts Institute of Technology

Annaswamy, Anuradha M.

Massachusetts Inst. of Tech

Convex optimization with equality and inequality constraints is a ubiquitous problem in several optimization and control problems in large-scale systems. Recently there has been a lot of interest in establishing accelerated convergence of the loss function. A class of high-order tuners was recently proposed in an effort to lead to accelerated convergence for the case when no constraints are present. In this paper, we propose a new high-order tuner that can accommodate the presence of equality constraints. In order to accommodate the underlying box constraints, time-varying gains are introduced in the high-order tuner which leverage convexity and ensure anytime feasibility of the constraints. Numerical examples are provided to support the theoretical derivations.

11:00-11:15 WeA05.5

An Event-Triggered Distributed Nonsmooth Resource Allocation Algorithm for Second-Order Multi-Agent Systems, pp. 222-227

Shi, Xiaosheng

China University of Mining and Technology

Ding, Lifu

Zhejiang University

Lin, Zhiyun

Southern University of Science and Technology

This brief aims to solve the distributed resource allocation problem for second-order multi-agent systems over an undirected network, where the global objective function is strongly convex but not necessarily Lipschitz continuous for its subgradient. The resource state is subject to a global equality constraint and several local inequality constraints with a convex function. Unlike existing tracking deviation control strategies, a dynamic event-triggered and initialization-free distributed resource allocation algorithm is proposed to reduce the communication burden among agents. The local constraints are solved by an adaptive control approach based on the Karush-Kuhn-Tucker condition. It is shown that the proposed algorithm asymptotically converges to the optimal solution by using the set-valued LaSalle’s invariance principle. Moreover, it is guaranteed that Zeno behavior is ruled out for any agent. Finally, a simulation example shows the effectiveness of the proposed algorithm.

11:15-11:30 WeA05.6

**Zero-Gradient-Sum Algorithm-Based Distributed Optimization in Finite Time for Agents on Signed Networks**, pp. 228-233

Yang, Ying

Northeastern University, China

Ma, Dan

Northeastern University

Zhang, Yingwei

Northeastern University

Based on zero-gradient-sum (ZGS) algorithm, this paper studies the finite-time distributed optimization problem for multi-agent systems (MASs) over signed networks. First, a finite-time distributed control protocol is designed to ensure all agent states to realize bipartite consensus in a finite time under undirected signed graphs. Meanwhile, the optimized solutions of minimizing global convex objective functions under undirected signed graphs also converge to the bipartite consensus values. Moreover, the finite-time upper bound is given, which depends on the initial states and also the choice of the parameters in the proposed protocols. Then, extend the results to the case of signed digraphs. Finally, simulation results show the validity of the proposed methods.

WeA06

**Nonlinear Systems (Regular Session)**

Sapphire 411B

Chair: Ma, Tong

Northeastern University

Co-Chair: Russo, Giovanni

University of Salerno

10:00-10:15 WeA06.1

**High-Gain Output Feedback Control Design for a Class of Uncertain Nonlinear Systems Using Gaussian Processes**, pp. 234-239

Ma, Tong

Northeastern University

This paper considers the tracking control problem of a class of uncertain nonlinear systems with partial noisy measurements. To cope with the uncertainties including the unknown nonlinear dynamics and unmeasured state variables, simultaneous estimation of all the hidden states and unknown dynamics are required for the controller design. In this paper, a high-gain observer delivers a good property of disturbance rejection and provides state estimates which serves as the training data for learning the unknown dynamics. Because the measurements are corrupted by noise, this leads to estimation error in the state estimates. Since the Gaussian process (GP) has high flexibility to capture the complex unknown functions by using very few parameters and it inherently handles measurement noise, a GP model is employed to learn the unknown dynamics from the state estimates. This provides critical information for the control design such that the
unknown dynamics is compensated and a good tracking performance is delivered. In short, the high-gain observer provides state estimates for the GP model to learn the unknown dynamics from noisy measurements, which enables the development of the controller. Comparisons against L1 adaptive control and high-gain output feedback controller without GP learning are carried out.

10:15-10:30 WeA06.2

On the Design of Multiplex Control to Reject Disturbances in Nonlinear Network Systems Affected by Heterogeneous Delays, pp. 240-245

Xie, Shihao University College Dublin
Russo, Giovanni University of Salerno

We consider the problem of designing control pro- tocols for nonlinear network systems affected by heterogeneous, time-varying delays and disturbances. For these networks, the goal is to reject polynomial disturbances affecting the agents and to guarantee the fulfillment of some desired network behavior. To satisfy these requirements, we propose an integral control design implemented via a multiplex architecture. We give sufficient conditions for the desired disturbance rejection and stability properties by leveraging tools from contraction theory. We illustrate the effectiveness of the results via a numerical example that involves the control of a multi-terminal high-voltage DC grid.

10:30-10:45 WeA06.3

Time Delay Based Neural Network Control for Systems with State-Dependent Nonlinearity, pp. 246-251

Patar, Abhishek Massachusetts Institute of Technology
Meng, Qinghui Weichai Power Co., Ltd
Wang, Hanrui Weichai Power
Youcef-Toumi, Kamal Massachusetts Inst. of Tech

This paper tackles the problem of control for a class of nonlinear systems with state-dependent nonlinearities. A new control algorithm combining Time Delay Control and Neural Networks is proposed for such systems. Assuming all state variables are available, the proposed control algorithm is shown to learn the nonlinearity online, provide closed loop stability and achieve tracking performance better than that of time delay control. The performance of the proposed control algorithm is evaluated and compared to that of Time Delay Control and traditional PI control through simulation studies of an Interior type Permanent Magnet Synchronous Motor (IPMSM).

10:45-11:00 WeA06.4

Small Gain Theorem and L2 Gain Computation in Large Using Koopman Spectrum, pp. 252-257

Sutavani, Sarang Clemson University
Umathe, Bhagya Shree Clemson University
Vaidya, Umesh Clemson University

The paper is about L2-gain computation and the small-gain theorem for nonlinear input-output systems. We show that the Koopman operator’s spectrum can provide conditions for L2-gain guarantees and small-gain theorem-based stability of interconnection over a large region of the state space. The large region in the state space can be characterized in terms of the region where Koopman eigenfunctions and the solution of the Hamilton Jacobi equation are well defined. The connection of system L2-gain to the spectral properties of the Koopman operator has led to a novel approach, based on the approximation of the Koopman spectrum, for the computation of the L2-gain and stability verification of the interconnected system. We present simulation results including application of the developed framework to a power system example.

11:00-11:15 WeA06.5

Discrete-Time Transverse Feedback Linearization, pp. 258-263

D’Souza, Rollen S. Unaffiliated

Applications of transverse feedback linearization (TFL) vary from path following mobile robots to vehicle formation control. These applications were, however, restricted to systems adequately modelled in continuous-time. Recent work demonstrated that the established technique fails when applied to a discrete-time system using a zero-order hold. An additional change of coordinates dependent on the sampling period that preserves the required properties was proposed as an alternative. This technique, however, only applies to sampled-data systems. This article instead proposes a direct design approach that starts with a discrete-time system and designs a discrete-time transverse feedback linearizing controller. The discrete-time transverse feedback linearization problem is posed, and resolved for a single-input nonlinear discrete-time system. An example of path following for a forward-Euler discretized, kinematic unicycle model is presented to demonstrate its effectiveness.

11:15-11:30 WeA06.6

Chance-Constrained State Feedback Control Law Design for Nonlinear Systems under Uncertainties, pp. 264-270

Yang, Yu California State University Long Beach
Dam, Nguyen Cam Thuy California State University Long Beach

A chance-constrained full-state feedback control law is designed to regulate nonlinear systems under uncertainties. The proposed scheme utilizes Monte Carlo sampling to generate multiple scenarios, formulates the optimal control problem as a scenario-based nonlinear optimization, and develops a sequential algorithm to obtain probabilistic feasible solutions. The resulting controller offers three advantages: First, the optimization-based design minimizes the tracking error across considered scenarios. Second, the sampling complexity is determined adaptively and the chance of constraint violation is bounded with a guaranteed confidence interval. Third, the sequential algorithm can reach a probabilistic feasible solution faster than directly using a state-of-the-art solver for the full-scenario optimization problem. Two case studies, including a CSTR and fermentor, are presented to demonstrate the effectiveness of the proposed method.

WeA07 Identification (Regular Session) Aqua 303

Chair: Chakravorty, Suman Texas A&M University
Co-Chair: Rivera, Daniel E. Arizona State Univ

10:00-10:15 WeA07.1

Temporal Forward-Backward Consistency, Not Residual Error, Measures the Prediction Accuracy of Extended Dynamic Mode Decomposition, pp. 271-276

Haseli, Masih University of California, San Diego
Cortes, Jorge University of California, San Diego

Extended Dynamic Mode Decomposition (EDMD) is a popular data-driven method to approximate the action of the Koopman operator on a linear function space spanned by a dictionary of functions. The accuracy of EDMD model critically depends on the quality of the particular dictionary span, specifically on how close it is to being invariant under the Koopman operator. Motivated by the observation that the residual error of EDMD, typically used for dictionary learning, does not encode the quality of the function space and is sensitive to the choice of basis, we introduce the novel concept of consistency index. We show that this measure, based on using EDMD forward and backward in time, enjoys a number of desirable qualities that make it suitable for data-driven modeling of dynamical systems: it measures the quality of the function space, it is invariant under the choice of basis, can be computed in closed form from the data, and provides a tight upper-bound for the relative root mean square error of all function predictions on the entire span of the dictionary.
The T26.4 Method is a new approach to identifying the parameters of overdamped or slightly underdamped 2nd order LTI systems either graphically or by table look-up. The method computes the ratio of the time at which the step response reaches 26.4% of its final value to the time at which it reaches a specific fraction of its final value (such as 60%, 75%, or 90%). This ratio is the input to a table or graph to determine the values of the poles normalized by the 26.4% time. Unlike the Beta T-star Method, the T26.4 method does not require differentiation of the step response, and thus it is well-suited to system identification from noisy or sparse step response data. This paper presents the use of disrete simultaneous perturbation stochastic approximation (DSPSA) as a routine method to efficiently determine features and parameters of idiographic (i.e. single subject) dynamic models for personalized behavioral interventions using various partitions of estimation and validation data. DSPSA is demonstrated as a valuable method to search over model features and regressor orders of AutoRegressive with eXogenous input estimated models using participant data from Just Walk (a behavioral intervention to promote physical activity in sedentary adults); results of DSPSA are compared to those of exhaustive search. In Just Walk, DSPSA efficiently and quickly estimates models of walking behavior, which can then be used to develop control systems to optimize the impacts of behavioral interventions. The use of DSPSA to evaluate models using various partitions of individual data into estimation and validation data sets also highlights data partitioning as an important feature of idiographic modeling that should be carefully considered.
Markov chains. In this approach, ODEs are used to represent classical compartmental models and Markov chains to govern the mutation of the virus between predetermined variants. This method considers a discrete variant space allowing for more simple parameter tuning to previously recorded data. A cost function is designed in order to study optimal decision making with respect to non-pharmaceutical interventions such as social distancing. This model will serve to highlight the importance of considering variants in the long-term decision making process.

10:15-10:30 WeA08.1

Parametric and Non-Parametric Estimation of a Random Diffusion Equation-Based Population Model for Deconvolving Blood/Breath Alcohol Concentration from Transdermal Alcohol Biosensor Data with Uncertainty Quantification (I), pp. 313-318

- Allayioti, Maria
  - University of Southern California
- Oszkinat, Clemens
  - University of Southern California
- Salidch, Emily
  - University of Southern California
- Goldstein, Larry
  - University of Southern California
- Luczak, Susan
  - University of Southern California
- Wang, Chunming
  - Univ. of Southern California
- Rosen, I. Gary
  - Univ. of Southern California

A population model for the transdermal transport of ethanol from the blood to an alcohol biosensor on the surface of the skin in the form of a random abstract parabolic hybrid system of coupled ordinary and partial differential equations is developed. Linear semigroup theory in a Gelfand triple of Bochner spaces is used to first formulate the model as an equivalent deterministic system in state space form and to then develop a finite dimensional approximation and convergence theory. Both parametric and non-parametric techniques, the method of moments and kernel density estimation, and clinically collected drinking data are used to estimate the distributions of the model's parameters. Numerical results demonstrate the efficacy of using our model to 1) deconvolve an estimate of blood alcohol concentration from biosensor measured transdermal alcohol level and 2) quantify the uncertainty in the estimate.

10:30-10:45 WeA08.2

Adaptive Alternatives in the Velocity Control of Mean-Field Kuramoto Models (I), pp. 319-324

Demetriou, Michael A.
Worcester Polytechnic Institute

This paper presents an alternative control design for the macroscopic model of Kuramoto oscillators. The resulting partial differential equation describing the density of the collective dynamics is a nonlinear version of the continuity equation in which the control signals are coupled to the state. An optimal control for the bilinear system provides optimality of the controllers but it also results in an open-loop policy due to the backward in time integration of adjacent states. To tackle this, an adaptive alternative is considered and which views the control signals corresponding to a target density, as unknown spatiotemporally varying parameters. An adaptive observer is proposed along with the Lyapunov-redesign of the parameter adaptive laws. The stability of the closed-loop density equation using adaptive estimates of the controllers along with tracking convergence are examined.

10:45-11:00 WeA08.3

H-Infinity Control of a Heated/Cooled Rod under Point Actuation and Point Sensing (I), pp. 325-329

Krener, Arthur J
Naval Postgraduate School

Our long term goal is to extend the H-Infinity paradigm to nonlinear, infinite dimensional systems under point actuation and point sensing. This paper is the first step in this direction. We find the minimum L2 gain from the noisy heat flux at one end of a rod to the temperature at an arbitrary point of the rod that can be achieved by state feedback on the heat flux at the other end of the rod. We do this by completing the square to obtain a Riccati partial differential equation whose solution yields a state feedback control law that achieves a given L2 gain. We solve the Riccati PDE by Fourier series. We iterate this process to find the minimum L2 gain.

11:00-11:15 WeA08.4

A Cascading Method for Reducing Asymptotic Errors in Feedback Control of Nonlinear Distributed Parameter Systems (I), pp. 330-335

Aulisa, Eugenio
Texas Tech University
Burns, John A
Virginia Tech
Gilliam, David S.
Texas Tech University

This paper presents an error feedback controller for approximate tracking and disturbance rejection for nonlinear distributed parameter systems. The controller is error feedback because the only information available to the controller is the error as given as the difference between the reference signal to be tracked and the measured output of the plant. In particular, the controller cannot directly access the output data. Also, the unknown disturbance corrupting the plant is unavailable to the controller. The controller is "approximate" in the sense it only guarantees a small tracking error rather than an asymptotic zero tracking error. However, the asymptotic tracking error can be reduced by solving a sequence of controllers, similar to cascade controllers, where the error at one level becomes the target to track at the next level. At each step, the error is reduced geometrically, so achieving the desired tracking level seldom requires more than one or two iterations. We present a numerical example to demonstrate the utility of the method.

11:15-11:30 WeA08.5

A Note on the Optimality of Balanced Truncation for a Class of Infinite Dimensional Systems (I), pp. 336-340

Djouadi, Seddik, M.
University of Tennessee

Balanced truncation is a popular model reduction method that uses balanced realizations for finite dimensional systems. The latter are state space realizations where the controllability and observability gramians are equal to the same diagonal positive matrix. In this paper, a generalization of balanced realizations for a class of infinite dimensional LTI systems is employed to perform balanced truncation. It is shown that balanced truncation is optimal in the Hilbert-Schmidt sense if a particular time-varying balanced realization is used for the original LTI system. It appears that the use of time-varying balanced realizations to study the optimality and perform balanced model reduction for LTI systems is novel.
locally optimal solution compared to other distributed methods. In addition, our algorithm achieves about the same communication overhead as the best competing distributed algorithm.

10:15-10:30 WeA09.2

Improved Action Potential Detection for Imaging Techniques by Exploiting Fuzzy C-Means Clustering, pp. 349-354

Fauser, Moritz
Rheinland-Pfälzische Technische Universität Kaiserslautern-Land

Zhang, Ping
Rheinland-Pfälzische Technische Universität Kaiserslautern-Land

Wadle, Simon
Technische Universität Kaiserslautern

Hirtz, Jan
Technische Universität Kaiserslautern

In recent years, observing neuronal activity by inferring action potentials (APs) in mammals has attracted much attention. A common way to observe thousands of neurons simultaneously is by using calcium imaging techniques. However, estimating the APs based on the fluorescence signal obtained by the calcium imaging technique is a challenging task due to noise, slow imaging rates and especially the nonlinearity of the calcium binding kinetics. Though the electrical recording technique can measure the APs very precisely, it is rather time consuming in practice. In this paper, an approach is proposed that reconstruct the APs based on the noisy fluorescence signal. For this purpose, at first the forward-backward filtering is applied on the fluorescence signal to reduce the level of noise and to avoid the nonlinear shift in time with respect to the true fluorescence signal. Then, for each local maximum in the filtered fluorescence signal, three characteristic values, namely, the integral, the amplitude and the gradient are extracted to localize the neuronal activity. By exploiting the fuzzy c-means clustering method, the time instants and the number of APs can be estimated. The proposed approach is validated by using the well-established spikefinder challenger data. The comparison shows that the proposed approach outperforms other existing AP estimation approaches.

10:30-10:45 WeA09.3

The Kernel-SME Filter with Adaptive Kernel Widths for Association-Free Multi-Target Tracking, pp. 355-361

Ernst, Eugen
Karlsruhe Institute of Technology (KIT)

Pfaff, Florian
Karlsruhe Institute of Technology (KIT)

Hanebeck, Uwe D.
Karlsruhe Institute of Technology (KIT)

Baum, Marcus
Karlsruhe Institute of Technology (KIT)

Different objectives and paradigms exist for tracking multiple targets when measurements do not contain information about the target identities (IDs). The Symmetric Measurement Equation (SME) filter can be used when one is agnostic to the labels and does not attempt to assign different IDs to the different targets. We present an extension of the Kernel-SME filter that, unlike the original variant, uses adaptive kernel widths that depend on the respective uncertainty. In our evaluation, it outperformed existing SME-based approaches, while it is only second to a more complex global nearest neighbor tracker.

10:45-11:00 WeA09.4

Closed-Form Hilbert Projection for Quantum State Observers, pp. 362-367

Clouatre, Maison
Texas A&M University

Balas, Mark
Texas A&M University

Thitsa, Makhin
Mercer University

Designing an observer of an unknown quantum density operator is difficult because the operator must be Hermitian positive semidefinite with unit trace. In this paper, we derive a closed-form solution for projecting an arbitrary matrix onto the set of valid density operators.

This allows us to design linear quantum state observers and retract the observer’s state back to this set while retaining the exponential convergence rate of the linear observer. The derived closed-form projection can be used alongside any quantum state estimation technique to produce a valid state estimate without increasing the state estimation error.

11:00-11:15 WeA09.5

REACTMIN: Reactive Scanning Based Single Particle Tracking Using a Minimum of Light, pp. 368-373

Vickers, Nicholas A.
Boston University

Subedi, Sandip
Boston University

Andersson, Sean B.
Boston University

Real-time feedback-driven single particle tracking is an emerging method of measuring the state and dynamics of individual molecules and particles at the nanometer scale as they move inside living cells. Two problems limit current performance: the photon budget of fluorescent labels, and the control temporal budget. REACTMIN overcomes these challenges by reactively scanning a minimum of light to track diffusing particles and molecules. It is comprised of a non-holonomic based extremum seeking controller and structured illumination using a laser with a central minimum. The controller allows for estimationless tracking, addressing the control temporal budget, and the structured illumination enables information-rich measurements, addressing the photon budget. We use two metrics of performance, Fisher information and tracking duration, to characterize the system and find optimal settings for one of the dominant controller parameters, the steady state orbital radius. We demonstrate a trade-off between tracking duration and localization precision and discuss how to select this parameter in the context of specific experimental aims.

11:15-11:30 WeA09.6

Digital Twin Design for hMSC Expansion in Hollow-Fiber Bioreactors, pp. 374-380

Kanwar, Bharat
Georgia Institute of Technology

Wang, Bryan
Georgia Institute of Technology

Roy, Krishnendu
Georgia Institute of Technology

Mazumdar, Anirban
Georgia Institute of Technology

Balakirsky, Stephen
Georgia Tech Research Institute

Human Mesenchymal Stromal Cells (hMSC) have shown promising pre-clinical results by eliciting immunomodulatory effects to alleviate inflammation. In order to further study these effects, consistent and automated expansion platforms are required. Recent theoretical innovations have shown that model-based automated controls can more effectively regulate key nutrient concentrations. However, this previous work did not account for time-varying cell growth and death which resulted in inconsistent modeling and controller performance. To mitigate these effects, we propose a new model with time-varying parameters to track viable, proliferating, and dead cells and their respective growth rates with algorithms to estimate these parameters as functions of our limited measured states. We then propose an updated control architecture (referred to as smooth-controller) to leverage the additional parameters for improved estimation and control. The control objective is to regulate glucose and lactate to fixed setpoints while minimizing total media usage and large flowrate disturbances. Finally, we demonstrate the new control architecture in hMSC expansion with improved lactate setpoint MSE (58% reduction), improved observer MSE (36% for glucose and 20% for lactate), and reduced process disturbance (1 to 0 lactate spikes). Although the smooth-controller did not improve cell yield (4.91*10^7 compared to 5.08*10^7), it did reduce media usage to match the reduced growth rate thereby increasing cell yield per mL of fed media (6.3*10^4 to 8.6*10^4).

WeA10

Agents-Based Systems I (Regular Session)

Aqua 309
In this work, a multi-agent system with emergent hypocyloidal and epicycloidal behaviors is analyzed. Agents are assumed to be modeled as double integrators with an acceleration law designed so that the swarm exhibits cycloidal-like trajectories. The resulting control protocol benefits from speeds and positions coupling among neighbors agents to let each agent perform hypocyloidal or epicycloidal curves according to the choice of the controller parameters and the agents initial conditions. As a first step, the model properties are obtained assuming that the communication topology of the multi-agent system is defined by a complete graph. As a further step, the model main features are extended by relaxing the complete connection assumption and replacing it with a more realistic one in which a connected graph is considered. This latter step is achieved by means of a consensus-based estimation of the swarm centroid, so that to virtualize the complete graph starting from a connected one. Simulations have been performed to show the properties of the obtained agents evolution.

This paper introduces the concept of formation switching in time-varying formation tracking (TVFT) control for linear time-invariant (LTI) multi-agent systems (MASs) under the collision avoidance constraints. One of the main challenges in designing a novel formation controller is that the leader agent does not prespecify the desired formation to the follower agents. Also, the former may change the desired formation to any other at the run time according to task requirements and environmental spatial constraints. Based on estimation of the so-called generator matrix and the formation vector, follower agents maintain the time-varying formation while tracking the leader. The exponential stability of the overall proposed distributed control scheme is proved using the Lyapunov stability theory. Finally, the effectiveness of the formation switching in TVFT is demonstrated using a numerical example.
be implemented locally since only the nodes or edge-weights involved in the cycle or adjacent to it need to effect changes to guarantee consensus while the rest of the agents remain unaffected.

In this work, we extend the convex body chasing problem to an adversarial setting, where an agent (the Player) is tasked to chase a sequence of convex bodies generated adversarially by an opponent. The Player aims to minimize the cost associated with its total movements, while the Opponent tries to maximize. The set of feasible convex bodies is finite and known to both agents, which allows us to provide performance guarantees with max-min optimality rather than via the competitive ratio. Under some mild assumptions, we show the continuity of the optimal value function and provide an algorithm to numerically generate the optimal policies with performance guarantees. Finally, the theoretical results are verified through numerical examples.

A salient feature of many optimal decision-making policies in adversarial environments is a level of unpredictability, or randomness, which keeps opponents uncertain about the system's strategies. These considerations, along with feedback from adversarial behaviors, are crucial in ensuring the security of modern infrastructures and complex systems. This paper considers policies that do just the opposite, namely ones that reveal strategic intentions to an opponent before engaging in competition. We consider such scenarios in the context of General Lotto games, which models the competitive allocation of resources between opposing players. Here, we consider a dynamic extension where one of the players has the option to publicly pre-commit assets to a battlefield in the first stage. In response, the opponent decides whether to secure the battlefield or withdraw from it entirely. They then engage over the remaining set of battlefields in the second stage. We show that the weaker-resource player can have incentives to pre-commit when the battlefield values are asymmetric across players. Previous work asserts this never holds when the values are symmetric across players. Our analysis demonstrates the viability of alternate strategic mechanisms that a competitor may be able to employ.

10:45-11:00 WeA11.3 Differentially Private Games Via Payoff Perturbation, pp. 429-434
Chen, Yijun University of Sydney
Shi, Guodong The University of Sydney

In this paper, we study network games where players are involved in information aggregation processes subject to the differential privacy requirement for players' payoff functions. We propose a Laplace linear-quadratic functional perturbation (LLQFP) mechanism, which perturbs players' payoff functions with linear-quadratic functions whose coefficients are produced from truncated Laplace distributions. For monotone games, we show that the LLQFP mechanism maintains the concavity property of the perturbed payoff functions, and produces a perturbed NE whose distance from the original NE is bounded and adjustable by Laplace parameter tuning. We focus on linear-quadratic games, which is a fundamental type of network games with players' payoffs being linear-quadratic functions, and derive explicit conditions on how the LLQFP mechanism ensures differential privacy with a given privacy budget. Lastly, numerical examples are provided for the verification of the advantages of the LLQFP mechanism.

10:00-10:15 WeA11.1 Defending a Target Area with a Slower Defender, pp. 417-422
Fu, Han University of Toronto
Liu, Hugh Hong-Tao Univ. of Toronto

The target defense game is an abstraction of the counter-UAV mission, where a defender intends to intercept an invading drone before it enters a target area. While most studies on target defense games assume the defender travels faster, defending a target area with a slower defender is a less studied yet challenging problem because capture cannot be guaranteed. This paper identifies two special cases where the defender has a chance to win, where the game region is bounded and where the target area is small. In the former case, the defender traps the invader at the corner. In the latter case, the defender delays the entering permanently by rotating around the target area at a sufficiently large angular speed. In both games, the optimal trajectory has a two-stage structure. Exploiting this feature, a novel method is proposed to solve for the barrier, which gives guidelines on how to deploy the defenders to ensure the target area been protected.

We investigate a multi-agent decision problem in population games where each agent in a population makes a decision on strategy selection and revision to engage in repeated games with others. The strategy revision is subject to time delays which represent the time it takes for an agent revising its strategy needs to spend before it can adopt a new strategy and return back to the game. We discuss the effect of the time delays on long-term behavior of the agents' strategy revision. In particular, when the time delays are large, the strategy revision would exhibit oscillation and the agents spend substantial time in "transitioning" between different strategies, which prevents the agents from attaining the Nash equilibrium of the game. As a main contribution of the paper, we propose an algorithm that tunes the rate of the agents' strategy revision and show such tuning approach ensures convergence to the Nash equilibrium. We validate our analytical results using simulations.
We consider a path guarding problem in dynamic Defender-Attacker Blotto games (dDAB), where a team of robots must defend a path in a graph against adversarial agents. Multi-robot systems are particularly well suited to this application, as recent work has shown the effectiveness of these systems in related areas such as perimeter defense and surveillance. When designing a defender policy that guarantees the defense of a path, information about the adversary and the environment can be helpful and may reduce the number of resources required by the defender to achieve a sufficient level of security. In this work, we characterize the necessary and sufficient number of assets needed to guarantee the defense of a shortest path between two nodes in dDAB games when the defender can only detect assets within k-hops of a shortest path. By characterizing the relationship between sensing horizon and required resources, we show that increasing the sensing capability of the defender greatly reduces the number of defender assets needed to defend the path.

Pappas, George J. University of Pennsylvania
Kumar, Vijay University of Pennsylvania

WeA12
Advanced Controls in Automotive Systems (Invited Session)
Chair: Chen, Pingen Tennessee Technological University
Co-Chair: Wang, Zejiang Oak Ridge National Laboratory
Organizer: Wang, Zejiang Oak Ridge National Laboratory
Organizer: Ozkam, Mehmet Texas Tech University
Organizer: Chen, Pingen Tennessee Technological University

A Novel and Elliptical Lattice Design of Flocking Control for Multi-Agent Ground Vehicles (I), pp. 454-459
Wang, Gang Arizona State University
Liu, Mingzhe Arizona State University
Wang, Fengchen The MathWorks, Inc
Chen, Yan Arizona State University

Flocking control of multi-agent ground vehicles recently attracted rising attention because of its strength in extending 1D platooning to coordinated 2D movements. However, the uniform interaction ranges and the non-defined orientation of the flocking lattice make flocking control of ground vehicles face some key issues. To achieve cooperative motions of connected and automated vehicles (CAVs), this letter proposed a novel and elliptical lattice to extend the existing flocking theory with a uniform hexagon lattice. The proposed elliptical lattice is designed based on the characteristics of the vehicle heading direction, velocity, minimum safety distance, and lane width to analytically adapt to vehicle driving environments. Moreover, a new flocking control law considering road boundaries’ (permanent) repulsive forces is developed to ensure the desired formation at a steady state. Simulation results show that the proposed elliptical lattice of flocking control can be applied to realize cooperative driving of multi-agent CAVs with the desired formation on the road.

Pacejka-Like Curve-Based Speed Reference Generators for Electric Vehicles Powered by In-Wheel Motors (I), pp. 460-465
Verrelli, Cristiano Maria Tor Vergata University
El Arayshi, Mohamed University of Rome Tor Vergata, Electronic Engineering Department

Recently, motor speed reference generators have been designed for the cruise control of electric vehicles with either centralized electric motors (straight manoeuvres) or in-wheel motors (bend manoeuvres with sufficiently small constant steering angles). Steady-state operation at a safe (though conservative) tire longitudinal slip can be achieved, with no a priori knowledge regarding the occurrence of a specific external condition. Here, an innovative solution is presented.

It is based on an ingenious use of Pacejka-like curves - representing the torque current-slip characteristics of the vehicle - to design a new contraction-mapping-based automatic tuning procedure for the longitudinal velocity of the vehicle. Such an innovative procedure overcomes the highly conservative nature of the previous approach in terms of unduly small longitudinal velocities (and yaw rates) under relatively favourable external conditions while guaranteeing a safe operating condition close to the maximum of the torque-slip characteristics with no knowledge of the tire-road adhesion coefficient. Comparative CarSim simulations illustrate the effectiveness of the proposed approach, in the presence of uncertain parameters and complex vehicle dynamics that are neglected at the control design stage.

10:30-10:45 WeA12.3
Koysuren, Muhammed Kemal Bilkent University
Keles, Ahmet Faruk Bilkent University
Cakmakci, Melih Bilkent University

Physics-informed deep learning is a popular trend in the modeling and control of dynamical systems. This paper presents a novel method for rapid online identification of vehicle cornering stiffness coefficient, a crucial parameter in vehicle stability control models and control algorithms. The new method enables designers to rapidly identify the vehicle front and rear cornering stiffness parameters so that the controller reference gains can be re-adjusted under varying road and vehicle conditions to improve the reference tracking performance of the control system during operation. The proposed method based on vehicle model-based deep learning is compared to other alternatives such as traditional network training and identification, and Pacejka model estimation with regression. Our initial findings show that, in comparison to these classical methods, high fidelity estimations can be done with much smaller data sets simple enough to be obtained from a lane-changing or vehicle overtake maneuver. In order to conduct experiments, and collect sensor data, a custom-built 1:8 scaled test vehicle platform is used to test results show that the reference gains updated with the proposed online estimation method improve the tracking performance in both simulations and vehicle experiments.

10:45-11:00 WeA12.4
Adversarial Learning for Safe Highway Driving Based on Two-Player-Zero-Sum Game (I), pp. 472-477
Li, Fangqian Clemson University
Zhao, Mengtjao Clemson University
Wagner, John R. Clemson University
Wang, Yue Clemson University

In this paper, we set up a two-player-zero-sum Markov game (TZMG) framework to train a safe driving policy network so that the worst intentions of the neighbor vehicles can be considered. Compared to the conventional policy learning frameworks, the TZMG framework can embed the adversary from the neighbor vehicle throughout its training process. Furthermore, a novel TZMG Q-learning algorithm based on the Wolpertinger policy is proposed to be scalable to multiple adversarial neighbor vehicles. Finally, simulations and human-in-the-loop experiments are conducted to verify the effectiveness of the TZMG framework and novel algorithm. Compared to the benchmarking safety controllers in the literature, our proposed novel TZMG algorithm can achieve a much lower collision rate when dealing with adversarial neighbor vehicles.

11:00-11:15 WeA12.5
Safe Lane-Keeping with Feedback Delay: Bifurcation Analysis and Experiments (I), pp. 478-483
A lane-keeping controller for automobiles is analyzed in this paper, with the consideration of time delay in the feedback loop. Using numerical continuation, unstable periodic orbits are identified inside the linearly stable domain of control gains. Based on the amplitude of these unstable solutions, safe parameter zones can be identified, where the closed loop system is robust against perturbations, i.e., where the basin of attraction of the stable equilibrium is larger. The sensitivity to initial conditions in different regions of linearly stable control gains is demonstrated by a series of real vehicle experiments. Finally, modifications of the control law are proposed that lead to significant improvements in terms of the robustness against perturbations of the controlled vehicle, achieving global stability in the practical sense.

11:15-11:30 WeA12.6

Energy Impact of Connecting Multiple Signalized Intersections to Energy-Efficient Driving: Simulation and Experimental Results (I), pp. 484-489

Han, Jihun
Shen, Daliang
Jeong, Jongryeol
Di Russo, Miriam
Kim, Namdoo
Karbossi, Dominik
Rousseau, Aymeric
Stutenberg, Kevin
Argonne National Laboratory
Argonne National Laboratory
Argonne National Laboratory
Argonne National Laboratory
Argonne National Laboratory
Argonne National Laboratory
Argonne National Laboratory

Vehicle-to-infrastructure (V2I) communication connects vehicles and enables collision-free and energy-efficient driving, such as eco-approaches and departures at signalized intersections. An increased connectivity range can connect multiple signalized intersections and lead to long-term energy-efficient driving using richer information. However, no published studies to date provide insights into the energy-saving potential of increasing the connectivity range. In this paper, we present a V2I-enabled eco-driving control that can perform multiple traffic signal eco-approaches, and we systematically design a large-scale simulation study to quantify the energy impact of the increased V2I range for various scenarios. Simulation results show that the V2I-enabled eco-driving control can reduce energy use by up to 40%, on average, compared to the baseline, depending on road attributes and vehicle powertrain type. We validate these findings by evaluating the controller through a vehicle-in-the-loop (VIL) testing platform.

WeA13

Distributed Control I (Regular Session)

Chair: Dogan, Kadriye Merve
Co-Chair: Loria, Antonio
Embry-Riddle Aeronautical University
CNRS
10:00-10:15 WeA13.1

An Agent-Related Asynchronous Consensus Method for Fast Scheduling of UAV Swarm, pp. 490-496

Chen, Runfeng
Li, Jie
Chen, Yiting
Huang, Yuchong
National University of Defense Technology
National University of Defense Technology
National University of Defense Technology
National University of Defense Technology

UAV swarm needs careful task and time arrangement to complete complex tasks with spatiotemporal constraints such as search and rescue, which requires distributed scheduling methods. Market-based approach is the optimal choice to satisfy the centerless and self-organized characteristics of the swarm. However, the consensus methods adopted by most market-based algorithms require synchronous communication, which takes time to wait, so scholars resort to asynchronous consensus methods. The existing asynchronous method's communication traffic increases with the number of tasks, and the total number of messages sent can be further reduced. Therefore, this paper proposes a new asynchronous method to further reduce the communication traffic and the number of messages sent required by the market-based approach. Firstly, the timestamp of when a UAV updates its information is used cleverly, which reduces the communication traffic of the original timestamp of when a task's information is updated. And the new timestamp contains more information about the non-winner that is absent in the original timestamp, which facilitates new asynchronous consensus rules to resolve task conflicts faster. Secondly, agent-related asynchronous consensus rules with new timestamps are designed to resolve task conflicts, which effectively solves the problem of information arriving out of order and potentially reduces the number of messages sent. Finally, through a self-developed ad-hoc network simulation system, the swarm scheduling under real networking conditions is simulated. A large number of Monte Carlo simulation experiments show that compared with the most representative asynchronous method Asynchronous Consensus-Based Bundle Algorithm (ACBBA), the number of messages sent and communication traffic can be reduced by 61% and 70% at most, and the scheduling time can be reduced by up to 60%.

10:15-10:30 WeA13.2

Localization and Tracking Control of Autonomous Vehicles in Time-Varying Bearing Formation, pp. 497-502

Tang, Zhiqi
Loria, Antonio
Instituto Superior Técnico, Universidade De Lisboa
CNRS

This letter proposes an observer-based formation tracking control approach for multi-agent velocity-controlled vehicles under the assumption that either relative or global position measurements are unavailable for all the vehicles. It is assumed that only some vehicles (at least one) have access to their own global position, and all vehicles are equipped with sensors capable of sensing the bearings relative to neighboring vehicles. Each vehicle estimates its global position using relative bearing measurements and estimates of neighboring vehicles received over a communications network. Then, a distributed output-feedback observer-based controller is designed relying on bearing measurements and the estimated global positions. In contrast with the literature on bearing-based localization and control, we relax the common assumption of so-called bearing rigidity, and, in addition, we do not assume that the interconnections are constant. To the best of our knowledge, the bearing-based localization-and-tracking control problem under such assumptions remains open. In support of our theoretical findings, some simulation results are presented to illustrate the performance of the proposed observer-based tracking controllers.

10:30-10:45 WeA13.3

On the Equivalence of Multi-Agent 2D Coverage Control and Leader-Follower Consensus Network, pp. 503-508

Xu, Xiaotian
Davydov, Alexander
Diaz-Mercado, Yancy
University of Maryland College Park
University of California, Santa Barbara
University of Maryland

Coverage control algorithms seek to spatially distribute agents in a domain of coverage, e.g., to minimize proximity to all points. Leader-follower consensus network algorithms use local coordination rules to influence the behavior of a multi-agent system (MAS) as a whole through explicit control of a subset of agents (called leaders).
and neighbor interactions. In this paper, the equivalence of these two classes of distributed algorithms for swarm robotics, that were once considered inherently different, is established. We present a swarm robotics application, where the real agents (i.e., the robots) in the domain of coverage are followers; and virtual agents (i.e., the leaders) are introduced based on the domain of coverage. The dynamics of followers are shown to be in a form of a weighted, state-dependent consensus protocol and the dynamics of the leaders (dependent on the evolution of the domain) are provided. Formulating a standard coverage algorithm (i.e., Lloyd’s algorithm) over 2D polygonal domains as a leader-follower consensus protocol makes the structure of the ensemble-level dynamics for the MAS explicit with respect to neighbor interaction. The resultant weighted graph Laplacian may contribute to the future investigation on the performance guarantees of a MAS tracking a time-varying domain. The equivalence of the two classes of algorithms is validated in simulation.

10:45-11:00  WeA13.4

Exponential Bipartite Containment Tracking Over Multi-Leader Cooperation Networks, pp. 509-514

Sekercioğlu, Pelin  ONERA, Univ Paris-Saclay
Panteley, Elena  CNRS
Sarras, Ioannis  ONERA
Loria, Antonio  CNRS
Marzat, Julien  ONERA - the French Aerospace Lab

This paper addresses the distributed bipartite containment tracking-control problem for autonomous vehicles steered by multiple leaders. Some leaders are cooperative and others are competitive, so the vehicles form a so-called cooperation network; in which the interaction links may be negative or positive. The presence of cooperative and antagonistic leaders does not enable the system to achieve consensus. Instead, the followers' states converge to a residual compact set, not predefined, but depending only by the leaders' states. We establish global exponential stability for this so-called bipartite containment set, and we compute the exact equilibria to which all agents converge inside of it. Our proofs are constructive, that is, we provide strict Lyapunov functions, which also allow us to establish robustness with respect to external disturbances.

Numerical simulations illustrate our theoretical findings.

11:00-11:15  WeA13.5

Distributed Nash Equilibrium Seeking for Single-Integrator Dynamics Subject to Disturbances with Unknown Bounds, pp. 515-520

He, Xiongnan  Chinese University of Hong Kong
Huang, Jie  The Chinese University of Hong Kong

In this paper, we study the problem of Nash equilibrium seeking of N-player games for single integrator dynamics subject to bounded disturbances with unknown bounds. Compared with the existing results, two new features are worth mentioning. First, the communication network among players is jointly strongly connected, which can be disconnected at every time instant. Second, the class of the disturbances contains any bounded time function with the bounds unknown. To achieve our objective, we have proposed a novel approach by integrating the distributed estimator, some nonlinear control technique, and adaptive control technique. Our design is illustrated by an example of a group of velocity-actuated robots in sensor networks.

11:15-11:30  WeA13.6

An Observer-Based Distributed Adaptive Control Algorithm for Coordination of Multiagent Systems in the Presence of Coupled Dynamics, pp. 521-526

Aly, Islam  Embry-Riddle Aeronautical University
Kurttisi, Atahan  Embry-Riddle Aeronautical University

In this paper, a distributed adaptive control algorithm is designed for an uncertain multiagent system in the presence of unmeasurable coupled dynamics that adopts user-assigned Laplacian matrix nullspaces. Specifically, we use observer dynamics that help us to guarantee the overall system stability, low-frequency learning methods to deal with high-frequency learning, and a modified Laplacian matrix to coordinate the multiagent system. Our algorithm proposes the coordination of multiagent systems and an asymptotic decoupling approach. An illustrative numerical example is given to demonstrate our theoretical contributions.

WeA14

10:30-10:45  WeA14.1

Predictive Control and Planning Methods for Robotic Systems (Invited Session)

Chair: Zhang, Fumin  Georgia Institute of Technology
Co-Chair: Hou, Mengxue  Purdue University
Organizer: Hou, Mengxue  Purdue University
Organizer: Zhang, Fumin  Georgia Institute of Technology
Organizer: Mou, Shaoshuai  Purdue University
Organizer: Sundaram, Shreyas  Purdue University

The process-aware source seeking (PASS) problem in flow fields aims to find an informative trajectory to reach an unknown source location while taking the energy consumption in the flow fields into consideration. Taking advantage of the existing methods on flow field partition, this paper formulates this problem as a task and motion planning (TAMP) problem and proposes a bi-level hierarchical planning framework to decouple the planning of inter-region transition and inner-region trajectory by introducing inter-region junctions. An integrated strategy is utilized to enable efficient upper-level planning by investigating the optimal solution of the lower-level planner. The proposed algorithm provides guaranteed convergence of the trajectory, and achieves automatic trade-off between exploration and exploitation, which has been validated by the simulation results.

WeA14.2

Variable Sampling MPC Via Differentiable Time-Warping Function (I), pp. 532-538

Lu, Zehui  Purdue University
Mou, Shaoshuai  Purdue University

Designing control inputs for a system that involves dynamical responses in multiple timescales is nontrivial. This paper proposes a parameterized time-warping function to enable a non-uniformly sampling along a prediction horizon given some parameters. The horizon should capture the responses under faster dynamics in the near future and preview the impact from slower dynamics in the distant future. Then a variable sampling MPC (VS-MPC) strategy is proposed to jointly determine optimal control and sampling parameters at each timestamp. VS-MPC adapts how it samples along a prediction horizon given some parameters. The resultant weighted graph Laplacian may contribute to the future investigation on the performance guarantees of a MAS tracking a time-varying domain. The equivalence of the two classes of algorithms is validated in simulation.
We propose an interleaved method for robotic task and motion planning (TAMP) problems, which involves optimizing both continuous and discrete dynamic behaviors. The coupling between the task planning and motion planning results in a large search space, causing challenge for computing the optimal solution. To address this challenge, we develop a novel bi-level algorithm leveraging the Depth First Search (DFS) algorithm and the Monte Carlo Tree Search (MCTS) algorithm to solve the TAMP. Incorporating task completion cost estimation from the motion planning level, we solve the task planning problem in a computationally efficient manner. We prove that our proposed TAMP algorithm is complete, i.e., it always finds the optimal solution if there exists one. Finally, we present simulation results to demonstrate that the proposed algorithm can find the optimal solution of the TAMP problem with lower computation cost than existing algorithms.

Data-driven predictive control (DPC) is a feedback control method for systems with unknown dynamics. It repeatedly optimizes a system’s future trajectories based on past input-output data. We develop a numerical method that computes poisoning attacks that inject additive perturbations to the online output data to change the trajectories optimized by DPC. This method is based on implicitly differentiating the solution map of the trajectory optimization in DPC. We demonstrate that the resulting attacks can cause an output tracking error one order of magnitude higher than random perturbations in numerical experiments.

Water flow plays an important role in the operation of marine robotic vehicles (MRVs). In confined survey areas, accurate perception of the flow field can greatly assist MRVs in path planning and improve energy efficiency. Traditional flow observations rely on data from buoys and satellites, which is expensive and time-consuming. Therefore, predicting the flow field using the vehicle’s position and velocity information can significantly enhance work efficiency. Motion tomography (MT) is a time-efficient and convenient technique that estimates the flow field by separating the movement caused by the flow field from the trajectory of the MRV. Additionally, robotic fish are ideal for this flow field sensing task due to their maneuverability and versatility. Using robotic fish to sense the flow field can greatly benefit transportation and environment studies. However, MT ignores the rigid-body dynamics, which can significantly undermine the estimation accuracy. To address this challenge, we add an active heading control (AHC) to moderate the passive heading change caused by the flow field. With AHC’s help, the position and direction data collected from a robotic fish can provide a promising estimation of the flow field in both simulations and experiments.
heating and cooling penalty that does not require any sensor measurements. The optimizer then minimizes this cost function by automatically adjusting the supply temperature setpoint in the air-handling unit. The paper describes the approach and shows results from application from field trials on a 27-zone building.

10:15-10:30  WeA15.2

Two-Level Decentralized-Centralized Control of Distributed Energy Resources in Grid-Interactive Efficient Buildings (I), pp. 570-575

Huo, Xiang  University of Utah
Dong, Jin  Oak Ridge National Laboratory
Cui, Borui  Oak Ridge National Laboratory
Liu, Boming  Oak Ridge National Laboratory
Lian, Jianming  Oak Ridge National Laboratory
Liu, Mingxi  University of Utah

The flexible, efficient, and reliable operation of grid-interactive efficient buildings (GEBs) is increasingly impacted by the growing penetration of distributed energy resources (DERs). Besides, the optimization and control of DERs, buildings, and distribution networks are further complicated by their interconnections. In this paper, we exploit the load-side flexibility and clean energy resources to develop a novel two-level hybrid decentralized-centralized (HDC) algorithm for the coordination and control of DER-connected GEBs. The proposed HDC 1) achieves scalability w.r.t. to a large number of grid-connected buildings and devices, 2) incorporates a two-level design where an aggregator centrally controls at the building level and the system operator coordinates at the distribution network level in a decentralized way, and 3) improves the computing efficiency and communicating resilience with heterogeneous temporal scales. Simulations are conducted based on the prototype of a campus building at the Oak Ridge National Laboratory to show the efficiency and efficacy of the proposed approach.

10:30-10:45  WeA15.3

LSR-BO: Local Search Region Constrained Bayesian Optimization for Performance Optimization of Vapor Compression Systems (I), pp. 576-582

Paulson, Joel  The Ohio State University
Sorousifar, Farshad  Ohio State University
Laughman, Christopher R.  Mitsubishi Electric Research Labs
Chakrabarty, Ankush  Mitsubishi Electric Research Laboratories (MERL)

Bayesian optimization (BO) has recently been demonstrated as a powerful tool for efficient derivative-free optimization of expensive black-box functions, such as those prevalent in performance optimization of complex energy systems. Classical BO algorithms ignore the relationship between consecutive optimizer candidates, resulting in jumps in the admissible search space which can lead to fail-safe mechanisms being triggered, or undesired transient dynamics that violate operational constraints. In this paper, we propose LSR-BO, a novel global optimization methodology that enforces local search region (LSR) constraints by design, which restricts how much the optimizer candidate can be changed at every iteration. We demonstrate that naively incorporating LSR constraints into BO causes the algorithm to get stuck in local sub-optimal solutions, and overcome this challenge through the development of a novel exploration strategy that can gracefully navigate the tradeoff between short-term local, and long-term global, performance improvement. Furthermore, we provide theoretical guarantees on the convergence of LSR-BO. Finally, we verify the effectiveness of our proposed LSR-BO method on an illustrative benchmark and a real-world energy minimization problem for a commercial vapor compression system.

10:45-11:00  WeA15.4

Uncertainty-Aware Flexibility Envelope Prediction in Buildings with Controller-Agnostic Battery Models (I), pp. 583-590

Scharnhorst, Paul  EPFL

Buildings are a promising source of flexibility for the application of demand response. In this work, we introduce a novel battery model formulation to capture the state evolution of a single building. Being fully data-driven, the battery model identification requires one dataset from a period of nominal controller operation, and one from a period with relative flexibility requests, without making any assumptions on the underlying, but fixed, controller structure. We consider parameter uncertainty in the model formulation and show how to use risk measures to encode risk preferences of the user in robust uncertainty sets. Finally, we demonstrate the uncertainty-aware prediction of flexibility envelopes for a building simulation model from the Python library Energym.

11:00-11:15  WeA15.5

Thermal Comfort Control on Sustainable Building Via Data-Driven Robust Model Predictive Control, pp. 591-596

Chen, Wei-Han  Cornell University
Yang, Shiyu  Cornell University
You, Fengqi  Cornell University

While implementing renewable energy systems and model predictive control (MPC) could reduce non-renewable energy consumption, one challenge to building climate control using MPC is the weather forecast uncertainty. In this work, we propose a data-driven robust model predictive control (DDR-MPC) framework to address climate control of a sustainable building with renewable hybrid energy systems under weather forecast uncertainty. The control and energy system configurations include heating, ventilation, and air conditioning, geothermal heat pump, photovoltaic panel, and electricity storage battery. Historical weather forecast and measurement data are gathered from the weather station to identify the forecast errors and for the use of uncertainty set construction. The data-driven uncertainty sets are constructed with multiple machine learning techniques, including principal component analysis with kernel density estimation, K-means clustering coupled with PCA and KDE, density-based spatial clustering of applications with noise, and the Dirichlet process mixture model. Lastly, a data-driven robust optimization problem is developed to obtain the optimal control inputs for a building with renewable energy systems. A case study on controlling a building with renewable energy systems located on the Cornell University campus is used to demonstrate the advantages of the proposed DDR-MPC framework.

11:15-11:30  WeA15.6

Mixed-Integer Real-Time Control of a Building Energy Supply System, pp. 597-602

Burda, Artyom  Hannover University of Applied Sciences and Arts
Bitner, Dimitri  Hannover University of Applied Sciences and Arts
Bestehorn, Felix  Technical University of Braunschweig
Kirches, Christian  Technical University of Braunschweig
Groljah, Martin  Hannover University of Applied Science and Arts, Faculty of Mech

We present a methodology based on mixed-integer nonlinear model predictive control for a real-time building energy management system in application to a single-family house with a combined heat and power (CHP) unit. The developed strategy successfully deals with the switching behavior of the system components as well as minimum admissible operating time constraints by use of a special switch-cost-aware rounding procedure. The quality of the presented solution is evaluated in comparison to the globally optimal dynamic programming method and conventional rule-based control strategy.
Based on a real-world scenario, we show that our approach is more than real-time capable while maintaining high correspondence with the globally optimal solution. We achieve an average optimality gap of 2.5% compared to 20% for a conventional control approach, and are faster and more scalable than a dynamic programming approach.

WeA16
Learning and Stochastic Optimal Control (Invited Session)

Chair: Halder, Abhishek University of California, Santa Cruz
Co-Chair: Mesbah, Ali University of California, Berkeley
Organizer: Halder, Abhishek University of California, Santa Cruz
Organizer: Mesbah, Ali University of California, Berkeley

10:00-10:15
Stochastic Model Predictive Control Utilizing Bayesian Neural Networks (I), pp. 603-608
Pohlodek, Johannes TU Darmstadt
Alsmeier, Hendrik TU Darmstadt
Morabito, Bruno OVG University Magdeburg
Savchenko, Anton Technical University of Darmstadt
Findeisen, Rolf TU Darmstadt

Integrating measurements and historical data can enhance control systems through learning-based techniques, but ensuring performance and safety is challenging. Robust model predictive control strategies, like stochastic model predictive control, can address this by accounting for uncertainty. Gaussian processes are often used but have limitations with larger models and data sets. We explore Bayesian neural networks for stochastic learning-assisted control, comparing their performance to Gaussian processes on a wastewater treatment plant model. Results show Bayesian neural networks achieve similar performance, highlighting their potential as an alternative for control designs, particularly when handling extensive data sets.

10:15-10:30
A Physics-Informed Deep Learning Approach for Minimum Effort Stochastic Control of Colloidal Self-Assembly (I), pp. 609-615
Nodozi, Iman University of California, Santa Cruz
O’Leary, Jared University of California, Berkeley
Mesbah, Ali University of California, Berkeley
Halder, Abhishek University of California, Santa Cruz

We propose formulating the finite-horizon stochastic optimal control problem for colloidal self-assembly in the space of probability density functions (PDFs) of the underlying state variables (namely, order parameters). The control objective is formulated in terms of steering the state PDFs from a prescribed initial probability measure towards a prescribed terminal probability measure with minimum control effort. For specificity, we use a univariate stochastic model from the literature. Both the analysis and the computational steps for control synthesis as developed in this paper generalize for multivariate stochastic state dynamics given by generic nonlinear in state and non-affine in control models. We derive the conditions of optimality for the associated optimal control problem. This derivation yields a system of three coupled partial differential equations together with the boundary conditions at the initial and terminal times. The resulting system is a generalized instance of the so-called Schrödinger bridge problem. We then determine the optimal control policy by training a physics-informed deep neural network, where the “physics” are the derived conditions of optimality. The performance of the proposed solution is demonstrated via numerical simulations on a benchmark colloidal self-assembly problem.
problem into an optimal control problem, and by approximately solving it (using, e.g., iLQR) we establish a superior proposal for particle smoothing. Combining it with a suitable designed sliding window mechanism, we obtain a particle filtering algorithm that suffers less from sample degeneracy compared with existing methods. Finally, we exemplify our algorithm in a filtering problem over SO(3) for satellite attitude estimation.

11:15-11:30  WeA16.6
Constrained Policy Optimization for Stochastic Optimal Control under Nonstationary Uncertainties (I), pp. 634-639
Shin, Sungho  Argonne National Laboratory
Pacaud, Francois  Argonne National Laboratory
Constantinescu, Emil Mihai  Argonne National Laboratory
Anitescu, Mihai  Argonne National Laboratory

This article presents a constrained policy optimization approach for the optimal control of systems under nonstationary uncertainties. We introduce an assumption that we call Markov embeddability that allows us to cast the stochastic optimal control problem as a policy optimization problem over the augmented state space. Then, the infinite-dimensional policy optimization problem is approximated as a finite-dimensional nonlinear program by applying function approximation, deterministic sampling, and temporal truncation. The approximated problem is solved by using automatic differentiation and condensed-space interior-point methods. We formulate several conceptual and practical open questions regarding the asymptotic exactness of the approximation and the solution strategies for the approximated problem. As proof of concept, we present numerical examples demonstrating the performance of the proposed method.

11:00-11:15  WeA17.4
What Is the Meaning of (battery) Life? (I)*
Paxton, William  VW

11:15-11:30  WeA17.5
Integrating Physics and Machine Learning for Battery Management in the Cloud (I)*
Li, Weihan  RWTH Aachen University

WeB01  Aqua 314
Combining Physics and Machine Learning Methods to Accelerate Innovation in Sustainability: A Control Perspective (Tutorial Session)
Chair: Onori, Simona  Stanford University
Co-Chair: Pozzato, Gabriele  Stanford University
Organizer: Onori, Simona  Stanford University
10:00-10:30  WeA17.1
Combining Physics-Based and Machine Learning Methods to Accelerate Innovation in Sustainable Transportation and Beyond: A Control Perspective (I), pp. 640-653
Pozzato, Gabriele  Stanford University
Onori, Simona  Stanford University

Lithium-ion batteries are playing a key role in the sustainable energy transition. To fully exploit the potential of this technology, a variety of modeling, estimation, and prediction problems need to be addressed to enhance its design and optimize its utilization. Batteries are complex electrochemical systems whose behavior drastically changes as a function of aging, temperature, C-rate, and state of charge, posing unique modeling and control research questions. In this tutorial paper, we provide insights into three battery modeling methodologies, namely first principle, machine learning, and hybrid modeling. Each approach has its own strengths and weaknesses, and by means of three case studies we describe main characteristics and challenges of each of the three methods.

10:30-10:45  WeA17.2
Machine Learning in Lithium-Sulfur Battery Modeling and Control: Key Challenges and Opportunities (I), pp. 654-654
Fathy, Hosam K.  University of Maryland

This talk is motivated by the potential of both solid-state and liquid electrolyte lithium-sulfur batteries to provide significant performance advantages over state-of-the-art lithium-ion batteries, especially in terms of specific energy. The talk provides a brief introduction to the lithium-sulfur chemistry, focusing on the modeling, estimation, and control challenges associated with this chemistry. The talk then surveys some of the key challenges and opportunities associated with the application of machine learning methods, especially the deep learning of battery dynamics, to this chemistry. Areas of overlap and potential synergy between machine learning and physics-based modeling approaches are particularly emphasized in this discussion.

10:45-11:00  WeA17.3
Physics-Constrained Learning with Application to Fuel Cells and Batteries (I)*
Siegel, Jason B.  University of Michigan

14:00-14:04  WeB01.1
Development and Application of a Novel High-Order Fully Actuated System Approach: Part I. 3-DOF Quadrotor Control (I), pp. 655-660
Lu, Shi  Arizona State University
Tsakalis, Kostas  Arizona State Univ
Chen, Yan  Arizona State University

The quadrotor hierarchical control design (position-attitude) based on the state-space modeling has been widely applied in the past. Although the state-space representation, based on a group of first-order differential equations, is effective in modeling many dynamic systems, inherent high-order dynamics and control of quadrotor systems may not be properly handled by the state-space modeling. This letter proposes a modified high-order fully actuated (HOFA) theory for a group of high-order dynamic systems, including the quadrotor system, without relying on pseudo strict-feedback forms required by the original HOFA approach. Hence, the quadrotor model can be essentially converted into two HOFA subsystems. A nonlinear 3-DOF quadrotor modeling and control is applied as an example to demonstrate the effectiveness of the proposed approach, which can achieve arbitrarily assignable eigenstructure like a stabilized linear system.

14:04-14:08  WeB01.2
Development and Application of a Novel High-Order Fully Actuated System Approach: Part II. 6-DOF Quadrotor Control (I), pp. 661-666
Lu, Shi  Arizona State University
Tsakalis, Kostas  Arizona State Univ
Chen, Yan  Arizona State University

Traditional cascade controller design based on state-space modeling has been widely applied for quadrotor systems. The state-space representation can effectively model many dynamic systems. Yet, a group of first-order differential equations may not be the most suitable way to model and control inherent high-order dynamic systems, such as quadrotors. This paper proposes a modified high-order fully actuated (HOFA) approach with recursive actions based on a
mixed-order quadrotor model. Unlike the existing HOFA approach developed for generalized strict-feedback systems, the modified HOFA method does not require the system in a strict-feedback form. Hence, the 6-DOF quadrotor model can be essentially converted into three HOFA subsystems. Based on the obtained HOFA systems, the control design of 6-DOF nonlinear quadrotor systems can be readily achieved like linear systems with arbitrarily assignable eigenstructure. Simulation and experimental results are shown to verify the effectiveness of the proposed HOFA modeling and control approach.

**Input Shaping Control of an Overhead Crane with Time-Varying Cable Length Using a Generalized Input Shaper**, pp. 667-672

Hö, Duc Tho Nagaoka University of Technology
Terashima, Kazuhiro Toyohashi Univ. of Tech
Miyoshi, Takanori Nagaoka Univ. of Tech

In this brief, a new input shaping-based control law is proposed for an overhead crane with time-varying cable length. The proposed approach can accommodate a generalized input shaper and general hoisting motions. It will be shown that a non-robust input shaper can be used within the established scheme to completely suppress residual vibration at the completion of a maneuver, outperforming the standard (robust) input shaping controllers. Simulation results are provided.

**Sequence-To-Sequence LSTM-Based Dynamic System Identification of Piezo-Electric Actuators**, pp. 673-678

Yin, Ruocheng Iowa State University
Ren, Juan Iowa State University

During the past few year, recurrent neural network (RNN) has been proposed to model the nonlinear dynamics of various dynamic systems, such as nano positioning systems (e.g. piezo electric actuators (PEAs)). Although high modeling accuracy has been demonstrated using RNNs, it has been found that the conventional RNNs (such as vanilla RNN) are susceptible to gradient vanishing or exploding issue and hence difficult to train. Deep RNNs, such as Long short-term memory (LSTM), have been proposed to address these issues. However, due to the conventional training data construction, the training is susceptible to overfitting and the computation is extensive. In this paper, we propose a new type of LSTM in the application of PEA system identification: a sequence-to-sequence learning approach (namely, LSTMSeq2seq). The structure of LSTMSeq2seq and its training data construction are presented in detail. The efficacy of LSTMSeq2seq in terms of modeling accuracy and computation speed is demonstrated by applying it for PEA system identification and comparing its performance with that of vanilla RNN.

**Feedforward Compensation of Scan-Induced Disturbances for a High-Precision Robotic 3D Measurement System**, pp. 679-684

Wirtzian, Daniel TU Wien
Kern, Thomas TU Wien
Csencsics, Ernst Vienna University of Technology
Schitter, Georg Vienna University of Technology

This paper proposes a feedforward compensation approach of scan-induced disturbances to improve the uncertainty of an active-sample tracking 3D measurement module. The measurement module acts as a robotic endeffector and is designed for precise robotic measurement applications directly in the vibration-prone environment of an industrial production line. By means of a feedback control-induced stiff link, a constant position of the electromagnetically levitated measurement platform (MP) is maintained with respect to the sample surface under test. Precise 3D imaging is enabled by scanning the measuring light spot of a 1D confocal chromatic sensor with a 2D fast steering mirror (FSM). Disturbances are caused due to scanning-induced reaction forces on the MP, impairing the system's sample-tracking and 3D measurement performance. Based on the identified disturbance dynamics, a tailored feedforward control is designed to compensate the causing reaction forces. To experimentally evaluate the system performance, 3D measurements at the maximum frame of 1 fps are performed with disabled and enabled feedforward control. Evaluating the experimental results, the sample-tracking error in the MP's translational degree of freedom z is significantly reduced by a factor of 7 down to 42 nm rms, being close to the MP's static positioning noise. The reduced sample-tracking error further enables a higher 3D measurement performance, reducing the structural height uncertainty by 36% down to 180 nm rms.

**Mitigating Non-Linear DAC Glitches Using Dither in Closed-Loop Nano-Positioning Applications**, pp. 685-691

Faza, Ahmad M.A. University of Stavanger
Leth, John Aalborg University
Eielsen, Amfnn A University of Stavanger

Digital-to-analog conversion is essential in digital signal processing applications, including closed-loop control schemes. Noise and distortion in digital-to-analog converters result in reduced performance for high-precision mechatronics such as nano-positioning. Glitches are common in practical switched systems such as digital-to-analog converters; observed as an output disturbance. Due to the wide-bandwidth, impulse-like behavior, control law bandwidth is generally too low to provide adequate attenuation; deteriorating open and closed-loop performance. This article demonstrates how large-amplitude high-frequency periodic dither mitigates the effect of glitches in a nano-positioning system under closed-loop control. Simulations are performed using a model that includes significant nonlinearities with a response fitted to an off-the-shelf commercial device, as well as using standard linear time-invariant models for other system components fitted to the responses of common, commercially available devices. The results highlight the significance of reconstruction filter design when applying dithering in this setting.
We present a point-to-point trajectory generation framework that helps in enhancing the positioning of systems having uncertain lightly-damped vibration modes. To avoid exciting these modes, their uncertainties are matched with frequency bands and then used to specify the rejected frequencies under a $k$-cascaded second-order notch filter. To facilitate trajectory generation, the impulse response of this filter is altered by composing it off-line with a certain polynomial function of even degree in the time domain followed by a transformation. This will result in a unit-pulse acceleration signal with attenuated frequency contents in the rejected frequency bands, and therefore a reduced excitation of the lightly-damped modes is achieved. The resulting off-line generated unit-pulse acceleration signal is used as a template to ease real-time trajectory extrapolation using simple calculations due to the closed-form solutions provided. Therefore, real-time computational overhead is significantly reduced. Comparisons between the proposed method and frequency-shaped polynomials, finite-impulse response and input shaping are provided. The effectiveness of the proposed framework is illustrated through a numeric simulation.

14:32-14:36 WeB01.9 Contactless Suspension of a Silicon Disk, pp. 704-709
Pyle, Kenneth University of California, Los Angeles
M’Closkey, Robert University of California, Los Angeles

A system to suspend a silicon disk between two sets of stator electrodes is reported. Electrode pairs are used for both control and sensing by exerting electrostatic forces on the disk and measuring differential capacitances related to the disk’s position. The disk is a six degree-of-freedom system, however, lateral and yaw motion are not measurable by the electrode arrangement so only the disk’s vertical position, roll, and pitch are regulated. Two separate control strategies are pursued—decentralized feedback around the electrode-disk gaps and feedback around a decoupled coordinate frame related to the disk’s controllable degrees-of-freedom. Experimental frequency responses obtained from closed-loop results of the suspended disk are reported and compared to analytical models.

14:36-14:40 WeB01.10 Learning Object Manipulation with Under-Actuated Impulse Generator Arrays, pp. 710-717
Kong, Chuizheng Mitsubishi Electric Research Laboratories
Yerazunis, William Mitsubishi Electric Research
Nikovski, Daniel Mitsubishi Electric Research Labs

For more than half a century, vibratory bowl feeders have een the standard in automated assembly for singulation, orientation, and manipulation of small parts. Unfortunately, these feeders are expensive, noisy, and highly specialized on single part design bases. We consider an alternative device and learning control method for singulation, orientation, and manipulation by means of seven fixed-position variable-energy solenoid impulse actuators located beneath a semi-rigid part supporting surface. Using computer vision to provide part pose information, we tested various machine learning (ML) algorithms to generate a control policy that selects the optimal actuator and actuation energy. Our manipulation test object is a 6-sided craps-style die. Using the most suitable ML algorithm, we were able to flip the die to any desired face 30.4% of the time with a single impulse, and 51.3% with two chosen impulses, versus a random policy succeeding 5.1% of the time (that is, a randomly chosen impulse delivered by a randomly chosen solenoid).

WeB02 Optimization (RI) (RI Session)

Chair: Kim, Hunmin
Co-Chair: Ghaffari, Azad

14:00-14:04 WeB02.1 GPU Accelerated Batch Trajectory Optimization for Autonomous Navigation, pp. 718-725
Rastgar, Fatemeh University of Tartu
Masnavi, Houman University of Tartu
Kruusmaa, Karl University of Tartu
Aabloo, Alvo University of Tartu
Singh, Arun Kumar University of Tartu

Trajectory optimizations encountered in mobile robot navigation are non-convex, and thus the solution process is prone to get stuck at poor local optima, resulting in collisions with the environment. A conceptually simple workaround is to simply run the optimizer from several initializations in parallel and choose the best solution. But realizing this simple trick with off-the-shelf optimizers is challenging since they are not customized for parallel/batch operation. We fill this gap by proposing a novel batchable and GPU accelerated trajectory optimizer for autonomous navigation. Our batch optimizer can run several hundred instances of the problem in parallel in real time. We improve the state-of-the-art in the following respects. First, we show that parallel initialization naturally discovers a distribution of locally optimal trajectories residing in different homotopies. Second, we improve the navigation quality (success rate, tracking) compared to the baseline approach that relies on computing a single locally optimal trajectory at each control loop. Finally, we show that when initialized with trajectory samples from a Gaussian distribution, our batch optimizer outperforms the state-of-the-art cross-entropy method in solution quality. Textbf{Codes:} [url{https://tinyurl.com/a3b99m8}], Video: [url{https://www.youtube.com/watch?v=ZIWJk-wO3d8}]

14:04-14:08 WeB02.2 Multi-Objective Trajectory Planning for Unmanned Aerial Vehicles Using CLF-CBF-Based Quadratic Programs, pp. 726-731
Khan, Sultyan Hafeez Wayne State University
Ghaffari, Azad Wayne State University

Control barrier function-based quadratic programs (CBF-basedQP) provide an avenue for agile and numerically efficient obstacle avoidance algorithms. However, the CBF-basedQP methods may lead to lengthy detours and undesirable transient tracking performance without proper trajectory planning. This paper expands the CBF-basedQP concept to create a modified safe reference trajectory with a prescribed avoidance radius and direction, where the modified reference shadows the actual reference during the avoidance maneuver. We use a control Lyapunov function (CLF) to match the modified reference with the actual reference and three CBFs to formulate safety and performance objectives to maintain distance, adjust velocity, and determine the direction of the avoidance maneuver. These formulations produce constraints that are synthesized by means of a quadratic program. The QP generates a desirable velocity profile for the safe reference trajectory. Numerical simulations verify the effectiveness of the proposed trajectory planning method.

14:08-14:12 WeB02.3 Safety Index Synthesis Via Sum-Of-Squares Programming, pp. 732-737
Zhao, Weiye Carnegie Mellon University
He, Tairan Carnegie Mellon University
Wei, Tianhao Carnegie Mellon University
Liu, Simin Carnegie Mellon University
Liu, Changliu Carnegie Mellon University

Control systems often need to satisfy strict safety requirements. Safety index provides a handy way to evaluate the safety level of the system and derive the resulting safe control policies. However, designing safety index functions under control limits is difficult and
requires a great amount of expert knowledge. This paper proposes a framework for synthesizing the safety index for general control systems using sum-of-squares programming. Our approach is to show that ensuring the non-emptiness of safe control on the safe set boundary is equivalent to a local manifold positiveness problem. We then prove that this problem is equivalent to sum-of-squares programming via the Positivstellensatz of algebraic geometry. We validate the proposed method on robot arms with different degrees of freedom and ground vehicles. The results show that the synthesized safety index guarantees safety and our method is effective even in high-dimensional robot systems.

14:12-14:16 Web02.4
Photovoltaic Inverter Efficiency and Lifetime Trade-Off Using Model Based Real-Time Optimization, pp. 738-743
Ingalalli, Aravind Siemens
Robinson, Jonathan Siemens
Nandola, Nareshkumar Siemens Technology

Lifetime of the photovoltaic (PV) inverters is influenced by its power profile. The reliability of such PV inverters is affected by the thermal fatigue cycles witnessed by the underlying components. However, there is a trade-off between the inverter efficiency and the fatigue witnessed by its components. With a systematic formulation of this trade-off, a real-time nonlinear optimization problem is formulated to generate the appropriate reactive power set-points to the PV inverter controller. The proposed approach improves the lifetime of the inverters while keeping its efficiency above desired threshold value. The time domain loss and damage models that uses PV power profile as an input are critical to the proposed optimization framework. The proposed framework provides an option to the customer to operate the PV inverter with an objective of lifetime improvement under the acceptable losses by flattening the component thermal fatigue cycles. The framework is evaluated using the PV power profile of a 10 kVA PV inverter with various simulated case studies.

14:16-14:20 Web02.5
Formal Comparison of Simultaneous Perturbation Stochastic Approximation and Random Direction Stochastic Approximation, pp. 744-749
Peng, Ducheng Johns Hopkins University
Chen, Yiwen Johns Hopkins University
Spall, James C. Johns Hopkins University

Stochastic approximation (SA) algorithms can be used in system optimization problems when only noisy measurements of a system are available. This paper formally compares the performance of two popular SA algorithms in a multivariate Kiefer-Wolfowitz setting of simultaneous-perturbation SA (SPSA) and the random-directions SA (RDSA). This paper provides sufficient conditions to demonstrate which algorithm has the smaller asymptotic mean squared error (MSE) and numerically presents comparison of SPSA and RDSA in a test function and a model-free control system. The theory and supporting numerics indicate that SPSA has better efficiency (lower MSE) across a broad range of problem settings.

14:20-14:24 Web02.6
From Open Loop to Real-Time Recipe Optimization for Complex Industrial Batch Processes, pp. 750-755
Kong, Lingxun Dow
Castillo, Ivan The Dow Chemical Company
Peng, You Massachusetts Institute of Technology
Rendall, Ricardo Dow Inc
Wang, Zhenyu Dow Chemical
Trahan, Daniel The Dow Chemical Company
Bentley, David Dow Inc

We propose a fundamental-model-based optimization framework for open-loop and real-time batch recipe optimization using mathematical programming (MP) and reinforcement learning (RL). The dynamic fundamental model gives rise to a complex nonlinear differential algebraic equations (DAE) system. We introduce a decomposition-based initialization algorithm for solving the large-scale nonlinear program (NLP) resulting from the discretization of the DAE system. The proposed MP and RL-based approaches are implemented to optimize the recipe of a semi-batch process in the Dow Chemical Company. For open-loop optimization, we find the optimal profiles of two input variables and the batch length that maximize average profit. For real time optimization, we train the RL agent using the fundamental model with uncertainties. The trained agent can interact with the actual process and provide control actions in real time.

14:24-14:28 Web02.7
Sequential Sum-Of-Squares Programming for Analysis of Nonlinear Systems, pp. 756-762
Cunis, Torbjorn University of Stuttgart
Legat, Benoît UCLouvain

Numerous interesting properties in nonlinear systems analysis can be written as polynomial optimization problems with nonconvex sum-of-squares problems. To solve those problems efficiently, we propose a sequential approach of local linearizations leading to tractable, convex sum-of-squares problems. We prove local convergence under the assumption of strong regularity, a common condition in variational analysis. The new approach is applied to estimate the region of attraction of a polynomial aircraft model, where it greatly outperforms previous methods for nonconvex sum-of-squares problems.

14:28-14:32 Web02.8
Guaranteed Privacy of Distributed Nonconvex Optimization Via Mixed-Monotone Functional Perturbations, pp. 763-768
Khajenejad, Mohammad University of California, San Diego
Martinez, Sonia University of California at San Diego

In this paper, we introduce a new notion of guaranteed privacy for distributed nonconvex optimization algorithms. In particular, leveraging mixed-monotone inclusion functions, we propose a privacy-preserving mechanism which is based on deterministic, but unknown affine perturbations of the local objective functions. The design requires a robust optimization method to characterize the best accuracy that can be achieved by an optimal perturbation. This is used to guide the refinement of a guaranteed-private perturbation mechanism that can achieve a quantifiable accuracy via a theoretical upper bound that is independent of the chosen optimization algorithm. Finally, simulation results illustrate that our approach outperforms a benchmark differentially private distributed optimization algorithm in the literature.

14:32-14:36 Web02.9
Robust Control Co-Design Using Tube-Based Model Predictive Control, pp. 769-775
Tsai, Ying-Kuan Texas A&M University
Malak, Richard Texas A&M University

Control co-design (CCD) has received much attention since it can achieve superior system performance by optimizing physical and control systems simultaneously. Despite many successful examples from diverse engineering fields using CCD, a lack of attention toward accounting for uncertainty hinders application to real-world systems. This paper aims to solve CCD problems under uncertainty by proposing a robust CCD formulation and algorithm. A robust feedback controller using tube-based model predictive control (tube-based MPC) approach is incorporated into a bi-level optimization architecture. The use of the set invariance theory and an approximation algorithm helps identify the set of all possible states due to disturbances, this set is known as a tube, and quantify system robustness by calculating the tube size. It enables designers to make performance-robustness tradeoffs with the approximate Pareto fronts.
A numerical example and a simplified model of the satellite attitude control system are used to demonstrate the proposed method. Results show that the CCD solutions dominate most of the solutions from the traditional sequential design and control design only. This study will be extended into nonlinear applications in our future work.

14:36-14:40 WeB02.10
RRT Guided Model Predictive Path Integral Method, pp. 776-781
Tao, Chuyuan University of Illinois Urbana-Champaign
Kim, Hunmin Mercer University
Hovakimyan, Naira University of Illinois at Urbana-Champaign

This work presents an optimal sampling-based model to solve the real-time motion planning problem in static and dynamic environments, exploiting the Rapid-exploring Random Trees (RRT) algorithm and the Model Predictive Path Integral (MPPI) algorithm. The RRT algorithm provides a nominal mean value of the random control distribution in the MPPI algorithm, resulting in satisfactory control performance in static and dynamic environments without a need for fine parameter tuning. We also discuss the importance of choosing the right mean of the MPPI algorithm, which balances exploration and optimality gap, given a fixed sample size. In particular, a sufficiently large mean is required to explore the state space enough, and a sufficiently small mean is required to guarantee that the samples reconstruct the optimal controls. The proposed methodology automates the procedure of choosing the right mean by incorporating the RRT algorithm. The simulations demonstrate that the proposed algorithm can solve the motion planning problem in real time for static or dynamic environments.

