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U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 70672-NS.27

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13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Panos Antsaklis
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RPPR Final Report
as of 28-Apr-2020

Agency Code:

Proposal Number: 70672NS **Agreement Number: W911NF-17-1-0072**

INVESTIGATOR(S):

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DUNS Number: 824910376 EIN: 350868188
Report Date: 20-Mar-2020 Date Received: 24-Apr-2020
Final Report for Period Beginning 21-Dec-2016 and Ending 20-Dec-2019
Title: Distributed Control of Cooperative Multi-Agent Systems: Combined Top-down and Bottom-up Design
Begin Performance Period: 21-Dec-2016 **End Performance Period:** 20-Dec-2019
Report Term: 0-Other
Submitted By: Panos Antsaklis Email: antsaklis.1@nd.edu
Phone: (574) 631-5792
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 3 **STEM Participants:** 3

Major Goals: The major goal of this project was to develop a hierarchical control architecture for cooperative multi-agent systems that has the potential to unify existing design methods for multi-agent systems from both top-down and bottom-up design perspectives.
Under this unified design framework, we explored both top-down and bottom-up design methods for cooperative multi-agent systems.

a. From the top-down design perspective, we studied the key issue, namely the task decomposition issue, which refers to how to decompose a given global mission for a team of cooperative agents into individual tasks so that the accomplishment of individual tasks by each agent implies the fulfillment of the global mission by the team.

b. From the bottom-up design perspective, we investigated a passivity based design method to explore the composition of basic dynamic motion primitives.

Accomplishments: The project was successfully accomplished. The main accomplishments are summarized in the pdf document attached.

Training Opportunities: Several graduate students were involved in research activities related to this project. Graduate students were given numerous chances to both work with researchers at other universities as well as visit these places in person to interact and collaborate with them. They obtained a cross-disciplinary training and expanded their horizons.

Results Dissemination: Primary means of disseminating the results has been through conference presentations, publications, workshops and invited talks.

Honors and Awards: Co-PI Vijay Gupta was awarded the 2018 Antonio Ruberti Young Researcher Prize of the IEEE CSS in December 2018. This award is to recognize distinguished cutting-edge contributions by a young researcher to the theory or application of systems and control.

Protocol Activity Status:

Technology Transfer: Nothing to Report

RPPR Final Report
as of 28-Apr-2020

PARTICIPANTS:

Participant Type: PD/PI
Participant: Panos Antsaklis
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Co PD/PI
Participant: Vijay Gupta
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: PD/PI
Participant: Hai Lin
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Participant: Zhiyu Liu
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Etika Agarwal
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
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Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
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Other Collaborators:

