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RPPR Final Report
as of 14-Oct-2021

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Proposal Number: 69075NSYIP **Agreement Number: W911NF-17-1-0058**

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Report Date: 12-Oct-2021 Date Received: 14-Oct-2021
Final Report for Period Beginning 19-Jan-2017 and Ending 12-Jul-2021
Title: Quantifying network controllability and observability using optimal control and estimation metrics
Begin Performance Period: 19-Jan-2017 **End Performance Period:** 12-Jul-2021
Report Term: 0-Other
Submitted By: Ph.D Tyler Summers Email: tyler.summers@utdallas.edu
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STEM Degrees: 1 **STEM Participants:** 4

Major Goals: The goal of this project is to develop methods to quantify network controllability and observability using optimal control and estimation metrics. Specifically, the three major goals of the project are:

(1) quantify and visualize network controllability and observability using metrics based on fundamental optimal feedback control and state estimation problems;
(2) develop algorithms for design of optimal sensor and actuator topologies and feedback information structures based on these metrics;
(3) illustrate the theoretical and methodological results with comprehensive case studies in various application domains, including intelligence, surveillance, and reconnaissance scenarios involving autonomous mobile robot teams; neuronal brain networks; and electric power grids and microgrids.

Accomplishments: Please see attached pdf in the upload section.

Training Opportunities: Four PhD students, Karthik Ganapathy, Venkatraman Renganathan, Benjamin Gravell, and Sleiman Safaoui, have been trained in several areas that are key to the ARO mission, namely control, optimization, and learning in complex networks. PI Summers has worked closely with them to achieve and go beyond the project goals. In addition, we have developed an experimental heterogeneous multi-robot research testbed that has been used to illustrate and validate some of project results in the context of intelligence, reconnaissance, and surveillance missions for autonomous robot teams, and will continue to serve as research infrastructure for future research in our lab.

Results Dissemination: Accepted conference papers:

1. T. Summers and J. Ruths, “Performance bounds for optimal control in networks”, American Control Conference, Milwaukee, WI, June 2018.

2. T. Summers, “Distributionally robust sampling-based motion planning under uncertainty,” IEEE/RSJ International Conference on Intelligent Robots & Systems, Madrid, Spain, October 2018.

3. K. Fathian, S. Safaoui, T. Summers, N. Gans, “Robust 3D Distributed Formation Control with Collision Avoidance and Application to Multirotor Aerial Vehicles”, IEEE International Conference on Robotics and Automation, Montreal, Canada, May 2019

4. K. Fathian, D. Rachinskii, M. Spong, T. Summers, N. Gans, “Distributed Formation Control via Mixed Barycentric Coordinate and Distance-Based Approach”, American Control Conference, Philadelphia, PA, June 2019.

5. T. Summers, M. Kamgarpour, “Performance guarantees for greedy maximization of non-submodular set functions in systems and control”, European Control Conference, Naples, Italy, June 2019.

6. B. Gravell, Y. Guo, T. Summers, "Sparse optimal control of networks with multiplicative noise via policy gradient", IFAC Workshop on Distributed Estimation and Control in Networked Systems, Chicago, IL, September 2019.

7. B. Guo, O. Karaca, T. Summers, M. Kamgarpour, "Actuator placement for optimizing network performance under controllability constraints", IEEE Conference on Decision and Control, Nice, France, December 2019.

8. W. Jongeneel, T. Summers, P. Mohajerin Esfahani, "Robust Linear Quadratic Regulator: Exact Tractable Reformulation", IEEE Conference on Decision and Control, Nice, France, December 2019.

9. V. Renganathan, N. Hashemi, J. Ruths, T. Summers, “Distributionally robust tuning of anomaly detectors in cyber-physical systems with stealthy attacks”, American Control Conference, July 2020.

10. K. Ganapathy, T. Summers, "Performance bounds for robust estimation using the H infinity filter", European Control Conference 2021.

11. S. Safaoui, B. Gravell, V. Renganathan, T. Summers, "Risk-Averse RRT* Planning with Nonlinear Steering and Tracking Controllers for Nonlinear Robotic Systems Under Uncertainty", IEEE/RSJ International Conference on Intelligent Robotics and Systems, 2021.

12. R. Quinonez, S. Safaoui, T. Summers, B. Thuraisingham and A.A. Cardenas, "Shared Reality: Detecting Stealthy Attacks Against Autonomous Vehicles", Joint Workshop on CPS and IoT Security and Privacy, in conjunction with the ACM Conference on Computer and Communications Security, 2021.

