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Reliable and optimal coordination of networked systems and action-based space trajectory generation/estimation

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14. ABSTRACT

We highlight several areas we have been working on and the results obtained so far. 1) Stochastic adaptive optimization: Optimization methods are essential and have been used extensively in a broad spectrum of applications. Most existing literature on optimization algorithms does not consider systems that involve unknown system parameters. This paper studies a class of stochastic adaptive optimization problems in which identification of unknown parameters and search for the optimal solutions must be performed simultaneously. Due to a fundamental conflict between parameter identifiability and optimality in such problems, we introduce a method of adding stochastic dither signals into the system, which provides a sufficient excitation for estimating the unknown parameters, leading to convergent adaptive optimization algorithms. Joint identification and optimization algorithms are developed and their simultaneous convergence properties of parameter estimation and optimization variable updates are proved.

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Final Project Report (Results and Progress Section)

Reliable and Optimal Coordination of Networked Systems and Action-Based Space Trajectory Generation/Estimation

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Results and Progress

There are two major directions in the research effort. The first concentrates on control and optimization of stochastic networked systems, and the second regards fundamental computational issues in dynamics and control of nonlinear systems.

With respect to the first overall direction, we note that networked control systems are of critical importance to Air Force missions. Due to technology advancement in communications, cloud and edge computing facility, and more sophisticated missions and tasks, emerging systems have become increasingly interconnected and data rich. This research effort addresses some core issues that will advance networked control methodologies under communication and system uncertainties, including adversary-induced performance degradations. Progress during the past year is substantial in theory and applications. Regarding the second direction, we note that the critical difficulty preventing application of a variety of control theories for more than a half-century is unfeasible computational cost. This bottleneck has been greatly reduced through several developments.

We made significant progress in multiple directions within these two areas, and specific items are briefly summarized below.

1. Stochastic Modeling and Optimization

1.1. Distributed Optimization and Applications.

In the past a few years, we have been working on distributed optimization algorithms for complex and interconnected systems. Our objectives are to reduce computing and communication complexity, sustain scalability, and enhance privacy and security. We have examined several classes of algorithms, including dual averaging push for distributed convex optimization over time-varying directed graphs and dual subgradient algorithms with iterate-averaging feedback for convex optimization with coupled constraints, among others. We have also worked on related applications such as cyber-physical systems, distributed energy management for smart grids with an event-triggered communication schemes, etc. In a number of applications, we are able to achieve global optimality, and global asymptotic convergence properties are proved. Under measurement/communication noises, convergence properties of the corresponding stochastic approximation algorithms are established, including strong convergence, mean square convergence, and their convergence rates. Case studies are also provided to illustrate the usage and properties of the algorithms.

1.2. Stochastic Adaptive Optimization.

Optimization methods are essential and have been used extensively in a broad spectrum of applications. Most existing literature on optimization algorithms does not consider systems that involve unknown system parameters. This paper studies a class of stochastic adaptive optimization problems in which identification of unknown parameters and search for the optimal solutions must be performed simultaneously. Due to a fundamental conflict between parameter identifiability and optimality in such problems, we introduce a method of adding stochastic dither signals into the system, which provides a sufficient excitation for estimating the unknown parameters, leading to convergent adaptive optimization algorithms. Joint identification and optimization algorithms are developed and their simultaneous convergence properties of parameter estimation and optimization variable updates are proved. Under both noise-free and noisy observations, the corresponding convergence rates are established. The main results of this paper reveal certain fundamental relationships and trade-off among updating step sizes, dither magnitudes, parameter estimation errors, optimization accuracy, and convergence rates. Simulation case studies are used to illustrate the adaptive optimization algorithms and their main properties.