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: IEEE Transactions on Control of Network Systems
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/27/19 12:00AM Date Published:
Publication Location:
Article Title: Distributed Communication-aware Motion Planning for Networked Mobile Robots under Formal Specifications
Authors: Zhiyu Liu, Bo Wu, Jin Dai, Hai Lin
Keywords: Networked mobile robots, formal methods, motion planning, spatial temporal logic, optimization, model predictive control.
Abstract: In this paper, we propose a control theoretical motion planning framework for a team of networked mobile robots in order to accomplish high-level spatial and temporal motion objectives while optimizing communication QoS. Desired motion specifications are formulated as Signal Temporal Logic (STL), whereas the communication performances to be optimized are captured by recently proposed Spatial Temporal Reach and Escape Logic (STREL) formulas. Both the STL and STREL specifications are encoded as mixed integer linear constraints posed on the system and/or environment state variables of the mobile robot network, where satisfactory control strategies can be computed by exploiting a distributed model predictive control (MPC) approach. A two-layer hierarchical MPC procedure is proposed to efficiently solve the problem, whose completeness is formally ensured. The effectiveness of the proposed framework is validated by simulation examples.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
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Publication Identifier Type: Publication Identifier:
Volume: 64 Issue: 8 First Page #: 3332
Date Submitted: 8/27/19 12:00AM Date Published: 11/5/18 5:00AM
Publication Location:
Article Title: Permissive Supervisor Synthesis for Markov Decision Processes through Learning
Authors: Bo Wu, Xiaobin Zhang, Hai Lin
Keywords: Discrete event systems; Supervisory control; Automata; Formal methods
Abstract: This paper considers the permissive supervisor synthesis for probabilistic systems modeled as Markov Decision Processes (MDP). Such systems are prevalent in power grids, transportation networks, communication networks and robotics. Unlike centralized planning and optimization based planning, we propose a novel supervisor synthesis framework based on learning and compositional model checking to generate permissive local supervisors in a distributed manner. With the recent advance in assume-guarantee reasoning verification for probabilistic systems, building the composed system can be avoided to alleviate the state space explosion and our framework learn the supervisors iteratively based on the counterexamples from verification. Our approach is guaranteed to terminate in finite steps and to be correct.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: SIAM J Control and Optimization
Publication Identifier Type: Other Publication Identifier:
Volume: 57 Issue: 2 First Page #: 1378
Date Submitted: 8/22/19 12:00AM Date Published:
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Article Title: On Passivity of Factional Order Systems
Authors: M. Rakhshan, V. Gupta, W. J. Goodwine
Keywords: Fractional Order, Passivity
Abstract: We have generalized notions of passivity and dissipativity to fractional order systems. Similar to integer order systems, we show that the proposed definitions generate analogous stability and compositionality properties for fractional order systems as well. We also studied the problem of passivating a fractional order system through a feedback controller.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
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Date Submitted: 8/30/18 12:00AM Date Published: 4/1/18 4:00AM
Publication Location:
Article Title: Conic-sector-based analysis and control synthesis for linear parameter varying systems
Authors: Sivaranjani S, J. R. Forbes, P. Seiler, V. Gupta
Keywords: Linear Parameter Varying Systems, conic sector theorem, passivity
Abstract: We present a conic sector theorem for linear parameter varying systems in which the traditional definition of conicity is violated for certain values of the parameter. We show that such systems can be defined to be conic in an average sense if the parameter trajectories are restricted so that the system operates with such values of the parameter sufficiently rarely. We then show that such an average definition of conicity is useful in analyzing the stability of the system when it is connected in feedback with a conic system with appropriate conic properties. This can be regarded as an extension of the classical conic sector theorem. Based on this modified conic sector theorem, we design conic controllers that allow the closed-loop system to operate in nonconic parameter regions for brief periods of time. Due to this extra degree of freedom, these controllers lead to less conservative performance than traditional designs.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 4-Under Review
Journal: IEEE Transactions on Automatic Control
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/22/19 12:00AM Date Published:
Publication Location:
Article Title: Analysis of Two-Dimensional Feedback Systems over Networks Using Dissipativity
Authors: Y. Yan, L. Su, V. Gupta, and P. J. Antsaklis
Keywords: Dissipativity, two-dimensional systems, networks
Abstract: This paper investigates the closed-loop L2 stability of two-dimensional (2-D) feedback systems across a digital communication network by introducing the tool of dissipativity. First, sampling of a continuous 2-D system is considered and an analytical characterization of the QSR-dissipativity of the sampled system is presented. Next, the input-feedforward output-feedback passivity (IF-OFP), a simplified form of QSR-dissipativity, is utilized to study the framework of feedback interconnection of two 2-D systems over networks. Then, the effects of signal quantization in communication links on dissipativity degradation of the 2-D feedback quantized system is analyzed. Additionally, an event-triggered mechanism is developed for 2-D networked control systems while maintaining ?2 stability of the closed-loop system. In the end, an illustrative example is provided.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 5-Submitted
Journal: IEEE Transactions on Power Systems
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Volume: Issue: First Page #:
Date Submitted: 8/30/18 12:00AM Date Published:
Publication Location:
Article Title: Mixed Voltage Angle and Frequency Droop Control for Transient Stability of Interconnected Microgrids with Loss of PMU Measurements
Authors: Sivaranjani S., E. Agarwal, L. Xie, V. Gupta, P. Antsaklis