WeB03 Sapphire EF
Robotics I (Regular Session)
Chair: Saldañiaga, Carlos Escuela Superior Politécnica Del Litoral
Co-Chair: Cai, Mingyu Lehigh University
14:00-14:15 WeB03.1
Decision Making of Ball-Batting Robots Based on Deep Reinforcement Learning, pp. 782-787
Hsiao, Tesheng National Yang Ming Chiao Tung University
Kao, Hsuan-Che National Yang Ming Chiao Tung University

Ball-batting is a challenging task because it requires excellent eye-hand coordination and instantaneous decision making. Moreover, as a winning strategy, the task of ball-batting concerns not only about “hitting a flying ball with a bat”, but about “sending the rebounding ball to a presupposed location”. Therefore, the decisions on when and where to hit the ball and what the velocity of the bat is at the impact time are crucial for a successful ball-batting. Making such decisions should consider the flying and rebounding behavior of the ball and is very complicated. In this paper, we apply the deep reinforcement learning (DRL) method to train the ball-batting robot developed by the authors for making timely and appropriate batting decisions. A simulated environment consisting of a physical flying model and a neural network rebounding model is constructed for efficient training. Then experiments in the real world are conducted and the results show that after being trained by DRL, the robot can hit the incoming ball in all tests and send the rebounding ball to the target location with a successful rate of 58.8%.

14:15-14:30 WeB03.2
Controlling a Double-Pendulum Crane by Combining Reinforcement Learning and Conventional Control, pp. 788-793
Eaglin, Gerald University of Louisiana at Lafayette
Poche, Thomas University of Louisiana at Lafayette
Vaughan, Joshua Oak Ridge National Laboratory

Controlling oscillation is vital for applications in which flexible systems are employed. Many existing control methods rely on knowledge of the system dynamics to mitigate unwanted vibration. However, model-free methods can also be employed to control vibration. One method for model-free control is reinforcement learning (RL). Although the RL agent does not require information about the system to learn a control policy, domain knowledge of dynamics and control can be used to augment the agent and aid in generating an effective control policy. This work analyzes the effectiveness of training RL controllers that operate in combination with conventional controllers. Agents were trained in simulation using a model of a small-scale double-pendulum crane. The effect of the conventional control component on training as well as sensitivity to modeling error are analyzed. Agent transferability is investigated by implementing the simulation-trained controllers on a physical small-scale double-pendulum crane.

14:30-14:45 WeB03.3
On Mapping Stiffness and Damping in Robotic Impedance Control: A Spatial Validation of Coupling, pp. 794-799
Patño Míñán, José Johil Escuela Superior Politécnica Del Litoral
Saldarriaga, Carlos Escuela Superior Politécnica Del Litoral

In order to calculate the necessary joint torques and end-effector forces in accordance with a desired dynamic behavior for assembly and manipulation tasks in the field of robotics, robotic impedance control has been extensively employed. Current complete congruent mapping equations have not been validated through actual robotic manipulators in impedance control tasks. In this paper, we show and validate from fundamental principles, with the use of a 6 DoF robotic manipulator, the transformation equations of the stiffness and damping matrices from Cartesian to joint space without losing generality. Our findings highlight the significance of the Cartesian damping coupling term, which is typically absent from the existent robotics literature, in the stiffness matrices after mapping them to the joint space.

14:45-15:00 WeB03.4
Adaptive Attitude Control for Foldable Quadrotors, pp. 800-805
Patnaik, Karishma Arizona State University
Zhang, Wenlong Arizona State University

Recent quadrotors have transcended conventional designs, emphasizing more on foldable and reconfigurable bodies. The state of the art still focuses on the mechanical feasibility of such designs with limited discussions on the tracking performance of the vehicle during configuration switching. In this article, we first present a common framework to analyse the attitude errors of a folding quadrotor via the theory of switched systems. We then employ this framework to investigate the attitude tracking performance for two case scenarios - one with a conventional geometric controller for precisely known system dynamics; and second, with our proposed morphology-aware adaptive controller that accounts for any modeling uncertainties. Finally, we cater to the desired switching requirements from our stability analysis by exploiting the trajectory planner to obtain superior tracking performance while switching. Simulation results are presented that validate the proposed controller and planning framework for a foldable quadrotor's flight through a passageway.

15:00-15:15 WeB03.5
Accelerated Learning and Control of Robots with Uncertain Kinematics and Unknown Disturbances, pp. 806-811
Yılmaz, Cemal Tugrul UC San Diego
Krštic, Miroslav University of California, San Diego

This paper develops accelerated model-free robust adaptive control
algorithms for unknown static maps which correspond to forward
kinematics in robotics. The technique is based on the estimation of
unknown Jacobian matrix by using a neural-network based
approximation and use of monotonically increasing gain functions in
the controller and update law. The introduced algorithms provide
robustness against the unknown environmental disturbances and
achieve asymptotic, exponential and prescribed-time reference
trajectory tracking. The fixed-time stabilization in prescribed time is
the strongest notion among them that allows user to predefine a
terminal time irrespective of initial condition and system parameters.
A formal stability analysis for each algorithm is presented and
theoretical results are validated through numerical simulations
conducted on a single-section three-actuator continuum robot.

15:15-15:30 WeB03.6
Vessel Inspection In-The-Wild: Practical Planning in Large-Scale
Industrial Environments, pp. 812-817

Hansen, Jakob Grimm  Aarhus University
Heiß, Micha  Aarhus University
Li, Dengyun  University of Twente
Kozłowski, Michal  Aarhus University
Kayacan, Erdal  Aarhus University

In this paper, a novel strategy for practical inspection planning in dry
docks using unmanned aerial vehicles (UAVs) is presented. Planning
is a fundamental prerequisite for accurate navigation and control of
the UAV. The proposed method utilises the random sample
consensus (RANSAC) algorithm to extract plane models from a voxel
grid representation of the environment. For high-level planning,
semantic knowledge of the environment is leveraged in a novel
manner to exploit of structured obstacles, such as straight walls and
orthogonal corners. In order to deal with lower-level navigation, the
approach incorporates a simple graph-based local replanner to
generate paths that avoid obstacles in the environment. The proposed
method is compared with state-of-the-art graph-based planner in simulation and subsequently evaluated in a real
environment. The paper maintains the use case of UAV vessel
inspection and presents exhaustive simulation and field testing, which
demonstrate the viability of the proposed approach in a fully working
large-scale industrial environment.

WeB04 Sapphire AB
Advanced Control of Wind Farms and Wind Turbines: Session II:
Wind Farm Wake Control (Invited Session)

Chair: Mulders, Sebastiaan
Paul  Delft University of Technology
Co-Chair: Zare, Armin  University of Texas at Dallas
Organizer: Mulders, Sebastiaan
Paul  Delft University of Technology
Organizer: Bay, Christopher  National Renewable Energy
Laboratory
Organizer: Fleming, Paul  National Renewable Energy
Laboratory
Organizer: van Wingerden, Jan-Willem  Delft University of Technology

14:00-14:15 WeB04.1
Robustness of Two-Dimensional Stochastic Dynamical Wake Models
for Yawed Wind Turbines (I), pp. 818-823

Rodrigues, Mireille  The University of Texas at Dallas
Burgess, Nicolas  University of Texas at Dallas
Bhatt, Aditya  The University of Texas at Dallas
Leonardi, Stefano  The University of Texas at Dallas
Zare, Armin  University of Texas at Dallas

We develop stochastic dynamical reduced-order models of wind farm
turbulence that capture the effects of yaw misalignment due to control
or atmospheric variability on turbine wakes and their interactions. Our
models are based on the stochastically forced linearized
Navier-Stokes equations around analytical descriptions of the wake
velocity provided by low-fidelity engineering wake models. The
power-spectral density of the source of additive stochastic excitation
is identified via convex optimization to ensure statistical consistency
with high-fidelity models while preserving model parsimony. We
demonstrate the utility of our approach in capturing turbulence
intensity variations in accordance with large-eddy simulations of the
flow over a cascade of wind turbines. While our models are
developed to match velocity correlations from sensors that are placed
directly behind perfectly aligned wind turbine rotors, their predictions
maintain a desirable level of accuracy even when the turbines are
yawed.

14:15-14:30 WeB04.2
Enhancing Wake Mixing in Wind Farms by Multi-Sine Signals in the
Helix Approach (I), pp. 824-830

Huang, Lu-Jan  Delft University of Technology
Mulders, Sebastiaan
Paul  Delft University of Technology
Taschner, Emanuel  TU Delft
van Wingerden, Jan-Willem  Delft University of Technology

In most current offshore wind farms, the turbines are controlled
greedily, neglecting any coupling by wake effects with other turbines.
By neglecting these effects of aerodynamic interactions, the power
production performance is substantially reduced.

Besides the well-known wake steering and dynamic induction control
wake control strategies, a novel wind farm flow control strategy called
the Helix approach has been recently proposed to mitigate the
impacts of wake effects and optimize wind farm performance. The
Helix approach adopts the individual pitch control (IPC) technique to
dynamically deform the wake into the helical shape, which induces
wake instability and thereby stimulates wake recovery. The first
results employing a single-harmonic signal have demonstrated promising
enhancement in wake recovery effects. However, more
complex signals to potentially improve the effectiveness of the Helix
approach have never been studied.

This paper explores the potential of using higher-harmonic signals in the
Helix approach to further enhance wake mixing. The aeroelastic
simulator, OpenFAST, with its recently developed free vortex wake
models is adopted to simulate the dynamic wake evolution. A Fourier
stability analysis is used to quantitatively identify the wake breakdown
position. Results show that the wake breaks down at 1.75 rotor
diameter (D) from the rotor using optimized multi-sine signals, which
is a significant improvement over the breakdown distance at 2.50 D
resulting from the conventional single-sine Helix. The earlier wake
breakdown indicates faster wake recovery and is to be validated by
future higher-fidelity simulation studies.

14:30-14:45 WeB04.3
Enhanced Wake Mixing in Wind Farms Using the Helix Approach: A
Loads Sensitivity Study (I), pp. 831-836

van Vondelen, Aemilius  TU Delft
Navalkar, Sachin  Delft University of Technology
Kerssemakers, Daan  TU Delft
van Wingerden, Jan-Willem  Delft University of Technology

The Helix approach is a control technology that reduces the wake
effect in wind farms by accelerating wake mixing through individual
pitch control, resulting in significant AEP gain. However, this study
found that the controller may increase pitch bearing damage and
loads on some turbine components, depending on its settings. Using
a modified version of NREL’s Reference OpenSource Controller in
OpenFAST, this study analysed the sensitivity of loads and pitch
bearing damage to different Helix controller settings on the
IEA-15MW reference offshore wind turbine. Results showed that
loads increased with the amplitude of the excitation signal but were
less affected by its frequency. Additionally, more pitch bearing
damage was observed in the counterclockwise Helix direction, while
slightly higher loads were observed in the clockwise direction when using the same excitation signal amplitude and frequency for both directions.

14:45-15:00 WeB04.4

Wind Tunnel Testing of Wake Tracking Methods Using a Model Turbine and Tailored Inflow Patterns Reasing a Meandering Wake (!), pp. 837-842

Onnen, David ForWind - Center for Wind Energy Research, University of Oldenburg

Petrović, Vlako Universität Oldenburg

Neuhaus, Lars University of Oldenburg, ForWind - Institute of Physics

Langidis, Apostolos University of Oldenburg

Kühn, Martin University of Oldenburg

Wind farm control can be enhanced by feedback information about the current flow situation in the farm. Especially for closed-loop wake-steering control, the position of a wind turbine's wake with respect to the next turbine is valuable. Depending on the context, e.g. installed sensory or required time- and wake position resolution, different methods for wake tracking exist. With increasing fidelity, not only time-averaged wakes but also instantaneous wake conditions, arising from the meandering nature of a wind turbine wake, are considered for control. In this work, two methods for the dynamic estimation of the wake centre position are experimentally tested. One of them is based on wind turbine blade loads, the other on a fixed-beam staring lidar. Both methods use an Extended Kalman Filter with a dynamic model that takes the meandering nature of a wind turbine wake into account. In the atmospheric boundary layer, turbulence patterns of multiple rotor diameters are driving the downstream meandering of the wake. In wind tunnel setups with large model turbines, these spatial scale ratios are hardly reachable, thus meandering conditions were difficult to reproduce up to now. In this work, the inflow conditions are generated in a wind tunnel with an active grid, which imprints both a wind speed deficit and additional turbulence in a meandering frame of reference. The paper describes the creation and characterization of such inflow, while not claiming for an exact representation of a meandering wake in an atmospheric boundary layer. Inflow conditions of different meandering dynamics are created and their impact on the tracking methods is analyzed. The experiments show that the generated inflow conditions both resemble a wake and induce an expected response of the model turbine. The results from the wake tracking methods are comparable with the available literature, thus further indicate the potential of the setup for control-oriented experiments in the context of meandering wakes, turbine-turbine interaction and load alleviation.

15:00-15:15 WeB04.5

Radar Based Wake Control for Reducing the Levelized Cost of Energy in Offshore Wind Farms (!), pp. 843-848

D’Amato, Fernando GE Research

Boutalis, George I. Georgia Institute of Technology

Bonanni, Pierino GE Global Research

Szczechanski, Walter Helios Remote Sensing Systems, Inc

Lopez-Negrete, Rodrigo General Electric Global Research

Wake controls in wind farms has evolved significantly in the last twenty years, motivated mainly by its potential to increase annual energy production (AEP) through reduction of wake losses. Engineering models that characterize the wakes in the farm have enhanced fidelity and computational efficiency. Computational environments have been developed to adjust turbine control settings based on these models to reduce the impact of wakes. Several experimental campaigns have been carried out to validate the computational predictions. Yet, experimental results have typically shown lower AEP gains than expected. The variability in wake characteristics and the inability to calculate them online are key factors limiting the practical value of existing wake control solutions.

This work presents a wake control approach that proposes new sensors to measure the wakes online and uses accurate wake characteristics to enable further energy capture in offshore wind farms. A network of low-cost radar sensors is specifically designed to detect wakes in wind farms. A model-based estimation approach is developed to reduce the online wake uncertainty. Then, a model-based optimization framework is used to calculate AEP gains achieved by steering wakes via yaw actuation. The feasibility of the proposed approach is assessed by quantifying the changes in the levelized cost of energy (LCOE) resulting from the additional AEP gains and the extra cost of the new sensors.

WeB05 Optimization Algorithms II (Regular Session) Sapphire 411A

Chair: Kia, Solmaz S. University of California Irvine (UCI)

Co-Chair: Hale, Matthew University of Florida

14:00-14:15 WeB05.1 Noise Amplification of Momentum-Based Optimization Algorithms, pp. 849-854

Mohammadi, Hesameddin University of Southern California

Razaviyayn, Meisam University of Southern California

Jovanovic, Mihailo R. University of Southern California

We study momentum-based first-order optimization algorithms in which the iterations utilize information from the two previous steps and are subject to additive white noise. For strongly convex quadratic problems, we utilize Jury stability criterion to provide a novel geometric characterization of linear convergence and exploit this insight to derive alternative proofs of standard convergence results and identify fundamental performance tradeoffs. We use the steady-state variance of the error in the optimization variable to quantify noise amplification and establish analytical lower bounds on the product between the settling time and the smallest/largest achievable noise amplification that scale quadratically with the condition number. This extends the prior work [1], where only the special cases of Polyak's heavy-ball and Nesterov's accelerated algorithms were studied. We also use this geometric characterization to introduce a parameterized family of algorithms that strikes a balance between noise amplification and settling time while preserving order-wise Pareto optimality.

14:15-14:30 WeB05.2 An Almost Sure Convergence Analysis of Zeroth-Order Mirror Descent Algorithm, pp. 855-860

Paul, Anik Kumar Jadavpur University

Mahindrakar, Arun D. Indian Institute of Technology Madras

Kalaimani, Rachel Kalpana Indian Institute of Technology Madras

In this paper, we study the almost sure convergence analysis of zeroth-order mirror descent algorithm. The algorithm admits non-smooth convex function with an estimate of gradient using Nesterov's Gaussian Approximation technique. We establish that under suitable condition of step-size iterates of the algorithm converge to a neighborhood of optimal function value almost surely. We extend the analysis in distributed optimization. We validate the almost sure convergence on a non-smooth optimization problem.

14:30-14:45 WeB05.3 Federated Learning Using Variance Reduced Stochastic Gradient for Probabilistically Activated Agents, pp. 861-866

Rostami, Mohammadreza University of California, Irvine

Kia, Solmaz S. University of California Irvine (UCI)

This paper proposes an algorithm for Federated Learning (FL) with a two-layer structure that achieves both variance reduction and a faster convergence rate to an optimal solution in the setting where each
On the Stability Analysis of Open Federated Learning Systems, pp. 867-872
Sun, YoubangNortheastern University
Fernando, HeshanRensselaer Polytechnic Institute
Chen, TianyiRensselaer Polytechnic Institute
Shahrampour, ShahinNortheastern University

We consider the open federated learning (FL) systems, where clients may join and/or leave the system during the FL process. Given the variability of the number of present clients, convergence to a fixed model cannot be guaranteed in open systems. Instead, we resort to a new performance metric that we term the stability of open FL systems, which quantifies the magnitude of the learned model in open systems. Under the assumption that local clients’ functions are strongly convex and smooth, we theoretically quantify the radius of stability for two FL algorithms, namely local SGD and local Adam. We observe that the radius relies on several key parameters, including the function condition number as well as the variance of the stochastic gradient. Our theoretical results are further verified by numerical simulations on synthetic data.

A Totally Asynchronous Block-Based Heavy Ball Algorithm for Convex Optimization, pp. 873-878
Hustig-Schultz, DawnUniversity of California, Santa Cruz
Hendrickson, KatherineUniversity of Florida
Hale, MatthewUniversity of Florida
Sanfelice, Ricardo G.University of California at Santa Cruz

We present a totally asynchronous multiagent algorithm, based on the heavy ball method, that guarantees fast convergence to the minimizer of a twice continuously differentiable, convex objective function over a convex constraint set. The algorithm is parallelized in the sense that the decision variable is partitioned into blocks, each of which is updated by only a single agent. We consider two types of asynchrony: in agents’ computations and in communications between agents, both under arbitrarily long delays. We show that, for certain values of the step size and other parameters, the heavy ball algorithm exponentially converges to a minimizer, even under total asynchrony. Numerical results validate these findings and demonstrate significantly faster convergence than a comparable gradient descent algorithm.

Online Convex Optimization with Long Term Constraints for Predictable Sequences, pp. 879-884
Muthirayan, DeepanUniversity of California at Irvine
Yuan, JianjunUniversity of Minnesota
Khargonekar, PramodUniv. of California, Irvine

In this paper, we investigate the framework of Online Convex Optimization (OCO) for online learning. OCO offers a very powerful online learning framework for many applications. In this context, we study a specific framework of OCO called (it OCO with (long-term) constraints). (Long-term) constraints are introduced typically as an alternative to reduce the complexity of projection at every update step in online optimization. While many algorithmic advances have been made towards online optimization with (long-term) constraints, these algorithms typically assume that the sequence of cost functions over a certain $T$ finite steps that determine the cost to the online learner are adversarially generated. In many circumstances, the sequence of cost functions may not be unrelated, and thus predictable from those observed till a point of time. In this paper, we study the setting where the sequences are predictable. We present a novel algorithm for online optimization with (long-term) constraints that can leverage such predictability for linear cost functions. We show that, with a predictor that can supply the gradient information of the next function in the sequence, our algorithm can achieve an overall regret and constraint violation rate that is strictly less than the rate that is achievable without prediction.
This paper uses time-reversal symmetry (T-symmetry), which is inherent in many mechanical systems, to establish global controllability results for a class of underactuated mechanical systems, i.e., the systems with fewer actuators than the number of degrees of freedom (DoF). The idea is to find a control law guaranteeing a globally asymptotically stabilizable equilibrium (GAS) state, at which small-time local controllability (STLC) is also granted. Then, such equilibrium state can be used as a connection to design a global controller by using the time-reversal symmetry, i.e., the system can be driven from any initial state to any target state within finite time via the connection. By using the same line of reasoning, an UMS with an almost GAS equilibrium state proves to be almost-globally controllable. It shows that underactuated pendula with one degree of unactuation are almost-globally controllable (except a set of Lebesgue measure zero), for which the connection state is when all the links are at the downmost positions.

Optimal Control of Nonholonomic Systems Via Magnetic Fields, pp. 903-908

Oprea, Maria Cornell University
Ruth, Maximilian Cornell University
Kassabova, Dora Cornell University
Clark, William Cornell University

Geometric optimal control utilizes tools from differential geometry to analyze the structure of a problem to determine the control and state trajectories to reach a desired outcome while minimizing some cost function. For a controlled mechanical system, the control usually manifests as an external force which, if conservative, can be added to the Hamiltonian. In this work, we focus on mechanical systems with controls added to the symplectic form rather than the Hamiltonian. In practice, this translates to controlling the magnetic field for an electrically charged system. We develop a basic theory deriving necessary conditions for optimality of such a system subjected to nonholonomic constraints. We consider the representative example of a magnetically charged Chaplygin Sleigh, whose resulting optimal control problem is completely integrable.

A New solution to the identification problem of current and flux fed Short Pitched Winding Switched Reluctance Motors (SPW-SRM) in the presence of strong saturation is developed. This is done by expanding the rotational periodicity and magnetic saturation in a high dimensional feature space spanned by a user defined combined periodic and smooth functions. The importance of this identification scheme lies in the good generalization ability of the constructed models, their robustness with respect to output measurement noise, and the diversity of their use as an estimation, prediction or diagnosis tool. Furthermore, no particular attention is required while the identification experiment since that data can be collected in vehicle normal operating regimes. Identification results obtained for a 60 kW SRM in the presence of measurement noise within automotive applications involving Fourier series and rational polynomial functions are quite satisfactory.

This paper concerns identification of uncontrolled or closed loop nonlinear systems using a set of trajectories that are generated by the system in a domain of attraction. The objective is to ensure that the trajectories of the identified systems are close to those of the real system, as quantified by an error bound that is prescribed a priori. A majority of existing methods for nonlinear system identification rely on techniques such as neural networks, autoregressive moving averages, and spectral decomposition that do not provide systematic approaches to meet pre-defined error bounds. The developed method is based on Carleman linearization-based lifting of the nonlinear system to an infinite dimensional linear system. The linear system is then truncated to a suitable order, computed based on the prescribed error bound, and parameters of the truncated linear system are estimated from data. The effectiveness of the technique is demonstrated by identifying an approximation of the Van der Pol oscillator from data within a prescribed error bound.
A Fading Memory Discontinuous EKF for the Online Model Identification of Cable-Driven Robots with Backlash, pp. 949-954

Poignonec, Thiibault University of Strasbourg
Nageotte, Florent University of Strasbourg
Bayle, Bernard University of Strasbourg

This paper deals with the online model identification of robots suffering from backlash in their transmission, such as is the case for cable-driven endoscopic robots. Although online backlash identification is advantageous due to potential textit{(in-situ) evolution of the backlash behavior}, most existing methods focus on offline identification. Existing online approaches are either designed for DOF-by-DOF identification or limited by the simplicity of the underlying backlash models. We propose a new identification method based on Discontinuous EKF (DEKF) filtering to learn, online, the correct parameters of a multi-DOF backlash model. This allows to account for measurement noise and to include more complex backlash behaviors. A proof of concept on a simulated 3 DOF flexible endoscopic robot is presented to demonstrate the potential of such an approach.

Task Space Tracking of Soft Manipulators: Inner-Outer Loop Control Based on Cosserat-Rod Models (I), pp. 967-972

Zheng, Tongjia University of Notre Dame
Han, Qing University of Notre Dame
Lin, Hai University of Notre Dame

The control problem of soft robots has been considered a challenging subject because they are of infinite degrees of freedom and highly under-actuated. Existing studies have mainly relied on approximated finite-dimensional models. In this work, we exploit infinite-dimensional feedback control for soft robots. We adopt the Cosserat-rod theory and employ nonlinear partial differential equations (PDEs) to model the kinematics and dynamics of soft manipulators, including their translational motions (for shear and elongation) and rotational
motions (for bending and torsion). The objective is to achieve position tracking of the entire manipulator in a planar task space by controlling the moments (generated by actuators). The design is inspired by the energy decay property of damped wave equations and has an inner-outer loop structure. In the outer loop, we design desired rotational motions that rotate the translational component into a direction that asymptotically dissipates the energy associated with position tracking errors. In the inner loop, we design inputs for the rotational components to track their desired motions, again by dissipating the rotational energy. We prove that the closed-loop system is exponentially stable and evaluate its performance through simulations.

15:00-15:15 WeB08.5
Output Model Predictive Control for a Wave Equation (I), pp. 987-992
Humalaja, Jukka-Pekka
University of Alberta
Dubljivic, Stevan
University of Alberta

We present an observer-based model predictive control scheme for a wave equation with non-collocated boundary control and observation. The design comprises a Luenberger-type state estimator combined with a model predictive controller which we show to stabilize the considered wave equation in the sense that the energy of the system decays asymptotically to zero. Moreover, if the initial state estimation error is sufficiently small, the controller is guaranteed to robustly satisfy given input constraints. The performance of the proposed design is demonstrated on a numerical simulation.

15:15-15:30 WeB08.6
Explicit Backstepping Kernel Solutions for Leak Detection in Branched Pipe Flows (I), pp. 993-998
Wilhelmsen, Nils Christian
Aars
Aamo, Ole Morten

Explicit solutions are given for a set of n + m linear hyperbolic observer backstepping kernel equations used for leak detection in branched pipe flows. It is identified that the kernel equations can be separated into N+1 distinct Goursat problems for 2j+1 coupled PDEs each, j in {0, 1, ..., N} and N+1 being the number of pipes connected via the branching point. Expressing the solutions as infinite matrix power series, the solution to each set of equations is shown to depend on a simplified, scalar Goursat problem, the solution of which is given in terms of derivatives of a modified Bessel function of the first kind. Furthermore, it is shown that the infinite matrix power series expressing the solution writes in terms of modified Bessel functions of the first kind and Marcum Q-functions, as is the case for the previously solved 2x2 constant coefficient case. A numerical example showing adaptive observer gains for leak detection computed via the explicit solutions for multiple operating points of a branched pipe flow is given to illustrate the results.

14:45-15:00 WeB08.4
Learning Theory Convergence Rates for Observers and Controllers in Native Space Embedding (I), pp. 979-986
Burns, John A
Virginia Tech
Kurdia, Andrew J.
Virginia Tech
Oesterheld, Derek
Virginia Tech
Stilwell, Daniel J.
Virginia Tech
Wang, Haoran
Virginia Tech

This paper derives rates of convergence of approximations of observers and controllers arising in the native space embedding method for adaptive estimation and control of a class of nonlinear ordinary differential equations (ODEs) that feature functional uncertainty. The native space embedding method views the nonlinear ODE as a type of distributed parameter system (DPS), and ideal controllers are derived from the DPS representation. Implementable estimators or controllers for the ODE are obtained by approximation of the DPS using history-dependent, scattered bases in the native space. The basis functions are defined in terms of their centers of approximation. This paper shows that for a large collection of choices of the native space, it is possible to derive convergence rates for implementable schemes that are expressed in terms of the fill distance of the centers of approximation in a subset that supports the observation or measurement process. The error bounds are derived in terms of the power function of the reproducing kernel and resemble those derived recently in machine learning theory and Bayesian estimation as applied to discrete stochastic systems.

14:00-14:15 WeB09.1
Vision-Based Approach for Estimating Lateral Dynamics of Powered Two-Wheeled Vehicles, pp. 999-1005
Alrazouk, Obaida
IBISC LAB
Chelliali, Amine
IBISC LAB
Nehaoua, Lamri
Evy University
Arioui, Hichem
Evy Val d’Essonne University

A novel approach based on a mounted monocular camera and an IMU to estimate the lateral dynamics (sideslip angle and lateral velocity) of Powered Two-Wheeled Vehicles (P2WV) is proposed in this paper. This approach is divided into two parts, the estimation of the derivative of the lateral offset and the relative heading. For the first, a method based on inverse perspective mapping to detect the lane markers and fit them into a second-degree polynomial that gives the lateral offset, then the derivative is estimated from the latter. For the relative heading, a method based on detecting the vanishing point is used to estimate it. Finally, these two main parameters are used to estimate the sideslip angle and the lateral velocity. The proposed method is tested on a popular motorcycle simulator software (BikeSim) throughout several scenarios on straight and curved roads with high and low speeds while executing a Double Lane Change (DLC) maneuver. The proposed method shows promising results in terms of error and real-time execution.

14:15-14:30 WeB09.2
Secure State Estimation for Multi-Agent Systems: On the Relationship between the Number of Agents and System Resilience, pp. 1006-1011
Shinohara, Takumi
Keio University
Namerikawa, Toru
Keio University

This paper addresses the problem of secure state estimation in multi-agent systems consisting of n agents. For the problem, the sparse observability index is a well-known measure of the system...
resilience. This index is defined as the largest integer $\delta$ for which the system observability is preserved even if any $\delta$ sensors are eliminated. The larger $\delta$ is, the more the system state can be reconstructed even if the system is subjected to more sensor attacks. In this paper, we analyze the relationship between the number of agents $n$ and the sparse observability index $\delta$ especially when the network structure is path and cycle graphs. Intuitively, it is assumed that, as the number of agents $n$ increases, the system resilience, i.e., $\delta$, increases accordingly. However, as this study provides, $\delta$ does not monotonically increase with an increase in $n$. In path graphs, $\delta$ depends on whether $n+1$ is prime or composite, while in cycle graphs, $\delta$ depends on whether $n$ is prime or composite. In path graphs, $\delta$ depends on whether $n+1$ is prime or composite, and the system resilience is enhanced when $n+1$ is prime. In cycle graphs, $\delta$ obeys whether $n$ is prime or composite, and the system is more resilient when $n$ is prime.

This paper considers the design of a multi-output high gain observer for a vehicle trajectory tracking application. The high gain observer approach offers the advantages of guaranteed feasibility and global stability with just one constant observer gain for this application. The challenges of transforming the vehicle dynamic model into the required companion form for applying the high gain observer technique are addressed. Transforming a traditional kinematic model to companion form is found to result in an increased number of states. Instead, a coordinate transformation that allows for varying velocity and varying slip angle is shown to be appropriate. The high gain observer methodology for a dynamic system with multiple outputs is presented and the calculation of the Lipschitz constant for the vehicle tracking application is discussed.

WeB09.3
Observability Gramian for Bayesian Inference in Nonlinear Systems with Its Industrial Application, pp. 1012-1017

Lee, Kunwoo
Kyoto University
Umuzi, Yusuke
Kawasaki Heavy Industries, Ltd
Konno, Kaiki
Kawasaki Heavy Industries, Ltd
Kashima, Kenji
Kyoto University

We present a novel (empirical) observability Gramian for nonlinear stochastic systems in the light of Bayesian inference. First, we define our observability Gramian, which we refer to as the estimability Gramian, based on the relation to the so-called Bayesian Fisher information matrix for initial state estimation. Then, we study the fundamental properties of an empirical version of the estimability Gramian. The practical usefulness of the proposed framework is examined through its application to a parameter and initial state estimation in a natural gas engine cylinder.

WeB09.4
Real-Time Clamping Force Estimation of Brake By-Wire System for Electric Autonomous Vehicles, pp. 1018-1023

Wei, Wenpeng
Southeast University
He, Tianyi
Utah State University
Pal, Anuj
Michigan State University

Brake-by-wire systems are prevailing more than ever for electric autonomous vehicles owing to several advantages, such as faster clamping force response, more accurate clamping force control, and more convenient to be integrated with other vehicle active safety functions. This paper mainly focuses on Electromechanical Brake (EMB) system. However, due to high sensor costs and limited sensor installation spaces, wide applications of EMB systems are prevented. One such example is the clamping force sensor. To replace the clamping force sensor, an innovative clamping force estimation method, i.e., the Braking Force Separation Strategy, is proposed in this paper. Different from existing estimation approaches that model the clamping force as a nonlinear polynomial function of motor position and brake gap distance, the proposed approach estimates the clamping force without brake gap distance. The decoupling is achieved by the application of an unknown input observer that enables simultaneous states and inputs estimation. To demonstrate the effectiveness of the proposed algorithm, simulations are performed under different input scenarios with or without fictitious measurement noise. The results show that the braking force can be accurately estimated by the proposed algorithm. It also demonstrates better performance by comparing with traditional method.

WeB10
Agents-Based Systems II (Regular Session)

Chair: Ramirez-Neria, Mario
Universidad Iberoamericana
Ciudad De Mexico
Co-Chair: Mandal, Nirabhra
University of California San Diego

14:00-14:15
Distance-Based Formation-Motion Control for Unicycle Agents, pp. 1036-1041

Chen, Jin
University of Groningen
Jayawardhana, Bayu
University of Groningen
Garcia de Marina, Hector
Universidad De Granada

We present a distance-based distributed formation-motion control law for unicycle agents that are required to move together at a constant reference speed. The distributed control law consists of the standard distance-based formation gradient control law, which is projected to the longitudinal and angular velocity inputs of the unicycle, and of a linear term that depends on the reference speed. The main contribution of this paper is to realize the consistency of unicycle agents’ orientations without orientation measurement, thereby reducing the possibility of significant orientation measurement errors in real-world applications. We prove and show numerically the local exponential convergence of the unicycle agents to the desired formation, where they eventually move in unison at a constant reference speed.
Private and Accurate Decentralized Optimization Via Encrypted and Structured Functional Perturbation, pp. 1042-1047

Zhou, YiJie The Chinese University of Hong Kong, Shenzhen
Pu, Shi The Chinese University of Hong Kong, Shenzhen

We propose a decentralized optimization algorithm that preserves the privacy of agents’ cost functions without sacrificing accuracy, termed EFPSPN. The algorithm adopts Paillier cryptosystem to construct zero-sum functional perturbations. Then, based on the perturbed cost functions, any existing decentralized optimization algorithm can be utilized to obtain the accurate solution. We theoretically prove that EFPSPN is (epsilon, delta)-differentially private and can achieve nearly perfect privacy under deliberate parameter settings. Numerical experiments further confirm the effectiveness of the algorithm.

Distributed Hybrid Attitude Estimation for Multi-Agent Systems on SO(3), pp. 1048-1053

Boughellaba, Mouaad Lakehead University
Tayebi, Abdelhamid Lakehead University

We consider the problem of distributed attitude estimation of multi-agent systems, evolving on $SO(3)$, relying on individual angular velocity and relative attitude measurements. We propose a nonlinear distributed hybrid attitude estimation scheme guaranteeing global asymptotic convergence of the attitude estimation errors to a common constant orientation, under an undirected, connected and acyclic graph topology. Moreover, in the presence of a leader in the group (knowing its absolute orientation), one can guarantee global asymptotic convergence of the attitude estimation errors to zero. Numerical simulation results are presented to illustrate the performance of our proposed scheme.

14:45-15:00

Opinion Dynamics for Utility Maximizing Agents with Heterogeneous Resources, pp. 1054-1061

Wankhede, Prashil Indian Institute of Science
Mandal, Nirabhra University of California San Diego
Tallapragada, Pavankumar Indian Institute of Science

In this paper we propose a continuous-time non-linear model of opinion dynamics. One of the main novelties of our model is that it costs resources for an agent to express an opinion. Each agent receives a utility based on the complete opinion profile of all agents. Each agent seeks to maximize its own utility function by suitably revising its opinion and the proposed dynamics arises from all agents simultaneously doing this. For the proposed model, we show ultimate boundedness of opinions. We also show stability of equilibrium points and convergence to an equilibrium point when all agents are non-contrarian. We give conditions for the existence of a consensus equilibrium and analyze the role that resources play in determining the social power of the agents in terms of the deviation of the consensus value from the agents’ internal preference. We also carry out a Nash equilibrium analysis of the underlying game and show that when all agents are non-contrarian, the set of equilibria of the opinion dynamics is the same as the set of Nash equilibria for the underlying game. We illustrate our results using simulations.

A Distributed Observer for Consensus of Multi-Agent Systems under Cyber Attack, pp. 1062-1067

Jinman, Yang Harbin Institute of Technology, Shenzhen
Li, Peng Harbin Institute of Technology, Shenzhen

In this paper, the consensus problem of the leader following system is addressed by considering the false data injection (FDI) attacks. An integral-based observer induced by nonlinear activation functions is proposed. By suitably choosing the activation function, the proposed observer is able to attenuate the effects of the fault data injection attack and achieve a no-error consensus. The consensus property and the attack rejection feature are analyzed considering both constant and time-varying attacks. It has been proven that the proposed method is able to mitigate the effects of different types of attacks. The effectiveness of the proposed observer is been verified by extensive numerical examples with comparisons to recent methods.

15:00-15:15

Consensus Robustness under PI Protocols with Undirected Graphs, pp. 1068-1073

Mao, Qi City University of Hong Kong
Ma, Dan Northeastern University
Ding, Yanling City University of Hong Kong
Peng, Hui Guangdong University of Technology, School of Automation
Chen, Jie City University of Hong Kong

This paper concerns robust consensus problems for continuous-time first-order multi-agent systems with respect to uncertain gain and phase of the agent's frequency response varying within certain ranges. We consider dynamic output feedback control protocol in the form of proportional-integral (PI) control. The agents can in general be nonminimum phase and unstable systems, which are interconnected by an undirected graph network. We seek to determine the largest ranges of gain and phase variations, referred to as the gain consensus margin (GCM) and the phase consensus margin (PCM), respectively, so that consensus can be achieved robustly within these ranges. Our main results consist of explicit analytical expressions of the GCM and PCM, which demonstrate how the agent's unstable pole and nonminimum phase zero, as well as the network connectivity may fundamentally confine the gain and phase variation ranges so that consensus can or cannot be maintained.
equilibrium, we show that the expected social cost is (often considerably) higher than that achieved when both nodes are completely truthful. Nonetheless, we prove that these equilibrium reporting strategies are never perverse, meaning that their resulting social cost is never worse than if traffic were uninformed as to network state.

14:15-14:30 WeB11.2
On the Convergence Rates of a Nash Equilibrium Seeking Algorithm in Potential Games with Information Delays, pp. 1080-1085
Huang, Yuanhanqing
Hu, Jianghai
Purdue University
This paper investigates the equilibrium convergence properties of a proposed algorithm for potential games with continuous strategy spaces in the presence of feedback delays, a main challenge in multi-agent systems that compromises the performance of various optimization schemes. The proposed algorithm is built upon an improved version of the accelerated gradient descent method. We extend it to a decentralized multi-agent scenario and equip it with a delayed feedback utilization scheme. By appropriately tuning the step sizes and studying the interplay between delay functions and step sizes, we derive the convergence rates of the proposed algorithm to the optimal value of the potential function when the growth of the feedback delays in time is subject to sublinear, linear, and superlinear upper bounds. Finally, simulations of a routing game are performed to empirically verify our findings.

14:30-14:45 WeB11.3
High-Order Decentralized Pricing Dynamics for Congestion Games: Harnessing Coordination to Achieve Acceleration, pp. 1086-1091
Chen, Yilan
Ochoa, Daniel E.
Poveda, Jorge I.
Marden, Jason R.
University of Colorado Boulder
University of California San Diego
University of California, Santa Barbara
We introduce a class of decentralized high-order pricing dynamics (HOPD) for the solution of optimal incentive problems in affine congestion games with full resource utilization. The dynamics incorporate momentum and decentralized coordinated resets to achieve better transient performance compared to traditional first-order gradient-based pricing algorithms. The proposed dynamics are studied using tools from graph theory, game theory, and hybrid dynamical systems theory. Our main results establish suitable stability and convergence properties with respect to the set of incentives that generate Nash flows that also maximize the social welfare function of the game. The theoretical results are illustrated via numerical examples in two different types of communication graphs, highlighting the effect of the communication topology and the coordination between players on the transient performance of the HOPD.

14:45-15:00 WeB11.4
Excess Payoff Evolutionary Dynamics with Strategy-Dependent Revision Rates: Convergence to Nash Equilibria for Potential Games, pp. 1092-1097
Kara, Semih
Martins, Nuno C.
University of Maryland, College Park
University of Maryland
Evolutionary dynamics in the context of population games models the dynamic non-cooperative strategic interactions among many nondescript agents. Each agent follows one strategy at a time from a finite set. A game assigns a payoff to each strategy as a function of the so-called population state vector, whose entries are the proportions of the population adopting the available strategies. Each agent repeatedly revises its strategy according to a revision protocol. We focus on a well-known class of protocols that prioritizes strategies with higher excess payoffs relative to a population-weighted average. In contrast to existing work for these protocols, we allow each agent's revision rate to depend explicitly on its current strategy. Motivated by applications and relevance to distributed optimization, we focus on potential games and investigate the population state's convergence to the game's Nash equilibria. Our contributions are twofold: (1) For the considered protocol class, prior work established conditions that ensure convergence under strategy-independent revision rates. We show that these conditions may be violated when the revision rates are strategy-dependent. (2) We prove that a minor, well-motivated modification of the considered protocol class satisfies these conditions for any strategy-dependent revision rates. We also illustrate our results using a distributed task allocation example.

15:00-15:15 WeB11.5
Sample Complexity of Decentralized Tabular Q-Learning for Stochastic Games, pp. 1098-1103
Gao, Zuguang
Ma, Qianqian
Basar, Tamer
Birge, John
The University of Chicago
Boston University
Univ of Illinois, Urbana-Champaign
University of Chicago
In this paper, we carry out finite-sample analysis of decentralized Q-learning algorithms in the tabular setting for a significant subclass of general-sum stochastic games (SGs) – weakly acyclic SGs, which includes potential games and Markov team problems as special cases. In the practical while challenging decentralized setting, neither the rewards nor the actions of other agents can be observed by each agent. In fact, each agent can be completely oblivious to the presence of other decision makers. In this work, the sample complexity of the decentralized tabular Q-learning algorithm to converge to a Markov perfect equilibrium is developed.

15:15-15:30 WeB11.6
Nash Equilibria for Exchangeable Team against Team Games and Their Mean Field Limit, pp. 1104-1109
Sanjari, Sina
Saldi, Naci
Yuksel, Serdar
University of Illinois at Urbana-Champaign
Bilkent University
Queen's University
We study stochastic mean-field games among finite number of teams each with large finite as well as infinite numbers of decision makers (DMs). We establish the existence of a Nash equilibrium (NE) and show that a NE exhibits exchangeability in the finite DM regime and symmetry in the infinite one. We establish the existence of a randomized NE that is exchangeable (not necessarily symmetric) among DMs within each team for a general class of exchangeable stochastic games. As the number of DMs within each team drives to infinity (that is for the mean-field games among teams), using a de Finetti representation theorem, we establish the existence of a randomized NE that is symmetric (i.e., identical) among DMs within each team and also independently randomized. Finally, we establish that a NE for a class of mean-field games among teams (which is symmetric) constitutes an approximate NE for the corresponding pre-limit game among teams with mean-field interaction and large but finite number of DMs.

15:45-16:00 WeB12
Advanced Vehicle Safety Controls (Invited Session)
This work provides formal safety guarantees for control systems with disturbance. A disturbance observer-based robust safety-critical control strategy is proposed, that estimates the effect of the disturbance on safety and utilizes this estimate with control barrier functions to attain provably safe dynamic behavior. The observer error bound – which consists of transient and steady-state parts – is quantified, and the system is endowed with robustness against this error via the proposed controller. An adaptive cruise control problem is used as illustrative example through simulations including real disturbance data.

This paper proposes a collision avoidance control strategy for constrained differential-drive robots moving in static but unknown obstacle scenarios. We assume that the robot is equipped with an on-board path planner providing a sequence of obstacle-free waypoints, and we design an ad-hoc constrained control strategy for ensuring absence of collisions and velocity constraints fulfillment. To this end, the nonlinear robot kinematics is redefined via a dynamic feedback linearization procedure, while a receding horizon control strategy is tailored to deal with time-varying state and input constraints. First, by considering the worst-case constraints realization, a conservative solution is offline determined to guarantee stability, recursive feasibility, and absence of collisions. Then, online, the tracking performance is significantly improved leveraging a non-conservative representation of the input constraints and set-theoretical containment conditions. Simulation results involving a differential-drive robot operating in a maze-like obstacle scenario are presented to show the effectiveness of the proposed solution.

Automated vehicles may encounter non-nominal situations called failure scenarios, due for instance to errors in perception or environment prediction. In some failure scenarios, a risk area must suddenly be avoided, possibly at the price of no longer satisfying all the constraints enforced in nominal driving conditions. We propose a design for a failure-safe controller that operates the vehicle according to the specifications in nominal conditions, while ensuring that, should a known failure occur, an evasive maneuver can be performed that avoids the risk area and satisfies a, possibly relaxed, set of driving constraints. We design evasive maneuver controllers parameterized in their reference, and we leverage set based methods to determine the region where such controllers satisfy the constraints and avoid the risk area. Membership in such a region during nominal operation is achieved by imposing additional constraints on the controller for nominal driving. We demonstrate the approach in simulations in a few different scenarios.
This paper investigates the optimal resource allocation problem for networked double-integrator systems with time-varying cost functions and resources. Due to the coexistence of challenges caused by non-identical Hessians and more complicated agents' dynamics, the extension from existing related results on single-integrator agents is nontrivial. A distributed algorithm is proposed to address the time-varying resource allocation problem and achieve the exact optimum tracking. Finally, an example is provided to illustrate the effectiveness of the proposed algorithm.
between the activities of catalytic enzymes and their regulation on slower timescales. To overcome this limitation and capture dynamic scenarios of interest, however, flux control can only capture steady-refined constraints, and optimization can be used to find behaviors in unknown fluxes (controller), so that data can be incorporated as an approach called flux control (e.g., flux balance analysis) was invented to demonstrate FEC can capture metabolism dynamics from network structure. More generally, FEC brings metabolic dynamics to the solvable via model predictive control. Glycolysis, which is known to demonstrate flux control. In FEC, dynamic regulations of metabolic systems are regulated not the fluxes themselves as in the flux control MPC framework only needs contact timings of each task and desired states to give MPC the knowledge of changes in contact through binding reactions. Since binding reactions effectively regulate fluxes' exponents, not the fluxes themselves as in flux control. In FEC, dynamic regulations of metabolic systems are solutions to optimal control problems that are computationally solvable via model predictive control. Glycolysis, which is known to have minute-timescale oscillations, is used as an example to demonstrate FEC can capture metabolism dynamics from network structure. More generally, FEC brings metabolic dynamics to the realm of control system analysis and design. where the entire closed-loop state and input trajectories stay within the state and input constraint sets and the final state reaches the desired terminal set. To enable longer missions under greater uncertainty, a wayset-based approach is proposed that allows for the prediction horizon of the MPC to be significantly shorter than the length of the mission. Using a scenario-based approach to stochastic MPC, the use of constrained zonotopes makes the computation of these waysets efficient and practical. Numerical results demonstrate the utility of the waysets for increasing the feasibility of MWPS constraints to longer missions and that the percentage of successful missions asymptotically converges above the desired probability.

In this paper, we develop an optimal weight adaptation strategy of model predictive control (MPC) for connected and automated vehicles (CAVs) in mixed traffic. We model the interaction between a CAV and a human-driven vehicle (HDV) as a simultaneous game and formulate a game-theoretic MPC problem to find a Nash equilibrium of the game. In the MPC problem, the weights in the HDV's objective function can be learned online using moving horizon inverse reinforcement learning. Using Bayesian optimization, we propose a strategy to optimally adapt the weights in the CAV's objective function so that the expected true cost when using MPC in simulations can be minimized. We validate the effectiveness of the optimal strategy by numerical simulations of a vehicle crossing example at an unsignalized intersection.

Metabolic dynamics such as stability of steady states, oscillations, lags and growth arrests in stress responses are important for microbial communities in human health, ecology, and metabolic engineering. Yet it is hard to model due to sparse data available on trajectories of metabolic fluxes. For this reason, a constraint-based approach called flux control (e.g., flux balance analysis) was invented to split metabolic systems into known stoichiometry (plant) and unknown fluxes (controller), so that data can be incorporated as refined constraints, and optimization can be used to find behaviors in scenarios of interest. However, flux control can only capture steady state fluxes well, limiting its application to scenarios with days or slower timescales. To overcome this limitation and capture dynamic fluxes, this work proposes a novel constraint-based approach, flux exponent control (FEC). FEC uses a different plant-controller split between the activities of catalytic enzymes and their regulation through binding reactions. Since binding reactions effectively regulate fluxes' exponents (from previous works), this yields the rule of FEC, that cells regulate fluxes' exponents, not the fluxes themselves as in flux control. In FEC, dynamic regulations of metabolic systems are solutions to optimal control problems that are computationally solvable via model predictive control. Glycolysis, which is known to have minute-timescale oscillations, is used as an example to demonstrate FEC can capture metabolism dynamics from network structure. More generally, FEC brings metabolic dynamics to the realm of control system analysis and design.

A stochastic Model Predictive Control (MPC) formulation is presented for systems with finite operation subject to constraints on the Mission-Wide Probability of Safety (MWPS). For linear discrete-time systems subject to unknown disturbances, the goal is to formulate an MPC controller to achieve a desired probability of mission success,
and dropping off objects while turning and walking.

WeB15  
Energy Systems I (Regular Session)  
Chair: Zlotnik, Anatoly  
Los Alamos National Laboratory  
Co-Chair: Bitar, Elyian  
Cornell University  
14:00-14:15 WeB15.1  
Optimal Control of Transient Flows in Pipeline Networks with Heterogeneous Mixtures of Hydrogen and Natural Gas, pp. 1221-1228  
Baker, Luke  
Arizona State University  
Kazi, Saif R.  
Los Alamos National Laboratory  
Platte, Rodrigo  
Arizona State University  
Zlotnik, Anatoly  
Los Alamos National Laboratory  

We formulate a control system model for the distributed flow of mixtures of highly heterogeneous gases through large-scale pipeline networks with time-varying injections of constituents, withdrawals, and control actions of compressors. This study is motivated by the proposed blending of clean hydrogen into natural gas pipelines as an interim means to reducing end use carbon emissions while utilizing existing infrastructure for its planned lifetime. We reformulate the partial differential equations for gas dynamics on pipelines and balance conditions at junctions using lumped elements to a sparse nonlinear differential algebraic equation system. Our key advance is modeling the mixing of constituents in time throughout the network, which requires doubling the state space needed for a single gas and increases numerical ill-conditioning. The reduced model is shown to be a consistent approximation of the original system, which we use as the dynamic constraints in a model-predictive optimal control problem for minimizing the energy expended by applying time-varying compressor operating profiles to guarantee time-varying delivery profiles subject to system pressure limits. The optimal control problem is implemented after time discretization using a nonlinear program, with validation of the results done using a transient simulation. We demonstrate the methodology for a small test network, and discuss scalability and potential applications.

WeB15  
Optimization of Hydrogen Blending in Natural Gas Networks for Carbon Emissions Reduction, pp. 1229-1236  
Sodwatana, Mo  
Stanford University  
Kazi, Saif R.  
Los Alamos National Laboratory  
Sundar, Kaarthik  
Los Alamos National Laboratory  
Zlotnik, Anatoly  
Los Alamos National Laboratory  

We present an economic optimization problem for allocating the flow of natural gas and hydrogen blends through a large-scale transportation pipeline network. Physical flow of the gas mixture is modeled using a state-estate relation between pressure decrease and flow rate, which depends on mass concentration of the constituents as it varies by location in the network. The objective reflects the economic value provided by the system, accounting for delivered energy in the form of compressor work, as well as hydrogen injections, and avoided carbon emissions. The problem is solved subject to physical flow equations, nodal balance and mixing laws, and engineering inequality constraints. The desired energy delivery rate and minimum hydrogen concentration can be specified as upper and lower bound values, respectively, of inequality constraints, and we examine the sensitivity of the physical pressure and flow solution to these parameters for two test networks. The results confirm that increasing hydrogen concentration requires greater energy expended for compression to deliver the same energy content, and the formulation could be used for valuation of the resulting mitigation of carbon emissions.

Valuing Uncertainties in Wind Generation: An Agent-Based Optimization Approach, pp. 1237-1242  
Shen, Daniel  
Massachusetts Institute of Technology  
Ilic, Marija  
Massachusetts Inst. of Tech  

The increasing integration of variable renewable energy sources such as wind and solar will require new methods of managing generation uncertainty. Existing practices of uncertainty management for these resources largely focuses around modifying the energy offers of such resources in the quantity domain and from a centralized system operator consideration of these uncertainties. This paper proposes an approach to instead consider these uncertainties in the price domain, where more uncertain power is offered at a higher price instead of restricting the quantity offered. We demonstrate system-level impacts on a modified version of the RTS-GMLC system where wind generators create market offers valuing their uncertainties over scenario set of day-ahead production forecasts. The results are compared with a dispatch method in which wind energy is offered at zero marginal price and restricted based on the forecast percentile.

WeB15  
A Multi-Battery Model for the Aggregate Flexibility of Heterogeneous Electric Vehicles, pp. 1243-1250  
Al Taha, Feras  
Cornell University  
Vincent, Tyrone L.  
Colorado School of Mines  
Bitar, Elyian  
Cornell University  

The increasing prevalence of electric vehicles (EVs) in the transportation sector will introduce a large number of highly flexible electric loads that EV aggregators can pool and control to provide energy and ancillary services to the wholesale electricity market. To integrate large populations of EVs into electricity market operations, aggregators must express the aggregate flexibility of the EVs under their control in the form of a small number of energy storage (battery) resources that accurately capture the supply/demand capabilities of the individual EVs as a collective. To this end, we propose a novel multi-battery flexibility model defined as a linear combination of a small number of base sets (termed batteries) that reflect the differing geometric shapes of the individual EV flexibility sets, and suggest a clustering approach to identify these base sets. We study the problem of computing a multi-battery flexibility set that has minimum Hausdorff distance to the aggregate flexibility set, subject to the constraint that the multi-battery flexibility set be a subset of the aggregate flexibility set. We show how to conservatively approximate this problem with a tractable convex program, and illustrate the performance achievable by our method with several numerical experiments.
while achieving an acceptable satisfaction of the exogenous power demand. Furthermore, the Monte Carlo simulations show that using the modified M-ENMPC decreases the average computational time by 17% compared with the conventional M-ENMPC from the literature.

15:15-15:30 WeB15.6
Ripple-Type Voltage Control for Extreme-Event Contingencies, pp. 1258-1263
Satkauska, Ignas National Renewable Energy Laboratory
Cavraro, Guido National Renewable Energy Laboratory
Bernstein, Andrey National Renewable Energy Laboratory

Frequent and intense extreme events make grid operation unprecedentedly challenging. Disruptive events could lead to dangerous voltage drops and even voltage collapse if corrective actions are not quickly taken. In this paper, we present a real-time algorithm for voltage control suitable for mitigating electric grid damage scenarios. In our strategy, when agents (generators, substations) experience a dangerous undervoltage, they first respond locally. When the local control resources are depleted, agents seek assistance from peer nodes over a communication network. The algorithm is simulated on a realistic test transmission system. Using fragility curve methodology, we simulate hurricane damages to the components of the synthetic 2000-bus grid representing the ERCOT system. Although being tested over a damaged grid after a hurricane event, our algorithm can be equally successfully applied to any other emergency low-voltage situation.

WeB16 Machine Learning I (Regular Session) Aqua 313
Chair: Sun, Wei University of Oklahoma
Co-Chair: Ferlez, James University of California, Irvine
14:00-14:15 WeB16.1
Safety-Aware Learning-Based Control of Systems with Uncertainty Dependent Constraints, pp. 1264-1270
Abbaszadeh Chekan, Jafar University of Illinois at Urbana Champaign
Langbort, Cedric Univ of Illinois, Urbana-Champaign

In this paper, we tackle the problem of safely stabilizing an originally (partially) unknown system while ensuring that it does not leave a prescribed ‘safe set’ whose structure itself depends on the unknown part of the system’s dynamics. For this aim, we apply a popular approach based on control Lyapunov functions (CLF), control barrier functions (CBF), and Gaussian processes (to build confidence set around the unknown term), which has proved successful in the known-safe set setting. However, with the mentioned safety set structure, we witness the introduction of higher-order terms to be estimated and bounded with high probability using only system state measurements. In this paper, we build on the recent literature on Gaussian Processes (GPs) and reproducing kernels to address the challenge and show how to modify the CLF-CBF-based approach correspondingly to obtain safety guarantees. To overcome the intractability of verification of these conditions on the continuous domain, we apply discretization of the state space and use Lipschitz continuity properties of dynamics to derive equivalent CLF and CBF certificates in discrete state space. Finally, we discuss the strategy for the control design aim using the derived certificates.

14:15-14:30 WeB16.2
Mean Field Games on Weighted and Directed Graphs Via Colored Digraphons, pp. 1271-1276
Fabian, Christian Technische Universität Darmstadt

Multi-agent systems are in general hard to model and control due to their complex nature involving many individuals. Numerous approaches focus on empirical and algorithmic aspects of approximating outcomes and behavior in multi-agent systems and lack a rigorous theoretical foundation. Graphon mean field games (GMFGs) on the other hand provide a mathematically well-founded and numerically scalable framework for a large number of connected agents. In standard GMFGs, the connections between agents are undirected, unweighted and invariant over time. Our paper introduces colored digraphon mean field games (CDMFGs) which allow for weighted and directed links between agents that are also adaptive over time. Thus, CDMFGs are able to model more complex connections than standard GMFGs. Besides a rigorous theoretical analysis including both existence and convergence guarantees, we employ the online mirror descent algorithm to learn equilibria. To conclude, we illustrate our findings with an epidemics model and a model of the systemic risk in financial markets.

14:30-14:45 WeB16.3
Polynomial-Time Reachability for LTI Systems with Two-Level Lattice Neural Network Controllers, pp. 1277-1282
Ferlez, James University of California, Irvine
Shoukry, Yasser University of California, Irvine

In this paper, we consider the computational complexity of bounding the reachable set of a Linear Time-Invariant (LTI) system controlled by a Rectified Linear Unit (ReLU) Two-Level Lattice (TLL) Neural Network (NN) controller. In particular, we show that for such a system and controller, it is possible to compute the exact one-step reachable set in polynomial time in the size of the TLL NN controller (number of neurons). Additionally, we show that a tight bounding box of the reachable set is computable via two polynomial-time methods: one with polynomial complexity in the size of the TLL and the other with polynomial complexity in the Lipschitz constant of the system and other problem parameters. Finally, we propose a pragmatic algorithm that adaptively combines the benefits of (semi-)exact reachability and approximate reachability, which we call L-TLLBox. We evaluate L-TLLBox with an empirical comparison to a state-of-the-art NN controller reachability tool. In our experiments, L-TLLBox completed reachability analysis as much as 5000× faster than this tool on the same network/system, while producing reach boxes that were from 0.08 to 1.42 times the area.
We consider the problem of harvesting data from a set of targets distributed throughout a two-dimensional environment. The targets broadcast their data to an agent flying above them, and the goal is for the agent to extract all the data and move to a desired final position in minimum time. While previous work developed optimal controllers for the one-dimensional version of the problem, such methods do not extend to the 2-D setting. Therefore, we first convert the problem into a Markov Decision Process in discrete time and then apply reinforcement learning to find high performing solutions using double deep Q learning. We use a simple binary cost function that directly captures the desired goal, and we overcome the challenge of the sparse nature of these rewards by incorporating hindsight experience replay. To improve learning efficiency, we also utilize prioritized sampling of the replay buffer. We demonstrate our approach through several simulations, which show a similar performance as an existing optimal controller in the 1-D setting, and explore the effect of both the replay buffer and the prioritized sampling in the 2-D setting.

A Tutorial on Policy Learning Methods for Advanced Controller Representations (Tutorial Session)

Chair: Paulson, Joel
The Ohio State University
Co-Chair: Mesbah, Ali
University of California, Berkeley
Organizer: Paulson, Joel
The Ohio State University
Organizer: Mesbah, Ali
University of California, Berkeley

This paper provides a tutorial overview of recent advances in learning control policy representations for complex systems. We focus on control policies that are determined by solving an optimization problem that depends on the current state and some adjustable parameters. We refer to such policies as interpretable in the sense that each of the individual components can be directly understood by practitioners once the parameters are set, i.e., the objective function encodes the desired goal and the constraint functions enforce the rules of the system. We discuss how various commonly used control policies can be viewed in this manner such as the linear quadratic regulator, (nonlinear) model predictive control, and approximate dynamic programming. Traditionally, the parameters that appear in these control policies have been tuned by hand, expert knowledge, or simple trial-and-error experimentation, which can be time consuming and lead to suboptimal results in practice. To this end, we describe how the Bayesian optimization framework, which is a class of efficient derivative-free optimization methods for noisy functions, can be used to efficiently automate this process. In addition to reviewing relevant literature and demonstrating the effectiveness of these new methods on an illustrative example problem, we also offer perspectives on future research in this area.

Reinforcement Learning with Guarantees (*)

Zanon, Mario
IMT Institute for Advanced Studies
Lucca

Safety-Critical Distributionally Robust Imitation Learning (*)

Zhong, Zhengang
Imperial College London
del Rio Chanona, Antonio
Imperial College London

This paper considers a distributed optimization problem in the presence of Byzantine agents capable of introducing untrustworthy information into the communication network. A resilient distributed subgradient algorithm is proposed based on graph redundancy and objective redundancy. It is shown that the algorithm causes all non-Byzantine agents’ states to asymptotically converge to the same optimal point under appropriate assumptions. A partial convergence rate result is also provided.

Potential Energy Saving by Different Cooperative Driving Automation Classes in Car-Following Scenarios, pp. 1313-1318

Hyeon, Eunjeong
Argonne National Laboratory
Karbowiak, Dominik
Argonne National Laboratory
Rousseau, Aymeric
Argonne National Laboratory

Cooperative driving automation (CDA) enables connected and automated vehicles to cooperate with surrounding vehicles and infrastructure for increased safety, mobility, and energy efficiency. CDA systems are categorized into four classes, depending on the cooperation level: status-sharing, intent-sharing, agreement-seeking, and prescriptive cooperation. In order to maximize the benefits of these systems, new communication frameworks and protocols need to be designed based on extensive studies on corresponding vehicle control performance and real-time implementation. The essential parameters of control and communication for reliable control performance and real-time implementation are identified, such as agreement-seeking frequency, prediction horizon length, and the number of CDA participants. In addition, important control design factors that need to be considered in CDA development are discussed, including the smooth transition between cooperative and individual driving plans and the proposals that maximize the probability of agreement from counterparts.

Multiagent Networks with Misbehaving Nodes: Control with Driver and Observer Nodes, pp. 1319-1324

Yildirim, Emre
University of South Florida
Saltos, Alexander
University of South Florida
Yucelen, Tansel
University of South Florida

As opposed to applying control signals to each node in multiagent networks for suppressing the negative effects of misbehaving nodes, this paper focuses on applying control signals to a small subset of nodes due to physical (i.e., inaccessible nodes) and/or economical (i.e., large number of nodes) constraints. To achieve this goal, we have recently focused on how to control misbehaving multiagent networks via sending control signals to a small subset of nodes (i.e., driver nodes) in the network, where the control signals are generated by their state information. In this study, we now consider that the control signals applied to driver nodes are generated based on the
This paper studies the problem of selecting input nodes (leaders) to make networks strong structurally controllable despite misbehaving nodes and edges. We utilize a graph-based characterization of network strong structural controllability (SSC) in terms of zero forcing in graphs, which is a dynamic coloring of nodes. We consider three types of misbehaving nodes and edges that disrupt the zero forcing process in graphs, thus, deteriorating the network SSC. Then, we examine a leader selection guaranteeing network SSC by ensuring the accuracy of the zero forcing process, despite $k$ misbehaving nodes/edges. Our main result shows that a network is resilient to $\$k$ misbehaving nodes/edges under one threat model if and only if it is resilient to the same number of failures under the other threat models. Thus, resilience against one threat model implies resilience against the other models. We then discuss the computational aspects of leader selection for resilient SSC and present a numerical evaluation.
systems. Given multiple autonomous leaders, a number of followers, and an H2 cost functional, we aim to design a distributed protocol that achieves containment control while the associated H2 cost is smaller than an a priori given upper bound. To that end, we first show that the H2 suboptimal containment control problem can be equivalently recast into the H2 suboptimal control problem of a set of independent systems. Based on this, a design method is provided to compute such a distributed protocol. The computation of the feedback gain involves a single Riccati inequality whose dimension is equal to the dimension of the states of the agents. The performance of the proposed protocol is illustrated by a simulation example.

16:36-16:40 WeC01.10
Distributed Cooperative Kalman Filter Constrained by Discretized Poisson Equation for Mobile Sensor Networks, pp. 1365-1370
Zhang, Ziqiao  Georgia Institute of Technology
Mayberry, Scott  Georgia Institute of Technology
Wu, Wencen  San Jose State University
Zhang, Fumin  Georgia Institute of Technology

This paper proposes cooperative Kalman filters for distributed mobile sensor networks where the mobile sensors are organized into cells that resemble a mesh grid to cover a spatial area. The mobile sensor networks are deployed to map an underlying spatial-temporal field modeled by the Poisson equation. After discretizing the Poisson equation with finite volume method, we found that the cooperative Kalman filters for the cells are subjected to a set of distributed constraints. The field value and gradient information at each cell center can be estimated by the constrained cooperative Kalman filter using measurements within each cell and information from neighboring cells. We also provide convergence analysis for the distributed constrained cooperative Kalman filter. Simulation results with a five cell network validates the proposed distributed filtering method.

WeC02  Sapphire IJ
Constrained Control (RI) (RI Session)
Chair: Burlion, Laurent  Rutgers, the State University of New Jersey
Co-Chair: Pangborn, Herschel  Pennsylvania State University

16:00-16:04 WeC02.1
Finite-Time Stability and Stabilization of Polynomial Systems (I), pp. 1371-1376
Tartaglione, Gaetano  Università Di Napoli Parthenope
Ariola, Marco  Univ. Degli Studi Di Napoli Parthenope
Amato, Francesco  Università Degli Studi Di Napoli Federico II

In this paper we consider the class of polynomial systems and we investigate on their finite-time stability properties. In this analysis, for the first time, finite-time stability is defined with respect to domains with polynomial bounds. A sufficient condition for finite-time stability is obtained, which can be solved recasting the feasibility problem in terms of SDP through SOS programming. Moreover, a nonlinear state-feedback control law is developed to stabilize the system in the finite-time notion. The effectiveness of the stabilizing control law is shown by a numerical example.

16:04-16:08 WeC02.2
Lyapunov-Based Current-Profile Feedback Control in Tokamaks with Nonsymmetric Individual Actuator Saturation, pp. 1377-1382
Paruchuri, Sai Tej  Lehigh University
Pajares, Andres  General Atomics
Schuster, Eugenio  Lehigh University

Advanced tokamak scenarios can achieve optimal tokamak operation by shaping the plasma internal profiles through the use of noninductive heating and current sources. As a result of the dynamic complexities, active control of the power of each noninductive heating and current source, a nonnegative value, may be necessary to achieve the desired tokamak performance. However, due to the inherent physical limitations, arbitrary power prescription by the controller may saturate the heating and current drives. Therefore, it is highly desirable to develop a class of active control algorithms that account for the saturation limits of these actuators. A Lyapunov-based nonlinear feedback control algorithm that intrinsically accounts for saturation limits is proposed in this work to regulate the spatial distribution of the toroidal current density in the tokamak. The controller does not rely on constrained optimization techniques, which can be computationally expensive for real-time implementation. Furthermore, the controller can handle nonsymmetric saturation limits, i.e., the absolute values of the upper and lower saturation limits do not have to be equal. The effectiveness of the control algorithm is demonstrated for a DIII-D tokamak scenario in nonlinear simulations.

16:08-16:12 WeC02.3
Successor Sets of Discrete-Time Nonlinear Systems Using Hybrid Zonotopes, pp. 1383-1389
Siefert, Jacob  Pennsylvania State University
Bird, Trevor J.  Purdue University
Koeln, Justin  University of Texas at Dallas
Jain, Neera  Purdue University
Pangborn, Herschel  Pennsylvania State University

This paper presents identities for calculating over-approximated successor sets of discrete-time nonlinear systems using hybrid zonotopes. The proposed technique extends the state-update set construct, previously developed for linear hybrid systems, to nonlinear systems. Forward reachability of nonlinear systems can then be performed using only projection, intersection, and Cartesian product set operations with the state-update set. It is shown that use of an over-approximation of the state-update set yields over-approximations of successor sets. A technique to over-approximate a nonlinear function using a special ordered set approximation, equivalently represented as a hybrid zonotope, is then presented. A numerical example of a nonlinear system controlled by a piecewise-affine control law demonstrates that the approach provides a computationally-efficient and tight over-approximation of the closed-loop reachable set.

16:12-16:16 WeC02.4
Robust Data-Driven Control Barrier Functions for Unknown Continuous Control Affine Systems, pp. 1390-1395
Jin, Zeyuan  Arizona State University
Khajenejad, Mohammad  University of California, San Diego
Yong, Sze Zheng  Northeastern University

In this letter, we introduce robust data-driven control barrier functions (CBF-DDs) to guarantee robust safety of unknown continuous control affine systems despite worst-case realizations of generalization errors from prior data under various continuity assumptions. To achieve this, we leverage results from data-driven abstraction that provide guaranteed upper and lower bounds of an unknown function from the data set to formulate/obtain a safe input set for a given state. By incorporating the safe input set into an optimization-based controller, the safety of the system can be ensured. Moreover, we present several complexity reduction approaches including providing subproblems that can be solved in parallel, closed-form solutions for a special case and downsampling strategies to improve computational performance.

16:16-16:20 WeC02.5
Anti-Windup Compensation for Stable and Unstable Quantized Systems with Saturation, pp. 1396-1401
Richards, Christopher  University of Louisville
Turner, Matthew C.  University of Southampton

It is well known that actuator saturation can cause destabilization and
degradation in performance; similar problems are faced when actuation is quantized. This paper proposes the design of an anti-windup compensator for systems with actuators that are limited to a textit{finite} number of quantization levels. This combination of discrete level actuation and saturation poses a unique anti-windup problem that has not yet been solved. To surmount this combined issue, an anti-windup compensator is proposed which provides ultimate-boundedness of the system state within a prescribed region, and also guarantees that the state does not stray outside a larger compact set. A numerical simulation example illustrates the effectiveness on a rigid-body system which inspired this work.

16:20-16:24  WeC02.6
Attacker-Resilient Adaptive Path Following of a Quadrotor with Dynamic Path-Dependent Constraints, pp. 1402-1407
Jin, Xu  
Hu, Zhongjun  
University of Kentucky

For most works on constrained motion control in the literature, only constant or time-varying constraints are discussed, which are often conservative and cannot adapt to the dynamically changing operation environment. In this work, in the context of quadrotor operations, we propose a new adaptive path following architecture with dynamic path-dependent constraints, in which the desired path coordinate, desired path speed, and constraint requirements not only depend on a path parameter associated with the desired path, but also can adapt to the presence of an "attacker" nearby. A new concept of "composite barrier function" has been proposed to address both safety and performance constraints in a unified structure. Adaptive laws are introduced to estimate the upper bounds of system uncertainties and unknown "attacker" velocity. Exponential convergence into a small neighborhood around the equilibrium for position tracking error can be guaranteed. In the end, a simulation example further demonstrates the effectiveness of the proposed architecture.

16:24-16:28  WeC02.7
Control Constrained Game Theoretic Differential Dynamic Programming, pp. 1408-1413
Sun, Wei  
Kleiber, Justin  
University of Oklahoma  
Virginia Tech

In this work, a control constrained version of the continuous time game theoretic differential dynamic programming (GT-DDP) algorithm is presented. The convergence of the GT-DDP algorithm is analyzed, and it is shown that control constraints can be successfully applied through solving quadratic programs during the control update phase of the GT-DDP. The control constrained GT-DDP is applied to the trajectory tracking problem of a quadrotor. Additionally, the proposed algorithm is demonstrated on a real world experiment of a pursuit-evasion game between two quadrotors to show its ability in planning trajectories for multiple quadrotors under different control constraints.

16:28-16:32  WeC02.8
Safety-Critical Control with Bounded Inputs Via Reduced Order Models, pp. 1414-1421
Molnar, Tamas G.  
Ames, Aaron D.  
California Institute of Technology  
California Institute of Technology

 Guaranteeing safe behavior on complex autonomous systems—from cars to walking robots—is challenging due to the inherently high dimensional nature of these systems and the corresponding complex models that may be difficult to determine in practice. With this as motivation, this paper presents a safety-critical control framework that leverages reduced order models to ensure safety on the full order dynamics—even when these models are subject to disturbances and bounded inputs (e.g., actuation limits). To handle input constraints, the backup set method is reformulated in the context of reduced order models, and conditions for the provably safe behavior of the full order system are derived. Then, the input-to-state safe backup set method is introduced to provide robustness against discrepancies between the reduced order model and the actual system. Finally, the proposed framework is demonstrated in high-fidelity simulation, where a quadrupedal robot is safely navigated around an obstacle with legged locomotion by the help of the unicycle model.

16:32-16:36  WeC02.9
Control Synthesis for Stability and Safety by Differential Complementarity Problem, pp. 1422-1427
Yi, Yinzhuang  
Koga, Shunon  
Gavrea, Bogdan  
University of California, San Diego  
Technical University of Cluj-Napoca  
University of California, San Diego

This paper develops a novel control synthesis method for safe stabilization of control-affine systems as a Differential Complementarity Problem (DCP). Our design uses a control Lyapunov function (CLF) and a control barrier function (CBF) to define complementarity constraints in the DCP formulation to certify stability and safety, respectively. The CLF-CBF-DCP controller imposes stability as a soft constraint, which is automatically relaxed when the safety constraint is active, without the need for parameter tuning or optimization. We study the closed-loop system behavior with the CLF-CBF-DCP controller and identify conditions on the existence of local equilibria. Although in certain cases the controller yields undesirable local equilibria, those can be confined to a small subset of the safe set boundary by proper choice of the control parameters. Then, our method can avoid undesirable equilibria that CLF-CBF quadratic programming techniques encounter.

16:36-16:40  WeC02.10
Reference Governor Design in the Presence of Uncertain Polynomial Constraints, pp. 1428-1433
Schieni, Rick  
Zhao, Chengwei  
Malisoff, Michael  
Burton, Laurent  
Rutgers University  
Rutgers University  
Louisiana State University  
Rutgers, the State University of New Jersey

Reference governors are add-on schemes that are used to prevent controlled dynamical systems from violating input and state constraints, and so are playing an increasingly important role in aerospace, robotic, and other engineering applications. Here we present a novel reference governor design for systems whose polynomial constraints depend on unknown bounded parameters. This is a significant departure from earlier treatments of reference governors, where the constraints were linear or known, because here we transfer the uncertainties into the constraints instead of having them in the closed-loop dynamics, which greatly simplifies the task of determining future evolution of the constraints. Unlike our earlier treatment of reference governors with polynomial constraints which transformed the constraints into linear ones that depend on the state of the system, here we transform the constraints into linear ones that depend on both the system's state and uncertain parameters. Convexity allows us to compute the maximal output admissible set for an uncertain pre-stabilized linear system. We show that it is sufficient to only consider the extreme values of the uncertain parameters when computing and propagating the polynomial constraints. We illustrate our method using an uncertain longitudinal dynamics for civilian aircraft which is controlled using a disturbance compensation method and needs to satisfy constraints, and where our reference governor method ensures that safety constraints are always satisfied.

WeC03
Robotics II (Regular Session)  
Chair: Tanner, Herbert G.  
Co-Chair: Cai, Mingyu  
University of Delaware  
Lehigh University

16:00-16:15  WeC03.1
A Transient Response Adjustable MPC for Following a Dynamic
As mobile robots increasingly interact with humans, vehicles, and other robots, the ability to follow these dynamic objects becomes a crucial capability. In this paper, a mobile robot motion controller based on a down-scaled Model Predictive Control (MPC) is proposed for performing dynamic object following. The controller can reflect the dynamics of an object for an appropriate response speed while ensuring the safety of the robot against predicted risks. In addition, an adaptive prediction time horizon is proposed to improve following robustness. The proposed motion controller is demonstrated through extensive simulations and real-time experiments on mobile robot hardware.

16:15-16:30 WeC03.2
Priority Patrol with a Single Agent - Bounds and Approximations, pp. 1440-1445
Mallya, Deepak Indian Institute of Technology, Bombay
Sinha, Arpita Indian Institute of Technology, Bombay
Vachhani, Leena Indian Institute of Technology Bombay

Priority patrolling is a particular case of the patrolling problem where a few locations have higher priority than others, and a patrolling agent must visit these locations more frequently. This work provides three results on the priority patrol problem. First, we study the minimum time interval between two visits to a priority node, which we term the time period. We show that there doesn’t exist a feasible patrol strategy for a time period less than a particular threshold. Next, we prove that a patrol strategy with recurring circuits always exists for this problem. Lastly, we provide an algorithm to obtain a patrol strategy with a constant factor approximation to the time period. We validated the results on grid graphs of various sizes, connectivity, and the number and placement of priority nodes in the graph.

