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Complexity, Robustness System Thermodynamics, and Optimality in Large-Scale Network Aerospace Defense Systems

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Controls research under this program concentrated on the development of a unified stochastic dynamical systems framework for nonlinear networks. In particular, control algorithms were developed to address agent interactions, cooperative and non-cooperative control, task assignments, resource allocations, and system optimality. To realize these tasks, appropriate sensory and cogitative capabilities such as adaptation, learning, decision-making, and agreement (or consensus) on the agent and multiagent levels were developed. Application areas included spacecraft stabilization, cooperative control of unmanned air vehicles, network systems, and swarms of air and space vehicle formations.

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1. Introduction

1.1. Research Objectives

As part of this research program, we proposed to develop a unified stochastic dynamical systems framework for nonlinear network systems. In particular, we concentrated on control algorithms to address agent interactions, cooperative and non-cooperative control, task assignments, resource allocations, and system optimality. To realize these tasks, appropriate sensory and cogitative capabilities such as adaptation, learning, decision-making, and agreement (or consensus) on the agent and multiagent levels were developed. Application areas include spacecraft stabilization, cooperative control of unmanned air vehicles, network systems, and swarms of air and space vehicle formations.

1.2. Overview of Research

Recent technological advances in communications and computation have spurred a broad interest in control of networks and control over networks. Network systems involve distributed decision making for coordination of networks of dynamic agents and address a broad area of applications including cooperative control of unmanned air vehicles, microsatellite clusters, mobile robotics, battle space management, and congestion control in communication networks. A key application area of multiagent network coordination within aerospace systems is cooperative control of unmanned air vehicles for combat, surveillance, and reconnaissance, and swarms of air and space vehicle formations for command and control between heterogeneous air and space vehicles.

As part of our research over the last three and a half years [1–43], we developed stochastic stability, dissipativity, and optimality notions for nonlinear stochastic dynamical systems. Specifically, we developed Lyapunov and converse Lyapunov theorems for stochastic semistable nonlinear dynamical systems [5]. Semistability is the property whereby the solutions of a stochastic dynamical system almost surely converges to (not necessarily isolated) Lyapunov stable in probability equilibrium points determined by the system initial conditions. This framework is used to capture communication uncertainty between agents in a network, wherein the evolution of each link of the random network communication topology follows a Markov process. Moreover, we developed stochastic dissipativity theory for nonlinear dynamical systems using basic input-output and state properties [9]. Specifically, a stochastic version of dissipativity using both an input-output as well as a state dissipation inequality in expectation for controlled Markov diffusion processes is presented. Then, we used these results to develop connections between stochastic dissipativity and stochastic optimal control to address robust stability and robust stabilization problems involving both stochastic and deterministic uncertainty as well as both averaged and worst-case performance criteria. In addition, we developed a unified framework to address the problem of optimal nonlinear analysis and feedback control for partial stability and partial-state stabilization of stochastic dynamical systems [8,12]. Finally, we developed a new and novel adaptive control architecture for addressing security and safety in cyber-physical systems [6,7,13,17,20,26].

To address the problem of optimal nonlinear analysis and feedback control for nonlinear stochastic dynamical systems, we developed a unified framework for stochastic optimal control that focus on connections between stochastic Lyapunov theory and stochastic Hamilton-Jacobi-Bellman theory [14]. In particular, we show that asymptotic stability in probability of the closed-loop nonlinear system is guaranteed by means of a Lyapunov function that can clearly be seen to be the solution to the steady-state form of the stochastic Hamilton-Jacobi-Bellman equation and, hence, guaranteeing both stochastic stability and optimality. In addition, we develop optimal feedback controllers for affine nonlinear systems using an inverse optimality framework tailored to the stochastic stabilization problem. These results are then used to provide extensions of the nonlinear feedback controllers obtained in the literature that minimize general polynomial and multilinear performance criteria.

In addition, we addressed the consensus problem for a group of agent robots with a connected, undirected, and time-invariant communication graph topology in the face of uncertain interagent measurement data. Using agent location uncertainty characterized by norm bounds centered at the neighboring agents' exact locations, we showed that the agents reach an approximate consensus state and converge to a set centered at the centroid of the agents' initial locations [11].

Moreover, we developed stability margins for optimal and inverse optimal stochastic feedback regulators [23]. Specifically, gain, sector, and disk margin guarantees are obtained for nonlinear stochastic dynamical systems controlled by nonlinear optimal and inverse optimal Hamilton-Jacobi-Bellman controllers that minimize a nonlinear-nonquadratic performance criterion with cross-weighting terms. Furthermore, using the newly developed notion of stochastic dissipativity [9] we derive a return difference inequality to provide connections between stochastic dissipativity and optimality of nonlinear controllers for stochastic dynamical systems. In particular, using extended Kalman-Yakubovich-Popov conditions characterizing stochastic dissipativity we show that our optimal feedback control law satisfies a return difference inequality predicated on the infinitesimal generator of a controlled Markov diffusion process if and only if the controller is stochastically dissipative with respect to a specific quadratic supply rate.

Furthermore, we developed constructive finite time stabilizing feedback controllers for stochastic dynamical systems driven by Wiener processes based on the existence of a stochastic control Lyapunov function. Necessary and sufficient conditions for such controllers are developed and a universal inverse optimal feedback control law for nonlinear stochastic dynamical systems that possesses guaranteed gain and phase margins is derived. The framework is applied to the control of thermoacoustic combustion instabilities in jet engines [24].