Keywords: Transient stability, interconnected microgrids,
Abstract: We consider the problem of guaranteeing transient stability in angle droop controlled microgrid networks where voltage angle measurements from phasor measurement units (PMUs) may be lost. In the event of PMU measurement losses, the network may become unstable if there is a mismatch between load and power generation. We present a novel approach to indirectly control the voltage angle via traditional frequency droop controllers at microgrids where angle measurements are unavailable. We show that this mixed voltage angle and frequency droop control (MAFD), along with a secondary controller, can guarantee transient stability of the microgrid network under intermittent losses of PMU measurements, where traditional angle droop controllers may fail. We introduce the idea of MAFD, derive a dynamical model for microgrid networks in the MAFD setting, design a secondary controller to guarantee transient stability under angle measurement losses, and illustrate the design using simulations.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
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Volume: 1 Issue: 2 First Page #: 262
Date Submitted: 8/30/18 12:00AM Date Published: 10/1/17 4:00AM
Publication Location:
Article Title: Provably Safe Cruise Control of Vehicular Platoons
Authors: Sadra Sadraddini, S. Sivaranjani, Vijay Gupta, Calin Belta
Keywords: Cruise control, platooning
Abstract: We synthesized performance-aware safe cruise control policies for longitudinal motion of platoons of autonomous vehicles. Using set-invariance theories, we guarantee infinite- time collision avoidance in the presence of bounded additive disturbances, while ensuring that the length and the cruise speed of the platoon are bounded to specified ranges. We propose (i) a centralized control policy, and (ii) a distributed control policy, where each vehicle's control decision depends solely on its relative kinematics with respect to the platoon leader. Numerical examples were also included. This is one of the first works that considered collision avoidance in platoons through formal methods.
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Journal: IEEE Transactions on Automatic Control
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Volume: Issue: First Page #:
Date Submitted: 8/22/19 12:00AM Date Published:
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Article Title: Distributed Synthesis of Local Controllers for Networked Systems with Arbitrary Interconnection Topologies
Authors: E. Agarwal, S. Sivaranjani, V. Gupta, and P. J. Antsaklis
Keywords: Compositional control, dissipaitivity, distributed and networked systems
Abstract: We consider the problem of designing distributed controllers to guarantee dissipativity of a networked system comprised of dynamically coupled subsystems. Additionally, we require that the control synthesis is carried out locally at the subsystem-level, without explicit knowledge of the dynamics of other subsystems in the network. We solve this problem in two steps. First, we provide an approach to decompose a dissipativity condition on the networked dynamical system into equivalent conditions on the dissipativity of individual subsystems. We then use these distributed dissipativity conditions to synthesize controllers locally at the subsystem-level, using only the knowledge of the dynamics of that subsystem, and limited information about the dissipativity of the subsystems to which it is dynamically coupled. We show that the subsystem-level controllers synthesized in this manner are sufficient to guarantee dissipativity and hence stability of the networked dynamical system.
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Volume: 3 Issue: 4 First Page #: 1068
Date Submitted: 8/27/19 12:00AM Date Published: 10/1/19 8:00AM
Publication Location:
Article Title: Active Perception and Control From Temporal Logic Specifications
Authors: Rafael Rodrigues da Silva, Vince Kurtz, Hai Lin
Keywords: Formal methods, autonomous robots, task planning
Abstract: Next-generation autonomous systems must execute complex tasks in uncertain environments. Active perception, where an autonomous agent selects actions to increase knowledge about the environment, has gained traction in recent years for motion planning under uncertainty. One prominent approach is planning in the belief space. However, most belief-space planning starts with a known reward function, which can be difficult to specify for complex tasks. On the other hand, symbolic control methods automatically synthesize controllers to achieve logical specifications, but often do not deal well with uncertainty. In this letter, we propose a framework for scalable task and motion planning in uncertain environments that combines the best of belief-space planning and symbolic control. Specifically, we provide a counterexample-guided-inductive-synthesis algorithm for probabilistic temporal logic over reals (PRTL) specifications in the belief space.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
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Publication Identifier Type: DOI Publication Identifier: 10.1080/00207179.2019.1632492
Volume: Issue: First Page #: 1
Date Submitted: Date Published: 7/1/19 4:00AM
Publication Location:
Article Title: Passivity and passivity indices of nonlinear systems under operational limitations using approximations
Authors: Hasan Zakeri, Panos J. Antsaklis
Keywords: Passivity indices, Approximations
Abstract: In this paper, we will discuss how operational limitations affect input–output behaviours of the system. In particular, we will provide a formulation for passivity and passivity indices of a nonlinear system given operational limitations on the input and state variables. This formulation is presented in the form of local passivity and indices. We will provide optimisation based formulation to derive passivity properties of the system through polynomial approximations. Two different approaches are taken to approximate the nonlinear dynamics of a system through polynomial functions; namely, Taylor's theorem and a multivariate generalisation of Bernstein polynomials. For each approach, conditions for stability, dissipativity, and passivity of a system, as well as methods to find its passivity indices, are given. Two different methods are also presented to reduce the size of the optimisation problem in Taylor's theorem approach. Examples are provided to show the applicability of the result
Distribution Statement: 1-Approved for public release; distribution is unlimited.
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CONFERENCE PAPERS:

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Conference Name: IEEE 56th IEEE Conference on Decision and Control
Date Received: 30-Aug-2018 Conference Date: 12-Dec-2017 Date Published: 15-Dec-2017
Conference Location: Melbourne, Australia
Paper Title: Distributed Communication-aware Motion Planning for Multi-agent Systems from STL and SpaTeL Specifications
Authors: Zhiyu Liu, Bo Wu, Jin Dai, Hai Lin
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Conference Name: 25th Mediterranean Conference on Control and Automation (MED’17)
Date Received: 28-Aug-2017 Conference Date: 03-Jul-2017 Date Published: 05-Jul-2017
Conference Location: Malta
Paper Title: Dissipativity of Finite and Hybrid Automata: An Overview
Authors: Etika Agarwal, Michael McCourt, Panos J. Antsaklis,
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Conference Name: American Control Conference
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Conference Location: Milwaukee, WI, USA
Paper Title: A Mean Field Game Approach to Swarming Robots Control
Authors: Liu, Zhiyu and Wu, Bo and Lin, Hai
Acknowledged Federal Support: **Y**

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Conference Name: American Control Conference
Date Received: 30-Aug-2018 Conference Date: 27-Jun-2018 Date Published: 29-Jun-2018
Conference Location: Milwaukee, WI, USA
Paper Title: Reactive Integrated Mission and Motion Planning for Mobile Robotic Manipulators
Authors: Partovi, Alireza and Rafael Rodrigues and Lin, Hai
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Conference Name: 2017 American Control Conference (ACC)
Date Received: 30-Aug-2018 Conference Date: 24-May-2017 Date Published:
Conference Location: Seattle, WA, USA
Paper Title: Distributed control policies for localization of large disturbances in urban traffic networks
Authors: Sivaranjani S., S. Sadraddini, V. Gupta, C. Belta
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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: American Control Conference 2019.
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Conference Location: Philadelphia, PA
Paper Title: Sequential Synthesis of Distributed Controllers for Cascade Interconnected Systems
Authors: E. Agarwal, S. Sivaranjani, V. Gupta, and P. J. Antsaklis
Acknowledged Federal Support: **Y**

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Paper Title: Recent Advances in Analysis and Design of Cyber-physical Systems using Passivity Indices
Authors: Hasan,Zakeri Panos,Antsaklis
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Conference Location: Akko, Israel
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Authors: Hasan,Zakeri Panos,Antsaklis
Acknowledged Federal Support: **Y**

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Title: Formal Methods for Control of Markov Decision Processes
Authors: Bo Wu
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Institution: University of Notre Dame
Date Received: 30-Aug-2018 Completion Date: 5/1/18 3:06PM
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Authors: Arash, Rahnama
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Institution: University of Notre Dame
Date Received: 26-Aug-2019 Completion Date: 5/1/19 2:40PM
Title: Compositional Control of Large Scale Cyber-Physical Systems Using Hybrid Models and Dissipativity Theory
Authors: Etika, Agarwal
Acknowledged Federal Support: **N**

Publication Type: Thesis or Dissertation
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Title: Dissipativity Analysis and Resilient Design for Cyber-Physical Systems
Authors: Yang, Yan
Acknowledged Federal Support: **N**

W911NF1710072

Contract Number: **Title:** Distributed Control of Cooperative Multi-Agent Systems: Combined Top-down and Bottom-up Design

PIs Panos Antsaklis, Hai Lin, Vijay Gupta

Major Goals:

The major goal of this project was to develop a hierarchical control architecture for cooperative multi-agent systems that has the potential to unify existing design methods for multi-agent systems from both top-down and bottom-up design perspectives.

Under this unified design framework, we explored both top-down and bottom-up design methods for cooperative multi-agent systems.

a. From the top-down design perspective, we studied the key issue, namely the task decomposition issue, which refers to how to decompose a given global mission for a team of cooperative agents into individual tasks so that the accomplishment of individual tasks by each agent implies the fulfillment of the global mission by the team.

b. From the bottom-up design perspective, we investigated a passivity based design method to explore the composition of basic dynamic motion primitives.

Accomplishments Under Goals:

The project was successfully accomplished. The main accomplishments include the following.

Top-down design:

1. We studied automatic task planning for autonomous robots with respect to formal specifications, and proposed a new smooth robustness measure of Signal Temporal Logic (STL) for symbolic control. Recent years have seen the increasing use of Signal Temporal Logic (STL) as a formal specification language for symbolic control, due to its expressiveness and closeness to natural language. Furthermore, STL specifications can be encoded as cost functions using STL's robust semantics, transforming the synthesis problem into an optimization problem. Unfortunately, these cost functions are non-smooth and non-convex, and exact solutions using mixed-integer programming do not scale well. Recent work has focused on using smooth approximations of robustness, which enable faster gradient-based methods to find local maxima, at the expense of soundness and/or completeness. We therefore propose a novel robustness approximation that is smooth everywhere, sound, and asymptotically complete. Our approach combines the benefits of existing approximations, while enabling an explicit tradeoff between conservativeness and completeness.