Accepted journal papers:

13. K. Fathian, T. Summers, N. Gans, “Robust Distributed Formation Control of Agents with Higher-Order Dynamics”, IEEE Control Systems Letters, Vol. 2, No. 3, July 2018.

14. A. Taha, N. Gatsis, T. Summers, S. Nugroho, “Time-varying sensor and actuator selection for uncertain cyber-physical systems”, IEEE Transactions on Control of Network Systems, Vol. 6, No. 2, June 2019.

15. K. Fathian, S. Safaoui, T. Summers, N. Gans, “Robust Distributed Planar Formation Control for Higher- Order Holonomic and Nonholonomic Agents”, IEEE Transactions on Robotics, accepted June 2020.

16. A. Vinod, A Thorpe, P. Olaniyi, T. Summers, M. Oishi, "Sensor selection for dynamics-driven user-interface design", IEEE Transactions on Control Systems Technology, accepted 2021.

17. K. Ganapathy, J. Ruths, T. Summers, "Performance bounds for optimal feedback control and robustness in networks", IEEE Transactions on Control of Network Systems, accepted 2021.

18. B. Guo, O. Karaca, T. Summers, M. Kamgarpour, "Actuator Placement under Structural Controllability.using Forward and Reverse Greedy Algorithms", IEEE Transactions on Automatic Control, accepted December 2021.

19. B. Gravell, T. Summers, "Centralized Collision-Free Polynomial Trajectories and Goal Assignment for Aerial Swarms", Control Engineering Practice, accepted 2021.

20. B. Gravell, P. Mohajerin Esfahani, T. Summers, "Learning Optimal Controllers for Linear Quadratic Systems with Multiplicative Noise via Policy Gradient", IEEE Transaction on Automatic Control, accepted 2020.

Submitted journal papers:

21. V. Renganathan, I. Shames, T. Summers, “Toward integrated perception and motion planning with distributionally robust risk constraints”, submitted, Artificial Intelligence Journal, special issue on risk-aware autonomous systems.

22. V. Renganathan, N. Hashemi, J. Ruths, T. Summers, “Distributionally robust tuning of anomaly detectors in cyber-physical systems with stealthy attacks”, submitted, IEEE Letters of the Control System Society and American Control Conference 2022.

Honors and Awards: The journal manuscript

B. Gravell, T. Summers, "Centralized Collision-Free Polynomial Trajectories and Goal Assignment for Aerial Swarms", Control Engineering Practice, Vol. 109, April 2021.

was accepted as part of an invited series in Control Engineering Practice for emerging leaders in control engineering.

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Tyler Summers
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
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Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Benjamin Gravell
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)

Participant: Sleiman Safaoui
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Karthik Ganapathy
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

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Journal: IEEE Transactions on Control of Network Systems
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Volume: Issue: First Page #:
Date Submitted: 10/15/18 12:00AM Date Published:
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Article Title: Time-Varying Sensor and Actuator Selection for Uncertain Cyber-Physical Systems
Authors: Ahmad Taha, Nikolaos Gatsis, Tyler Summers, Sebastian Nugroho
Keywords: Sensor and actuator selection, cyber-physical systems, linear matrix inequalities, controller design, observer design, greedy algorithms
Abstract: We propose methods to solve time-varying, sensor and actuator (SaA) selection problems for uncertain cyber- physical systems. We show that many SaA selection problems for optimizing a variety of control and estimation metrics can be posed as semidefinite optimization problems with mixed-integer bilinear matrix inequalities (MIBMIs). Although this class of op- timization problems are computationally challenging, we present tractable approaches that directly tackle MIBMIs, providing both upper and lower bounds, and that lead to effective heuristics for SaA selection. The upper and lower bounds are obtained via successive convex approximations and semidefinite programming relaxations, respectively, and selections are obtained with a slicing algorithm from the solutions of the bounding problems. Custom branch-and-bound and combinatorial greedy approaches are also developed for a broad class of systems for comparison. Comprehensive numerical simulations are performed to compare the methods.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
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Volume: 2 Issue: 3 First Page #:
Date Submitted: 10/15/18 12:00AM Date Published: 7/1/18 10:00AM
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Article Title: Robust Distributed Formation Control of Agents with Higher-Order Dynamics
Authors: Kaveh Fathian, Tyler Summers, Nicholas Gans
Keywords: Multi-agent systems, formation control, distributed control, agent-based systems
Abstract: We present a distributed control strategy for agents with a variety of holonomic dynamics to autonomously achieve a desired formation. The proposed control is fully distributed, and can be implemented locally on agents using the relative position measurements. Furthermore, agents do not need to communicate or have a common sense of orientation. Our strategy allows control gains designed for agents with single-integrator dynamics to be used directly for agents with higher-order linear (or linearizable) holonomic dynamics. We provide rigorous mathematical analysis to prove convergence of the agents to the desired formation. The proposed method is applied to quadrotors with linearized dynamics, and simulations are provided to typify the theoretical results.
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Journal: IEEE Transactions on Robotics
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Article Title: Robust Distributed Planar Formation Control for Higher-Order Holonomic and Nonholonomic Agents
Authors: Kaveh Fathian, Sleiman Safaoui, Tyler Summers, Nicholas Gans
Keywords: Multi-agent systems, formation control, distri- buted collision avoidance, distributed robotic platform
Abstract: We present a distributed formation control strategy for agents with a variety of dynamics to achieve a desired planar formation. The proposed strategy is fully distributed, does not require inter-agent communication or a common sense of orientation, and can be implemented using relative position measurements acquired by agents in their local coordinate frames. We show how the control designed for agents with the simplest dynamical model, i.e., the single-integrator dynamics, can be extended to holonomic agents with higher-order dynamics such as quadrotors, and nonholonomic agents such as unicycles and cars. We prove that the proposed strategy is robust to saturations in the input, unmodeled dynamics, and switches in the sensing topology. We further show that the control is relaxed in the sense that agents can move along a rotated and scaled control direction without affecting the convergence to the desired formation. This observation is used to design a distributed collision avoidanc
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Acknowledged Federal Support: **Y**