1.3. Filtering, state estimation, learning, and control.

Given the state of a system that is not completely observable, filtering focuses on estimation based on partial observations of the system state. A nonlinear filter calculates the conditional distribution of the state under the given observations. Early developments in nonlinear filtering can be found in the classical work of Kushner, Duncan, Mortensen, Zakai, et al. Although the theoretical foundation was set up, the computation remains a challenging problem because of the inherent infinite dimensionality. Our recent work uses a new approach that is based on neural networks and machine learning to resolve the computational issues in nonlinear filtering problems. The results show some promising features that enable the treatment of systems with switching dynamics, which cannot be dealt with otherwise.

For learning, we have examined adaptive inverse reinforcement learning of stochastic gradient algorithms, and proposed multi-kernel passive stochastic gradient algorithms and transfer learning. Rigorous convergence and rates of convergence results are obtained.

1.4. Identification of nonlinear systems.

In a series of papers, we treated identification of nonlinear systems, including sparse system identification and nonparametric system identification. The main idea is to combine stochastic approximation methods with identification. Hopefully, our approaches will provide new methodologies and tools to treat emerging technologies in a wide range of applications.

1.5. Switching Diffusions with Mean-Field Interactions.

We have continued our work on switching diffusions, where the systems are stochastic differential equations modulated by a randomly switching process. We have considered sustainable harvesting policies under long-run average criteria and near optimality, stability of stochastic functional differential equations with random switching, applications to multi-agent systems, limit results, maximum principle, and non-Markov systems for switching-diffusion-type systems with mean-field interactions, time-inconsistent control problems for controlled Markov chains with non-exponential discounting and distribution dependent costs, and optimal control and numerical methods for hybrid stochastic infectious disease models. It should be mentioned that for the mean-field models, we have obtained a rather general maximum principle.

2. Fundamental Computational Issues in Dynamics and Control of Nonlinear Systems

2.1. Conversion of Stochastic Control Problems into Deterministic Problems.

We developed a completely new means for addressing nonlinear stochastic control problems driven by Brownian motion. This was performed through approximate conversion of the original problems into nonlinear deterministic control problems. Importantly, this was not achieved through the employment of any small-noise type of approximation, but instead, through the use of a staticization-based dual-space conversion. In the resulting Hamilton-Jacobi partial differential equation (PDE), there remains a term corresponding to a second-derivative in the original space variable which is small on short time-segments. The resulting solution error is greatly reduced through solution of a second PDE over these segments, resulting in extremely accurate solutions. This approach is important because there are numerical methods for extremely rapid solution of classes of nonlinear deterministic control problems. Those techniques are not applicable to stochastic control problems. Numerical demonstrations were included.

2.2. Diffusion Representations of Quantum Mechanical Systems

It was first demonstrated that there exists a stochastic-process representation for solutions of the Schrdinger equation, through the use of staticization and complex-valued diffusion processes. However, that was demonstrated only for the unrealistic harmonic oscillator potential. This was extended to include a Coulomb potential and the lowest energy "electron shell" of the Bohr model, as a demonstration of the validity for general quantum systems. The effort required a substantial extension of existence and uniqueness results for degenerate stochastic differential equations with discontinuities and asymptotes in the drift dynamics.

2.3. A new Method for Convex Barrier Constraints in Otherwise Linear-Quadratic Problems

A supremum-of-quadratics representation for a class of convex barrier-type constraints was developed and applied in a class of continuous time state constrained linear regulator problems. Using this representation, it was demonstrated that a linear regulator problem constrained by such a convex barrier-type constraint could be equivalently formulated as an unconstrained linear quadratic game. The existence of value for the game was proved, and state feedback characterizations for the optimal policies were obtained. Numerical computations were included.

2.4 Staticization. The classical approach to solution of energy-conserving dynamical systems is integration of Newton's second law. An alternative viewpoint is that a system evolves along a path that makes the action functional stationary, i.e., such that the first-order differential around the path is the zero element. In our recent efforts, we have shown that the stationary-action formulation can be used to generate fundamental solutions to two-point boundary-value problems (TPBVPs) for conservative dynamical systems. This approach is also turning out to be similarly useful and profound as a tool in solution of Schrödinger initial value problems (IVPs).