2. We investigated the communication-aware motion planning problem for multi-agent systems, and proposed a mathematical framework for synthesizing motion plans for multi-agent systems that fulfill complex, high-level and formal local specifications in the presence of inter-agent communication. Control and communication are often tightly coupled for networked mobile robots; motions of robots impact communication quality, and communication quality of service (QoS) in turn affects coordination performance of robots. In this paper, we propose a theoretical motion planning control framework for a team of networked mobile robots to accomplish high-level spatial and temporal motion specifications while optimizing communication QoS. Desired motion specifications are formulated as Signal Temporal Logic (STL), whereas the communication QoS to be optimized is captured by Spatial Temporal Reach and Escape Logic (STREL) formulas. Both the STL and STREL specifications are encoded as mixed integer linear constraints posed on the system and environment state variables of the mobile robot network, where satisfactory control strategies can be computed by exploiting a distributed model predictive control (MPC) approach. A two-layer hierarchical MPC procedure is proposed to efficiently solve the co-optimization problem, whose recursive feasibility is formally ensured. The effectiveness of the proposed framework is validated by simulation.

3.We studied the permissive supervisor synthesis for probabilistic systems modeled as Markov Decision Processes (MDP). Such systems are prevalent in power grids, transportation networks, communication networks and robotics. Unlike centralized planning and optimization based planning, we propose a novel supervisor synthesis framework based on learning and compositional model checking to generate permissive local supervisors in a distributed manner. With the recent advance in assume-guarantee reasoning verification for probabilistic systems, building the composed system can be avoided to alleviate the state space explosion and our framework learn the supervisors iteratively based on the counterexamples from verification. Our approach is guaranteed to terminate in finite steps and to be correct.

4. We further extended our work to a more realistic cases with only partial observablility. Partially observable Markov decision process (POMDP) is a comprehensive modeling framework that captures uncertainties from different sources such as sensing noises, actuation errors, and uncertain environments. It has been widely used in decision-making with uncertainties and reinforcement learning. Traditional POMDP planning usually focuses on finding an optimal policy to maximize the expectation of accumulated rewards. However, for safety-critical applications, we need to provide guarantees of system performance described by high-level temporal logic specifications. Hence, we are motivated to develop formal methods for the synthesis of supervisors for POMDP with respect to given high-level formal specifications. We proposed a learning-based supervisory control framework, where a controller in the form of deterministic finite automaton is learned iteratively. A human-robot collaboration case study validates the proposed supervisor synthesis algorithm.

5. We investigated the design of swarming robotic systems using mean field game theory. Controlling the collective behavior through individuals of swarming robots to accomplish the tasks which are beyond the capability of an individual robot is an important yet challenging problem for both research and industry communities, since the relationship

between individual behavior and collective behavior for swarming robots still remain unclear. To bridge this gap, mean field game is applied using two coupled PDEs where the backward equation is used to understand the behavior of individual robots while the forward equation governs the evolution of the robots' distribution. The proposed approach aims to provide an optimal control strategy for each individual such that the desired swarm distribution generated by random forest regression can be tracked. The discrete mean field game is solved numerically to find the optimal control where the running cost is learned instead of directly given.

6. We also studied the complex pattern generation problem for swarm robotic systems using spatial-temporal logic and density feedback control. The last decade has seen increasing research activities in swarming robotics, where major efforts followed a bottom-up philosophy with predefined local coordination and control laws, e.g., the nearest neighbor control law. However, the key challenge is how to design these local coordination and control laws to guarantee a desired global specification. This motivates us to pursue a top-down approach, and propose a provable design framework for the complex pattern generation problem of a swarm of robots. Specifically, we use a spatial-temporal logic to specify the global configuration, which is capable of describing a wide range of time-varying and complex spatial patterns. Synthesis is performed by first generating a sequence of probability density functions (pdf) that fulfill the spatial-temporal requirements, and then using a partial differential equation (PDE)-based density feedback control strategy to track the reference pdf sequence. The density feedback control law is proved to be exponentially stable and thus can efficiently track the desired pdf sequence. The effectiveness of the proposed control framework is verified using agent-based simulations.

Bottom-up design:

1. We solved the problem of compositional control using a top-down approach. Specifically, we considered the problem of designing distributed controllers to ensure passivity of a large-scale interconnection of linear subsystems connected in a cascade and an arbitrary topology. The control design process needs to be carried out at the subsystem-level with no direct knowledge of the dynamics of other subsystems in the interconnection. We solved this problem in two steps. First, we provided an approach to decompose a dissipativity condition on the networked dynamical system into equivalent conditions on the dissipativity of individual subsystems. We then used these distributed dissipativity conditions to synthesize controllers locally at the subsystem-level, using only the knowledge of the dynamics of that subsystem, and limited information about the dissipativity of the subsystems to which it is dynamically coupled. We showed that the subsystem-level controllers synthesized in this manner are sufficient to guarantee dissipativity of the networked dynamical system. We also provided an approach to make this synthesis compositional, that is, when a new subsystem is added to an existing network, only the dynamics of the new subsystem, and information about the dissipativity of the subsystems in the existing network to which it is coupled are used to design a controller for the new subsystem, while guaranteeing dissipativity of the networked system including the new subsystem. Finally, we demonstrated the application of this synthesis in enabling plug-and-play operations of generators in a microgrid by extending

our results to networked switched systems.