We also developed distributed state and output feedback adaptive consensus control protocols for addressing networked multiagent systems subject to exogenous stochastic disturbances and sensor and actuators attacks [20, 26]. Specifically, for a class of linear leader-follower multiagent systems with an undirected communication topology we develop state and output feedback adaptive control design protocols for each follower agent to address malicious attacks on the actuator signals of the follower agents as well as sensor attacks on the state and output neighborhood synchronization error measurements. The proposed adaptive controllers guarantee uniform ultimate boundedness of the state tracking error for each agent in a mean-square sense. Several designs involving multiple aircraft consensus control problems are presented to demonstrate the efficacy of the proposed adaptive control architectures.

Moreover, we developed a dynamical systems formulation of stochastic thermodynamics [16]. This research lays down the theoretical foundation necessary for developing a thermodynamics-based control framework for stochastic consensus problems by addressing random communication between agents in the network, wherein the evolution of each link of the random network follows a Markov process. More specifically, this framework is being used to develop almost sure consensus for multiagent systems with nonlinear stochastic dynamics under distributed nonlinear consensus protocols. In particular, we are developing almost sure convergence and stochastic Lyapunov stability properties to address almost sure semistability requiring the trajectories of a stochastic nonlinear system to converge almost surely to a set of equilibrium solutions, wherein every equilibrium solution in the set is almost surely Lyapunov stable. This will allow us to extend the deterministic thermodynamics-based control framework developed under previous AFOSR support to a stochastic setting and consequently derive (asymptotic and finite-time) convergence conditions for agreement problems of multiple agents with nonlinear stochastic dynamics over random networks and under nonlinear consensus protocols.

Furthermore, we completed a book on thermodynamics titled *A Dynamical Systems Theory of Thermodynamics* [44]. Although this book is written for the mathematical physics community, its relevance to network control systems is paramount. Specifically, it lays down the theoretical foundation necessary for developing a thermodynamics-based control framework for deterministic and stochastic consensus problems by addressing communication uncertainty between agents in the network.

Finally, we are in the process of completing yet another book on *Stochastic Nonlinear Control: Stability, Dissipativity, and Optimality*, which will be appearing in Princeton University Press [45]. This monograph develops stability theory, dissipativity theory, and optimal feedback control architectures for nonlinear stochastic dynamical systems.

1.3. Goals of this Report

The main goal of this report is to summarize the progress achieved under the program during the past three and a half years. Since most of the technical results appeared or will soon appear in over 40 archival journal and conference publications, we shall only summarize these results and remark on their significance and interrelationship.

2. Description of Work Accomplished

The following partial research accomplishments have been completed over the past three and a half years.

2.1. Nonlinear-Nonquadratic Optimal and Inverse Optimal Control for Stochastic Dynamical Systems

Under certain conditions nonlinear controllers offer significant advantages over linear controllers. In particular, if the plant dynamics and/or system measurements are nonlinear, the plant/measurement disturbances are either nonadditive or non-Gaussian, the performance measure considered in nonquadratic, the plant model is uncertain , or the control signals/state amplitudes are constrained, then nonlinear controllers yield better performance than the best linear controllers. The current status of *deterministic* continuous-time, nonlinear-nonquadratic optimal control problems is presented in [46] in a simplified and tutorial manner. The basic underlying ideas of the results in [46] are based on the fact that the steady-state solution of the Hamilton-Jacobi-Bellman equation is a Lyapunov function for the nonlinear system and thus guaranteeing both stability and optimality.

Building on the results of [46], in this research [14] we present a framework for analyzing and designing feedback controllers for nonlinear *stochastic* dynamical systems. Specifically, we consider a feedback stochastic optimal control problem over an infinite horizon involving a nonlinear-nonquadratic performance measure. The performance measure can be evaluated in closed form as long as the nonlinear-nonquadratic cost functional considered is related in a specific way to an underlying Lyapunov function that guarantees asymptotic stability in probability of the nonlinear closed-loop system. This Lyapunov function is shown to be the solution of the steady-state stochastic Hamilton-Jacobi-Bellman equation. The overall framework provides the foundation for extending linear-quadratic control for stochastic dynamical systems to nonlinear-nonquadratic problems with polynomial and multilinear cost functionals.

Our approach focuses on the role of the Lyapunov function guaranteeing stochastic stability of the closed-loop system and its seamless connection to the steady-state solution of the stochastic Hamilton-Jacobi-Bellman equation characterizing the optimal nonlinear feedback controller. In order to avoid the complexity in solving the stochastic steady-state, Hamilton-Jacobi-Bellman equation we do not attempt to minimize a given *given* cost functional, but rather, we parameterize a family of stochastically stabilizing controllers that minimizes a *derived* cost functional that provides the flexibility in specifying the control law. This corresponds to addressing an *inverse optimal stochastic control problem*.

The inverse optimal control design approach provides a framework for constructing the Lyapunov function for the closed-loop system that serves as an optimal value function and, as shown in [23], achieves desired stability margins. Specifically, nonlinear inverse optimal controllers that minimize a *meaningful* nonlinear-nonquadratic performance criterion involving a nonlinear-nonquadratic, nonnegative-definite function of the state and a quadratic positive-definite function of the feedback control are shown to possess sector margin guarantees to component decoupled input nonlinearities in the conic sector $(\frac{1}{2}, \infty)$.