16:30-16:45 WeC03.3
Learning Minimally-Violating Continuous Control for Infeasible Linear Temporal Logic Specifications, pp. 1446-1452
Cai, Mingyu Lehigh University
Mann, Makai MIT Lincoln Laboratory
Serlin, Zachary MIT Lincoln Laboratory
Leahy, Kevin MIT Lincoln Laboratory
Vasile, Cristian Ioan Lehigh University

This paper explores continuous-time control synthesis for target-driven navigation to satisfy complex high-level tasks expressed as linear temporal logic (LTL). We propose a model-free framework using deep reinforcement learning (DRL) where the underlying dynamic system is unknown (an opaque box). Unlike prior work, this paper considers scenarios where the given LTL specification might be infeasible and therefore cannot be accomplished globally. Instead of modifying the given LTL formula, we provide a general DRL-based approach to satisfy it with minimal violation. %minline{Need to decide if we’re comfortable calling these “guarantees” due to the stochastic policy. I’m not repeating this comment everywhere that says “guarantees” but there are multiple places.} To do this, we transform a previously multi-objective DRL problem, which requires simultaneous automata satisfaction and minimum violation cost, into a single objective. By guiding the DRL agent with a sampling-based path planning algorithm for the potentially infeasible LTL task, the proposed approach mitigates the myopic tendencies of DRL, which are often an issue when learning general LTL tasks that can have long or infinite horizons. This is achieved by decomposing the infeasible LTL formula into several reach-avoid sub-tasks with shorter horizons, which can be trained in a modular DRL architecture. Furthermore, we overcome the challenge of the exploration process for DRL in complex and cluttered environments by using path planners to design rewards that are dense in the configuration space. The benefits of the presented approach are demonstrated through testing on various complex nonlinear systems and compared with state-of-the-art baselines. The Video demonstration can be found on YouTube Channel:[https://youtu.be/BJnx8Nv224E].

16:45-17:00 WeC03.4
Rodwell, Colin Clemson University
Buzhardt, Jake Clemson University
Tallapragada, Phanindra Clemson University

The control of swimming robots presents several challenges, in large part due to the complex fluid-structure interaction. Low fidelity simplified formulas for drag and lift force lead to control amenable models, but do not capture key physics that can play an especially important role in the swimming of small-scale robots with limited actuation. Higher fidelity models of the fluid-structure interaction lead to nonlinear high dimensional control systems for which solution methods are not obvious. We propose the use of the Koopman operator in developing a linear representation for both the complex fluid structure interaction as well as actuation effects. As a test case for this framework we address the problem of stabilizing the pitching oscillations of a hydrofoil that is hinged in a simulated unsteady free stream flow. The actuator for the hydrofoil is an internal reaction wheel which presents an integral saturation constraint. Using the Koopman operator, the lifted control system is used to formulate a constrained optimal control problem which we solve using model predictive control. The framework proposed in this paper can potentially be extended to design a combination of data-driven and physics based control algorithms for swimming robots.

17:00-17:15 WeC03.5
Geometry of Radial Basis Neural Networks for Safety Biased Approximation of Unsafe Regions, pp. 1459-1466
Abuaish, Ahmad Georgia Institute of Technology
Srinivasan, Mohit Ford Motor Company
Vela, Patricio A. Georgia Institute of Technology

Barrier function-based inequality constraints are a means to enforce safety specifications for control systems. When used in conjunction with a convex optimization program, they provide a computationally efficient method to enforce safety for the general class of control-affine systems. One of the main assumptions when taking this approach is the a priori knowledge of the barrier function itself, i.e., knowledge of the safe set. In the context of navigation through unknown environments where the locally safe set evolves with time, such knowledge does not exist. This manuscript focuses on the synthesis of a zeroing barrier function characterizing the safe set based on safe and unsafe sample measurements, e.g., from perception data in navigation applications. Prior work formulated a supervised machine learning algorithm whose solution guaranteed the construction of a zeroing barrier function with specific level-set properties. However, it did not explore the geometry of the neural network design used for the synthesis process. This manuscript describes the specific geometry of the neural network used for zeroing barrier function synthesis, and shows how the network provides the necessary representation for splitting the state space into safe and unsafe regions.

17:15-17:30 WeC03.6
Multi-Behavioral Multi-Robot Systems Driven by Motivation Dynamics, pp. 1467-1472
Baxevani, Kleio University of Delaware
Tanner, Herbert G. University of Delaware

This paper outlines a methodology for constructing multiple dynamical behaviors for a multi-agent system within the motivation dynamics theoretical framework. Recent work introduced analytical conditions
for a dynamical system to undergo a Hopf bifurcation and generate multiple dynamical behaviors from a single family of continuous dynamics. The paper contributes by leveraging these recent results to develop a multi-agent system capable of switching its dynamic behavior without changing its underlying continuous dynamics. Simulation and experimental results are provided, confirming the theoretical results which guarantee the existence of a Hopf bifurcation in the dynamics of the multi-robot system.

Nonlinear Model Predictive Controller (ENMPC), which maximizes augmented ROM is then used as the internal model in an Economic behavior without changing its underlying continuous dynamics. determines the required rating of the actuation motors and the mean nontrivial factor in LCOE estimation. The peak power consumption power consumed by blade-pitch actuation is an often neglected, but assessed and compared with the non-augmented ROM. The is augmented by training a Neural Network (NN) offline. The leading to an improved performance. A Reduced Order Model (ROM) mismatch is assessed in closed loop with the NREL 5MW onshore performance of the controller and the impact of a reduced plant model implemented using the state-of-the-art ACADOS framework. The designed ENMPC is formulated directly within the controller using the Parametric Online Predictive control of a wind turbine. In fact, an adaptive internal model without the need for wind speed measurements. Analysis and simulations show that the proposed algorithm corrects for model uncertainties in the form of magnitude scaling errors under ideal constant and realistic turbulent wind conditions.

Reducing Plant-Model Mismatch for Economic Model Predictive Control of Wind Turbine Fatigue by a Data-Driven Approach (I), pp. 1473-1479
Anand, Abhinav Technical University of Munich, Wind Energy Institute Bottasso, Carlo Luigi Technical University of Munich

This paper considers the inclusion of an adaptive element in the model-predictive control of a wind turbine. In fact, an adaptive internal model can reduce the plant-model mismatch, in turn potentially leading to an improved performance. A Reduced Order Model (ROM) is augmented by training a Neural Network (NN) offline. The improvement in state predictions due to model augmentation is assessed and compared with the non-augmented ROM. The augmented ROM is then used as the internal model in an Economic Nonlinear Model Predictive Controller (ENMPC), which maximizes profit by optimally balancing tower fatigue damage costs with revenue due to power generation. The tower cyclic fatigue costs are formulated directly within the controller using the Parametric Online Rainflow Counting (PORFC) approach. The designed ENMPC is implemented using the state-of-the-art ACADOS framework. The performance of the controller and the impact of a reduced plant model mismatch is assessed in closed loop with the NREL 5MW onshore wind turbine, simulated using OpenFAST. Results show that the ENMPC utilizing the augmented ROM yields higher economic profit, slightly higher torque travel, and significantly lower pitch travel, compared to the ENMPC utilizing only the baseline ROM.

Modeling Blade-Pitch Actuation Use in Wind Turbines (I), pp. 1480-1485
Henry, Aolfe University of Colorado Boulder
Pusch, Manuel Munich University of Applied Sciences Pao, Lucy Y. University of Colorado Boulder

Estimating the levelized cost of energy (LCOE) of a wind turbine is useful for performing a cost-benefit analysis of potential designs. The power consumed by blade-pitch actuation is an often neglected, but nontrivial factor in LCOE estimation. The peak power consumption determines the required rating of the actuation motors and the mean power consumption impacts the net annual energy production (nAEP) of the turbine. The closed-loop blade-pitch actuation and the power consumed by its motors are complex functions of the wind field disturbance and internal turbine states. They can only be predicted well with reasonably high-fidelity and computationally expensive simulations or field tests. We present an alternative approach to modeling these signals using the Sparse Identification of Nonlinear Dynamics with Control (SINDyC) methodology. It is computationally tractable to generate these models for large datasets and to simulate power consumption for a given wind field. Furthermore, the models provide intuition as to how the turbine states and disturbances contribute to the signal dynamics. By generating a closed-form dynamic state equation for the blade-pitch actuation and an algebraic equation for the blade-pitch motor power, we can efficiently predict the mean and maximum power required for a given turbulent wind field and turbine design. The model is trained and validated using data generated from the open-source aero-servo-hydro-elastic wind turbine simulation tool OpenFAST.

Uncertainties in Advanced Wind Turbine Controllers: A Wind Speed Measurement-Free Approach (I), pp. 1486-1492
Mulders, Sebastiaan Paul Delft University of Technology Brandetti, Livia Delft University of Technology Spagnolo, Fabio Vestas Wind Systems A/S Liu, Yichao Delft University of Technology Christensen, Pou Brandt Vestas Wind Systems A/S van Wingerden, Jan-Willem Delft University of Technology

Wind turbine partial-load controllers have evolved from simple static nonlinear function implementations to more advanced dynamic controller structures. Such dynamic control schemes have the potential to improve power production performance in realistic environmental conditions and allow for a more granular trade-off between loads and energy capture. The control structure generally consists of a wind speed estimator (WSE) combined with a controller aiming to track the commanded tip-speed ratio (TSR) reference. The performance and resulting closed-loop system stability are however highly dependent on the accuracy of the internal model in the WSE-TSR tracking scheme. Therefore, developing learning algorithms to calibrate the internal model is of particular interest. Previous works have proposed such algorithms; however, they all rely on the availability of (rotor-effective) wind speed measurements. For the first time, this paper proposes an excitation-based learning algorithm that exploits the closed-loop dynamic structure of the WSE-TSR tracking scheme. This algorithm calibrates the internal model without the need for wind speed measurements. Analysis and simulations show that the proposed algorithm corrects for model uncertainties in the form of magnitude scaling errors under ideal constant and realistic turbulent wind conditions.

Robustness of an Economic Nonlinear Model Predictive Control for Wind Turbines under Changing Environmental and Wear Conditions (I), pp. 1493-1498
Pustina, Luca Roma Tre University Serafini, Jacopo Roma Tre University Biral, Francesco University of Trento

In this letter, the authors have assessed the robustness of an Economic Nonlinear Model-Predictive Controller (ENMPC) aimed at maximizing the power production of wind turbines. The scope of this letter is to quantify the sensitivity of this type of controller concerning wind conditions, climate, wind speed prediction unavailability, and aerodynamic performance degradation. A power production controller's robustness is crucial for the wind turbine industry due to the extreme variability of external conditions and the wear caused by long-term continuous operativity. Model-Predictive controllers are, in principle, more prone to robustness issues concerning standard controllers, a fact that limits their adoption on actual wind turbines. The analysis is performed with the fully-aeroelastic solver OpenFAST.
considering a wide set of realistic load cases. It is demonstrated that
the ENMPC previously developed is robust to wind prediction
unavailability and change in wind turbulence intensity. Conversely, it
is not robust to the modelling error due to aerodynamic degradation.
Indeed, a reduction in generated power concerning the reference
controller is observed, especially for operating region two and end-life
blades. Finally, a significant increase in power production is achieved
considering the external temperature variation thanks to the
ENMPC's direct handling of the generator temperature constraint.

Wake steering is currently being implemented on commercial wind
turbines to increase the power output from densely-packed wind farm
layouts. Apart from increased power capture, wake steering also has
an impact on the loads of both the upstream turbine due to operation
in yawed inflow conditions, and on the downstream turbine due to
reduction in the effective turbulence caused by the deflection of the
wake. In this paper, commonly used wake expansion and wake
deflection models are extended to obtain an analytical expression for
wake overlap and hence modified effective turbulence experienced by
the downwind turbine. The impact of the modified yaw inflow and turbulence on wind turbine fatigue loads are investigated in a
calculating aeroelastic environment. It is concluded that for a full
wake overlap situation, wake steering has minimal impact on the
loads of the downwind turbine. However, with partial overlap,
significant changes in the effective turbulence and the loading of the
downwind turbine can be observed. Wake steering strategies are
hence recommended to consider both power and loads
consequences in order to achieve the correct balance between
turbine lifetime extension and short-term energy gains.

This article presents the design of an integrated control strategy to
improve performance and reduce load variations in large wind
turbines using torque control, collective pitch control (CPC), and
individual pitch control (IPC). The nonlinear CPC and torque
controller are designed to regulate the rotor speed and power
generation of variable-speed wind turbines in multi-regime operations.
The IPC controller is designed to provide blade pitch corrections for
load reduction and improved performance of the wind turbines. A
Control-oriented, Reconfigurable, and Acuasal Floating Turbine
Simulator (CRAFTS), developed in-house, is used for the control
design, implementation, and evaluation. CRAFTS enables rapid
simulation of wind turbines, integration of control modules, and testing
of controllers in several load cases. It has been validated against
experimental data and against the well-known OpenFAST platform.
Extensive simulations show that the IPC controller makes a
significant load reduction in blade root bending moment, tower
side-by-side, and tower fore-aft bending moments at the frequencies
of interest. The IPC controller has no detrimental effects on the rotor
speed and power generation that are regulated by the CPC and
torque controller. Comparisons with simulation data from OpenFAST
and the standard ROSCO controller are also performed in this study.

In this paper, we first develop analytical expression of storage
investment decision and then of solar investment decision for a
household which is under net metering billing mechanism with time of
use pricing condition. Using real data of a residential household in
Austin, TX, USA, we study how the investment decisions would
provide benefit for a period of one year. Results show significant profit
when using storage devices and solar panels optimally for the
system. It is important to note that though our approach can help
significantly to take investment decisions, the solution will still be
sub-optimal for somebody who needs optimal investment jointly on
both storage and solar systems.
This paper presents a controller design and optimization framework for nonlinear dynamic systems to track a given reference signal in the presence of disturbances when the task is repeated over a finite-time interval. This novel framework mainly consists of two steps. The first step is to design a robust linear quadratic tracking controller based on the existing control structure with a Youla-type filter T$f(t)Q$. Secondly, an extra degree of freedom: a parameterization in terms of T$f(t)Q$, is added to this design framework. This extra design parameter is tuned iteratively from measured tracking cost function with the given disturbances and modeling uncertainties to achieve the best transient performance. The proposed method is validated with simulation placed on a Furuta inverted pendulum, showing significant tracking performance improvement.

17:00-17:15  WeC06.5
Novel Matrix Decomposition for Fast and Scalable Model Predictive Control, pp. 1529-1534
Adil, Muhammad  Wartsila
Goyal, Raman  Palo Alto Research Center
Mostafavi, Saman  Palo Alto Research Center, Inc

This paper presents an inverse-free algorithm that exploits the inherent structural sparsity of a model predictive control problem. The scalability associated with large problem sizes and time horizons is one of the major obstacles in model predictive control applications. We address scalability issues by proposing a novel matrix decomposition technique, coupled with a first-order method, to efficiently solve predictive control problems. This approach solves the system of linear equations in an inverse-free manner. The iterative steps of the proposed approach are computationally efficient, require less memory, and can be easily warm-started based on the solution of the previous horizon. We evaluate the performance of the proposed approach on benchmark model predictive control problems, demonstrating its computational advantages over other state-of-the-art algorithms.

17:15-17:30  WeC06.6
Traffic Congestion Control Using Distributed Extremum Seeking and Filtered Feedback Linearization Control Approaches, pp. 1535-1540
Karimi Shahri, Pouria  UNC Charlotte
HomChaudhuri, Baisravan  Illinois Institute of Technology
Pulugurtha, Srinivas  University of North Carolina at Charlotte
Mesbah, Ali  University of California, Berkeley
Ghasemi, Amirhossein  University of North Carolina Charlotte

This paper presents a hierarchical infrastructure-based control algorithm to manage mainstream traffic flow on freeways. At the upper level, a distributed Extremum-Seeking-control algorithm is employed to determine the optimal density of vehicles in a congested cell. The local objective function is defined such that the average flow within the target cell is maximized to resolve the congestion, and the flow difference with its upstream cell is minimized to prevent back-propagating the congestion. At the lower level, a distributed Filtered Feedback Linearization controller is used to update the suggested velocity communicated to the vehicles so that the desired density determined by the upper level can be achieved in each cell. We adopted the METANET model to describe the aggregated dynamics of the traffic network. We tested the performance of these controllers via a MATLAB-VISSIM COM interface. The results demonstrate that the designed distributed controllers can achieve the desired closed-loop performance despite unknown disturbances in an uncertain large-scale traffic network.

WeC06  Sapphire 411B
Student Best Paper Finalists (Special Session)
Chair: Hall, Carrie  Illinois Institute of Technology

WeC07  Aqua 303
Mechatronics (Invited Session)
Chair: Al Janaideh, Mohammad  Memorial University
Co-Chair: Najeg, William S.  Widener University
Organizer: Al Janaideh, Mohammad  Memorial University of Newfoundland
Organizer: Flores, Gerardo  Center for Research in Optics
Organizer: Heertjes, Marcel  Eindhoven University of Technology
Organizer: Najeg, William S.  Widener University
Organizer: Khaled, Najih  University of Sharjah
Organizer: Rakotondrabe, Micky  ENIT Tarbes, INPT, University of Toulouse

16:00-16:15  WeC07.1
Reference Modulation for High-Quality Scan Images of...
For laser scanner systems, the most critical issue for high-quality images is the linearity of the slow axis. The laser scanner systems have various disturbances and uncertainties, such as manufacturing tolerances, structure vibrations, and parameter uncertainties. Further, there are vertical and horizontal resonance modes that hinder controller design. In this paper, we propose a reference modulation technique to enhance the vertical angle linearity of the slow axis for two-dimensional laser scanner systems. First, the laser scanner system is mathematically modeled in the state-space form. Then, the reference modulation is designed to boost the loop gain over the desired frequency range. The reference modulation can guarantee high-quality scan images by redesigning the desired reference based on the output feedback. The current tracking controller was then implemented with virtual references for the states. We investigated its tracking performance via sensitivity function analysis against the disturbances. Experiments were performed to evaluate the effectiveness of the proposed method using four different laser scanners. We confirmed that the proposed method achieved up to 48% improvement in the angle tracking error from the experimental results.

In this work, a distributed control method to achieve the leaderless disturbance rejection and interconnection delays. The efficacy of the proposed method is shown in simulation results.

In this article, we investigate how to identify faulty sensors in piezoelectric actuators used for precise positioning. Four sensors are distributed along the actuator’scantilever structure to measure the deflection (displacement) at various points. We suggest identifying the sensor and detecting the fault in one of the sensors, which is thought to be faulty or producing a degraded signal. To address this, we use transmissibility operators, which are mathematical operators that can be used to estimate sensor measurements based on another set of sensor measurements within the same system. This estimation is highly robust against any external excitations/disturbances, as well as unknown nonlinearities or unmodeled dynamics. The estimation robustness allows for failure detection to be carried out even in the presence of significant actuator hysteresis nonlinearity and outside disturbance. Simulation results with various sensor fault conditions are used to verify the suggested strategy.

The aim of this study is to investigate the output feedback tracking control of an Unmanned Aerial Vehicle (UAV) using only measured inertial coordinate information. The proposed approach involves two cascade high-gain observers combined with a full state feedback control based on the backstepping approach. The backstepping controller is designed to solve the tracking control problem of the underactuated system. The observer consists of two cascaded high-gain observers with different speeds, where the faster observer estimates the output position and velocity of the system in three dimensions and feeds a virtual nonlinear output to estimate the Euler angles (pitch, roll, and yaw) and angular velocity. The study shows that the equilibrium point of the full state feedback control system is exponentially stable when the system information is fully known. Simulation results indicate that the output feedback control achieves the tracking control objective and recovers the performance of the state feedback control. Additionally, the study demonstrates the convergence and boundedness of the estimation errors.
Modern control theory provides us with a spectrum of methods for studying the interconnection of dynamic systems using input-output properties of the interconnected subsystems. Perhaps the most advanced framework for such input-output analysis is the use of Integral Quadratic Constraints (IQCs), which considers the interconnection of a nominal linear system with an unmodelled nonlinear or uncertain subsystem with known input-output properties. Although these methods are widely used for Ordinary Differential Equations (ODEs), there have been fewer attempts to extend IQCs to infinite-dimensional systems. In this paper, we present an IQC-based framework for Partial Differential Equations (PDEs) and Delay Differential Equations (DDEs). First, we introduce infinite-dimensional signal spaces, operators, and feedback interconnections. Next, in the main result, we propose a formulation of hard IQC-based input-output stability conditions, allowing for infinite-dimensional multipliers. We then show how to test hard IQC conditions with infinite-dimensional multipliers on a nominal linear PDE or DDE system via the Partial Integral Equation (PIE) state-space representation using a sufficient version of the Kalman-Yakubovich-Popov lemma (KYP). The results are then illustrated using four example problems with uncertainty and nonlinearity.

In this paper we consider a family of linear evolution equations in infinite dimensions (Hilbert spaces) with initial state, input and output bounded uncertainty, and allow the possibility of switching between the given systems. The achievable measurement/actuator location will be fixed over certain time intervals. Based on uncertain output measurements, we use a minimax sliding mode control approach to design a switching controller which steers a state to a finite-dimensional hyperplane in finite time. We show that the switching controller provides an optimal solution to a particular optimal mini-max sliding mode control problem with switching modes and state/measurement/input disturbances. The proposed approach is summarized in an algorithm and it is illustrated through a numerical study on a family of delay evolution equations with switching modes and bounded disturbances.

Tokamaks are toroidal devices that confine a very hot plasma (hydrogenic ionized gas) by using strong magnetic fields. When the kinetic energy is high, positively charged nuclei in the plasma can overcome the Coulomb forces of repulsion and fuse to form a heavier nucleus. A tremendous amount of energy is released during this reaction. The pitch of the magnetic field in a tokamak, measured by the safety factor profile, plays a crucial role in ensuring the magnetohydrodynamic (MHD) stability of the tokamak plasma. MHD instabilities like the Neoclassical Tearing Mode (NTM), which can deteriorate or even terminate plasma confinement, can appear at regions in the tokamak where the safety factor profile assumes a rational value. Since the safety factor profile is a continuous function of location in the tokamak, rational values at specific locations are inevitable. Controlling the gradient of the safety factor profile at these locations can prevent or mitigate the effect of MHD instabilities. In this work, a one-dimensional model that approximates the safety factor gradient dynamics at one of the locations where the safety factor achieves a rational value is developed. A controller based on feedback linearization of this model is designed to track a target gradient value in the steady-state scenario. The effectiveness of this controller is demonstrated in nonlinear numerical simulations powered by the Control Oriented Transport SIMulator (COTSIM) for a DIII-D tokamak scenario.

We utilize stochastically-forced compressible linearized Navier-Stokes equations to study the dynamics of hypersonic flows over blunt bodies. Our analysis of the energy of the flow fluctuations around the laminar stagnation flow reveals strong amplification of specific streamwise and spanwise length scales. We also provide insights into how changes in different physical parameters, such as the temperature of the blunt body and its curvature, influence the amplification of flow fluctuations. We show that increasing the bluntness and decreasing the wall temperature can significantly enhance the amplification of flow fluctuations. Our approach offers a systematic control-theoretic framework for quantifying the influence of stochastic excitation sources (e.g., free-stream turbulence and surface roughness) that are unavoidable in experiments and paves the way for the development of control-oriented models of hypersonic flows over blunt bodies.

In this work, we consider the problem of stabilization of spatially-distributed dynamical systems described by nonlinear parabolic PDEs controlled over resource-constrained sensor-controller communication channels subject to process parametric variations. A framework for augmenting model-based feedback control with error-triggered parameter re-identification is developed to address this problem. The goal is to maintain closed-loop stability in the presence of varying levels of plant-model mismatch during periods of parametric drift, while simultaneously keeping the sensor-controller communication rate to a minimum and maintaining acceptable levels of closed-loop performance. Initially, a stabilizing nonlinear state feedback controller based on an approximate finite-dimensional model of the infinite-dimensional system is designed. The controller utilizes model-generated state estimates which are periodically updated using the available state measurements. An estimate of the maximum allowable update period is obtained and characterized in terms of the parametric uncertainty and the controller design parameters. An error monitoring scheme with a time-varying instability alarm threshold is then devised to determine on-line if, and when, the model parameters need to be updated. A breach of the instability threshold at some time triggers a safe-parking phase in which the sensor-controller communication rate is adjusted to mitigate the destabilizing impact of increased plant-model mismatch. The measurements collected during the safe-parking mode are used to obtain new estimates of the process parameters using nonlinear grey-box parameter estimation techniques. An explicit characterization of the closed-loop stability region associated with the new model parameters is obtained to determine the appropriate post-drift sensor-controller communication
rate that should be used when the model parameters are updated. The implementation of the proposed methodology is illustrated using a representative diffusion-reaction process example with a time varying parametric drift.

Adaptive Stabilization of the Kuramoto-Sivashinsky Equation Subject to Intermittent Sensing, pp. 1608-1613
Belhadjoujda, Mohamed Camil Gipsa Lab / Cnrs
Maghenem, Mohamed Adlene Gipsa Lab, CNRS, France
Witrant, Emmanuel Université Grenoble Alpes
Prieur, Christophe CNRS

We study in this paper the one-dimensional Kuramoto-Sivashinsky equation (KS), subject to intermittent sensing. Namely, we measure the state on a sub-interval of the spatial domain during certain intervals of time, and we measure the state on the remaining sub-intervals of space during the remaining intervals of time. As a result, we assign an active control at the boundaries of the spatial domain, and we set a zero boundary condition at the junction of the two spatial sub-intervals. Under the assumption that the destabilizing coefficient is unknown, we design adaptive boundary controllers that guarantee global exponential stability (GES) of the trivial solution in the $L^2$ norm. Numerical simulations are performed to illustrate our results.

Generalized Moving Horizon Estimation for Nonlinear Systems with Robustness to Measurement Outliers, pp. 1614-1621
Cao, Wenhan Tsinghua University
Liu, Chang Cornell University
Lan, Zhiquan Tsinghua University
Piao, Yingxi Tsinghua University
Li, Shengbo Eben Tsinghua University

Moving horizon estimation (MHE) is an effective filtering technique for nonlinear systems subjected to arbitrary, non-Gaussian noise distributions. While there has been noticeable progress in the stability analysis of MHE, there is lack of research on robustifying MHE against measurement outliers. To bridge this gap, we propose a generalized MHE approach by utilizing the loss-theoretic perspective of Generalized Bayesian Inference. In particular, we design a robust loss function by leveraging the $\beta$-divergence and propose the $\beta$ moving horizon estimator to handle the outliers. Analytical influence functions are derived to analyze the robustness of the MHE methods. Based on this, we prove that for the case of linear Gaussian systems, the gross error sensitivity of the proposed estimator remains bounded, while for the standard MHE, it is unbounded. The effectiveness of the proposed approach is demonstrated in simulations on both linear and nonlinear systems, where the estimator outperforms commonly used linear and nonlinear filters while keeping the computational overhead comparable to that of the standard MHE.

On the Lack of Robustness of Observers for Systems with Uncertain, Unstable Dynamics, pp. 1643-1648
Kamaldar, Mohamadreza University of Michigan
Goel, Ankit University of Maryland Baltimore County
Islam, Syed Aseem Ul University of Michigan
We consider the robustness of state estimation for linear, time-invariant systems. Since state estimation is dual to full-state feedback, it may be expected that stability of the error dynamics depends continuously on perturbations of the dynamics matrix. This paper shows, however, that, if the system dynamics are unstable, then, regardless of how the filter gain is chosen, there always exist arbitrarily small perturbations of the system dynamics that give rise to unbounded state-estimation error. Since this phenomenon cannot occur in full-state feedback control, this result reveals a surprising breakdown in the duality between estimation and control.

This paper deals with distributed Bayesian state estimation of generally nonlinear stochastic dynamic systems. In particular, distributed point-mass filter algorithm is developed. It is comprised of a basic part that is accurate but data intense and optional step employing advanced copula theory. The optional step significantly reduces data transfer for the price of a small accuracy decrease. In the end, the developed algorithm is numerically compared to the usually employed distributed extended Kalman filter.

We consider a variant of pursuit-evasion games where a single defender is tasked to defend a static target from a sequence of periodically arriving intruders. The intruders' objective is to breach the boundary of a circular target without being captured and the defender's objective is to capture as many intruders as possible. At the beginning of each period, a new intruder appears at a random location on the perimeter of a fixed circle surrounding the target and moves radially towards the target center to breach the target. The intruders are slower in speed compared to the defender and they have their own sensing footprint through which they can perfectly detect the defender if it is within their sensing range. Considering the speed and sensing limitations of the agents, we analyze the entire game by dividing it into partial information and full information phases. We address the defender's capturability using the notions of engagement surface and capture circle. We develop and analyze three efficient strategies for the defender and derive a lower bound on the capture fraction. Finally, we conduct a series of simulations and numerical experiments to compare and contrast the three proposed approaches.

We address the robustness of state estimation for linear, time-invariant systems. Since state estimation is dual to full-state feedback, it may be expected that stability of the error dynamics depends continuously on perturbations of the dynamics matrix. This paper shows, however, that, if the system dynamics are unstable, then, regardless of how the filter gain is chosen, there always exist arbitrarily small perturbations of the system dynamics that give rise to unbounded state-estimation error. Since this phenomenon cannot occur in full-state feedback control, this result reveals a surprising breakdown in the duality between estimation and control.

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network structure. Finally, the effectiveness of the proposed learning algorithm is tested. The connection between network structure and classical system identification theory is covered by our work, which advances the literature.

17:15-17:30 WeC10.6
Non-Sequential Decentralized Stochastic Control and Static Reduction, pp. 1686-1691
Simpson, Ryan
Queen’s University
Yuksel, Serdar
Queen’s University

In decentralized stochastic control (or stochastic team theory) and game theory, if there is a pre-defined order in a system in which agents act, the system is called sequential, otherwise it is non-sequential. Much of the literature on stochastic control theory, such as studies on the existence analysis, approximation methods, and on dynamic programming or other analytical or learning theoretic methods, have focused on sequential systems. The static reduction method for sequential control problems (via change of measures or other techniques), in particular, has been shown to be very effective in arriving at existence, structural, approximation and learning theoretic results. Many practical systems, however, are non-sequential where the order of agents acting is random, and dependent on the realization of solution paths and prior actions taken. The study of such systems is particularly challenging as tools applicable for sequential models are not directly applicable. In this paper, we will study static reducibility of non-sequential stochastic control systems, including by change of measure methods. We revisit the notion of Causality (a definition due to Witsenhausen and which has been refined by Andersland and Tekenetzis), and provide an alternative representation using imaginary agents. Via this representation, we show that Causality, under an absolute continuity condition, allows for an equivalent static model whose reduction is policy-independent. This facilitates much of the stochastic analysis available for sequential systems to also be applicable for non-sequential systems. We further show that under more relaxed conditions on the model, such as solvability, such a reduction, when possible at all, is policy-dependent and includes policies as parameters in the cost of the reduced model, and thus has limited utility. We will also present a further reduction method for partially nested causal non-sequential systems.

WeC11 Game Theory III (Regular Session) Aqua Salon AB
Chair: Marden, Jason R. University of California, Santa Barbara
Co-Chair: Malikopoulos, Andreas A. University of Delaware

16:00-16:15 WeC11.1 When Would Online Platforms Pay Data Dividends?, pp. 1692-1697
Kudva, Sukanya UC Berkeley
Aswani, Anil UC Berkeley

Online platforms, including social media and search platforms, have routinely used their users’ data for targeted ads, to improve their services, and to sell to third-party buyers. But an increasing awareness of the importance of users’ data privacy has led to new laws regulating platform data-sharing. Further, there have been political discussions on introducing data dividends, that pay users for their data. Three interesting questions are then: When would these online platforms be incentivized to pay data dividends? How does their decision depend on whether users value their privacy more than the platform’s free services? And should platforms invest in protecting users’ data? This paper considers various factors affecting the users’ and platform’s decisions through utility functions. We construct a principal-agent model using a Stackelberg game to calculate their optimal decisions and qualitatively discuss the implications. Our results could inform a policymaker trying to understand the consequences of mandating data dividends.

16:15-16:30 WeC10.2 Mobility Equity and Economic Sustainability Using Game Theory, pp. 1698-1703
Chremos, Ioannis Vasileios University of Delaware
Malikopoulos, Andreas A. University of Delaware

In this paper, we consider a multi-modal mobility system of travelers each with an individual travel budget, and propose a game-theoretic framework to assign each traveler to a “mobility service” (each one representing a different mode of transportation). We are interested in the question of whether travelers can maximize the worst-case revenue of the mobility system while ensuring “mobility equity,” which we define it in terms of accessibility. In the proposed framework, we ensure that travelers are truthful and voluntarily participate under informational asymmetry, and the solution respects the individual budget of each traveler. Each traveler may seek to travel using multiple services (e.g., car, bus, train, bike). The services are capacitated and can serve up to a fixed number of travelers at any instant of time. Thus, our problem falls under the category of many-to-one assignment problems, where the goal is to find the conditions that guarantee the stability of the assignment. We formulate a linear program of maximizing worst-case revenue of the constraints of mobility equity, and we fully characterize the optimal solution.

16:30-16:45 WeC11.3 Cost Design in Atomic Routing Games, pp. 1704-1709
Yu, Yue The University of Texas at Austin
Chen, Shenghui University of Texas at Austin
Fridovich-Keil, David The University of Texas at Austin
Topcu, Ufuk The University of Texas at Austin

An atomic routing game is a multiplayer game on a directed graph. Each player in the game chooses a path—a sequence of links that connect its origin node to its destination node—with the lowest cost. To model players’ interaction, we develop a novel numerical method to design the link cost function in atomic routing games such that the players’ choices at the Nash equilibrium minimize a given smooth performance function. This method first approximates the nonsmooth Nash equilibrium conditions with smooth ones, then iteratively improves the link cost function via implicit differentiation. We demonstrate the application of this method to atomic routing games that model noncooperative agents navigating in grid.

16:45-17:00 WeC11.4 A Weakest-Link Extension Theorem for General Lotto Games, pp. 1710-1715
Aghajan, Adel University of California Santa Barbara
Paarporn, Keith University of Colorado, Colorado Springs
Marden, Jason R. University of California, Santa Barbara

The General Lotto game is a well-studied model where two opposing players strategically allocate a limited amount resources to multiple contests. In the classic setup, each contest represents an individual battlefield with an associated value, and the objective is to maximize the accumulated value by winning individual battlefields. In this paper, we consider scenarios beyond the classic setup, where (i) success on a contest can depend on securing subsets of battlefields, and (ii) the winner of a battlefield can be based on alternate winning rules other than the classic winner-take-all rule. Our main results demonstrate that having an equilibrium solution to a single contest scenario can provide immediate equilibrium characterizations for the weakest-link extension (best-shot), where one player must win all (at least one) of the constituent contests in order to earn any value. We highlight the applicability of the derived theory on network defense problems.

17:00-17:15 WeC11.5
WeC12
Advanced Controls in Vehicle Electrification (Invited Session)

Chair: Borhan, Hoseinali
Co-Chair: Chen, Pingen
Organizer: Chen, Pingen
Organizer: Draelmeier, Joseph
Organizer: Ghasemi, Amirhossein
Organizer: Borhan, Hoseinali

Cummins Inc
Tennessee Technological University
Tennessee Technological University
University of Michigan
University of North Carolina
Cummins Inc

Real Time Passenger Mass Estimation for E-Scooters (I), pp. 1741-1746

Leoni, Jessica
Strada, Silvia
Tanelli, Mara
Savaresi, Sergio M.
Politecnico Di Milano
Politecnico Di Milano
Politecnico Di Milano
Politecnico Di Milano

Dockless electric scooters have proven, nowadays, to be a competitive solution in the urban micro-mobility environment. However, recent studies underline how electric scooters' sustainability is closely related to their lifetime and recharging frequency. Since these depend significantly on the onboard mass, this paper presents two approaches, i.e., gray-box and black-box, to estimate this parameter relying only on the measurements from GPS and IMU sensors installed on the e-scooter. The robustness and accuracy of the mass estimation is tested on extensive datasets collected in ad-hoc experimental campaigns.
Heavy-duty trucks are currently contributing to a significant portion of greenhouse gas emissions from the transportation sector. Electrification of heavy-duty vehicle fleet can potentially reduce the energy consumption for freight delivery due to high powertrain efficiency. However, the high cost of vehicles due to large battery size and range anxiety due to limited charging infrastructures are considered as the main barriers for adoption. The main objective of this paper is to design a comprehensive platoon management framework for an electric truck fleet which incorporates cargo allocation, platooning sequence change, and charging time coordination. Three planning problems are formulated in this paper for different phases of freight delivery by electric truck fleets and analytical solutions are offered for each scenario. Linear Programming was used as a backup method when analytical solutions are infeasible. Numerical results demonstrated that the proposed solutions can potentially reduce the energy consumption or charging time for an electric truck fleet.

HEV Energy Management Strategy Based on TD3 with Prioritized Exploration and Experience Replay (I), pp. 1753-1758

He, Yu
University of Michigan Dearborn
Kim, Youngki
University of Michigan - Dearborn

This paper presents a novel energy management strategy for hybrid electric vehicles (HEVs) that is based on an expert twin-delayed deep deterministic policy gradient with prioritized exploration and experience replay (TD3-PEER). State-of-the-art TD3 requires critic networks to generate predicted Q value for state-action pairs to update a policy network. However, the critic networks may struggle with predicting Q values for certain states when the Q values of these states are sensitive to action selection. To address this issue, this paper proposes a prioritized exploration technique that encourages the agent to visit action-sensitive states more frequently in the application of HEV energy management. The proposed algorithm is tested and validated on a P0+P4 HEV model. To simplify the control application of HEV energy management, the proposed algorithm is considered as the main barriers for adoption. The main objective of this paper is to design a comprehensive platoon management framework for an electric truck fleet which incorporates cargo allocation, platooning sequence change, and charging time coordination. Three planning problems are formulated in this paper for different phases of freight delivery by electric truck fleets and analytical solutions are offered for each scenario. Linear Programming was used as a backup method when analytical solutions are infeasible. Numerical results demonstrated that the proposed solutions can potentially reduce the energy consumption or charging time for an electric truck fleet.

On the Optimal Control of Network LQR with Spatially-Exponential Decaying Structure, pp. 1775-1780

Zhang, Runyu
Harvard University
Li, Weiyu
Harvard University
Li, Na
Harvard University

This paper studies network LQR problems with system matrices being spatially-exponential decaying (SED) between nodes in the network. The major objective is to study whether the optimal controller also enjoys a SED structure, which is an appealing property for ensuring the optimality of decentralized control over the network. We start with studying the open-loop asymptotically stable system and show that the optimal LQR state feedback gain $K$ is upper-bound on the performance of $kappa$-truncated local controllers, suggesting that distributed controllers can achieve near-optimal performance for SED systems. We develop these results via studying the structure of another type of controller.
this paper, we address the problem of discrete-time average consensus, where agents (nodes) exchange information over unreliable communication links. We enhance the Robustified Ratio Consensus algorithm by embedding the Automatic Repeat ReQuest (ARQ) protocol used for error control of data transmissions, in order to allow the agents to reach asymptotic average consensus while handling time-varying delays induced by retransmissions of erroneous packets, and possible packet drops that occur due to excess of a predefined packet retransmission limit imposed by the ARQ protocol. Invoking the ARQ protocol allows nodes to: (a) exploit the incoming error-free acknowledgement feedback signals to initially acquire or later update their out-degree, (b) know whether a packet has arrived or not, and (c) determine a local upper-bound on the delays which is imposed by the retransmission limit. The analysis of our proposed algorithm, herein called the ARQ-based Ratio Consensus algorithm relies on augmenting the network's corresponding weighted adjacency matrix, to handle time-varying (yet bounded) delays and possible packet drops. To the best of the authors' knowledge, this is the first consensus algorithm that incorporates a communication protocol for error control used in real communication systems with feedback.

In this paper, we present the Partial Integral Equation (PIE) representation of linear Partial Differential Equations (PDEs) in one spatial dimension, where the PDE has spatial integral terms appearing in the dynamics and the boundary conditions. The PIE representation is obtained by performing a change of variable where every PDE state is replaced by its highest, well-defined derivative appearing in the dynamics and the boundary conditions. The PIE representation can be written in terms of explicit maps from the PDE parameters to PIE parameters. Lastly, we present numerical examples to demonstrate the application of the PIE representation by performing stability analysis of PDEs via convex optimization methods.

This paper proposes an event-triggered boundary control for the safe stabilization of the Stefan PDE system with actuator dynamics. The control law is designed by applying Zero-Order Hold (ZOH) to the continuous-time safe stabilizing controller developed in our previous work. The event-triggering mechanism is then derived so that the imposed safety conditions associated with high order Control Barrier Function (CBF) are maintained and the stability of the closed-loop system is ensured. We prove that under the proposed event-triggering mechanism, the so-called "Zeno" behavior is always avoided, by showing the existence of the minimum dwell-time between two triggering times. The stability of the closed-loop system is proven by employing PDE backstepping method and Lyapunov analysis. The efficacy of the proposed method is demonstrated in numerical simulation.

This paper provides a novel periodic event-triggered boundary control (PETBC) strategy for a class of reaction-diffusion PDEs with Robin actuation using infinite-dimensional backstepping boundary control. We propose a method for converting a certain class of continuous-time dynamic event-triggers that require continuous monitoring to periodic event-triggers that require only periodic evaluation. We achieve this by finding an upper bound on the underlying continuous-time event-trigger between two successive periodic evaluations. We provide an explicit criterion for choosing a sampling period for periodically evaluating the event-trigger. The control input is updated only at events indicated by the periodic event-trigger and is applied in a Zero-Order-Hold fashion between two events. We prove that the closed-loop system well-posedness and global $L^2$-exponential convergence to zero under continuous-time event-triggered boundary control (CETBC) are preserved under the proposed PETBC. We provide simulation results to validate the theoretical claims.

In this paper, we present the Partial Integral Equation (PIE) representation of linear Partial Differential Equations (PDEs) in one spatial dimension, where the PDE has spatial integral terms appearing in the dynamics and the boundary conditions. The PIE representation is obtained by performing a change of variable where every PDE state is replaced by its highest, well-defined derivative using the Fundamental Theorem of Calculus to obtain a new equation (a PIE). We show that this conversion from PDE representation to PIE representation can be written in terms of explicit maps from the PDE parameters to PIE parameters. Lastly, we present numerical examples to demonstrate the application of the PIE representation by performing stability analysis of PDEs via convex optimization methods.

The efficiency of the solar plants is conditioned by the control strategies applied in their operation. In this paper, an application of a Model Predictive Controller based on nonlinear models of the TCP-100 parabolic trough collector solar plant is presented as one example of the advanced control techniques that can contribute to enhance the efficiency of this type of plants. Both types of nonlinear models of the TCP-100 facility are applied for this application: lumped and distributed parameters ones. The objective of the proposed control strategy is to face a problem that arises in current commercial solar trough plants, with hundreds of loops, where in practice each of those loops get a different outlet temperature of the heat transfer fluid. These temperature differences might cause inefficiency in the operation and/or irreversible damages by overheating, if not properly controlled. The presented control strategy computes the set-points of the control valves of each of the loops to achieve a good thermal balance of the solar plant. The proposed strategy implements also a heuristic based algorithm when strong transients are affecting the field. The simulation results show that the application of the proposed control technique balances the outlet temperatures of the loops, protecting the TCP-100 facility from damages and increasing its efficiency in the operation.
Control of non-condensing non-ideal gas power cycles is challenging because (1) their output power dynamics depend on complex system interactions, (2) turbomachinery cannot be modelled by simple analytical relations, and (3) state constraints must be respected. This article presents a control methodology for these systems, comprising a control modelling approach and model predictive control (MPC) strategy. We demonstrate this methodology on the high-pressure side of a simple supercritical CO$_2$ cycle power plant. We develop a novel control model by using timescale-separation arguments, then implement MPC by linearizing this control model online at each sampling instant. Closed-loop simulations with a full-order gas-dynamics truth model demonstrate the good dynamic performance and constraint management of this approach. This article demonstrates the suitability of MPC for the supercritical CO$_2$ cycle, and provides a pathway to implementing MPC for more complex cycle variants such as the recuperated and recompression cycle.

16:30-16:45 WeC14.3
Control Lyapunov-Barrier Function-Based Predictive Control Using a Deep Hybrid Model with Guarantees on Domain of Applicability, pp. 1819-1824

Bangi, Mohammed Saad Texas A&M University
Faizan
Kwon, Joseph Texas A&M University

The domain of applicability (DA) of a data-driven model is limited by its training data. Consequently, the DA of a hybrid model which combines a first-principles model with a data-driven model is also limited by its training data even though it has better extrapolation capabilities compared to a data-based model. Nonetheless, the domain of applicability (DA) of a hybrid model is finite and should be taken into account when developing a hybrid model-based predictive controller in order to maximize its performance. To this end, a Control Lyapunov-Barrier Function-based model predictive controller (CLBF-based MPC) is developed which utilizes a deep hybrid model (DHM), i.e., a deep neural network (DNN) combined with a first-principles model. Additionally, theoretical guarantees are provided on stability as well as on system states to stay within the DA of the DHM. The efficacy of the proposed framework is demonstrated on a continuous stirred tank reactor.

16:45-17:00 WeC14.4
A Vessel Propulsion Controller Based on Economic Model Predictive Control, pp. 1825-1831

Papadimitrakis, Myron University of West Attica
Alexandrini, Alex University of West Attica

The importance of reducing energy expenditure in vessel propulsion is underlined by recent environmental mandates in the maritime sector. Vessel propulsion is a multi-objective problem, since the overall energy expenditure of the powertrain must be minimized, while the vessel speed must be maximized. This paper proposes an economic model predictive control (EMPC) approach, which can accommodate powertrain efficiency maps and thus evaluate candidate input trajectories in terms of energy efficiency. The proposed EMPC controller utilizes recent theoretical developments in order to guarantee stability. Simulation results are presented in comparison to a standard MPC scheme, for two different vessel sizes under environmental disturbances, and are evaluated in terms of the overall energy expenditure and the settling time to the desired vessel speed. It is demonstrated that the proposed approach achieved a reduction in energy consumption of up to 1.9% in a rough sea scenario.

17:00-17:15 WeC14.5
conditions under which one can estimate the spatial distribution of concentrations in a nonlinear SPM. Specifically, we examine a nonlinear SPM where terminal voltage and its resistive component are measured independently. Butler-Volmer polarization potentials are assumed to be concentration-dependent. Under these assumptions, we show that electrode spatial concentration distributions can be estimated if the Jacobian of the voltage measurements with respect to surface concentrations is full rank. This condition applies for an arbitrary finite difference discretization of solid-phase diffusion dynamics. The paper demonstrates this insight numerically, for a model of a nickel-manganese-cobalt (NMC) battery.

**A Novel Scheme for Randomized Customer-Sensitivity-Based Control of Thermostatic Loads for Better Integration of Intermittent Renewables**, pp. 1850-1855

Julien, Tanguy Polytèchnique Montréal
Malhame, Roland P. Ecole Poly. De Montréal

Increased electric grid penetration of intermittent renewable energy sources has reduced the controllability of the generation side, and created a need for more coordination between generation and load to maintain grid stability. Thermostatically controlled loads (TCLs) have long been seen as capable of providing a source of load flexibility. However, controlling thousands of small loads to create a better match between generation and consumption is a challenging task. Direct load control methods tend to be imprecise, invasive, and somewhat coercive, while pricing-based methods can result in social push-back and produce unreliable results. We propose and analyze a probabilistic control scheme based on a novel type of aggregator-customer contracts. The latter are tailored a priori so as to account for a customer's particular tolerance to loss of comfort versus interest in cost reduction. While through these contracts, aggregators have to obey pre-agreed constraints on their controls, the up-side for them is that they can reliably anticipate the aggregate behaviors that their pool of loads can achieve. The control is decentralized via a single so-called pressure signal which is broadcasted and acts locally, in a probabilistic manner, on thermostat set-points. We demonstrate how the probabilistic nature of the control allows achieving a continuum of smooth potentially desirable aggregate load behaviors.

**Reduced-Order Model of Lithium-Iron Phosphate Battery Dynamics: A POD-Galerkin Approach**, pp. 1856-1861

Fasolato, Simone Pavia
Allam, Anirudh Stanford University
Li, Xueyan LG Energy Solutions
Lee, Donghoon LG Energy Solutions
Ko, Johan LG Energy Solutions
Onori, Simona Stanford University

A lithium iron phosphate battery is characterized by a plateau in its open circuit voltage, hysteresis, and path dependence due to phase transition during intercalation/deintercalation. The core-shell electrochemical modeling technique is an accurate tool to capture this phase transition behavior. However, the model requires fine-grained spatial grids to transform the governing Partial Differential Algebraic Equations into Ordinary Differential Algebraic Equations to accurately capture the battery dynamics, which results in a computationally expensive system intractable for design of realtime battery management system algorithms. To that end, this paper presents a reduced-order modeling paradigm to transform the high-dimensional model into a low-dimensional yet accurate core-shell electrochemical model. The Proper Orthogonal Decomposition-Galerkin method is used to reduce the state variables from 169 to a meagre 9 with negligible loss in fidelity. The reduced-order model's accuracy is validated against both experimental data and high-dimensional model for discharging and charging load profiles of different C-rates. Promising results with one-third the computational burden and a voltage RMS error of less than 0.6% are achieved.


Abdelghany, Muhammad Bakr University of Sannio
Al-Dura, Ahmed Khalifa University

The environmental goals set out in the 2015 Paris Agreement on climate change lead to the design and the definition of energy management strategies based on renewable energy sources (RESs). In this regard, the integration of energy storage systems (ESSs) into the microgrid requires the development of sophisticated control systems for their management and the reduction of their degradation. Moreover, external agents, e.g., battery/fuel cell electric vehicles, exchange energy with microgrids using electricity and hydrogen in energy markets. This paper presents a novel energy management strategy to control a microgrid which includes RESs paired with a battery-ESS and a hydrogen-ESS, and consumer loads. The strategy, based on the model predictive control (MPC) framework, takes into account ESSs' economical and operating costs, degradation issues, and physical and dynamical system constraints. Numerical simulations show the effectiveness of the strategy, which successfully manages the plant by fulfilling constraints and energy requests while reducing device costs and increasing battery life.

**An Online Feedback Optimization Approach to Voltage Regulation in Inverter-Based Power Distribution Networks**, pp. 1868-1873

Dominguez-Garcia, Alejandro University of Illinois at Urbana-Champaign
Zhlobarysov, Madi Typhoon HIL
Amuda, Temitope University of Illinois at Urbana-Champaign
Ajala, Olaoluwapo University of Illinois at Urbana-Champaign

We address the problem of controlling the reactive power setpoints of a set of distributed energy resources (DERs) in a power distribution network so as to mitigate the impact of variability in uncontrolled power injections associated with, e.g., renewable-based generation. We formulate the control design problem as a stochastic optimization problem, which we solve online using a modified version of a projected stochastic gradient descent (PSGD) algorithm. The proposed PSGD-based algorithm utilizes sensitivities of changes in bus voltage magnitudes to changes in DER reactive power setpoints; such sensitivities are learned online via a recursive least squares estimator (rLSE). To ensure proper operation of the rLSE, the sequence of incremental changes in DER reactive power setpoints needs to be persistently exciting, which is guaranteed by a mechanism built into the controller. We analyze the stability of the closed-loop system and showcase controller performance via numerical simulations on the IEEE 123-bus distribution test feeder.

**Robust Decentralized Secondary Control Scheme for Inverter-Based Power Networks**, pp. 1874-1880

Bhelra, Siddharth Siemens Technology
Banerjee, Abhishek Siemens Technology
Münz, Ulrich Siemens AG
Bamberger, Joachim Siemens AG

Inverter-dominated microgrids are quickly becoming a key building block of future power systems. They rely on centralized controllers that can provide reliability and resiliency in extreme events. Nonetheless, communication failures due to cyber-physical attacks or natural disasters can make autonomous operation of islanded microgrids challenging. This paper examines a unified decentralized secondary control scheme that is robust to inverter clock synchronization errors and can be seamlessly applied to grid-following or grid-forming control architectures. The proposed scheme overcomes the well-known stability problem that arises from
WeC16 Aqua 313

**Machine Learning II (Regular Session)**

Chair: Xu, Xiangru  
University of Wisconsin-Madison

Co-Chair: Tron, Roberto  
Boston University

**16:00-16:15**  
WeC16.1

**Tailored Output Layers of Neural Networks for Satisfaction of State Constraints in Nonlinear Control Systems**, pp. 1881-1888  
Markolf, Lukas  
University of Kassel  
Stursberg, Olaf  
University of Kassel

This work considers the synthesis of state feedback controllers established as deep artificial feed-forward neural networks for the control of discrete-time nonlinear but input-affine systems. The idea is to design output layers of particular structure to guarantee the satisfaction of state constraints in form of control-invariant ellipsoids. Since an analytical expression can be derived for the resulting neural network controller, the latter can be stored and evaluated efficiently. Moreover, the proposed output layer guarantees the satisfaction of the considered state constraints for each specification of the parameter vector. Numerical examples are provided for illustration and evaluation of the approach, in which the approximation of a nonlinear model predictive control law is considered as application.

**16:15-16:30**  
WeC16.2

**Application of eXplainable AI and Causal Inference Methods to Estimation Algorithms in Networks of Dynamic Systems**, pp. 1889-1894  
Biparva, Darya  
University of Minnesota  
Matersassli, Donatello  
University of Minnesota

While continuous progress in the area of machine learning is producing algorithms capable of achieving better and better decision and predictive performance, the way such algorithms operate is also becoming more and more inescapable. When an increasing amount of decisions is being ceded to often inexplicable algorithms which are not susceptible to any form of human supervision or scrutiny, it is just natural to start raising doubts about their fairness, soundness, and reliability. This has motivated a growing need for tools capable of disentangling and explaining the mechanisms behind AI based decisions, creating a new field of research referred to as explainable AI (XAI). Given the significant impact that machine learning is having also on the area of estimation and control, this article advances the idea of borrowing and adapting methodologies from the area of XAI and apply them to estimation and control algorithms involving networks of dynamic processes. Specifically, we translate the methodology known as Local Interpretable Model-Agnostic Explanations (LIME) in order to explain the mechanisms behind a black-box estimation algorithm processing time-series. Furthermore, we find that LIME can be extended using notions of causal inference to detect cause-effect relations among the input features that the estimation algorithm takes as inputs. This causal inference procedure provides LIME with additional explanatory power.

**16:30-16:45**  
WeC16.3

**Safety Certification for Stochastic Systems Via Neural Barrier Functions**, pp. 1895-1900  
Mathiesen, Frederik Baymler  
Delft University of Technology  
Calvert, Simeon Craig  
Delft University of Technology  
Laurenti, Luca  
TU Delft

Providing non-trivial certificates of safety for non-linear stochastic systems is an important open problem. One promising solution to address this problem is the use of barrier functions. Barrier functions are functions whose composition with the system forms a Martingale and enable the computation of the probability that the system stays within a safe set over a finite time horizon. However, existing approaches to find barrier functions generally restrict the search to a small class of functions, often leading to conservatism. To address this problem, in this paper, we parameterize barrier functions as neural networks and show that bound propagation techniques and linear programming can be successfully employed to find Neural Barrier Functions. Further, we develop a branch-and-bound scheme based on linear relaxations that improves the scalability of the proposed framework. On several case studies we show that our approach scales to neural networks of hundreds of neurons and multiple hidden layers and often produces certificates of safety that are tighter than state-of-the-art methods.

**16:45-17:00**  
WeC16.4

**Neural Lyapunov Control for Nonlinear Systems with Unstructured Uncertainties**, pp. 1901-1906  
Wei, Shiqing  
New York University  
Krishnamurthy, Prashanth  
NYU Polytechnic School of Engineering  
Khorrami, Farshad  
NYU Tandon School of Engineering

Stabilizing controller design and region of attraction (RoA) estimation are essential in nonlinear control. Moreover, it is challenging to implement a control Lyapunov function (CLF) in practice when only partial knowledge of the system is available. We propose a learning framework that can synthesize state-feedback controllers and a CLF for control-affine nonlinear systems with unstructured uncertainties. Based on a regularity condition on these uncertainties, we treat them as bounded disturbances and prove that a CLF for the nominal system (estimate of the true system) is an input-to-state stable control Lyapunov function (ISS-CLF) for the true system when the CLF’s gradient is bounded. We integrate the robust Lyapunov analysis with the learning of both the control law and CLF. We demonstrate the effectiveness of our learning framework on two examples, such as an inverted pendulum system and a cart-pole system.

**17:00-17:15**  
WeC16.5

**Learning Signal Temporal Logic through Neural Network for Interpretable Classification**, pp. 1907-1914  
Li, Danyang  
Boston University  
Cai, Mingyu  
Lehigh University  
Vasile, Cristian Ioan  
Lehigh University  
Tron, Roberto  
Boston University

Machine learning techniques using neural networks have achieved promising success for time-series data classification. However, the models that they produce are challenging to verify and interpret. In this paper, we propose an explainable neural-symbolic framework for the classification of time-series behaviors. In particular, we use an expressive formal language, namely Signal Temporal Logic (STL), to constrain the search of the computation graph for a neural network. We design a novel time function and sparse softmax function to improve the soundness and precision of the neural-STL framework. As a result, we can efficiently learn a compact STL formula for the classification of time-series data through off-the-shelf gradient-based tools. We demonstrate the computational efficiency, compactness, and interpretability of the proposed method through driving scenarios and naval surveillance case studies, compared with state-of-the-art baselines.

**17:15-17:30**  
WeC16.6

**Reachability Analysis and Safety Verification of Neural Feedback Systems Via Hybrid Zonotopes**, pp. 1915-1921  
Zhang, Yuhao  
University of Wisconsin-Madison  
Xu, Xiangru  
University of Wisconsin-Madison
Hybrid zonotopes generalize constrained zonotopes by introducing additional binary variables and possess some unique properties that make them convenient to represent nonconvex sets. This paper presents novel hybrid zonotope-based methods for the reachability analysis and safety verification of neural feedback systems. Algorithms are proposed to compute the input-output relationship of each layer of a feed-forward neural network, as well as the exact reachable sets of neural feedback systems. It is shown that a ReLU-activated feed-forward neural network can be exactly represented by a hybrid zonotope. In addition, a sufficient and necessary condition is formulated as a mixed-integer linear program to certify whether the trajectories of a neural feedback system can avoid unsafe regions. The proposed approach is shown to yield a formulation that provides the tightest convex relaxation for the reachable sets of the neural feedback system. Two numerical examples demonstrate the superior performance of the proposed approach compared to other existing methods.

The ushering in of the big-data era, ably supported by exponential advances in computation, has provided new impetus to data-driven control in several engineering sectors. The rapid and deep expansion of this topic has precipitated the need for a showcase of the highlights of data-driven approaches. There has been a rich history of contributions from the control systems community in the area of data-driven control. At the same time, there have been several new concepts and research directions that have also been introduced in recent years. Many of these contributions and concepts have started to transition from theory to practical applications. This paper will provide an overview of the historical contributions and highlight recent concepts and research directions.
Why Would We Want a Multi-Agent System Unstable (Plenary Session)

Chair: Wang, Yan
Ford Research and Advanced Engineering, Ford Motor Company

Co-Chair: Fekih, Afef
University of Louisiana at Lafayette

ThA01.1
08:30-09:30

Why Would We Want a Multi-Agent System Unstable*
Jankovic, Mrdjan
Ford Research (retired)

ThA01
Sapphire MN
Networked Control Systems (RI) (RI Session)

Chair: Verginis, Christos
Uppsala University

Co-Chair: Jahnandari, Sina
University of Southern California

10:00-10:04
ThA01.1

Output-Based Adaptive Distributed Observer for General Linear Leader Systems Over Periodic Switching Digraphs, pp. 1940-1945
He, Changran
The Chinese University of Hong Kong

Huang, Jie
The Chinese University of Hong Kong

In this paper, we first establish an output-based distributed observer for a general linear leader system over a periodic jointly connected switching communication network, which extends the applicability of the output-based distributed observer from a marginally stable linear leader system to any linear leader system and from an undirected switching graph to a directed switching graph. Then we further solve the cooperative output regulation problem of linear multi-agent systems utilizing the output-based distributed observer.

10:04-10:08
ThA01.2

How Can We Be Robust against Graph Uncertainties?, pp. 1946-1951
Jahnandari, Sina
University of Southern California

Materassi, Donatello
University of Minnesota

The article shows that it is possible to leverage relevant recent results developed in the area of identification of dynamic networks to introduce a notion of robustness with respect to uncertainties in the graph structure of a distributed system. It is assumed that in an observational framework, only a subset of the variables of a networked system are measured and the topology of the interconnections between the variables is partially known. The focus of the paper is the challenging scenario where it is not possible to measure any variables on the directed paths from the confounding variable to either the input or the output of the transfer function of interest. Sufficient conditions are derived to determine a set of instrumental variables and a set of auxiliary variables that guarantee consistent identification of the transfer function using an algorithm based on prediction error method for the class of acyclic networks. It is also shown that using similar ideas, the results could be extended to cyclic networks. In particular, we show how consistent estimates of some transfer functions in a network with feedback loops could be used to identify some other transfer functions whose inputs and outputs are influenced by unmeasured confounding variables.

10:12-10:16
ThA01.4

Ning, Chuanyi
Beihang University

Xi, Zhiyu
Beihang University

Zhang, Xingpeng
Beihang University

In this paper, problems of designing advanced stealthy false data injection (FDI) attack sequences are investigated. It is proved that, for systems with spectral radius larger than or equal to 1, abnormal increments of residual data are incurred for finite number of steps by improved stealthy FDI attack strategy proposed in this paper while diverging estimation error is achieved. For systems with spectral radius less than 1, infinite estimation error can never be achieved by stealthy FDI attacks. Therefore, an optimal FDI attack strategy is proposed to achieve largest possible steady state estimation error while remaining stealthy. Stealthiness of proposed attack sequences is proved in the presence of a summation (SUM) detector. Finally, simulation results are given to verify the effectiveness of attack strategies designed in this paper.

10:16-10:20
ThA01.5

Secure Control for Networked Control System under Multiple Cyber-Attacks, pp. 1966-1971
Wu, Yuliang
Shanghai Jiao Tong University

Qu, Gang
East Branch of State Grid Corporation of China

Wu, Jing
Shanghai Jiao Tong University

Long, Chengnian
Shanghai Jiao Tong University

Li, Shaoyuan
Shanghai Jiao Tong University

This paper focuses on the stability and controller design problem of networked control systems (NCSs) under multiple cyber-attacks, which are random and no priority has been pre-defined. A Markovian-based observer is designed to estimate the affected system states, with the desired gain changing with different attacks. Furthermore, a criterion is obtained in LMI to guarantee stochastically stable for closed-loop system and the corresponding controller design is addressed. Finally, the effectiveness of the proposed method is demonstrated by evaluating contrast simulation example.

10:20-10:24
ThA01.6

Coverage Control on the Special Euclidean Groups, pp. 1972-1979
Lin, Ruoyu
University of California, Irvine

Egerstedt, Magnus
University of California, Irvine

In this paper, we investigate a coverage strategy for a multi-robot system across a domain of interest for applications involving...
pose-sensitive event services. The resulting problem is modeled as a coverage control problem on the special Euclidean groups. Based on the geometry inherent to the unimodular Lie groups, the geodesic-based Voronoi cell of a robot in charge of a subdomain and the locational cost function representing the coverage quality are defined. The controller for driving a team of planar robots to a critical point of the locational cost is derived and augmented by a control barrier certificate for the purpose of collision avoidance. The performance of the proposed controller is compared with the situation where the orientations of the robots are ignored during the coverage process using the standard Lloyd’s algorithm for both homogeneous and heterogeneous (in terms of robots’ relative mobility and safe radii) multi-robot teams.

10:24-10:28
Nobili, Alberto Maria University of Pisa
Qin, Yuzhen University of California, Riverside
Avizzano, Carlo Alberto Scuola Superiore Sant’Anna
Bassett, Danielle University of Pennsylvania
Pasqualetti, Fabio University of California, Riverside

Many natural and man-made network systems need to maintain certain patterns, such as working at equilibria or limit cycles, to function properly. Thus, the ability to stabilize such patterns is crucial. Most of the existing studies on stabilization assume that network systems’ states can be measured online so that feedback control strategies can be used. However, in many real-world scenarios, systems’ states, e.g., neuronal activity in the brain, are often difficult to measure. In this paper, we take this situation into account and study the stabilization problem of linear network systems with an open-loop control strategy: vibrational control. We derive a graph-theoretic sufficient condition for structural vibrational stabilizability, under which network systems can always be stabilized. We further provide an approach to select the locations in the network for control placement and design corresponding vibrational inputs to stabilize systems that satisfy this condition. Finally, we provide some numerical results that demonstrate the validity of our theoretical findings.

10:28-10:32
Jahandari, Sina University of Southern California
Srivastava, Ajitsh University of Southern California

The paper presents systematic tests to determine if a particular transfer function in an interconnected system is strictly proper or has a feedthrough. Considering a strictly proper module between two nodes in a networked system, if only the data of the two nodes are used, there are situations where numerical tests to determine if the module is strictly proper will fail. It is shown, however, that marginalizing some of the nodes of a networked system under certain conditions preserves delays and feedthroughs in certain links. Therefore, using a set of auxiliary nodes that satisfies certain conditions, it is possible to design a systematic test to determine if a module in the networked system is strictly proper. The conditions are proven to be sufficient. Similar ideas are used to formulate a systematic test to determine if a module has a feedthrough.

10:32-10:36
Verginis, Christos Uppsala University

We consider the asymptotic consensus problem for 2nd-order nonlinear multi-agent systems subject to predefined constraints for the system response, such as maximum over-shoot or minimum convergence rate. We design a distributed discontinuous adaptive control protocol that guarantees that the inter-agent consensus errors evolve in a prescribed funnel and converge to zero. The multi-agent dynamics contain parametric and structural uncertainties, without boundedness or approximation/parametric factorization assumptions. The response of the closed-loop system is solely determined by the predefined funnel and is independent from the control gain selection. Finally, simulation results verify the theoretical findings.

10:36-10:40
Chen, Tao Zhejiang University
Wang, Lei Zhejiang University
Liu, Zhitaoy Zhejiang University
Wang, Wenhai Zhejiang University
Su, Hongye Zhejiang University

This paper proposes an attack strategy for remote estimators in cyber-physical systems. In contrast with the common approaches by maximizing the state estimation difference and estimation error covariance of a remote estimator, we consider the scenario where attackers expect to regulate the estimation error to the value arbitrarily defined by attackers, which not only enables attackers to release attacks of different intensities according to their intentions, but also reduces the possibility detected by the amplitude detector and the human monitor. By taking advantage of the dynamic programming, an explicit expression of the optimal attack sequence is derived, and its convergence and feasibility are analyzed. Finally, simulation results are presented to validate the effectiveness of the proposed strategy.

10:40-10:44
Dey, Anchita Indian Institute of Technology Delhi
Dhar, Abhishek Linköping University
Bhasin, Shubhendu Indian Institute of Technology Delhi

Model predictive control (MPC) for uncertain systems in the presence of hard constraints on state and input is a non-trivial problem, and the challenge is increased manyfold in the absence of state measurements. In this paper, we propose an adaptive output feedback MPC technique, based on a novel combination of an adaptive observer and robust MPC, for single-input single-output discrete-time linear time-invariant systems. At each time instant, the adaptive observer provides estimates of the states and the system parameters that are then leveraged in the MPC optimization routine while robustly accounting for the estimation errors. The solution to the optimization problem results in a homothetic tube where the state estimate trajectory lies. The true state evolves inside a larger outer tube obtained by augmenting a set, invariant to the state estimation error, around the homothetic tube sections. The proof for recursive feasibility for the proposed ‘homothetic and invariant’ two-tube approach is provided, along with simulation results on an academic system.
controller uses a reduced-order model that approximates the slow decision variables in the MPC problem to achieve a time-varying recursive feasibility and provide an average asymptotic cost bound for numerical robustness. This enables the computation of an optimal control input in real-time rather than having to use a suboptimal solution as is the case in most current real-time MPC approaches. The computational complexity of the presented method is linear w.r.t. the prediction horizon, state and input dimension, which makes it ideal for fast sampled, large systems. The functionality of the new approach is demonstrated in a laboratory setup of an underactuated, crane-like system. Furthermore, its performance is compared with a suboptimal MPC based on an active-set method with warm-start (ASM-MPC). It is shown that the optimization problems are solved to achieve similar and in some cases even better tracking accuracy.

Dynamic Walking of Bipedal Robots on Uneven Stepping Stones Via Adaptive-Frequency MPC, pp. 2047-2052

This paper presents a novel Adaptive-frequency MPC framework for bipedal locomotion over terrain with uneven stepping stones. In detail, we intend to achieve adaptive gait periods with variable MPC frequency for bipedal periodic walking gait to traverse terrain with discontinuities without slowing down. We pair this adaptive-frequency MPC with kino-dynamics trajectory optimization to obtain MPC adaptive frequencies (in terms of sampling times), center of mass (CoM) trajectory, and foot placements. We use whole-body control (WBC) along with adaptive-frequency MPC to track the optimal trajectories from offline optimization. In numerical validations, our adaptive-frequency optimization and MPC framework have shown advantages over fixed-frequency MPC. The proposed framework can control the bipedal robot to traverse through uneven stepping stone terrains with perturbed stone heights, widths, and surface shapes while maintaining an average speed of 1.5 m/s.

Output Feedback Stochastic MPC with Hard Input Constraints, pp. 2034-2039

We present an output feedback stochastic model predictive controller (SMPC) for constrained linear time-invariant systems. The system is perturbed by additive Gaussian disturbances on state and additive Gaussian measurement noise on output. A Kalman filter is used for state estimation and an SMPC is designed to satisfy chance constraints on states and hard constraints on actuator inputs. The proposed SMPC constructs bounded sets for the state evolution and uses a tube-based constraint tightening strategy where the tightened constraints are time-invariant. We prove that the proposed SMPC can guarantee an infeasibility rate below a user-specified tolerance. We numerically compare our method with a classical output feedback SMPC with simulation results which highlight the efficacy of the proposed algorithm.
Port-controlled Hamiltonian system, and a task-invariant controller was designed for a knee-ankle exoskeleton using interconnection-damping assignment passivity-based control. In this paper, we extend this framework to design a controller for a backdrivable hip exoskeleton to assist multiple tasks. A set of basis functions that connect information of kinematic and corresponding coefficients are optimized, which allows the controller to provide torque that fits normative human torque for different activities of daily life. Human-subject experiments with two able-bodied subjects demonstrated the controller’s capability to reduce muscle effort across different tasks.

10:15-10:30 ThA02.2

Relaxed Pfaffian Constraints with Application to the Minimum-Energy Control of Swarms of Brushbots (I), pp. 2071-2076

Notomista, Gennaro
University of Waterloo

Kinematic constraints can be used to describe the behavior of systems by specifying a set of admissible motions. When the systems interact with each other, a large number of constraints have to be enforced in order to completely specify the admissible motions. At the same time, because of the interaction, some kinematic constraints might be violated. This violation leads to energy dissipation. In this work, we consider swarms of robots physically interacting among each other and with the environment in which they are deployed in order to accomplish a given task. The constraints coming from the physical interaction may restrict or even impede the motion of the robots, leading to dissipation of energy. Leveraging insights from Lagrangian mechanics and optimization, we design controllers for swarm of brushbots with the objective of minimizing the power dissipated because of the physical interaction constraints. The devised controller is showcased in simulation on a swarm of brushbots.

10:30-10:45 ThA02.3

Predictive Velocity Trajectory Control for a Persistently Operating Solar-Powered Autonomous Surface Vessel (I), pp. 2077-2083

Govindarajan, Kavin
North Carolina State University

Haydon, Benjamin
North Carolina State University

Vermillion, Christopher
North Carolina State University

The Gulf Stream represents a major potential resource for renewable energy but is presently only sparsely characterized via radar, buoys, gliders, and intermittently operating human-operated research vessels. Dramatically greater resolution is possible through the use of persistently operating autonomous surface vessels (ASVs), which are powered by wind, wave, or solar resources. Optimizing the control of these ASVs, taking into account the devices’ energetic performance and constraints, in addition to the renewable resource and flow profile, is crucial to obtaining good data. An ASV’s path and velocity profile along that path both significantly influence the amount of a mission domain that can be covered and, ultimately, the scientific quality of the mission. While our previous work focused on optimizing the path of a solar-powered ASV with fixed speed, the present work represents the complement: optimizing the speed for a given path, accounting for the ASV dynamics, flow resource, and solar resource. We perform this optimization through a model predictive controller that maximizes the projected distance traversed by the ASV, with a terminal incentive that captures the estimated additional long-duration range that is achievable from a given terminal battery state of charge. We present simulation results based on the SeaTrac SP-48 ASV, Mid-Atlantic Bight/South-Atlantic Bight Regional Ocean Model, and European Centre for Medium-Range Weather Forecasts solar model. Our results show improved performance relative to simpler heuristic controllers that aim to maintain constant speed or constant state of charge. However, we also show that the design of the MPC terminal incentive and design of the heuristic comparison controller can significantly impact the achieved performance; by examining underlying simulation results for different designs, we are able to identify likely causes of performance discrepancies.

10:45-11:00 ThA03.4

Optimal Cyclic Control of a Structurally Constrained Span-Morphing
Underwater Kite in a Spatiotemporally Varying Flow (I), pp. 2084-2090
Fine, Jacob University of Michigan
McGuire, Carson North Carolina State University
Reed, James North Carolina State University
Bryant, Matthew North Carolina State University
Vermillion, Christopher North Carolina State University

This work presents a control methodology for maximizing the net power generated by an underwater kite capable of adjusting wingspan in real time. Underwater kite systems generate energy by performing cross-current figure-eight flight maneuvers while tethered to a winch system. These systems generate net positive power through cyclic spooling: spooling out under high-tension cross-current flight and spooling in radially under low tension. In the presence of structural constraints, simultaneous variation in the kite’s angle of attack and span is superior to simply reducing the angle of attack in order to stay within permissible structural loading. Furthermore, the optimal combination of these variables depends on the amount of tether spooled out and the spatiotemporally-varying flow field. Leveraging a multi-degree-of-freedom model previously developed by the authors, the performance of three kites—two with fixed span and one with variable span—was compared. To maximize the performance of the modeled kites, an optimal control framework was developed. For the fixed-span case, spool-out speeds and mean elevation angles for the kite were optimized to maximize energy generation over a spool-out cycle. For the morphing span case, spool-out speeds and mean elevation angle, and wingspan were optimized to maximize energy generation over a spool-out cycle while considering the energetic cost of morphing. Simulation results show that the kite capable of span-morphing generated 38.7% more energy than a fixed-span kite of maximum allowable span and 13.2% more energy than a kite of the optimal fixed-span.

11:00-11:15 ThA03.5
Study of Fixed-Points in the Self-Repair Process of a 3D Printer (I), pp. 2091-2096
Caballero, Renzo King Abdullah University of Science and Technology
Feron, Eric King Abdullah University of Science and Technology

We present and prove a theorem guaranteeing global stability in a non-linear system representing the iterative self-repair process where a 3D printer repairs its timing pulley. The process consists of gradually improving the broken part in the 3D printer until the printer reaches its repaired state. To prove global stability, we verify that the limit of the self-repair sequence does not depend on the initial condition, and always converges to the repaired state. Even though the convergence of this process has been analyzed under strong assumptions, in the present work, the convergence is proven for a more general case.

11:15-11:30 ThA03.6
Necessary Conditions for Feasibility of Linear, Time-Invariant Self-Powered Feedback Control Laws (I), pp. 2097-2104
Scruggs, Jeff University of Michigan
Ligeikis, Connor University of Michigan

A control system is called self-powered if the only energy it requires for operation is that which it absorbs from the plant. For a linear feedback law to be feasible for a self-powered control system, its feedback signal must be colocated with the control inputs, and its input-output mapping must satisfy an associated passivity constraint. In this paper, we consider the use of actively-controlled electronics to impose a self-powered linear feedback law. In this case, the feasibility of a linear feedback law must account for parasitic losses in the electronics and energy storage system. For the case in which the feedback law is linear and time-invariant, this paper derives necessary feasibility conditions which explicitly account for these losses. This feasibility condition is then illustrated in a simple example.
We propose a computational method for the finite-time nonlinear optimal control problem. We compute the solutions by first performing a coordinate transformation using the principle Koopman eigenfunctions. Then, we synthesize past and present techniques for obtaining a general explicit solution to the resulting differential Riccati equation. We demonstrate our method on a numerical example, for which the analytic Koopman eigenfunctions are known.