CONFERENCE PAPERS:

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Conference Name: American Control Conference
Date Received: 15-Oct-2018 Conference Date: 27-Jun-2018 Date Published:
Conference Location: Milwaukee, WI, USA
Paper Title: Performance bounds for optimal feedback control in networks
Authors: Tyler Summers, Justin Ruths
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: IEEE/RSJ International Conference on Intelligent Robots & Systems
Date Received: 15-Oct-2018 Conference Date: 04-Oct-2018 Date Published:
Conference Location: Madrid, Spain
Paper Title: Distributionally robust sampling-based motion planning under uncertainty
Authors: Tyler Summers
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Date Received: 15-Oct-2018 Conference Date: 20-May-2019 Date Published:
Conference Location: Montreal, Canada
Paper Title: Robust 3D Distributed Formation Control with Collision Avoidance and Application to Multirotor Aerial Vehicles
Authors: Kaveh Fathian, Sleiman Safaoui, Tyler Summers, Nicholas Gans
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: American Control Conference
Date Received: Conference Date: 10-Jul-2019 Date Published:
Conference Location: Philadelphia, PA
Paper Title: Distributed Formation Control via Mixed Barycentric Coordinate and Distance-Based Approach
Authors: Kaveh Fathian, Dmitrii Rachinskii, Mark Spong, Tyler Summers, Nicholas Gans
Acknowledged Federal Support: **Y**

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Conference Location: Miami, FL
Paper Title: Performance guarantees for greedy maximization of non-submodular set functions in systems and control
Authors: Tyler Summers, Maryam Kamgarpour
Acknowledged Federal Support: **Y**

Partners

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RPPR Final Report
as of 14-Oct-2021

I certify that the information in the report is complete and accurate:
Signature: Tyler Summers
Signature Date: 10/14/21 7:36AM

1 Scientific progress and accomplishments

1.1 Introduction

The goal of this project is to develop methods to quantify network controllability and observability using optimal control and estimation metrics. Specifically, the three major goals of the project are

1. quantify and visualize network controllability and observability using metrics based on fundamental optimal feedback control and state estimation problems;

2. develop algorithms for design of optimal sensor and actuator topologies and feedback information structures based on these metrics;

3. illustrate the theoretical and methodological results with comprehensive case studies in various application domains, including intelligence, surveillance, and reconnaissance scenarios involving autonomous mobile robot teams; neuronal brain networks; and electric power grids and microgrids.

We have achieved all of the project goals. Various aspects of the goals are addressed in the extensive peer-reviewed publications that have been produced during the project. In particular, 20 papers have been published or accepted in major international conferences and journals (12 peer-reviewed, full-length conference papers, and 8 journal papers), and a further 2 journal papers have been submitted and are currently under review. During the final period of the project, we have also gone above and beyond the original project goals to address several topics at the intersection of data-driven learning and control, which is a critical topic for future research. Highlights from the final reporting period are summarized below.