2.2. Dissipativity Theory for Nonlinear Stochastic Dynamical Systems

Many physical and engineering systems are *open systems*, that is, the system behavior is described by an evolution law that involves the system state and the system input with, possibly, an output equation wherein past trajectories together with the knowledge of any inputs define future trajectories (uniquely or nonuniquely) and the system output depends on the instantaneous (present) values of the system state. Dissipativity theory is a system-theoretic concept that provides a powerful framework for the analysis and control design of open dynamical systems based on generalized system energy considerations. In particular, dissipativity theory exploits the notion that numerous physical dynamical systems have certain input-output and state properties related to conservation, dissipation, and transport of mass and energy.

Such conservation laws are prevalent in dynamical systems, in general, and feedback control systems, in particular. The dissipation hypothesis on dynamical systems results in a fundamental constraint on the system dynamical behavior, wherein the stored energy of a dissipative dynamical system is at most equal to sum of the initial energy stored in the system and the total externally supplied energy to the system. Thus, the energy that can be extracted from the system through its input-output ports is less than or equal to the initial energy stored in the system, and hence, there can be no internal creation of energy; only conservation or dissipation of energy is possible. This results in dissipative systems providing strong links between physics, system theory, and control design.

In light of the fact that energy notions involving conservation, dissipation, and transport also arise naturally for dissipative diffusion processes, it seems natural that dissipativity theory can play a key role in the analysis and control design of stochastic dynamical systems. Specifically, as in the analysis of deterministic dynamical systems [46], dissipativity theory for stochastic dynamical systems can involve conditions on drift and diffusion system parameters that render an input, state, and output system dissipative. In addition, robust stability for stochastic dynamical systems with stochastic uncertainty can be analyzed by viewing the uncertain stochastic dynamical system as an interconnection of stochastic dissipative dynamical subsystems. Alternatively, stochastic dissipativity theory can be used to design feedback controllers that add dissipation and guarantee stability robustness in probability allowing stochastic stabilization to be understood in physical terms. As for deterministic dynamical systems, stochastic dissipativity theory can play a fundamental role in addressing stochastic robustness, risk-sensitive disturbance rejection, stability in probability of feedback interconnections, and optimality with averaged performance measurers for stochastic dynamical systems.

In this research [9], a general theory of stochastic dissipativity and stochastic losslessness involving connections between input-output and state properties, which include the notable special cases of stochastic passivity and stochastic finite-gain nonexpansivity using extended Kalman-Yakubovich-Popov conditions in terms of the drift and diffusion terms in the system dynamics, and stability in probability of general feedback interconnections is developed. Specifically, a stochastic version of dissipativity using both an input-output as well as a state dissipation inequality in expectation for controlled Markov diffusion processes is presented. Furthermore, we show that the average stored system energy in a dissipative stochastic dynamical system is a supermartingale with respect to the system filtration and is bounded from below by the mean energy that can be extracted from the system and bounded from above by the mean energy that can be delivered to the stochastic dynamical system in order to transfer it from the origin to an arbitrary nonempty closed or open subset in the state space over a finite stopping time. Moreover, we develop necessary and sufficient extended Kalman-Yakubovich-Popov conditions in terms of the drift and diffusion dynamics for characterizing stochastic dissipativity via two-times continuously differentiable storage functions.

Finally, using the concepts of stochastic dissipativity for stochastic dynamical systems with appropriate storage functions and supply rates, we construct smooth Lyapunov functions for stochastic feedback systems by appropriately combining the storage functions for the forward and feedback subsystems. General stability criteria are given for Lyapunov, asymptotic, and exponential mean square stability in probability for feedback interconnections of stochastic dynamical systems. These results generalize the feedback interconnection result appearing in the literature, and in the case where the supply rate involves the net system power or weighted input-output energy, these results provide extensions of the classical positivity and small gain theorems to stochastic dynamical systems.

2.3. Stochastic Finite-Time Partial Stability, Partial-State Stabilization, and Finite-Time Optimal Feedback Control

The notions of asymptotic and exponential stability in dynamical systems theory imply convergence of the system trajectories to an equilibrium state over the infinite horizon. In many applications, however, it is desirable that a dynamical system possesses the property that trajectories that converge to a Lyapunov stable equilibrium state must do so in finite time rather than merely asymptotically. In order to achieve convergence in finite time for deterministic dynamical systems, the closed-loop system dynamics need to be non-Lipschitzian giving rise to non-uniqueness of solutions in backward time. Uniqueness of solutions in forward time, however, can be preserved in the case of finite-time convergence.

For deterministic dynamical systems, *finite-time stabilization*, that is, the problem of finding state-feedback control laws that guarantee finite-time stability of the closed-loop system, as well as the problem of *partial-state stabilization*, wherein stabilization with respect to a subset of the system state variables is desired has been considered by the Principle Investigator [2,3]. In this research [8,12], we extend this framework to address the combined problem of *optimal finite-time*, *partial-state stochastic stabilization*. Specifically, we address these problems by considering a notion of optimality that is directly related to a given Lyapunov function that is positive definite and decrescent with respect to part of the system state, and satisfies a differential inequality involving fractional powers. In particular, an optimal finite-time, partial-state stochastic stabilization control problem is stated and sufficient stochastic Hamilton-Jacobi-Bellman conditions are used to characterize an optimal feedback controller.