Our main objective is to maximize the energy produced and transmitted to the user's network. In particular, we investigate the issue of determining an optimal investing strategy that monitors the deployment of treatment plants. Using Pontryagin's maximum principle (PMP), we characterize, over a fixed time-frame $[0, T]$, the optimal investment that maximizes the produced energy while limiting the overall production costs. In addition, the efficiency of the suggested strategy is validated and illustrated throughout this work using a direct optimization method.

Iterative Learning Control of Discrete Systems with a Switching Reference Trajectory and Saturating Inputs, pp. 2153-2158

Pakshin, Pavel University of Arctic Technology
Rogers, Eric University of Southampton
Galkowski, Krzysztof Univ. of Zielona Gora

Iterative learning control has been developed for application to systems that repetitively execute the same finite duration task, where the objective is to follow a supplied reference trajectory. In many current designs, the reference trajectory is specified at the outset, but others, such as materials processing, may require one or more changes in the reference trajectory.
changes, or switching, of this trajectory. This paper develops a new design for the previously unconsidered case of discrete linear dynamics with a switching reference trajectory and saturation of the input signal. The design is established using the stability theory for nonlinear repetitive processes, a class of $2$D systems, and uses vector Lyapunov functions. A numerical case study demonstrates the applicability of the new design.

11:45-11:50 ThA06.4

**Data-Driven Robust Optimal Iterative Learning Control of Linear Systems with Strong Cross-Axis Coupling**, pp. 2159-2164

Zhang, Zezhou  
Rutgers University  
Zou, Qingze  
Rutgers, the State University of New Jersey

We propose a Model-Based Reinforcement Learning (MBRL) algorithm named VF-MC-PILCO, specifically designed for application to mechanical systems where velocities cannot be directly measured. This circumstance, if not adequately considered, can compromise the success of MBRL approaches. To cope with this problem, we define a velocity-free state formulation which consists of the collection of past positions and inputs. Then, VF-MC-PILCO uses Gaussian Process Regression to model the dynamics of the velocity-free state and optimizes the control policy through a particle-based policy gradient approach. We compare VF-MC-PILCO with our previous MBRL algorithm, MC-PILCO4PMS, which handles the lack of direct velocity measurements by modeling the presence of velocity estimators. Results on both simulated (cart-pole and URS robot) and real mechanical systems (Furuta pendulum and a ball-and-plate rig) show that the two algorithms achieve similar results. Conveniently, VF-MC-PILCO does not require the design and implementation of state estimators, which can be a challenging and time-consuming activity to be performed by an expert user.

ThA07  
**Variable-structure/Sliding-Mode Control** (Regular Session)

Chair: Mirinejad, Hossein  
Kent State University  
Co-Chair: Fekih, Afef  
University of Louisiana at Lafayette

10:00-10:15 ThA07.1

**Leader-Follower Formation of Unicycle Mobile Robots Using Sliding Mode Control**, pp. 2179-2184

Díaz, Yoshua  
Instituto Politécnico Nacional  
Davila, Jorge  
Instituto Politecnico Nacional  
Mera, Manuel  
Eisime Upt Ipn

This article presents a distributed controller for the formation of unicycle mobile robots whose aim is to follow the leader position maintaining a certain geometry in the horizontal plane. The proposed control law provides the formation of the followers with the leader’s position using sliding mode control techniques. The sliding mode controllers are designed using local interactions to ensure the convergence to zero of a couple of suitable sliding variables. The particular design of the sliding variables guarantees that the resulting sliding motion provides the asymptotic convergence of the formation errors to a bounded region around the origin.

10:15-10:30 ThA07.2

**A Non-Singular Fast Terminal SMC to Enhance the Dynamic Stability of Wind Energy Conversion System-Based Microgrids During Grid Faults**, pp. 2185-2190

Musarrat, Md Nafiz  
University of Louisiana at Lafayette  
Fekih, Afef  
University of Louisiana at Lafayette

Fast and accurate mitigation of dynamic instabilities resulting from grid faults is critical for the safe and reliable operation of microgrids. This paper proposes a non-singular fast terminal sliding mode control (NFTSMC)-based approach to enhance the dynamic stability of wind energy conversion system-based microgrids. The approach combines the fast convergence and robustness of NFTSMC with the fast current controllability of static synchronous compensators (STATCOM) to provide reactive power support and stabilize the grid voltage in the presence of grid faults and mismatched disturbances.
The stability of the NFTSMC approach is established using the Lyapunov stability theory. The control approach is implemented in a test microgrid system and assessed in the presence of mismatched disturbances and a symmetrical grid fault. Its dynamic performance is also compared to that of a standard sliding mode controller. The obtained results confirmed the ability of the proposed scheme to effectively mitigate dynamic instabilities resulting from grid faults and provide grid support under faulty conditions.

10:30-10:45  ThA07.3
Guidance of Quadrotor Unmanned Aerial Vehicles Via Adaptive Multiple-Surface Sliding Mode Control, pp. 2191-2196

Incarnemona, Gian Paolo  Politecnico Di Milano
Ferrara, Antonella  University of Pavia

In many application domains, navigation of unmanned aerial vehicles (UAVs) requires a planar flight to move along a desired path or to track a moving object under uncertain conditions. In this paper, we propose a robust control approach for quadrotor UAVs performing a nonholonomic-like navigation with a predefined velocity based guidance law. Specifically, the quadrotor model is first recast in the framework of nonholonomic systems, and then an adaptive multiple-surface sliding mode approach, with suboptimal second order sliding mode control, is applied. The robustness features of the proposed approach are discussed and assessed in simulation.

10:45-11:00  ThA07.4
Quantifiable Convergence Time in Stabilization of Uncertain Dynamical Systems with a Sliding Mode Adaptive Control Architecture, pp. 2197-2202

Deniz, Meryem  University of Texas at Arlington
Dogan, Kadiye Merve  Embry-Riddle Aeronautical University
Yucelen, Tansel  University of South Florida
Wan, Yan  University of Texas at Arlington

Although literature has presented effective approaches using adaptive control methods to tackle system uncertainties, these methods typically guarantee asymptotic stabilization without a defined convergence time unless the controlled system adheres to the persistent excitation condition. Unfortunately, this condition may not always be applicable in practice. This paper proposes a sliding mode adaptive stabilization architecture that uses nonlinear reference models to control a class of uncertain nonlinear dynamical systems with a quantifiable convergence time. Along with presenting our main results, we also showcase the effectiveness of our approach by providing two illustrative numerical examples.

11:00-11:15  ThA07.5
Switched Combination Synchronization of Nonidentical Fractional-Order Chaotic Systems Using Neuro-Fuzzy Sliding Mode Control, pp. 2203-2209

Kharabian, Behrouz  Kent State University
Mirinejad, Hossein  Kent State University

This work presents a novel chaos synchronization scheme for nonidentical fractional-order chaotic systems. The new scheme, called switched combination synchronization, integrates the concepts of switched synchronization and combination synchronization where two drive systems, called base systems, are swapped using a switching factor and are combined with a third drive system, called the masking system. A response system is synchronized with the resulting multi-drive systems using a neuro-fuzzy sliding mode control (NFSMC) approach. A soft switching algorithm using the neuro-fuzzy switch is designed to ensure the stability of the system during the transition of drive systems. Simulation results confirm the higher performance of the proposed control approach than a regular sliding mode control (SMC) and a proportional integrative derivative (PID) controller in switched combination synchronization of chaotic systems.

11:15-11:30  ThA07.6
A Sliding Mode Observer with Homogeneous Estimation Error for a Class of Linear Time-Invariant Systems, pp. 2210-2215

Maravilla Castro, Merln  Instituto Politécnico Nacional Octavio Davila, Jorge  Instituto Politécnico Nacional

This article presents a robust observer for a class of continuous-time linear time-invariant systems affected by unknown inputs. The sufficient conditions under which this observer allows the estimation error to possess the homogeneity property are studied. Furthermore, the observer algorithm comprises a linear compensation term that enables the observer nonlinear output injection term to provide global finite-time convergence despite bounded unknown inputs and system instability.

10:00-10:15  ThA08.1
Modelling of Blood Loss Influence on Propofol Concentrations and Anesthetic States in Critical Responses (I), pp. 2216-2221

Ghita, Mihaela  Ghent University
Copot, Dana  Ghent University
Birs, Isabela  Technical University of Cluj-Napoca
Muresan, Cristina  Technical University of Cluj-Napoca
Martine, Necebroek  UZ GENT
Ionescu, Clara  Ghent University

This work studies the classical pharmacokinetic-pharmacodynamic (PK-PD) model of Propofol for total intravenous anesthesia in response to intraoperative blood loss. Anesthetic and hemodynamic stability are impaired in the setting of trauma surgeries or major procedures with high hemorrhage risk. Blood loss has immediate effects on the cardiovascular system, but also affects the plasma concentration of the perioperatively infused drugs. During perioperative transition periods, when fast blood losses occur, the PK models on which the target-controlled infusion (TCI) is based should be updated. Then, the population-based parameters move towards an individualized strategy that accounts also for the actual blood volume in the patient. This paper evaluates the influence of changing blood volume on the PK model of Propofol, hence on the anesthesia state of the patient. The simulations also account for the hemodynamic responses due to the conflicting interactions of both hemorrhage and anesthetic drug infusion. This model has great potential for inclusion in multiple-closed loop control strategies of anesthesia-hemodynamic states, as it is simple and adapted from well-known PK models, for which control strategies are already mature.

10:15-10:30  ThA08.2
Hemodynamic Safety Assurance in Closed-Loop Controlled Critical Care: Hemorrhage Resuscitation and Sedation Case Study, pp. 2222-2227

Yin, Wei  University of Maryland
Tivay, Ali  University of Maryland
Fathy, Hosam K.  University of Maryland
Hahn, Jin-Oh  University of Maryland
This letter presents a novel approach to assure hemodynamic safety in closed-loop controlled critical care. The approach is equipped with safety-preserving control based on control barrier functions to ensure the safety of hemodynamic state, hemodynamic monitoring to estimate hemodynamic state, and probabilistic recursive therapeutic target guidance to direct a patient as closely as possible to a prescribed therapeutic target along a desired trajectory. A notable advantage of the approach is that it can be augmented to single-input-single-output critical care control loops developed in isolation to guard hemodynamic safety against conflicts between them, providing a practical alternative to sophisticated multi-input-multi-output control loop design. The efficacy of the approach was examined in a hemorrhage resuscitation-intravenous sedation case study using realistic virtual patients. The approach as a whole assured the boundedness of hemodynamic state by reconciling conflicts between the two control loops. The recursive therapeutic target guidance directed patients to personalized reachable targets while maintaining the patients' therapeutic responses near the desired therapeutic trajectory. The approach may serve as an effective means to reconcile multiple critical care control loops and assure holistic hemodynamic safety.

Mitigating Epilepsy by Stabilizing Linear Fractional-Order Systems (I), pp. 2228-2233

Reed, Emily
University of Southern California

Ramos, Guilherme
Instituto De Telecomunicacoes, 1049-001 Lisbon, Portugal

Bogdan, Paul
University of Southern California

Pequito, Sergio
Uppsala University

Epilepsy affects approximately 50 million people worldwide. Despite its prevalence, the recurrence of seizures can be mitigated only 70% of the time through medication. Furthermore, surgery success rates range from 30% - 70% because of our limited understanding of how a seizure starts. However, one leading hypothesis suggests that a seizure starts because of a critical transition due to an instability. Unfortunately, we lack a meaningful way to quantify this notion that would allow physicians to not only better predict seizures but also to mitigate them. Hence, in this paper, we develop a method to not only characterize the instability of seizures but also to leverage these conditions to stabilize the system underlying these seizures. Remarkably, evidence suggests that such critical transitions are associated with long-term memory dynamics, which can be captured by considering linear fractional-order systems. Subsequently, we provide for the first time tractable necessary and sufficient conditions for the global asymptotic stability of discrete-time linear fractional-order systems. Next, we propose a method to obtain a stabilizing control strategy for these systems using linear matrix inequalities. Finally, we apply our methodology to a real-world epileptic patient dataset to provide insight into mitigating epilepsy and designing future cyber-neural systems.

Effects of Driver Placement and Phase on Multi-Actuator Magnetic Resonance Elastography Via Finite Element Analysis (II), pp. 2234-2239

Nieves-Vazquez, Heriberto
Georgia Institute of Technology

Ozkaya, Efe
Icahn School of Medicine at Mount Sinai

Meinhold, Waiman
Georgia Institute of Technology

Ueda, Jun
Georgia Institute of Technology

Multi-actuator magnetic resonance elastography (MRE) has previously been studied for overcoming wave attenuation and generating uniform displacements throughout a targeted imaging region. While the actuators’ locations, relative phase offsets, and angles are known to influence the generated displacements, their effects are dependent on the geometry and properties of the specific target. Experimental optimization of these MRE parameters can be performed but is time-consuming. Alternatively, finite element analysis (FEA) is used for three-dimensional model-specific characterization of displacement fields induced by MRE mechanical excitation loads across varying actuator locations. Cubic, tissue-like homogeneous and heterogeneous models were created and loaded were applied to simulate single actuator and multi-actuator cases. Multi-actuator cases were phase-matched to promote constructive interference of the induced waves. An additional investigation was performed by repeating a single multi-actuator configuration with various loading angles in the heterogeneous model. The mean displacement amplitudes and the corresponding standard deviations throughout the imaging target volumes are compared across the multiple configurations. Wave images of selected configurations are presented for comparison. Multi-actuator configurations induced the greatest mean $\Delta z$ displacement amplitudes within the imaging target of both models. To further increase the $\Delta z$ displacement, the excitation loads can be angled towards the imaging target. The differences in simulated displacement fields demonstrate the potential for future automated parameter optimization for closed-loop MRE driver positioning using more complex FEA models.

Activity Recognition Using a High Gain Observer and Spectrograms (I), pp. 2246-2251

Nouriani, Ali
Ali Nouriani
McGovern, Robert A
University of Minnesota
Rajamani, Rajesh
Univ. of Minnesota

This paper proposes a novel algorithm for human activity recognition that is a combination of a high-gain observer and deep learning-based classification algorithms. The nonlinear high-gain observer designed using Lyapunov analysis accurately estimates the attitude of the chest of a human subject using measurements from a single Inertial Measurement Unit (IMU). The signals processed by the observer are then converted into spectrograms to obtain “images” of the frequency response of the signals. The images for activities from a dataset of 7 human subjects are annotated and used for training/ fine-tuning of several well-known deep learning algorithms for image processing. The results from the best combination of our algorithms shows an exceptional accuracy of 98% for activity recognition.
Estimation of Locomotive Adhesion Coefficients and Slip Ratios

van de Merwe, Charl
Le Roux, Derik
University of Pretoria

Wheel slip control of locomotive traction systems is difficult because of the uncertainty in the non-linear wheel-surface behaviour, the unknown adhesion conditions and the difficulty in obtaining the slip ratio. Continuous controllers can perform better than traditional rule-based controllers if the uncertainty can be reduced using effective estimation. A novel linear state-observable estimator is presented that produces estimates of the slip ratios and adhesion coefficients of each locomotive wheelset. The estimator requires measurements of the locomotive velocity and acceleration. The estimator includes the estimation of the normal forces of each wheelset to increase the adhesion coefficient estimation accuracy.

Optimal Robust Filter of Uncertain Fractional Order Systems: A Penalized Deterministic Approach

Nosrati, Komeil
Belikov, Juri
Tallinn University of Technology
Tallinn University of Technology

Developing accurate and optimum state estimation methods for fractional order systems is highly relevant since it provides vital information related to memory effects. The optimum estimation of these systems can be guaranteed using the Kalman filter (KF) when all parameter matrices are not subject to uncertainties. Nevertheless, this fundamental principle of the filter is violated, and its performance can be degraded when the model is uncertain. In this light and to limit this deterioration, the present study introduces an optimal solution for filtering uncertain fractional order systems, which operates as follows. First, using the robust regularized least-squares (RLSs) problem combined with penalty functions, a robust penalty game approach is proposed. Then, in an independent framework of any auxiliary parameters, unified recursive Riccati equation and optimal robust filter are derived subject to norm-bounded uncertainties of parameter matrices. To accomplish this step, the stability and convergence analysis of the filter are illustrated based on the singular theory conception.

Stability of a Distributed Consensus-Based Kalman Filter under Limited Communication

Benalcazar, Diego R.
Enyioha, Chinwendu
University of Central Florida
University of Central Florida

In this paper, we address the stability of a Quantized Distributed-Consensus Kalman Filter (Q-DCKF) operating in a limited communication environment. In the QDCDF, agents share a quantized version of their state estimates with neighboring nodes, as they reach a consensus on the state of a mobile target. Even though the stability of the single and distributed Kalman filters has been studied in the past, the effect of quantization of the states and resulting estimation error covariances have not been characterized for the distributed setting considered in this paper. We show, via passivity theory, that the Q-DCKF is stable under mild assumptions and validate the theoretical results obtained via numerical experiments.

State and Parameter Estimation for Stochastic Open Two-Level Quantum Systems

In this paper, a driven and damped two-level quantum system under continuous observation is considered. Its time evolution is governed by an operator-valued stochastic master equation and conditioned on the recorded measurement data. The system is transformed to state space representation and its observability is proven analytically. An extended Kalman filter is employed in order to both reconstruct the density operator describing the full state of the system, and to dynamically identify key parameters. Convincing results are obtained in numerical simulations. Overall, a practical engineering approach to quantum control is presented.
only. In this case, the output estimation is independent of the process noise or unmodeled dynamics. This allows for the estimation of process noise regardless of its probability distribution. The proposed approach takes into account the possibility of using the Kalman filter theme in the filtering of output noise regardless of the process noise distribution. The proposed approach does not require the covariance estimation of the process noise. Since the proposed approach considers the ability to formulate unmodeled dynamics or parameter uncertainties as non-Gaussian process noise, it can handle both. The potential of this approach is demonstrated by implementing it in a group of connected autonomous robots.

**ThA10** Modeling I (Regular Session)  
Aqua 309

Chair: Gayme, Dennice  
The Johns Hopkins University
Co-Chair: O'Brien, Richard  
United States Naval Academy

10:00-10:15  
**ThA10.1**

Model Identification of an Unmanned Surface Vessel without Actuator Calibration, pp. 2289-2294

O'Brien, Richard  
United States Naval Academy

Linear and nonlinear models of a modified commercially available unmanned surface vessel are identified without actuator calibration. The unknown actuator calibration is represented by a piecewise linear function of the normalized force, the actuator force divided by the unknown maximum force. The drag coefficients are estimated in terms of the experimentally observed steady-state response and the maximum force is estimated using the experimental transient response. The models are validated via simulation and by comparison with a previously-developed model for an unmodified version of the unmanned surface vessel.

10:15-10:30  
**ThA10.2**

Modelling and Identification of Li-Ion Cells, pp. 2295-2300

Lopes dos Santos, P.  
INESC TEC
Azevedo Perdicoulis, T-P  
ISR-Coimbra & UTAD
Salgado, Paulo  
Universidade De Trás-Os-Montes & E Alto Douro

To develop a full battery model in view to accurate battery management, Li-ion cell dynamics is modelled by a capacitor in series with a simplified Randles circuit. The open circuit voltage is the voltage at the capacitor terminals, allowing, in this way, for the dependence of the open circuit voltage on the state-of-charge to be embedded in its capacitance. The Randles circuit is recognised as a trusty description of a cell dynamics. It contains a semi-integrator of the current, known as the Warburg impedance, that is a special case of a fractional integrator. To enable the formulation of a time-domain system identification algorithm, the Warburg impedance impulse response was calculated and normalised, in order to derive a finite order state-space approximation, using the Ho-Kalman algorithm. Thus, this Warburg impedance LTI model, with known parameters (normalised impedance) in series with a gain block, is suitable for system identification, since it has only one unknown parameter. A LTI System identification Algorithm was formulated to estimate the model parameters and the initial values of both the open circuit voltage and the states of the normalised Warburg impedance. The performance of the algorithm was very satisfactory on the whole state-of-charge region and when compared with low order Thelenin models. Once it is understood the parameters variability on the state-of-charge, temperature and ageing, we envisage to continue the work using parameter-varying algorithms.

10:30-10:45  
**ThA10.3**

Reduced-Order Approximation of Fractional-Order Controllers by Keeping Robust Stability and Robust Performance, pp. 2301-2306

Mihaly, Vlad Mihai  
Technical University of Cluj-Napoca
Susca, Mircea  
Technical University of Cluj-Napoca

Recently, the fractional-order element has been integrated into the Robust Control Framework considering the Oustaloup method. As such, the resulting infinite impulse response approximation manages to satisfy the robust stability and the robust performance criteria according to a given uncertainty block. However, the recommended approximation order for each fractional-order element is the number of decades of the frequency range where the approximation is valid, which can lead to a high-order controller. The current paper describes an optimization-based technique to find a low-order approximation of a fractional-order controller such that the resulting controller maintains the robust stability and robust performance as well. A set of numerical experiments have also been performed in order to illustrate the proposed method.

10:45-11:00  
**ThA10.4**

Graph-Theoretic Analyses and Model Reduction for an Open Jackson Queueing Network, pp. 2307-2312

Zhu, Chenyan  
Washington State University
Roy, Sandip  
Washington State University

A graph-theoretic analysis of the steady-state behavior of an open Jackson queueing network is developed. In particular, a number of queueing-network performance metrics are shown to exhibit a spatial dependence on local drivers (e.g. increments to local exogenous arrival rates), wherein the impacts fall off across graph cutsets away from a target queue. This graph-theoretic analysis is also used to motivate a structure-preserving model reduction algorithm, and an algorithm that exactly matches performance statistics of the original model is proposed. The graph-theoretic results and model-reduction method are evaluated via simulations of an example queueing-network model.

11:00-11:15  
**ThA10.5**

On the Endemic Behavior of a Competitive Tri-Virus SIS Networked Model, pp. 2313-2318

Gracy, Sebin  
Rice University
Ye, Mengbin  
Curtin University
Anderson, Brian D.O.  
Australian National University
Uribe, Cesar A.  
Rice University

We study the endemic behavior of a multi-competitive networked susceptible-infected-susceptible (SIS) model. In particular, we focus on the case where there are three competing viruses (i.e., tri-virus system). First, we show that the tri-virus system is not monotone. Thereafter, we identify necessary conditions and a sufficient condition for local exponential convergence to a boundary equilibrium (exactly one virus is alive, the other two are dead) and identify a special case that admits the existence and local exponential attractivity of a line of coexisting equilibria (at least two viruses are active). Finally, we identify a particular case (subsumed by the aforementioned special case) such that for all nonzero initial infection levels, the dynamics of the tri-virus system converge to a plane of coexisting equilibria.

11:15-11:30  
**ThA10.6**

A Structured Input-Output Approach to Characterizing Optimal Perturbations in Wall-Bounded Shear Flows, pp. 2319-2325

Liu, Chang  
University of California, Berkeley
Shuai, Yu  
Princeton University
Rath, Aishwarya  
Johns Hopkins University
Gayme, Dennice  
Johns Hopkins University

This work builds upon recent work exploiting the notion of structured singular values to capture nonlinear interactions in the analysis of wall-bound shear flows. In this context, the structured uncertainly can be interpreted in terms of the flow structures most likely to be...
attacks from a strategic opponent. Detection is assumed to be imperfect and depends on the detectors' technology and the infrastructure's properties. We analytically characterize Nash equilibria of this large-scale game for problem instances where each component is detected from one detector location and the attacker has limited resources. Our equilibrium analysis provides a criticality assessment of the infrastructure's components in strategic settings. It also demonstrates new equilibrium behavior from the players that intricately depends on their amount of resources, as well as the detection technology and infrastructure topology.

10:45-11:00

ThA11.4


Aghanawi, Khushboo

IIT Bombay, India

Veeraruna, Kavitha

IIT Bombay, India

Crowd-sourcing models, which leverage the collective opinions/signals of users on online social networks (OSNs), are well-accepted for fake post detection; however, motivating the users to provide the crowd signals is challenging, even more so in the presence of adversarial users. We design a participation (mean-field) game where users of the OSN are lured by a reward-based scheme to provide the binary (real/fake) signals such that the OSN achieves $(\theta, \delta)$-level of activity identification (AI) - not more than $\delta\$ fraction of non-adversarial users incorrectly judge the real post, and at least $\theta\$ fraction of non-adversarial users identify the fake post as fake. An appropriate warning mechanism is proposed to influence the decision-making of the users such that the resultant game has at least one Nash Equilibrium (NE) achieving AI. We also identify the conditions under which all NEs achieve AI. Further, we numerically illustrate that one can always design an AI game if the normalized difference in the innate identification capacities of the users is at least $1\%$; when desired $\theta = 75\%$.

11:00-11:15

ThA11.5

An LSTM-Based Game Theory Method for Multi-Agent Decision-Making in Highway Scenarios, pp. 2351-2356

Hu, Siyuan

Tongji University

Zhang, Chaojie

Tongji University

Wang, Jun

Tongji University

Decision-making plays a critical role in autonomous driving, connecting the upstream perception task and the downstream planning task. The interaction among vehicles and the uncertainty of driving intentions are two main challenges of lane change decision-making. To meet these challenges, a game theory method based on the LSTM (Long Short-Term Memory) neural network is proposed. The game theory method is adopted to model the interaction among vehicles and the LSTM network is used to precisely fit the complex nonlinear relationship between payoffs and decisions. For highway scenarios with ramps, discretionary and mandatory lane change scenarios are specifically extracted and the lane priority is added to features. The improved GPOSO-DE optimizer is used to accelerate network training and reduce the local optimal solutions. Finally, experiments on real-world dataset NGSIM I-80 show that the prediction accuracy of other vehicles' intentions and the decision-making accuracy of ego vehicles have reached state-of-the-art performance. Moreover, the model is capable of improving the robustness of decision-making and reducing unreasonable jumps effectively.

11:15-11:30

ThA11.6

Distributed Online Generalized Nash Equilibrium Tracking for Prosumer Energy Trading Games, pp. 2357-2364

Xie, Yongkai

Shanghai Jiao Tong University

Wang, Zhaojian

Shanghai Jiao Tong University

Pang, John

California Institute of Technology

Yang, Bo

Shanghai Jiao Tong University

We consider a two-player zero-sum inspection game, in which a limited number of detectors are coordinated in an infrastructure system according to a probability distribution to detect multiple

We consider a two-player zero-sum inspection game, in which a limited number of detectors are coordinated in an infrastructure system according to a probability distribution to detect multiple
Krammer, Christoph
Technical University of Munich

Falconí, Guillermo P.
Technische Universität München

Holzapfel, Florian
Technische Universität München

The interest in multirotor systems has significantly increased over the last decade, with considerable further potential application scenarios in the future. Multiple adaptive control strategies have been developed to account for uncertainties and disturbances during operation. In this paper, we derive an adaptive backstepping position controller by utilizing the tuning functions methodology. This allows compensating for both matched and unmatched disturbances in the system. Asymptotic stability of the reference model is proved by Lyapunov's second method. The derived control laws are implemented and finally validated during flight tests with a hexacopter system.

10:45-11:00
ThA12.4

Command Governor-Based Adaptive Control for Constrained Linear Systems in Presence of Unmodelled Dynamics, pp. 2387-2392
Magnani, Guido
ONERA

dos Reis de Souza, Alex
Onera - the French Aerospace Lab

Cassaro, Mario
ONERA

Biannic, Jean-Marc
ONERA

Evain, Hélène
CNES

Burlion, Laurent
Rutgers, the State University of New Jersey

This paper deals with the control of uncertain constrained linear systems. The plant's dominant dynamics are controlled via a simple linear control law, while uncertainties are handled by an adaptive strategy that appropriately modifies the law by monitoring the system state in accordance with some desired dynamics. The closed-loop system is augmented with a robust command governor scheme to enforce state and input constraints by modifying the reference point-wisely. Thanks to the adaptive law performance guarantees, large uncertainties can be handled and the computational complexity of the governor's optimization problem is limited compared to the standard strategy. Stability and feasibility are discussed. Numerical simulations illustrate the methodology applied to a geostationary satellite. Discussions and future perspectives conclude the paper.

11:00-11:15
ThA12.5

Discrete-Time Adaptive Control of a Class of Nonlinear Systems Using High-Order Tuners, pp. 2393-2398
Fisher, Peter
Massachusetts Institute of Technology

Annaswamy, Anuradha M.
Massachusetts Inst. of Tech

This paper concerns the adaptive control of a class of discrete-time nonlinear systems with all states accessible. Recently, a high-order tuner algorithm was developed for the minimization of convex loss functions with time-varying regressors in the context of an identification problem. Based on Nesterov's algorithm, the high-order tuner was shown to guarantee bounded parameter estimation when regressors vary with time, and to lead to accelerated convergence of the tracking error when regressors are constant. In this paper, we apply the high-order tuner to the adaptive control of a particular class of discrete-time nonlinear dynamical systems. First, we show that for plants of this class, the underlying dynamical error model can be causally converted to an algebraic error model. Second, we show that using this algebraic error model, the high-order tuner can be applied to provably stabilize the class of dynamical systems around a reference trajectory.

11:15-11:30
ThA12.6

Adaptive Static-Output-Feedback Stabilization with Warm-Start, pp. 2399-2404

This paper proposes a hierarchical control architecture to mitigate faults and modeling errors in an engine system. A hybrid approach is used to model the complete engine system with the main cylinder combustion process represented using a neural network model and the rest of the system is modeled using well-studied physics-based analytical equations. A control calibration map that consists of the optimal engine control parameters to maintain the desired engine torque using the minimum fuel consumption rate is generated offline by performing Bayesian optimization on this high-fidelity hybrid engine model. We then use proportional-integral (PI) and extremum seeking (ES) controllers on top of the offline map to compensate for any engine faults and modeling errors for online calibration. The work is motivated by optimally reconfiguring autonomous systems. We test three different scenarios through numerical simulations which require online calibration of the engine control parameters. It is shown that the PI+ES controller can overcome the fault by maintaining the desired torque and also lowers the fuel consumption rate compared to a PI controller.

10:30-10:45
ThA12.3

With the proliferation of distributed generations, traditional passive consumers in distribution networks are evolving into “prosumers”, which can both produce and consume energy. Energy trading with the main grid or between prosumers is inevitable if the energy surplus and shortage exist. To this end, this paper investigates the peer-to-peer (P2P) energy trading market, which is formulated as a generalized Nash equilibrium (GNE). Then, an distributed online algorithm is proposed to track the GNE in the time-varying environment. Its regret is proved to be bounded by a sublinear function of learning time, which indicates that the online algorithm has an acceptable accuracy in practice. Finally, numerical results with six microgrids validate the performance of the algorithm.

ThA12
Adaptive Control I (Regular Session)

Chair: Annaswamy, Anuradha
Massachusetts Inst. of Tech M.

Co-Chair: Burlion, Laurent
Rutgers, the State University of New Jersey

10:00-10:15
ThA12.1
Learning-Based Adaptive Control for Stochastic Linear Systems with Input Constraints, pp. 2365-2370
Siriya, Seth
University of Melbourne

Zhu, Jingge
University of Melbourne

Nesic, Dragan
University of Melbourne

Pu, Ye
The University of Melbourne

We propose a certainty-equivalence scheme for adaptive control of scalar linear systems subject to additive, i.i.d. Gaussian disturbances and bounded control input constraints, without requiring prior knowledge of the bounds of the system parameters, nor the control direction. Assuming that the system is at-worst marginally stable, mean square boundedness of the closed-loop system states is proven. Lastly, numerical examples are presented to illustrate our results.

10:15-10:30
ThA12.2
Adaptive Online Fault Mitigation Using Hierarchical Engine Control, pp. 2371-2378
Chowdhury, Dhrubajit
Palo Alto Research Center

Goyal, Raman
Palo Alto Research Center

Khawale, Raj Pradip
Clemson University

Crawford, Lara S.
Palo Alto Research Center

Rai, Rahul
University at Buffalo, SUNY

This paper proposes a hierarchical control architecture to mitigate faults and modeling errors in an engine system. A hybrid approach is used to model the complete engine system with the main cylinder combustion process represented using a neural network model and the rest of the system is modeled using well-studied physics-based analytical equations. A control calibration map that consists of the optimal engine control parameters to maintain the desired engine torque using the minimum fuel consumption rate is generated offline by performing Bayesian optimization on this high-fidelity hybrid engine model. We then use proportional-integral (PI) and extremum seeking (ES) controllers on top of the offline map to compensate for any engine faults and modeling errors for online calibration. The work is motivated by optimally reconfiguring autonomous systems. We test three different scenarios through numerical simulations which require online calibration of the engine control parameters. It is shown that the PI+ES controller can overcome the fault by maintaining the desired torque and also lowers the fuel consumption rate compared to a PI controller.

10:30-10:45
ThA12.3

Guan, Xin-Ping
Shanghai Jiao Tong University

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ThA12
Adaptive Control I (Regular Session)

Chair: Annaswamy, Anuradha
Massachusetts Inst. of Tech M.

Co-Chair: Burlion, Laurent
Rutgers, the State University of New Jersey

10:00-10:15
ThA12.1
Learning-Based Adaptive Control for Stochastic Linear Systems with Input Constraints, pp. 2365-2370
Siriya, Seth
University of Melbourne

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ThA12.2
Adaptive Online Fault Mitigation Using Hierarchical Engine Control, pp. 2371-2378
Chowdhury, Dhrubajit
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This paper develops an approach to static output feedback under the assumption that a stabilizing static-output-feedback gain is known for an approximate plant model. This approach is motivated by the fact that system identification may be used to obtain an approximate plant model, and optimization can be used to stabilize a static-output-feedback gain. This gain provides the initial guess for the adaptive static-output-feedback control law, which iteratively refines the gain based on the response of the actual system dynamics.

ThA13  
Fast Extremum Seeking Control for a Class of Generalized Hammerstein Systems with the Knowledge of Relative Degree, pp. 2405-2410

Liu, Hengchang  
University of Melbourne
Tan, Ying  
The University of Melbourne
Bacek, Tomislav  
University of Melbourne
Kulic, Dana  
Monash University
Oetomo, Denny Nurjanto  
The University of Melbourne
Manzie, Chris  
The University of Melbourne

This work extends the existing fast extremum seeking control (ESC) for a class of Hammerstein systems to a class of generalized Hammerstein systems, in which the nonlinear affine dynamic system is connected directly after a given cost function. With the relative degree information of the unknown nonlinear dynamics, a new output is generated. The mapping between the new output and the input has two parts. The first part is proportional to the cost function and the second part is related to the state. By inserting a fast dither signal, the proposed ESC can seek the optimum of this cost function without time-scale separation. Our main results show that with proper selection of tuning parameters, this scheme can achieve arbitrarily fast semi-global practical asymptotic (SPA) convergence. Simulation results support the theoretical findings.

10:15-10:30  
Robust Local Stabilization of Nonlinear Systems with Controller-Dependent Norm Bounds: A Convex Approach with Input-Output Sampling, pp. 2411-2416

Cheah, Sze Kwan  
University of Minnesota
Bhattacharjee, Diganta  
The University of Minnesota, Twin Cities
Hemati, Maziar  
University of Minnesota
Caverly, Ryan James  
University of Minnesota

This letter presents a framework for synthesizing a robust full-state feedback controller for systems with unknown nonlinearities. Our approach characterizes input-output behavior of the nonlinearities in terms of local norm bounds using available sampled data corresponding to a known region about an equilibrium point. A challenge in this approach is that if the nonlinearities have explicit dependence on the control inputs, an a priori selection of the control input sampling region is required to determine the local norm bounds. This leads to a "chicken and egg" problem, where the local norm bounds are required for controller synthesis, but the region of control inputs needed to be characterized cannot be known prior to synthesis of the controller. To tackle this issue, we constrain the closed-loop control inputs within the sampling region while synthesizing the controller. As the resulting synthesis problem is non-convex, three semi-definite programs (SDPs) are obtained through convex relaxations of the main problem, and an iterative algorithm is constructed using these SDPs for control synthesis. Two numerical examples are included to demonstrate the effectiveness of the proposed algorithm.

10:30-10:45  
Gain-Scheduled QSR-Dissipative Systems: An Input-Output Approach, pp. 2417-2423

Anderson, Logan  
University of Minnesota
Caverly, Ryan James  
University of Minnesota
Lamerski, Andrew  
University of Minnesota

This letter presents a framework for the gain scheduling of QSR-dissipative systems and quantifies the resulting QSR-dissipative properties of the overall gain-scheduled system. This work constitutes a generalization of prior work in the literature involving the gain scheduling of passive and conic systems, providing a practical extension to non-square QSR-dissipative systems. The derived results are presented for two classes of systems that account for many well-known special cases of QSR-dissipative systems, including passive, conic, and finite L2 gain systems. Special cases of the developed theory are shown to match closely to existing results in the literature. A numerical example is included that demonstrates the benefits of the derived results within the context of gain-scheduled control with a comparison to a passivity-based control.

10:45-11:00  
Nontangency-Based Lyapunov Tests for Convergence in Discrete-Time Dynamical Systems, pp. 2424-2429

Lee, Junsoo  
University of South Carolina
Bhat, Sanjay P.  
Tata Consultancy Services Limited
Haddad, Wassim M.  
Georgia Inst. of Tech
The COVID-19 pandemic has witnessed the role of online social networks (OSNs) in the spread of infectious diseases. The rise in severity of the epidemic augments the need for proper guidelines, but also promotes the propagation of fake news-items. The popularity of a news-item can reshape the public health behaviors and affect the epidemic processes. There is a clear inter-dependency between the epidemic process and the spreading of news-items. This work creates an integrative framework to understand the interplay. We first develop a population-dependent 'saturated branching process' to continually track the propagation of trending news-items on OSNs. A two-time scale dynamical system is obtained by integrating the news-propagation model with SIRS epidemic model, to analyze the holistic system. It is observed that a pattern of periodic infections emerges under a linear behavioral influence, which explains the waves of infection and reinforcement that we have experienced in the pandemic. We use numerical experiments to corroborate the results and use Twitter and COVID-19 data-sets to recreate the historical infection curve using the integrative model.

ThA14
Observers for Linear Systems (Regular Session)
Chair: Anubi, Olugbenga, M Florida State University
Co-Chair: Martinez, Sonia University of California at San Diego

This paper proposes a novel distributed interval observer design for linear time-invariant (LTI) discrete-time systems subject to bounded disturbances. In the proposed observer algorithm, each agent in a networked group, exchanges locally computed framers or interval-valued state estimates with neighbors and coordinates its update via an intersection operation. We show that the proposed framers are guaranteed to bound the true state trajectory of the system by construction, i.e., without imposing any additional assumptions or constraints. Moreover, we provide necessary and sufficient conditions for the collective stability of the distributed observer, i.e., to guarantee the uniform boundedness of the observer error sequence. In particular, we show that such conditions can be tractably satisfied through a constructive and distributed approach. Moreover, we provide an algorithm to verify some structural conditions for a given system, which guarantee the existence of the proposed observer. Finally, simulation results demonstrate the effectiveness of our proposed method compared to an existing distributed observer in the literature.

ThA14.1
Distributed Interval Observers for Bounded-Error LTI Systems, pp. 2444-2449
Khajenejad, Mohammad University of California, San Diego
Brown, Scott University of California, San Diego
Martinez, Sonia University of California at San Diego

ThA14.2
Uncertainty Disturbance Estimator Control for Delayed Linear Systems with Input Constraint
Mirshamsi, Alireza Sharif University of Technology
Nobakhti, Amin Sharif University of Technology

ThA14.3
Functional Observer Design for Parallel Connected Li-Ion Battery: A

ThA14.4
Robust Resilient Signal Reconstruction under Adversarial Attacks, pp. 2456-2462
Zheng, Yu Florida State University
Anubi, Olugbenga, M Florida State University
Mestha, Lalit K. KinetiCor
Achanta, Hema GE Global Research

We consider the problem of signal reconstruction for a system under sparse signal corruption by a malicious agent. The reconstruction problem follows the standard error coding problem that has been studied extensively in the literature. We include a new challenge of robust estimation of the attack support. The problem is then cast as a constrained optimization problem merging promising techniques in the area of deep learning and estimation theory. A pruning algorithm is developed to reduce the "false positive" uncertainty of data-driven attack localization results, thereby improving the probability of correct signal reconstruction. Suitable conditions for the correct reconstruction and the associated reconstruction error bounds are obtained for both exact and inexact attack support estimation. Moreover, a simulation of a water distribution system is presented to validate the proposed techniques.

ThA14.5
ADMM Based Distributed State Observer Design under Sparse Sensor Attacks, pp. 2463-2468
Mary Prinse, Vinaya Indian Institute of Technology Madras
Kalaimani, Rachel Kalpana Indian Institute of Technology Madras

This paper considers the design of a distributed state observer for discrete-time Linear Time Invariant (LTI) systems in the presence of sensor attacks. We assume there is a network of observer nodes, communicating with each other over an undirected graph, each with partial measurements of the output corrupted by some adversarial attack. We address the case of sparse attacks where the attacker targets a small subset of sensors. An algorithm based on Alternating Direction Method of Multipliers (ADMM) is developed which provides an update law for each observer that ensures convergence of each observer node to the actual state asymptotically.

ThA14.6
An Observer-Based Switching Algorithm for Safety under Sensor Denial-Of-Service Attacks, pp. 2469-2474
J. Leudo, Santiago University of California, Santa
This paper proposes a control barrier function (CBF) approach for fast charging of batteries under temperature, charge and terminal voltage constraints. To improve numerical efficiency, we derive a cascade CBF formulation, which divides this safety problem into multiple layers that are easier to formulate and implement. Experimental results demonstrate the effectiveness of the fast charging algorithm, decreasing charging time by $22\%$ when compared to state-of-art constant current, constant voltage (CC-CV) methods and without violating electro-thermal safety constraints.

10:30-10:45  
**Optimal Operation with Robo-Chargers in Plug-In Electric Vehicle Charging Stations (I)**, pp. 2487-2492

- Ju, Yi  
  University of California, Berkeley
- Zeng, Teng  
  University of California, Berkeley
- Allybokus, Zaid  
  TotalEnergies OneTech
- Moura, Scott  
  University of California, Berkeley

Plug-in electric vehicles have seen unprecedented market growth, while charging facility infrastructure is falling behind. Worse still, these limited charging resources are being utilized quite uneconomically - commonly occupied by fully charged PEVs for a long time, known as overstay. In this paper, we propose a charging facility and operation innovation to tackle this challenge. We introduce the idea of Robo-chargers, an automated charger that can proactively rotate among PEVs for charging service. We develop an operation model for management in a mixed-type charger charging station, equipped with both Fixed-chargers and Robo-chargers. The model incorporates the combinatorial nature of vehicle-charger assignments, charging dynamics, and customer waiting behavior in order to maximize the station's revenue. We further reformulate the model as a mixed integer linear programming problem. In numerical studies based on real-world data, we find that incorporating Robo-chargers into a charging station is profitable when heavy overstay occurs, justifying the increased capital cost. For a given budget, a mix of Fixed chargers and Robo-chargers can achieve the best operation performance by balancing robo-charger flexibility, cost, and total charging points.

10:45-11:00  
**Model Predictive Control of a Hybrid Thermal Management System Using State of Charge Estimation (I)**, pp. 2493-2499

- Inyang-Udoh, Uduak  
  Purdue University
- Shanks, Michael  
  Purdue University
- Jain, Neera  
  Purdue University

In this paper, we consider the problem of controlling a hybrid thermal management system (TMS) in which thermal energy may be temporarily rejected to a phase change material (PCM)-based energy storage device. We define the state of charge (SOC) as the amount of thermal energy that can yet be absorbed by the PCM at that instant. The hybrid TMS control objective is to optimally determine when and by how much heat should be rejected to (discharge) the PCM, or removed from (recharge) it during the operation, while meeting some system performance specification. In order to design the feedback control scheme, we require knowledge of the temperature and/or melt fraction across the PCM volume to determine SOC at each sampling instant. Using a graph-based diffusion model of the heat transfer in the PCM volume, we show that the temperature distribution across the PCM may be estimated using a State-Dependent Riccati Equation Estimator (SDRE). Thus, we develop a model predictive control (MPC) scheme in which the SDRE is used to estimate the temperature distribution, and hence the SOC. The MPC is designed to minimize the system's pump energy requirement, maximize the SOC at the end of the operation period, and satisfy critical temperature constraints. Through simulation results, we demonstrate the importance of the SOC estimate in achieving control objectives in a hybrid thermal management system.
Predictive Control with Temperature and Venting Pressure Constraints (I), pp. 2500-2505
Tran, Vivian University of Michigan, Ann Arbor
Siegel, Jason B. University of Michigan
Stefanopoulou, Anna G. University of Michigan

Because thermal events in battery systems can evolve quickly, any response to prevent thermal runaway propagation and re-ignition will need to be fast, including an emergency fast discharge. However, a fast discharge can create internal heat generation and lead to high temperatures where gas generation and venting of the flammable electrolyte can occur. This work formulates the fast discharge as a multi-objective, nonlinear model predictive control problem that leverages an electro-thermo-mechanical model. Constraints are placed on temperature and pressure to avoid cell venting. The controller is applied to simulate a fast discharge of a fully-charged, 4.6 Ah pouch cell under three constraint scenarios. When the maximum temperature is set to 45 degreeC, representative of an upper limit during normal operation, discharging down to 60%SOC took 13 minutes. When the constraint was increased to 80 degreeC, discharging to 60%SOC was four times faster, but the cell vented after 14 minutes. Adding a pressure constraint to the latter case allowed the cell to discharge to 60%SOC equally as fast while also avoiding cell venting in the future, achieving a safe emergency discharge. This is the first work that applies a nonlinear controller with venting considerations to manage abnormal battery behavior for mitigating thermal runaway in a Li-ion battery.

Control of Heterogeneous Battery Energy Storage Systems-Based Microgrid Connected Via Detail-Balanced Communication Topology, pp. 2506-2511
Vaishnav, Vaibhav Indian Institute of Technology, Jodhpur
Sharma, Dushyant IIT (ISM) Dhanbad
Jain, Anoop Indian Institute of Technology, Jodhpur, India

This paper proposes a distributed secondary control for heterogeneous battery energy storage systems (BESSs) to achieve finite-time consensus in frequency and active power while maintaining a balanced energy-level. The proposed scheme incorporates heterogeneity in electrical as well as control aspects and models heterogeneous BESS-based islanded AC microgrid as a multi-agent system with agents interacting according to a detail-balanced topology with heterogeneous edge weights. The finite-time stability of the closed-loop system, under the proposed controllers, is rigorously proved by considering a single composite homogeneous Lyapunov function, thereby calculating an upper limit on convergence time. Efficacy of the proposed controllers is illustrated by simulating a BESS-based microgrid in a Simulink environment.

Control of Floating Wind Energy Systems (Tutorial Session)
Chair: Pao, Lucy Y. University of Colorado Boulder
Co-Chair: Pusch, Manuel Munich University of Applied Sciences
Organizer: Pao, Lucy Y. University of Colorado Boulder
Organizer: Pusch, Manuel Munich University of Applied Sciences
Organizer: Sinner, Michael University of Colorado Boulder
Organizer: Nagamune, Ryozo University of British Columbia
Organizer: Schlief, David Flensburg University of Applied Sciences

Within the rapidly growing wind energy sector, floating offshore wind turbines are expected to be the fastest growing portion. This is largely driven by the immense offshore wind resources that are mostly over deep water, where fixed-bottom concepts become cost-prohibitive. However, compared to fixed-bottom wind turbines, floating wind turbines are more dynamic and exhibit potential instabilities, which requires advanced control technologies to ensure a safe and efficient operation. Beyond their existing objectives of maximizing power production while minimizing structural loads, floating wind turbine controllers must also avoid large platform oscillations and accommodate ocean wave and current disturbances. This paper provides an overview of the challenges and opportunities in the control of floating offshore wind energy systems.

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A Tutorial on Lidar-Assisted Control for Floating Offshore Wind Turbines (I), pp. 2530-2535
Stockhouse, David University of Colorado Boulder
Pao, Lucy Y. University of Colorado Boulder

Lidar-assisted control is very promising to reduce the cost of energy for large floating offshore wind turbines by reacting proactive to wind changes. This paper presents a tutorial on how to develop and test a lidar-assisted controller using examples of a 15 MW floating reference wind turbine.

Floating Offshore Wind Farm Control Via Turbine Repositioning with Aerodynamic Force (I), pp. 2542-2547
Niu, Yue The University of British Columbia
Lathi, Parth Prashant Indian Institute of Technology Madras
Nagamune, Ryozo University of British Columbia
This paper overviews a wind farm control technique via turbine repositioning, which is exclusively applied to floating offshore wind turbines. The wind turbines are repositioned to modify the wind farm layout based on the wind condition and the power demand, in order to maximize the wind farm efficiency. The repositioning mechanism which manipulates the aerodynamic force by means of conventional wind turbine control inputs is explained. Potential advantages of the turbine repositioning for wind farm control are demonstrated in simulations using the medium-fidelity wind farm simulator FAST. Farm developed by the National Renewable Energy Laboratory (NREL) and an example floating offshore wind farm which consists of three NREL 5MW semi-submersible baseline wind turbines. Finally, potential future research directions in this wind farm control technique are provided.

Chair: Oishi, Meeko
Co-Chair: Ahn, Heejin

14:30-14:34
ThB01.1

Data-Driven Stochastic Optimal Control Using Kernel Gradients, pp. 2548-2553
Thorpe, Adam
Gonzales, Jake
Oishi, Meeko
University of New Mexico
University of New Mexico
University of New Mexico

We present an empirical, gradient-based method for solving data-driven stochastic optimal control problems using the theory of kernel embeddings of distributions. By embedding the integral operator of a stochastic kernel in a reproducing kernel Hilbert space (RKHS), we can compute an empirical approximation of stochastic optimal control problems, which can then be solved efficiently using the properties of the RKHS. Existing approaches typically rely upon finite control spaces or optimize over policies with finite support to enable optimization. In contrast, our approach uses kernel-based gradients computed using observed data to approximate the cost surface of the optimal control problem, which can then be optimized using gradient descent. We apply our technique to the area of data-driven stochastic optimal control, and demonstrate our proposed approach on a linear regulation problem for comparison and on a nonlinear target tracking problem.

14:34-14:38
ThB01.2

Safety Embedded Stochastic Optimal Control of Networked Multi-Agent Systems Via Barrier States, pp. 2554-2559
Song, Lin
Zhao, Pan
Wan, Neng
Hovakimyan, Naira
University of Illinois
University of Illinois
University of Illinois at Urbana-Champaign
Zhejiang University of Technology

This paper presents a novel approach for achieving safe stochastic optimal control in networked multi-agent systems (MASs). The proposed method incorporates barrier states (BaSs) into the system dynamics to embed safety constraints. To accomplish this, the networked MAS is factorized into multiple subsystems, and each one is augmented with BaSs for the central agent. The optimal control law is obtained by solving the joint Hamilton-Jacobi-Bellman (HJB) equation on the augmented subsystem, which guarantees safety via the boundedness of the BaSs. The BaS-based optimal control technique yields safe control actions while maintaining optimality. The safe optimal control solution is approximated using path integrals. To validate the effectiveness of the proposed approach, numerical simulations are conducted on a cooperative UAV team in two different scenarios.

14:38-14:42
ThB01.3

Belief State Actor-Critic Algorithm from Separation Principle for POMDP, pp. 2560-2567
Yang, Yujie
Jiang, Yuxuan
Chen, Jianyu
Li, Shengbo Eben
Gu, Ziqing
Yin, Yuming
Zhang, Qian
Yu, Kai
Tsinghua University
Tsinghua University
Tsinghua University
Tsinghua University
Tsinghua University
Zhejiang University of Technology
Horizon Robotics
Horizon Robotics

Partially observable Markov decision process (POMDP) is a general framework for decision making and control under uncertainty. A large class of POMDP algorithms follows a two-step approach, in which the first step is to estimate the belief state, and the second step is to solve for the optimal policy taking the belief state as input. The optimality guarantee of their combination relies on the so-called separation principle. In this paper, we propose a new path to prove the separation principle for infinite horizon general POMDP problems under both discounted cost and average cost. We use a nominal horizon to split a virtual objective function into two parts and prove that it converges to the optimal state-value function. Based on the separation principle, we design a two-step POMDP algorithm called Belief State Actor-Critic (BSAC), which first estimates the belief state and then takes it as input to solve for the optimal policy. The belief state is learned using variational inference, and the policy is learned through model-based reinforcement learning. We test our algorithm in a partially observable multi-lane autonomous driving task. Results show that our algorithm achieves lower costs than the baselines and learns safe, efficient, and smooth driving behaviors.

14:42-14:46
ThB01.4

Chance-Constrained Optimal Control with Imperfect Perception, pp. 2568-2573
Kim, BeomJun
Ahn, Heejin
SNU
KAIST

Autonomous systems are required to operate in different environments, but recognizing the current environment is often challenging. For example, an autonomous vehicle should stop or obey a speed limit according to a traffic sign, but state-of-the-art perception modules (e.g., neural networks) do not guarantee the correctness of their reading of the traffic sign. Considering such uncertain outputs of a perception module, which in effect determines modes, we propose a chance-constrained control formulation that with high probability guarantees the satisfaction of a set of constraints associated with the possible modes. To do this, we present a method based on the Bayes rule and sampling to calculate the probability of each mode. We prove that our approach can ensure satisfying constraints of novel situations, which have not been used during training of the perception module. Also, to account for the error due to limited data, we present a robust formulation that guarantees constraint satisfaction with high confidence. In an autonomous vehicle example, we train a neural network that classifies traffic signs and show that given each output of the neural network, our motion planning approach guarantees the constraint satisfaction with high probability.

14:46-14:50
ThB01.5

Parameterized Input Inference for Approximate Stochastic Optimal Control, pp. 2574-2579
Syed, Shababz Peeraan Qadri
Bai, He
Oklahoma State University
Oklahoma State University

Probabilistic inference approaches to stochastic optimal control have attracted significant interest from researchers in the past decade. Existing inference-based optimal control approaches are limited to linear controllers in a finite-horizon model-based setting. Since nonlinear systems typically admit nonlinear optimal controllers, linear
controllers may yield sub-optimal trajectories when applied to nonlinear systems. In this paper, we propose a new Expectation-Maximization (EM) based inference algorithm for stochastic optimal control. The algorithm employs nonlinear basis functions to infer nonlinear controllers. We formulate the estimation problem of optimal control as a parameter inference problem. We demonstrate the effectiveness of the algorithm on a simulated nonlinear oscillator system for nonlinear control and a linear thermal system for structured control.

14:50-14:54   ThB01.6
**A Dual-Control Effect Preserving Formulation for Nonlinear Output-Feedback Stochastic Model Predictive Control with Constraints**, pp. 2580-2585
Messerer, Florian  
Baumgärtner, Katrin  
Diehl, Moritz  
University of Freiburg  
University of Freiburg  
University of Freiburg

In this paper we propose an formulation for approximate constrained nonlinear output-feedback stochastic model predictive control. Starting from the ideal but intractable stochastic optimal control problem (OCP), which involves the optimization over output-dependent policies, we use linearization with respect to the uncertainty to derive a tractable approximation which includes knowledge of the output model. This allows us to compute the expected value for the outer functions of the OCP exactly. Crucially, the dual control effect is preserved by this approximation. In consequence, the resulting controller is aware of how the choice of inputs affects the information available in the future which in turn influences subsequent controls. Thus, it can be classified as a form of implicit dual control.

14:54-14:58   ThB01.7
**Covariance Steering of Discrete-Time Linear Systems with Mixed Multiplicative and Additive Noise**, pp. 2586-2591
Balci, Isin M  
Bakolas, Efstathios  
The University of Texas at Austin  
The University of Texas at Austin

In this paper, we study the covariance steering (CS) problem for discrete-time linear systems subject to multiplicative and additive noise. Specifically, we consider two variants of the CS problem. The goal of the first problem, which is called the exact CS problem, is to steer the mean and covariance of the state process to their desired values in finite time. In the second problem, which is called the "relaxed" CS problem, the covariance assignment constraint is relaxed into a positive semi-definite constraint. We show that after applying suitable variable transformations and constraint relaxations, the relaxed CS problem can be cast as an equivalent convex semi-definite program (SDP). Furthermore, we propose a two-step solution procedure for the exact CS problem based on the relaxed problem formulation which returns a feasible solution, if there exists one. Finally, results from numerical experiments are provided to show the efficacy of the proposed solution methods.

14:58-15:02   ThB01.8
**Existence of Unique Invariant Measure and Ergodic Property in AIMD-Based Multi-Resource Allocation**, pp. 2592-2598
Alam, Syed Ejgal  
Shukla, Dhireendra  
University of New Brunswick  
University of New Brunswick

Distributed resource allocation arises in many application domains, such as smart energy systems, intelligent transportation systems, cloud computing, edge computing, etc. To realize many of these applications, agents in a network may require multiple shared resources to complete a task and aim to maximize the network utility. Additionally, they may demand resources based on their preferences. Furthermore, they may not wish to share their cost functions, partial derivatives of the cost functions, etc., with other agents or a central server; however, they share their resource demands with the central server that aggregates the demands and sends one-bit resource-capacity constraint notification in the network. The single resource allocation algorithms are inefficient and provide sub-optimal solutions for multi-resource allocations, especially when the cost functions are multi-variate and non-separable. We present additive increase and multiplicative decrease algorithm (AIMD)-based distributed solutions for multi-resource allocation. We formulate the resource allocation problem over finite window sizes and model the system as a homogenenous Markov chain with place-dependent probabilities. We show that the time-averaged allocations over the finite window size converge to a unique invariant measure. We also show that the ergonomic property holds for the model.

15:02-15:06   ThB01.9
Priore, Shawn  
Bidram, Ali  
Oishi, Meeko  
University of New Mexico  
University of New Mexico  
University of New Mexico

We propose an open loop control scheme for linear systems with time-varying random elements in the state matrix. This paper focuses on joint chance constraints for potentially time-varying target sets. Under assumption of finite and known expectation and variance, we use the one-sided Vysochanskij-Petunin inequality to reformulate joint chance constraints into a tractable form. We demonstrate our methodology on a two-bus power system with stochastic load and wind power generation. We compare our method with situation approach. We show that the proposed method had superior solve times and favorable optimally considerations.

15:06-15:10   ThB01.10
**Distributionally Robust Covariance Steering with Optimal Risk Allocation**, pp. 2607-2614
Renganathan, Venkatraman  
Piliptsivosky, Joshua  
Tsiotras, Panagiotis  
Lund University  
Georgia Institute of Technology  
Georgia Institute of Technology

This article extends the optimal covariance steering (CS) problem for discrete time linear stochastic systems modeled using moment-based ambiguity sets. To hedge against uncertainty in the state distributions while performing covariance steering, distributionally robust risk constraints are employed during the optimal allocation of the risk. Specifically, a distributionally robust iterative risk allocation (DR-IRA) formalism is used to solve the optimal risk allocation problem for the CS problem using a two-stage approach. The upper-stage of DR-IRA is a convex problem that optimizes the risk, while the lower-stage optimizes the controller with the new distributionally robust risk constraints. The proposed framework results in solutions that are robust against arbitrary distributions in the considered ambiguity set. Finally, we demonstrate our proposed approach using numerical simulations. Addressing the covariance steering problem through the lens of distributional robustness marks the novel contribution of this article.

**Predictive Control for Nonlinear Systems (RI)**  
**Data-Driven Model Predictive Control for Drop Foot Correction**, pp. 2615-2620
Singh, Mayank  
Sharma, Nitin  
North Carolina State University  
North Carolina State University

Functional Electrical Stimulation (FES) is an effective method to restore the normal range of ankle motion in people with Drop Foot. This paper aims to develop a real-time, data-driven MPC scheme of FES for drop foot correction (DFC). We utilize a Koopman operator-based framework for system identification required for setting up the MPC scheme. We use inertial measurement units
(IMUs) for collecting the foot pitch and roll rate state information to build an approximate linear predictor. In doing so, we also account for the implicit muscle actuation dynamics which are dependent on the activation and fatigue levels of the Tibialis Anterior muscle. Hence, contribution and develop a relationship between FES input parameters and ankle motion, tailored to an individual user. Using the Koopman operator we can fully capture the nonlinear dynamics through an infinite dimensional linear operator describing the evolution of functions of state space. The approximation, although computationally expensive, leads to reformulating the optimization problem as a quadratic program for the MPC problem. Further, we show the closed-loop system’s recursive feasibility and asymptotic stability analysis. Simulation and experimental results from a subject with Multiple Sclerosis show the effectiveness of the data-driven MPC scheme of FES for DFC.

14:34-14:38
Self-Stabilizing Economic Nonlinear Model Predictive Control of Modular Membrane Reactor Systems, pp. 2621-2626
Dinh, San
Lin, Kuan-Han
Lima, Fernando V.
Biegler, Lorenz T.
West Virginia University
Carnegie Mellon University
West Virginia University
Carnegie Mellon Univ
In recent years, economic nonlinear model predictive control (eNMPC) has emerged as a viable alternative for distributed control systems. Because eNMPC involves the solution of a dynamic programming problem, it provides the control actions that lead the system to the most economical transient operations, which may be periodic instead of converging to a steady state (angle2012). Since eNMPC has been typically used for stand-alone unit operations instead of plantwide control, an unstable operation of a unit may lead to undesirable operations of downstream units. This work proposes a self-stabilizing eNMPC formulation, in which a pre-calculated steady-state condition is not required. Lyapunov functions with embedded steady-state optimal conditions are employed as additional constraints of the eNMPC formulation, so that the asymptotically stable behavior can be achieved. The performance of the proposed eNMPC is demonstrated with two case studies of a membrane reactor for natural gas utilization. In the first case study, the proposed eNMPC can effectively bring the system toward the feasible steady-state optimal operation. In the second case study, a cost-optimal steady-state does not exist due to the time-varying disturbance, and the closed-loop behavior is shown to be bounded if the disturbance is also bounded.

14:38-14:42
Computationally Efficient Data-Driven MPC for Agile Quadrotor Flight, pp. 2627-2632
Choo, Wonoo
Kayacan, Erkan
University of Queensland
University of Oklahoma
This paper develops computationally efficient data-driven model predictive control (MPC) for Agile quadrotor flight. Agile quadrotors in high-speed flights can experience high levels of aerodynamic effects. Modeling these turbulent aerodynamic effects is a cumbersome task and the resulting model may be overly complex and computationally infeasible. Combining Gaussian Process (GP) regression models with a simple dynamic model of the system has demonstrated significant improvements in control performance. However, direct integration of the GP models to the MPC pipeline poses a significant computational burden to the optimization process. Therefore, we present an approach to separate the GP models to the MPC pipeline by computing the model corrections using reference trajectory and the current state measurements prior to the online MPC optimization. This method has been validated in the Gazebo simulation environment and has demonstrated of up to 50% reduction in trajectory tracking error, matching the performance of the direct GP integration method with improved computational efficiency.

14:42-14:46
Numerical Integration for Nonlinear Model Predictive Control of a Fuel Cell System, pp. 2633-2639
Schmitt, Lukas Rudolf
Abel, Dirk
RWTH Aachen University
RWTH Aachen University
A two-stage nonlinear model predictive controller for the task of power tracking with a fuel cell system is presented. In the first stage, an economic optimization problem is solved for optimal steady states and inputs, which are tracked in the subsequent stage. For the dynamic tracking using MPC, a nonlinear, stiff ordinary differential equation must be discretized. A numerical study of different integration schemes reveals that the first order implicit Runge-Kutta integration scheme is appropriate for discretization. Compared to a high accuracy numerical integration and the standard explicit Runge-Kutta method of order four, the computation time on embedded hardware can be reduced by more than 30% and 10% respectively without loss in closed-loop cost.

14:46-14:50
Vibrational Stabilization of the Kapitza Pendulum Using Model Predictive Control with Constrained Base Displacement, pp. 2640-2645
Ahrazoglu, Mehmet Akif
Islam, Syed Aseem Ul
Goel, Ankit
University of Michigan, Ann-Arbor
University of Michigan
University of Maryland Baltimore County
Berstein, Dennis S.
Univ. of Michigan
It is well known that, for some systems, stabilization can be achieved by open-loop control in the form of high-frequency vibrations. Vibrational control is attractive since it requires no sensors. On the other hand, however, vibrational control requires careful selection of the frequency and amplitude of the input. The present paper is aimed at understanding the robustness of vibrational control and the required control effort by applying nonlinear model predictive control to the classical Kapitza pendulum. A numerical investigation shows that closed-loop control using nonlinear model predictive control is significantly more efficient than open-loop vibrational control with respect to signal power.

14:50-14:54
Soft-Minimum Barrier Functions for Safety-Critical Control Subject to Actuation Constraints, pp. 2646-2651
Rabiee, Pedram
Hoagg, Jesse B.
University of Kentucky
University of Kentucky
This paper presents a new control approach for guaranteed safety (remaining in a safe set) subject to actuator constraints (the control is in a convex polytope). The control signals are computed using real-time optimization, including linear and quadratic programs subject to signal power. The control method relies on a new soft-minimum barrier function that is constructed using a finite-time-horizon prediction of the system trajectories under a known backup control. The main result shows that: (i) the control is continuous and satisfies the actuator constraints, and (ii) a subset of the safe set is forward invariant under the control. We also demonstrate this control on numerical simulations of an inverted pendulum and a double-integrator ground robot.

14:54-14:58
Choi, Kyunghwan
Kim, Wooyong
GIST
Hoseo University
The predictive energy management (PEM) problem for hybrid electric powertrains is challenging to solve in real time, mainly due to the nonconvexity from the battery state of energy (SOE) model, which is nonlinear. This study proposes a control-oriented battery model consisting of a stochastic linear SOE model and a quadratic power
loss model to realize real-time PEM. The stochastic linear model describes the SOE trajectory from an average point of view. The quadratic power loss model describes the nonlinear power loss that the stochastic linear SOE model cannot consider. By replacing the nonlinear SOE model with the control-oriented model, the PEM problem is reformulated into quadratic programming (QP), which can be easily solved in real time by a QP solver. Simulation results obtained using a fuel cell-powered unmanned aerial vehicle (UAV) show that the proposed model predicts the trend of the SOE trajectory well, even for long prediction horizons (maximum of 750 s). In addition, PEM based on the proposed model results in near-optimal performance (0.36% difference from the global solution) with real-time capability (solved within 0.27 s).

GP-based hybrid residual dynamics model, which switches between different residual models across regions of the state and input space of a dynamics model. We also design a Model Predictive Controller (MPC) that can leverage this hybrid residual dynamics model to ensure probabilistic constraint satisfaction. Through numerical studies, we demonstrate how the proposed controller outperforms a baseline single GP-based MPC baseline. Simulations show a 45% improvement in control performance in the best-case and probability of constraint violations within the desired threshold in contrast to the baseline approach.

ThB03
Autonomous Systems (Regular Session)
Sapphire EF
Chair: Verginis, Christos
Co-Chair: Lindemann, Lars
University of Southern California

Safe and Quasi-Optimal Autonomous Navigation in Sphere Worlds, pp. 2678-2683
Cheniouni, Ishak
Lakehead University
Tayebi, Abdelhamid
Lakehead University
Berkane, Soulaime
University of Quebec in Outaouais

We propose a continuous feedback control strategy that steers a point-mass vehicle safely to a desired destination, in a quasi-optimal manner, from almost all initial conditions in an $n$-dimensional Euclidean space cluttered with spherical obstacles. The main idea consists in avoiding each obstacle via the shortest path within the cone enclosing the obstacle, and moving straight towards the target when the vehicle has a clear line of sight to the target location. The proposed control strategy ensures safe navigation with almost global asymptotic stability of the equilibrium point at the target location. Simulation results, illustrating the effectiveness of the proposed approach, are presented.

ThB03.2
Bearing-Only Formation Control Using Sign-Elevation Angle Rigidity for Avoiding Formation Ambiguities, pp. 2684-2689
Garainayak, Chimmay
Indian Institute of Technology
Bombay
Mukherjee, Dwaiypayan
Indian Institute of Technology
Bombay

Flip, flex, and reflection ambiguities, which can arise in bearing-only formation control with elevation angle rigid configurations, are addressed in this paper. Elevation angle rigidity achieves formation control in agents' local co-ordinate system using bearing-only sensors, without any orientation synchronization or estimation algorithm. Considering elevation angle constraints to determine the formation shape, and then using a gradient-based control law offers the benefit of a co-ordinate free control. However, flip, flex, and reflection ambiguities might be present in the final formation shape. To tackle this, we first develop sign-elevation angle rigidity theory to uniquely (locally) characterize formation shapes up-to a translation and rotation using elevation angle and signed area/volume constraints. Thereafter, a formation control law is proposed (for 2$\times$2-D and 3$\times$3-D) using bearing-only information for single integrator systems, and local exponential stability is proved for formation tracking error. Finally, simulations validate the presented results.

ThB03.3
Linear-Sized Sensor Scheduling Using Regret Minimization, pp. 2690-2696
Vafaei, Reza
Northeastern University
Siami, Milad
Northeastern University

In this paper, we investigate the problem of time-varying sensor selection for linear time-invariant (LTI) dynamical systems. We develop a framework to design a sparse sensor schedule for a given
large-scale LTI system with guaranteed performance bounds using a learning-based algorithm. We show how the observability Gramian matrix of an LTI system can be interpreted as the sum of rank-1 matrices indicating the contribution of the available sensors distributed in time. We then employ a regret minimization framework over density matrices to sparsify this sum of rank-1 matrices to approximate fully sensed LTI dynamics up to a multiplicative factor in some certain observability senses. Our main result provides a linear-sized (in dimension of system) sensor schedule that on the average activates only a constant number of sensors at each time step and significantly improves the previous linearithmic results. Our results naturally apply to the dual problem of actuator selection where we present the conditions necessary to generate unbounded trajectories depending on both the control inputs and the initial conditions. We also present the conditions necessary to generate a complete characterisation of agent trajectories in the given framework with the linear speed constrained to be positive. We present a two case studies to illustrate how the proposed temporal robustness accounts for timing uncertainties.

We develop a cooperative sampling-based motion planning algorithm for two autonomous agents under coupled tasks expressed as signal temporal logic constraints. The algorithm builds incrementally two spatio-temporal trees, one for each agent, by sampling points in an extended space, which consists of a compact subset of the time domain and the physical space of the agents. The trees are built by checking if newly sampled points form edges in time and space that satisfy certain parts of the coupled task. Therefore, the constructed trees represent time-varying trajectories in the agents’ state space that satisfy the task. The algorithm is distributed in the sense that the agents build their trees individually by communicating with each other. The proposed algorithm inherits the properties of probabilistic completeness and computational efficiency of the original sampling-based procedures.

The paper focuses on the generation of planar trajectories using an autonomous agent modelled as a unicycle. The agent can be controlled using its linear and angular speeds. It is assumed that only range information is available to the agent with respect to a stationary point, known as the target. The latter could be representative of any beacon, a building of interest or a landmark in real world scenarios. Both of the speeds are designed as continuous functions of range information available to the agent with respect to the target. The former speed is adjusted based on control input errors. Moreover, the concurrent NN-based actor generates the optimal control input, and its weights are adjusted based on control input errors. The critic weights are tuned using the hybrid technique, whose weights are updated once at the sampling instants and in an iterative manner over finite times within the sampling instants. The proposed hybrid technique helps accelerate the convergence of the approximated value function to its actual value, which makes the optimal policy attain quicker. A two-layer NN-based actor generates the optimal control input, and its weights are adjusted based on control input errors. Moreover, the concurrent learning method is utilized to ease the requirement of persistent excitation. Further, the Lyapunov method investigates the stability of the closed-loop system. Finally, the proposed method is evaluated on a two-link robot arm and demonstrates promising results.

Many modern autonomous systems, particularly multi-agent systems, are time-critical and need to be robust against timing uncertainties. Previous works have studied left and right robustness of signal temporal logic specifications by considering time shifts in the predicates that are either only to the left or only to the right. We propose a combined notion of temporal robustness which simultaneously considers left and right time shifts. For instance, in a scenario where a robot plans a trajectory around a pedestrian, this combined notion can now capture uncertainty of the pedestrian arriving earlier or later than anticipated. We first derive desirable properties of this new notion with respect to left and right time shifts and then design control laws for linear systems that maximize temporal robustness using mixed-integer linear programming. Finally, we present two case studies to illustrate how the proposed temporal robustness accounts for timing uncertainties.
This paper proposes an algorithm for solving perturbed dynamic programs, where first-order corrections are applied to a pre-computed optimal strategy and its corresponding value function using local quadratic approximation. The technique is developed to handle perturbations of external inputs and parameters affecting system dynamics, objective and constraint functions, allowing the application to a wide variety of perturbed problems. The method is applied to the energy optimization of an electric vehicle thermal management system, formulated as a constrained dynamic program where external conditions and target set-point are perturbed from their nominal values. Simulations result in 80% reduction in computation time from a Dynamic Programming (DP) solution, with only minimal effect on the overall controller performance.

15:15-15:30

Min-Max and Stat Game Representations for Nonlinear Optimal Control Problems, pp. 2733-2738

Dower, Peter M.  
University of Melbourne

McEneaney, William M.  
Univ. California San Diego

Zheng, Yifei  
University of California San Diego

A finite horizon nonlinear optimal control problem is considered for which the associated Hamiltonian satisfies a uniform semiconcavity property with respect to its state and costate variables. It is shown that the value function for this optimal control problem is equivalent to the value of a min-max game, provided the time horizon considered is sufficiently short. This further reduces to maximization of a linear functional over a convex set. It is further proposed that the min-max game can be relaxed to a type of stat (stationary) game, in which no time horizon constraint is involved.

15:30-15:45

Cooperative Control of a Hybrid Exoskeleton Using Optimal Time Varying Impedance Parameters During Stair Ascent, pp. 2739-2744

Iyer, Ashwin  
North Carolina State University

Singh, Mayank  
North Carolina State University

Sharma, Nitin  
North Carolina State University

Potentially, cooperative control of functional electrical stimulation (FES) and electric motors in a hybrid exoskeleton can perform stair ascent while adapting to a user's locomotion. Towards this goal, it would be essential to determine the time-varying impedance model parameters of each user while ensuring the stability of the closed loop system. While some previous studies address the stability problem when estimating time-varying impedance model parameters, constraints on the parameters to their physiological values are not guaranteed. In this paper, we develop a model predictive control (MPC) based approach to prescribe physiologically constrained time-varying stiffness and damping parameters for an impedance model. A terminal cost and controller for the stiffness and damping are designed to ensure the MPC problem is recursively feasible, satisfy physiological constraints, and is asymptotically stable. Another MPC-based cooperative control approach is then used to ensure that the knee joint follows the knee trajectory generated via the impedance model with optimized parameters. Simulations results show foot, knee joint, and impedance model tracking while allocating inputs between FES and motors during stair ascent and adequate foot clearance and placement.

15:45-16:00

Incentivizing Local Controllability in Optimal Trajectory Planning, pp. 2745-2750

Skoraczynski, Antoni Z.  
The University of Melbourne

Manzie, Chris  
The University of Melbourne

Dower, Peter M.  
The University of Melbourne

Controllability metrics are used to determine or incentivize the ease with which a system can be driven to a specified target. Such metrics stemming from the controllability gramian are currently used to analyse the local controllability of nonlinear systems about precomputed trajectories. This paper introduces an alternative application of these metrics to generate an optimal trajectory that directly incentivises the local controllability of a nonlinear system. Such optimal trajectory design techniques would be useful for reducing the additional control energy requirement necessary to achieve control objective satisfaction in the presence of unmodelled disturbances. We present an approach in which the LTV controllability gramian is used to construct an augmented optimal control problem that incentivises the local controllability of a nonlinear system about the optimal trajectory. A modified form of Zermelo's boat problem is used to demonstrate the approach, showing that trajectories generated by solution of the augmented optimal control problem require the system to expend less additional control energy to recover the optimal terminal state following perturbation due to an unmodelled disturbance.

14:30-14:45

Exploring the Use of Deep Learning in Task-Flexible ILC, pp. 2751-2756

Vinjarapu, Anantha Sai  
Hariharan

Broens, Yorick  
Eindhoven University of Technology

Butler, Hans  
ASML

Tóth, Roland  
Eindhoven University of Technology

Growing demands in today's industry results in increasingly stringent performance and throughput specifications. For accurate positioning of high-precision motion systems, feedforward control plays a crucial role. Nonetheless, conventional model-based feedforward approaches are no longer sufficient to satisfy the challenging performance requirements. An attractive method for systems with repetitive motion tasks is iterative learning control (ILC) due to its superior performance. However, for systems with non-repetitive motion tasks, ILC is (generally) not applicable, (despite of some recent promising advances). In this paper, we aim to explore the use of deep learning to address the task flexibility constraint of ILC. For this purpose, a novel Task Analogy based Imitation Learning (TAIL)-ILC approach is developed. To benchmark the performance of the proposed approach, a simulation study is presented which compares the TAIL-ILC to classical model-based feedforward strategies and existing learning-based approaches, such as neural network based feedforward learning.