1.2 Risk-Averse RRT* Planning with Nonlinear Steering and Tracking Controllers for Nonlinear Robotic Systems Under Uncertainty

We have developed a two-phase risk-averse architecture for controlling stochastic nonlinear robotic systems. Risk-Averse Nonlinear Steering RRT* (RANS-RRT*) ss an RRT* variant that incorporates nonlinear dynamics by solving a nonlinear program (NLP) and accounts for risk by approximating the state distribution and performing a distributionally robust (DR) collision check to promote safe planning. The generated plan is used as a reference for a low-level tracking controller. We demonstrated three controllers: finite horizon linear quadratic regulator (LQR) with linearized dynamics around the reference trajectory, LQR with robustness-promoting multiplicative noise terms, and a nonlinear model predictive control law (NMPC). We demonstrated the effectiveness of our algorithm using unicycle dynamics under heavy-tailed Laplace process noise in a cluttered environment.

1.3 Risk Bounded Nonlinear Robot Motion Planning WithIntegrated Perception & Control

Robust autonomy stacks require tight integration of perception, motion planning, and control layers, but these layers often inadequately incorporate inherent perception and prediction uncertainties, either ignoring them altogether or making questionable assumptions of Gaussianity. Robots with nonlinear dynamics and complex sensing modalities operating in an uncertain environment demand more careful consideration of how uncertainties propagate across stack layers. We developed a framework to integrate perception, motion planning, and control by explicitly incorporating perception and prediction uncertainties into planning so that risks of constraint violation can be mitigated. Specifically, we use a nonlinear model predictive control based steering law coupled with a decorrelation scheme based the Unscented Kalman Filter for state and environment estimation to propagate the robot state and environment uncertainties. Subsequently, we use distributionally robust risk constraints to limit risk in the presence of these uncertainties. Finally, we developed a layered autonomy stack consisting of a nonlinear steering-based distributionally robust motion planning module and a reference trajectory tracking module. Our numerical experiments with nonlinear robot models and an urban driving simulator show the effectiveness of our proposed approaches.

1.4 Performance bounds for robust estimation using the H infinity filter

A key concern in network observability is to quantify performance and robustness limitations for state estimation from noisy sensors in terms of its dynamical properties and sensor architecture. We developed performance bounds for the robust H infinity filter, a generalization of the Kalman filter. Utilizing an eigenvalue bound on the observability Gramian, we derived a related eigenvalue bound on the estimation error covariance matrix from the generalized Riccati equation of the H infinity filter. As a special case, we obtained estimation performance bounds on the Kalman Filter. The bounds reflect the cardinality of the network and sensor set, the stability of the network, and the number and specific set of states to be estimated. We illustrated our results with numerical analysis on a regular network showing how the bounds change with system parameters.

1.5 Learning Optimal Controllers for Linear Systems with Multiplicative Noise via Policy Gradient

The linear quadratic regulator (LQR) problem has reemerged as an important theoretical benchmark for reinforcement learning-based control of complex dynamical systems with continuous state and action spaces. In contrast with nearly all recent work in this area, we consider multiplicative noise models, which are increasingly relevant because they explicitly incorporate inherent uncertainty and variation in the system dynamics and thereby improve robustness properties of the controller. Robustness is a critical and poorly understood issue in reinforcement learning; existing methods which do not account for uncertainty can converge to fragile policies or fail to converge at all. Additionally, intentional injection of multiplicative noise into learning algorithms can enhance robustness of policies, as observed in ad hoc work on domain randomization. Although policy gradient algorithms require optimization of a non-convex cost function, we show that the multiplicative noise LQR cost has a special property called *gradient domination*, which is exploited to prove global convergence of policy gradient algorithms to the globally optimum control policy with polynomial dependence on problem parameters. Results are provided both in the model-known and model-unknown settings where samples of system trajectories are used to estimate policy gradients.

1.6 Shared Reality: Detecting Stealthy Attacks Against Autonomous Vehicles

Autonomous Vehicles (AVs), also known as self-driving cars, are becoming more prevalent in our daily lives. AVs rely on sensor information to evaluate their environment and make crucial decisions in real-time, however, new attacks can create false sensor and actuation commands. As technological advancements expand the usage of AVs to perform more complex tasks, it is imperative to secure the integrity of these devices against malicious external tampering. We developed a security framework we call Shared Reality, which consists of verifying that sensors perceive the same physical reality. We implement our design on a custom hardware platform that uses the popular Robot Operating System (ROS) software. Our experiments show that AVs utilizing our proposed security framework ensured security with low overhead while performing several autonomous tasks.