The steady-state solution of the stochastic Hamilton-Jacobi-Bellman equation is clearly shown to be a Lyapunov function for part of the closed-loop system state that guarantees both finite-time partial stability in probability and optimality. In addition, we explore connections of our approach with inverse optimal control, wherein we parametrize a family of finite-time, partial-state stabilizing stochastic feedback controllers that minimize a derived cost functional. Another important application of deterministic partial stability and partial stabilization theory is the unification it provides between time-invariant stability theory and stability theory for time-varying systems [46]. We exploit this unification and specialize our results to address the problem of optimal finite-time control for nonlinear time-varying stochastic dynamical systems [12].

2.4. Stochastic Differential Games and Inverse Optimal Control and Stopper Policies

Differential games have been studied in various contexts in the literature including risk-sensitive control, mathematical finance, communication networks, and network resource allocation. The pioneering work on the subject involved a deterministic two-player, zero-sum differential game problem whose solution is characterized by the Hamilton-Jacobi-Isaacs equation. This work was extended to a stochastic setting, wherein the lower and the upper value functions of this game satisfy the dynamic programming principle. Specifically, the lower and the upper value functions of this game are the unique viscosity solutions of the associated stochastic Hamilton-Jacobi-Isaacs equation. Furthermore, it was shown that these solutions coincide under the Isaacs minimax condition. These results have further been extended by relaxing the minimax Isaacs condition and considering a saddle point property that generates approximately optimal control strategies for the maximizing and minimizing players. In particular, even though both players choose specific strategies, in the upper game characterized by the upper value function the strategies chosen by the minimizer are restricted to a subclass of Elliott-Kalton strategies.

Building on our recent research [14], in this research [19] we present a two-player stochastic differential game framework for designing optimal feedback control and stopper policies for each player. Specifically, we consider feedback stochastic optimal control policies for attaining higher utilities or lower costs over an infinite horizon involving a nonlinear-nonquadratic performance functional. The performance functional can be evaluated in closed form as long as the nonlinear-nonquadratic cost functional considered is related in a specific way to an underlying Lyapunov function that guarantees asymptotic stability in probability of the nonlinear differential game problem. This Lyapunov function is shown to be the solution of the steady-state stochastic Hamilton-Jacobi-Isaacs equation. The overall framework provides the foundation for extending linear-quadratic controller and stopper policies for stochastic differential games to nonlinear-nonquadratic differential games with polynomial and multilinear cost functionals.

Our approach focuses on the role of the Lyapunov function guaranteeing stochastic stability of the differential game and its connection to the steady-state solution of the stochastic Hamilton-Jacobi-Isaacs equation characterizing the optimal nonlinear feedback controller and stopper policies. In order to avoid the complexity in solving the stochastic steady-state, Hamilton-Jacobi-Isaacs equation we do not attempt to minimize/maximize a given cost functional, but rather, we parameterize a family of stochastically stabilizing controller and stopper policies that minimizes/maximizes a derived cost functional and provides the flexibility in specifying the control and stopper policies. This corresponds to addressing an *inverse optimal* stochastic differential game problem.

2.5. Implications of Dissipativity, Inverse Optimal Control, and Stability Margins for Nonlinear Stochastic Regulators

As discussed in Section 2.1, in recent research [14] we presented a framework for analyzing and designing feedback controllers for nonlinear stochastic dynamical systems. Specifically, a stochastic feedback control problem over an infinite horizon involving a nonlinear-nonquadratic performance functional was considered and the performance functional was evaluated in closed form as long as the nonlinear-nonquadratic cost functional considered was related in a specific way to an underlying Lyapunov function that guarantees asymptotic stability in probability of the nonlinear closed-loop system. Furthermore, the Lyapunov function was shown to be the solution of the steady-state stochastic Hamilton-Jacobi-Bellman equation. The overall framework provides the foundation for extending stochastic linear-quadratic control to nonlinear-nonquadratic problems.

Using the framework developed in [14], in this research [23] we derive stability margins for optimal and inverse optimal nonlinear stochastic feedback regulators. Specifically, sufficient conditions for gain, sector, and disk margin guarantees are obtained for nonlinear stochastic dynamical systems controlled by nonlinear optimal and inverse optimal Hamilton-Jacobi-Bellman controllers that minimize a nonlinear-nonquadratic performance criterion *with* cross-weighting terms. In the case where the cross-weighting term in the performance criterion is deleted our results recover the gain, sector, and disk margins for the deterministic optimal control problem presented in the literature.

Alternatively, retaining the cross-terms in the performance criterion and specializing the optimal nonlinear-nonquadratic problem to a stochastic linear-quadratic problem with a multiplicative noise disturbance, our results recover the analogous gain and phase margins for the deterministic linear-quadratic optimal control problem. Even though the inclusion of cross-weighting terms in the performance criterion is shown to degrade gain, sector, and disk margins, the extra flexibility provided by the cross-weighting terms makes it possible to guarantee optimal and inverse optimal nonlinear controllers that may be far superior in terms of transient performance over meaningful inverse optimal controllers.