14:45-15:00

Reinforcement Learning-Based Robust Tracking Control Application to Morphing Aircraft, pp. 2757-2762

Yang, Zhicheng  
Tsinghua University

Tan, Junbo  
Tsinghua University

Wang, Xueqian  
Tsinghua University

Yao, Zongxin  
Shenyang Aircraft Design and Research Institute, China

Liang, Bin  
Tsinghua University

Morphing aircraft is a key component of intelligent control of aircraft. In this paper, a complete framework and process are established to model, analyze and control a morphing aircraft, so that the aircraft can achieve the tracking ability for a certain trajectory. In the control framework, the decoder method is used to reduce the size
of the value function network of reinforcement learning, which leads to that the learning becomes easier to converge and the calculation speed is faster. First, the aircraft is designed by using CATIA software and 3D modeled. Then, the different variants of the morphing aircraft were imported into ansys—fluent for force analysis. Finally, a real physical model is built according to the obtained dynamics data, and a complete reinforcement learning-based control algorithm is proposed to realize the trajectory tracking of the morphing aircraft.

15:00-15:15 ThB06.3
A Novel Entropy-Maximizing TD3-Based Reinforcement Learning for Automatic PID Tuning, pp. 2763-2768
Chowdhury, Myisha Ahmed
Lu, Qiugang (Jay)

Proportional-integral-derivative (PID) controllers have been widely used in the process industry. However, the satisfactory control performance of a PID controller depends strongly on the tuning parameters. Conventional PID tuning methods require extensive knowledge of the system model, which is not always known especially in the case of complex dynamical systems. In contrast, reinforcement learning-based PID tuning has gained popularity since it can treat PID tuning as a black-box problem and deliver the optimal PID parameters without requiring explicit process models. In this paper, we present a novel entropy-maximizing twin-delayed deep deterministic policy gradient (EMTD3) method for automating the PID tuning. In the proposed method, an entropy-maximizing stochastic actor is employed at the beginning to encourage the exploration of the action space. Then a deterministic actor is deployed on local exploitation and discover the optimal solution. The incorporation of the entropy-maximizing term can significantly improve the sample efficiency and assist in fast convergence to the global solution. Our proposed method is applied to the PID tuning of a second-order system to verify its effectiveness in improving the sample efficiency and discovering the optimal PID parameters compared to traditional TD3.

15:15-15:30 ThB06.4
Towards Personalized Plasma Medicine Via Data-Efficient Adaptation of Fast Deep Learning-Based MPC Policies, pp. 2769-2775
Chan, Kimberly J
Makrygiorgos, Georgios
Mesbah, Ali

Plasma medicine has emerged as a promising approach for treatment of biofilm-related and virus infections, assistance in cancer treatment, and treatment of wounds and skin diseases. Despite advances in learning-based and predictive control of plasma medical devices, there remains major challenges towards personalized and point-of-care plasma medicine. In particular, an important challenge arises from the need to adapt control policies after each treatment using (often limited) observations of therapeutic effects that can only be measured in-between treatments. Control policy adaptation is necessary to account for variable characteristics of plasma and target surfaces across different subjects and treatment scenarios, thus personalizing the plasma treatment to enhance its efficacy. To this end, this paper presents a data-efficient, “globally” optimal strategy to adapt deep learning-based controllers that can be readily embedded on resource-limited hardware for portable medical devices. The proposed strategy utilizes multi-objective Bayesian optimization (MOBO), a derivative-free, “global” optimization method, to use observations of closed-loop performance measures in order to adapt parameters of a deep neural network (DNN)-based control laws. The proposed strategy for adaptive DNN-based control is demonstrated experimentally on a cold atmospheric plasma jet with prototypical applications in plasma medicine.

15:30-15:45 ThB06.5
Novelty Search for Neuroevolutionary Reinforcement Learning of Deceptive Systems: An Application to Control of Colloidal Self-Assembly, pp. 2776-2781
O'Leary, Jared
Khare, Mira
Mesbah, Ali

Colloidal self-assembly systems are generally difficult to control due to their highly nonlinear and stochastic dynamics and sparse rewards. These systems are also inherently deceptive, as successful control policies must be able to smooth out unavoidable defects and therefore temporarily move farther away from their goal in order to eventually realize the desired goal. This paper investigates the viability of evolutionary reinforcement learning (RL) based on novelty search, wherein behavioral novelty alone is used to learn control policies that can systematically mitigate deceptive dynamics. As such, for stochastic nonlinear systems that are prone to a deceptive behavior, novelty search is a promising alternative to the widely used objective search RL, where merely progress towards a pre-defined goal is used to learn and update control policies. In this work, we pair novelty search RL with a complexifying algorithm that simultaneously learns the neural network architecture and parameters of a control policy. This complexifying algorithm principles the novelty search by ensuring that simple behaviors must be discovered before more complex ones. We evaluate the performance of evolutionary RL based on objective search and novelty search on a benchmark in-silico colloidal self-assembly problem.

15:45-16:00 ThB06.6
Zhai, Lijing
Fotiadis, Filippos
Vamvoudakis, Kyriakos G.
Hugues, Jerome

In this paper, we study the impact of clock offsets among different components of cyber-physical systems on data-driven off-policy reinforcement learning (RL) for linear quadratic regulation (LQR). Our results show that under certain conditions the control policies generated by data-driven off-policy RL with clock offsets are stabilizing policies. With clock offsets what directly influences the learning behavior is not only the values of clock offsets but also the dynamics change caused by clock offsets. In particular, larger values of clock offsets do not necessarily lead to non-stabilizing policies. The proposed conclusions are illustrated by numerical simulations.

ThB07
Sampled-Data Control (Regular Session)
Chair: Avestruz, Al-Thaddeus
Co-Chair: Kim, Junsoo

14:30-14:45 ThB07.1
Model-Free Undetectable Attacks on Linear Systems Using LWE-Based Encryption, pp. 2788-2793
Alisic, Rajad
Kim, Junsoo
Sandberg, Henrik

We show that the homomorphic property, a desired property in encrypted control, can lead to failure in the cyber defense of a dynamical control system from undetectable attacks, even though individual signal sequences remain unknown to the attacker. We consider an encryption method based on the Learning with Errors (LWE) problem and demonstrate how model-undetectable attacks on linear systems over integers can be computed from sampled inputs and outputs that are encrypted. Previous work has shown that computing such attacks is possible on nonencrypted systems. Applying this earlier work to our scenario, with minor modifications, typically amplifies the error in encrypted messages unless a short vector problem is solved. Given that an attacker
obtains a short vector, we derive the probability that the attack is detected and show how it explicitly depends on the encryption parameters. Finally, we simulate an attack obtained by our method on an encrypted linear system over integers and conduct an analysis of the probability that the attack will be detected.

14:45-15:00  ThB07.2

Sampled-Data Steering of Unicycles Via PBC, pp. 2794-2799

Mattioni, Mattia  Università Degli Studi Di Roma La Sapienza
Moreschini, Alessio  Imperial College London
Monaco, Salvatore  Università Di Roma
Normand-Cyrot, Dorothée  CNRS-CentraleSupélec-Univ. ParisSaclay

In this paper, on the basis of a recently proposed discrete-time port-Hamiltonian representation of sampled-data dynamics, we propose a new time-varying digital feedback for steering mobile robots. The quality of the proposed passivity-based control is validated and compared through simulations with the existing literature and the continuous-time implementation using the unicycle as a case study.

15:00-15:15  ThB07.3

On the Complexity of Linear Systems: An Approach Via Rate Distortion Theory and Emulating Systems, pp. 2800-2805

Wendel, Eric  Boston University, Draper
Baillieu, John  Boston Univ
Hollmann, Joseph  The Charles Stark Draper Laboratory, Inc

We define the complexity of a continuous-time linear system to be the minimum number of bits required to describe its forward increments to a desired level of fidelity, and compute this quantity using the rate distortion function of a Gaussian source of uncertainty in those increments. The complexity of a linear system has relevance in control-communications contexts requiring local and dynamic decision-making based on sampled data representations. We relate this notion of complexity to the design of attention-varying controllers, and demonstrate a novel methodology for constructing source codes via the endpoint maps of so-called emulating systems, with potential for non-parametric, data-based simulation and analysis of unknown dynamical systems.

15:15-15:30  ThB07.4

Data-Driven Inverse of Linear Systems and Application to Disturbance Observers, pp. 2806-2811

Eun, Yongsoon  DGIST
Lee, JaeHo  Daegu Gyeongbuk Institute of Science and Technology
Shim, Hyungbo  Seoul National University

This work develops a data-based construction of inverse dynamics for LTI systems. Specifically, the problem addressed here is to find an input sequence from the corresponding output sequence based on pre-collected input and output data. The problem can be considered as a reverse of the recent use of the behavioral approach, in which the output sequence is obtained for a given input sequence by solving an equation formed by pre-collected data. The condition under which the problem gives a solution is investigated and turns out to be $\mathcal{L}_2$-delay invertibility of the plant and a certain degree of persistent excitation of the data input. The result is applied to form a data-driven disturbance observer. The plant dynamics augmented by the data-driven disturbance observer exhibits disturbance rejection without the model knowledge of the plant.

15:30-15:45  ThB07.5

Large-Signal Stability Guarantees for Cycle-By-Cycle Controlled DC-DC Converters, pp. 2812-2817

Cui, Xiaofan  University of Michigan Ann Arbor

Stability guarantees are critical for cycle-by-cycle controlled dc-dc converters in consumer electronics and energy storage systems. Traditional stability analysis of cycle-by-cycle dc-dc converters is incomplete because the inductor current ramps are considered fixed; but instead, inductor ramps are not fixed because they are dependent on the output voltage in large-signal transients. We demonstrate a new large-signal stability theory which treats cycle-by-cycle controlled dc-dc converters as a particular type of feedback interconnection system. An analytical and practical stability criterion is provided based on this system. The criterion indicates that the LR and RC time constants are the design parameters which determine the amount of coupling between the current ramp and the output voltage.

15:45-16:00  ThB07.6

Data-Driven Feedback Linearization of Nonlinear Systems with Periodic Orbits in the Zero-Dynamics, pp. 2818-2823

Shenoy, Karthik  Indian Institute of Technology, Madras
Saradagi, Akshith  Luleå University of Technology, Luleå, Sweden
Pasumarthy, Ramkrishna  Indian Institute of Technology, Madras
Chellaboina, Vijaya  GITAM Deemed to Be University

In this article, we present data-driven feedback linearization for nonlinear systems with periodic orbits in the zero-dynamics. This scenario is challenging for data-driven control design because, the higher-order terms of the internal dynamics in the discretization appear as disturbance inputs to the controllable subsystem of the normal form. Our design consists of two parts: a data-driven feedback linearization-based controller and a two-part estimator that can reconstruct the unknown nonlinear terms in the normal form of a nonlinear system. We investigate the effects of coupling between the subsystems in the normal form of the closed-loop nonlinear system and conclude that the presence of such a coupling prevents asymptotic convergence of the controllable states. We also show that the estimation error in the controllable states scales linearly with the sampling time. Finally, we present a simulation-based validation of the proposed data-driven feedback linearization.

ThB08  Aqua 305

Flight Control (Regular Session)

Chair: Lee, Taeyoung  George Washington University
Co-Chair: He, Tianyi  Utah State University

14:30-14:45  ThB08.1

Tracking Control of Multi-Input Multi-Output Multicopter Unmanned Aerial Vehicles with Auxiliary Systems, pp. 2824-2829

Lyshhevski, Sergey  Rochester Institute of Technology
Smith, Trevor  Rochester Institute of Technology

We research control schemes for unmanned aerial vehicles (UAVs) with propulsion, steering and power modes. Physical limits, aerodynamic instabilities, blade flapping, cross-axis coupling, data heterogeneity and other factors affect design. In multicopter UAVs, the differential thrust is regulated by changing the angular velocity of propellers, rotated by brushless electric motors. Voltages applied, phase currents, propeller speed and thrust cannot exceed specific limits. To accomplish aerial photography, airborne intelligence, surveillance, reconnaissance and support missions, multicopter and fixed-wing vehicles integrate active electronically scanned array radar, light detection and ranging modules, transceivers, controllers-drivers, steered pylon mounts, dc-dc regulators, battery pack, charger, etc. The differential thrust is regulated by changing propellers’ angular velocity. We design constrained tracking control laws to govern aerial systems regulating state and error dynamics. Minimizing design-consistent functionals with range-restricted descriptive bounded functions, limits are accounted for by integrands,
and control laws are analytically designed. Nonquadratic functionals with domain-specific positive-definite integrands and Hamiltonians admit closed-form solutions. The Hamilton-Jacobi equation is satisfied by continuous positive-definite return functions. Descriptive state-space models and error governance support a design to ensure optimal tracking error evolution. Bounded algorithms with state and tracking error feedback guarantee system optimality subject to minimized functionals. Control schemes, optimization tools, and algorithms are experimentally substantiated for a quadrotor helicopter. Controllers are designed and characterized for flight control systems, direct-drive steering mount pylons, brushless motors, and dc-dc switching regulators.

14:45-15:00  ThB08.2
Unified Attitude Control Strategy for Tilt-Rotor VTOL Aircraft, pp. 2830-2835
Belá, Jan  Czech Technical University in Prague
Hromčik, Martin  Czech Technical University

This paper introduces a unified approach to attitude control of tilt-rotor aircraft. The method utilizes moments-based actuation, based on real-time local linearization and LTI feedback systems. The main advantage of our approach is that it relies on fixed gain control laws throughout the entire flight envelope, including the transition from hover to cruise. This is achieved through sophisticated control allocation and model-matching algorithms. The method is designed with simple reconfiguration in case of an actuator failure, minimal computing power and future certification in mind. As a result, the developed algorithms were included in the development of the fly-by-wire system by a collaboration company.

15:00-15:15  ThB08.3
Trajectory Planning and LPV Model Predictive Control of Tilt-Rotor VTOL Aircraft, pp. 2836-2841
Burton, Samantha  Utah State University
He, Tianyi  Utah State University
Su, Weihua  The University of Alabama

This paper presents a novel approach for trajectory planning and tracking control of Vertical-TakeOff-and-Landing (VTOL) aircraft with tilt-rotors during the transition phase. The proposed method employs the multiple shooting method (MSM) on a nonlinear dynamic model to determine the optimal trajectory, with given initial and final states, constraints of states and inputs, as well as the objective of minimizing a weighted cost function. Unlike other trajectory planning techniques that yield quasi-equilibrium points, MSM generates dynamic state-control trajectories in time sequences. Subsequently, the nonlinear model is converted into a Linear Parameter-Varying (LPV) representation by treating velocity, pitch rate, and rotor tilt angle as scheduling parameters, which is then used in LPV Model Predictive Control (LPV-MPC) to track the planned trajectory. The LPV-MPC efficiently updates predictive models in future horizons based on predictions of scheduling parameters. The proposed systematic approach is verified through simulation on a tilt-rotor quadrotor VTOL aircraft, where the MSM generates a smooth transition from vertical take-off to level flight, and the LPV-MPC accurately tracks the trajectory despite measurement noise.

15:15-15:30  ThB08.4
Equivariant Reinforcement Learning for Quadrotor UAV, pp. 2842-2847
Yu, Beomyeol  The George Washington University
Lee, Taeyoung  George Washington University

This paper presents an equivariant reinforcement learning framework for quadrotor unmanned aerial vehicles. Successful training of reinforcement learning often requires numerous interactions with the environments, which hinders its applicability especially when the available computational resources are limited, or when there is no reliable simulation model. We identified an equivariance property of the quadrotor dynamics such that the dimension of the state required in the training is reduced by one, thereby improving the sampling efficiency of reinforcement learning substantially. This is illustrated by numerical examples with popular reinforcement learning techniques of TD3 and SAC.

15:30-15:45  ThB08.5
Altitude Control of a Tethered Multi-Rotor Autogyro in 2-D Using Pitch Actuation Via Differential Rotor Braking, pp. 2848-2854
Noboni, Tasnia  University of Central Florida
McConnell, Jonathan  University of Central Florida
Das, Tuvin  University of Central Florida

For tethered multi-rotor autogyros to be viable energy efficient unmanned aerial vehicles (UAVs), control analysis and stability investigation of autorotative flight are vital. In this paper, a simplified model-based attitude control technique is presented which is effective in the presence of both uniform and variable wind profile. A two-rotor autogyro, tethered to the ground and constrained to move in the 2D plane of the wind direction, is adopted for the study. The reduction to 2D simplifies the system and helps focus on the feasibility of attitude control and pitch modulation by exclusively using differential braking, which is a novel concept. In this arrangement, control inputs are the braking torques in each of the two rotors. The assumption is that with another two rotors in the lateral direction the roll and yaw motion of the system can be controlled when extended to 3D. The aerodynamics and tether modeling are based on Blade Element Momentum (BEM) method and catenary mechanics respectively. The characteristics of the equilibria of the tethered multi-rotor autogyro are investigated. For the aforementioned set-up, the differential rotor braking input is designed based on a proportional feedback law, and is effective in controlling the autogyro’s attitude with the help of restoring effect provided by the tether tension.
The overexpression of many proteins can often have a detrimental impact on cellular growth. This expression-growth coupling leads to positive feedback - any increase of intracellular protein concentration reduces the growth rate of cell size expansion that in turn enhances the concentration via reduced dilution. We investigate how such feedback amplifies intrinsic stochasticity in gene expression to drive a skewed distribution of the protein concentration. Our research provides the analytical expression of the distribution after solving the associated Chapman-Kolmogorov equation. With these results, we quantify the enhancement of noise/skewness as a function of expression-growth coupling. This analysis has important implications for the expression of stress factors, where high levels provide protection from stress, but come at the cost of reduced cellular proliferation. Finally, we connect these analytical results to the case of an actively degraded gene product, where the degradation machinery is working close to saturation.

This paper discusses reliable yet minimal computational models for predicting the patient's response to anticancer multi-drug combined therapy. The distribution of the drugs into the local heterogeneity of healthy-tumor tissues can be translated into mathematical models. Ideally, these should best describe the physiological processes and physical mechanisms, together with the interactions between the contributing components of the tumor growth dynamic system. Our previously proposed pharmacokinetic-pharmacodynamic (PKPD) mathematical model is revisited for different spatiotemporal fractional drug diffusion patterns. In particular, we examine the specific diffusion-related factors that limit drug effect through the tumor's surface. The ability of the tumor growth PKPD model to predict patient responsiveness was evaluated using prior radiation therapy data in a patient with lung cancer. This study shows that the effect of anomalous diffusion mechanisms within tumor tissue should be considered while modeling the dose-response relationship for optimal results of cancer therapies.
This paper presents a feedback control design that stabilizes the position of a drifting vortex in a freestream over a deformable Joukowski foil using camber control. We derive the dynamics of a point vortex in flow around a Joukowski foil using a potential flow model and provide numerical analysis of the number, stability, and controllability of open-loop equilibrium points of the vortex-foil system. We show that the position of a point vortex can effectively be stabilized using a full-state feedback camber control law while maintaining the validity of the dynamics model. We present sample stable and unstable trajectories found using closed-loop control along with a visualization of the region of convergence.

ThB10.1
Designing Hybrid Neural Network Using Physical Neurons - a Case Study of Drill Bit-Rock Interaction Modeling, pp. 2901-2906
Zhang, Zhihong
Texas A&M University
Song, Xingyong
Texas A&M University, College Station

Neural networks have been widely applied in system dynamics modeling. One particular type of networks, hybrid neural networks, combine a neural network model with a physical model which can increase rate of convergence in training. However, most existing hybrid neural network methods require an explicit physical model constructed, which sometimes might not be feasible in practice or could weaken the capability of capturing complex and hidden physical phenomena. In this paper, we propose a novel approach to construct a hybrid neural network. The new method incorporates the physical information to the structure of network construction, but does not need an explicit physical model constructed. The method is then applied to modeling of bit-rock interaction in the down-hole drilling system as a case study, to demonstrate its effectiveness in modeling complex process and efficiency of convergence in training.

15:00-15:15
Modeling Partially Unknown Dynamics with Continuous Time DMD, pp. 2913-2918
Gonzalez, Efrain
University of South Florida
Avazpour, Ladan
University of South Florida
Kamalapurkar, Rushikesh
Oklahoma State University

This paper discusses a Bond Graph (BG) Structural Analysis Toolbox developed in MATLAB (MATSAT) that performs causal analysis on the BG and assists the user in the sensor selection process for a multi-domain physical system. MATSAT contains modules for performing the Sequential Causality Assignment Procedure (SCAP) and Causal Path Search (CaPS). The modules can be combined to check for structural properties such as structural observability (SO) for any sensor set. The working of MATSAT is shown for standard systems. Verification of SCAP, CaPS, and necessary and sufficient SO conditions is shown.

15:15-15:30
Learned Lifted Linearization Applied to Unstable Dynamic Systems Enabled by Koopman Direct Encoding, pp. 2919-2924
Ng, Jerry
Massachusetts Institute of Technology
Asada, H. Harry
Massachusetts Inst. of Tech

This paper presents a Koopman lifting linearization method that is applicable to nonlinear dynamical systems having both stable and unstable regions. It is known that DMD and other standard data-driven methods face a fundamental difficulty in constructing a Koopman model when applied to unstable systems. Here we solve the problem by incorporating knowledge about a nonlinear state equation with a learning method for finding an effective set of observables. In a lifted space, stable and unstable regions are separated into independent subspaces. Based on this property, we propose to find effective observables through neural net training where training data are separated into stable and unstable trajectories. The resultant learned observables are used for constructing a linear state transition matrix using method known as Direct Encoding, which transforms the nonlinear state equation to a state transition matrix through inner product computations with the observables. The proposed method shows a dramatic improvement over existing DMD and data-driven methods.
We consider networked systems comprised of interconnected sets of non-linear subsystems and develop linear matrix inequality (LMI) techniques for their analysis and interconnection topology synthesis using only the dissipativity properties of the involved subsystems. In particular, we consider four networked system configurations (NSCs) and show that the empirical analysis of their stability/dissipativity can be formulated as corresponding LMI problems. Using some matrix identities and mild assumptions, we also show that the empirical synthesis of interconnection topologies for these NSCs can also be formulated as LMI problems. This enables synthesizing the interconnection topology among subsystems to enforce/optimise specific stability/dissipativity properties over the networked system. The formulated LMI problems can be solved efficiently and scalably using standard convex optimization toolboxes. We also provide several numerical examples to illustrate our theoretical results.

**ThB11**

**Network Analysis and Control (Regular Session)**

Chair: Lestas, Ioannis
Co-Chair: Mallada, Enrique

14:30-14:45

**ThB11.1**

**Propagation Stability Concepts for Network Synchronization**

Processes, pp. 2939-2944

Roy, Sandip
Washington State University
Sarker, Subir
Washington State University
Xue, Mengran
Raytheon BBN Technologies

A notion of disturbance propagation stability is defined for dynamical network processes, in terms of decrescence of an input-output energy metric along cutsets away from the disturbance source. A characterization of the disturbance propagation notion is developed for a canonical model for synchronization of linearly-coupled homogeneous subsystems. Specifically, propagation stability is equivalenced with the frequency response of a certain local closed-loop model, which is defined from the subsystem model and local network connections, being sub-unity gain. For the case where the subsystem is single-input single-output (SISO), a further simplification in terms of the subsystem's open loop Nyquist plot is obtained. An extension of the disturbance propagation stability concept toward imperviousness of subnetworks to disturbances is briefly developed, and an example focused on networks with planar subnetworks is considered.

14:45-15:00

**ThB11.2**

**Distributed Design of Controllable and Robust Networks Using Zero Forcing and Graph Grammars**, pp. 2945-2950

Patel, Priyanshskumar
The University of Texas at Dallas
Ishwarbhai
Suresh, Johir
The University of Texas at Dallas
Abbas, Waseem
University of Texas at Dallas

This paper studies the problem of designing networks that are strongly structurally controllable, and robust simultaneously. For given network specifications, including the number of nodes $N$, the number of leaders $N_L$, and diameter $D$, where $2 \leq D \leq N/N_L$, we propose graph constructions generating strongly structurally controllable networks. We also compute the number of edges in graphs, which are maximal for improved robustness measured by the algebraic connectivity and Kirchhoff index. For the controllability analysis, we utilize the notion of zero forcing sets in graphs. Additionally, we present graph grammars, which are sets of rules that agents apply in a distributed manner to construct the graphs mentioned above. We also numerically evaluate our methods. This work exploits the trade-off between network controllability and robustness and generates networks satisfying multiple design criteria.

15:00-15:15

**ThB11.3**


Welikala, Shirantha
University of Notre Dame
Lin, Hai
University of Notre Dame
Antsaklis, Panos J.
University of Notre Dame

We consider networked systems comprised of interconnected sets of non-linear subsystems and develop linear matrix inequality (LMI)
This paper presents an adaptive control approach for uncertain nonlinear systems subject to safety constraints that allows for modularity in the selection of the parameter estimation algorithm. Such modularity is achieved by unifying the concepts of input-to-state stability (ISS) and input-to-state safety (ISSf) via Lyapunov functions (CLFs) and control barrier functions (CBFs), respectively. In particular, we propose a class of exponential ISS-CLFs and ISSf-high order CBFs that can be combined with a general class of parameter estimation algorithms akin to those found in the literature on concurrent learning adaptive control. We demonstrate that the unified ISS and ISSf in an adaptive control setting allows for maintaining a single set of parameter estimates for both the CLF and CBF that can be generated by a class of update laws satisfying a few general properties. The modularity of our approach is demonstrated via numerical examples by comparing performance in terms of stability and safety across different parameter estimation algorithms.

In this paper, we propose a data-driven adaptive control method for trajectory tracking problems with unmatched uncertainty. The method is characterized by a basis augmentation rule triggered by an expressiveness-based event, which provides extra adaptivity to the controller to overcome unmatched uncertainty. The augmented basis functions take the form of kernel basis functions whose centers are located along the trajectory. The triggering event is defined by selecting an upper threshold for the value of power function associated to the dictionary of basis functions. The event-triggered basis augmentation (ETBA) rule can be viewed as a realization of the nonparametric adaptive controller embedded in reproducing kernel Hilbert spaces (RKHS). By leveraging the properties of RKHS, we show that 1) the tracking error asymptotically converges to zero, and 2) the inter-event time of basis augmentation is bounded below by a positive value when the reference trajectory is a set point. A numerical example is presented to illustrate performance of the proposed method and verify the theoretical results.
The presented work addresses the motion control problem for a class of musculoskeletal systems, composed of the combination of a rigid multibody system (i.e., the skeletal part) subjected to efforts produced by a set of muscle-tendon complexes. A control law, prescribing the rate of change of muscle fiber activation, is proposed and shown to guarantee exponential convergence of skeletal joint angles to user-defined desired trajectories. Results of numerical simulations, for a simple two degree of freedom skeletal system actuated by five muscle-tendon complexes, illustrate efficacy of the approach.

A Graphical Interpretation and Universal Formula for Safe Stabilization

Li, Ming
Eindhoven University of Technology
Sun, Zhiyong
Eindhoven University of Technology (TU/e)

The safe stabilization problem is studied via a graphical approach in this paper. Firstly, the compatibility condition for the control Lyapunov function (CLF) and control barrier function (CBF) is provided by visualizing and analyzing the geometry of safe stabilization. Related graphical interpretations are provided to show the proposed condition's connections with the current results. Next, the analytical solution of the CLF and CBF-based quadratic program (CLF-CBF-QP) is obtained with a graphical interpretation. Because Sontag's universal formula for nonlinear stabilization is a special solution of the pointwise minimal norm (PMN) controller, generalized universal formulas for both compatible and incompatible safe stabilization are derived. Afterward, some essential properties of the two proposed universal formulas are discussed, such as Lipschitz continuity, continuity at origin, locally asymptotic stability, safety, etc. Finally, we use the proposed generalized universal formulas to address the safe stabilization problem in adaptive cruise control (ACC) systems. The efficacy of the generalized universal formulas is exhibited with numerical results.

Asymmetric Dissipativity and Supply Rates for Compartmental Systems with Logarithmic Storage Functions

Ito, Hiroshi
Kyushu Institute of Technology

Many compartmental models in biology, chemistry, ecology, sociology, and related sciences have positive variables, for which equilibrium points of interest are in the interior of the positive orthant. Reactions are often modeled as bilinearly, which renders a boundary of the positive orthant a separatrix. In such situations, the capability of Lyapunov functions defined on symmetric domains is very limited, and logarithmic functions are sometimes used in mathematical biology. The domain of a logarithm function is a ray, which is asymmetric with respect to the equilibrium of interest. This paper aims to add a useful tool to dissipativity theory for analyzing networks via storage functions defined on asymmetric spaces. The paper focuses on an asymmetric supply rate and discusses its properties and utilities which standard symmetric supply rates do not offer. The power of the asymmetric supply rate is illustrated briefly by establishing asymptotic stability of the endemic equilibrium of the SIRS model of infectious diseases in an arbitrarily large domain.

Partial Stability of Nonlinear Dissipative Feedback Systems

Haddad, Wassim M.
Georgia Institute of Technology
Somers, Luke
Georgia Institute of Technology

Partially stable systems involve dynamical systems whose motion lie in a subspace of the state space resulting in system stability respect to part of the system's states. In this paper, we develop partial stability theorems for non-linear dissipative feedback systems. Specifically, by invoking additional structural constraints on the forward loop and feedback loop system storage functions, we develop feedback interconnection partial stability results for dissipative nonlinear dynamical systems. Our results provide extensions of the positivity and small gain theorems for guaranteeing partial stability of feedback interconnected systems.
parameters and states of systems whose non-linearities have order two near the origin, which include cubic terms arising in the study of jump phenomena, process control, and bistable models of aerospace systems. This yields local exponential convergence of the state estimation error to zero, basin of attraction estimates, and fixed time parameter identification. We illustrate our result using Duffing’s equation, whose cubic term puts it outside the scope of prior methods.

14:45-15:00 ThB14.2

Learning-Based Design of Luenberger Observers for Autonomous Nonlinear Systems, pp. 3048-3055

Niazi, Muhammad Umar B. Massachusetts Institute of Technology
Cao, John KTH Royal Institute of Technology
Sun, Xudong KTH Royal Institute of Technology
Das, Amritam University of Cambridge
Johansson, Karl H. KTH Royal Institute of Technology

Designing Luenberger observers for nonlinear systems involves the challenging task of transforming the state to an alternate coordinate system, possibly of higher dimensions, where the system is asymptotically stable and linear up to output injection. The observer then estimates the system’s state in the original coordinates by inverting the transformation map. However, finding a suitable injective transformation whose inverse can be derived remains a primary challenge for general nonlinear systems. We propose a novel approach that uses supervised physics-informed neural networks to approximate both the transformation and its inverse. Our method exhibits superior generalization capabilities to contemporary methods and demonstrates robustness to both neural network’s approximation errors and system uncertainties.

15:00-15:15 ThB14.3

Data-Driven Analytic Differentiation Via High Gain Observers and Gaussian Process Priors, pp. 3056-3061

Trimarchi, Biagio Università Di Bologna
Gentilini, Lorenzo Università Di Bologna
Schiano, Fabrizio Leonardo S.p.a
Marconi, Lorenzo Univ. Di Bologna

The presented paper tackles the problem of modeling an unknown function, and its first Sr-1 derivatives, out of scattered and poor-quality data. The considered setting embraces a large number of use cases addressed in the literature and fits especially well in the context of control barrier functions, where high-order derivatives of the safe set are required to preserve the safety of the controlled system. The approach builds on a cascade of high-gain observers and a set of Gaussian process regressors trained on the observers’ data. The proposed structure allows for high robustness against measurement noise and flexibility with respect to the employed sampling law. Unlike previous approaches in the field, where a large number of samples are required to fit correctly the unknown function derivatives, here we suppose to have access only to a small window of samples, sliding in time. The paper presents performance bounds on the attained regression error and numerical simulations showing how the proposed method outperforms previous approaches.

15:15-15:30 ThB14.4

Non-Asymptotic Neural Network-Based State and Disturbance Estimation for a Class of Nonlinear Systems Using Modulating Functions, pp. 3062-3068

Marani, Yasmine King Abdullah University of Science and Technology
N’Doye, Ibrahim King Abdullah University of Science and Technology (KAUST)
Laleg-Kirati, Taous-Meriem King Abdullah University of Science and Technology (KAUST)

Model disturbances result from model uncertainties or external factors acting on the system. They usually affect the closed-loop performance in a control loop system. However, they are often unknown and cannot be then compensated. Therefore, it is crucial to develop estimation methods for the effective estimation of the disturbances which can be then considered appropriately in the control design. This paper proposes a hybrid method for the joint estimation of the state and the disturbance for a class of nonlinear systems in two steps. The approach consists in a neural network with time-varying weights used to approximate the disturbance term and a modulating function method for the finite-time estimation of the state and the weights. The modulating functions approach simplifies the estimation problem into solving an algebraic systems of equations. Both offline and online frameworks are presented and discussed. An example is presented to demonstrate the performance of the proposed algorithm.

15:30-15:45 ThB14.5

IPG Observer: A Newton-Type Observer Robust to Measurement Noise, pp. 3069-3074

Chakrabarti, Kushal Tata Consultancy Services Research
Chopra, Nikhil University of Maryland, College Park

The previously proposed Newton observer for nonlinear systems has fast exponential convergence and applies to a wide class of problems. However, the Newton observer lacks robustness against measurement noise due to the computation of a matrix inverse. In this paper, we propose a novel observer for discrete-time system with sampled measurements to alleviate the impact of measurement noise. The key to the proposed observer is an iterative pre-conditioning technique for the gradient-descent method, used previously for solving general optimization problems. The proposed observer utilizes a non-symmetric pre-conditioner to approximate the observability mapping’s inverse Jacobian so that it asymptotically replicates the Newton observer with an additional benefit of enhanced robustness against measurement noise. Our observer applies to a wide class of nonlinear systems, as it is not contingent upon linearization or any specific structure in the plant nonlinearity. Its improved robustness compared to the prominent nonlinear observers is demonstrated through empirical results.
Accurate, real-time state of charge (SoC) and state of health (SoH) estimation is essential for lithium-ion battery management systems to ensure safe and extended life of battery packs. For the large battery packs associated with battery electric locomotives and grid applications, computational efficiency is critical, especially for onboard implementation. This paper presents real-time SoC and batch least square SoH and current sensor bias estimation using measured cell voltage and current from large battery packs. An online gradient-based SoH estimator, coupled with the online SoC estimator, provides real-time onboard health monitoring. The online and offline SoC-SoH algorithms are tested using data from a battery electric locomotive. The SoC-SoH estimation results show tightly clustered capacity, resistance, and current sensor bias estimates for an 11-cell module. The batch and online capacity estimates match to within 5% after the startup transients decay.

14:45-15:00  ThB15.2
Discovering Governing Equations of Li-Ion Batteries Pertaining State of Charge Using Input-Output Data (I), pp. 3081-3086
Rodriguez Nunez, Renato
Ahmadzadeh, Omidreza
Wang, Yan
Soudabakhsh, Damoon
Temple University
Ford Research and Advanced Engineering, Ford Motor Company
Temple University

Lithium-ion batteries (LIBs) have complex electrochemical behaviors, which result in nonlinear and high-dimensional dynamics. The modeling of this complex system often requires models involving PDEs, which are costly to develop and require invasive experiments to identify battery parameters. Here, we propose a data-driven technique to discover nonlinear reduced-order models that govern state-of-charge (SOC) dynamics from non-invasive input/output data. Accurate SOC estimation is paramount for increased performance, improved operational safety, and extended longevity of LIBs. The SOC model is developed from a library of candidate terms via a sparsity-promoting algorithm and data generated by the Doyle-Fuller-Newman (P2D) model with a thermal model to characterize the cell’s thermal effects. We tuned the model’s performance and sparsity by exploring different combinations of candidate terms (basis functions) and data sampling rates. Using current, voltage, and SOC, the model was trained and validated on the UDDS city driving cycle. It achieved a predictive performance (RMSE) of 3e-5% and 0.22% for training and model validation, respectively. The generalizability of the model was assessed via cross-validation on the US06 highway driving cycle, where an RMSE of 0.47% was achieved. The modeling technique includes explicit physics-inspired terms, which allows for interpretable and generalizable models. Furthermore, the procedures and methods developed in this research are generic and can guide machine learning modeling of other dynamical systems.

15:00-15:15  ThB15.3
A Physics-Inspired Machine Learning Nonlinear Model of Li-Ion Batteries (I), pp. 3087-3092
Ahmadzadeh, Omidreza
Rodriguez Nunez, Renato
Wang, Yan
Soudabakhsh, Damoon
Temple University
Ford Research and Advanced Engineering, Ford Motor Company
Temple University

Accurate modeling of Lithium-ion batteries (LIBs) allows for more efficient utilization of their potential without compromising their safety or useful life. Accurate physics-based models require in-situ measurements and proprietary information unavailable for each cell. Data-driven models offer a solution to identify governing equations of individual cells using only the excitation inputs and measured outputs. However, the main drawback of such models is their performance in unseen scenarios, as they tend to overfit the training data and perform poorly in other scenarios. We seek physics-informed reduced-order nonlinear models of LIBs from measured data. The model was trained using a high-fidelity model of a Li-Ion cell. We used Sequentially Thresholded Ridge regression (STRidge) optimization to determine the optimal reduced-order model. Using a validation set, we proposed an algorithm to tune hyperparameters (threshold and regularization parameters). A stochastic electrical current signal up to 2C4C-rates charge/discharge was used in the training set, and the US highway profile (US06 drive cycle) was used for the validation. The model was validated with EPA Urban Dynamometer Driving Schedule (UDDS) as the test set. The test errors (normalized root mean square error (NRMSE)) were 6.3e-3 for SOC and Voltage predictions.

15:15-15:30  ThB15.4
Excitation Optimization for Estimating Battery Health Parameters Using Reinforcement Learning Considering Information Content and Bias (I), pp. 3093-3098
Huang, Rui
Jones, Morgan
Lin, Xinfan
University of California, Davis
Sheffield University
University of California, Davis

Accurate parameter estimation has been a long-pursued objective in battery modeling and control practice. To this end, optimization of excitation to improve the estimation accuracy has been an emerging topic, since the quality of data critically determines the accuracy of estimation. However, there are several major drawbacks with existing approaches. First, the commonly used criterion for optimization, e.g., Fisher information, is limited in performance due to not considering the estimation bias caused by inevitable system uncertainties. In addition, alternative existing methods rely on a good a priori knowledge of the parameter to be estimated, which is intrinsically contradictory to the goal of estimation. To address these issues, we propose a reinforcement learning (RL) framework to learn the optimal policy for excitation generation that is robust to system uncertainties. In particular, the framework involves a non-additive objective/reward associated with the newly established optimization criterion, and a state augmentation technique is applied to address the ensuing challenge. It is shown that, when applied to estimate a key health-related battery electrochemical parameter, the RL-based approach achieves significantly higher objective value under nominal conditions, and reduces the estimation error by one-order-of-magnitude in the presence of uncertainties compared with the baseline in existing approaches.

15:30-15:45  ThB15.5
Error Analysis for Parameter Estimation of Li-Ion Battery Subject to System Uncertainties (I), pp. 3099-3105
Fogelquist, Jackson
Lai, Qingzhi
Lin, Xinfan
University of California, Davis
University of California, Davis
University of California, Davis

Lithium-ion battery parameter estimation is a dynamic research field in which creative and novel algorithms are being developed to tune high-fidelity models for advanced control of energy systems. Amidst these efforts, little focus has been placed on the fundamental mechanisms associated with estimation accuracy, giving rise to the question, why is an estimate accurate or inaccurate? In response, we derive a generalized multivariate estimation error equation for the least-squares algorithm, which reveals that the error can be represented as the product of system uncertainties (i.e., in model, measurement, and parameter) and uncertainty-propagating sensitivity structures. We then relate the error equation to conventional error analysis criteria, such as parameter sensitivity, the Fisher information matrix, and the Cramer-Rao bound, to assess the benefits and limitations of each. Broadly, these criteria share the principal deficiency of neglecting estimation bias and system uncertainties, which are inevitable in practice. The error equation is validated through a series of experimental univ- and bivariate estimations of
lithium-ion battery electrochemical parameters. These results are also analyzed using the error equation to study the composition of errors under various data sets. Finally, the bivariate analysis indicates that adding an additional target parameter to the estimation without increasing the amount of data intrinsically reduces the error robustness to the influence of system uncertainties.

15:45-16:00  ThB15.6


Farahkar, Amir  University of Kansas
Wang, Yebin  Mitsubishi Electric Research Labs
Wu, Di  Pacific Northwest National Laboratory
Fang, Huazhen  University of Kansas

Optimal power management (OPM) is critical for large-scale battery energy storage systems. Today’s methods often require formidable computational effort due to the design based on centralized numerical optimization. Thus, this paper investigates computationally distributed OPM where the agents based on the cells communicate over a network to cooperatively solve the OPM problem. We propose an accelerated tracking alternating direction method of multipliers (ADMM) algorithm to solve the distributed OPM. The proposed algorithm embeds dynamic average consensus and Nesterov’s acceleration technique in the ADMM algorithm. Not only is the proposed algorithm fully distributed without a need for fusion or aggregating nodes, but it also accelerates the convergence. The paper formulates the OPM in a model predictive control framework where it seeks to regulate the charging/discharging power of each battery cell to minimize the total power losses and promote balanced use of the constituent cells while complying with the safety constraints. The paper provides ample simulation results to demonstrate the effectiveness and advantages of the proposed distributed OPM in terms of computation and convergence.

ThB17  Aqua 314

Decomposition and Decomposition-Based Algorithms for Control and Optimization of Large-Scale Systems (Tutorial Session)

Chair: Allman, Andrew  University of Michigan
Co-Chair: Tang, Wentao  NC State University
Organizer: Daoutidis, Prodromos
Organizer: Tang, Wentao  NC State University
Organizer: Allman, Andrew  University of Michigan

14:30-15:00  ThB17.1

Resolving Large-Scale Control and Optimization through Network Structure Analysis and Decomposition (I), pp. 3113-3129

Tang, Wentao  NC State University
Allman, Andrew  University of Michigan
Mitrai, Ilia  University of Minnesota
Daoutidis, Prodromos  Univ. of Minnesota

Large-scale systems comprising of components with complex interactions and nonlinear physics are ubiquitous in modern engineering systems, including integrated and intensified chemical processes and supply chains. Mathematical optimization provides a means of automated decision making for problems of, for example, process control, design, production and maintenance scheduling, and supply chain management, which has formed the backbone of process systems research over the past several decades. Unfortunately, for large-scale and complex systems, it is often the case that the off-the-shelf solution methods (i.e. CPLEX, Ipopt, BARON, …) cannot directly return an optimal decision in an amount of time relevant for the problem (i.e. on the order of seconds for process control). In these instances, it is a natural but also profound idea to decompose the decision-making problem into a set of easier to solve subproblems, often corresponding to subsystems that can be controlled or optimized in a distributed architecture. Historically, this has been done by a systems expert who uses their intuition and knowledge of the underlying process to develop the subproblem structure; however, recent advances in network theory allow for the automatic identification of structure amenable to solution via decomposition approaches.

15:00-15:20  ThB17.2

Decomposition and Distributed Predictive Control of Integrated Energy Systems (I), pp. 3130-3136

Wu, Long  University of Alberta
Liu, Jinfeng  University of Alberta

Integrated energy systems (IESs) play an important role in absorbing renewable energy and improving overall fuel efficiency in distributed energy systems. An IES typically consists of a few energy generation and storage units (e.g., solar panels, wind turbines, battery banks, water tanks) that are closely interconnected. Given the distinct dynamics of the different energy generation and storage units, a centralized control scheme in general does not work well. In this work, we show how an IES can be decomposed into smaller subsystems and how distributed economic model predictive control (EMPC) can be designed based on the decomposed subsystems to optimize the operation of the IES. In the decomposition of the IES, we explore both decomposing the entire system vertically based on the time-scale multiplicity exhibited in the IES dynamics and horizontally based on the closeness of the interconnection between the various operating units. The impact of the order of applying the vertical and horizontal decomposition is also discussed. Based on the decomposed subsystems, a distributed EMPC scheme is designed. We illustrate how the features of the decomposed subsystem models can be used in the design of the local EMPCs to reduce the computational complexity and information exchange between the controllers.

15:20-15:40  ThB17.3

Graph-Structured Nonlinear Programming: Properties and Algorithms (I), pp. 3136-3136

Shin, Sungho  Argonne National Laboratory

A graph-structured nonlinear program (NLP) is a nonlinear optimization problem whose algebraic structure is induced by a graph. These problems arise in diverse applications such as dynamic optimization, network optimization, partial differential equation-constrained optimization, and multi-stage stochastic programming. Building on the NLP sensitivity theory, we show that the nodal solution sensitivity against parametric perturbation decays exponentially in the distance on the graph. Remarkably, this result (exponential decay of sensitivity; EDS) holds under standard regularity assumptions: second-order sufficiency conditions and the linear independence constraint qualification. EDS allows the creation of a novel computing strategy, the overlapping Schwarz method. This method decomposes a graph-structured NLP into multiple smaller subproblems and solves them iteratively with the exchange of information at boundaries. Based on EDS, we prove that the convergence rate of the overlapping Schwarz method for uniformly regular graph-structured NLPs improves exponentially with the size of overlap.

15:40-16:00  ThB17.4

Distributed MPC of Large-Scale Industrial Processes on the Shell-Yokogawa Platform for Advanced Control and Estimation (PACE) (I)*

Carrette, Pierre  Linkoping Univ.
Cai, Yongsong  Shell Global Solutions (U.S.) Inc.
Lundberg, Bruce  Shell Global Solutions (U.S.) Inc.
Williamson, John M.  Shell Global Solutions (U.S.) Inc.
Precision Rocket Landing Model Predictive Control Algorithm

In future interplanetary missions (such as Mars), rockets need to land on smooth terrain to avoid damaging their boosters or tipping over. Scientists can narrow down Mars mission landing spots within an ellipse measuring 7.7km x 6.6km, making the landing vehicle vulnerable to boulders or hills. This is acceptable for current landing vehicles which use parachutes, cushioning, or skycranes. However, these methods are not applicable to full-scale rockets (such as SpaceX’s Starship).

In this project, an autonomous precision rocket landing algorithm capable of guaranteeing precision landings for full-scale rockets for interplanetary missions was developed. A model predictive control (MPC) algorithm was developed to land a rocket on a target landing spot by controlling the rocket’s engine and cold gas thrusters. A physics simulation environment was built to test the accuracy of the rocket landing algorithm.

The precision landing MPC algorithm is able to manipulate/control the rocket’s landing spot by up to 250 meters in any direction; guaranteeing safe and accurate precision landings on any target within 250 meters of the original trajectory. The algorithm achieved safe landing in all simulations run in Mars-like environments where the rocket had an initial altitude of 5000 meters and a downwards velocity of 30-60 meters/second with less than or equal to 250 meters of required trajectory correction. The simulated rocket had characteristics similar to SpaceX’s Starship rocket. The algorithm is feasible on a real rocket that has a flight computer equivalent with power equivalent to that of ~7 Intel Xeon chips.

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particular, the EIPC is effectively used for semi active control of the processes involving unknown impacting object mass, force disturbance, leakage disturbance and double impact conditions. The method is positively verified experimentally by using pneumatic absorber equipped with fast piezoelectric valve. It can be concluded that EIPC is efficient and robust control which can be successfully applied for the problem of adaptive impact mitigation.

16:30-17:15     ThC01.9

Designing and Testing a Secure Cooperative Adaptive Cruise Control Under False Data Injection Attack*
Holland, James University of South Florida
Cunningham-Rush, Jonas Tennessee Technological University
Noei, Shirin University of Florida
Sargolzaei, Arman University of South Florida

Summary: Vehicles with intelligent features can operate safely, reliably, and smoothly. An Intelligent Human Vehicle (IHV) refers to a human-driven vehicle that can interact and communicate with other vehicles via Vehicle-to-vehicle (V2V) communication, while also providing drivers with advice on the optimal maneuver to execute. The IHV is a complex system that incorporates both continuous and discrete dynamics, where the transitions between discrete states are influenced by both deterministic and stochastic events. In a mixed-traffic environment consisting of both IHVs and Autonomous Vehicles (AVs), our research provides a framework for modeling the intricate hybrid interactions between the IHVs and AVs using Mixed Integer Programming (MIP) and optimizing control inputs for the AVs and advisory directives for the drivers in IHVs. Our preliminary modeling results and experimental data from a human-in-the-loop (HITL) driving simulator demonstrate successful coordination between the IHV and AV. Moreover, our approach leads to improved merging performance compared to the scenario without advisory directives.

16:30-17:15     ThC01.10

Coordination of Autonomous and Human-Driven Vehicles in a Mixed Traffic Scenario Considering Stochastic Human Behavior, pp. 3139-3139
Hossain, Sanzida Oklahoma State University
Lu, Jiaxing Oklahoma State University
Bai, He Oklahoma State University
Sheng, Weihua Oklahoma State University

We consider a dynamic game setting in which a large population of strategic individuals decide whether to adopt protective measures to protect themselves against an infectious disease, specifically the susceptible-infected-susceptible (SIS) epidemic. Protection is costly, partially effective, and adopting protection reduces the probability of becoming infected for susceptible individuals and the probability of transmitting the infection for infected individuals. In a departure from most prior works that assume the decision-makers to be myopic, we model individuals who choose their action to maximize the infinite horizon discounted expected reward. We define the notion of best response and Nash equilibrium in this class of games, and completely characterize the equilibrium policy and stationary state distribution for different parameter regimes. Numerical results illustrate convergence behavior for a class of evolutionary learning dynamics to the equilibrium policy together with convergence of the (infection) state distribution.

16:30-17:15     ThC01.11

Building an Adaptive Behavioral Intervention for Obstructive Sleep Apnea Using Control Systems Engineering, pp. 3140-3140
Maurer, Matthew Arizona State University
Rivera, Daniel E. Arizona State Univ
Anand, Harsh Arizona State University
Awan, Hafsa Arizona State University
Leonard, Krista Arizona State University
Hasanaj, Kristina Arizona State University
Epstein, Dana Arizona State University
Buman, Matthew Arizona State University
Petrov, Megan Arizona State University

Obstructive Sleep Apnea (OSA) is a sleep disorder affecting 9-38% of the general population. The standard treatment for OSA is continuous positive airway pressure therapy (CPAP), but patient adoption and long-term adherence of CPAP remains suboptimal. Adaptive time-varying interventions, formulated using control engineering principles, offer significant promise with regards to improving CPAP adoption and long-term use in patients newly diagnosed with OSA. This poster considers a previously developed mobile health (mHealth) application called SleepWell24, which integrated CPAP and consumer wearable device data with chronic disease self-management tools to support CPAP adoption and adherence; a feasibility trial involving 40 SleepWell24 and 47 usual care patients in a 60-day intervention was completed in 2020. In this work, a next-generation version of SleepWell24 under development is described, representing an emerging application of control systems engineering in behavioral medicine. Relying on insights from behavioral scientists, psychologists, and clinicians, a conceptual model for how outcomes of interest captured in SleepWell24 (e.g., symptoms, CPAP device troubleshooting, physical activity) has been developed. Using fluid analogies for the conceptual model results in a system of ordinary differential equations constituting a dynamical model of OSA treatment via CPAP use. Given this model, a MATLAB w/Simulink model has been proposed, which is being validated with participant data and clinical insight. The model has been used to test the disturbance rejection response of an IMC-PI controller adjusting troubleshooting to restore perceived sleep quality following a step change in symptoms. Next steps for this work include system identification of the ODE-model based on individual data from SleepWell24 trial participants, development of a more realistic simulation model involving hybrid dynamics, and the development of a software platform for design and implementation of two control-oriented adaptive interventions (to be done in collaboration with Mayo Clinic in Phoenix and Rochester): the first for improving short-term CPAP adoption and the second for enhancing long-term adherence.

16:30-17:15     ThC02.1

Maity, Umme Indian Institute of Technology, Kharagpur
Hota, Ashish Indian Institute of Technology (IIT), Kharagpur
Srivastava, Vaibhav Michigan State University

Order Gradient Play vs. Nash Equilibrium*  
Toonsi, Sarah University of Illinois Urbana-Champaign
Shamma, Jeff S. University of Illinois at Urbana-Champaign

16:30-17:15     ThC02.3

Switch Open-Circuit Fault Detection and Localization for Modular Multilevel Converters*  
Wang, Haoran University of Alberta
Li, Yuan Altalink Management LTD
Science instruments often take up a great amount of power and space within small satellites, which is drawn away from other components including attitude control hardware. As such, new actuator configurations are required to minimize space and power usage. The dual-spin-stabilized configuration equips a spinning satellite with a single reaction wheel with its momentum axis pointed along the spin axis, such that the satellite is passively stabilized. This configuration is especially advantageous if the satellite is not required to maintain direct pointing at an inertially-fixed object, but is otherwise able to drift within some pointing tolerance. These satellites are usually equipped with three magnetic torque rods when operated within low-Earth orbit. Using torque rods alone to control a spacecraft does not provide full controllability, as the satellite has no way to induce a torque in the direction of the Earth's magnetic field at any instance in time. However, continually spinning the satellite around any direction (other than the direction of the magnetic field) recovers full controllability due to gyroscopic coupling in the directions orthogonal to the spin axis. This complete configuration is tested in an inertial pointing mission directed at the Crab Nebula, a location of recent scientific interest. The simulation includes perturbations such as gravity gradient and residual magnetic dipole torques. Results from a carefully-tuned LQR controller and a model predictive controller (MPC) are compared. LQR was tuned to ensure the system does not violate state or control saturation constraints, although it does not provide any guarantee of not exceeding these bounds. Meanwhile, MPC can explicitly account for the state and control constraints while utilizing drift within the allowable pointing cone. MPC was shown to decrease the accumulated control effort required (and subsequently power used) by a factor of two.

DiffTune: Auto-Tuning through Auto-Differentiation*

Cheng, Sheng
University of Illinois Urbana-Champaign

Kim, Minkyung
University of Illinois Urbana-Champaign

Song, Lin
University of Illinois Urbana-Champaign

Wu, Zhuhuan
University of Illinois Urbana-Champaign

Wang, Shenlong
UIUC

Hovakimyan, Naira
University of Illinois at Urbana-Champaign

This work presents a mu-tip passivity-based control method for the end-effector position tracking of an overactuated planar flexible-joint serial manipulator. While passivity-based controllers for flexible-joint manipulators have been explored in the literature, they typically focus on robustly tracking joint-space trajectories, rather than task-space trajectories. Mu-tip passivity-based control has been proposed as a method of task-space control of flexible manipulators, however, its theory is limited to systems that have as many actuators or twice as many actuators as end-effector degrees of freedom. The motivation for our work is to generalize mu-tip control theory for redundantly-acted flexible robotic manipulators with an arbitrary number of actuators. The proposed method uses the massive payload assumption which is based on the idea that when the payload is in motion the only energy present in the system is the payload's kinetic energy, and with this the system dynamics are completely described by two decoupled dynamic equations with one dynamic equation being valid when the payload is in motion and the other dynamic equation being valid when the payload is at rest. The translational payload dynamics are considered for tracking, and using a feedforward control term the translational tip dynamics of the payload are exactly linearized to a feedback control input which is chosen such that it guarantees tracking of the desired tip position. A scalar tuning parameter \( \mu \) is then used to define a filtered mu-tip error whose regulation is equivalent to the regulation of the payload position error and the payload velocity. Using the approximate stationary tip dynamic equations, passivity from the tip linearized feedback control input to the filtered mu-tip error is proven, from which the robust input-output stability of the chosen regulatory feedback control input is also shown. The proposed controller is validated through a dynamic simulation, with results indicating that the controller is able to effectively track desired end-effector positions.

Optimal Safety-Critical Control of Epidemic Processes, pp. 3142-3144

Butler, Brooks
Purdue University

Pare, Philip E.
Purdue University

We present a generalized model for epidemic processes that partitions control into changes in linear and non-linear flow rates between compartments, respectively. We then define an optimal control problem that minimizes the weighted cost of rate control on the generalized model while maintaining conditions that guarantee system safety using control barrier functions. Using this formulation, we prove that under homogeneous penalties the optimal controller will always favor increasing the linear flow out of an infectious process over reducing nonlinear flow in. Further, in the case of heterogeneous penalties, we provide necessary and sufficient conditions under which the optimal controller will set control of non-linear rates (i.e., the reduction of flow rate into the infection process) to zero. We then illustrate these results through the simulation of a bi-virus SEIQRS model.

Frequency Spectrum Analyze about the Discrete Control System, pp. 3145-3145

Yin, Chang
Chongqing Vocational and Technical University of Mechatronics

Wang, Ning
Chongqing Vocational and Technical University of Mechatronics

This paper analyses some key point's frequency spectrum characteristic in the discrete control system. Based on this analysis, this article points out some problem which maybe we've ignored in the discrete control system analyses and design. Excepting in the A/D step, in the D/A step, we also need to consider the Shannon's sampling law. This paper also makes some modification about the current SCR and PWM modelling in the voltage regulating system.

Neural Operators for Bypassing Kernel Gain Computations in PDE Control*

Bhan, Luke
University of California, San Diego

Shi, Yuan yuan
University of California San Diego

Krstic, Miroslav
University of California, San Diego

This paper analyses some key point's frequency spectrum characteristic in the discrete control system. Based on this analysis, this article points out some problem which maybe we've ignored in the discrete control system analyses and design. Excepting in the A/D step, in the D/A step, we also need to consider the Shannon's sampling law. This paper also makes some modification about the current SCR and PWM modelling in the voltage regulating system.
**Risk-Constrained Reinforcement Learning for Wide-Area Damping Control with Communication Delays**, pp. 3146-3148

Kwon, Kyung-bin, The University of Texas at Austin
Zhu, Hao, The University of Texas at Austin

We develop a framework to find the structured feedback controller for Wide-area damping control (WADC) considering the signal time delay in the communication network. To mitigate the uncertainty caused by both the time delay and the noise in the transition, we consider the mean-variance risk constraints along with the Linear Quadratic Regulator (LQR) objective function for the WADC problem. After reformulating the risk constraint as a quadratic function, we formulate the problem as a minimax problem and adopt the reinforcement learning-based algorithm called Stochastic Gradient Descent with Max-oracle (SGDmax) algorithm. By directly using the uncertainty data with this model-free approach, we estimate the gradient by Zero-order Policy Gradient (ZOPG) algorithm and adopt a gradient-descent method to update the optimal feedback controller for WADC. The numerical tests based on the IEEE 68-bus feeder have demonstrated the performance improvement of WADC by mitigating the fluctuation of the frequency deviation and reducing the variance of the objective function values for more stable wide-area damping control along the areas.

**Virtual Viscoelastic-Based Multi-Agent Systems: Pushing the Limits of Disturbance Propagation in Mini Self-Driving Cars**, pp. 3147-3147

Murugan, Dinesh, Northeastern University
Siami, Milad, Northeastern University

This work uses a graph theoretic approach to investigate the trade-offs between performance measures and update cycles in second-order consensus networks. Additionally, the study examines the real-time application of the theoretical advancements on Quanser's Qcars, a scaled model vehicle used for academic purposes. The findings are highly relevant to the design and implementation of large-scale consensus networks and autonomous vehicle platoons, as they emphasize the importance of balancing network density and update cycle speed for optimal performance. To extend the findings of the research to viscoelastic-based networks, the interaction between agents is modeled as a fractional-order system. Preliminary results are presented to capture the robustness of these networks.

**An LMI Approach to Closed-Loop Intravenous Medication Infusion Control with Guaranteed Absolute Stability**

Yin, Weidi, University of Maryland
Hohenhaus, Drew, University of Maryland
Hahn, Jin-Oh, University of Maryland
Rajamani, Rajesh, University of Minnesota

**Model-Free Reinforcement Learning for Automated Fluid Administration in Critical Care**

Estiri, Elham, Kent State University
Mirinejad, Hossein, Kent State University

**Modeling and Control of Autonomous Mobility-On-Demand Systems: A Model Predictive Approach**

Aalipour, Ali Khani, Alireza
University of Minnesota University of Minnesota-Twin Cities

Autonomous vehicles are rapidly evolving and will soon enable the application of large-scale mobility-on-demand (MoD) systems. Managing the fleets of available vehicles, commonly known as "rebalancing", is crucial to ensure that vehicles are distributed properly to meet customer demands. This paper presents an optimal control approach to optimize vehicle scheduling and rebalancing in an autonomous mobility-on-demand (AmoD) system. We use graph theory to model a city partitioned into virtual zones. Zones represent small areas of the city where vehicles can stop and pick up/drop off customers, whereas links denote corridors of the city along which autonomous vehicles can move. They are considered vertices and edges in the graph. Vehicles employed in the AmoD scheme are autonomous, and rebalancing can be executed by dispatching available empty vehicles to areas undersupplied. Rebalancing is performed on the graph's vertices, i.e., between city areas. We propose a novel linear discrete-time model of an AmoD system using a transformed network. After acquiring the model, the optimal rebalancing policy is derived analytically, and it is shown to prevent the system from becoming imbalanced. Moreover, the well-posedness of the model is illustrated, and an algorithm to derive the desired equilibrium points is introduced. To leverage the proposed model, we implemented the model predictive control (MPC) framework to find the optimal rebalancing and scheduling policy. We show the MPC's effectiveness and how the MPC framework can be implemented in real-time for a real-world case study. Numerical results show that for the smaller dispatching time intervals for the customer-carrying and rebalancing vehicles, there will be a significant improvement in the quality of service to customers. Moreover, the MPC with a quadratic cost function enhances the quality of service to customers and lowers the variation in performance measures among different origin-destination pairs.

**Dynamic Intermediate Routing in Traffic Networks**, pp. 3149-3149

Chiu, Chih-Yuan, University of California, Berkeley
Maheshwari, Chinmay, University of California Berkeley
Su, Pan-Yang, University of California, Berkeley
Sastry, Shankar, Univ. of California at Berkeley

In modern traffic networks, self-interested travelers independently select routes to minimize the remaining travel time to their destination. We present perturbed best-response traffic flow dynamics that capture the traffic redistribution that result from these intermediate routing decisions. We demonstrate that, under continuous-time dynamics, the flows converge to the Markovian Traffic Equilibrium (MTE), a notion of steady-state traffic assignment based on a sequential arc-selecting process. Moreover, the corresponding discrete-time dynamics converge to a neighborhood of the MTE. Our method generalizes to any arbitrary traffic network, even those with bi-directional edges. Finally, we provide numerical results on simulated traffic networks that corroborate our theoretical results.
Linearization of the Response of Piezoelectric Synthetic Jet Actuators through Input Signal Harmonic Tuning*

He, Zixin  
Mongeau, Luc G.  
McGill University  
Purdue University

Model Predictive Control (MPC) is widely used in industry for control of complex dynamic systems. MPC performance can be greatly improved by incorporating a data-driven approach that provides higher predictive accuracy through system identification of plant data. This poster presents a Model-on-Demand (MoD) approach to system identification and its integration into a 3-Degree of Freedom (3DoF) MPC framework. MoD is a data-centric, hybrid global-local modeling algorithm that builds models "on demand," relying on simple user decisions. At each time step, MoD fits a local polynomial over an adaptive neighborhood of an operating point. Through a synergism of local regression methods with database systems technology, MoD enables a controller to adapt to changes in the process dynamics, thus effectively providing the sophistication of global modeling frameworks while preserving the simplicity of local modeling techniques. The 3-DoF MoDMPC framework consequently provides a data-centric control approach that meets fundamental and practical needs typical for high-performance control of nonlinear systems.

Independent control actions for setpoint tracking, measured and unmeasured disturbance rejection are accomplished with specially formulated Kalman filters, while simultaneously satisfying output and input constraints. This facilitates better predictive actions and enables improved robustness in the face of uncertainty. The performance of the 3DoF MoD-MPC framework is validated through a case study involving an exothermic Continuous Stirred Tank Reactor (CSTR), a highly nonlinear industrial problem. It is contrasted with an ARX-based 3DoF MPC which generates highly underdamped and oscillatory responses for the same tuning parameters, in contrast to the smooth, superior setpoint tracking and disturbance rejection of the 3-DoF MoDMPC. Variations of the local NARX-based dynamic model are clearly evident in the simulation results, which explain the superior performance of 3DoF MoD-MPC.

He, Zixin  
Mongeau, Luc G.  
McGill University  
Purdue University

Fault-Prognostic Model Predictive Control with Physics-Data Driven Monitoring*  
Braniff, Austin  
Masud, Md Abdullah Al  
Tian, Yuhe  
West Virginia University  
WEST VIRGINIA UNIVERSITY  
West Virginia University

17:30-18:15  
ThD01.7

Learn-To-Race: An Open-Source Environment for Autonomous Racing*

Agarwal, Arav  
Chen, Bingqing  
Nyberg, Eric  
Francis, Jonathan  
Carnegie Mellon University  
Bosch Center for Artificial Intelligence  
Carnegie Mellon University  
Bosch Center for Artificial Intelligence

17:30-18:15  
ThD01.8

Data-Driven Nonlinear Control of a CSTR Using Three-Degree-Of-Freedom Model-On-Demand Model Predictive Control, pp. 3150-3150

Banerjee, Sarajii  
Khan, Owais  
El Mistiri, Mohamed  
Rivera, Daniel E.  
Arizona State University  
Arizona State University  
Arizona State University  
Arizona State University

17:30-18:15  
ThD01.9

Structured Neural-PI Control for Networked Systems: Stability and Steady-State Optimality Guarantees*

Cui, Wenqi  
Jiang, Yan  
Zhang, Baoesen  
Shi, Yuanyuan  
University of Washington  
University of Washington  
University of Washington  
University of California San Diego

17:30-18:15  
ThD01.10

Robust Prescribed-Time Stabilization of a Chain of Integrators Using Output Measurements and Finite Time-Varying Gains*

Verdés Kairuz, Ramón Imad  
Orlov, Yury  
Aguilar, Luis T.  
Instituto Politécnico Nacional  
CICESE  
Instituto Politecnico Nacional

17:30-18:15  
ThD01.11

Learning SIR Epidemic Behavior from Testing Data: Regression and Adaptive Observer Approaches*

Leung, Humphrey  
Rehnejar, William Ebenezaraj  
Hota, Ashish  
Pare, Philip E.  
Purdue University  
IIT Kharagpur  
Indian Institute of Technology (IIT), Kharagpur  
Purdue University

17:30-18:15  
ThD02.1

Robust MHE for Lateral Vehicle Dynamics, pp. 3151-3151

Arezki, Hasni  
Alessandri, Angelo  
Zemouche, Ali  
Università Degli Studi Di Genova  
University of Genoa  
CRAN UMR CNRS 7039 & Inria: EPI-DISCO

17:30-18:15  
ThD02.2

Hybrid Systems under Adversarial Scenarios*

J. Leudo, Santiago  
Garg, Kunal  
Sanfelice, Ricardo G.  
Cardenas, Alvaro A.  
University of California, Santa Cruz  
University of California at Santa Cruz  
University of California at Santa Cruz  
University of California, Santa Cruz

17:30-18:15  
ThD02.3

Unsupervised Learning SIR Epidemic Behavior from Testing Data: Regression and Adaptive Observer Approaches*  
Leung, Humphrey  
Rehnejar, William Ebenezaraj  
Hota, Ashish  
Pare, Philip E.  
Purdue University  
IIT Kharagpur  
Indian Institute of Technology (IIT), Kharagpur  
Purdue University

17:30-18:15  
ThD02.4

Robust MHE for Lateral Vehicle Dynamics, pp. 3151-3151

Arezki, Hasni  
Alessandri, Angelo  
Zemouche, Ali  
Università Degli Studi Di Genova  
University of Genoa  
CRAN UMR CNRS 7039 & Inria: EPI-DISCO

17:30-18:15  
ThD02.5

Hybrid Systems under Adversarial Scenarios*  
J. Leudo, Santiago  
Garg, Kunal  
Sanfelice, Ricardo G.  
Cardenas, Alvaro A.  
University of California, Santa Cruz  
University of California at Santa Cruz  
University of California at Santa Cruz  
University of California, Santa Cruz

17:30-18:15  
ThD02.6
problem in the presence of an opponent under dynamics that might exhibit both continuous and discrete behaviors. This setting is framed as a noncooperative game in which the dynamics of the players are modeled as a single hybrid equation. We present sufficient conditions with Hamilton-Jacobi-Isaacs-like equations to attain a saddle-point equilibrium in zero-sum games with hybrid dynamics. Connections between optimality and asymptotic stability are invoked, and a numerical example is used to illustrate the results. On the other hand, we study a switching-observer control design for safety under sensor Denial-of-Service attacks. We propose an attack-recovery strategy for scenarios where attack-mitigation approaches are not feasible, and the system needs to maintain safety under adversarial attacks. We design a switching observer and characterize bounds in the error of a state estimation scheme by specifying tolerable limits on the time length of attacks. We propose a switching control algorithm that renders forward invariant a set for the observer. By satisfying the error bounds of the state estimation, we guarantee that the safe set is rendered conditionally invariant with respect to a set of initial conditions.

17:30-18:15  ThD02.4
Sivashangaran, Shathushan Virginia Polytechnic Institute and State University
Khaimar, Apoorva Virginia Tech
Eskandarian, Azim Virginia Tech

Over 600,000 individuals go missing in the United States annually according to the U.S. Department of Justice (DOJ) National Missing and Unidentified Persons System (NamUs). Recent advancements in computer technology, sensors and communication have augmented historically human-intensive Search and Rescue (SAR) operations with utilitarian aerial and ground robotics systems that serve as useful tools for SAR personnel. The effectiveness of Unmanned Aerial Vehicles (UAVs) is limited in wilderness search areas with thick foliage, and urban environments effected by natural disasters, covered in rubble, which limit aerial visibility. This poster presents and evaluates a new reward formulation, and Deep Reinforcement Learning (DRL) framework for SAR Autonomous Ground Vehicle (AGV) navigation in areas with poor aerial coverage. Realistic outdoor and urban environments are used for training and evaluation in AutoVRL (AUTonomous ground Vehicle deep Reinforcement Learning simulator), a new high-fidelity AGV simulator we developed for sim-to-real DRL research, built upon the Bullet physics engine using OpenAI Gym and Stable Baselines3 (SB3) which utilizes the PyTorch ML framework. The DRL agent is trained for 50,000,000 steps over 9.5 days in a realistic outdoor environment resembling wilderness, and rural locations. Post-training results demonstrate the effectiveness of the proposed reward formulation and DRL framework for quick and efficient SAR subject location. The trained policy is further evaluated in a larger urban environment with no prior training or knowledge of environment characteristics to test the robustness, and extensibility of the DRL method, and shown to cognitively locate SAR subjects in areas unobservable to aerial surveillance.

17:30-18:15  ThD02.6
Application of Domain Adaptation Extreme Learning Machine in Multi-Fault Detection and Isolation*, pp. 3153-3153
Yao, Jiabao University of Alberta
Zhao, Qing Univ. of Alberta

17:30-18:15  ThD02.7
Modeling and Path Planning of a Quadcopter Testbed for Space Vehicle Control Design*
Elke, William University of Minnesota
Caverly, Ryan James University of Minnesota

17:30-18:15  ThD02.8
Optimality of Information-State Based Feedback for Partially Observed Linear Systems*
Gul Mohamed, Mohamed Texas A&M University
Naveed Texas A&M University
Goyal, Raman Texas A&M University
Wang, Ran Texas A&M University
Sharma, Aayushman Texas A&M University
Chakravorty, Suman Texas A&M University

17:30-18:15  ThD02.9
Bias Compensating Reinforcement Learning Control with Feedforward Adaptation for HVAC Systems, pp. 3154-3154
Anwar, Junaid Tennessee Tech University
Rizvi, Syed Ali Asad Tennessee Technological University

Around 76% of US electricity consumption is attributed to buildings [2]. Optimal control of the heating, ventilation, and air conditioning (HVAC) systems is essential for energy efficient buildings and thermal comfort of the occupants. However, modeling building HVAC systems for optimal control design purposes is challenging as such systems employ a variety of complex equipment. The presence of external disturbances arising from unknown heat gains, occupancy variations, light sources, and outside weather changes, further adds to the difficulty. Reinforcement learning (RL) has recently been popular in HVAC controls owing to its model-free capabilities. However, the treatment of disturbances is a harder problem in the RL framework because the presence of unknown disturbances can lead to inconsistencies in the associated learning equation that results in estimation bias [1]. Different from the game-theoretic approaches [4] and output regulation framework [5] employed in RL, we present a two-step design approach that consists of a bias compensating feedback controller and a feedforward adaptation mechanism both of which prevent estimation bias from incurring in the presence of unknown disturbances. The presented scheme is entirely output feedback driven and does not require the precise knowledge of system parameters (only the sign of the high-frequency gain is needed). Preliminary results have been obtained that show the effectiveness of the proposed scheme.

17:30-18:15  ThD02.10
Guidance and Control for Targeted Reentry of Drag-Modulated Spacecraft*
Hayes, Alex D. University of Minnesota
Caverly, Ryan James University of Minnesota
Comparative Study of Cooperative Platoon Merging Control Based on Reinforcement Learning

Irshayyid, Ali
Oakland University

Chen, Jun
Oakland University
Towards Flow Control: From Boundary Layers to Wind Farms and Back Again (Plenary Session)

Chair: Zhang, Wenlong
Arizona State University
Co-Chair: Hall, Carrie
Illinois Institute of Technology

08:30-09:30
FrSP1.1
Towards Flow Control: From Boundary Layers to Wind Farms and Back Again
Gayme, Dennice
Johns Hopkins University

FrSP2
A Journey through Diffusions (Plenary Session)

Chair: Andersson, Sean B.
Boston University
Co-Chair: Jain, Neera
Purdue University

08:30-09:30
FrSP2.1
A Journey through Diffusions*
Chen, Yongxin
Georgia Institute of Technology

FrA01
Automotive Systems (RI) (RI Session)

Chair: Dai, Ran
Purdue University
Co-Chair: Hashemi, Ehsan
University of Alberta

10:00-10:04
FrA01.1
Integral Action NMPC for Tight Maneuvers of Articulated Vehicles (I)
pp. 3155-3161
You, Sixiong
Purdue University
Greiff, Marcus Carl
Mitsubishi Electric Research Laboratories
Quirynen, Rien
Mitsubishi Electric Research Laboratories (MERL)
Ran, Shuangxuan
University of Michigan
Wang, Yebin
Mitsubishi Electric Research Labs
Berntorp, Karl
Mitsubishi Electric Research Labs
Dai, Ran
Purdue University
Di Cairano, Stefano
Mitsubishi Electric Research Labs

We propose an integral action nonlinear model predictive controller (NMPC) for trajectory tracking of an articulated vehicle with an uncertain hitching offset. The controller is intended for complex parking maneuvers including forward and backward maneuvering with tight specifications on the lateral positional tracking error of the trailer. In order to assess performance with uncertain hitching offsets, disturbances, and sensor noise, we conduct extensive hardware-in-the-loop simulations using a dSPACE Scalexio unit. With high-grade sensing, we demonstrate that the closed-loop control system achieves a lateral tracking error of <3 [cm] in expectation, and an absolute terminal error of <15 [cm] with high probability p>0.97. The proposed integral action is shown to be essential in achieving this performance, and the efficacy of the proposed NMPC is evaluated by comparison to previously reported MPCs.

10:04-10:08
FrA01.2
Optimization-Based Coordination and Control of Traffic Lights and Mixed Traffic in Multi-Intersection Environments (I)
pp. 3162-3168
Suriyarachchi, Nilesch
University of Maryland
Quirynen, Rien
Mitsubishi Electric Research Laboratories (MERL)
Baras, John S.
University of Maryland
Di Cairano, Stefano
Mitsubishi Electric Research Labs

Coordinating the flow of traffic through urban areas with multiple intersections is a complex problem whose solution has the potential to improve safety, increase throughput, and optimize energy efficiency. In addition to controlling traffic lights, the introduction of connected and automated vehicles (CAVs) offers opportunities in terms of additional sensing and actuation points within the traffic network. This paper proposes a centralized and a decentralized implementation for the joint coordination and control of both traffic signals and mixed traffic, including CAVs and human driven vehicles (HDVs), in a network of multiple connected traffic intersections. Mixed-integer linear programming (MILP) is used to compute safe control trajectories for both CAVs and traffic light signals, which minimize overall congestion and fuel consumption. Our approaches are validated using extensive traffic simulations on the SUMO platform and they are shown to provide improvements of around 32-60%, 90-96% and 40-60% in travel time, waiting time and fuel consumption, respectively, when compared to gap-based adaptive and timed traffic lights.