2. Passivity is an important compositional concept that has shown promise for large scale systems. However, the concept has traditionally been limited in its applicability to deterministic systems that are described by differential or difference equations. We have worked on extending its applicability to more general systems. Following the recent interest in fractional order systems that seem to better describe systems with long range connections, we have generalized notions of passivity and dissipativity to fractional order systems. Similar to integer order systems, we show that the proposed definitions generate analogous stability and compositionality properties for fractional order systems as well. We also studied the problem of passivating a fractional order system through a feedback controller.

3. We have also shown how passivity can be used for design for practical systems that may not be passive throughout their region of operation. Specifically, we have developed a conic sector theorem for linear parameter varying (LPV) systems in which the traditional definition of conicity is violated for certain values of the parameter. We show that such LPV systems can be defined to be conic in an average sense if the parameter trajectories are restricted so that the system operates with such values of the parameter sufficiently rarely. We then show that such an average definition of conicity is useful in analyzing the stability of the system when it is connected in feedback with a conic system with appropriate conic properties. This can be regarded as an extension of the classical conic sector theorem. Based on this modified conic sector theorem, we design conic controllers that allow the closed-loop system to operate in nonconic parameter regions for brief periods of time. Due to this extra degree of freedom, these controllers may lead to less conservative performance than traditional designs, in which the controller parameters are chosen based on the largest cone that the plant dynamics are contained in. We showed the utility of these results in large scale systems such as the power grid.

4. We studied extensions of passivity and dissipativity to finite automata and we showed that dissipativity is a necessary and sufficient condition for invariance of given subset of states and limit cycle behavior of state trajectories; these properties for discrete event systems correspond to stability properties in continuous physical systems. We extended these notions from finite automata to hybrid automata that describe hybrid systems. These advances allow us to study CPS and infer properties of large scale systems by analyzing dissipativity characteristics of smaller systems modeled as hybrid automata.

5. We studied local dissipativity, passivity and passivity indices of nonlinear systems based on polynomial approximations using an optimization-based approach. Since most behaviors of nonlinear systems vary depending on the neighborhood of interest, the focus here is on local properties of systems. Two different approaches were taken to approximate the nonlinear dynamics of a system through polynomial functions; namely, Taylor's theorem and a multivariate generalization of Bernstein polynomials. For each approach, conditions for stability, dissipativity, and passivity of a system, as well as methods to find its passivity indices, were derived. Two different methods were also introduced to reduce the size of the optimization problem in the Taylor's theorem approach.

6. Model predictive control is a powerful method for control that can be utilized even in the presence of non-linear dynamics and constraints. Essentially, it relies on solving for a control trajectory repeatedly in a receding horizon fashion, while implementing the first control input from the trajectory. A hidden assumption in the method is that the solution of the optimization problem to generate the control trajectory is fast, such that the plant does not run open loop for a long time. This assumption limits the applicability of this method in practical scenarios of interest to the department of defense where safety constraints and dynamics may be highly non- trivial. Further, most existing methods of distributed model predictive control rely on communication of the trajectories by each plant to its neighbor at every time step, which is communication inefficient. To remove such limiting assumptions, we developed a new method for distributed fast model predictive control for linear systems. Specifically, we employed distributed fast model predictive control with a realization of a primal-dual algorithm embedded in the controller dynamics. In this method, only one iteration of the numerical algorithm solving the optimization problem for calculating the control input trajectory is performed at every time step. This speeds up the calculations considerably. Further, the communication requirements are reduced since only the control input corresponding to the current time step needs to be exchanged. Although constraint satisfaction is only guaranteed asymptotically, we developed an explicit reference governor based approach in the interconnected system to guarantee the extent of constraint violations during the transient. Under mild assumptions, we showed that the input and state trajectories of the closed-loop system asymptotically converge to the desired reference using passivity based analysis. The analysis shows that there is a trade-off between the magnitude of constraint violation and the speed of convergence to the desired reference, which can be optimized in a design process.

7. We investigated the closed-loop L2 stability of two-dimensional (2-D) feedback systems across a digital communication network by introducing the tool of dissipativity. First, sampling of a continuous 2-D system is considered and an analytical characterization of the QSR-dissipativity of the sampled system was presented. Next, the input-feedforward output- feedback passivity (IF-OFP), a simplified form of QSR-dissipativity, was utilized to study the framework of feedback interconnection of two 2-D systems over networks. Then, the effects of signal quantization in communication links on dissipativity degradation of the 2-D feedback quantized system were analyzed. Additionally, an event-triggered mechanism was developed for 2-D networked control systems while maintaining L2 stability of the closed-loop system. In the end, an illustrative example was provided.