Finally, using the newly developed notion of stochastic dissipativity for controlled Markov diffusion processes characterized via extended Kalman-Yakubovich-Popov conditions in terms of the drift and diffusion dynamics developed in our earlier research [9], we provide explicit connections between stochastic stability margins, stochastic meaningful inverse optimality, and stochastic dissipativity with respect to a specific quadratic supply rate. Specifically, we derive a stochastic counterpart to the classical return difference inequality for continuous-time systems with continuously differentiable flows for stochastic dynamical systems and provide connections between stochastic dissipativity and optimality for stochastic nonlinear controllers. In particular, we show an equivalence between stochastic dissipativity and optimality holds for stochastic dynamical systems. Specifically, we show that an optimal nonlinear feedback controller $\phi(x)$ satisfying a return difference condition predicated on the infinitesimal generator of a controlled Markov diffusion process is equivalent to the fact that the stochastic dynamical system with input u and output $y = -\phi(x)$ is stochastically dissipative with respect to a supply rate of the form $[u + y]^{\mathrm{T}}[u + y] - u^{\mathrm{T}}u$.

2.6. Universal Feedback Controllers and Inverse Optimality for Nonlinear Stochastic Dynamical Systems

The consideration of Lyapunov functions for proving stability of feedback dynamical systems is one of the cornerstones of systems and control theory. For dynamical systems with continuously differentiable flows, the concept of smooth control Lyapunov functions was developed by Artstein to show the existence of a feedback stabilizing controller. A constructive feedback control law based on a universal construction of smooth control Lyapunov functions was given by Sontag. An extended notion of nonsmooth control Lyapunov functions as well as a universal feedback controller for discontinuous dynamical systems based on the existence of nonsmooth Lyapunov functions defined in the sense of generalized Clarke gradients and set-valued Lie derivatives was developed by the Principal Investigator under previous AFOSR support.

The aforementioned results on control Lyapunov functions along with the constructive feedback control laws predicated on these generalized energy functions are developed for deterministic dynamical systems. In numerous applications where dynamical models are used to describe the behavior of natural and engineering systems, stochastic components and random disturbances are often incorporated into the models. The stochastic aspects of the models are used to quantify system uncertainty as well as the dynamic relationships of sequences of random events between system-environment interactions. In this research [24], we provide Lyapunov-like techniques for stochastic stabilization. Specifically, asymptotic stability in probability of affine in the control stochastic dynamical systems using stochastic control Lyapunov functions leading to the existence of smooth, except possibly at the equilibrium point of the system, stochastically stabilizing feedback control laws are provided.

Furthermore, we build on the results of [9] as well as on the recent stochastic finite time stabilization framework of [8] to develop a constructive universal feedback control law for stochastic finite time stabilization of stochastic dynamical systems. In addition, we present necessary and sufficient conditions for continuity of such controllers. Finally, we show that for every nonlinear stochastic dynamical system for which a stochastic control Lyapunov function can be constructed there exists an inverse optimal feedback control law in the sense of with guaranteed sector and gain margins of $(\frac{1}{2}, \infty)$.

2.7. Energy-Based Feedback Control for Stochastic Dynamical Systems

In numerous applications where dynamical system models are used to describe the behavior of natural and engineering systems, stochastic components and random disturbances are typically incorporated into the models. The stochastic aspects of the models are used to quantify system uncertainty and system disturbances as well as the dynamic relationships of sequences of random events between system-environment interactions. In recent research [9], we extend classical deterministic dissipativity theory to nonlinear stochastic dynamical systems using basic input-output and state properties. Specifically, a stochastic version of dissipativity theory using both an input-output as well as a state dissipation inequality in expectation for controlled Markov diffusion processes is presented.

Dissipativity theory and in particular passivity-based control frameworks for deterministic port-controlled Hamiltonian systems using energy shaping have been developed in the literature (see [46] and the numerous references therein). Specifically, researchers have developed a control design methodology that achieves stabilization via system passivation. In light of the fact that energy notions involving conservation, dissipation, and transport of energy also arise naturally for dissipative diffusion processes, it seems natural that dissipativity theory can play a key role in the control design of stochastic dynamical systems. Specifically, stochastic dissipativity and passivity theory can be used to design feedback controllers that add dissipation and guarantee stability robustness in probability allowing stochastic stabilization to be understood in physical terms.

In this research [18], we use the stochastic stability and dissipativity framework developed in [9] to extend the deterministic passivity-based control framework for port-controlled Hamiltonian systems to nonlinear stochastic port-controlled Hamiltonian systems. Specifically, an energy-based control framework for stochastic port-controlled Hamiltonian systems is developed using a stochastic controller design methodology that achieves stabilization via stochastic system passivation. The interconnection and damping matrix functions of the stochastic port-controlled Hamiltonian system are shaped so that the physical (Hamiltonian) system structure is preserved at the closed-loop level and the closed-loop average energy function is equal to the difference between the average physical energy of the system and the average energy supplied by the controller. Since the Hamiltonian structure is preserved at the closed-loop level, the passivity-based stochastic controller is *robust* with respect to unmodeled passive dynamics. Passivity-based control architectures are extremely appealing since the control action has a clear *physical* energy interpretation, which can considerably simplify controller implementation.

Finally, we also consider energy-based *dynamic* controllers for stochastic port-controlled Hamiltonian systems, wherein energy shaping is achieved by combining the physical energy of the plant and the emulated energy of the feedback controller. For deterministic systems, this approach has been extensively studied by Ortega *et al.* to design Euler-Lagrange controllers for potential energy shaping of mechanical systems.