10:08-10:12
FrA01.3
Heavy-Duty Vehicle Air Drag Coefficient Estimation: From an Algebraic Perspective (I)
pp. 3169-3174
Wang, Zejiang
Oak Ridge National Laboratory
Cook, Adian
Oak Ridge National Laboratory
Shao, Yunli
Oak Ridge National Lab
Sujan, Vivek
Oak Ridge National Laboratory
Chambon, Paul
Oak Ridge National Laboratory
Deter, Dean
Oak Ridge National Laboratory
Perry, Nolan
Oak Ridge National Laboratory

When a heavy-duty vehicle (HDV) operates at the nominal highway speed, over two-thirds of its total resistive force comes from the air drag, contributing to more than half of its fuel consumption. One effective countermeasure to reduce the fuel consumption of HDVs is platooning, which employs connectivity and automated driving technologies to link two or more HDVs in convoy. Platooning allows HDVs to drive closer together and yields improved fuel economy and less CO2 emission thanks to the reduced air drag. Maximizing the energy benefits of an HDV platoon requires quantifying the drag interaction between vehicles. In practice, modeling the drag reduction in a platoon boils down to identifying the relationship between the air drag coefficient and the inter-vehicle distance. Existing approaches to identify the air drag coefficient include vehicle field test, wind tunnel experiment, and computational fluid dynamics simulation, which can be time-consuming and cost prohibitive. In contrast, this paper proposes an algebraic approach, which relies on onboard-measurable variables, to estimate the air drag coefficient of an HDV in a platoon. Its algebraic nature avoids the classical persistence of excitation condition for parameter identification and can yield the identified parameter almost instantaneously. Simulation results demonstrate its effectiveness and the improved estimation speed over a recursive least squares identifier.

10:12-10:16
FrA01.4
Hydrodynamics and Friction Estimation for Wet Tire/Ground Interactions (I)
pp. 3175-3180
Gong, Yongbin
Rutgers, the State University of New Jersey
Chen, Xunjie
Rutgers, the State University of New Jersey
Yi, Jingang
Rutgers University
Wang, Hao
Rutgers University

Understanding wet tire/road interactions is critical for predicting
Comparison results with other existing models illustrate the length of the contact patch and a LuGre friction model. Simulation etiquette. A key challenge is in determining a minimum set of parameters to parameterize the driving behavior for example in curves or for general traffic. However, whether these systems are actually used, depends on the driver's satisfaction with the system's way of driving. A promising approach to met the driver's individual preferences, is to personalize the assistance system. This paper presents a recursive Gaussian Process based analysis to determine the driver's preferences, during manual vehicle guidance, separately for various driving maneuvers. The recursive process enables an online-capable analysis where no maneuver data has to be stored. In addition, an event detection approach to identify relevant driving situations is proposed. The gained information about the driver's preferences can be accessed by modern assistance systems to individually parameterize the driving behavior for example in curves or for general velocity adjustments at speed limit changes.

Evaluating the safety of an autonomous vehicle (AV) depends on the behavior of surrounding agents which can be heavily influenced by factors such as environmental context and formally-defined driving etiquette. A key challenge is in determining a minimum set of assumptions on what constitutes reasonable foreseeable behaviors of other road users for the development of AV safety models and techniques. In this paper, we propose a data-driven AV safety design methodology that first learns "reasonable" behavioral assumptions from data, and then synthesizes an AV safety concept using these learned behavioral assumptions. We borrow techniques from control theory, namely high order control barrier functions and Hamilton-Jacobi reachability, to provide inductive bias to aid interpretability, verifiability, and tractability of our approach. In our experiments, we learn an AV safety concept using demonstrations collected from a highway traffic-weaving scenario, compare our learned concept to existing baselines, and showcase its efficacy in evaluating real-world driving logs.

This paper analyzes the xyz-motion planning problem for autonomous vehicles with active suspension systems. A generic nonlinear optimization problem based on a 3D quarter car model is formulated, where vertical motion planning and the knowledge of road surface data are taken into consideration for planning the motion of the vehicle body in 3D space. A novel z-motion planning methodology is proposed and integrated with a sampling-based xyz-motion planning framework. Finally, simulated driving scenarios are presented to illustrate the advantages of using the proposed planning framework.

Advanced driver assistance systems improve the driving comfort and contribute to enhance safety and energy efficiency in automotive traffic. However, whether these systems are actually used, depends on the driver's satisfaction with the system's way of driving. A promising approach to met the driver's individual preferences, is to personalize the assistance system. This paper presents a recursive Gaussian Process based analysis to determine the driver’s preferences, during manual vehicle guidance, separately for various driving maneuvers. The recursive process enables an online-capable analysis where no maneuver data has to be stored. In addition, an event detection approach to identify relevant driving situations is proposed. The gained information about the driver's preferences can be accessed by modern assistance systems to individually parameterize the driving behavior for example in curves or for general velocity adjustments at speed limit changes.

A distributed robust adaptive control framework is proposed for an adaptive cruise control system. The proposed approach is designed based on the model reference adaptive control approach. A robust control term is employed to make the system robust to any bounded disturbances, and a concurrent learning framework is leveraged to ensure the convergence of estimated parameters. The main feature of the developed robust adaptive cruise controller is that it does not require the speed of the lead vehicle. It also considers uncertainties in
both position and speed in the double integrator model. The string
stability notion of the proposed approach is also investigated, and the
performance of the control framework is evaluated in simulations in
the presence of parametric uncertainties, disturbances, and noise.

FrA02
Control Applications I (RI) (RI Session)
Sapphire IJ
Chair: Garcia Carrillo, Luis New Mexico State University
Rodolfo
Co-Chair: Wan, Yan University of Texas at Arlington

10:00-10:04 FrA02.1
High-Confidence Trajectory Planning for Off-Road Automated
Vehicles under Energy Constraints (I), pp. 3221-3226
Goulet, Nathan Clemson University
Ayalew, Beshah Clemson University
Castanier, Matthew US Army CCDC Ground Vehicle Systems Center
Skowronska, Annette US Army CCDC Ground Vehicle Systems Center

For automated vehicles operating in off-road environments, there is
substantial uncertainty in their energy needs and utilization. To
account for this uncertainty, we propose a high-confidence global
planner that obtains the path with the highest-confidence energy
constraints are met. We outline a sampling-based method to
approximate the energy stage cost uncertainty as a normal random
variable, and then transform the uncertain optimal control problem to
a deterministic one that can be solved using standard methods. We
couple this with a local nominal model predictive controller that
employs a dynamics model of the off-road vehicle on deformable
terrains. We show through Monte-Carlo simulations that the
framework is robust in the face of uncertainty in terms of energy
consumption and outperforms approaches that simply plan for the
minimum expected energy consumption.

10:04-10:08 FrA02.2
LQG Cycle-To-Cycle Knock Control Based on Identified Exhaust
Temperature Model (I), pp. 3227-3232
Tang, Jian Robert Bosch LLC
Dai, Wen Ford Motor Company
Archer, Chad Ford Motor Company
Yi, James Ford Motor Company
Zhu, Guoming Michigan State University

Spark ignition engines are often calibrated to operate as close to its
knock borderline as possible when MBT (maximum brake torque)
cannot be achieved. However, the existing combustion cycle-to-cycle
variations result in a relative conservative borderline knock control. To
reduce these variations, a real-time cycle-wised knock variation
control is proposed in this paper using measured exhaust
temperature as feedback. $Q$-Markov COVER (COVariance
Equivalent Realization) system identification was used to obtain a
linearized engine exhaust system model from spark timing deviation
to associated exhaust temperature and knock intensity variations.
Accordingly, a Linear–Quadratic–Gaussian (LQG) controller is
designed, based on the identified model, to minimize the knock
fluctuations based on exhaust temperature deviations. Note that the
cycle-based compensation adds spark timing deviation control to the
baseline so that knock combustion variations can be reduced. With
the help of the LQG control, the engine bench test shows a significant
reduction of knock combustion variations with its variance reduced by
28%.

10:08-10:12 FrA02.3
Stabilization and Trajectory Tracking of a Subactuated Aircraft Based
on a Geometric Algebra Approach, pp. 3233-3238
Escamilla, Leonardo New Mexico State University
Garcia Carrillo, Luis Rodolfo New Mexico State University
Sandoval, Steven New Mexico State University
Espinoza Quesada, Eduardo Steed Center for Research and
Advanced Studies of the National Polytecnico

A novel approach to the modeling and control of a subactuated
aircraft is performed based on Geometric Algebra (GA). The selected
platform for analysis is a quad rotorcraft. The derived model
leverages objects from GA, such as the rotor, to perform rotations,
replacing the need for Euler angles and quaternions. Controllers,
which operate exclusively on GA objects, are developed to regulate the
attitude, altitude, and translation of the quad rotorcraft. Numerical
examples, including way-point navigation and trajectory tracking,
illustrate the feasibility of the GA approach.

10:12-10:16 FrA02.4
A Transmission Rate Estimator & Controller for Infectious Disease
SIR Models - Constant Case, pp. 3239-3244
Barbieri, Enrique University of Houston
Tzouanas, Vassilios University of Houston - Downtown

A widely studied susceptible S(t), infectious I(t), and removed R(t)
(SIR) family of deterministic, lumped-parameter models of directly
transmitted infectious diseases is considered to estimate the
transmission rate assumed to be piecewise constant via a linear,
extended-state observer. Then, although the transmission rate is not
a control signal in the traditional sense, the application of feedback
control design offers guidance in implementing mitigating actions that
curb the disease spread. A linearized model at each measurement
point is used for offline observer design with the transmission rate
treated as an unknown but constant disturbance. The observer-based
controller simulations in discrete time explore heuristic policies that
could be implemented by public health and government organizations.

10:16-10:20 FrA02.5
Optimal Control of Stochastic Power Buffers in DC Microgrids, pp.
3245-3250
Valsala Priyadarshini University of Texas at Arlington
Premakumar, Abhiram University of Texas at Arlington
Chakravarthy, Abhiram University of Texas at Arlington
Qian, Yang-Yang University of Virginia
Wan, Yan University of Texas at Arlington
Davoudi, Ali University of Texas-Arlington

Power buffers are DC-DC converters where a large capacitor helps
shield the DC grid from abrupt load changes. While point of load
collectors (PoLCs) are mainly tasked with meeting the terminal load
requirements, power buffers add inertia to the DC grid during
transients. The stochastic behaviour of loads could necessitate an
adaptive optimal control strategy for power buffers. The optimal
control of power buffers is usually formulated as a non-zero-sum
differential game. The load behaviour can be captured using a
multivariate probabilistic collocation method (MPCM) to sample its
uncertainty. An integral reinforcement learning (IRL) algorithm,
applied to the multiplayer differential game, finds the optimal control
policy. Simulation studies demonstrate the performance of the
IRL-based stochastic optimal control of power buffers in a DC
microgrid.

10:20-10:24 FrA02.6
Model Predictive Control of Cadmium Telluride (CdTe) Quantum
Dot(QD) Crystallization, pp. 3251-3256
Sitapure, Niranjan Texas A&M University
Kwon, Joseph Texas A&M University

Inorganic semiconductor quantum dots (QDs) have emerged as a
promising alternative to silicon with widespread applications in
next-generation displays and high-efficiency solar cells. Generally, the
optoelectronic properties of QDs are majorly dictated by their
bandgap energy (related to their size), which makes it important to
accurately predict and control size of QD crystals. Unfortunately,
unlike protein or sugar crystallization, there are very few models that describe QD crystallization. Moreover, the existing QD models are either based on computationally demanding multiscale modeling approaches making them unsuitable for direct implementation in a controller framework or based on black-box modeling providing little insight into crystallization kinetics. To address this knowledge gap, we present a population balance equation (PBE)-based model for QD crystallization. Specifically, the PBE along with mass and energy balance equations, growth and nucleation kinetics are decomposed into first-order ordinary differential equations (ODEs) that can be easily solved using present-day python solvers. Further, a model predictive controller (MPC) is demonstrated for set-point tracking of crystal size and distribution (CSD). Also, given the high computational efficiency of the developed simulation it can be directly incorporated within the MPC without the requirement of a surrogate model, thereby reducing the plant-model mismatch. Further, the case study of CdTe QDs, which are widely utilized in displays and solar cells, has been investigated. The simulation results are in good agreement with experimental observations, and the proposed MPC demonstrates effective size-control of CdTe QDs by manipulating the solute-concentration using a semi-batch addition operation. Overall, to the best of our knowledge, the current work is the first instance of utilizing well-established PBE-based crystallization model for accurate modeling and MPC-based control of QDs, and will serve as a foundation for modeling other QD systems.

10:24-10:28 FrA02.7
Improving Accuracy of Optical Sorters Using Closed-Loop Control of Material Recirculation, pp. 3257-3263
Vieth, Jonathan Hamburg University of Technology
Reith-Braun, Marcel Karlsruhe Institute of Technology (KIT)
Bauer, Albert Technical University of Berlin
Pfaff, Florian Karlsruhe Institute of Technology (KIT)
Maier, Georg Fraunhofer Institute of Optronics, System Technologies and Image Gruna, Robin Fraunhofer Institute of Optronics, System Technologies and Image Längle, Thomas Fraunhofer Institute of Optronics, System Technologies and Image Krugel-Emden, Harald Technische Universität Berlin Hanebeck, Uwe D. Karlsruhe Institute of Technology (KIT)

Optical sorting is a key technology for the circular economy and is widely applied in the food, mineral, and recycling industries. Despite its widespread use, one typically resorts to expensive means of adjusting the accuracy, e.g., by reducing the mass flow or changing mechanical or software parameters, which typically requires manual tuning in a lengthy, iterative process. To circumvent these drawbacks, we propose a new layout for optical sorters along with a controller that allows re-feeding of controlled fractions of the sorted mass flows. To this end, we build a dynamic model of the sorter, analyze its static behavior, and show how material recirculation affects the sorting accuracy. Furthermore, we build a model predictive controller (MPC) employing the model and evaluate the closed-loop sorting system using a coupled discrete element–computational fluid dynamics (DEM–CFD) simulation, demonstrating improved accuracy.

10:28-10:32 FrA02.8
A Control-Oriented Reduced-Order Model for Lithium-Metal Batteries, pp. 3264-3269
Kawakita de Souza, Aloisio University of Colorado at Colorado Springs
Henrique Wesley, Hileman University of Colorado at Colorado Springs
Trimboli, Michael University of Colorado, Colorado Springs
Plett, Gregory L. University of Colorado, Colorado Springs

Lithium-metal batteries (LMB) are attractive for energy-storage applications because of their high specific energy and energy density. Unlike lithium-ion batteries (LIB), LMB have metallic lithium anodes which introduce complications to modeling their long-term behavior. In particular, a dead-lithium layer grows over time, and this must be described in any battery-management-system (BMS) model to enable producing good long-term estimates of state-of-charge, state-of-health, and power limits. This paper shows how to convert an LMB PDE model from the literature into a reduced-order control-oriented format suitable for implementation in BMS algorithms.

10:32-10:36 FrA02.9
2D Density Control of Micro-Particles Using Kernel Density Estimation, pp. 3270-3275
Matei, Ion Palo Alto Research Center
de Kleer, Johan Palo Alto Research Center
Zhenirovskyy, Maksym Palo Alto Research Center

We address the challenge of controlling the density of particles in two dimensions by manipulating the electric field acting on the particles immersed in a dielectric fluid. An array of electrodes is used to control the electric field, which applies dielectrophoretic forces to achieve the desired pattern of particle density. To model the motion of a particle, we use a lumped, 2D, capacitive-based, and nonlinear model. We estimate the spatial dependence of the capacitances using electrostatic COMSOL simulations. We formulate an optimal control problem to determine the electrode potentials that will produce the desired particle density pattern. The loss function is defined in terms of the difference between the target density and the particle density at a specific final time. To estimate the particle density, we use a kernel density estimator (KDE) computed from the particle positions that vary with the electrode potentials. The effectiveness of our approach is demonstrated through numerical simulations that illustrate how the particle positions and electrode potentials change when shaping the particle density from a uniform to a Gaussian distribution.

10:36-10:40 FrA02.10
Implementation and Initial Testing of a Model Predictive Controller for Safety Factor Profile and Energy Regulation in the EAST Tokamak, pp. 3276-3281
Wang, Zibo Lehigh University
Wang, Hexiang Shanghai Institute of Applied Physics, Chinese Academy of Sciences
Schuster, Eugenio Lehigh University
Luo, Zhengping Institute of Plasma Physics, Chinese Academy of Sciences
Huang, Yao Institute of Plasma Physics, Chinese Academy of Sciences
Yuan, Quiping Institute of Plasma Physics, Chinese Academy of Sciences
Xiao, B. J. Institute of Plasma Physics, Chinese Academy of Sciences
Humphreys, D.A. General Atomics
Paruchuri, Sai Tej Lehigh University

The tokamak, a potential candidate for realizing nuclear fusion energy on Earth, uses strong magnetic fields to confine a hot ionized gas (plasma) in a toroidal vacuum chamber. The ability of tokamaks to run in high-performance modes of operation demands advanced control capabilities to regulate the spatial distribution (profile) of several plasma properties such as the safety factor $\text{qS}$. A model predictive control (MPC) approach has been followed to further advance such control capabilities for the EAST tokamak. The proposed controllers have the capability of simultaneously regulating the $\text{qS}$-profile and the plasma stored energy $\text{SWS}$ by controlling the plasma current $\text{i}_p$, the individual powers of four neutral beam injectors.
further training using Proximal Policy Optimization (PPO). We show that the real-time optimization is successfully carried out within the time constraints imposed by the dynamics of the plasma.

Controller design for bipedal walking on dynamic rigid surfaces (DRSes), which are rigid surfaces moving in the inertial frame (e.g., ships and airplanes), remains largely underexplored. This paper introduces a hierarchical control approach that achieves stable underactuated bipedal walking on a horizontally oscillating DRS. The highest layer of our approach is a real-time motion planner that generates desired global behaviors (i.e., center of mass trajectories and footstep locations) by stabilizing a reduced-order robot model. One key novelty of this layer is the derivation of the reduced-order model by analytically extending the angular momentum based linear inverted pendulum (ALIP) model from stationary to horizontally moving surfaces. The other novelty is the development of a discrete-time foot-placement controller that exponentially stabilizes the hybrid, linear, time-varying ALIP. The middle layer translates the desired global behaviors into the robot's full-body reference trajectories for all directly actuated degrees of freedom, while the lowest layer exponentially tracks those reference trajectories based on the full-order, hybrid, nonlinear robot model. Simulations confirm that the proposed framework ensures stable walking of a planar underactuated biped under different swaying DRS motions and gait types.

Reinforcement learning (RL) may enable fixed-wing unmanned aerial vehicles (UAVs) to achieve more agile and complex objectives than typical methods. However, RL has yet struggled to achieve even minimal success on this problem; fixed-wing flight with RL-based guidance has only been demonstrated in literature with reduced state and/or action spaces. In order to achieve full 6-DOF RL-based guidance, this study begins training with imitation learning from classical guidance, a method known as warm-starting (WS), before further training using Proximal Policy Optimization (PPO). We show that warm starting is critical to successful RL performance on this problem. PPO alone achieved a 2% success rate in our experiments. Warm-starting alone achieved 32% success. Warm-starting plus PPO achieved 57% success over all policies, with 40% of policies achieving 94% success.

10:30-10:45 FrA03.3

Extraction of Unknown Scalar Fields with Multifidelity Gaussian Processes under Local Uncertainty, pp. 3296-3303

Coleman, Demetrus Michigan State University
Bopardikar, Shaunak D. Michigan State University
Srivastava, Vaibhav Michigan State University
Tan, Xiaobo Michigan State University

Autonomous marine vehicles are deployed in oceans and lakes to collect spatio-temporal data. GPS is often used for localization, but is inaccessible underwater. Poor localization underwater makes it difficult to pinpoint where data are collected, to accurately map, or to autonomously explore the ocean and other aquatic environments. This paper proposes the use of multifidelity Gaussian process regression to incorporate data associated with uncertain locations. With the proposed approach, an adaptive sampling algorithm is developed for exploration and mapping of unknown scalar fields. The reconstruction performance based on the multifidelity model is compared to that based on a single-fidelity Gaussian process model that only uses data with known locations, and to that based on a single-fidelity Gaussian process model that ignores the localization error. Numerical results show that the proposed multifidelity approach outperforms both single-fidelity approaches in terms of the reconstruction accuracy.

10:45-11:00 FrA03.4

A Smoothing Algorithm for Minimum Sensing Path Plans in Gaussian Belief Space, pp. 3304-3309

Pedram, Ali Reza University of Texas at Austin
Tanaka, Takashi University of Texas at Austin

This paper explores minimum sensing navigation of robots in environments cluttered with obstacles. The general objective is to find a path plan to a goal region that requires minimal sensing effort. In [1], the information-geometric RRT* (IG-RRT*) algorithm was proposed to efficiently find such a path. However, like any stochastic sampling-based planner, the computational complexity of IG-RRT* grows quickly, impeding its use with a large number of nodes. To remedy this limitation, we suggest running IG-RRT* with a moderate number of nodes, and then using a smoothing algorithm to adjust the path obtained. To develop a smoothing algorithm, we explicitly formulate the minimum sensing path planning problem as an optimization problem. For this formulation, we introduce a new safety constraint to impose a bound on the probability of collision with obstacles in continuous-time, in contrast to the common discrete-time approach. The problem is amenable to solution via the convex-concave procedure (CCP). We develop a CCP algorithm for the formulated optimization and use this algorithm for path smoothing. We demonstrate the efficacy of the proposed approach through numerical simulations.

11:00-11:15 FrA03.5

CHAMP: Integrated Logic with Reinforcement Learning for Hybrid Decision Making for Autonomous Vehicle Planning, pp. 3310-3315

Jafari, Rouhollah General Motors
Esna Ashari, Alireza General Motors
Huber, Marcus GM LLC

A Cognitive Hybrid Autonomous Motion Planner (CHAMP) is developed for autonomous driving applications in challenging driving scenarios. The proposed hybrid planner unifies a hierarchical rule-based decision-making architecture with Reinforcement Learning (RL). For challenging intersection scenarios, RL agents are trained to replace a subset of the rules in the logical planner. The hybrid planner is systematically tested and benchmarked to demonstrate its effectiveness in handling challenging road scenario with congested
and chaotic traffic conditions.

11:15-11:30 FrA03.6

**RGB-LiDAR Pipeline for 3D Bounding Box Estimation in Low SWaP-C Indoor Navigation Applications**, pp. 3316-3323

Hoobler, Richard University of Texas at Austin
Wilberg, Dallin University of Texas at Austin
Akella, Maruthi The University of Texas at Austin

The generation of 3D bounding boxes from a combination of RGB images and depth data is an important area of research for autonomous systems. Additional constraints must be considered in order for any method to be implemented in a small form factor unmanned aerial vehicle (UAV) or other robotic system. In this work, an "ultra-lightweight" pipeline is developed and used to generate 3D bounding boxes from aligned RGB-LiDAR images. Different from current implementations, the design of this pipeline was made to maintain a similar performance to more computationally intensive algorithms while also being implementable onboard low SWaP-C systems. The pipeline is demonstrated in a computationally restricted indoor environment by a small rover to navigate around obstacles while searching for a target object.

| FrA04 | Sapphire AB |
| Methods in Robotics, Optimization, Learning, and Safety for Control of Cyber-Physical Systems | Invited Session |

**Chair**: Cao, Yongcan University of Texas, San Antonio
**Co-Chair**: Garcia, Eloy Air Force Research Laboratory
**Organizer**: Sinha, Abhinav University of Texas at San Antonio
**Organizer**: Cao, Yongcan University of Texas, San Antonio
**Organizer**: Garcia, Eloy Air Force Research Laboratory

10:00-10:15 FrA04.1

**Future-Focused Control Barrier Functions for Autonomous Vehicle Control (I)**, pp. 3324-3331

Black, Mitchell University of Michigan
Jankovic, Mrdjan Ford Research (retired)
Sharma, Abhishek Ford Motor Company
Panagou, Dimitra University of Michigan, Ann Arbor

In this paper, we introduce a class of future-focused control barrier functions (ff-CBF) aimed at improving traditionally myopic CBF based control design and study their efficacy in the context of an unsigned four-way intersection crossing problem for collections of both communicating and non-communicating autonomous vehicles. Our novel ff-CBF encodes that vehicles take control actions that avoid collisions predicted under a zero-acceleration policy over an arbitrarily long future time interval. In this sense the ff-CBF defines a virtual barrier, a loosening of which we propose in the form of a relaxed future-focused CBF (rff-CBF) that allows a relaxation of the virtual ff-CBF barrier far from the physical barrier between vehicles. We study the performance of ff-CBF and rff-CBF based controllers on communicating vehicles via a series of simulated trials of the intersection scenario, and in particular highlight how the rff-CBF based controller empirically outperforms a benchmark controller from the literature by improving intersection throughput while preserving safety and feasibility. Finally, we demonstrate our proposed ff-CBF control law on an intersection scenario in the laboratory environment with a collection of 5 non-communicating AION ground rovers.

10:15-10:30 FrA04.2


Bhargav, Jayanth Purdue University
Ghasemi, Mahsa Purdue University
Sundaram, Shreyas Purdue University

Mixed-Observable Markov Decision Processes (MOMDPs) are used to model systems where the state space can be decomposed as a product space of a set of state variables, and the controlling agent is able to measure only a subset of those state variables. In this paper, we consider the setting where we have a set of potential sensors to select for the MOMDP, where each sensor measures a certain state variable and has a selection cost. We formulate the problem of selecting an optimal set of sensors for MOMDPs (subject to certain budget constraints) to maximize the expected infinite-horizon reward of the agent and show that this sensor placement problem is NP-Hard, even when one has access to an oracle that can compute the optimal policy for any given instance. We then study a greedy algorithm for approximate optimization and show that there exist instances of the MOMDP sensor selection problem where the greedy algorithm can perform arbitrarily poorly. Finally, we provide experimental results for the greedy algorithm for randomly generated MOMDP instances and show that, in practice, the greedy algorithm provides near-optimal solutions for many cases, but one cannot provide general theoretical guarantees for its performance. In total, our work establishes fundamental complexity results for the problem of optimal sensor placement for MOMDPs.

10:30-10:45 FrA04.3

**Dynamic Component-Based Design Optimization of Multicopter Aircraft (I)**, pp. 3338-3343

Renkert, Philip University of Illinois at Urbana-Champaign
Alleyne, Andrew G. University of Minnesota

Rising complexity of engineered systems, increasing needs for coordination among specialized design teams, and the emergence of component-based design modalities have created a need for component-based design optimization tools. Further, many modern systems are dynamic, and dynamic performance is a core component of the design objective. This paper builds on a hybrid methodology for component-based design optimization by expanding the formulation to dynamic systems. The method is applied to select a planar quadrotor's components and input trajectory to minimize the total to complete a dynamic mission.

10:45-11:00 FrA04.4

**Two-Player Reconnaissance Game with Half-Planar Target and Retreat Regions (II)**, pp. 3344-3349

Lee, Yoonjae The University of Texas at Austin
Bakolas, Efthathios The University of Texas at Austin

This paper discusses the reconnaissance game that involves two mobile agents: the Intruder and the Defender. The Intruder is tasked to reconnoiter a territory of interest (target region) and then return to a safe zone (retreat region), where the two regions are disjoint half-planes, while being chased by the faster Defender. This paper focuses on the scenario where the Defender is not guaranteed to capture the Intruder before the latter agent reaches the retreat region. The goal of the Intruder is to minimize its distance to the target region, whereas the Defender's goal is to maximize the same distance. The game is decomposed into two phases based on the Intruder's myopic goal. The complete solution of the game corresponding to each phase, namely the Value function and state-feedback equilibrium strategies, is developed in closed-form using differential game methods. Numerical simulation results are presented to showcase the efficacy of our solutions.

11:00-11:15 FrA04.5

**Perimeter Defense Using a Turret with Finite Range and Startup Times (I)**, pp. 3350-3355

Bajaj, Shivam Michigan State University
Bopardikar, Shaunak D. Michigan State University
Von Moll, Alexander Air Force Research Laboratory
Tomg, Eric Michigan State University
Casbeer, David W. Air Force Research Laboratory

We consider a perimeter defense problem in a planar conical
environment comprising a turret that has a finite range and non-zero startup time. The turret seeks to defend a concentric perimeter against N>1 intruders. Upon release, each intruder moves radially towards the perimeter with a fixed speed. To capture an intruder, the turret’s angle must be aligned with that of the intruder’s angle and must spend a specified startup time at that orientation. We address offline and online versions of this optimization problem. Specifically, in the offline version, we establish that in general parameter regimes, this problem is equivalent to solving a Travelling Repairperson Problem with Time Windows (TRP-TW). We then identify specific parameter regimes in which there is a polynomial time algorithm that maximizes the number of intruders captured. In the online version, we present a competitive analysis technique in which we establish a fundamental guarantee on the existence of at best (N-1)-competitive algorithms. We also design two online algorithms that are provably 1 and 2-competitive in specific parameter regimes.

11:15-11:30 FrA04.6
An Optimization-Based Human Behavior Modeling and Prediction for Human-Robot Collaborative Disassembly (I), pp. 3356-3361

Tian, Sibo
University at Buffalo
Liang, Xiao
University at Buffalo
Zheng, Minghui
University at Buffalo

To achieve a safe and seamless human-robot collaboration in intelligent remanufacturing, robot agents should be able to understand human behaviors, predict human future motion, and incorporate motion prediction into their planning process. While most existing human prediction algorithms suffer from poor generalization and huge training data requirements, this paper models the human agent as a rational model seeking to minimize an unknown cost function along the motion trajectory. With such modeling, we design a set of features, such as collision avoidance, maintaining comfort during the motion, and reaching the goal point without too much detour, that could capture human intents during HRC. Maximum-Entropy inverse reinforcement learning is then leveraged to learn the underlying cost function from noisy human demonstrations. The human motion prediction is obtained by solving an optimization problem with a learned cost function. We particularly build an HRC dataset for human-robot-collaborative disassembly tasks and applied the proposed algorithm to this new dataset. Experimental studies are extensively conducted to validate our human motion prediction model.

10:00-10:15 FrA05.1
Reinforcement Learning Based Approximate Optimal Control of Nonlinear Systems Using Carleman Linearization, pp. 3362-3367

Kar, Jishnu deep
North Carolina State University
Bai, He
Oklahoma State University
Chakrabortty, Aranya
North Carolina State University

We develop a policy iteration-based model-free reinforcement learning (RL) control for nonlinear systems with single input. First, Carleman linearization, a commonly used linearization technique in the Hilbert space, is applied to express the nonlinear system as an infinite-dimensional Carleman state-space model, followed by derivation of an online state-feedback RL controller using state and input data in this infinite-dimensional space. Next, the practicality of using (it any) finite-order truncation of this controller, and the corresponding closed-loop stability of the nonlinear plant is established. Results are validated using two numerical examples, where we show how our proposed method provides solutions close to the optimal control resulting from the model-based Carleman controllers. We also compare our controller to alternative data-driven methods, showing its advantage in terms of shorter learning time.

10:15-10:30 FrA05.2
Iterative Convex Optimization for Model Predictive Control with Discrete-Time High-Order Control Barrier Functions, pp. 3388-3375

Liu, Shuo
Boston University
Zeng, Jun
University of California, Berkeley
Sreenath, Koushil
University of California, Berkeley
Belta, Calin
Boston University

Safety is one of the fundamental challenges in control theory. Recently, multi-step optimal control problems for discrete-time dynamical systems were formulated to enforce stability, while subject to input constraints as well as safety-critical requirements using discrete-time control barrier functions within a model predictive control (MPC) framework. Existing work usually focus on the feasibility or the safety for the optimization problem, and the majority of the existing work restrict the discussions to relative-degree one control barrier functions. Additionally, the real-time computation is challenging when a large horizon is considered in the MPC problem for relative-degree one or high-order control barrier functions. In this paper, we propose a framework that solves the safety-critical MPC problem in an iterative optimization, which is applicable for any relative-degree control barrier functions. In the proposed formulation, the nonlinear system dynamics as well as the safety constraints modeled as discrete-time high-order control barrier functions (DHO CBF) are linearized at each time step. Our formulation is generally valid for any control barrier function with an arbitrary relative-degree. The advantages of fast computational performance with safety guarantee are analyzed and validated with numerical results.

10:30-10:45 FrA05.3
Nonsmooth Herglotz Variational Principle, pp. 3376-3381

Lopez Gordon, Asier
Instituto De Ciencias Matematicas
Colombo, Leonardo Jesus
Spanish National Research Council
de Leon, Manuel
ICMAT, CSIC

In this paper, the theory of smooth action-dependent Lagrangian mechanics (also known as contact Lagrangians) is extended to a non-smooth context appropriate for collision problems. In particular, we develop a Herglotz variational principle for non-smooth action-dependent Lagrangians which leads to the preservation of energy and momentum at impacts. By defining appropriately a Legendre transform, we can obtain the Hamilton equations of motion for the corresponding non-smooth Hamiltonian system. We apply the result to a billiard problem in the presence of dissipation.

10:45-11:00 FrA05.4
Continuous-Time Policy Optimization, pp. 3382-3388

Zhan, Guojian
Tsinghua University
Jiang, Yuxuan
Tsinghua University
Duan, Jingliang
National University of Singapore
Li, Shengbo Eben
Tsinghua University
Cheng, Bo
TSINGHUA UNIVERSITY
Li, Keqiang
Tsinghua University, Beijing, China

Discretized dynamics is widespread in numerical optimization and optimal control. However, the physical system is inherently continuous at the macroscopic scale, thus handling the original continuous-time problem is desirable. In this paper, we focus on learning an optimal policy under the continuous-time finite-horizon optimal control setting. We introduce continuous-time policy optimization (CTPO), which employs the adjoint method to calculate the policy gradient, then implements optimization by gradient descent. The nature of CTPO is to minimize the integral of Hamiltonian over the time horizon to approach optimality, which fits the framework of Pontryagin’s minimum principle. We further reveal that the intrinsic connection to its discrete-time counterpart lies in the different order of
Lyapunov stability is employed to demonstrate the uniform ultimate in the critic MNN update law to overcome catastrophic forgetting. Hamilton-Jacobi-Bellman (HJB) error. This WVA term is incorporated proposed wherein the significance of weights is derived by using function gradient. The NN identifier, on the other hand, provides the identifier. The critic MNN weight tuning is accomplished using an continuous-

In this paper, we introduce a reduced order Iterative Linear Quadratic Regulator (RO-ILQR) approach for the optimal control of nonlinear Partial Differential Equations (PDE). The approach proposes a novel modification of the ILQR technique: it uses the Method of Snapshots to identify a reduced order Linear Time Varying (LTW) approximation of the nonlinear PDE dynamics around a current estimate of the optimal trajectory, utilizes the identified LTW model to solve a time varying reduced order LQR problem to obtain an improved estimate of the optimal trajectory along with a new reduced basis, and iterates till convergence. The proposed approach is tested on the viscous Burger's equation and two phase field models for microstructure evolution in materials, and the results show that there is a significant reduction in the computational burden over the standard ILQR approach, without sacrificing performance.

This study provides a lifelong integral reinforcement learning (LIRL)-based optimal tracking scheme for uncertain nonlinear continuous-time (CT) systems using multilayer neural network (MNN). In this LIRL framework, the optimal control policies are generated by using both the critic neural network (NN) weights and single-layer NN identifier. The critic MNN weight tuning is accomplished using an improved singular value decomposition (SVD) of its activation function gradient. The NN identifier, on the other hand, provides the control coefficient matrix for computing the control policies. An online weight velocity attenuation (WVA)-based consolidation scheme is proposed wherein the significance of weights is derived by using Hamilton-Jacobi-Bellman (HJB) error. This WVA term is incorporated in the critic MNN update law to overcome catastrophic forgetting. Lyapunov stability is employed to demonstrate the uniform ultimate boundedness of the overall closed-loop system. Finally, a numerical example of a two-link robotic manipulator supports the theoretical claims.

We consider the control of a Markov decision process (MDP) that undergoes an abrupt change in its transition kernel (mode). We formulate the problem of minimizing regret under control switching based on mode change detection, compared to a mode-observing controller, as an optimal stopping problem. Using a sequence of approximations, we reduce it to a quickest change detection (QCD) problem with Markovian data, for which we characterize a state-dependent threshold-type optimal change detection policy. Numerical experiments illustrate various properties of our control-switching policy.

In this paper, we propose a static observation space partitioning approach to solve a continuous-time control problem with Markovian data, for which we characterize a state-dependent threshold-type optimal change detection policy. Numerical experiments illustrate various properties of our control-switching policy.

This paper studies the deployment of joint moving target defense (MTD) and deception against multi-stage cyberattacks. Given the system equipped with MTD that randomizes between different configurations, we investigate how to allocate a bounded number of sensors in each configuration to optimize the probability of detecting the attack before the attacker achieves its objective. Specifically, two types of sensors are considered: intrusion detectors that are observable by the attacker and stealthy sensors that are not observable to the attacker. We propose a two-step optimization-based approach: Firstly, the defender allocates intrusion detectors assuming the attacker will best respond to evade detection. Secondly, the defender will allocate stealthy sensors, given the best response attack strategy computed in the first step, to further reduce the attacker’s chance of success. We illustrate the effectiveness of the proposed methods using a cyber defense example.

Controlling a Markov Decision Process with an Abrupt Change in the Transition Kernel, pp. 3401-3408

Dahlin, Nathan University of Illinois at Urbana-Champaign
Bose, Subhonnesh University of Illinois at Urbana Champaign
Veeravalli, Venugopal V. Univ of Illinois, Urbana-Champaign

Markov Processes (Regular Session) Sapphire 411B
FrA06
Chair: Han, Shuo University of Illinois Chicago
Co-Chair: Dahlin, Nathan University of Illinois at Urbana-Champaign

10:00-10:15 FrA06.1

Provably-Correct Partitioning Approach for Continuous-Observation POMDPs with Special Observation Distributions, pp. 3422-3427

Zheng, Wei University of Notre Dame
Lin, Hai University of Notre Dame

The partially observable Markov decision process with continuous observations has emerged as a popular model for system modeling and sequential decision-making for many real-world problems. The main challenge induced by continuous observations is its high computational complexity in the planning process because it is impossible to enumerate all observations in a continuous space. In this paper, we propose a static observation space partitioning approach to solve a continuous-observation POMDP approximately.
Although observation space partitioning approaches have been investigated in the literature, a formal analysis of the partitioning effect on the system performance is still missing. We aim to fill this gap by providing a formal analysis of the approximation error. For this, the belief update function is shown to be Lipschitz continuous for the observation when the observation function satisfies certain properties. With this property, we formally prove that the approximation error of each value iteration is bounded. Meanwhile, we show that the proposed approach can be integrated into the heuristic search value iteration algorithm with performance guarantees. Finally, the advantage of using the static partitioning approach rather than the Monte Carlo sampling approach is validated by experimental results.

11:00-11:15 FrA06.5

Finite-Region Asynchronous Fault-Tolerant Control of 2-D Markov Jump Systems with Sensor Faults (I), pp. 3428-3433
Ren, Chengcheng
Xia, Zeliang
He, Shuping
Anhui University

This paper investigates the finite-region asynchronous fault-tolerant control problem for 2-D Markov jump systems with sensor faults. Considering the system mode and controller mode are asynchronous, we aim to derive a suitable asynchronous fault-tolerant controller such that the closed-loop 2-D Markov jump systems be finite-region stabilizable and satisfies the given $\|\cdot\|_{\infty}$ performance index. Applying the stochastic Lyapunov-Krasovskii functional methods, some sufficient conditions are given to obtain the finite-region controller. Finally, a numerical example is used to show the feasibility and validity of the main results.

FrA07
Computational Methods (Regular Session)
Chair: Liu, Jinfeng
Co-Chair: Hafstein, Sigurdur
University of Alberta
University of Iceland
Computing Forward Reachable Sets for Nonlinear Adaptive Multirotor Controllers, pp. 3434-3441
Han, Juyeop
Korea Advanced Institute of Science and Technology
Choi, Han-Lim
KAIST

In multirotor systems, guaranteeing safety while considering unknown disturbances is essential for robust trajectory planning. The Forward reachable set (FRS), the set of feasible states subject to bounded disturbances, can be utilized to identify robust and collision-free trajectories by checking the intersections with obstacles. However, in many cases, the FRS is not calculated in real time and is too conservative to be used in actual applications. In this paper, we address these issues by introducing a nonlinear disturbance observer (NDOB) and an adaptive controller to the multirotor system. We express the FRS of the closed-loop multirotor system with an adaptive controller in augmented state space using Hamilton-Jacobi reachability analysis. Then, we derive a closed-form expression that over-approximates the FRS as an ellipsoid, allowing for real-time computation. By compensating for disturbances with the adaptive controller, our over-approximated FRS can be smaller than other ellipsoidal over-approximations. Numerical examples validate the computational efficiency and the smaller scale of our proposed FRS.

10:00-10:15 FrA07.1

Sensor Placement for Post-Combustion CO2 Capture Plants, pp. 3454-3459
Liu, Siyu
Jiangnan University
Yin, Xunyuan
Nanyang Technological University
Liu, Jinfeng
University of Alberta

The process monitoring and control of post-combustion CO2 capture plants (PCCPs) is crucial. In this work, we consider the problem of placing sensors for PCCPs and propose a computationally efficient method to perform sensor placement. The objective is to find the (near-)optimal set of sensors that gives the maximum degree of observability for state estimation while satisfying certain budget constraint. Specifically, we resort to the information contained in the sensitivity matrix calculated around the operating region of a PCCP to quantify the degree of observability of the states corresponding to the placed sensors. The sensor placement problem is formulated as an optimization problem and is efficiently solved by a one-by-one removal approach through orthogonalization. The proposed approach is demonstrated to be applicable and efficient through simulations.

10:15-10:30 FrA07.2

Neural Koopman Control Barrier Functions for Safety-Critical Control of Unknown Nonlinear Systems, pp. 3442-3447
Zinage, Vrushabh
University of Texas at Austin
Bakolas, Efstatios
The University of Texas at Austin

We consider the problem of synthesis of safe controllers for nonlinear systems with unknown dynamics using Control Barrier Functions (CBF). We utilize Koopman operator theory (KOT) to associate the (unknown) nonlinear system with a higher dimensional bilinear system and propose a data-driven learning framework that uses a learner and a falsifier to simultaneously learn the Koopman operator based bilinear system and a corresponding CBF. We prove that the learned CBF for the latter bilinear system is also a valid CBF for the unknown nonlinear system by characterizing the $\ell_2/\ell_\infty$ norm error bound between these two systems. We show that this error can be partially tuned by using the Lipschitz constant of the Koopman based observables. The CBF is then used to formulate a quadratic program to compute inputs that guarantee safety of the unknown nonlinear system. Numerical simulations are presented to validate our approach.
We study the stability of an equilibrium of arbitrarily switched, autonomous, continuous-time systems through the computation of a common Lyapunov function (CLF). The switching occurs between a finite number of individual subsystems, each of which is assumed to be linear. We present a linear programming (LP) based approach to compute a continuous and piecewise affine (CPA) CLF and compare this approach with different methods in the literature. In particular we compare it with the prevalent use of linear matrix inequalities (LMIs) and semidefinite optimization to parameterize a quadratic common Lyapunov function (QCLF) for the linear subsystems.

We propose a computational framework for optimal control design of oscillator networks. We first introduce a new system representation to eliminate challenges arising from the periodic nature of oscillators. The representation allows us to consider the general problem of pattern formation for oscillators as a classical point-to-point steering. We then develop a novel control design technique that offers the flexibility to blend the time-optimal and energy-optimal considerations with a parameter of choice. We demonstrate the applicability of the proposed framework to a variety of neuroscience applications.

The disturbance response of the angle dynamics for a droop-controlled islanded microgrid is characterized. Specifically, a notion of propagation stability is defined, which is concerned with spatial attenuation vs amplification of input-output responses in the network in a H-infinity or H-2 sense. Criteria for propagation stability are developed, phrased in terms of the microgrid's inverter control parameters. The input frequency range over which the network is susceptible to amplification is also characterized, in the case that the criteria are not met. Based on the formal analysis, the design of resilient controls that trade off coherence and disturbance propagation goals is briefly conceptualized. Finally, the propagation stability analysis is illustrated using a 15-bus example microgrid network.
control problem subject to differential privacy constraints. Differential privacy ensures that the published signals of an algorithm are not too sensitive to the data of any single participating agent. We propose a two-stage architecture for differentially private LQG control and show how to optimize it by leveraging a solution that we previously developed for the Kalman filtering problem. The first stage of this architecture is most easily implemented by a coordinator aggregating and perturbing the agents' measurements appropriately, but it can also be implemented without a trusted aggregator by using a secure sum protocol. Numerical simulations illustrate the performance improvement of this architecture over simpler alternatives such as directly perturbing the agents' measurements.

11:00-11:15  FrA08.5

Statistical Verification of Traffic Systems with Expected Differential Privacy (I), pp. 3496-3501

Yen, Mark  University of Florida
Dullerud, Geir E.  Univ of Illinois, Urbana-Champaign
Wang, Yu  University of Florida

Traffic systems are multi-agent cyber-physical systems whose performance is closely related to human welfare. They work in open environments and are subject to uncertainties from various sources, making their performance hard to verify by traditional model-based approaches. Alternatively, statistical model checking (SMC) can verify their performance by sequentially drawing sample data until the correctness of a performance specification can be inferred with desired statistical accuracy. This work aims to verify traffic systems with privacy, motivated by the fact that the data used may include personal information (e.g., daily itinerary) and get leaked unintentionally by observing the execution of the SMC algorithm. To formally capture data privacy in SMC, we introduce the concept of expected differential privacy (EDP), which constrains how much the algorithm execution can change in the expectation sense when data change. Accordingly, we introduce an exponential randomization mechanism for the SMC algorithm to achieve the EDP. Our case study on traffic intersections by Vissim simulation shows the high accuracy of SMC in traffic model verification without significantly sacrificing computing efficiency. The case study also shows EDP successfully bounding the algorithm outputs to guarantee privacy.

11:15-11:30  FrA08.6

Distributed Resilient Interval Observers for Bounded-Error LTI Systems Subject to False Data Injection Attacks, pp. 3502-3507

Khajenijad, Mohammad  University of California, San Diego
Brown, Scott  University of California, San Diego
Martinez, Sonia  University of California at San Diego

Abstract—This paper proposes a novel distributed interval-valued simultaneous state and input observer for linear time-invariant (LTI) systems that are subject to attacks or unknown inputs, injected both on their sensors and actuators. Each agent in the network leverages a singular value decomposition (SVD) based transformation to decompose its observations into two components, one of them unaffected by the attack signal, which helps to obtain local interval estimates of the state and unknown input and then uses intersection to compute the best interval estimate among neighboring nodes. We show that the computed intervals are guaranteed to contain the true state and input trajectories, and we provide conditions under which the observer is stable. Furthermore, we provide a method for designing stabilizing gains that minimize an upper bound on the worst-case steady-state observer error. We demonstrate our algorithm on an IEEE 14-bus power system.

FrA09  Aqua 307

Formal Verification/Synthesis (Regular Session)

Chair: Coogan, Samuel  Georgia Institute of Technology
Co-Chair: Rutledge, Kwesi  University of Michigan - Ann Arbor

10:00-10:15  FrA09.1

Controller Synthesis for Unknown-Mode Linear Systems with an Epistemic Variant of LTL, pp. 3508-3515

Rutledge, Kwesi  Massachusetts Institute of Technology
Mei, Yuhang  University of Michigan, Ann Arbor
Ozay, Necmiye  Univ. of Michigan

Linear temporal logic (LTL) with the knowledge operator, denoted as KLTL, is a variant of LTL that incorporates what an agent knows or learns at run-time into its specification. Therefore it is an appropriate logical formalism to specify tasks for systems with unknown components that are learned or estimated at run-time. In this paper, we consider a linear system whose system matrices are unknown but come from a priori known finite set. We introduce a form of KLTL that can be interpreted over the trajectories of such systems. Finally, we show how controllers that guarantee satisfaction of specifications given in fragments of this form of KLTL can be synthesized using optimization techniques. Our results are demonstrated in simulation and on hardware in a drone scenario where the task of the drone is conditioned on its health status, which is unknown a priori and discovered at run-time.

10:15-10:30  FrA09.2

Iterative Planner/Controller Design to Satisfy Signal Temporal Logic Specifications, pp. 3516-3522

Buyukkocak, Ali Tevfik  University of Minnesota
Seiler, Peter  University of Michigan, Ann Arbor
Aksaray, Derya  Northeastern University
Gupta, Vijay  Purdue University

This paper considers the design of a planner/tracker for a dynamical system with complex mission specifications expressed as a Signal Temporal Logic (STL) formula. The design consists of two parts: (i) a high-level planner to generate a reference trajectory to satisfy the desired STL formula, and (ii) a low-level controller to infer the control inputs to track the given reference trajectory. Traditionally, these two parts are often designed in a decoupled fashion. Moreover, the planner is often designed using an open-loop plant model that neglects (or only loosely accounts for) the low-level controller. We propose a control synthesis framework in which the high-level planner and the low-level controller are designed simultaneously in an iterative process. We demonstrate our results using a quadcopter scenario and benchmark our results with existing methods in the literature.

10:30-10:45  FrA09.3

A Hybrid Partitioning Strategy for Backward Reachability of Neural Feedback Loops, pp. 3523-3528

Rober, Nicholas  MIT
Everett, Michael  Northeastern University
Zhang, Songan  Ford Motor Company
How, Jonathan, P.  MIT

As neural networks become more integrated into the systems that we depend on for transportation, medicine, and security, it becomes increasingly important that we develop methods to analyze their behavior to ensure that they are safe to use within these contexts. The methods used in this paper seek to certify safety for closed-loop systems with neural network controllers, i.e., neural feedback loops, using backward reachability analysis. Namely, we calculate backprojection (BP) set over-approximations (BPOAs), i.e., sets of states that lead to a given target set that bounds dangerous regions of the state space. The system’s safety can then be certified by checking its current state against the BPOAs. While over-approximating BPs is significantly faster than calculating exact BP sets, solving the relaxed problem leads to conservativeness. To combat conservativeness, partitioning strategies can be used to split the problem into a set of sub-problems, each less conservative than the unpartitioned problem. We introduce a hybrid partitioning method
that uses both target set partitioning (TSP) and backreachable set partitioning (BRSP) to overcome a lower bound on estimation error that is present when using BRSP. Numerical results demonstrate a near order-of-magnitude reduction in estimation error compared to BRSP or TSP given the same computation time.

We consider the problem of controlling a heterogeneous multi-agent system required to satisfy temporal logic requirements. Capability Temporal Logic (CaTL) was recently proposed to formalize such specifications for deploying a team of autonomous agents with different capabilities and cooperation requirements. In this paper, we extend CaTL to a new logic CaTL+, which is more expressive than CaTL and has semantics over a continuous workspace shared by all agents. We define a novel robustness metric for CaTL+, which is sound, differentiable almost everywhere and eliminates masking, which is one of the main limitations of existing traditional robustness metrics. We formulate a control synthesis problem to maximize CaTL+ robustness and propose a two-step optimization method to solve this problem. Simulation results are included to illustrate the increased expressivity of CaTL+ and the efficacy of the proposed control synthesis approach.

In this paper, we propose a runtime assurance mechanism for online verification of a control system given a signal temporal logic (STL) specification that, at each time step, must hold for the remaining state trajectory. Given a nominal control input, we propose a mechanism that minimally adjusts the input at each time step in order to ensure existence of future inputs that maintain satisfaction of the STL specification. Because STL constraints generally impose requirements on future states, the runtime assurance mechanism also enforces continued satisfaction of the STL constraint evaluated at all past time steps. Lastly, to ensure a feasible input is always available, we provide a novel characterization of a persistently feasible set and require that the system state is always able to reach this set. We formulate this approach as a mixed integer convex program and demonstrate it on examples.

Preferences play a key role in determining what goals/constraints to satisfy when not all constraints can be satisfied simultaneously. In this paper, we study how to synthesize preference-satisfying plans in a stochastic system modeled as an MDP, given a (possibly incomplete) combinatorial preference model over temporally extended goals. We start by introducing new semantics to interpret preferences over infinite plays of the stochastic system. Then, we introduce a new notion of 'improvement' to enable comparison between two prefixes of an infinite play. Based on this, we define two solution concepts called Safe and Positively Improving (SPI) and Safe and Almost-Sure Improving (SASI) that enforce improvements with a positive probability and with probability one, respectively. We construct a model called an improvement MDP, in which the synthesis of SPI and SASI strategies that guarantee at least one improvement, reduces to computing positive and almost-sure winning strategies in an MDP. We present an algorithm to synthesize the SPI and SASI strategies that induce multiple sequential improvements. We demonstrate the proposed approach using a robot motion planning problem.
evolution. Using a hybrid systems framework, we propose a hybrid gradient descent algorithm that operates during both flows and jumps. We show that this algorithm guarantees exponential convergence of the parameter estimate to the unknown parameter under a new notion of discretized hybrid persistence of excitation that relaxes the classical discrete-time persistence of excitation condition. Simulation results validate the properties guaranteed by the new algorithm.

10:45-11:00 FrA10.4
Zhao, Mi 
Verriest, Erik I. 
Guan, Yue 
Abdallah, Chaouki T. 

This paper presents the jump law of co-states in optimal control for state-dependent switched systems. The number of switches and the switching modes are assumed to be known a priori. A proposed jump law is rigorously derived by theoretical analysis and illustrated by simulation results. An algorithm is then proposed to solve optimal control for state-dependent hybrid systems. Through numerical simulations, we further show that the proposed approach is more efficient than existing methods in solving optimal control for state-dependent switched systems.

11:00-11:15 FrA10.5
Design of the Impulsive Goodwin's Oscillator: A Case Study, pp. 3572-3577
Medvedev, Alexander V. 
Proskurnikov, Anton V. 
Zhushabaliyev, Zhanybai 

The impulsive Goodwin's oscillator (IGO) is a hybrid model composed of a third-order continuous linear part and a pulse-modulated feedback. This paper introduces a design problem of the IGO to admit a desired periodic solution. The dynamics of the continuous states represent the plant to be controlled, whereas the parameters of the impulsive feedback constitute design degrees of freedom. The design objective is to select the free parameters so that the IGO exhibits a stable 1-cycle with desired characteristics. The impulse-to-impulse map of the oscillator is demonstrated to always exist. An IGO design procedure is proposed and validated by simulation. The nonlinear dynamics of the designed IGO are reviewed by means of bifurcation analysis. Applications of the design procedure to dosing problems in chemical industry and biomedicine are envisioned.

11:15-11:30 FrA10.6
Piecewise Quantization-Dependent Approach to Quantized Stabilization of Piecewise-Affine Systems, pp. 3578-3583
Ning, Zepeng 
Cheng, Yiming 
Li, Zhaojian 
Yin, Xunyuan 

This paper studies the stability and stabilization problems for discrete-time piecewise-affine (PWA) systems with single input and state quantization. The PWA controller is considered to have dependence on the controlled PWA system modes; the adopted logarithmic quantization scheme is in a piecewise form, which is synchronized with the operating mode of the PWA system. A piecewise Lyapunov function that is dependent on the sector-bounded uncertainties of both the control input and the state-feedback signal is constructed. Then, the stability and the stabilization criteria are derived based on the constructed Lyapunov function. The proposed quantized control strategy is illustrated via an application to a simulated temperature control system.

10:15-10:30 FrA11.1
Scalable Stability of Nonlinear Interconnected Systems in Case of Amplifying Perturbations, pp. 3584-3589
Mirabilio, Marco 
Iovine, Alessio 

This paper investigates the stability of large-scale systems (LSSs) in the presence of subsystems that amplify the perturbations propagated by their neighborhood, possibly leading to undesired behaviors of the overall interconnected system. Then, sufficient conditions ensuring the system trajectories boundedness and the subsequent LSS asymptotic stability in the sense of scalable Mesh Stability are proven to exist. The theoretical results show that there exists a dependence between the stability and the topology of the inter connected system. The obtained framework is then exploited for the stability analysis of a network of electrical microgrids, showing the effectiveness of the theoretical results.

10:30-10:45 FrA11.2
Minimum Perfect Critical Sets with 4 Vertices of Tree Graphs, pp. 3590-3594
Dai, Li 

Minimal Laplacian Controllability problem plays an important role in the field of network control. A new way to construct the Minimum Leader Set is proposed. For $$|S|=4$$, this work proved that there are two and only two types of MPCSs of tree graphs. To illustrate how to use MPCSs to find all of the Minimum Leader Sets, three examples are given.

10:45-11:00 FrA11.3
Differentially Private Timeseries Forecasts for Networked Control, pp. 3595-3601
Li, Po-han 
Chinchali, Sandeep 
Topcu, Ufuk 

We analyze a cost-minimization problem in which the controller relies on an imperfect timeseries forecast. Forecasting models generate imperfect forecasts because they use anonymization noise to protect input data privacy. However, this noise increases the control cost. We consider a scenario where the controller pays forecasting models incentives to reduce the noise and combines the forecasts into one. The controller then uses the forecast to make control decisions. Thus, forecasting models face a trade-off between accepting incentives and protecting privacy. We propose an approach to allocate economic incentives and minimize costs. We solve a biconvex optimization problem on linear quadratic regulators and compare our approach to a uniform incentive allocation scheme. The resulting solution reduces control costs by 2.5 and 2.7 times for the synthetic timeseries and the Uber demand forecast, respectively.

10:45-11:00 FrA11.4
Harmonic Balance Analysis of Lur'e Oscillator Network with Non-Diffusive Weak Coupling, pp. 3602-3607
Lee, Bryan 
Iwasaki, Tetsuya 

The central pattern generator (CPG) is a group of interconnected neurons, existing in biological systems as a control center for oscillatory behaviors. We propose a new approach based on the
multivariable harmonic balance to characterize the relationship between the oscillation profile (frequency, amplitude, phase) and interconnections within the CPG, modeled as weakly coupled oscillators. In particular, taking advantage of the weak coupling, we formulate a low-dimensional matrix whose eigenvalue/eigenvector capture the perturbation in the oscillation profile due to the coupling. Then we develop an algorithm to estimate the perturbed oscillation profile of a given CPG, and suggest an optimization to synthesize the interconnections to produce a given oscillation profile.

The aim of this paper is to investigate the fixed-time consensus problems of cooperative and antagonistic multi-agent systems (CAMSSs) with both antagonistic interactions and external disturbances under directed topologies. Toward this end, a nonlinear control protocol is constructed according to the nearest neighbor information. With the aid of the properties of improved Laplacian potentials, the associated convergence analyses can be developed from the viewpoint of Lyapunov stability theory. It is shown that all the agents can accomplish the bipartite consensus (respectively, state stability) objective within a fixed time under structurally balanced (respectively, unbalanced) signed digraphs in spite of the existing external disturbances. Additionally, simulations are included to validate the developed results.

In this study, we propose a novel adaptive control architecture, which provides dramatically better performance compared to conventional methods. What makes this architecture unique is the synergistic employment of a traditional, Adaptive Neural Network (ANN) controller and a Long Short-Term Memory (LSTM) network. LSTM structures, unlike the standard feed-forward neural networks, take advantage of the dependencies in an input sequence, which helps predict the evolution of an uncertainty. Through a training method we introduced, the LSTM network learns to compensate for the deficiencies of the ANN controller. This substantially improves the transient response by allowing the controller to quickly react to unexpected events. Through careful simulation studies, we demonstrate that this architecture can improve the estimation accuracy on a diverse set of unseen uncertainties. We also provide an analysis of the contributions of the ANN controller and LSTM network, identifying their individual roles in compensating low and high frequency error dynamics. This analysis provides insight into why and how the LSTM augmentation improves the system's transient response.

In this paper, we propose a combined Magnitude Saturated Adaptive Control (MSAC)-Model Predictive Control (MPC) approach to linear quadratic tracking optimal control problems with parametric uncertainties and input saturation. The proposed MSAC-MPC approach first focuses on a stable solution and parameter estimation, and switches to MPC when parameter learning is accomplished. We show that the MSAC, based on a high-order tuner, leads to parameter convergence to true values while providing stability guarantees. We also show that after switching to MPC, the optimality gap is well-defined and proportional to the parameter estimation error. We demonstrate the effectiveness of the proposed MSAC-MPC algorithm through a numerical example based on a linear second-order, two input, unstable system.

This work proposes a switched model reference adaptive control (S-MRAC) architecture for a multi-input multi-output (MiM0) switched linear system with memory for enhanced learning. A salient feature of the proposed method that separates it from most previous results is the use of memory that store the estimator states at switching and facilitate parameter learning during both active and inactive phases of a subsystem, thereby improving the tracking performance of the overall switched system. Specifically, the learning experience from the previous active duration of a subsystem is retained in the memory and reused when the subsystem is inactive and when the subsystem becomes active again. Parameter convergence is shown based on an intermittent initial excitation (IEE), which is significantly relaxed than the classical persistence of excitation (PE) condition. A common Lyapunov function is considered to ensure closed-loop stability with S-MRAC. Further under IEE, the exponential stability of tracking and parameter estimation error dynamics are guaranteed.
Motorized functional electrical stimulation (FES) induced cycling is a rehabilitation intervention and exercise strategy that can benefit people with movement disorders. Power tracking is an objective in which leg muscles are artificially activated to track an active torque trajectory while an electric motor achieves a desired speed (cadence). Technical challenges remain to enhance muscle torque tracking performance since muscles experience saturation, which can induce error build-up. Further, the electric motor controller needs to account for the cross muscle torque input in the kinematic tracking loop and thus reduce potential cycling fluctuations. In this paper, a FES muscle torque tracking controller is designed with an anti-windup term in an integral torque error signal to mitigate the effect of muscle saturation. Then, an adaptive-based concurrent learning controller is developed for the electric motor to track cadence and estimate uncertain constant parameters of the cycle-riding system. The adaptive motor controller embeds the muscle torque (since the muscle controller is implementable) in the regressor and exploits it as a feedforward term in the cadence loop, rather than canceling the muscle torque input as it is usually performed in robust control designs. Globally uniformly ultimately bounded (GUUB) tracking is obtained for the torque tracking objective and exponential cadence tracking and parameter convergence is obtained by the learning controller after a finite excitation condition is satisfied.

**FrA13**

Safe and Constrained Rendezvous, Proximity Operations and Docking (Tutorial Session)

Chair: Petersen, Chris  
Co-Chair: Caverly, Ryan James  
Organizer: Petersen, Chris Caverly, Ryan James  
Organizer: Weiss, Avishai  
Organizer: Phillips, Sean

**FrA13.1**  
10:00-10:45  
Safe and Constrained Rendezvous, Proximity Operations and Docking (I), pp. 3645-3661

Petersen, Chris  
Caverly, Ryan James  
Phillips, Sean  
Weiss, Avishai

University of Florida  
University of Minnesota  
Air Force Research Laboratory  
Mitsubishi Electric Research Labs

This tutorial paper discusses the rising need for safe and constrained spacecraft Rendezvous, Proximity Operations, and Docking (RPOD). This class of problems brings with it i) a unique set of equations of motion, ii) a variety of constraints and objectives that are specialized to RPOD, and iii) a number of traditional and current Guidance, Navigation, and Control (GNC) considerations. There are strong connections between the work done in RPOD and a variety of other research domains that have synergistically aided in pushing forward the state-of-the-art. This tutorial paper discusses the above, provides an entry point into the field of spacecraft RPOD, and highlights a selection of open problems that still exist in the field.

**FrA13.2**  
10:45-11:00  
Ensuring Future Safety in Spacecraft Rendezvous and Proximity Operations (II)

Zappulla, Richard

United States Space Force/Air Force Research Laboratory

**FrA13.3**  
11:00-11:15  
The Future of Satellite Logistics and the Mission Extension Vehicle (MEV) (II)

Kwas, Andrew

Northrop Grumman

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**FrA14**

Control Barrier Functions (Regular Session)

**FrA14.1**  
10:00-10:15  
Unmatched Control Barrier Functions: Certainty Equivalence Adaptive Safety, pp. 3662-3668

Lopez, Brett  
Slotine, Jean-Jacques

University of California - Los Angeles  
Massachusetts Institute of Technology

This work applies universal adaptive control to control barrier functions to achieve safety control of dynamical systems with parametric model uncertainties. The proposed approach utilizes the certainty equivalence principle to methodically select a model-parameterized control barrier function and corresponding safety controller from an allowable set with instantaneous parameter estimates. While such a combination does not necessarily yield forward invariance without additional requirements on the barrier function, we show that safety can indeed be established by simply adjusting the adaptation gain online. Simulation results demonstrate the approach.

**FrA14.2**  
10:15-10:30  
Barrier Pairs for Safety Control of Uncertain Output Feedback Systems, pp. 3669-3674

He, Binghan  
Tanaka, Takashi

University of California, Berkeley  
University of Texas at Austin

The barrier function method for safety control typically assumes the availability of full state information. Unfortunately, in many scenarios involving uncertain dynamical systems, full state information is often unavailable. In this paper, we aim to solve the safety control problem for an uncertain single-input single-output system with partial state information. First, we develop a synthesis method that simultaneously creates a barrier function and a dynamic output feedback safety controller. This safety controller guarantees that the unit sub-level set of the barrier function is an invariant set under the uncertain dynamics and disturbances of the system. Then, we build an identifier-based estimator that provides a state estimate affine to the uncertain model parameters of the system. To detect the potential risks of the system, a fault detector uses the state estimate to find an upper bound for the barrier function. The fault detector triggers the safety controller when the system's original action leads to a potential safety issue and resumes the original action when the potential safety issue is resolved by the safety controller.

**FrA14.3**  
10:30-10:45  
Data-Efficient Control Barrier Function Refinement, pp. 3675-3680

Dai, Bolun  
Huang, Heming  
Krishnamurthy, Prashanth  
Khorrami, Farshad

New York University  
New York University  
NYU Tandon School of Engineering  
Northrop Grumman

Control barrier functions (CBFs) have been widely used for
synthesizing controllers in safety-critical applications. When used as a safety filter, a CBF provides a simple and computationally efficient way to obtain safe controls from a possibly unsafe performance controller. Despite its conceptual simplicity, constructing a valid CBF is well known to be challenging, especially for high-relative degree systems under nonconvex constraints. Recently, work has been done to learn a valid CBF from data based on a handcrafted CBF (HCBF). Even though the HCBF gives a good initialization point, it still requires a large amount of data to train the CBF network. In this work, we propose a new method to learn more efficiently from the collected data through a novel prioritized data sampling strategy. A priority score is computed from the loss value of each data point. Then, a probability distribution based on the priority score of the data points is used to sample data and update the learned CBF. Using our proposed approach, we can learn a valid CBF that recovers a larger portion of the true safe set using a smaller amount of data. The effectiveness of our method is demonstrated in simulation on a two-link arm.

10:45-11:00 FrA14.4

**Disturbance Observer-Based Robust Control Barrier Functions**, pp. 3681-3687

Wang, Yujie – University of Wisconsin-Madison
Xu, Xiangru – University of Wisconsin-Madison

This work presents a safe control design approach that integrates the disturbance observer (DOB) and the control barrier function (CBF) for systems with external disturbances. Different from existing robust CBF results that consider the "worst case" of disturbances, this work utilizes a DOB to estimate and compensate for the disturbances. DOB-CBF-based controllers are constructed with provably safe guarantees by solving convex quadratic programs online, to achieve a better tradeoff between safety and performance. Two types of systems are considered individually depending on the magnitude of the input and disturbance relative degrees. The effectiveness of the proposed methods is illustrated via numerical simulations.

11:00-11:15 FrA14.5

**Compositions of Multiple Control Barrier Functions under Input Constraints**, pp. 3688-3695

Breeden, Joseph – University of Michigan, Ann Arbor
Panagou, Dimitra – University of Michigan, Ann Arbor

This paper presents a methodology for ensuring that the composition of multiple Control Barrier Functions (CBFs) always leads to feasible conditions on the control input, even in the presence of input constraints. In the case of a system subject to a single constraint function, there exist many methods to generate a CBF that ensures constraint satisfaction. However, when there are multiple constraint functions, the problem of finding and tuning one or more CBFs becomes more challenging, especially in the presence of input constraints. This paper addresses this challenge by providing tools to 1) decouple the design of multiple CBFs, so that a CBF can be designed for each constraint function independently of other constraints, and 2) ensure that the set composed from all the CBFs together is a viability domain. Thus, a quadratic program subject to all the CBFs simultaneously is always feasible. The utility of this methodology is then demonstrated in simulation for a nonlinear orientation control system.

FrA15

**Dynamics and Control of Marine Energy Systems** (Invited Session)

Chair: Tang, Yufei – Florida Atlantic University
Co-Chair: Li, Perry Y. – Univ. of Minnesota
Organizer: Tang, Yufei – Florida Atlantic University
Organizer: Abdelkhalik, Ossama – Iowa State University
Organizer: Amini, Mohammad – University of Michigan

Reza
Organizer: Hasankhani, A rezoo – Cornell University

10:00-10:15 FrA15.1

**A Kalman Filter Approach to the Estimation and Reconstruction of Ocean Wave Fields (I)**, pp. 3696-3702

Chen, Zihao – University of Minnesota
Wu, Jie – University of Minnesota
Shen, Lian – University of Minnesota
Li, Perry Y. – Univ. of Minnesota

This paper considers the problem of real-time reconstruction of ocean wave field with a network of discrete wave height sensors. Being able to predict incoming wave characteristics helps individual or collections of wave energy converters to increase the amount of energy that they can capture. In this paper, the wave field is modeled to consist of a frequency spectrum of monotone Airy waves with unknown strengths and phases. Kalman filter based observers are then designed to estimate the wave fields. The observers' performance in reconstructing the wave field accurately is validated in simulation for 1-D and 2-D linear and nonlinear waves. Wave tank experiments have also been performed to validate its ability to reconstruct a wave field in real-time using noisy data obtained from a vision-based wave height sensor.

10:15-10:30 FrA15.2

**FEM-Aided Modeling and Control of a Tethered Hydrokinetic Energy Kite (I)**, pp. 3703-3708

Torres, Gabriel – Worcester Polytechnic Institute
Olinger, David – Worcester Polytechnic Institute
Demetriou, Michael A. – Worcester Polytechnic Institute

In this paper, a six-degree-of-freedom tethered rigid kite with a kite-mounted turbine is modeled using Newtonian and Lagrangian formulations supplemented with corresponding kinematic analysis and an Euler-angle representation. In addition, to capture the coupled effects of kite and tether dynamics, the Euler-Bernoulli bending equations are taken into their weak form to be spatially discretized into N-segments utilizing a Galerkin Finite Element Method (FEM) strategy. Consequently, the infinite-dimensional beam governing equations become a finite set of 5(N + 1) ordinary time differential equations. The kite and tether dynamics are placed into their state-space form and their interactions are characterized by the force balance at the tip of the tether at which the kite is attached. The formulations obtained in this work provide a baseline for the study of the effect of the tether loads on the energy generation of the kite.

10:30-10:45 FrA15.3

**Passivity-Based Control of a Hydrokinetic Energy Kite with a Multi-Element Tether (I)**, pp. 3709-3714

Torres, Gabriel – Worcester Polytechnic Institute
Olinger, David – Worcester Polytechnic Institute
Demetriou, Michael A. – Worcester Polytechnic Institute

This paper studies passivity-based control of a tethered underwater kite used for energy generation. The mathematical formulation of the motion of a 6-degree-of-freedom (DOF) rigid kite is coupled with the continuous governing equations of a flexible tether. The tether is spatially discretized as N-frame elements so that the intrinsic infinitedimensional set of partial differential equations (PDEs) is reduced to a finite second-order set of ordinary differential equations (ODEs). Using this formulation, a Lyapunov stability analysis is conducted to establish operational conditions on the system parameters and states to achieve a certain level of internal and input-output stability and to provide proof of system trajectory boundedness. Previous passivity-based control schemes on tethered kite systems are used to establish a baseline scheme for the control logic that can accommodate the previously defined tether dynamics. A Lyapunov-based feedback linearization control is imposed on the rotational dynamics of the rigid kite according to overall stability and
This paper presents a reinforcement learning (RL) framework applied for an autonomous underwater vehicle (AUV) path planning, focusing on a specific type of energy-harvesting AUV, entitled marine current turbine (MCT). The proposed RL-based approach improves a classical path planning to adopt with an underwater environment prone to spatiotemporal uncertainties. The path planning problem is formulated to achieve the goal of maximizing the harnessed energy from the MCT subject to the agent dynamics and the spatiotemporal environment constraints. Three RL algorithms, including Q-learning, deep Q-network (DQN), and proximal policy optimization (PPO), are nominated to deal with the path planning over both discrete gridded and continuous underwater environments modeling. The experimental results demonstrate the efficiency of the RL-based approaches in seeking the optimal path in the underwater environment, where further discussion is presented to generalize the proposed approach to other energy-harvesting autonomous vehicles operating in the spatiotemporally varying environment, such as airborne wind turbines.

Ocean wave energy has the potential to play a crucial role in the shift to renewable energy. In order to improve wave energy conversion techniques, it is necessary to recognize the sub-optimal nature of traditional sequential design processes due to the interconnectedness of subsystems. A codesign optimization in this paper seeks to include effects of all subsystems within one optimization loop in order to reach a fully optimal design. A width and height sweep serves as a brute force geometry optimization while optimizing the power take-off components and controls using a pseudo-spectral method for each geometry. An investigation of electrical power and mechanical power maximization also outlines the contrasting nature of the two objectives to illustrate electrical power maximization's importance for identifying optimality. The codesign optimization leads to an optimal design with a width of 12 m and a height of 10 m. Ultimately, the codesign optimization leads to a 62% increase in the objective function over the optimal design from a sequential design process while also requiring only about half the power take-off torque.

Control co-design (CCD) explores physical and control design spaces simultaneously to optimize a system's performance. A commonly used CCD framework aims to achieve open-loop optimal control (OLOC) trajectory while optimizing the physical design variables subject to constraints on control and design parameters. In this study, in contrast with the conventional CCD methods based on OLOC schemes, we present a CCD formulation that explicitly considers a feedback controller. In the formulation, we consider two control laws based on proportional linear and quadratic state feedback, where the control gain is optimized. The simulation results show that the OLOC trajectory could be approximated by a feedback controller. While the total energy generated from the CCD with a feedback controller is slightly lower than that of the CCD with OLOC, it results in a much simpler control structure and more robust performance in the presence of uncertainties and disturbances, making it suitable for real-time control. The study in this paper investigates the performance of optimal hydrokinetic turbine design with a feedback controller in the presence of uncertainties and disturbances to demonstrate the benefits and highlight challenges associated with incorporating the feedback controller explicitly in the CCD stage.
overview of the recent advances in PIML for dynamical system modeling and control. Specifically, the paper covers an overview of the theory, fundamental concepts and methods, tools, and applications on topics of: 1) physics-informed learning for system identification; 2) physics-informed learning for control; 3) analysis and verification of PIML models; and 4) physics-informed digital twins. The paper is concluded with a perspective on open challenges and future research opportunities.

Due to their great expressiveness, ease of implementation, and scale up capabilities, Neural Networks (NNs) are gaining popularity to model and/or control potentially large and complex physical systems. On the other hand, NNs are infamously known for their brittleness and poor generalization capabilities, which poses serious problems in real-world applications. Since they are indeed completely oblivious to the underlying physical laws, NNs might predict physically inconsistent states or take spurious decisions, which can have potentially catastrophic consequences. There is thus a need to understand when NNs fail, why this happens, and – most importantly – how to avoid these situations, before deploying them on real physical systems. This talk will hence first focus on the latest developments around Physics-inspired NNs (PiNNs), a new type of network designed to respect the underlying physics of the system to model. While some of these solutions only steer the NNs towards a three-layer-model for programming real-time computations. The tutorial also presents some filter and state-space structures that are useful for real-time computation. It concludes with an overview of the different sample rate ranges currently used in some typical control problems and a short discussion of how businesses model affect our choices in real-time computation.
mismatch (MPM) and improves dynamic performance by predicting multi-step-ahead disturbance from similar DWCC tasks. First, a state-space model augmented by disturbance variables ensures offset-free control for MPM. Second, a dynamic autoencoder is constructed to extract private features from process sequences based on long short-term memory and fully connected networks. DWCC scenarios similar to the current scenario are located from the historical database by calculating the distance between extracted features. Finally, the multi-step-ahead disturbance and its uncertainty representation are predicted through multi-output Gaussian process regression based on the located scenarios. The obtained multi-step-ahead disturbance is incorporated into the state-space MPC framework. A nonlinear case is conducted to demonstrate the effectiveness of the proposed method.

13:34-13:38 FrB01.2
A Reachable Set-Based Cyberattack Detection Scheme for Dynamic Processes, pp. 3777-3782
Narasimhan, Shilpa University of California, Davis
El-Farra, Nael H. University of California, Davis
Ellis, Matthew University of California, Davis

Recent cyberattacks targeting process control systems have motivated the need for operational technology-based approaches, such as detection schemes that monitor processes for attacks. Chemical processes are normally operated at/near the steady-state for extended periods. To account for this, attack detection schemes may be designed to monitor the process operated near the steady-state. Attack-free transient operation (e.g., during process start-up and set point changes) may render detection schemes designed for steady-state operation ineffective by generating false alarms. In this work, a reachable set-based detection scheme is proposed to monitor the process during transient operation. Additive and multiplicative false data injection attacks (FDIAs) that alter data communicated over the sensor-controller and controller-actuator communication links are considered. Based on the ability of the proposed detection scheme to detect an FDIA, an approach to classify attacks is presented. The reachable set-based detection scheme and attack classification are applied to two illustrative processes.