8. We addressed the problem of designing an optimal output feedback controller with a specified controller structure for linear time-invariant (LTI) systems to maximize the passivity level for the closed-loop system, in both continuous-time (CT) and discrete-time (DT). Specifically, the set of controllers under consideration is linearly parameterized with constrained parameters. Both input feedforward passivity (IFP) and output feedback passivity (OFP) indices were used to capture the level of passivity. Given a set of stabilizing controllers, a necessary and sufficient condition was proposed for the existence of such fixed-structured output feedback controllers that can passivate the closed-loop system. Moreover, it was shown that the condition can be used to obtain

the controller that maximizes the IFP or the OFP index by solving a convex optimization problem.

9. We considered a group of nodes aiming to solve a resource allocation problem cooperatively and in a distributed way. Specifically, each node has access to its own local cost function and local network resource, and the goal is to minimize the sum of the local cost functions subject to a global network resource constraint. The communication among the nodes occurs at discrete-time steps and the communication topology is described by a strongly connected and weight-balanced digraph that may be time-varying. We proposed a continuous- time algorithm that solves this problem. Particularly, a novel passivity-based perspective of the proposed algorithmic dynamic at each individual node was provided, which enables us to analyze the convergence of the overall distributed algorithm over time-varying digraphs. To exempt from the difficult-to-satisfy assumption of continuous-time communication among nodes, we also developed an asynchronous distributed event-triggered scheme building on the passivity-based notion. Additionally, a synchronous periodic communication strategy was also derived through analyzing the passivity degradation over sampling of the distributed dynamic at each node.

10. We developed a model predictive control (MPC) approach for continuous systems using approximate models. Plant model discrepancies are considered and it is shown that under certain dissipativity conditions the supply rate of the approximate representation always upper bounds the supply rate of the real system. Stabilization of dissipative systems and feedback passivation were then investigated. Based on these results, a stability constraint for MPC was introduced based on feedback control of dissipative systems. In particular, a LMI was proposed, under which the interconnected system achieves desired dissipativity properties. Furthermore, it was shown that the stabilizing MPC approach guarantees the stability of the real dynamic system using only an approximate model. Finally, intermittent behavior is considered as a special case of approximation and a robust event-triggered MPC was developed as an example.

11. We presented a new data-driven fault identification and controller reconfiguration algorithm. The presented algorithm relies only on the system’s input and output data, and it does not require a detailed system description. The proposed algorithm detects changes in the input- output behavior of the system, whether due to faults or malicious attacks and then reacts by reconfiguring the existing controller. This method does not identify the internal structure of the system nor the extent and nature of the attack; hence it can quickly react to faults and attacks. The proposed method can be readily applied to various applications without significant modifications or tuning, as demonstrated by the examples in the paper.

Case studies:

We also worked on two case studies to design distributed and local controllers for stability and performance in two example large scale systems. These systems provide test cases for studying the integration of top-down and bottom-up decision making since goals such as stability and performance are system-wide and mandate a top-down approach, while many of the decisions are made by individual participants (human operators and drivers) for their own goals in a bottom-up fashion. A further complication is the need of distributed controllers given the large scale of the system.

1. Interconnected microgrids: Our first example system was a system formed by interconnected microgrids. This system features fast dynamics, high uncertainty due to renewable penetration, and a natural need for distributed control. Our work was along three directions

a. We considered the problem of guaranteeing transient stability in angle droop controlled microgrid networks where voltage angle measurements from phasor measurement units (PMUs) may be lost. In the event of PMU measurement loss at some microgrids, the network may become unstable if there is a mismatch between load and power generation. To address this issue, we presented a novel approach to indirectly control the voltage angle via traditional frequency droop controllers at microgrids where angle measurements are unavailable. We showed that this mixed voltage angle and frequency droop control (MAFD), along with a secondary controller, can be used to guarantee transient stability of the microgrid network under intermittent losses of PMU measurements, where traditional angle droop controllers may fail. We introduced the idea of MAFD, derived a dynamical model for microgrid networks in the MAFD setting, designed a secondary controller to guarantee transient stability under angle measurement losses, and illustrated the design using numerical simulations.