2.8. Lyapunov and Converse Lyapunov Theorems for Stochastic Semistability

As noted in Section 2.6, in numerous applications where dynamical models are used to describe the behavior of natural and engineering systems, stochastic components and random disturbances are incorporated into the models. The stochastic aspects of the models are used to quantify system uncertainty as well as the dynamic relationships of sequences of random events between system-environment interactions. For example, stochastic modeling can be used to capture communication uncertainty between agents in a network, wherein the evolution of each link of the random network communication topology follows a Markov process. In this case, the development of almost sure consensus of multiagent systems with nonlinear stochastic dynamics under distributed nonlinear consensus protocols is necessary. And from a practical viewpoint, it is not sufficient to only guarantee that the network almost surely converges to a state of consensus since steady-state convergence is not sufficient to guarantee that small perturbations from the limiting state will lead to only small transient excursions from a state of consensus. It is also necessary to guarantee that the equilibrium states representing consensus are Lyapunov stable in probability, and consequently, stochastically semistable.

In this research [5], we extend the notion of semistability to nonlinear stochastic systems involving Markov diffusion processes that have a continuum of equilibrium solutions. In particular, we develop almost sure convergence and stochastic Lyapunov stability properties to address almost sure semistability requiring the trajectories of a nonlinear stochastic dynamical system to converge almost surely to a set of equilibrium solutions, wherein every equilibrium solution in the set is almost surely Lyapunov stable. Furthermore, we provide necessary and sufficient Lyapunov conditions for semistability and show that semistability implies the existence of a continuous Lyapunov function whose infinitesimal generator decreases along the dynamical system trajectories and is such that the Lyapunov function satisfies inequalities involving the average distance to the set of equilibria.

2.9. A Conservation-Based Distributed Control Architecture for Network Consensus with Communication Uncertainty

As noted in Section 1, recent technological advances in communications and computation have spurred a broad interest in control of networks and control over networks. Network systems involve distributed decision-making for coordination of networks of dynamic agents and address a broad area of applications including cooperative control of unmanned air vehicles (UAV's) and autonomous underwater vehicles (AUV's) for combat, surveillance, and reconnaissance, distributed reconfigurable sensor networks for managing power levels of wireless networks, air and ground transportation systems for air traffic control and payload transport and traffic management, swarms of air and space vehicle formations for command and control between heterogeneous air and space vehicles, and congestion control in communication networks for routing the flow of information through a network.

To enable the applications for these multiagent systems, cooperative control tasks such as formation control, rendezvous, flocking, cyclic pursuit, cohesion, separation, alignment, and consensus have been developed in the literature. To realize these tasks, individual agents need to share information of the system objectives as well as the dynamical network. In particular, in many applications involving multiagent systems, groups of agents are required to agree on certain quantities of interest. Information consensus over static and dynamic information-exchange topologies guarantees agreement between agents for a given coordination task.

Distributed consensus algorithms involve neighbor-to-neighbor interaction between agents, wherein agents update their information state based on the information states of the neighboring agents. A unique feature of the closed-loop dynamics under any control algorithm that achieves consensus in a dynamical network is the existence of a continuum of equilibria representing a state of consensus. Under such dynamics, the limiting consensus state achieved is not determined completely by the dynamics, but depends on the initial system state as well.

As noted in Section 2.8, in systems possessing a continuum of equilibria, *semistability* and not asymptotic stability is the relevant notion of stability [5]. Semistability is the property whereby every trajectory that starts in a neighborhood of a Lyapunov stable equilibrium converges to a (possibly different) Lyapunov stable equilibrium. Semistability thus implies Lyapunov stability, and is implied by asymptotic stability. As further noted in Section 2.8, from a practical viewpoint, it is not sufficient to only guarantee that a network converges to a state of consensus since steady state convergence is not sufficient to guarantee that small perturbations from the limiting state will lead to only small transient excursions from a state of consensus. It is also necessary to guarantee that the equilibrium states representing consensus are Lyapunov stable, and consequently, semistable.

To capture network system uncertainty and communication uncertainty between the agents in a network, wherein the evolution of each link of the network communication topology follows a Markov process, in this research [21] we are developing almost sure consensus protocols for multiagent systems with nonlinear stochastic dynamics. Specifically, we extend the notion of semistability to nonlinear stochastic dynamical systems that posses a continuum of equilibrium solutions to develop almost sure convergence and stochastic Lyapunov stability properties. In particular, we address almost sure semistability requiring that the sample trajectories of the stochastic nonlinear system almost surely converge to a set of equilibrium solutions, wherein every equilibrium solution in the set is almost surely Lyapunov stable. The proposed controller architecture is predicated on the recently developed notion of dynamical thermodynamics [16, 44] resulting in controller architectures involving the exchange of generalized charge or energy between agents that guarantee that the closed-loop dynamical network is consistent with basic thermodynamic principles.

Furthermore, we address almost sure finite time semistability requiring that the sample trajectories of the stochastic nonlinear system almost surely converge to a set of equilibrium solutions in finite time, wherein every equilibrium solution in the set is almost surely Lyapunov stable. Specifically, we design distributed finite time consensus protocols for cooperative control over random networks.

2.10. An Adaptive Control Architecture for Mitigating Sensor and Actuator Attacks in Cyber-Physical Systems

The design and implementation of control law architectures for modeling and controlling complex dynamical systems is a nontrivial control engineering task involving the consideration and operation of computing and communication components interacting with the physical system to be controlled. These complex dynamical systems merge the cyber-world of computing and communications with the physical world, and are known as *cyber-physical systems*. Cyber-physical systems are characterized by a large number of highly coupled heterogeneous dynamic network components and have become ubiquitous in the control of complex dynamical systems given the recent advances in embedded sensor, computation, and communication technologies. Such systems include safety-critical aerospace systems, power systems, communications systems, network systems, transportation systems, large-scale manufacturing systems, integrative biological systems, economic systems, process control systems, and health-care systems, to name but a few examples.