13:38-13:42 FrB01.3
Necessary Optimality Conditions for Fast Lithium-Ion Battery Charging Via Hybrid Simulations, pp. 3783-3789
Matschek, Janine TU Darmstadt
Berliner, Marc D. Massachusetts Institute of Technology
Himmel, Andreas TU Darmstadt
Braatz, Richard D. Massachusetts Institute of Technology
Findeisen, Rolf TU Darmstadt

Fast yet health-conscious and safe optimal charging for lithium-ion batteries is essential for resource efficiency, increased battery lifetime, and overall usability. While quick and resource-efficient charging can be formulated as an optimal control problem, it often cannot be solved in real-time on computationally limited, embedded systems. We build upon a mathematical reformulation of the constrained optimal control problem into hybrid simulations, which allows for computationally efficient solutions and provides operation modes beyond existing charging profiles. We analyze under which conditions this mathematical reformulation can lead to the optimality of the resulting charging protocols. Physics-based battery models are analyzed from a systems theory perspective using controllability and flatness properties, necessary optimality conditions for the charging protocols are established.

13:42-13:46 FrB01.4
Fish Growth Tracking and Mortality Monitoring: Control Design and Comparisons, pp. 3790-3796
Aljahani, Fahad King Abdullah University of Science and Technology (KAUST)

Monitoring the water quality and controlling the feeding are essential functions in balancing fish productivity and shaping fish’s life history in the fish growth process. Currently, most fish feeding processes are conducted manually in different phases and not optimized. The feeding technique influences fish growth through the feed conversion rate. In addition, the high concentration level of ammonia affects the water quality, resulting in fish survival and mass death. Therefore, there is a crucial need to develop control strategies to determine optimal, efficient, and reliable feeding processes and to monitor water quality at the same time. In this paper, we revisit the representative fish growth model describing the total biomass change by incorporating the fish population density and mortality. We specifically focus on relative feeding as a manipulated variable to design traditional and optimal control to track the desired weight reference within the sub-optimal temperature and Dissolved Oxygen (DO) profiles under different levels of unionized ammonia (UAI) exposures. Then, we propose an optimal algorithm that optimizes the feeding and water quality of the dynamic fish population growth process. We also show that the model predictive control decreases fish mortality and also reduces food consumption in all different cases by an average of 26.9% compared to the bang-bang controller, 22.6% compared to the PID controller.

13:46-13:50 FrB01.5
Model Predictive Control for Distributed Energy Systems Management in Electrifying the Building Sector: Carbon Emission Reduction in Response to Dynamic Electricity Price and Carbon Intensity, pp. 3797-3802
Yang, Shiyu Cornell University
Gao, H. Oliver Cornell University
You, Fengqi Cornell University

Electrification and deploying distributed energy systems are two integral strategies to decarbonize buildings. However, integrating buildings to intermittent on-site distributed energy systems and power grids with dynamic carbon intensity requires a much more intelligent building energy management (BEM) system than the current reactive-control-based BEM practice. This study proposes an electricity-mix-responsive model predictive control (MPC) framework for integrated control of building and distributed energy systems considering the dynamics of electricity carbon intensity and prices. A novel linear integrated model, including sub-models of adaptive thermal comfort, building thermodynamics, humidity, space heating, space cooling, water heating, renewable energy system, electric energy storage, and electric vehicle, is developed. A linear MPC controller is developed based on the linear integrated model. The proposed MPC framework is applied to a simulation case study for integrated control of building energy systems and multiple distributed energy resources (solar photovoltaic, electric energy storage, and electric vehicle charging) in a residential test building. The proposed MPC approach vastly reduces the electricity cost by up to 38.3% and carbon emission by up to 25.1%, for the test building, compared to conventional reactive-based control. Meanwhile, the proposed MPC approach largely enhances the test building’s thermal comfort and demand flexibility. The case study results also show that maximizing carbon emission reduction does not necessarily degrade the electricity cost-saving in buildings. Instead, they can be optimized simultaneously with the proposed MPC approach.

13:50-13:54 FrB01.6
Dynamic Optimization and Control of a Renewable Microgrid Incorporating Ammonia, pp. 3803-3808
Kong, Baiwen University of Minnesota
Zhang, Qi University of Minnesota
Daulutidis, Prodromos Univ. of Minnesota
A renewable microgrid using green ammonia and hydrogen for energy storage is proposed in the work. Wind and solar energy are captured as power inputs for water electrolysis to produce hydrogen which can be further transformed to ammonia through the Haber-Bosch process. Gensets are dispatched to generate power from hydrogen or ammonia for meeting residential demands. Local control structures are designed for each module in the framework, which takes hourly commands from an upper level dynamic real-time optimization (D-RT) layer. Case studies in Duluth, MN are conducted for summer and winter in a 24-hour time horizon, demonstrating the stability of system under disturbances in renewable sources. Results confirm that ammonia is more preferred for long-term energy storage.

Estimating Parameter Regions for Structured Parameter Tuning Via Reduced Order Subsystem Models, pp. 3809-3814
Schurig, Roland
TU Darmstadt, Control and Cyber-Physical Systems Laboratory
Himmel, Andreas
TU Darmstadt
Mesarovic, Amer
Siemens AG, Munich; Otto-Von-Guericke University Magdeburg
Braatz, Richard D.
Massachusetts Institute of Technology
Findeisen, Rolf
TU Darmstadt

Many large-scale systems are composed of subsystems operated by decentralized controllers, which are fixed in their structure, yet have parameters to tune. Initial tuning or subsequent adjustments do those parameters use to varying operating conditions or changes in the network of interconnected systems, while ensuring stability, performance, and security, pose a challenging task due to the overall complexity and size. Subsystems may not be willing or allowed to expose detailed information for safety and privacy reasons. In some cases, a comprehensive system model might not be available for global tuning, or the resulting problem might be computationally infeasible. To enable meaningful global parameter tuning while allowing for data privacy and security, we propose that the subsystems themselves should provide reduced-order models. These models capture the parametric dependency of the subsystem dynamics on the controller parameters. Specifically, we present a method to construct a region in the subsystems’ parameter space in which the deviation of the subsystem and the reduced-order model stays below a specified error bound and in which both systems are stable. A necessary and sufficient condition for such regions is derived using robust control theory. Notably, sufficiency can be expressed in terms of a linear matrix inequality. We demonstrate the approach by considering the temperature control of a large-scale building complex.

Cyberattack Awareness and Resiliency of Integrated Moving Horizon Estimation and Model Predictive Control of Complex Process Networks, pp. 3815-3820
Sundberg, Brayden
Kansas State University
Babaei Pourkargar, Davood
Kansas State University

This paper explores data-assisted cyber-attack awareness and resiliency of optimization-based estimation and control of integrated process systems to malicious attacks on measurement sensors. The proposed optimization-based estimation and control architecture consists of an integrated nonlinear moving horizon estimation (MHE) and model predictive control (MPC), where the MHE estimates the unmeasured state variables of the system required by MPC design. In addition, a measured output data-driven cyberattack detection framework is developed by frequently employing a feedforward neural network during the closed-loop process, identifying the cyberattacks from the interactive network-level dynamics. Finally, the integrated process of benzene alkylation with ethylene to produce ethylbenzene is considered a benchmark to demonstrate the application of cyberattack awareness and resiliency of the proposed control architecture in the presence of different types of adversarial cyberattacks interfering with the temperature measurement sensors.

A Systematic Method for the Selection of Feedback Variables in MIMO RF Impedance Matching Systems, pp. 3821-3826
Guc, Furkan
University of California Merced
Chen, YangQuan
University of California, Merced

An impedance matching between the Radio-Frequency (RF) generator and the equipment is required in order to achieve maximum power transfer or minimum reflection. Different architectures of impedance matching control circuits are utilized in this problem depending on the selection of the tunable elements and topological structure. The matching network may not show expected topology behavior due to unknown elements and parameter drifting. Although there exist suggestions for the selection of feedback variables for various impedance matching control schemes, a comprehensive justification for the feedback variable selection on RF impedance matching is still missing in the literature to our best knowledge. To introduce a systematic approach on the feedback variable selection methodology, a coupling analysis for the MIMO impedance matching problem is introduced using Relative Gain Array (RGA) and interaction index analysis. Two most common matching networks are used for demonstration of the procedure namely L-Type up converting and T-Type considering additional inductor due to additional unknown element in the structure. At the end, a novel interaction coefficient is presented to as a metric for the coupling quantification of impedance matching MIMO problem for 6 candidate feedback variable scenarios. Clearly, one should select feedback variables in the impedance matching control so that the coupling effect is as small as possible. Topology changes due to performance degradation or unknown elements can be monitored with predictive maintenance and health monitoring applications. Hence, the selection of feedback variables can be updated to achieve possible error recovery. Results show that the selection of feedback variables with the aid of proposed systematic methodology enables to achieve higher convergence rate within feasible load impedance region.

Towards Efficient Modularity in Industrial Drying: A Combinatorial Optimization Viewpoint, pp. 3827-3832
Bayati, Alisina
University of Illinois at Urbana Champaign
Srivastava, Amber
ETH Zurich
Malvandi, Amir
University of Illinois at Urbana Champaign
Feng, Hao
North Carolina Agricultural and Technical State University
Salapaka, Srinivasa M.
University of Illinois

The industrial drying process consumes approximately 12% of the total energy used in manufacturing, with the potential for a 40% reduction in energy usage through improved process controls and the development of new drying technologies. To achieve cost-efficient and high-performing drying, multiple drying technologies can be combined in a modular fashion with optimal sequencing and control parameters for each. This paper presents a mathematical formulation of this optimization problem and proposes a framework based on the Maximum Entropy Principle (MEP) to simultaneously solve for both optimal values of control parameters and optimal sequence. The proposed algorithm addresses the combinatorial optimization problem with a non-convex cost function riddled with multiple poor local minima. Simulation results on drying distillers dried grain (DDG) products show up to 12% improvement in energy consumption compared to the most efficient single-stage drying process. The proposed algorithm converges to local minima and is designed heuristically to reach the global minimum.
Disturbances. For strongly convex quadratic optimization algorithms in the presence of additive white stochastic noise, there are non-quadratic in structure but yield optimal controls in the form of a non-robust LQR designed for a nominal model not reflecting the system uncertainty. The analysis of this paper largely relies on the concept of inverse optimal control to construct suitable performance measures for uncertain linear systems, which are non-convex in structure but yield optimal controls in the form of LQR. The relationship between robust LQR and zero-sum linear quadratic dynamic games is established.

Performance of Noisy Higher Order Accelerated Gradient Flow Dynamics for Strongly Convex Quadratic Optimization Problems, pp. 3833-3838

S. Russo, A. Proutiere

We study performance of momentum-based accelerated first-order optimization algorithms in the presence of additive white stochastic disturbances. For strongly convex quadratic problems with a condition number , we determine the best possible convergence rate of continuous-time gradient flow dynamics of order . We also demonstrate that additional momentum terms do not affect the tradeoffs between convergence rate and variance amplification that exist for gradient flow dynamics with .

Tube-Based Zonotopic Data-Driven Predictive Control, pp. 3845-3851

S. Russo, A. Proutiere

We present a novel tube-based data-driven predictive control method for linear systems affected by a bounded additive disturbance. Our method leverages recent results in the reachability analysis of unknown linear systems to formulate and solve a robust tube-based predictive control problem. More precisely, our approach consists in deriving, from the collected data, a zonotope that includes the true state error set. We show how to guarantee the stability of the resulting error zonotope, which can be exploited to increase the computational efficiency of existing zonotopic data-driven MPC formulations. Results on a double-integrator affected by strong adversarial noise demonstrate the effectiveness of the proposed control approach.

Maintaining Robust Stability and Performance through Sampling and Quantization, pp. 3852-3858

M. Susca, M. Mihaly, P. Dobra

The inherent problem with continuous-time robust control synthesis is that it returns a controller which cannot directly be implemented on a numeric device. The discrete-time robust control synthesis does not fully solve this problem, as the sampling rate is considered as an input hyperparameter, without explicitly performing a selection, and the quantization of the controller coefficients is not encompassed in the synthesis procedure. The aim of this paper is to provide rigorous means to efficiently compute the sampling rate and quantization step for a given continuous regulator in order to maintain the robust stability and robust performance specifications guaranteed in the analog domain, assuming a constant rate and fixed-point arithmetic, using the structured singular value framework and global optimization techniques. A numerical example is further presented and discussed, emphasizing practical implications.
However, at higher noise levels, the LQG control strategy fails to achieve robust performance against the model mismatch. Adaptive robust control (ARC) has demonstrated its superiority in handling disturbances and parametric uncertainties in the past decades. However, the conventional ARC designs cannot effectively handle the hard state constraints. To deal with the state constraints while maintaining a good tracking performance and robustness, a two-layer constrained adaptive robust control (CARC) strategy is proposed in this paper. In the outer layer, a planner continuously monitors level of tracking errors. When the tracking errors become large, the planner redesigns the reference trajectory by solving a constrained optimization problem. In the inner layer, a Saturated-ARC controller is synthesized to achieve a high tracking performance in the presence of external disturbances and parametric modeling uncertainties. The interaction between the two layers was analyzed to achieve guaranteed performance. The optimization cost function can be arbitrarily selected based on different needs, with time-optimal trajectory tracking re-planning solved in this paper due to its wider potential applications. The focus of this paper is not on solving the optimization problems, but rather incorporating the existing algorithms into our two-layer structure. Unlike model predictive control (MPC) based strategies, the proposed design does not rely on the fast iterative computation of solving the constrained optimization problem to achieve stability and robustness. Comparative simulations were carried out on an unmatched system. The results demonstrate the improvement of the proposed design over the past ones in dealing with hard state constraints.

It has been well understood that the estimation error of uncertainty and disturbance estimator (UDE) can be arbitrarily small provided the bandwidth of UDE is chosen to be sufficiently high. Unfortunately, due to many physical constraints, the allowed bandwidth of UDE is always practically limited, the UDE is not so ideal and its actual estimation performance may not be satisfactory. Motivated by this observation, we formulate a simple inequality constraint on the UDE bandwidth and propose an uncertainty and disturbance estimator with phase-lead compensation (UDE-PLC) to improve the estimation performance under such a constraint. The main idea behind the design is to use the cascade of a first-order phase lead compensator and a first-order Butterworth filter, instead of a single Butterworth filter, to build the estimation relationship. By choosing properly the involved three parameters, the obvious phase lag of the non-ideal Butterworth filter is well compensated and both the disturbance estimation error and trajectory tracking error are reduced by the proposed design. The design specifications and the guideline for parameter tuning are provided to make the philosophy behind the UDE-PLC easy to follow. The effectiveness of UDE-PLC is verified by simulation on a 2-DOF AERO attitude control platform.

The Koopman operator is a promising approach for learning nonlinear dynamics using linear operators in high-dimensional function space. However, due to finite-dimensional approximation and imperfect data, model mismatch can arise, resulting in a discrepancy from the actual nonlinear model. As a result, robustness against model mismatch is a critical, objective in Koopman-model-based control design. This paper presents a robust dual-loop control scheme for the finite-dimensional Koopman model to address this issue. Firstly, the biased dynamics of the finite-dimensional Koopman model are illustrated by a nonlinear bilinear motor. Multiple trajectory data sets are assumed with measurement noises and used to identify a Koopman model using the extended Dynamic Mode Decomposition (EDMD). The resulting Koopman model is examined to yield biased dynamics from actual nonlinear dynamics. Then, a robust dual-loop control is designed, consisting of an observer-based state-feedback control for the nominal Koopman model and an additional robust loop to improve robustness. The numerical results show that the dual-loop control can improve the robustness of the Koopman operator against model mismatch compared to simply applying nominal control. At low noise levels, both LQG and dual-loop control can regulate the system. However, at higher noise levels, the LQG control strategy fails to regulate the system, but the dual-loop control drives the system to achieve robust performance against the model mismatch.

Adaptive robust control (ARC) has demonstrated its superiority in handling disturbances and parametric uncertainties in the past decades. However, the conventional ARC designs cannot effectively handle the hard state constraints. To deal with the state constraints while maintaining a good tracking performance and robustness, a two-layer constrained adaptive robust control (CARC) strategy is proposed in this paper. In the outer layer, a planner continuously monitors level of tracking errors. When the tracking errors become large, the planner redesigns the reference trajectory by solving a constrained optimization problem. In the inner layer, a Saturated-ARC controller is synthesized to achieve a high tracking performance in the presence of external disturbances and parametric modeling uncertainties. The interaction between the two layers was analyzed to achieve guaranteed performance. The optimization cost function can be arbitrarily selected based on different needs, with time-optimal trajectory tracking re-planning solved in this paper due to its wider potential applications. The focus of this paper is not on solving the optimization problems, but rather incorporating the existing algorithms into our two-layer structure. Unlike model predictive control (MPC) based strategies, the proposed design does not rely on the fast iterative computation of solving the constrained optimization problem to achieve stability and robustness. Comparative simulations were carried out on an unmatched system. The results demonstrate the improvement of the proposed design over the past ones in dealing with hard state constraints.

**FrB02.8**

UDE-PLC: Uncertainty and Disturbance Estimator with Phase-Lead Compensation, pp. 3877-3882
- Zhang, Te
  - University of Electronic Science and Technology of China
- Zhang, Lei
  - Sun Yat-Sen University
- Zhu, Bo
  - Sun Yat-Sen University
- Zhang, Qingrui
  - Sun Yat-Sen University

**FrB02.9**

A Robust Dual-Loop Control for Finite-Dimensional Koopman Model of Nonlinear Dynamical Systems, pp. 3883-3888
- Pal, Anuj
  - Michigan State University
- He, Tianyi
  - Utah State University

**FrB03.1**

Human-As-Advisor in the Loop for Autonomous Lane-Keeper (I), pp. 3895-3900
- Mai, Rene
  - Rensselaer Polytechnic Institute
- Mishra, Sandipan
  - Rensselaer Polytechnic Institute
- Julius, Agung
  - Rensselaer Polytechnic Institute

This paper presents a human-as-advisor architecture for shared human-machine autonomy in dynamic systems. In the human-as-advisor architecture, the human provides suggested control actions to the autonomous system; the system uses a model of the human controller to ascertain the system's state as perceived by the human. The system combines this information with additional sensor measurements, yielding an improved state estimate. We apply this architecture to the problem of lane-centering an autonomous vehicle in the presence of conflicting lane markings that render the true lane center uncertain. We model conflicting lane markings with a multi-component Gaussian mixture model. The human-suggested course of action is interpreted as an additional sensor measurement, which a Kalman filter is designed to combine with a speedometer and camera for improving the state estimate. With human input from our human-as-advisor architecture, the vehicle centers itself in the lane; without human input, the vehicle does not center itself. We also demonstrate the human-as-advisor architecture is robust to additive output matrix uncertainty and non-linear perturbations in the human model used to interpret the human-suggested control actions.

**FrB03.2**

On Trust-Aware Assistance-Seeking in Human-Supervised Autonomy (I), pp. 3901-3906
- Mangalindan, Dong Hae
  - Michigan State University
- Rovira, Ericka
  - U.S. Military Academy
- Srivastava, Vaibhav
  - Michigan State University
Using the context of human-supervised object collection tasks, we explore policies for a robot to seek assistance from a human supervisor and avoid loss of human trust in the robot. We consider a human-robot interaction scenario in which a mobile manipulator chooses to collect objects either autonomously or through human assistance; while the human supervisor monitors the robot’s operation, assists when asked, or intervenes if the human perceives that the robot may not accomplish its goal. We design an optimal assistance-seeking policy for the robot using a Partially Observable Markov Decision Process (POMDP) setting in which human trust is a hidden state and the objective is to maximize collaborative performance. We conduct two sets of human-robot interaction experiments. The data from the first set of experiments is used to estimate POMDP parameters, which are used to compute an optimal assistance-seeking policy that is used in the second experiment. For most participants, the estimated POMDP reveals that humans are more likely to intervene when their trust is low and the robot is performing a high-complexity task; and that robot asking for assistance in high-complexity tasks can increase human trust in the robot. Our experimental results show that the proposed trust-aware policy yields superior performance compared with an optimal trust-agnostic policy.

14:00-14:15 FrB03.3

Modeling Dynamical Systems with Neural Hybrid System Framework Via Maximum Entropy Approach (I), pp. 3907-3912

Yang, Yejiang
Augusta University

Xiang, Weiming
Augusta University

In this paper, a data-driven neural hybrid system modeling framework via the Maximum Entropy partitioning approach is proposed for complex dynamical system modeling such as human motion dynamics. The sampled data collected from the system is partitioned into segmented data sets using the Maximum Entropy approach, and the mode transition logic is then defined. Then, as the local dynamical description for their corresponding partitions, a collection of small-scale neural networks is trained. Following a neural hybrid system model of the system, a set-valued reachability analysis with low computation cost is provided based on interval analysis and a split and combined process to demonstrate the benefits of our approach in computationally expensive tasks. Finally, a numerical examples of the limit cycle and a human behavior modeling example are provided to demonstrate the effectiveness and efficiency of the developed methods.

14:15-14:30 FrB03.4

A Two-Layer Human-In-The-Loop Optimization Framework for Customizing Lower-Limb Exoskeleton Assistance (I), pp. 3913-3920

Zheng, Siqi
Clemson University

Lv, Ge
Clemson University

Task-invariant control paradigms can enable lower-limb exoskeletons to provide assistance for their users across various locomotor tasks without prescribing to specific joint kinematics. As an energetic control method, energy shaping can alter a human’s body energetics in the closed-loop to provide gait benefits. To obtain the energy shaping law for underactuated systems, a set of nonlinear partial differential equations, called the matching condition, needs to be solved to determine the achievable closed-loop dynamics. However, solving matching conditions for high-dimensional nonlinear systems is generally difficult. In addition, how to define parameters for the closed-loop dynamics that render the optimal exoskeleton assistance remains unclear. In this paper, we proposed a two-layer, human-in-the-loop optimization framework for lower-limb exoskeletons to customize their assistance to human users. The inner-layer optimization finds solutions to the matching condition meanwhile following the energy trajectories of a virtual reference model defined based on the self-selected gait of humans and a scaled version of their anatomical parameters. The outer-layer incorporates human-in-the-loop Bayesian Optimization to update reference energy’s parameters for reducing metabolic costs. Simulation results on two biped models demonstrate that the proposed framework can solve matching conditions numerically at the selected timestamps and the associated energy shaping strategies can reduce human metabolic cost. Moreover, exoskeletons torques calculated using an able-bodied subject’s kinematic data well match human biological torques.

14:30-14:45 FrB03.5

Input-Constrained Human Assist Control Via Control Barrier Function for Viability Kernel, pp. 3921-3926

Tezuka, Issei
Tokyo University of Science

Nakamura, Hisakazu
Tokyo University of Science

Hatano, Takashi
Mazda Motor Corporation

Kamijo, Kenji
Mazda Motor Corporation

Sato, Shota
Mazda Motor Corporation

This paper introduces control barrier functions for viability kernels, where a control input that enforces the safety of a system exists, to address a human assist control problem under input constraints. This paper also introduces a CBF-based human assist controller that satisfies both state and input constraints if an initial state of a system is contained in viability kernels. We lastly demonstrate how viability kernels are represented by system states and confirm the effectiveness of the proposed controller by computer simulation.

14:45-15:00 FrB03.6

Multi-Scenario Tube-Based Model Predictive Control for Irrigation Canals with Human Interventions, pp. 3927-3932

Lopez Rodriguez, Francisco
University of Seville

Muros, Francisco Javier
University of Seville

Shahverdi, Kazem
Bu-Ali Sina University, Hamedan, Iran

Maestre, Jose Maria (Pepe)
University of Seville

This article considers irrigation canal control problems where human agents are free to move along the canal temporarily overriding the position of actuators, which are considered to be electromechanical gates. To deal with this issue, the centralized controller is robustified against human interventions by following a tube-based model predictive control approach. To decrease conservatism, the controller considers explicitly the different scenarios for human interventions. Also, the ancillary control law implemented by the tube-based MPC controller is computed using a modular feedback gain that is designed to be resilient against the loss of control inputs. To illustrate the effectiveness of the proposed method, the American Society of Civil Engineers (ASCE) Test Canal 2 is used as a case study.

FrB04 Sapphire AB

Statistical Learning (Regular Session)

Chair: Imani, Mahdi
Northeastern University

Co-Chair: Moothedath, Shana
Iowa State University

13:30-13:45 FrB04.1

Optimal Recursive Expert-Enabled Inference in Regulatory Networks, pp. 3933-3938

Ravari, Amirhossein
Northeastern University

Ghoreishi, Seyedeh Fatemeh
Northeastern University

Imani, Mahdi
Northeastern University

Accurate inference of biological systems, such as gene regulatory networks and microbial communities, is a key to a deep understanding of their underlying mechanisms. Despite several advances in the inference of regulatory networks in recent years, the existing techniques cannot incorporate expert knowledge into the inference process. Expert knowledge contains valuable biological information and is often reflected in available biological data, such as interventions made by biologists for treating diseases. Given the complexity of regulatory networks and the limitation of biological data, ignoring expert knowledge can lead to inaccuracy in the inference.
process. This paper models the regulatory networks using Boolean network with perturbation. We develop an expert-enabled inference method for inferring the unknown parameters of the network model using expert-acquired data. Given the availability of information about data-acquiring objectives and expert confidence, the proposed method optimally quantifies the expert knowledge along with the temporal changes in the data for the inference process. The numerical experiments investigate the performance of the proposed method using the well-known p53-MDM2 gene regulatory network.

13:45-14:00 FrB04.2
Feature Selection in Distributed Stochastic Linear Bandits, pp. 3939-3944
Lin, Jiabin Iowa State University
Mootechath, Shana Iowa State University

In this paper, we study the problem of feature selection in distributed stochastic multi-arm bandits, in which M agents work collaboratively to choose optimal actions under the coordination of a central server in order to minimize the total regret. We consider a learning situation where there is a set of feature maps, each map is best suited for a certain state of the system and the best feature map is unknown to the agent at the time of learning. In our model, an adversary chooses a distribution on the set of possible feature maps and the agents observe only the distribution and the true feature map are unknown to the agents. Our goal is to develop a distributed algorithm that selects a sequence of optimal actions to maximize the cumulative reward. By performing a feature vector transformation we propose an elimination algorithm and prove regret and communications bounds for linearly parameterized reward functions. We implement our algorithm and validate the performance of our approach through numerical simulations.

14:00-14:15 FrB04.3
Dynamic Probabilistic Latent Variable Model with Exogenous Variables for Dynamic Anomaly Detection, pp. 3945-3950
Xu, Bo University of Waterloo
Zhu, Qinqin University of Waterloo

A novel dynamic probabilistic latent variable model with exogenous variables (DPLVMX) is proposed in this article to capture system dynamics with the existence of random noises. The dynamic auto-regressive relations between current and past latent variables are extracted in a Markov state-space form in the proposed model. Furthermore, to strengthen the utilization of valuable information in the collected data, a composite loading index is designed to select some interested variables as the exogenous variables, which is explicitly incorporated into the model relations of DPLVMX. An improved DPLVM based monitoring scheme is also designed, where a new dynamic monitoring index is proposed to detect dynamic anomalies. The Tennessee Eastman process is used to illustrate the superiority of the proposed algorithm.

14:15-14:30 FrB04.4
A Computationally-Friendly Data-Driven Safety Filter for Control-Affine Discrete-Time Systems Subject to Unknown Process Noise, pp. 3951-3956
Farokhi, Farhad The University of Melbourne
Leong, Alex S. DST Group
Shames, Iman Australian National University
Zamani, Mohammad DSTG

A supervisory safety filter is developed to minimally modify nominal control inputs to a nonlinear control-affine discrete-time system to ensure satisfaction of potentially time-varying state and input constraints, i.e., safety constraints, with high probability. The system model is known while the environment model, i.e., distribution of additive Gaussian process noise, is unknown. State measurements are used to learn the statistics of the process noise. The safety filter employs a robust optimization problem involving tightening of the safety constraints based on the learned statistics and the corresponding confidence.

14:30-14:45 FrB04.5
Reinforcement Learning Data-Acquiring for Causal Inference of Regulatory Networks, pp. 3957-3964
Alali, Mohammad Northeastern University
Imani, Mahdi Northeastern University

Gene regulatory networks (GRNs) consist of multiple interacting genes whose activities govern various cellular processes. The limitations in genomics data and the complexity of the interactions between components often pose huge uncertainties in the models of these biological systems. Meanwhile, inferring/estimating the interactions between components of the GRNs using data acquired from the normal condition of these biological systems is a challenging or, in some cases, an impossible task. Perturbation is a well-known genomics approach that aims to excite targeted components to gather useful data from these systems. This paper models GRNs using the Boolean network with perturbation, where the network uncertainty appears in terms of unknown interactions between genes. Unlike the existing heuristics and greedy data-acquiring methods, this paper provides an optimal Bayesian formulation of the data-acquiring process in the reinforcement learning context, where the actions are perturbations, and the reward measures step-wise improvement in the inference accuracy. We develop a semi-gradient reinforcement learning method with function approximation for learning near-optimal data-acquiring policy. The obtained policy yields near-exact Bayesian optimality with respect to the entire uncertainty in the regulatory network model, and allows learning the policy offline through planning. We demonstrate the performance of the proposed framework using the well-known p53-Mdm2 negative feedback loop gene regulatory network.
Improving High Efficiency and Reliability of Pump Systems Using Optimal Fractional-Order Integral Sliding-Mode Control Strategy, pp. 3971-3976

Nassiri, Samir
Engineering for Smart and Sustainable Systems Research Center, M

Labbadi, Moussa
Univ. Grenoble Alpes, CNRS, Grenoble INP, GIPSA-Lab, 38000 Grenoble

Cherkaoui, Mohamed
Engineering for Smart and Sustainable Systems Research Center, M

In this paper, a robust optimal efficiency Controller for a Complete water pumping system is designed based on the Fractional order Integral Sliding Surface (FISTSM) with Linear Quadratic Regulator (LQR) related to the Minimum Electric Loss (MEL) condition and tuned using an adaptive Genetic Algorithm optimization tool (GA). The whole control system is simulated in MATLAB SIMULINK workspace and the results show that the optimal controller allows, at the same time, the maximization of the overall efficiency and stabilization of the discharge flow rate for every operation point of the pumping system, offering a suitable operating mode by balancing efficiency and reliability of the Moto Pump Pipeline system. A comparative analysis based on control energy, chattering phenomena, and control robustness has been conducted between the conventional PI, LQR, Integral SuperTwisting Sliding Mode Surface (ISTSMC) and the proposed control strategy FISTSM-LQR for moto pump pipeline systems based on the simulated results. Finally, we evaluated the performance of the designed controls, including the Integral Absolute Error (IAE). The results of a simulation demonstrate that the proposed controller proves energy efficiency, robustness achievement, and chattering reduction.

14:00-14:15 FrB05.3
Scalable Multi-Agent Reinforcement Learning with General Utilities, pp. 3977-3982

Ying, Donghao
UC Berkeley

Ding, Yuhao
University of California, Berkeley

Koppel, Alec
JP Morgan Chase

Lavaei, Javad
UC Berkeley

We study the scalable multi-agent reinforcement learning (MARL) with general utilities, defined as nonlinear functions of the team’s long-term state-action occupancy measure. The objective is to find a localized policy that maximizes the average of the team’s local utility functions without the full observability of each agent in the team. By exploiting the spatial correlation decay property of the network structure, we propose a scalable distributed policy gradient algorithm with shadow reward and localized policy that consists of three steps: (1) shadow reward estimation, (2) truncated shadow Q-function estimation, and (3) truncated policy gradient estimation and policy update. Our algorithm converges, with high probability, to $\epsilon$-stationarity with $\widetilde{O}(\epsilon^{-2})$ samples up to some approximation error that decreases exponentially in the communication radius. This is the first result in the literature on multi-agent RL with general utilities that does not require the full observability.

14:15-14:30 FrB05.4
Optimality of Zeno Executions in Hybrid Systems, pp. 3983-3988

Clark, William
Cornell University

Oprea, Maria
Cornell University

A unique feature of hybrid dynamical systems (systems whose evolution is subject to both continuous- and discrete-time laws) is Zeno trajectories. Usually these trajectories are avoided as they can cause incorrect numerical results as the problem becomes ill-conditioned. However, these are difficult to justifiably avoid as determining when and where they occur is a non-trivial task. It turns out that in optimal control problems, not only can they not be avoided, but are sometimes required in synthesizing the solutions. This work explores the pedagogical example of the bouncing ball to demonstrate the importance of “Zeno control executions.”

14:30-14:45 FrB05.5
Nonuniqueness and Convergence to Equivalent Solutions in Observer-Based Inverse Reinforcement Learning, pp. 3989-3994

Town, Jared
Oklahoma State University

Morrison, Zachary
Oklahoma State University

Kamalapurkar, Rushikesh
Oklahoma State University

A key challenge in solving the deterministic inverse reinforcement learning problem online and in real-time is the existence of non-unique solutions. Nonuniqueness necessitates the study of the notion of equivalent solutions and convergence to such solutions. While offline algorithms that result in convergence to equivalent solutions have been developed in the literature, online, real-time techniques that address nonuniqueness are not available. In this paper, a regularized history stack observer is developed to generate solutions that are approximately equivalent. Novel data-richness conditions are developed to facilitate the analysis and simulation results are provided to demonstrate the effectiveness of the developed technique.

14:45-15:00 FrB05.6
Exploiting GPU/SIMD Architectures for Solving Linear-Quadratic MPC Problems, pp. 3995-4000

Cole, David
University of Wisconsin-Madison

Shin, Sung-Ho
Argonne National Laboratory

Pacaud, Francois
Argonne National Laboratory

Zavala, Victor M.
University of Wisconsin-Madison

Anitescu, Mihai
Argonne National Laboratory

We report numerical results on solving linear-quadratic model predictive control (MPC) problems by exploiting graphics processing units (GPUs). The presented method reduces the MPC problem by eliminating the state variables and applies a condensed-space interior-point method to remove the inequality constraints in the KKT system. The final condensed matrix is positive definite and can be efficiently factorized in parallel on GPU/SIMD architectures. In addition, the size of the condensed matrix depends only on the number of controls in the problem, rendering the method particularly effective when the problem has many states but few inputs and moderate horizon length. Our numerical results for PDE-constrained problems show that the approach is of order magnitude faster than a standard CPU implementation. We also provide an open-source Julia framework that facilitates modeling (DynamicNLPModels.jl) and solution (MadNLP.jl) of MPC problems on GPUs.

15:00-15:15 FrB06
Stochastic Systems (Regular Session)

Chair: Lee, Junsoo
University of South Carolina

Co-Chair: Hoshino, Kentaro
Kyoto University

13:30-13:45 FrB06.1
Fixed Time Stability of Discrete-Time Stochastic Dynamical Systems, pp. 4001-4006

Lee, Junsoo
University of South Carolina

Haddad, Wassim M.
Georgia Inst. of Tech

In this paper, we address fixed time stability in probability of discrete-time stochastic dynamical systems. Unlike finite time stability in probability, wherein the finite time almost sure convergence behavior of the dynamical system depends on the system initial conditions, fixed time stability in probability involves finite time stability in probability for which the stochastic settling-time is guaranteed to be independent of the system initial conditions. More specifically, we develop Lyapunov theorems for fixed time stability in probability for Itô-type stationary nonlinear stochastic difference equations including...
a Lyapunov theorem that involves an exponential inequality of the
Lyapunov function that gives rise to a minimum bound on the average
stochastic settling-time characterized by the primary and secondary
branches of the Lambert W function.

In this paper, we consider an open quantum system undergoing
imperfect and indirect measurement. For quantum non-demolition
(QND) measurement. Simulations suggest the efficiency of the
proposed quantum projection filter, even in presence of a
stabilizing feedback control which depends on the projection filter.

Automatically synthesizing controllers for continuous-state nonlinear
stochastic systems, while giving guarantees on the probability of
satisfying (infinite-horizon) temporal logic specifications crucially
depends on abstractions with a quantified accuracy. For this similarity
quantification, approximate stochastic simulation relations are often
used. To handle the nonlinearity of the system effectively, we use
finite-state abstractions based on piecewise-affine approximations
together with tailored simulation relations that leverage the local affine
structure. In the end, we synthesize a robust controller for a nonlinear
stochastic Van der Pol oscillator.

Dissipative dynamical systems provide fundamental connections
between physics, dynamical systems theory, and control science and
engineering. In the deterministic setting, dissipativity theory has been
extensively developed in the literature to provide a general framework
for the analysis and design of control systems using an
input-state-output system description based on generalized system
energy considerations that uses a state-space formalism to link
engineering systems with memory to well known physical
phenomena. Recently, several results have appeared in the literature
extending dissipativity notions to the stochastic setting in order to
develop an analogous theory for stochastic dynamical systems.

In this paper, we consider an open quantum system undergoing
imperfect and indirect measurement. For quantum non-demolition
(QND) measurement. Simulations suggest the efficiency of the
proposed quantum projection filter, even in presence of a
stabilizing feedback control which depends on the projection filter.

13:45-14:00 FrB06.2
Temporal Logic Control of Nonlinear Stochastic Systems Using a
Piecewise-Affine Abstraction, pp. 4007-4012
van Huijgevoort, Birgit
Eindhoven University of
Technology
Weiland, Siep
Eindhoven Univ. of Tech
Haesaert, Sofie
Eindhoven University of
Technology

14:00-14:15 FrB06.3
Dissipative Stochastic Dynamical Systems, pp. 4013-4018
Lanchares, Manuel
Georgia Institute of Technology
Haddad, Wassim M.
Georgia Inst. of Tech

14:15-14:30 FrB06.4
Exact Solution and Projection Filters for Open Quantum Systems
Subject to Imperfect Measurements, pp. 4019-4024
Ramadan, Ibrahim
CentraleSupelec/Université
Paris-Saclay
Amini, Nina H.
CNRS, L2S, CentraleSupelec
Mason, Paolo
CNRS, Laboratoire Des Signaux
Et Systèmes, Supélec

In this paper, we consider an open quantum system undergoing
imperfect and indirect measurement. For quantum non-demolition
(QND) measurement. Simulations suggest the efficiency of the
proposed quantum projection filter, even in presence of a
stabilizing feedback control which depends on the projection filter.

14:30-14:45 FrB06.5
Scalable Long-Term Safety Certificate for Large-Scale Systems, pp.
4025-4031
Hoshino, Kenta
Kyoto University
Wang, Zhuoyuan
Carnegie Mellon University
Nakahira, Yorie
Carnegie Mellon University

This paper focuses on safe control problems for high-dimensional
systems with large uncertainties. A major challenge is the
computation load to account for long outlook horizons in large-scale
systems. This challenge is tackled using an integration of probabilistic
forward invariance, the comparison theorem, and PDE techniques.
Specifically, we propose a probabilistic certificate for long-term safety
that only requires myopically ensuring linear control constraints and
evaluating two-dimensional PDEs regardless of the system
dimension. The certificate is constructed by obtaining a long-term
safe probability bound as a solution of the PDE using the comparison
theorem and applying a new notion of probabilistic forward invariance
on the probability bound. The use of forward invariance directly on
probabilistic reachability allows our method to carry the former's
computational efficiency and the latter's control over long-term
behaviors. Its capability to efficiently ensure long-term safety for
high-dimensional systems can be useful in many large-scale
distributed autonomous systems operating with limited onboard
resources in latency- critical environments.

14:45-15:00 FrB06.6
4032-4037
Hsieh, Chung-Han
National Tsing Hua University

A trading system is said to be robust if it generates a robust return
regardless of market direction. To this end, a consistently positive
expected trading gain is often used as a robustness metric for a
trading system. In this paper, we propose a new class of trading
policies called the double linear policy in an asset trading scenario
when the transaction costs are involved. Unlike many existing papers,
we first show that the desired robust positive expected gain may
disappear when transaction costs are involved. Then we quantify
under what conditions the desired positivity can still be preserved. In
addition, we conduct heavy Monte-Carlo simulations for an underlying
asset whose prices are governed by a geometric Brownian motion
with jumps to validate our theory. A more realistic backtesting
example involving historical data for cryptocurrency Bitcoin-USD is
also studied.

13:30-13:45 FrB07.1
Model Predictive Control of Sputter Processes, pp. 4038-4043
Woelfel, Christian Tobias
Ruhr-Universität Bochum

A new model is developed to approximate the multivariable nonlinear
sputter process with respect to the argon gas flow and the generator
temperature as the inputs and the argon pressure and the self-bias voltage
as the outputs. The identification of the process parameters is
discussed based on experimental data. A novel control strategy for
sputter processes is presented that applies an offset-free predictive
controller based on the approximated model. Experiments are shown
to validate the control system.

13:45-14:00 FrB07.2
Control Applications I (Regular Session)
Chair: Woelfel, Christian Tobias
Co-Chair: Ayalew, Beshah
Clemson University

Aqua 303

FrB07

13:30-13:45 FrB07.1
Model Predictive Control of Sputter Processes, pp. 4038-4043
Woelfel, Christian Tobias
Ruhr-Universität Bochum

A new model is developed to approximate the multivariable nonlinear
sputter process with respect to the argon gas flow and the generator
temperature as the inputs and the argon pressure and the self-bias voltage
as the outputs. The identification of the process parameters is
discussed based on experimental data. A novel control strategy for
sputter processes is presented that applies an offset-free predictive
controller based on the approximated model. Experiments are shown
to validate the control system.
Heat pump water heaters (HPWHs) are more energy-efficient than electric resistance water heaters and have inherent load-shifting potential due to their built-in storage tank. Most HPWHs currently employ rule-based control (RBC) strategies that track a temperature setpoint, regardless of the cost of electricity or marginal grid voltage.

Microgrids. DC microgrids are exposed to small disturbances in their operating conditions for global asymptotic stability are established for the control for a DC microgrid to guarantee the stability of the DC bus voltage. Regulators are used in many aerial, automotive, communication, electronic and electromechanical systems. We investigate an FPGA based management system to control power modules and interconnected components. This implies solving problems such as sensing and filtering, components aggregation, interfacing, etc. The system requirements imply design and implementation of minimal complexity control laws for high-performance switching converters. FGPs enable adaptive control, filtering and estimation to guarantee optimal performance, robustness, and interoperability for a broad range of applications. Our findings are experimentally validated.

This paper studies the problem of using a group of mobile robots to drive a group of humans to an exit for emergency evacuation. The interactions between the robots and the humans are modeled by a social force model. A novel optimization problem is formulated to drive the robots and maintain user comfort. Simulation results demonstrate that the MPC approach can reduce operating costs and GHG emissions with no comfort violations compared to a conventional RBC strategy for HPWHs.

This paper studies the problem of using a group of mobile robots to drive a group of humans to an exit for emergency evacuation. The interactions between the robots and the humans are modeled by a social force model. A novel optimization problem is formulated to drive the robots and maintain user comfort. Simulation results demonstrate that the MPC approach can reduce operating costs and GHG emissions with no comfort violations compared to a conventional RBC strategy for HPWHs.

The growing interest in green energy and the necessity of reliable electricity in remote areas take the researchers' interest toward DC microgrids. DC microgrids are exposed to small disturbances in their DC sources due to weather uncertainties and ripples resulting from AC/DC converters in their AC sources. These uncertainties may cause instability in microgrids especially in the presence of constant power loads (CPLs). DC microgrids' stability highly depends on DC bus voltage deviation. This paper proposes a new sliding mode control for a DC microgrid to guarantee the stability of the DC bus voltage.
We develop a novel framework to assess the risk of misperception in a traffic sign classification task in the presence of exogenous noise. We consider the problem in an autonomous driving setting, where visual input quality gradually improves due to improved resolution, and less noise since the distance to traffic signs decreases. Using the estimated perception statistics obtained using the standard classification algorithms, we aim to quantify the risk of misperception to mitigate the effects of imperfect visual observation. By exploring perception outputs, their expected high-level actions, and potential costs, we show the closed-form representation of the conditional value-at-risk (CVaR) of misperception. Several case studies support the effectiveness of our proposed methodology.

Adversarial Tradeoffs in Robust State Estimation (I), pp. 4083-4089
Zhang, Thomas  
Lee, Bruce  
Hassani, Hamed  
Matni, Nikolai  

Adversarially robust training has been shown to reduce the susceptibility of learned models to targeted input data perturbations. However, it has also been observed that such adversarially robust models suffer a degradation in accuracy when applied to unperturbed data sets, leading to a robustness-accuracy tradeoff. Inspired by recent progress in the adversarial machine learning literature which characterize such tradeoffs in simple settings, we develop tools to quantitatively study the performance-robustness tradeoff between nominal and robust state estimation. In particular, we define and analyze a novel adversarially robust Kalman Filtering problem. We show that in contrast to most other problem instances in adversarial machine learning, we can precisely derive the adversarial perturbation in the Kalman Filtering setting. We provide an algorithm to find this optimal adversarial perturbation given data realizations, and develop upper and lower bounds on the adversarial state estimation error in terms of the standard (non-adversarial) estimation error and the spectral properties of the resulting observer. Through these results, we show a natural connection between a filter’s robustness to adversarial perturbation and underlying control theoretic properties of the system being observed, namely the spectral properties of its observability gramian.

Certified Robust Control under Adversarial Perturbations (I), pp. 4090-4095
Yang, Jinghan  
Kim, Hunmin  
Wan, Wenbin  
Hovakimyan, Naira  
Vorobeychik, Yevgeniy  

Certified Robust Control under Adversarial Perturbations (I), pp. 4090-4095
Yang, Jinghan  
Kim, Hunmin  
Wan, Wenbin  
Hovakimyan, Naira  
Vorobeychik, Yevgeniy  

Autonomous systems increasingly rely on machine learning techniques to transform high-dimensional raw inputs into predictions that are then used for decision-making and control. However, it is often easy to maliciously manipulate such inputs and, as a result, predictions. While effective techniques have been proposed to certify the robustness of predictions to adversarial input perturbations, such techniques have been disembodied from control systems that make downstream use of the predictions. We propose the first approach for composing robustness certification of predictions with respect to raw input perturbations with robust control to obtain certified robustness of control to adversarial input perturbations. We use a case study of adaptive vehicle control to illustrate our approach and show the value of the resulting end-to-end certificates through extensive experiments.

Risk-Awareness in Learning Neural Controllers for Temporal Logic Objectives (I), pp. 4096-4103
Hashemi, Navid  
Qin, Xin  
Deshmukh, Jyotirmoy  
Fainekos, Georgios  
Hoxha, Bardh  
Yamaguchi, Tomoya  

In this paper, we consider the problem of synthesizing a controller in the presence of uncertainty such that the resulting closed-loop system satisfies certain hard constraints while optimizing certain (soft) performance objectives. We assume that the hard constraints encoding safety or mission-critical specifications are expressed using Signal Temporal Logic (STL), while performance is quantified using standard cost functions on system trajectories. To ensure satisfaction of the STL constraints, we algorithmically obtain control barrier functions (CBFs) from the STL specifications. We model controllers as neural networks (NNs) and provide an algorithm to train the NN functions (CBFs) from the STL specifications. We assume that the hard constraints satisfy the CBF conditions (with a user-specified robustness margin). We evaluate the risk incurred by the trade-off between the robustness margin of the system and its performance using the formalism of risk measures. We demonstrate our approach on challenging nonlinear control examples such as quadcopter motion planning and a unicycle.

Exponential TD Learning: A Risk-Sensitive Actor-Critic Reinforcement Learning Algorithm (I), pp. 4104-4109
Noorani, Erfan  
Mavridis, Christos  
Baras, John S.  

Incorporating risk in the decision-making process has been shown to lead to significant performance improvement in optimal control and reinforcement learning algorithms. We construct a temporaldifference risk-sensitive reinforcement learning algorithm using the exponential criteria commonly used in risk-sensitive control. The proposed method resembles an actor-critic architecture with the ‘actor’ implementing a policy gradient algorithm based on the exponential of the reward-to-go, which is estimated by the ‘critic’. The novelty of the update rule of the ‘critic’ lies in the use of a modified objective function that corresponds to the underlying multiplicative Bellman#39;s equation. Our results suggest that the use of the exponential criteria accelerates the learning process and reduces its variance, i.e., risk-sensitivity can be utilized by actor-critic methods and can lead to improved performance.

Cascading Waves of Fluctuation in Time-Delay Multi-Agent Rendezvous (I), pp. 4110-4115
Liu, Guangyi  
Pandey, Vivek  
Somarakis, Christofores  
Motee, Nader  

We develop a framework to assess the risk of cascading failures when a team of agents aims to rendezvous in time in the presence of exogenous noise and communication time-delay. The notion of value-at-risk (VaR) measure is used to evaluate the risk of cascading failures (i.e., waves of large fluctuations) when some agents have failed to rendezvous. Furthermore, an efficient explicit formula is
obtained to calculate the risk of higher-order cascading failures recursively. Finally, from a risk-aware design perspective, we report an evaluation of the most vulnerable sequence of agents in various communication graphs.

FrB09
Lyapunov Methods (Regular Session)
Chair: Peet, Matthew M. Arizona State University
Co-Chair: Ahmed, Qadeer The Ohio State University
13:30-13:45
Convex Synthesis and Verification of Control-Lyapunov and Barrier Functions with Input Constraints, pp. 4116-4123
Dai, Hongkai Toyota Research Institute
Permter, Frank Toyota Research Institute

Control Lyapunov functions (CLFs) and control barrier functions (CBFs) are widely used tools for synthesizing controllers subject to stability and safety constraints. Paired with online optimization, they provide stabilizing control actions that satisfy input constraints and avoid unsafe regions of state-space. Designing CLFs and CBFs with rigorous performance guarantees is computationally challenging. To certify existence of control actions, current techniques not only design a CLF/CBF, but also a nominal controller. This can make the synthesis task more expensive, and performance estimation more conservative. In this work, we characterize polynomial CLFs/CBFs using sum-of-squares conditions, which can be directly certified using convex optimization. This yields a CLF and CBF synthesis technique that does not rely on a nominal controller. We then present algorithms for iteratively enlarging estimates of the stabilizable and safe regions. We demonstrate our algorithms on a 2D toy system, a pendulum and a quadrotor.

13:45-14:00
Barrier Functions for Robust Safety in Differential Inclusions, Part III: Inner and Outer Perturbations, pp. 4124-4129
Maghenem, Mohamed Adlene Gipsa Lab, CNRS, France
Karaki, Diana CEA Paris Saclay

This paper introduces a new robust-safety notion for differential inclusions. That is, we say that the system is strongly robustly safe if it remains safe in the presence of a continuous and positive perturbation, named robustness margin, added to both the argument and the image of its right-hand side. While in existing literature, including the preceding Parts I and II, the perturbation term is added only to the image of the right-hand side, the notion proposed in this paper is shown to be relatively stronger, especially when the right-hand side is a general set-valued map. Furthermore, we show that some of the existing sufficient conditions for robust safety, in term of barrier functions, are strong enough to guarantee strong robust safety, provided that mild assumptions on the right-hand side hold. Following that, we establish the equivalence between strong robust safety and the existence of a smooth barrier certificate.

14:00-14:15
Existence of Partially Quadratic Lyapunov Functions That Can Certify the Local Asymptotic Stability of Nonlinear Systems, pp. 4130-4135
Jones, Morgan Sheffield University
Peet, Matthew M. Arizona State University

This paper proposes a method for certifying the local asymptotic stability of a given nonlinear Ordinary Differential Equation (ODE) by using Sum-of-Squares (SOS) programming to search for a partially quadratic Lyapunov Function (LF). The proposed method is particularly well suited to the stability analysis of ODEs with high dimensional state spaces. This is due to the fact that partially quadratic LFs are parametrized by fewer decision variables when compared with general SOS LFs. The main contribution of this paper is using the Center Manifold Theorem to show that partially quadratic LFs that certify the local asymptotic stability of a given ODE exist under certain conditions.

14:15-14:30 FrB09.4
Cruise Controllers for Vehicles on Lane-Free Ring-Roads, pp. 4136-4141
Theodosios, Dionysios Technical University of Crete
Karafyllis, Iasson National Technical University of Athens
Papageorgiou, Markos Technical Univ. of Crete

The paper introduces novel families of cruise controllers for autonomous vehicles on lane-free ring-roads. The design of the cruise controllers is based on the appropriate selection of a Control Lyapunov Function expressed on measures of the energy of the system with the kinetic energy expressed in ways similar to Newtonian or relativistic mechanics. The derived feedback laws (cruise controllers) are decentralized (per vehicle), as each vehicle determines its control input based on: (i) its own state; (ii) either only the distance from adjacent vehicles (inviscid cruise controllers) or the state of adjacent vehicles (viscous cruise controllers); and (iii) its distance from the boundaries of the ring-road.

14:30-14:45
Uncertainty Propagation for Nonlinear Dynamics: A Polynomial Optimization Approach, pp. 4142-4147
Covella, Francesca Politecnico Di Milano
Fantuzzi, Giovanni FAU Erlangen-Nuernberg

We use Lyapunov-like functions and convex optimization to propagate uncertainty in the initial condition of nonlinear systems governed by ordinary differential equations. We consider the full nonlinear dynamics without approximation, producing rigorous bounds on the expected future value of a quantity of interest even when only limited statistics of the initial condition (e.g., mean and variance) are known. For dynamical systems evolving in compact sets, the best upper (lower) bound coincides with the largest (smallest) expectation among all initial state distributions consistent with the known statistics. For systems governed by polynomial equations and polynomial quantities of interest, one-sided estimates on the optimal bounds can be computed using tools from polynomial optimization and semidefinite programming. Moreover, these numerical bounds provably converge to the optimal ones in the compact case. We illustrate the approach on a van der Pol oscillator and on the Lorenz system in the chaotic regime.

14:45-15:00 FrB09.6
Safe Control Using High-Order Measurement Robust Control Barrier Functions, pp. 4148-4154
Oruganti, Pradeep Sharma The Ohio State University
Naghizadeh, Parinaz Ohio State University
Ahmed, Qadeer The Ohio State University

We study the problem of providing safety guarantees for dynamic systems of high relative degree in the presence of state measurement errors. To this end, we propose High-Order Measurement Robust Control Barrier Functions (HO-MR-CBFs), an extension of the recently proposed Measurement Robust Control Barrier Functions. We begin by formally defining HO-MR-CBF, and identify conditions under which the proposed HO-MR-CBF can render the system's safe set forward invariant. In addition, we provide bounds on the state measurement errors for which the optimization problem for identifying the corresponding safe controllers is feasible for all states within the safe set and given restricted control inputs. We demonstrate the proposed approach through numerical experiments on a collision avoidance scenario in presence of measurement noise using a nonlinear kinematic model of a wheeled robot. We show that using our proposed control method, the robot, who has access to only biased state estimates, will be successful in avoiding the obstacle.
A Quantitative and Constructive Proof of Willems’ Fundamental Lemma and Its Implications, pp. 4155-4160

Berberich, Julian  University of Stuttgart
Iannelli, Andrea  University of Stuttgart
Padoan, Alberto  ETH Zürich
Coulson, Jeremy  University of Wisconsin-Madison
Dörfler, Florian  Swiss Federal Institute of Technology (ETH) Zurich
Allgöwer, Frank  University of Stuttgart

Willems’ Fundamental Lemma provides a powerful data-driven parametrization of all trajectories of a controllable linear time-invariant system based on one trajectory with persistently exciting (PE) input. In this paper, we present a novel proof of this result which is inspired by the classical adaptive control literature and differs from existing proofs in multiple aspects. The proof involves a quantitative and directional PE notion, allowing to characterize robust PE properties via singular value bounds, as opposed to binary rank-based PE conditions. Further, the proof is constructive, i.e., we derive an explicit PE lower bound for the generated data. As a contribution of independent interest, we generalize existing PE results from the adaptive control literature and reveal a crucial role of the system’s zeros.

Ubiquitous Controllability of Single Input Linear Time-Invariant Systems, pp. 4161-4166

Hays, Christopher  Embry-Riddle Aeronautical University
Soderlund, Alexander  The Ohio State University
Phillips, Sean  Air Force Research Laboratory
Henderson, Troy  Embry-Riddle Aeronautical University

In this paper, we consider the case of a particular class of linear time-invariant (LTI) dynamic systems that only require the actuation of a single state to yield controllability of the entire system, dually, only a single state need be observed to render the system observable. This work ties together elements of the state-space, graph, and transfer function representations of dynamic systems to evaluate the controllability and observability properties of a system. More specifically, necessary and sufficient conditions for Ubiquitous Single-Input Controllability (USIC) are introduced using traditional state-feedback perspectives, transfer functions, and a graph theoretical perspective is used to define an additional set of both necessary conditions and sufficient conditions. Ties are also made to structural controllability, and it is shown that any LTI system that meets the USIC condition also meets the structural controllability condition. Finally, brief practical examples are presented.

A Quantitative Notion of Persistency of Excitation and the Robust Fundamental Lemma, pp. 4167-4172

Coulson, Jeremy  ETH Zürich
van Waarde, Henk J.  University of Groningen
Lygeros, John  ETH Zurich
Dörfler, Florian  Swiss Federal Institute of Technology (ETH) Zurich

The fundamental lemma by Willems and coauthors enables a parameterization of all trajectories of a linear time-invariant system in terms of a single, measured one. This result plays a key role in data-driven simulation and control. The fundamental lemma relies on a persistently exciting input to the system to ensure that the Hankel matrix of resulting input/output data has the “right” rank, meaning that its columns span the entire subspace of trajectories. However, such binary rank conditions are known to be fragile in the sense that a small additive noise could already cause the Hankel matrix to have full rank. In this letter we present a robust version of the fundamental lemma. The idea behind the approach is to guarantee certain lower bounds on the singular values of the data Hankel matrix, rather than qualitative rank conditions. This is achieved by designing the inputs of the experiment such that the minimum singular value of an input Hankel matrix is sufficiently large, inspiring a quantitative notion of persistency of excitation. We highlight the relevance of the result in a data-driven control case study by comparing the predictive control performance for varying degrees of persistently exciting data.
sense, such as temporal smoothing and removing high-pass noise components, causing delays and phase distortions, or limiting bandwidths. In this work, we instead show that low-pass filtering and the temporal averaging that underlies it can also have a major and fundamental impact on the linearity of the dynamics. We show using rigorous analysis that across a wide range of stochastic nonlinear systems, temporal averaging dampens nonlinearities and leads to more and more linear dynamics with stronger temporal averaging (lower LPF cutoff frequency), leading asymptotically to a completely linear system as the width of the window over which temporal averaging occurs tends to infinity (LPF cutoff frequency tends to zero). Our results have major implications in a wide range of application areas, including the study of the nervous system whereby LPFs are biologically and algorithmically abundant and a growing body of empirical evidence has found linear models as capable as nonlinear ones in describing neuronal time series.

This paper addresses the problem of robust consensus of an undirected network of homogeneous multi-agent systems with uncertain agent dynamics and system noise. We consider uncertain time-varying input matrices that are arbitrary up to a known bound for the singular values. We also assume that each agent's controller is able to access the neighbors' relative states. We focus on the design of a linear controller gain that is to be identical across all agents and the inputs and outputs of the agents' subsystems have the same dimension. Following a presentation of the consensus-control architecture synthesis. We then propose a decentralized, norm-free, adaptive event-triggering rule for $c$-multilateration scheme is proposed to leverage RSSI and position measurements for localization. To minimize estimation error: i) a RSSI-based position measurement covariance matrix at runtime that is robust to unreliable state estimates. The proposed framework is implemented at each agent is based on predicted outputs of itself and its neighboring agents. It implements a fluid-flow version of the Newton-Raphson method for solving equations, and this, together with the way the predictions are used, guarantees asymptotic consensus for a general class of systems defined by ordinary differential equations. The scope of the analysis includes heterogeneous systems whose subsystems have different state-space models with different dimensions, but it requires that all the inputs and outputs of the agents' subsystems have the same dimension. Following a presentation of the consensus-control technique, we analyse its convergence and present simulation results for a heterogeneous nonlinear system.

In practical networking scenarios, communication links can rarely be considered to be deterministic, yet the influence of stochastic interconnections on multi-agent systems is neglected most of the time. To bridge this gap, this paper develops synthesis conditions for distributed state- and output-feedback controllers that guarantee an upper bound on the closed-loop $H_\infty$-norm under the effect of Bernoulli distributed packet loss. Utilizing the frameworks of Markov jump linear system and decomposable systems, the synthesis problem is formulated as a linear matrix inequality problem with complexity that scales linearly with the number of agents. Finally, the closed-loop performance is assessed in simulation studies with a signal-to-interference-plus-noise ratio based packet loss model for communication between autonomous underwater vehicles.
Simulation results validate the effectiveness of the adaptive controller. An approach is required to estimate the length of the pendulum. This is because when used by people of different heights, the hoverboard being used may not have the same length. Indeed, in certain applications, this length is unknown a priori. It is found that unknown length of the pendulum causes the system to fall in the category of unmatched uncertainty. A concurrent learning adaptive controller, which avoids the use of persistently exciting signals, is then utilized to estimate the unmatched uncertainty and hence the length of the pendulum. Simulation results validate the effectiveness of the adaptive controller for the proposed problem.

14:15-14:30 FrB12.1
Attention-Enabled Memory for Concurrent Learning Adaptive Control, pp. 4241-4246
Habboush, Abdullah
Bilkent University
Yildiz, Yildiray
Bilkent University

Transient tracking error dynamics are inevitable in any practical closed-loop control system. While numerous works are devoted to improving these dynamics, in this paper, we focus on taking advantage of it first, in the context of adaptive control. We propose a memory architecture that can make use of stored significant data about the transients of previously experienced anomalies to aid in obtaining a resilient system against uncertainties. The proposed architecture consists of 1) a memory containing data about a variety of uncertainties, 2) a short-term memory that aids in handling new uncertainties, and 3) an attention-based reading mechanism that enables the controller to retrieve only relevant data from the memory. The effectiveness of the architecture is validated through numerical simulations, and a rigorous Lyapunov stability analysis is provided.

14:30-14:45 FrB12.2
Adaptive Tracking Control of Uncertain Euler-Lagrange Systems with State and Input Constraints, pp. 4229-4234
Ghosh, Poulosee
Indian Institute of Technology Delhi
Bhasin, Shubhendu
Indian Institute of Technology Delhi

This paper proposes a novel control architecture for state and input constrained Euler-Lagrange (E-L) systems with parametric uncertainties. A simple saturated controller is strategically coupled with a Barrier Lyapunov Function (BLF) based controller to ensure state and input constraint satisfaction. To the best of the authors’ knowledge, this is the first result for E-L systems that guarantees asymptotic tracking with user-specified state and input constraints. The proposed controller also ensures that all the closed-loop signals remain bounded. The efficacy of the proposed controller in terms of constraint satisfaction and tracking performance is verified using simulation on a robot manipulator system.

14:45-14:55 FrB12.3
A Flying Inverted Pendulum with Unknown Length, pp. 4235-4240
Barawkar, Shraddha
University of Cincinnati
Kumar, Manish
University of Cincinnati

Balancing an inverted pendulum on an unmanned aerial vehicle has been a topic of interest in recent literature. For example, a recent study uses an LQR controller to balance the inverted pendulum on a quadrotor drone. However, these studies consider the length of the pendulum to be known a priori. Indeed, in certain applications this assumption might not hold true. For example, consider a quadrotor hoverboard being used by people of different heights. In such cases, an approach is required to estimate the length of the pendulum. This paper analyzes the linearized dynamics of the combined system of quadrotor and inverted pendulum. It is found that unknown length of pendulum causes the system to fail in the category of unmatched uncertain systems where the control input cannot be used to cancel the uncertainty. This paper formulates the problem in such a manner that the system is still controllable in presence of this unmatched uncertainty. A concurrent learning adaptive controller, which avoids the use of persistently exciting signals, is then utilized to estimate the unmatched uncertainty and hence the length of the pendulum. Simulation results validate the effectiveness of the adaptive controller.
This paper proposes a model predictive control based on set-membership filtering for a time-varying discrete system with an unknown but bounded process and measurement noise. The estimated states are computed from set-membership filtering by solving a semi-definite program utilizing ellipsoidal bounds. The estimated sets are used for optimization in the model predictive control. Control input sequence is computed from model predictive control by minimizing the cost function. At each time step, a two-step prediction and measurement update process is used for ellipsoidal state estimation. Set-membership filtering guarantees that the true states lie within the ellipsoid. Finally, a rendezvous and proximity operation simulation is executed to guide the chaser to a target to illustrate the efficacy of the proposed approach.

**13:45-14:00**

**A Universal Framework for Generalized Run Time Assurance with JAX Automatic Differentiation (I), pp. 4264-4269**

Ravaioli, Umberto - Toyota Research Corporation
Dunlap, Kyle - Parallax Advanced Research
Hobbs, Kerianne - Air Force Research Laboratory

With the rise of increasingly complex autonomous systems powered by black box AI models, there is a growing need for Run Time Assurance (RTA) systems that provide online safety filtering to untrusted primary controller output. Currently, research in RTA tends to be ad hoc and inflexible, diminishing collaboration and the pace of innovation. The Safe Autonomy Run Time Assurance Framework presented in this paper provides a standardized interface for modular RTA building blocks and a set of universal implementations of constraint-based RTA modules. By leveraging JAX Automatic Differentiation, a technique popularized by deep learning, this framework provides unmatched flexibility in the RTA space by automatically populating advanced optimization based RTA methods from user defined constraints and dynamics. This eliminates tedious manual differentiation and minimizes user effort and error. To validate the feasibility of this framework, a simulation of a multi-agent spacecraft inspection problem is shown with differentiable safety constraints on position and velocity.

**14:00-14:15**

**Rapid Construction of Safe Search-Trees for Spacecraft Attitude Planning (I), pp. 4270-4275**

Danielson, Claus - University of New Mexico
Kloeppe1, Joseph - University of New Mexico

This paper adapts the rapidly-exploring variant of invariant-set motion planner (ISMP) for spacecraft attitude motion planning and control. The ISMP is a motion-planning algorithm that uses positive-invariant sets of the closed-loop dynamics to find a constraint admissible path to a desired target through an obstacle filled environment. We present four mathematical results that enable the sub-routines used to rapidly construct a search-tree for the ISMP. These mathematical results describe how to uniformly sample safe quaternions, how to find the nearest orientation in the search-tree, how to move the sampled orientation to form an edge, and how to scale the invariant set to guarantee constraint admissibility. We present simulation results that demonstrate the ISMP for spacecraft attitude motion planning.

**14:15-14:30**

**Randomized Greedy Algorithms for Sensor Selection in Large-Scale Satellite Constellations (I), pp. 4276-4283**

As both the number and size of satellite constellations continue to increase, there likewise exists a growing need for incorporating methods for autonomous sensor selection into these networks. Particularly, constraints due to computation and communication can often prevent all available satellite sensors from actively making observations at a given time. We pose this constrained sensor selection problem in terms of a submodular optimization problem and explore the use of randomized greedy algorithms to obtain an approximately optimal sensor selection. To this end, we propose a novel pair of randomized greedy algorithms, namely, modified randomized greedy and dual randomized greedy to approximately solve budget and performance-constrained problems, respectively. For each of these algorithms, we derive theoretical high-probability guarantees bounding their suboptimality. We then demonstrate the efficacy of these algorithms in several pertinent applications for Earth-observing constellations, specifically, state estimation for atmospheric weather conditions and ground coverage.

**14:30-14:45**

**Sensor Safety and Multi-Objective Satellite Control under Nonlinear Dynamics (I), pp. 4284-4289**

We, Tianhao - Carnegie Mellon University
Kang, Shucheng - Tsinghua University
Zhao, Weiye - Carnegie Mellon University
Liu, Changli - Carnegie Mellon University

The safe operation of satellites is critical as the space domain becomes more cluttered with resident objects. Controller synthesis is a technique used to automatically generate correct-by-construction controllers that guarantee a system will satisfy some requirements, such as safety. In this work, we cast the safe satellite operation problem as a controller synthesis problem, and propose an algorithm that synthesizes full-state control of a satellite. This is done by decoupling the translational control from the attitude control. We deploy this algorithm in a close-proximity scenario and show that the synthesized controller satisfies our requirements and guarantees the safety of a chasing satellite.

**14:45-15:00**

**Persistently Feasible Robust Safe Control by Safety Index Synthesis and Convex Semi-Infinite Programming, pp. 4290-4295**

Wei, Tianhao - Carnegie Mellon University
Kang, Shucheng - Tsinghua University
Zhao, Weiye - Carnegie Mellon University
Liu, Changli - Carnegie Mellon University

Model mismatches prevail in real-world applications. Ensuring safety for systems with uncertain dynamic models is critical. However, existing robust safe controllers may not be realizable when control limits exist. And existing methods use loose over-approximation of uncertainties, leading to conservative safe controllers. To address these challenges, we propose a control-limits aware robust safe control framework for bounded state-dependent uncertainties. We propose safety index synthesis to find a robust safe controller guaranteed to be realizable under control limits. And we solve for robust safe control via Convex Semi-Infinite Programming, which is the tightest formulation for convex bounded uncertainties and leads to the least conservative control. In addition, we analyze when and how safety can be preserved under unmodeled uncertainties. Experiment results show that our robust safe controller is always realizable under control limits and is much less conservative than strong baselines.
We study the dynamics of belief formation on multiple interconnected topics in networks of agents with a shared belief system. We establish sufficient conditions and necessary conditions under which sustained oscillations of beliefs arise on the network in a Hopf bifurcation and characterize the role of the communication graph and the belief system graph in shaping the relative phase and amplitude patterns of the oscillations. Additionally, we distinguish broad classes of graphs that exhibit such oscillations from those that do not.

**Sustained Oscillations in Multi-Topic Belief Dynamics Over Signed Networks (I), pp. 4296-4301**

Bizyaeva, Anastasia University of Washington Seattle Franci, Alessio Universidad Nacional Autónoma de Mexico (UNAM) Leonard, Naomi Ehrich Princeton University

Reproduction numbers are widely used for the estimation and prediction of epidemic spreading processes over networks. However, reproduction numbers do not enable estimation and prediction in individual communities within networks, and they can be difficult to compute due to the aggregation of infection data that is required to do so. Therefore, in this work we propose a novel concept of distributed reproduction numbers to capture the spreading behaviors of each entity in the network, and we show how to compute them using certain parameters in networked SIS and SIR epidemic models. We use distributed reproduction numbers to derive new conditions under which an outbreak can occur. These conditions are then used to derive new conditions for the existence, uniqueness, and stability of equilibrium states. Finally, in simulation we use synthetic infection data to illustrate how distributed reproduction numbers provide more fine-grained analyses of networked spreading processes than ordinary reproduction numbers.

**Distributed Reproduction Numbers of Networked Epidemics (I), pp. 4302-4307**

She, Baike University of Florida Pare, Philip E. Purdue University Hale, Matthew University of Florida

In this paper, we propose a method to control large-scale multiagent systems swarming in a ring. Specifically, we use a model predictive control (MPC) method for real-time intervention of spreading processes, such as epidemics and wildfire, over large-scale networks. The goal is to allocate budgeted resources each time step to minimize the risk of an undetected outbreak, i.e., the product of the probability of an outbreak and the impact of that outbreak. By using dynamic programming relaxation, the MPC controller is reformulated as a convex optimization problem, in particular an exponential cone programming. We also provide sufficient conditions for the closed-loop risks to asymptotically decrease and a method to estimate the upper bound of the risk when the risk will monotonically decrease. Numerical results are provided for a wildfire example.

**Model Predictive Control of Spreading Processes Via Sparse Resource Allocation (I), pp. 4320-4325**

Wang, Ruigang The University of Sydney Zafar, Armaghan The University of Sydney Manchester, Ian R. University of Sydney

A major factor contributing to the difficulties in epidemic forecasting is the unpredictable nature of the population behavior that can either mitigate or exacerbate the spread of a disease. In this paper, we consider a game-theoretic framework for modeling the disease prevalence dependent response of the population behavior in a susceptible-infected-susceptible (SIS) epidemiological model. Our behavioral response model is based on replicator dynamics, where the individuals’ underlying payoffs dynamically change in response to the prevalence of the disease. The coupled dynamics highlight the interplay between the epidemic state and distancing behaviors. We establish a critical threshold on the incentive parameters for which below the threshold, the state in which the disease is endemic and the population does not cooperate with the recommended public health measures is globally asymptotically stable (GAS). Above the threshold, we find through extensive numerical simulations that a variety of dynamical outcomes emerge. For some parameters, an interior equilibrium in which the endemic state is mitigated and a fraction of the population socially distancing is stable. For other parameters, a stable limit cycle about this interior state emerges. The arising rich set of dynamics demonstrate the potential of the modeling framework for epidemic forecasting.

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14:15-14:30 FrB14.4

The Impact of Deniers on Epidemics: A Temporal Network Model (I), pp. 4314-4319

Zino, Lorenzo Politecnico Di Torino Rizzo, Alessandro Politecnico Di Torino Porfiri, Maurizio Polytechnic Institute of New York University

We propose a novel network epidemic model to elucidate the impact of deniers on the spread of epidemic diseases. Specifically, we study the spread of a recurrent epidemic disease, whose progression is captured by a susceptible-infected-susceptible model, in a population partitioned into two groups: cautious and deniers. Cautious individuals may adopt self-protective behaviors, possibly incentivized by information campaigns implemented by public authorities; on the contrary, deniers reject their adoption. Through a mean-field approach, we analytically derive the epidemic threshold for large-scale homogeneous networks, shedding light onto the role of deniers in shaping the course of an epidemic outbreak. Specifically, our analytical insight suggests that even a small minority of deniers may jeopardize the effort of public health authorities when the population is highly polarized. Numerical results extend our analytical findings to heterogeneous networks.

14:30-14:45 FrB14.5

Model Predictive Control of Spreading Processes Via Sparse Resource Allocation (I), pp. 4320-4325

Wang, Ruigang The University of Sydney Zafar, Armaghan The University of Sydney Manchester, Ian R. University of Sydney

In this paper, we propose a model predictive control (MPC) method for real-time intervention of spreading processes, such as epidemics and wildfire, over large-scale networks. The goal is to allocate budgeted resources each time step to minimize the risk of an undetected outbreak, i.e., the product of the probability of an outbreak and the impact of that outbreak. By using dynamic programming relaxation, the MPC controller is reformulated as a convex optimization problem, in particular an exponential cone programming. We also provide sufficient conditions for the closed-loop risks to asymptotically decrease and a method to estimate the upper bound of the risk when the risk will monotonically decrease. Numerical results are provided for a wildfire example.
In this paper, we propose a Risk-Averse Priced Timed Automata (PTA) Model Predictive Control (MPC) framework to increase flexibility of cyber-physical systems. To improve flexibility in these systems, our risk-averse framework solves a multi-objective optimization problem to minimize the cost and risk, simultaneously. While minimizing cost ensures the least effort to achieve a task, minimizing risk provides guarantees on the feasibility of the task even during uncertainty. Our framework explores the trade-off between these two qualities to obtain risk-averse control actions. The solution of risk-averse PTA MPC dynamic decision-making algorithm reacts relatively better to PTA changes compared to PTA MPC without risk-averse feature. An example from manufacturing systems is presented to show the application of the proposed control strategy.

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*The authors are: Chen, Gang, Lu, Yu, Su, Rong, Xie, Longhan, Hou, Junyao, Liu, Siyuan, Yin, Xiang.
In the setting of learning in games, player strategies evolve in an effort to maximize utility in response to the evolving strategies of other players. In contrast to the single agent case, learning in the presence of other learners induces a non-stationary environment from the perspective of any individual player. Depending on the specifics of the game and the learning dynamics, the evolving strategies may exhibit a variety of behaviors ranging from convergence to Nash equilibrium to oscillations to even chaos. This talk presents a basic introduction to learning in games through the presentation of selected results for finite normal form games, i.e., games with a finite number of players having a finite number of actions. The talk starts with a representative sample of learning dynamics that converge to Nash equilibrium for special classes of games. Specific learning dynamics include better reply dynamics, joint strategy fictitious play, and log-linear learning, with results for potential games and weakly acyclic games. These results apply to specifically pure Nash equilibrium. The talk also presents dynamics that address mixed/randomized strategy Nash equilibria, specifically smooth fictitious play and gradient play. The talk concludes with limitations in learning that stem from the notion of uncoupled dynamics, where a player's learning dynamics cannot depend explicitly on the utility functions of other players.

Learning algorithm behavior highly depends on the game setting. In this tutorial talk, we discuss how these dependencies can be explained, if one regards them through a passivity lens. We focus on two representative instances in reinforcement learning: payoff-based play, and Q-learning. We show how one can exploit geometric features of different classes of games, together with dissipativity/passivity properties of interconnected systems to guarantee global convergence to a Nash equilibrium. Besides simplifying the proof of convergence, one can generate algorithms that work for classes of games with less stringent assumptions, by using passivity and basic properties of interconnected systems.