(b) We extended this solution and proposed a novel distributed mixed voltage angle and frequency droop control (D-MAFD) framework to enhance the reliability of angle droop controlled microgrid interconnections, where conventional frequency droop controllers are employed in place of angle droop controllers to maintain stability when micro-PMU phase angle measurements are lost. Recent advances in micro phasor measurement unit (micro-PMU) technology have enabled the use of voltage phase angle measurements for direct load sharing control in distribution-level microgrids with power electronic converter interfaced renewable distributed energy resources (DERs). In particular, micro-PMU enabled voltage angle droop controllers have the potential to enhance stability and transient performance in such interconnected microgrids. However, these angle droop controllers are particularly vulnerable to loss of angle measurements that may frequently result from the unavailability of a GPS signal for synchronization or sensor failure. We modeled this D-MAFD framework as a nonlinear switched system and designed distributed dissipativity-based controllers that use only local micro-PMU phase angle or frequency measurements at every microgrid to guarantee transient stability of the system of interconnected microgrids.

(c) We considered the problem of stabilizing a power grid with high penetration of renewable energy. To this end, we presented a conic sector theorem for linear parameter varying (LPV) systems in which the traditional definition of conicity is violated for certain values of the parameter. We showed that such LPV systems can be defined to be conic in an average sense if the parameter trajectories are restricted so that the system operates with such values of the parameter sufficiently rarely. We then showed that such an average definition of conicity is useful in analyzing the stability of the system when it is connected in feedback with a conic system with appropriate conic properties. This can be regarded as an extension of the classical conic sector theorem. Based on this modified conic sector theorem, we designed conic controllers that allow the closed-loop system to operate in nonconic parameter regions for brief periods of time. Due to this extra degree of freedom, these controllers lead to less conservative performance than traditional designs, in which the controller parameters are chosen based on the largest cone that the plant dynamics are contained in. We demonstrated the effectiveness of the proposed design in stabilizing a power grid with very high penetration of renewable energy while minimizing power transmission losses.

2. Transportation networks: Our second example system was an urban transportation system. This system features complicated non-linear dynamics, high uncertainty due to non-availability of the decisions being made by individual drivers and sensor presence only at intersections, and a natural need for distributed control. Our work in transportation networks has focused on many directions as listed below.

(a). We designed a distributed control strategy to localize and attenuate traffic jams caused by large disturbances in urban arterial transportation networks. The control policy is distributed in the sense that it uses those traffic lights that are in the vicinity of the jammed area. We model urban traffic using a discrete fluid-like model which is then reduced to a hybrid dynamical system with binary control inputs. For this system, we define notions of local control and localizability of disturbances. We then present a control strategy that uses only local controllers to attenuate traffic jams. This control design is formulated as a mixed-integer linear program (MILP) whose solution provides traffic light schedules. We show that the feasibility of this MILP is both necessary and sufficient for localizability. We then illustrate this design on a test urban transportation network. This work is a new approach to disturbance localization in urban traffic networks that can consider large disturbances that may drive the system from a free flow mode to a congested mode. Of note, no analytical approaches that could consider such large disturbances and mode switches with guaranteed performance were available in the literature before our work.

(b). We considered traffic flow on a network whose dynamics are described by the Cell Transmission Model with the driver behavior at diverging intersections being modeled by a first-in-first-out rule. We prove that the system admits multiple congested equilibria when inflows are constant. Drawing upon entropy-like Lyapunov functions from chemical reaction network theory, we then show that these equilibria are locally asymptotically stable. With further restrictions on system inflows, we show that these equilibria degenerate to a unique free flow equilibrium. When system inflows are time-varying, we show that the system is persistent, that is, any trajectory starting out in the vicinity of an equilibrium corresponding to a nominal inflow will always remain in its vicinity for small variations around the nominal inflow. This work significantly generalizes the few results that are available about properties of the dynamics of the traffic network. Of note, we can consider arbitrary traffic networks with merge and diverge intersections, traffic dynamics that may not be monotone, equilibria in congested regimes, and time-varying inputs to the network.

(c) We synthesized performance-aware safe cruise control policies for longitudinal motion of platoons of autonomous vehicles. Using set-invariance theories, we guarantee infinite- time collision avoidance in the presence of bounded additive disturbances, while ensuring that the length and the cruise speed of the platoon are bounded to specified ranges. We propose (i) a centralized control policy, and (ii) a distributed control policy, where each vehicle's control decision depends solely on its relative kinematics with respect to the platoon leader. Numerical examples were also included. This is one of the first works that considered collision avoidance in platoons through formal methods.

Training Opportunities:

Several graduate students were involved in research activities related to this project. Graduate students were given numerous chances to both work with researchers at other universities as well as visit these places in person to interact and collaborate with them. They obtained a cross-disciplinary training and expanded their horizons.

Results Dissemination

Primary means of disseminating the results has been through conference presentations, publications, workshops and invited talks.

Participants

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Honors and Awards

Co-PI Vijay Gupta was awarded the 2018 Antonio Ruberti Young Researcher Prize of the IEEE CSS in December 2018. This award is to recognize distinguished cutting-edge contributions by a young researcher to the theory or application of systems and control.

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