In all of the aforementioned applications, reliable system analysis and decentralized control system design, with integrated verification and validation, are essential for providing high system performance and reconfigurable system operation in the presence of system uncertainties and system component failures. Even though cyber-physical systems are transforming the way we are interacting with the physical world, they introduce several grand research challenges. In particular, the complex, large-scale heterogeneous architectures and components that are pervasive in cyber-physical systems demands system robustness, resiliency, reliability, safety, and security for addressing the constantly changing and reconfiguring dynamics of these systems whose computation, information, and control processing is tightly coupled with the physical process. And given that a wide range of cyber-physical systems involve the use of open communication and computation platform architectures, they are vulnerable to adversarial cyber-attacks that can have drastic societal ramifications.

In particular, attackers can gain access to sensing and actuation computing platforms and manipulate system measurement data and control input commands to severely compromise system performance and integrity, and hence, security and safety in cyber-physical systems is of paramount importance. In contrast to classical estimation and control problems, wherein physical system variables cannot be measured directly due to sensor noise and are typically assumed to fluctuate about their true value, controlled systems with measurement and actuation devices that are hijacked and controlled by an adversarial entity that actively engages to maximally degrade system information and control require new and novel control algorithms to recover system performance.

In this research [6, 7, 13], we build on the solid foundation of adaptive control theory to develop new adaptive control architectures that can foil malicious sensor and actuator attacks. Specifically, we develop an adaptive controller for mitigating time-varying and time-invariant, state-dependent sensor and actuator attacks. We show that the proposed controller guarantees uniform ultimate boundedness of the closed-loop dynamical system when the adversarial sensor and actuator attacks are time-varying and partial asymptotic stability when the sensor and actuator attacks are time-invariant. Finally, we discuss the practicality of the proposed approach and provide a representative model involving the lateral directional dynamics of an aircraft to illustrate the efficacy of the proposed adaptive control architecture.

2.11. Cyber-Physical System Security in the Face of Sensor-Actuator Attacks and Stochastic Disturbances

In this research [17], we build on our previously supported AFOSR research on adaptive control theory to develop new adaptive control architectures that can foil malicious sensor and actuator attacks in the face of exogenous stochastic disturbances. Specifically, to address the dynamic relationships of sequences of random events between system-environment interactions, we extend our recent work on cyber-physical security and safety [6, 7, 13] to develop an adaptive controller for mitigating time-invariant, state-dependent sensor and actuator attacks subject to random disturbances modeled as Markov processes. Furthermore, we show that the proposed controller guarantees uniform ultimate boundedness in probability of the closed-loop stochastic dynamical system in a mean-square sense.

The proposed controller is composed of two components, namely a nominal controller and an additive corrective signal. It is assumed that the nominal controller has been already designed and implemented to achieve a desired closed-loop nominal performance. Using the nominal controller, an additive adaptive corrective signal is designed and added to the output of the nominal controller in order to suppress the effects of the sensor and actuator attacks. Thus, the proposed controller is modular in the sense that there is no need to redesign the nominal controller in the proposed framework; only the adaptive corrective signal is designed using the available information from the nominal controller and the system.

2.12. Adaptive Consensus Control Protocols for Leader-Follower Air Vehicles subject to Sensor-Actuator Attacks

Leader-follower multiagent systems have a wide range of application in aerospace engineering which includes surveillance, formation control, and search and rescue. In such systems, the system information of different agents or air vehicles is exchanged through communication channels represented by a given graph communication topology, and each vehicle utilizes the information received from its neighbors for the control design protocol. For multiple vehicle leader-follower consensus problems, most of the results in the literature assume that at least a subset of the followers have access to the exact leader information as well as each follower vehicle has exact measurements of all the neighboring follower vehicles. However, in realistic situations, the leader information measured or received by the follower vehicles may be corrupted due to an attack on the communication channel. In addition, follower vehicles may measure or receive erroneous information from the neighboring follower vehicles.

In this research [26], we extend our recent work in [20] to develop a distributed state and output feedback adaptive control architecture that can foil malicious sensor and actuator attacks in the face of exogenous stochastic disturbances and sensor and actuator attacks. Specifically, for a class of linear multiagent systems with an undirected communication graph topology we develop a state and output neighborhood synchronization error for the distributed state and output feedback adaptive control protocol designs of each follower to account for actuator and sensor attacks on the leader output as well as all of the follower agent in the network.

Unlike the results in the literature, which assume a state feedback architecture and the neighborhood synchronization error is accurately available to the agents, in the present research [26] we address information uncertainty between the follower agents as well as the leader agent and consider a general dynamic output feedback control architecture. The proposed state and output feedback adaptive controllers guarantee uniform ultimate boundedness in probability of the state tracking error for each follower agent in a mean-square sense. Finally, to show the efficacy of our adaptive control consensus architecture, we provide several illustrative numerical examples involving the lateral directional dynamics of an aircraft group of agents subject to state-dependent atmospheric drag disturbances and sensor and actuator attacks.