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Non-Equilibrium Learning in Stochastic Games (I), pp. 4384-4384
Vamvoudakis, Kyriakos G. Georgia Inst. of Tech

Reinforcement learning (RL) is effective in optimizing cumulative rewards, and it provides policies that account for how the system will interact over the future with the agent. However, when more than one learning agent is present, developing efficient collaborations/interactions is a challenging issue; not every agent may have access to the same amount of information and computational resources; not every agent may make the same assumptions about the decision-making mechanisms of one another; and many agents may not even be aware of the existence of other agents. These cognitive and physical limitations can be seen as a form of bounded rationality. Several recent experimental and empirical studies have found that the initial responses of decision-makers in multi-player games are often far from the equilibrium, which is very often out-predicted by structural non-equilibrium (e.g., cognitive hierarchy) models. This is because non-equilibrium play models allow for players who are boundedly rational and have limited information, so that the policy is not necessarily a best response to the actual adjustment laws of other agents. This tutorial talk will present computationally and communicatively efficient approaches for decision-making in boundedly rational stochastic games. Motivated by the inherent complexity of computing Nash equilibria, as well as the innate tendency of agents to choose non-equilibrium strategies, two models of bounded rationality based on recursive reasoning will be described.

In the first model, named level-k thinking, each agent assumes that everyone else has a cognitive level immediately lower than theirs, and—given such an assumption—chooses their policy to be a best response to them. In the second model, named cognitive hierarchy, each agent conjectures that the rest of the agents have a cognitive level that is lower than theirs, but follows a distribution instead of being deterministic. To explicitly compute the boundedly rational policies, this tutorial talk will present both a level-recursive as well as a level-parallelized algorithm, where the latter can have an overall reduced computational complexity. For more information please see the main tutorial paper.

Potential Game-Based Decision Making in Autonomous Driving (I), pp. 4385-4385

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Game-theoretic approaches characterize agents' interactions from a self-interest optimization perspective, consistent with human reasoning, and therefore, are believed to have the potential to solve the decision making for autonomous vehicles (AVs) when they interact with human-driven vehicles and/or pedestrians. However, despite high hopes, conventional game-theoretic approaches often suffer from scalability issues due to the complexity of multi-player games and from incomplete information challenges such as the lack of knowledge of other traffic agents' cost functions that reflect the variability in human driving behaviors. In this talk, we will show how to address these challenges by developing a novel potential game (PG) based framework. Specifically, we will propose a new PG framework that not only solves the multi-player game in real time but also guarantees the ego vehicle safety under appropriate conditions despite unexpected behaviors from the surrounding agents.

Despite the potential benefits of a traffic system with only Coordinated and Automated Vehicles (CAVs), it is expected that Human Driven Vehicles (HDVs) and CAVs co-exist for the foreseeable future. Due to uncertainty and the unpredictability of human drivers, developing a control framework with safety guarantees, especially in the traffic bottlenecks such as merging points is a challenging problem. Motivated by this fact, in this paper we study a merging problem in mixed vehicular traffic and we develop a safety-critical real-time decentralized control of CAVs in the presence of HDVs. We use Control Lyapunov Functions (CLFs) to attain the desired control objectives, and Control Barrier Functions (CBFs) to guarantee the safety of the merging operation. It is assumed that a high level coordinator determines the sequence of vehicles pass the merging area and forms a triplet of vehicles in the main lane and the merging lane. Then, three different combinations of CAVs and HDVs are considered and for each one, required CLFs and CBFs to safely accomplish the merging operation are developed. Simulation results are provided to demonstrate the efficacy of the proposed schemes.

Low-altitude aircraft is being developed as a new mode of urban transport. This will give rise to new urban air transport systems, called low-altitude air city transport (LAAT) systems. Recent works show that the Macroscopic Fundamental Diagram (MFD) is a powerful tool for understanding LAAT systems from a theoretical perspective, and allows to detect congestion conditions in the airspace. In this paper, aircraft departures management for LAAT systems with the help of MFD modeling is developed and evaluated. A unique framework, which couples both microscopic and macroscopic levels of LAAT operation, is established. The plant model considers the microscopic level, where an aircraft collision-avoidance model with a cooperative control algorithm from the literature is implemented to describe the low-altitude aircraft interactions, implying the microscopic traffic behavior. At the macroscopic level, an accumulation-based model for distributed regions is introduced, which is used as the control model. Then, based on the developed framework, an optimal control strategy is formulated to optimize (AVs) aircraft inflow rate by manipulating their departure times to mitigate congestion. Different control strategies are tested: Greedy Controller and Model Predictive Controller. The strategies are deployed for the whole network or for each region at the macroscopic level and then transformed to the microscopic level. This study demonstrates that the MFD-based traffic control strategies can reduce congestion in LAAT systems.
strategies need to explicitly account for vehicle interactions and require extensive simulation tests before actual deployment. The proposed environment aims to facilitate such simulation tests to better assess, validate, and improve the forced merging strategies. The simulation environment consists of several control strategies for the merging vehicle, different highway vehicle models that can represent interactions with the merging vehicle, and a set of metrics to evaluate the performance of the merging strategies. As an example of the evaluation, a Leader Follower Game Controller (LFGC) [1] is implemented and tested in this environment. Based on the analysis of the simulation tests, we propose an Enhanced LFGC (e-LFGC). It is shown that our methodology facilitates the development of merging controllers so that corner cases are revealed and control requirements can be improved.

Re-Routing Strategy of Connected and Automated Vehicles Considering Coordination at Intersections, pp. 4419-4424
Bang, Heeseung University of Delaware Mallikopoulos, Andreas A. University of Delaware

In this paper, we propose a re-routing strategy for connected and automated vehicles (CAVs), considering coordination and control of all the CAVs in the network. The objective for each CAV is to find the route that minimizes the total travel time of all CAVs. We coordinate CAVs at signal-free intersections to accurately predict the travel time for the routing problem. While it is possible to find a system-optimal solution by comparing all the possible combinations of the routes, this may impose a computational burden. Thus, we instead find a person-by-person optimal solution to reduce computational time while still deriving a better solution than selfish routing. We validate our framework through simulations in a grid network.

Throughput of Freeway Networks under Ramp Metering Subject to Vehicle Safety Constraints, pp. 4425-4430
Pooladsanj, Milad Univ. of Southern California Savia, Ketan University of Southern California Ioannou, Petros A. Univ. of Southern California

Ramp metering is one of the most effective tools to combat traffic congestion. In this paper, we present a ramp metering policy for a network of freeways with arbitrary number of on- and off-ramps, merge, and diverge junctions. The proposed policy is designed at the microscopic level and takes into account vehicle following safety constraints. In addition, each on-ramp operates in cycles during which it releases vehicles as long as the number of releases does not exceed its queue size at the start of the cycle. Moreover, each on-ramp dynamically adjusts its release rate based on the traffic condition. To evaluate the performance of the policy, we analyze its throughput, which is characterized by the set of arrival rates for which the queue sizes at all on-ramps remain bounded in expectation. We show that the proposed policy is able to maximize the throughput if the merging speed at all the on-ramps is equal to the free flow speed and the network has no merge junction. We provide simulations to illustrate the performance of our policy and compare it with a well-known policy from the literature.

Monte Carlo Tree Search Based Trajectory Generation for Automated Vehicles in Interactive Traffic Environments, pp. 4431-4436
Vellamattathil Baby, Tinu Illinois Institute of Technology HomChaudhuri, Baisravan Illinois Institute of Technology

This paper focuses on the development of a trajectory planning method for connected and automated vehicles (CAVs) that takes into account the interactive nature of the vehicles. The proposed approach is based on Monte Carlo Tree Search (MCTS) that traverse possible actions from each state of the system to identify the trajectory with highest reward. Here, the trajectory is planned and the actions of surrounding vehicles are predicted jointly. Planning the trajectory and predicting the surrounding vehicles jointly in an interactive environment can result in a large action-space, which is not computationally tractable. Hence, we propose an adaptive action-space, which includes pruning the action-space so that the actions resulting in unsafe trajectories are eliminated. The simulation studies show that the proposed approach is capable of identifying less conservative yet safe trajectories for CAVs in a multi-vehicle environment.
derived by vectorizing the component-wise AC power flow equations and manipulating them into a novel equivalent fixed-point form. Preliminary theoretical results guaranteeing convergence are reported for the case of a two-bus power system. We validate the algorithm through extensive simulations on test systems of various sizes under different loading levels, and compare its convergence behavior against those of classic power flow algorithms.

An Energy Management System for electric vessels is described, based on a Model Predictive Control (MPC) with Anticipative Action. The electric ship has a power system composed of a hydrogen fuel cell generator, a battery storage system, a propulsion system, an auxiliary load module, and a command system. The controller defines the power allocated among the vessel's power system components. The MPC design uses a Linear Parameter-Varying (LPV) model to approximate the nonlinear dynamics of the vessel's power system and components. To improve the performance of the LPV-MPC, an additional predictor is included, based on data-driven Machine Learning. This is included in the LPV-MPC so the future predicted trajectory of the reference signals can be estimated to improve the allocation of power. The reference trajectory is generated using a Neural Network trained to estimate the future power demand determined by representative ship manoeuvres. A simple baseline Rule-based (RB) strategy was compared with the basic LPV-MPC and with the data-driven LPV-MPC that includes the prediction generated by the Neural Network.

To address computational challenges associated with power flow nonconvexities, significant research efforts over the last decade have developed convex relaxations and approximations of optimal power flow (OPF) problems. However, benefits associated with the convexity of these relaxations and approximations can have tradeoffs in terms of solution accuracy since they may yield voltage phasors that are inconsistent with the power injections and line flows, limiting their usefulness for some applications. Inspired by state estimation (SE) techniques, this paper proposes a new method for obtaining an AC power flow feasible point from the solution to a relaxed or approximated optimal power flow (OPF) problem. By treating the inconsistent voltage phasors, power injections, and line flows analogously to noisy measurements in a state estimation algorithm, the proposed method yields power injections and voltage phasors that are feasible with respect to the AC power flow equations while incorporating information from many quantities in the solution to a relaxed or approximated OPF problem. We improve this method by adjusting weighting terms with an approach inspired by algorithms used to train machine learning models. We demonstrate the proposed method using several relaxations and approximations. The results show up to several orders of magnitude improvement in accuracy over traditional methods.

We consider the problem of controlling the frequency of low-inertia power systems via inverter-based resources (IBRs) that are weakly connected to the grid. We propose a novel grid-forming control strategy, the so-called frequency shaping control, that aims to shape the frequency response of synchronous generators (SGs) to load perturbations so as to efficiently arrest sudden frequency drops. Our solution relaxes several existing assumptions in the literature and is able to navigate tradeoffs between peak power requirements and maximum frequency deviations. Finally, we analyze the robustness to imperfect knowledge of network parameters, while particularly highlighting the importance of accurate estimation of these parameters.

Load redistribution (LR) attacks are covert, damaging, and able to achieve various attack objectives. Effective defensive measures are required to reduce the impact of LR attacks on power grids. Existing moving target defense (MTD) methods have been studied for attack detection based on transmission line reactance perturbation, but require sufficient deployment of distributed flexible AC transmission system (D-FACTS) devices to ensure the detection performance. However, large-scale D-FACTS device deployments are costly, which limit the efficiency of MTD methods in practical operations. As such, this paper coordinates the reactance control of a single transmission line with the generation dispatch to defend the power grid against LR attacks. Specifically, a reactance-control-based robust dispatch model is presented, which guarantees the system security as well as the economic performance without changing the reactance of a large number of transmission lines. A two-stage methodology utilizing the pattern search algorithm and column constraint generation (C&CG) algorithm is proposed to solve the dispatch model in an iterative process. Case studies based on the IEEE 14- and 118-bus systems verify the effectiveness of the proposed method in breaking through the security limits of the existing power grid and improving the economics of the robust defense.

Load frequency control (LFC) is a key factor to maintain stable frequency in multi-area power systems. As modern power systems evolve from a centralized to distributed paradigm, LFC needs to consider the peer-to-peer (P2P) based scheme that considers limited information from the information-exchange graph for the generator control of each interconnected area. This paper aims to solve a data-driven constrained LQR problem with mean-variance risk constraints and output structured feedback, and applies this framework to solve the LFC problem in multi-area power systems. By reformulating the constrained optimization problem into a minimax problem, the stochastic gradient descent max-oracle (SGDmax) algorithm with zero-order policy gradient (ZOPG) is adopted to find...
the optimal feedback gain from the learning, while guaranteeing convergence. In addition, to improve the adaptation of the proposed learning method to new or varying models, we construct an emulator grid that approximates the dynamics of a physical grid and performs training based on this model. Once the feedback gain is obtained from the emulator grid, it is applied to the physical grid with a robustness test to check whether the controller from the approximated emulator applies to the actual system. Numerical tests show that the obtained feedback controller can successfully control the frequency of each area, while mitigating the uncertainty from the loads, with reliable robustness that ensures the adaptability of the obtained feedback gain to the actual physical grid.

15:54-15:58 FrC02.7

Optimal Placement of PMUs in Power Networks: Modularity Meets a Priori Optimization, pp. 4489-4494
Kazma, Mohamad, Taha, Ahmad, Vanderbilt University

This paper revisits the optimal phasor measurement unit (PMU) placement problem (P3) in transmission networks. We examine P3 from a control-theoretic and dynamic systems perspectives. Relevant prior literature studied this problem through formulations that are based on empirical observability maximization for nonlinear dynamic power system models. While such studies addressed a plethora of challenges, they mostly adopt a simple representation of system dynamics, ignore basic algebraic equations modeling power flows, forgo including renewables and their uncertainty. This paper offers a fresh perspective on this problem by leveraging the observability matrix’s modularity property under a moving horizon estimation theoretic. A nonlinear differential algebraic representation of the system is implicitly discretized while explicitly accounting for uncertainty. To that end, the posed challenges are addressed for the optimal P3 via a computationally tractable integer program formulation. The validity of the approach is illustrated on an IEEE 39-bus power system.

15:58-16:02 FrC02.8

On Wide-Area Control of Solar-Integrated DAE Models of Power Grids, pp. 4495-4500
Nadeem, Muhammad, Bahavarnia, MirSaleh, Taha, Ahmad, Vanderbilt University

Today’s power systems are controlled based on decades of experience with the fundamentals of physics-based properties of synchronous generators. Future power grids however must cope with the increasing penetration of renewable energy resources (RERs) and require a much more sophisticated control architecture. This is because RERs are formed by uncertain solar- and wind-based resources and are connected to the grid via advanced (power electronics)-based technologies. These are, in short, far more complex to control than traditional generators. RERs also do not provide inertia to damp frequency oscillations, and thus the grid’s operating point changes frequently causing deterioration in the overall transient stability of the power system. This short paper proposes a robust wide-area controller for an advanced power system model having a higher order generator model, advanced (power electronics)-based solar plants model, and composite load dynamics. The simulation studies show that the proposed controller can significantly improve the transient stability of the system against uncertainty from load demand and renewables.

16:02-16:06 FrC02.9

Explicit Reinforcement Learning Safety Layer for Computationally Efficient Inverter-Based Voltage Regulation, pp. 4501-4506
Zhao, Xingyu, Xu, Qianwen, KTH Royal Institute of Technology, KTH Royal Institute of Technology

To mitigate fast voltage fluctuations caused by high penetration of renewable energy, efficient control and coordination methods to utilize the reactive power support of inverters are required. Capturing the nonlinear power flow dynamics while enforcing feasibility of safety constraints, reinforcement learning (RL) with safety layer is highly preferred by safety-critical voltage regulation task. This paper proposes an explicit DRL safety layer to achieve computationally efficient voltage regulation of distribution grids with guaranteed hard constraints of voltage security. To achieve this, we firstly construct the explicit form of safety layer via offline search based on multiparametric programming. Then, instead of doing exhaustive search with exponential complexity, we propose a sample-based approach to identify active constraint sets relevant to safe operations, which makes the offline construction tractable even for large-scale systems. Based on the explicit safety layer, an end-to-end trainable and computationally efficient safe reinforcement learning approach for voltage regulation is proposed. The performance and computational efficiency of proposed method is verified by case study.
way, by taking the neighbors of the neighbors into account with aggregated risk evaluation, agents facing higher risk from multi-agent interaction can have larger relative cells compared to agents exposed to lower risk. With our proposed CBF-inspired WBVC, multi-agent systems are able to perform tasks in a risk-aware manner with the enhanced knowledge of risk provided by the CBF-inspired risk evaluation framework, but without the usage requirement of CBF-based controllers. It is therefore generally applicable to various agent controllers while providing safety guarantees.

15:45-16:00  FrC03.2

On the Design of Control Invariant Regions for Feedback Linearized Car-Like Vehicles, pp. 4519-4524
Tirio, Cristian  Concordia University
Lucia, Walter  Concordia University

This paper proposes a novel procedure to design a control invariant region for feedback-linearized car-like vehicles subject to linear and steering velocity constraints. To this end, first, it is formally proved that the state-dependent input constraints acting on the feedback-linearized car model admit a worst-case circular inner approximation. Then, it is shown that such a characterization can be used to analytically design a tracking controller with an associated invariant region capable of ensuring constraints fulfillment. Finally, simulation results show the effectiveness of the proposed solution and its potential to enable the design, via control invariance, of a new class of constrained and model predictive solutions for input-constrained feedback-linearized car-like vehicles.

16:00-16:15  FrC03.3

Adaptive Backstepping Control for Vehicular Platoons with Mismatched Disturbances Using Vector String Lyapunov Functions, pp. 4525-4530
Song, Zhiho  University of Notre Dame
Welikala, Shirantha  University of Notre Dame
Antsaklis, Panos J.  University of Notre Dame
Lin, Hai  University of Notre Dame

In this paper, we consider the problem of platooning control with mismatched disturbances using adaptive backstepping method. We aim at simultaneously retaining the compositionality and the robustness of the controller with respect to general types of disturbances. To this end, motivated by the vector Lyapunov function-based analysis, we propose a novel notion called emph{Vector String Lyapunov Function}, whose existence implies $\mathcal{L}_{2}\text{weak string stability}$. Based on this notion, we propose an adaptive backstepping controller for the platoon, where the compositionality and robustness are guaranteed with centralized adaptive laws. Besides, the internal and the $\mathcal{L}_{2}\text{weak string stability}$ are proved under the designed controller. By comparing with an existing method and two different types of disturbances and topologies, we numerically illustrate the effectiveness of the proposed control algorithm.

16:15-16:30  FrC03.4

Towards Physically Adversarial Intelligent Networks (PAINS) for Safer Self-Driving, pp. 4531-4536
Gupta, Piyush  Michigan State University
Coleman, Demetris  Michigan State University
Siegel, Joshua  Michigan State University

Neural networks in autonomous vehicles suffer from overfitting, poor generalizability, and untrained edge cases due to limited data availability. Researchers often synthesize randomized edge-case scenarios to assist in the training process, though simulation introduces the potential for overfitting to latent rules and features. Automating worst-case scenario generation could yield informative data for improving self-driving. To this end, we present a “Physically Adversarial Intelligent Network”, wherein self-driving vehicles interact aggressively in the CARLA simulation. We train two agents, a protagonist, and an adversary, using dueling double deep Q networks with prioritized experience replay. The coupled networks alternately seek to collide and avoid collisions such that the “defensive” avoidance algorithm increases the mean time to failure and distance traveled under non-hostile operating conditions. The trained protagonist becomes more resilient to environmental uncertainty and less prone to corner case failures resulting in collisions than the agent trained without an adversary.

16:30-16:45  FrC03.5

A Physics-Informed Neural Network Approach towards Cyber Attack Detection in Vehicle Platoons, pp. 4537-4542
Vyas, Shashank Dhananjay  The Pennsylvania State University
Padisala, Shanthan Kumar  Penn State
Dey, Satadru  The Pennsylvania State University

Connected and Autonomous Vehicles (CAVs) are seen as a promising solution to reduce traffic congestion, improve passenger comfort and fuel economy. Although CAVs address such needs in an effective way, they are vulnerable to cyber attacks due to their extensive utilization of communication networks. In light of this problem, we present a cyber attack detection framework for a vehicle platoon based on physics-informed neural network (PINN) framework. The proposed algorithm exploits the physics based model of the platoon as well as limited available data to detect and distinguish cyber-attacks from various sources, namely, attacks affecting communication network and attacks affecting local vehicular sensors. Essentially, the PINN framework learns an uncertain parameter from the physics model and utilizes the learned parameter knowledge to infer attack scenarios. Finally, as shown through the simulation studies, the proposed algorithm is able to detect and distinguish various cyber attacks showing its potential.

16:45-17:00  FrC03.6

Dynamics and Control of AUVs Using Buoyancy-Based Soft Actuation, pp. 4543-4548
Hoppe, Christopher  Rice University
Ghorbel, Fathi H.  Rice Univ
Chen, Zheng  University of Houston

Nonlinear control of Autonomous Underwater Vehicles (AUVs) via the use of thrusters has been well established. These AUVs can be used for various applications, including subsea inspection and maintenance, exploration, research, and observation. These thrusters are best suited for large thrust forces required by large movements, but require a lot of energy to operate for long periods of time. Research into Buoyancy Control Devices (BCDs) using reversible fuel cells (RFCs) has proven their viability. This paper demonstrates nonlinear control of BCD-based AUVs while picking up tools with unknown weights. An adaptive control law is derived that ensures stability and good performance throughout the completion of the desired mission. Simulation results demonstrate desired performance with low energy requirements.

FrC04 Learning (Regular Session)  Sapphire AB

Chair: Halder, Abhishek  University of California, Santa Cruz
Co-Chair: Shen, Jiujin  Purdue University

15:30-15:45  FrC04.1

Learning the Kalman Filter with Fine-Grained Sample Complexity, pp. 4549-4554
Zhang, Xiangyuan  University of Illinois at Urbana-Champaign
Hu, Bin  University of Illinois at Urbana-Champaign
Basar, Tamer  Univ of Illinois, Urbana-Champaign
We develop the first end-to-end sample complexity of model-free policy gradient (PG) methods in discrete-time infinite-horizon Kalman filtering. Specifically, we introduce the receding-horizon policy gradient (RHPG-KF) framework and demonstrate $\tilde{\mathcal{O}}(\epsilon^{-2})$ sample complexity for RHPG-KF in learning a stabilizing filter that is $\epsilon$-close to the optimal Kalman filter. Notably, the proposed RHPG-KF framework does not require the system to be open-loop stable nor assume any prior knowledge of a stabilizing filter. Our results shed light on applying model-free PG methods to control a linear dynamical system where the state measurements could be corrupted by statistical noises and other (possibly adversarial) disturbances.

**15:45-16:00**

**FrC04.2**

*On the Benefits of Leveraging Structural Information in Planning Over the Learned Model*, pp. 4555-4560

Shen, Jiajun, Purdue University
Kuwarananchaoren, Kananart, Purdue University
Ayoub, Raid, Intel Corporation
Mercati, Pietro, Intel
Sundaram, Shreyas, Purdue University

Model-based Reinforcement Learning (RL) integrates learning and planning and has received increasing attention in recent years. However, learning the model can incur a significant cost (in terms of sample complexity), due to the need to obtain a sufficient number of samples for each state-action pair. In this paper, we investigate the benefits of leveraging structural information about the system in terms of reducing sample complexity. Specifically, we consider the setting where the transition probability matrix is a known function of a number of structural parameters, whose values are initially unknown. We then consider the problem of estimating those parameters based on the interactions with the environment. We characterize the difference between the Q estimates and the optimal Q value as a function of the number of samples. Our analysis shows that there can be a significant saving in sample complexity by leveraging structural information about the model. We illustrate the findings by considering how to control a queueing system with heterogeneous servers.

**16:00-16:15**

**FrC04.3**

*Thompson Sampling for Partially Observable Linear-Quadratic Control*, pp. 4561-4568

Kargin, Taylan, California Institute of Technology
Lale, Sahin, Caltech
Azizzadenesheli, Kamyar, Purdue University
Anandkumar, Animashree, California Institute of Technology
Hassibi, Babak, Caltech

Thompson Sampling (TS) is a popular method for decision-making under uncertainty, where an action is sampled from a carefully constructed distribution based on the data collected. In this work, we study the problem of adaptive control in partially observable linear quadratic Gaussian, i.e., LQG, control systems using TS, when the model dynamics are unknown. Prior works have established an $\&Otide(\frac{37}{T})$ regret upper bound for the adaptive control of such systems, after $T$ time steps. However, the algorithms that achieve this result employ computationally intractable policies. We propose an efficient TS-based adaptive control algorithm, Thompson Sampling under Partial Observability, TSPO, to effectively balance the exploration vs. exploitation trade-off and minimize the overall control cost in epochs. TSPO utilizes closed-loop system identification to estimate the underlying model parameters up to their confidence intervals. It then deploys the optimal policy of a sampled system, which is selected at random from the distribution constructed with the model estimates and their confidence intervals. We show that using only logarithmic policy updates, TSPO attains $\&Otide(\frac{37}{T})$ regret against the optimal control policy that knows the system dynamics. To the best of our knowledge, TSPO is the first computationally efficient algorithm that achieves $\&Otide(\frac{37}{T})$ regret in adaptive control of unknown partially observable LQG control systems with convex cost.

Further, we empirically study the performance of TSPO in an adaptive measurement-feedback control problem.

**16:15-16:30**

**FrC04.4**

*An Online Deep Learning - Production Scheduling - Optimal Control Framework for Batch Chemical Processes*, pp. 4569-4574

Santander, Omar, The University of Texas at Austin
Giannikopoulos, Ioannis, The University of Texas at Austin
Stadtherr, Mark, University of Texas at Austin
Baldea, Michael, The University of Texas at Austin

Integrating production scheduling and optimal control is a key step towards increasing the efficiency of the decision-making process in chemical process operations. In this paper, we introduce a novel framework that couples short term production scheduling and optimal control using deep learning (recurrent neural networks) techniques for process modeling, capturing nonlinear process behavior and accounting for varying processing times. The models remain computationally tractable, leading to fast solutions with potential for online implementation. The capabilities of the framework are showcased with a prototype case study.

**16:30-16:45**

**FrC04.5**

*Learning Adaptive Optimal Controllers for Linear Time-Delay Systems*, pp. 4575-4580

Cui, Leilei, New York University
Pang, Bo, New York University
Jiang, Zhong-Ping, New York University

This paper studies the learning-based optimal control for a class of infinite-dimensional linear time-delay systems. The aim is to fill the gap of adaptive dynamic programming (ADP) where adaptive optimal control of infinite-dimensional systems is not addressed. A key strategy is to combine the classical model-based linear quadratic (LQ) optimal control of time-delay systems with the state-of-art reinforcement learning (RL) technique. Both the model-based and data-driven policy iteration (PI) approaches are proposed to solve the corresponding algebraic Riccati equation (ARE) with guaranteed convergence. The proposed PI algorithm can be considered as a generalization of ADP to infinite-dimensional time-delay systems. The efficiency of the proposed algorithm is demonstrated by the practical application arising from autonomous driving in mixed traffic environments, where human drivers’ reaction delay is considered.

**16:45-17:00**

**FrC04.6**

*Convex and Nonconvex Sublinear Regression with Application to Data-Driven Learning of Reach Sets*, pp. 4581-4586

Haddad, Shadi, University of California, Santa Cruz
Halder, Abhishek, University of California, Santa Cruz

We consider estimating a compact set from finite data by approximating the support function of that set via sublinear regression. Support functions uniquely characterize a compact set up to linear scaling. We propose an efficient TS-based adaptive control algorithm, Thompson Sampling under Partial Observability, TSPO, to effectively balance the exploration vs. exploitation trade-off and minimize the overall control cost in epochs. TSPO utilizes closed-loop system identification to estimate the underlying model parameters up to their confidence intervals. It then deploys the optimal policy of a sampled system, which is selected at random from the distribution constructed with the model estimates and their confidence intervals. We show that using only logarithmic policy updates, TSPO attains $\&Otide(\frac{37}{T})$ regret against the optimal control policy that knows the system dynamics. To the best of our knowledge, TSPO is the first computationally efficient algorithm that achieves $\&Otide(\frac{37}{T})$ regret in adaptive control of unknown partially observable LQG control systems with convex cost.

We leverage this property to transcribe the task of learning a compact set up to learning its support function. We propose two algorithms to perform the sublinear regression, one via convex and another via nonconvex programming. The convex programming approach involves solving a quadratic program (QP). The nonconvex programming approach involves training an input sublinear neural network. We illustrate the proposed methods via numerical examples on learning the reach sets of controlled dynamics subject to set-valued input uncertainties from trajectory data.
In this paper, we model a passive walker with foot slip by using techniques of geometric mechanics, and we construct forced variational integrators for the system. Moreover, we present a methodology for generating (locally) optimal control policies for simple hybrid holonomically constrained forced Lagrangian systems, based on discrete mechanics, applied to a controlled walker with foot slip in a trajectory tracking problem.

Forced variational integrators are given by the discretization of the Lagrange-d'Alembert principle for systems subject to external forces, and have proved useful for numerical simulation studies of complex dynamical systems. In this paper we model a passive walker with foot slip by using techniques of geometric mechanics, and we construct forced variational integrators for the system. Moreover, we present a methodology for generating (locally) optimal control policies for simple hybrid holonomically constrained forced Lagrangian systems, based on discrete mechanics, applied to a controlled walker with foot slip in a trajectory tracking problem.

This paper demonstrates how quantum optimal control can be used to perform shaken lattice interferometry. The first objective is to translate the five fundamental stages of interferometry (splitting, propagation, reflection, counter propagation and recombination) into quantum optimal control problems parametrized by the time horizon of each stage. The timing of each stage is then studied in relationship to its overall influence on the interferometer performance. This is done by comparing the population distributions obtained for a range of different accelerations and using Fisher information to estimate the sensitivity of the resulting accelerometer. These encouraging results highlight the effectiveness of quantum optimal control for the design of next-generation atom-based interferometers.

This study presents a novel inverse optimal control (IOC) approach that can account for uncertainties in measurements and system models. The proposed IOC approach aims to recover an objective function including a time-varying term, called variability, from a given demonstration. All uncertainties of the demonstration and the system model can be lumped into the variability such that the optimality condition violation is further reduced. The inferred objective function including the variability has two advantages over the objective function inferred by existing IOC approaches: first, the variability can enhance the capability of describing the given demonstration since it represents how the uncertainties of the system affect the objective function; and second, the proposed IOC approach can reproduce the trajectories such that we can predict the behavior of the system even with system modeling errors. We show that the variability exists and is unique under attainable assumptions. Illustrative numerical examples are presented to demonstrate the proposed method.

In this paper, we introduce GrAViTree, a tree- and sampling-based algorithm to compute a near-optimal value function and corresponding feedback policy for indefinite time-horizon, terminal state-constrained nonlinear optimal control problems. Our algorithm is suitable for arbitrary nonlinear control systems with both state and input constraints. The algorithm works by sampling feasible control inputs and branching backwards in time from the terminal state to build the tree, thereby associating each vertex in the tree with a feasible control sequence to reach the terminal state. Additionally, we embed this stochastic tree within a larger graph structure, rewiring of which enables rapid adaptation to changes in problem structure due to, e.g., newly detected obstacles. Because our method reasons about global problem structure without relying on (potentially imprecise) derivative information, it is particularly well suited to controlling a system based on an imperfect deep neural network model of its dynamics. We demonstrate this capability in the context of an inverted pendulum, where we use a learned model of the pendulum with actuator limits and achieve robust stabilization in both straight and curve courses.

In this paper, we propose a motion planner for quadrotors in windy environments. We extend a well-known convex polynomial optimization (CPO) method to incorporate known stochastic input uncertainties. In particular, we focus on a quadrotor unmanned aerial vehicle (UAV), and propose a new objective for direct minimization of the squared L2-norm of the UAV thrust. We show that the first two moments of this norm are convex in the optimization variables of the CPO problem, and can be minimized directly. Furthermore, we...
demonstrate that a constrained CPO approach can be used in this setting, contrary to the more popular unconstrained approaches. We provide examples demonstrating: (i) that inclusion of wind can yield significant improvements in the considered cost; (ii) that re-planning of complex paths can be done at rates exceeding 100 Hz; and (iii) that the proposed method facilitates online re-planning leveraging wind in free-space defined as the union of convex sets.

FrC06
Uncertain Systems (Regular Session)
Chair: Kontoudis, George University of Maryland
Co-Chair: Farhood, Mazen Virginia Tech
15:30-15:45 FrC06.1
Closed-Form Active Learning Using Expected Variance Reduction of Gaussian Process Surrogates for Adaptive Sampling, pp. 4626-4632
Kontoudis, George University of Maryland
Otte, Michael University of Maryland College Park
Adaptive sampling of latent fields remains a challenging task, especially in high-dimensional input spaces. In this paper, we propose an active learning method of expected variance reduction with Gaussian process (GP) surrogates using a closed-form gradient. The use of closed-form gradient leads the optimization to find better solutions with reduced computations. We derive the closed-form gradient for active learning Cohn (ALC) using GP surrogates that are formed with the separable squared exponential covariance function. Moreover, we provide algorithmic details for the execution of the closed-form ALC (cALC). Numerical experiments with multiple input space dimensions illustrate the efficacy of our method.

15:45-16:00 FrC06.2
Identifying Critical Attack Points in Cyber-Physical Systems Using Integral Quadratic Constraints, pp. 4633-4638
Sinha, Sourav Virginia Tech
Farhood, Mazen Virginia Tech
This paper gives a systematic approach for identifying critical attack points in cyber-physical systems leveraging recently developed robustness analysis tools for finite horizon systems based on integral quadratic constraints (IQCs). The controlled system is expressed as a linear fractional transformation on uncertainties and is affected by exogenous inputs, where both the modeling uncertainties and disturbance inputs are characterized using IQCs. The attacks are assumed to target the sensor measurements and actuator inputs over a finite time interval, and are in the form of additive perturbations that are bounded pointwise in time. The pointwise-bounded adversarial perturbations and the finite-horizon disturbance signals are properly characterized to reduce conservatism. The robust performance level obtained from IQC analysis is used as a qualitative measure to identify critical sensor and actuator attack points. The proposed approach is applied to identify the critical sensor and actuator attack points in an unmanned aircraft system, and its advantages over nonlinear optimization techniques are demonstrated.

16:00-16:15 FrC06.3
On Robust Control of Partially Observed Uncertain Systems with Additive Costs, pp. 4639-4644
Dave, Aditya University of Delaware
Senthil Kumar, Nishanth University of Delaware
Venkatesh
Malikopoulos, Andreas A. University of Delaware
In this paper, we consider the problem of optimizing the worst-case behavior of a partially observed system. All uncontrolled disturbances are modeled as finite-valued uncertain variables. Using the theory of cost distributions, we present a dynamic programming (DP) approach to compute a control strategy that minimizes the maximum possible total cost over a given time horizon. To improve the computational efficiency of the optimal DP, we introduce a general definition for information states and show that many information states constructed in previous research efforts are special cases of ours. Additionally, we define approximate information states and an approximate DP that can further improve computational tractability by concealing a bounded performance loss. We illustrate the utility of these results using a numerical example.

16:15-16:30 FrC06.4
Funnel Control for Uncertain Nonlinear Systems Via Zeroing Control Barrier Functions, pp. 4645-4650
Virgiris, Christos Uppsala University
We consider the funnel-control problem for control-affine nonlinear systems with unknown drift term and parametrically uncertain control-input matrix. We develop an adaptive control algorithm that uses zeroing control barrier functions to accomplish trajectory tracking in a pre-defined funnel, achieving hence pre-defined transient and steady-state performance. In contrast to standard funnel-control works, the proposed algorithm can retain the system's input-bound constraints in pre-defined bounds without resorting to reciprocal terms that can lead to arbitrarily large control effort. Moreover and unlike the previous works on zeroing control barrier functions, the algorithm uses appropriately designed adaptation variables that compensate for the uncertainties of the system; namely, the unknown drift term and parametric uncertainty of the control-input matrix. Comparative computer simulations verify the effectiveness of the proposed algorithm.

16:30-16:45 FrC06.5
Safe and Stable Control Synthesis for Uncertain System Models Via Distributionally Robust Optimization, pp. 4651-4658
Long, Kehan University of California San Diego
Yi, Yinzhuang University of California San Diego
Cortes, Jorge University of California, San Diego
Atanovsk, Nikolay University of California, San Diego
This paper considers enforcing safety and stability of dynamical systems in the presence of model uncertainty. Safety and stability constraints may be specified using a control barrier function (CBF) and a control Lyapunov function (CLF), respectively. To take model uncertainty into account, robust and chance formulations of the constraints are commonly considered. However, this requires known error bounds or a known distribution for the model uncertainty, and the resulting formulations may suffer from over-conservatism or over-confidence. In this paper, we assume that only a finite set of model parametric uncertainty samples is available and formulate a distributionally robust chance-constrained program (DRCCP) for control synthesis with CBF safety and CLF stability guarantees. To facilitate efficient computation of control outputs during online execution, we present a reformulation of the DRCCP as a second-order cone program (SOCP). This formulation is evaluated in an adaptive cruise control example in comparison to 1) a baseline CLF-CBF quadratic programming approach, 2) a robust approach that assumes known error bounds of the system uncertainty, and 3) a chance-constrained approach that assumes a known Gaussian Process distribution of the uncertainty.
Due to ever increasing demand for different types of paper, it is crucial to optimize the Kraft pulping process to achieve the required paper properties. This work proposes a framework to regulate these paper properties by building a novel closed-loop long short-term memory (LSTM)-based model predictive control system. First, a multiscale model was developed by combining the mass and thermal energy balance equations adopted from Purdue model with a layered kinetic Monte Carlo (kMC) algorithm that describes the time-evolution of microscopic events such as fiber morphology, kappa number, and cellulose Degree of Polymerization (DP). Then, this model was run over different operating conditions by varying the temperature, concentration, and cooking time to generate data. An LSTM-ANN network was trained using these datasets with a prediction accuracy of over 98% capturing the behavior of kappa number and cellulose DP and considering the effects of time-varying and time-invariant operating conditions together. Finally, a closed-loop LSTM-based multi-objective optimal controller was designed, which was demonstrated to achieve the target set-point values and obtain optimal constant value inputs along with time-series inputs while considering process constraints. The results showed excellent accuracy and the controller was computationally less expensive due to the use of a well-trained LSTM network in the proposed framework.

This letter investigates a real-time of a finite-time control for permanent magnet synchronous motor in the presence of external load disturbance. Firstly, an integral terminal sliding manifold is designed to achieve fast speed, high precision performance, and enhance the quality of currents by reducing the total harmonic distortion. Indeed, the proposed surface manifold ensures a finite-time convergence of the states. Secondly, a switching control scheme is added in the system control to force the state systems converge to their desired values in the presence of load disturbance. The finite-time stability is proved based on Lyapunov theory. Finally, the effectiveness of the designed controller is validated and evaluated by carrying out real-time experimental studies using eZdspTM F28335 board. Experimental results demonstrate that the proposed controller is simple to implement, has better tracking accuracy, reduces the chattering phenomenon, and ensures robustness against external load disturbance.

This paper presents a robust passivity-based payload trajectory tracking control method for redundantly-actuated flexible robotic manipulators. The proposed approach is based on mu-tip control, which involves the use of a modified system output to ensure a passive input-output mapping. This work distinguishes itself from prior implementations of mu-tip control with flexible manipulators by demonstrating the generality with which redundant actuation can be accounted for. In particular, it is shown that prior load-sharing-parameter-based approaches are a special case of a more general kinematic constraint that is to be enforced to ensure passivity. Numerical results with an overactuated cable-driven parallel robot demonstrate the performance of the proposed mu-tip control method.
A new approach to orbital stabilization of underactuated systems with one passive degree-of-freedom (DOF) is presented. Virtual holonomic constraints are enforced using partial feedback linearization; this results in a dense set of periodic orbits on a constraint manifold. Every orbit on the constraint manifold is associated with a unique time-period. A desired orbit is selected and the impulse controlled Poincare map (ICPM) approach is utilized to stabilize the orbit by regulating the time-period. By treating the time period as the output, it is possible to design a dead-beat controller that achieves orbital stabilization in a single time-step. The effectiveness of the dead-beat design is demonstrated for the cart-pendulum system.

This paper uses output-only measurements to localize faults within flexible structures. These measurements are used to construct transmissibility operators, which are mathematical models that are independent of the excitation acting on the structure. Faults considered in this paper are formulated as unknown disturbances acting on the underlying structure. The proposed approach is illustrated on a class of flexible cantilever beams, which can be modeled as a connection of finite lumped segments. The output (e.g. deflection of the beam) at one location on the beam can be predicted using a transmissibility operator and the output at a different location on the beam. The discrepancy between the measured and predicted outputs at a specific location on the beam can be used as a fault indicator. If this discrepancy is small, the beam is considered healthy. Any deviation from the healthy conditions of the beam will cause an increase in the transmissibility discrepancy, which indicates a fault. This allows early fault and crack detection even if the fault is not clearly visible to the human eye. The proposed approach can be used online during system operation and is illustrated using a numerical example.

This paper presents an onboard diagnostic of an electro-hydraulic actuator in closed-loop based on inverse model estimation and its frequency domain analysis. The developed diagnostic has two sequential steps. In the first step, an inverse model of the electro-hydraulic actuator in closed-loop is adaptively updated to retain changing dynamics due to the occurrence of faults. To address an estimation bias and covariance windup under non-persistent excitation of closed-loop system identification, an indirect two-stage directional forgetting recursive least squares method is applied to estimate the inverse model parameters. In the second step, the estimated inverse model is analyzed in frequency domain to extract fault features for diagnostic. The developed diagnostic is illustrated numerically with the most common and critical faults including incorrect pump pressure, fluid leakage and changes of friction and bulk modulus.

The confidence region of state prediction is necessary for anomaly detection and robust control design in stochastic dynamical systems. This paper addresses the problem of computing the tightest ellipsoidal region of state prediction with a required probability confidence level for stochastic dynamical discrete-time systems. This problem is not directly tractable. In this paper, a sample-based method is proposed to construct a solvable approximate problem of the original problem. By solving the approximate problem, the approximate confidence region can be obtained. We prove that the approximate confidence region converges to the optimal confidence region with probability 1 when the number of sample data increases to infinity. Numerical simulations have been implemented to validate the effectiveness of the proposed method.

This paper proposes a universal guaranteed active fault diagnosis framework for systems with zonotopic, polytopic or ellipsoidal uncertainties. Based on the notion of the second-order cone, a novel set representation that unifies the above set forms for set-membership estimation in fault diagnosis is derived. The principle of fault diagnosis within a specified time horizon is to design an input sequence to separate the output sets of all fault scenarios. In our framework, the input design problem is formulated as a mathematical program with complementarity constraints. To reduce computational complexity, a smoothing approach is applied such that gradient based methods can be utilized to search solutions efficiently. The effectiveness of the proposed method is demonstrated by a numerical example.
Deep learning techniques have become prominent in modern fault diagnosis for complex processes. In particular, convolutional neural networks (CNNs) have shown an appealing capacity to deal with multivariate time-series data when converted into images. However, existing CNN techniques mainly focus on capturing local or multi-scale features from input images. A deep CNN is often required to indirectly extract global features, which are critical to describing the images converted from multivariate dynamical data. This paper proposes a novel local-global scale CNN (LGS-CNN) architecture that directly accounts for both local and global features for fault diagnosis. Specifically, the local features are acquired by traditional local kernels, whereas global features are extracted using one-dimensional tall and fat kernels that span the entire height and width of the image. Both local and global features are then merged for classification using fully-connected layers. The proposed LGS-CNN is validated on the benchmark Tennessee Eastman process dataset. Comparison with traditional CNN shows that the proposed LGS-CNN can greatly improve the fault diagnosis performance without significantly increasing the model complexity. This is attributed to the much wider local receptive field created by the LGS-CNN than that by CNN. The proposed LGS-CNN can also outperform artificial neural networks and Fisher discriminant analysis in FD on the same dataset.

This paper synthesizes a gain-scheduled controller to stabilize all possible Linear Parameter-Varying (LPV) plants that are consistent with measured input/state data records. Inspired by prior work in data informativity and LTI stabilization, a set of Quadratic Matrix Inequalities is developed to represent the noise set, the class of consistent LPV plants, and the class of stabilizable plants. The bilinearity between unknown plants and 'for all' parameters is avoided by vertex enumeration of the parameter set. Effectiveness and computational tractability of this method is demonstrated on example systems.

In this paper, we address the control of a class of switched systems cast in the framework of singularly perturbed systems. The class of switched systems that we deal with here is a particular case of switched affine systems where the state matrices are the same for all modes. These systems have been studied in the literature, wherein control design is carried out by solving Linear Matrix Inequalities (LMIs). However, the presence of the small parameter $\epsilon$, characteristic of singularly perturbed systems, in the dynamical equation introduces numerical stiffness. To the best of the authors' knowledge, these issues have not been addressed in the literature for the class of switched systems studied here. We propose an $\epsilon$-dependent controller stabilizing the system and also an $\epsilon$-independent controller, in the case where the parameter $\epsilon$ is not well-known. The design of these control laws is based on LMIs that do not present the ill-conditioning linked to $\epsilon$. The proposed approach is illustrated by simulation results.

The main objective of this work is to propose a solution to observer design for triangular systems where additional output measurements are available, which may improve the estimation quality. In fact, such additional measurements prevent the standard high-gain observer methodology to provide solutions for the estimation problem. In this paper, motivated by this issue, we propose two novel observer design methods to handle the additional output measurements. The first one can be viewed as an extension of the standard high-gain observer by introducing a weighting matrix as a tuning parameter, while the second method, which can be viewed as an alternative method, exploits jointly the high-gain methodology and the LPV/LMI technique to overcome some limitations related to the first design method. The proposed methods are applied to a vehicle trajectory estimation problem using the well-known kinematic model. The efficiency of the estimation using both proposed methods and a comparative study between them are provided.

This paper extends algorithms that solve the distributed consensus problem to solve the more general problem of distributed optimization over subspace constraints. Leveraging the integral quadratic constraint framework, we analyze the performance of these generalized algorithms in terms of worst-case robustness and convergence rate. The utility of our framework is demonstrated by showing how one of the extended algorithms, originally designed for consensus, is now able to solve a multitask inference problem.
Asynchronous Dynamic Quantization for Nonlinear Systems with One-Bit Data Transmission* 
Almakhles, Dhafer J. 
Abdelrahim, Mahmoud 

16:30-16:45 
Output Regulation of Nonlinear Systems by an Emulation-Based Approach, pp. 4779-4784 
Wu, Jieshuai 
Lu, Maobin 
Deng, Fang 
Chen, Jie 
Beijing Institute of Technology 

In this paper, we investigate the semi-global robust output regulation problem of a class of nonlinear networked control systems by an emulation approach. We propose a class of sampled-data control laws to solve this problem. In particular, by the emulation approach, we first develop a class of sampled-data dynamic output feedback control laws. Then, based on the internal model principle, we convert the semiglobal robust output regulation problem into a semi-global robust stabilization problem of an augmented hybrid system composed of the internal model and the original system. Next, we show that semi-global robust stabilization of the augmented hybrid system can be achieved by a sampled-data control law and thus leading to the solution of the semi-global robust output regulation problem. Finally, an example is given to illustrate our control approach.

Adaptive Systems (Regular Session) 
Chair: Tanner, Herbert G. 
Co-Chair: Li, Perry Y. 
University of Delaware 
Univ. of Minnesota 

15:30-15:45 
Receding Horizon Cost-Aware Adaptive Sampling for Environmental Monitoring, pp. 4785-4790 
Westermann, Johannes 
Mayer, Jana 
Peteriet, Janko 
Noack, Benjamin 
Otto Von Guericke Universität Magdeburg 
Karlsruhe Institute of Technology 
Fraunhofer IOSB 
Otto Von Guericke University Magdeburg (OVGU) 

In this paper, environmental monitoring by mobile robots is considered, where expensive or time-consuming sampling has to be carried out in order to obtain a metamodel of the phenomenon investigated. Due to limited resources, often not only a limited number of samples can be taken, but also the cost and time of the traveled distance between the sample points must be considered. We present an adaptive sampling method that greatly reduces the robot's travel costs for all common sampling criteria with minimal impact on model accuracy. This is achieved by predicting future sample points based on virtual sampling over a horizon in each iteration of the algorithm and suggesting a next sample point after a cost optimization. The algorithm is simultaneously evaluated for application to global exploration and reconstruction of unknown phenomena on a variety of randomly generated phenomena. It is shown that our method vastly outperforms standard adaptive sampling.

16:45-17:00 
Sanjeevin, Sneha 
Bernstein, Dennis S. 
University of Michigan 
Univ. of Michigan 

Numerical integration of measured signals is challenging due to
sensor noise, where sensor bias leads to a spurious ramp, and white noise leads to random-walk divergence. This paper presents a novel approach to numerical integration of sensor data based on adaptive input estimation. In particular, retrospective cost input estimation (RCIE) is applied to a one-step-delayed differentiator model to estimate the unknown input, which is the desired integral of the output. Numerical examples show that, for harmonic signals corrupted by white noise, RCIE integration eliminates the random walk that arises from standard numerical integration.

16:00-16:15 FrC12.3

Error Bounds for Native Space Embedding Observers with Operator-Valued Kernels, pp. 4796-4801

Burns, John A, Virginia Tech
Guo, Jia, Georgia Institute of Technology
Kurdila, Andrew J., Virginia Tech
Paruchuri, Sai Tej, Lehigh University
Wang, Haoran, Virginia Tech

This paper derives new rates of convergence for observers for a class of uncertain systems governed by nonlinear ODEs. We assume that the generally nonlinear function appearing in the ODEs that represents the unknown dynamics is an element of a vector-valued reproducing kernel Hilbert space $\mathbb{H}$ (RKHS) that is induced by an operator-valued kernel. The vector-valued RKHS embedding method described in the paper yields a nonparametric adaptive estimator that takes the form of distributed parameter system (DPS). The original ODEs in $\mathbb{H}$ are thus embedded in a product space $\mathbb{H} \times \mathbb{H}$ in which state and functional uncertainty estimates evolve. We first discuss the well-posedness of the DPS formulation, and subsequently describe an approximation scheme in finite-dimensional subspaces based on certain types of history dependent bases. We derive sufficient conditions that ensure the consistency of the finite-dimensional approximation scheme, and further derive rates of convergence in some particular cases when the samples that define the scattered bases are dense in some sufficiently regular and invariant subset of the observation space. A numerical example is given to illustrate the qualitative behavior of implementations of the theoretical results derived in the paper.

16:15-16:30 FrC12.4

Online Learning and Control of an Internal Combustion Engine for UAS Using Simplex Tessellation and Recursive Least Squares, pp. 4802-4807

Tranquillo, Holden, University of Minnesota
Sonstegard, Jack, University of Minnesota
Kim, Kenneth, DEVCOM Army Research Laboratory
Kweon, Chol-Bum, DEVCOM Army Research Laboratory
Li, Perry Y., Univ. of Minnesota

As Unmanned Aircraft Systems demand more fuel flexibility, engine control for these systems will need to adapt to unknown fuels. To do so, a computationally efficient method for the online learning and adaptive control of an engine based on real-time input and output engine measurements is developed. The method, based on recursive least-squares estimation and multi-dimensional piecewise-linear splines, has been developed for systems with one input (injection timing), two inputs (injection timing, glow-plug power/fuel mass), as well as for general systems with arbitrary dimensions. The online learning model in turn generates an adaptive feedforward signal which is combined with integral feedback with decoupling control to achieve a desired combustion phasing (CAS50) and other outputs such as mean effective pressure (MEP) or power.

16:30-16:45 FrC12.5

Extremum Seeking Regulator for a Class of Nonlinear Systems with Unknown Control Direction, pp. 4808-4813

Wang, Shimin, Queen's University
Guay, Martín, Virginia Tech

Nussbaum function techniques are commonly used to investigate output regulation problems for various systems subject to unknown control direction. However, their implementation often leads to large overshoots when the initial estimates of the control direction are wrong, which yields systems with poor transient performance. This study proposes an extremum-seeking control approach to overcome the need for Nussbaum-type functions. The approach yields control laws that can handle the robust practical output regulation problem for a class of nonlinear systems subject to an unknown time-varying control direction. The stability of the design is proven using a Lie bracket averaging technique. It is shown that uniform ultimate boundedness of the closed-loop system is guaranteed. Finally, a simulation study is performed involving a chaotic control problem for the generalized Lorenz system with an unknown time-varying coefficient to illustrate the validity of the theoretical results.

15:30-15:45 FrC13

Autonomous Satellite Control Systems (Invited Session)

Chair: Phillips, Sean, Air Force Research Laboratory
Co-Chair: Petersen, Chris, University of Florida
Organizer: Petersen, Chris, University of Florida
Organizer: Phillips, Sean, Air Force Research Laboratory
Organizer: Soderlund, Alexander, The Ohio State University

LISA (Laser Interferometer Space Antenna) is a space mission, under study by the European Space Agency (ESA) and other institutions, with the objective of detecting, observing, and measuring gravitational waves. It consists of a triangle constellation of three spacecraft connected through bi-directional laser links to measure gravitational waves by means of interferometry. During the Science mode, also called Drag-free mode, micrometeoroids may collide with the spacecraft surface, generating impulsive forces and torques, which can cause the loss of links. Impulsive disturbances may lead to a significant performance degradation and even to instability, especially in the presence of actuator saturations. In this paper, a Navigation strategy based on a sliding mode observer is proposed to improve the closed-loop system stability properties, allowing the spacecraft to quickly restore the laser links, safely returning to the Science mode. Simulation results show the effectiveness of the proposed solution. Moreover, a comparison with classical methods is carried out, based on the combination of an Extended Kalman Filter and an Anti-windup strategy.

15:45-16:00 FrC13.2

Attitude Control System Design for Multibody Flexible Spacecraft (I), pp. 4820-4825

Tagliani, Gianluca, Politecnico Di Torino
Mancini, Mauro, Politecnico Di Torino
Capello, Elisa, Politecnico Di Torino, CNR-IEIIT

This paper considers control design and model validation for attitude dynamics of a multi-body flexible spacecraft. The spacecraft is designed in MSC Adams with a main rigid body and four deployable flexible solar panels. MSC Adams allows to simulate the attitude dynamics of the satellite, taking into account: (i) the disturbances due to both flexible dynamics and torques exchanged during the solar...
panels deployment and (ii) the vibrations of the flexible panels due to attitude maneuvers. In addition, MSC Adams gives the parameters of the multibody spacecraft for each configuration it can assume, thus simplifying the design of the controller. In fact, those parameters are used to design a robust Sliding Mode Control (SMC) able to manipulate the perturbed, uncertain, and time-varying attitude dynamics of the spacecraft. Numerical simulations are performed to show the effectiveness of the proposed approach.

16:00-16:15 FrC13.3
**Autonomous Information Gathering Guidance for Distributed Space Systems with Optical Sensors (I)**, pp. 4826-4831

Greaves, Jesse
University of Colorado Boulder
Scheeres, Daniel J.
The University of Colorado

Spacecraft to spacecraft tracking using optical sensors is a promising approach to autonomous navigation of distributed space systems. Previous works have shown that optical spacecraft to spacecraft tracking can provide an absolute navigation estimate for all vehicles in the distributed system, but the relative range between the spacecraft is often weakly observable. The observability issues motivate the development of guidance capabilities to gather information on a desired sub-space of the state, such as relative range, to ensure accurate state estimation. This paper starts by developing a simplified model and heuristic policy for information gathering with optical measurements. Then a general analytic guidance policy for information gathering is derived. The guidance methods are tested via a covariance analysis in the cislunar environment with an optical sensor. In all test scenarios the analytic method is fast to calculate and nearly optimal, making it suitable as an autonomous guidance algorithm for information gathering.

16:15-16:30 FrC13.4
**Constellation Phasing of Spacecraft in Near-Circular, In-Plane Orbits Using Low-Thrust Trajectory Optimization (I)**, pp. 4832-4837

Sin, Emmanuel
University of California, Berkeley
Arcak, Murat
University of California, Berkeley

We present a trajectory optimization problem to be used in the planning of orbital maneuvers for spacecraft operating in a constellation. The 3-DOF orbital motion of each spacecraft, governed by central body gravity and low-thrust propulsion, is expressed in a planet-centered inertial frame with Cartesian state vectors. Path constraints on each spacecraft include bounds on altitude, thrust magnitude, and propellant consumption. Terminal constraints enforce all spacecraft to achieve near-circular motion in the same orbital plane with desired altitude and in-plane angular spacing between spacecraft. The numerical example in this paper considers a cluster of spacecraft deployed into the same parking orbit by a launch vehicle. We apply our problem formulation to perform simultaneous orbit phasing and station-keeping of the spacecraft in minimum-time. The problem is approached using recent advances in sequential convex programming (SCP) and the solution is applied in simulation to verify satisfaction of constraints.

16:30-16:45 FrC13.5
**Strong Observability of LTV Systems with Feedthrough and On-Orbit Reconnaissance and Evasion Applications (I)**, pp. 4838-4843

Woodford, Nathaniel
Utah State University
Harris, Matthew W.
Utah State University

This paper considers linear time-varying control systems with feedthrough. A necessary and sufficient condition for strong observability (also known as observability with unknown inputs) is stated in terms of the observability matrix and newly redefined invertibility matrix. This is followed by an observer for pointwise reconstruction of the state from the output and its time derivatives. A variable-time weakly unobservable subspace is then introduced such that the rank test can be recast in terms of this subspace and the kernel of a certain matrix. The subspace characterization leads to results on the existence and construction of unobservable state and control functions. The theoretical results are illustrated in an on-orbit reconnaissance application. Within the context of a time-varying relative orbital motion model, it is shown that strong observability is satisfiable with any constant or bounded feedthrough matrix. In the absence of strong observability, control functions to evade observation are constructed.

16:45-17:00 FrC13.6
**Consensus Over Clustered Networks Using Output Feedback and Asynchronous Inter-Cluster Communication (I)**, pp. 4844-4851

Nino, Cristian F.
University of Florida
Zegers, Federico
Johns Hopkins University Applied Physics Laboratory
Phillips, Sean
Air Force Research Laboratory
Dixon, Warren E.
University of Florida

This paper develops a method to yield state consensus and state reconstruction for a clustered multi-agent system (C-MAS). The agents within the network are organized into disjoint clusters, where each cluster induces a connected sub-graph. Agents contained within the same cluster are capable of communicating continuously with their neighbors. Between some cluster pairs, there exists an inter-cluster, where agents contained within the same inter-cluster can intermittently communicate with their neighbors. In addition, the communication between distinct inter-clusters may be asynchronous. Since we assume no agent can completely measure its own state, a model-based observer utilizing intermittent output feedback is developed to facilitate state reconstruction. The combination of continuous-time dynamics with intermittent communication and sensing is modeled as a hybrid system. The state consensus and state reconstruction problems are formulated as set stabilization problems for hybrid dynamical systems, where Lyapunov-based stability analyses show that the state consensus and state reconstruction sets are globally exponentially stable.

15:30-15:45 FrC14.1
**An Online Learning Based Extended Kalman Filtering Approach for Intelligent Vehicles Localization During Short-Term GNSS Outages**, pp. 4852-4857

Li, Zipeng
Tongji University
Guo, Yafeng
Tongji University
Wang, Jun
Tongji University

Real-time and accurate localization is a prerequisite for intelligent vehicles control. GNSS is an important information source for localization. However, GNSS signal may be short-term blocked by large buildings and tunnels inevitably. Therefore, it is a practical issue to retain localization accuracy during short-term GNSS outages. By improving the modeling accuracy of the vehicle motion and sensor measurements, localization is expected to maintain a satisfactory performance during GNSS short-term outages. In this paper, dual neural extended kalman filtering approach (DN-EKF) is introduced to compensate for the unmodeled errors of vehicle motion and statistical modeling error of sensor measurement noise, and consequently improves estimator accuracy. Experiments on our test platform have demonstrated the effectiveness of proposed method during GNSS short-term outages. It is worth noting that the proposed method in this paper is open-ended. Therefore, it can be easily integrated with other solutions to further improve the performance of localization.

16:15:15-16:30 FrC14.2
**INS-GNSS Navigation for Large Attitude Uncertainties with the Matrix
In this paper, we present a new recursive Bayesian filter for loosely coupled INS-GNSS navigation to handle large attitude uncertainty. The filter replaces the Gaussian distribution assumed in Kalman filters by the matrix Fisher-Gaussian (MFG) distribution, which is defined intrinsically on the product manifold of the three-dimensional special orthogonal group and the Euclidean space of an arbitrary dimension. The MFG models large attitude uncertainty accurately, which can be frequently encountered in robot and pedestrian localization, for example when the robot or person enters a building where the heading direction is unobservable. It is validated by simulation studies illustrating that the proposed filter has a substantially faster convergence rate, when compared with the extended Kalman filter.

Continuous optimization methods for multiple object tracking allow to jointly estimate continuous object trajectories and perform implicit data association. However, the local minima that arise from including data association in a continuous optimization problem pose challenges. In addition, optimization is usually performed either over a fixed or an indefinitely growing time frame. This either discards valuable past information or is computationally unsustainable. Hence, in this work, a flexible continuous optimization based framework for multiple object tracking that accounts for these issues is proposed. The framework provides a unified approach to not only include data association but also multiple motion models and temporary interactions between objects in a continuous optimization problem. It leverages the concept of graduated optimization, a heuristic, which allows to avoid local minima. The proposed framework's performance is benchmarked on a synthetic dataset, showing its capabilities and indicating areas of possible improvement.

The new generation of industrial cyber-physical systems (ICPS) supported by the edge computing technology enables efficient distributed sensing under massive data volumes and frequent transmissions. Observability is essential to obtain good sensing performance, and most of existing sensing works directly assume that the system is observable. However, it is difficult to satisfy the assumption with the increasingly expanded network scale and dynamic scheduling of devices. To solve this problem, we propose an observability guaranteed distributed method (OGDM) for edge sensing with the cooperation of sensors and edge computing units (ECUs). We analyze the relationship between sensor scheduling and observability based on the network topology and graph signal processing (GSP) technology. In addition, we transform the observability condition into a convex form and take into account sensing error and energy consumption for optimization. Finally, our algorithm is applied to estimate the slab temperature in the hot rolling process. The effectiveness is verified by simulation results.

Though wireless sensor networks (WSNs) help to enhance data fusion accuracy, measurement exchanges between sensors are not always reliable due to inherent open communication channels. In this paper, a distributed interval type-2 (IT2) fuzzy filter is presented in the context of WSNs with intermittent measurements. Firstly, IT2 fuzzy models are employed to formulate one type of nonlinear systems with parameter uncertainties. Then, dual random data packet dropouts phenomena are considered, including the measurements transmitting from sensors to data fusion centers, and the measurements transmitting from data fusion centers to distributed filters. Bernoulli variables are adopted to depict the random data packet dropouts. Furthermore, to guarantee the robust mean-square asymptotic stability of the filtering error system, less conservative sufficient conditions are derived to seek for distributed filter gains. Finally, simulation results on Henon mapping systems with parameter uncertainties verify the robustness of the presented distributed fuzzy filter for WSNs with intermittent measurements.

We consider a network of controlled sensors that monitor the unknown health state of a patient. We assume that the health state process is a Markov chain with a transition matrix that is unknown to the controller. At each timestep, the controller chooses a subset of sensors to activate, which incurs an energy (i.e., battery) cost. Activating more sensors improves the estimation of the unknown state, which introduces an energy-accuracy tradeoff. Our goal is to minimize the combined energy and state misclassification costs over time. Activating sensors now also provides measurements that can be used to learn the model, improving future decisions. Therefore, the learning aspect is intertwined with the energy-accuracy tradeoff. While reinforcement learning (RL) is often used when the model is unknown, it cannot be directly applied in health monitoring since the controller does not know the (health) state. Therefore, the monitoring problem is a partially observable Markov decision process (POMDP) where the cost feedback is also only partially available since the misclassification cost is unknown. To overcome this difficulty, we propose a monitoring algorithm that combines RL for POMDPs and online estimation of the expected misclassification cost based on a hidden Markov model (HMM). We show empirically that our algorithm achieves comparable performance with a monitoring system that assumes a known transition matrix and quantizes the belief state. It also outperforms the model-based approach where the estimated transition matrix is used for value iteration. Thus, our algorithm can be useful in designing energy-efficient and personalized health monitoring systems.

Fisher-Gaussian Distribution, pp. 4858-4863
Wang, Weixin, George Washington University
Lee, Taeyoung, George Washington University

OGDM: An Observability Guaranteed Distributed Edge Sensing Method for Industrial Cyber-Physical Systems, pp. 4871-4876
Wang, Shigeng, Shanghai Jiao Tong University
Ji, Zhiduo, Shanghai Jiao Tong University
Chen, Caillian, Shanghai Jiao Tong University

Distributed Interval Type-2 Fuzzy Filtering for Wireless Sensor Networks with Intermittent Measurements, pp. 4877-4882
Hu, Zhijian, Nanyang Technological University
Su, Rong, Nanyang Technological University
Wang, Yujia, Harbin Institute of Technology
Xu, Zeyuan, Harbin Institute of Technology
Wang, Bohui, Nanyang Technological University
Lu, Yun, Nanyang Technological University

Personalized and Energy-Efficient Health Monitoring: A Reinforcement Learning Approach, pp. 4883-4888
Eden, Batchen, Tel Aviv University
Bistritz, Ilai, Stanford University
Bambos, Nicholas, Stanford University
Ben-Gal, Itad, Tel-Aviv University
Khmelnitsky, Eugene, Tel Aviv University

Delay Systems (Regular Session)
Chair: Peet, Matthew M. Arizona State University
Co-Chair: Yao, Bin Purdue University
15:30-15:45 FrC15.1
Strong Left-Invertibility and Strong Input-Observability of Nonlinear
In this paper, we study the problem of unknown inputs reconstruction for nonlinear time-delay systems. First we define two notions called strong left-invertibility and strong input-observability and the word "strong" is to address the causality properties of those two notions. Then necessary and sufficient conditions for the strong left-invertibility and the strong input-observability are given under the algebraic framework. We find that a sequence of inputs submodules plays an important role for the strong left-invertibility of time-delay systems. A structure algorithm is provided to construct that sequence and to formulate an input reconstructor. At last, several examples are given to illustrate how to check the strong left-invertibility and the strong input-observability by applying the proposed structure algorithm and to show how to recover the inputs via causal outputs and the initial value functions of states (strong left-invertibility) or only via causal outputs (strong input-observability).

15:45-16:00  FrC15.2

Delay Estimation for Nonlinear System with Unknown Output Delay, pp. 4895-4900

Dam, Quang Truc
Normandy University, UNIROUEN, ESIGELEC, IRSEEM

Thabet, Rihab El Houda
IRSEEM ESIGELEC

Ahmed Ali, Sofiane
IBISC, Evry-Val-d'Essonne University, University of Paris-Saclay, E

Guerin, Francois
University Le Havre

Khemmar, Redouane
ESIGELEC, IRSEEM

In this paper, the problems of delay identifiability and delay estimation for a nonlinear systems subject to constant unknown output delay are studied. Usually, the estimation of such delay is based on a monotonic condition which is hard to satisfy in the case of nonlinear systems. To deal with this open and interesting problem and overcome this issue, a change of coordinates is introduced in this paper to transform the nonlinear system to the triangular form. Then, the Newton method and a finite-time observer are used to identify the unknown but bounded delay of the nonlinear systems. The convergence of the proposed observer is proved and the effectiveness of the proposed method is illustrated through simulation results of an Electro-Hydraulic Actuator (EHA) system.

16:00-16:15  FrC15.3

Event-Triggered Control under Unknown Input and Unknown Measurement Delays Using Interval Observers, pp. 4901-4906

Malisoff, Michael
Louisiana State University

Mazenc, Frederic
Inria Saclay

Barbalata, Corina
Louisiana State University

We provide a new input-to-state stabilizing event-triggered feedback design for linear systems with unknown input delays, unknown measurement delays, and unknown additive disturbances. Our trigger times are computed using only the matrices defining the system and time-lagged sampled state values. We use the theory of positive systems, interval observers, and a vector version of Halanay's inequality. We illustrate our method using a marine robotic model.

16:15-16:30  FrC15.4

Adaptive Robust Tracking Control for First-Order Linear Systems with Input Delay and Lipschitz Nonlinear Disturbance, pp. 4907-4911

Lai, Han
Zhejiang University

Zhu, Yang
Zhejiang University

Chen, Zheng
Zhejiang University

Yao, Bin
Purdue University

In this paper, an adaptive robust tracking controller is proposed for first-order linear systems with input delay, unknown plant parameters and Lipschitz nonlinear disturbance. The controller employs the predictor feedback to compensate for the effect of input delay, the robust feedback to deal with uncertainties, the model compensation for trajectory tracking, and projection-type adaptation laws are designed. By the stability analysis with a Lyapunov function in integral form, the closed-loop system is locally stable in the sense that the tracking error is bounded above by a known function which exponentially converges to a specified accuracy provided that the initial states and control parameters meet certain conditions. Furthermore, when the disturbance is reduced to a constant, the controller guarantees the semi-global stability that the tracking error asymptotically converges to zero. Simulation results demonstrate the effectiveness of the proposed controller.

16:30-16:45  FrC15.5

Task-Space Teleoperation with Time-Delays and without Velocity Measurements Via a Bounded Controller, pp. 4912-4917

Aldana, Carlos Ivan
University of Guadalajara (UDG)

Garcia-Lopez, Karina A.
Universidad De Guadalajara

Nurio, Emmanuelle
University of Guadalajara

Cruz-Zavala, Emmanuel
University of Guadalajara (UdG)

Perez-Cisneros, Marco A.
University of Guadalajara

This paper reports a novel controller for robot teleoperation systems in the task-space. The local and the remote robots are kinematically and dynamically different and they are modeled as Euler-Lagrange agents. We consider the realistic scenario where the robot actuators are not ideal and thus they are prone to saturation. Moreover, velocity measurements are not available and variable time-delays arise in the communications. The human operator and the remote environment are assumed to be passive. The controller is dynamical and it consists of a gravity cancellation plus a plant-controller interconnection term. The controller dynamics is of second-order and damping is injected to ensure convergence. Unit-quaternions are used to obtain a singularity-free representation of the orientation. When the human and the environment forces are zero, then we prove that the pose of both robots converges to a common pose. Experimental results of the proposed scheme are provided to illustrate the controller performance.

FrC16
Aerospace (Regular Session)

Chair: Mukherjee, Dwaipayan
Indian Institute of Technology Bombay

Co-Chair: Sinha, Abhinav
University of Texas at San Antonio

15:30-15:45  FrC16.1

3-D Nonlinear Guidance Law for Target Circumnavigation, pp. 4918-4923

Sinha, Abhinav
University of Texas at San Antonio

Cao, Yongcan
University of Texas, San Antonio

In this letter, we address the problem of circumnavigating a stationary target using a single vehicle. Unlike most existing results wherein the target is encircled in a two-dimensional plane, we focus on devising a guidance strategy that enables a vehicle to encircle a target in a three-dimensional space using the relative information between the vehicle and the target. In particular, we assume that the vehicle has lateral acceleration capabilities only and that the radial acceleration is unavailable, thereby making the proposed design favorable for a class of aerial vehicles (e.g., aircraft and fixed-wing UAVs, which cannot hover and have to maneuver constantly). The vehicle's steering controls are its lateral acceleration components in the pitch and yaw channels. In addition, we also consider nonlinear, coupled three-dimensional engagement kinematics between the vehicle and the target to preserve the inherent coupling between various channels and to achieve satisfactory control precision even if
the channels are strongly coupled. Furthermore, we minimize a relevant weighted cost function to obtain the lateral acceleration components in the pitch and the yaw channels. We finally demonstrate the efficacy of our design via simulations.

15:45-16:00 FrC16.2

**Biologically Plausible Robust Control with Neural Network Weight Reset for Unmanned Aircraft Systems under Impulsive Disturbances**, pp. 4924-4929

Rubio Scola, Ignacio INTI - Conicet - National University of Rosario

Garcia Carrillo, Luis Rodolfo New Mexico State University

Sornborger, Andrew T. Los Alamos National Laboratory

Hespanha, Joao P. Univ. of California, Santa Barbara

Self-learning control techniques mimicking the functionality of the limbic system in the mammalian brain have shown advantages in terms of superior learning ability and low computational cost. However, accompanying stability analyses and mathematical proofs rely on unrealistic assumptions which limit not only the performance, but also the implementation of such controllers in real-world scenarios. In this work the limbic system inspired control (LISIC) framework is revisited, introducing three contributions that facilitate the implementation of this type of controller in real-time. First, an extension enabling the implementation of LISIC to the domain of SISO affine systems is proposed. Second, a strategy for resetting the controller's Neural Network (NN) weights is developed, in such a way that now it is possible to deal with piece-wise smooth references and impulsive perturbations. And third, for the case when a nominal model of the system is available, a technique is proposed to compute a set of optimal NN reset weight values by solving a convex constrained optimization problem. Numerical simulations addressing the stabilization of an unmanned aircraft system via the robust LISIC demonstrate the advantages obtained when adopting the extension to SISO systems and the two NN weight reset strategies.

16:00-16:15 FrC16.3

**A Feedback-Feedforward Controller for Hybrid Flight Regimes in Transitioning Aerial Vehicles**, pp. 4930-4935

McIntosh, Kristoff Rensselaer Polytechnic Institute

Reddinger, Jean-Paul DEVCOM Army Research Laboratory

Mishra, Sandipan Rensselaer Polytechnic Institute

This paper presents a guidance and control methodology for transitioning unmanned aerial vehicles (UAS) designed around hybrid flight, i.e., flight states purely in the transition regime. The control architecture, designed for a tailsitter vehicle, consists of a trajectory planner, an outer loop position controller, an inner loop attitude controller, and a control allocator. The trajectory planner uses a simplified vehicle model with aerodynamic and wake effects for generating optimal trajectories and associated aerodynamic feedforward information for minimum time transition between flight modes. The outer loop position controller then uses these approximate aerodynamic forces computed by the trajectory planner in feedforward along with feedback linearization of the outer loop dynamics. The inner loop attitude controller is a standard nonlinear dynamic inversion control law that generates the desired pitch, roll and yaw moments, which are then used to compute rotor angular velocity commands. We derive analytical conditions that guarantee robust stability of the outer loop position controller, in the presence of uncertainty in the feedback aerodynamic force compensation. Finally, the performance of the control architecture is evaluated on a high fidelity flight dynamics simulation of a quadrotor biplane tailsitter for various transitioning flight missions that demand high maneuverability.

16:15-16:30 FrC16.4

**Free Will Arbitrary Time Consensus-Based Cooperative Salvo Guidance Over Leader-Follower Network**, pp. 4936-4941

Pal, Rajib Shekhar Indian Institute of Technology Bombay

Kumar, Shashi Ranjan Indian Institute of Technology Bombay

Mukherjee, Dwipayan Indian Institute of Technology Bombay

In this paper, a cooperative salvo guidance strategy using free-will arbitrary time consensus over a leader-follower communication network is proposed. Guidance commands are derived considering nonlinear engagement kinematics and a system lag to account for the effect of interceptor autopilot, so as to capture realistic scenarios. The guidance schemes utilize the time-to-go estimates of all interceptors to achieve simultaneous target interception. The agreement among time-to-go of all interceptors is achieved within a fixed time, to which the interceptors' time-to-go converge within a settling time that is bounded above. This time-to-go, as well as the aforesaid bound on settling time, can be pre-specified arbitrarily independent of the initial conditions or the design parameters, which allows the interceptors to converge on a stationary target simultaneously at a predetermined impact time. Numerical simulations are presented to demonstrate the efficacy of the proposed guidance strategy.

16:30-16:45 FrC16.5

**A UDE-Based Controller with Targeted Filtering for the Stabilization of a Fixed-Wing UAV in the Harrier Maneuver**, pp. 4942-4947

Wedage, Pravin University of Toronto

Liu, Hugh Hong-Tao Univ. of Toronto

Autonomous aerobatic flight for fixed-wing aerial vehicles is studied. This paper proposes an uncertainty and disturbance estimator (UDE) based controller that attenuates the special effect of model uncertainty and external disturbances during the aerobatic harrier maneuver using a novel targeted filtering structure. Knowledge of the disturbance frequency content and the undisturbed system dynamics are used in filter design to improve disturbance rejection compared with standard UDE-based controllers with low-pass filtering structures. The controller performance is validated on a simulated model of a vehicle performing the low-speed, high angle-of-attack harrier aerobatic maneuver.

16:45-17:00 FrC16.6

**PowerLine Unmanned Surfer (PLUS): Concept and Morphing Flight Dynamics**, pp. 4948-4953

Patel, Ujjval Oklahoma State University

Faruque, Imraan University of Maryland

Henry, Todd US Army Research Laboratory

Hrynuk, John DEVCOM Army Research Lab

Phillips, Francis DEVCOM Army Research Laboratory

Significant energetic challenges remain for long range, small unmanned aerial systems (UAS), and the potential to recover powerline energy would significantly increase range. This study investigates a long range fixed wing UAS that uses morphing aerodynamics to enable near proximity powerline flight. A bilinear flight dynamics model is developed incorporating generalized aerodynamic morphing, and a frequency-correspondence established to a characteristic powerline. The resulting feedforward control architecture is tested in simulation using a camber-actuated RQ-11 airframe, showing that the control approach results in several seconds of powerline contact and a required morphing range (11-13 % camber) within aerostuctural feasibility expectations.