The approach is leading to the development of a new area of control theory. In particular, we define the problem class where one seeks a stationary point of a payoff, rather than a minimum or maximum. This, in turn, leads to the definition of a "staticization" operator (i.e., a stat operator), and the development of a theory of dynamic programming appropriate to problems in stationarity. Interestingly and importantly, although minimization and maximization are valid only for real-valued functions, staticization is valid more generally for functions taking values in Hilbert spaces, including the complex field and Euclidean space. The stat operator maps a function to the values at the points where the function is stationary (roughly speaking, where the derivative is zero). In the case of differentiable coercive, convex functionals, stat generalizes minimization. As currently defined, it does not extend to nonsmooth functionals, although it is important to note that the stat over controls of a payoff often generates a nonsmooth value function. One can develop a theory of dynamic programming for staticization. The development of this theory is allowing for the extension of the above approach for finding fundamental solutions of TPBVPs to indefinitely long duration problems.

In this effort, we have found it extremely useful to represent potential fields in a radically new way. Specifically, the gravitational and Coulomb fields are represented in terms of stat operations over functions which are quadratic in position and cubic in a new parameter. These representations are critical to the application of stat based methods for the development of fundamental solutions to n-body, astrodynamic and Schrödinger applications.

The introduction of stat-based representations for potentials leads to forms for their solutions in terms of iterated staticization operations. Key to the methods is the ability to commute these operations for the problems of interest. This commutativity was first obtained for quadratic cases, allowing for a new method for propagation of differential Riccati equation solutions (DREs) past escape times, where this is necessary for solution of conservative dynamical systems. However, the domains of more interest are those where one of the staticization operators is used to define a potential field. In that case, the results for quadratic functions are not valid. However, fortuitously, in the case where the inner staticization is generating a gravitational or Coulomb field, and the outer staticzation is quadratic in the control value, we are able to show that the order of the staticization operators may be reversed, yielding fundamental solutions and curse-of-dimensionality-free numerical methods. In particular, although the commutativity has been rigorously demonstrated only on a relatively small set of functions, this set includes all the known cases of interest.

With this approach, an issue arises when one encounters TPBVPs which may have multiple solutions. As an example of such degenerate behavior, simply consider a point mass in orbit around a spherically symmetric body such that the initial and terminal positions are antipodal, and with a time duration of the appropriate half-period. Then, there are an infinite number of solutions obtained by rotating any solution around the axis defined by the two points. We are able to show that under certain reasonable conditions, such problematic situations only occur on a set of measure zero.

2.5 TPBVPs in Astrodynamics and Schrödinger IVPs.

Our motivating interests are the solution of TPBVPs in conservative systems (specifically astrodynamics and the wave equation) and the solution of Schrödinger IVPs. In particular, we are developing tools for extremely rapid solution of these classes of problems. Previous efforts by the PI in the area of conservative systems have mainly developed the least-action approach, which is only viable for short durations, combined with a method for stitching such together by a stationarity condition at the intersection points, where this condition is quite reasonable from a computational standpoint. However, a much cleaner approach, both theoretically and computationally, requires the development of the new area of staticization, which is discussed above.

The action functional encountered in the above-discussed approach to fundamental solutions of TPBVPs also arises in the Schrödinger equation. The solution of the Schrödinger initial value problem (IVP) is a complex-valued function over real space and time. Although minimization and maximization are restricted to real-valued functionals, staticization extends to the complex case. Using staticization and an extension of the space domain to the complex-valued case, we obtain a Feynman-Kac representation for the solution of the Schrödinger IVP in the case of a holomorphic potential as the stationary-value of the expectation of the action functional, with dynamics given as a linear, complex-valued stochastic differential equation over indefinitely long duration problems. Although such has been long expected, dating back to Feynman's original model development, previous efforts had been unable to obtain such. This is being extended to cover not only potentials with holomorphic complex extensions, but to also cover other relevant cases, such as the Coulomb potential. We are currently in the process of developing both curse-of-dimensionality-free and fundamental-solution methods for these problems.