2.13. An Adaptive Learning and Control Architecture for Connected Autonomous Vehicle Platoons

The problem of control design of vehicle platoons has attracted considerable attention among researchers in the field of control, optimization, and communication. Given the increasing number of transportation congestion and accidents world-wide, extensive research efforts have been devoted to increasing the adaptation, autonomy, connectivity, safety, and reliability of vehicular platoon control systems. Connected networks of vehicles often involve distributed decision-making for coordination involving information flow enabling enhanced operational effectiveness via cooperation.

It is evident that as the technology and complexity of autonomous vehicles evolves, several grand research challenges need to be addressed. These include securing the autonomous vehicle from malicious cyber attacks that might increase engine revolutions per minute, disabling a cylinder or even disengaging the engine completely, activating airbags while driving to obscure vision, tampering with the breaking system causing skidding or preventing the braking system from being engaged when driving, setting the vehicle data display to an erroneous speed so that the driver is unaware that they are violating speed limits, or instigating a malfunction in the vehicle's position system.

The design and implementation of a secure control framework for connected autonomous transportation systems is a nontrivial task involving the consideration and operation of computing and communication components interacting with the physical, cyber, and human-in-the-loop processes. Even though adaptive control can be used to address autonomous networked systems, the pervasive security and safety challenges underlying connected autonomous transportation systems place additional burdens on standard adaptive control methods. Specifically, although adaptive control and learning architectures have been used in numerous applications to achieve stability and improve system performance, their standard architectures are *not* designed to address adversarial actuator, sensor, and communication attacks.

In recent research [6,7,13,17], we have developed new adaptive control architectures that can foil malicious sensor and actuator attacks for linear systems. The proposed adaptive control frameworks provide an integrated alternative to traditional methods inspired by fault detection, isolation, and recovery. More specifically, the proposed architectures utilize adaptive control theory to effectively address malicious sensor and actuator attacks and enable adaptive autonomy. Unlike other approaches focusing on fault detection, isolation, and recovery, our framework is not only computationally inexpensive but also do not require boundedness of all of the compromised closed-loop system signals. In addition, we can account for sensor and actuator attacks that can corrupt *all* or *part* of the available sensor and actuator signals simultaneously; that is, we do not assume that only a subset of the sensor and actuator channels are corrupted at any given time. Furthermore, we do not assume that the sensor and actuator attacks are constrained to a particular model, which does not necessarily capture a realistic behavior of an attacker. Finally, unlike the results in the literature, which only consider steady-state operation models, our framework can address transient performance as well as steady-state system stability and performance.

In this research [25, 41], we build on the adaptive control framework of [17] to develop an adaptive controller for a team of connected vehicles subject to time-invariant, state-dependent sensor and actuator attacks. The proposed controller guarantees uniform ultimate boundedness of the closed-loop networked system. The adaptive controller is composed of two components, namely a nominal controller and an additive corrective signal. It is assumed that the nominal controller has been already designed and implemented to achieve a desired closed-loop nominal performance. Using the nominal controller, an additive adaptive corrective signal is designed and added to the output of the nominal controller in order to suppress the effects of the sensor and actuator attacks. Thus, the proposed controller is modular in the sense that there is no need to redesign the nominal controller in the proposed framework; only the adaptive corrective signal is designed using the available information from the nominal controller and the system.

To account for variability in the system model parameters for different drivers, we additionally present an adaptive learning framework for identifying the state space model using input-output data. Specifically, a concurrent learning algorithm is employed to identify the model parameters under a relaxed excitation condition rather than the classical presistency of excitation condition.

3. Research Personnel Supported

Faculty

Wassim M. Haddad, Principal Investigator

Graduate Students

T. Rajpurohit, Ph. D, and X. Jin, Ph. D.

Two Ph. D. dissertations were completed under partial support of this program; namely:

T. Rajpurohit, *Stochastic Nonlinear Control: A Unified Framework for Stability, Dissipativity, and Optimality*, July 2018.

X. Jin, *Cyber-Physical System Security, Optimal Control, and Consensus Protocols for Nonlinear Stochastic Systems*, July 2019.

Dr. Rajpurohot has accepted a position with Genpact Inovation as Vice President for Artificial Intelligent Systems, Palo Alto, CA, and Dr. Jin has accepted a position as an Assistant Professor with the Department of Mechanical Engineering at the University of Kentucky, Lexington, KY.

4. Interactions and Transitions

4.1. Participation and Presentations

The following conferences were attended over the past three years.

American Control Conference, Boston, MA, July 2016.
IEEE Conference on Decision and Control, Las Vegas, NV, December 2016.
American Control Conference, Seatle, WA, May 2017.
American Control Conference, Milwaukee, WI, June 2018.
IEEE Conference on Decision and Control, Miami, FL, December 2018.

Furthermore, conference articles [27–43] were presented.

4.2. Transitions

Our work partially supported under this program has resulted in the startup company Autonomous Healthcare, Inc. with the Principal Investigator serving as chief scientific advisor and Dr. Behnood Gholami (678-886-6400) serving as the chief executive officer and running the daily affairs of the company. Autonomous Healthcare, Inc. is accelerating the use of information technology in healthcare. Its innovative solutions help reduce intensive care unit costs and increase quality of care. Its core technology utilizes mathematical modeling to predict patient outcome and improve quality of care. The technology provides an efficient method to analyze and interpret patient data already available at the hospitals. For further details see [47].

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