Research Statement

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1 Overview

My research lies at the intersection of optimization, control, and estimation with applications ranging from networked systems to energy-efficient buildings.

1.1 Networks of dynamical systems

Large-scale networks of dynamical systems are becoming increasingly important in science and technology. These systems arise in applications ranging from social networks to power systems to robotics. In the modeling, analysis, and control of networked systems, understanding the interplay between the network structure and the underlying dynamical properties is of fundamental importance. My research centers on the design of distributed controllers and the analysis of performance limitations in large-scale networks of dynamical systems, with emphasis on identifying communication architectures and designing structured controllers.

With Fardad and Jovanović, I developed a sparsity-promoting optimal control framework to quantify the tradeoff between the performance of systems and the sparsity of controllers [1]. Subsequently, we developed efficient algorithms for the synthesis of distributed controllers in the formation of vehicles [2], robust consensus for leader-follower networks [3], and the synchronization of oscillators [4].

1.2 Structured optimal state feedback gains

One thread in my research is the optimal design of structured controllers. This design problem arises in wide-area control of power systems where the communication between subsystems is limited. The resulting structural constraints are in the form of sparsity requirements for the feedback matrix, implying that each controller has access to information from only a limited number of subsystems. With Fardad and Jovanović, I developed an augmented Lagrangian method and showed that this approach does not require a stabilizing structured gain to initialize the optimization algorithm [5]. This feature is important in practice because finding a structured stabilizing gain is numerically challenging. I also utilized the sensitivity interpretation of the Lagrange multipliers to identify favorable communication architectures. The structured controllers have been used in frequency regulation of power systems [6] and control of high-density microcantilevers [7].

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1.3 Input estimation via structured covariances

Another aspect of my work is the input estimation of dynamical systems using second-order statistics. State covariances of linear systems must satisfy certain constraints that are imposed by the underlying dynamics. However, sample covariances in practice almost always fail to have the required structure. Renewed interest in using state covariances for estimating the power spectra of inputs gives rise to the approximation problem. With Jovanović, I studied the structured covariance least-squares problem and converted the Lyapunov-type matrix linear constraint into an equivalent set of trace constraints [8]. This reformulation enables the development of efficient quasi-Newton methods for the associated dual problem. This work was cited in a recent SIAM review article [9].

1.4 Mixed-integer programming with application to cogeneration in buildings

I am also interested in optimization algorithms with applications in energy systems. At Argonne National Laboratory, I have been exposed to a wide range of challenging problems that arise in power systems. One project involves the design of cogeneration systems in buildings. Recent advances in renewable technologies have motivated designing economically viable cogeneration systems to reduce energy consumption and emission of green house gases by buildings.

The design and operation of the purchased renewable machines give rise to a two-stage mixed-integer program with more than 1 million binary variables to model the on/off operation over a 10-year horizon. This problem also arises in other applications such as the transmission network expansion subject to unit commitment constraints. With Leyffer and Munson, I developed a two-level approach in [10] by constructing a semi-coarse model (coarsened with respect to variables) and a coarse model (coarsened with respect to both variables and constraints). The coarsened models can be solved in a fraction of the time required to solve the original problem. The algorithm was implemented in AMPL and verified by using simulation data for a variety of commercial buildings. The developed numerical tools are valuable for a realistic savings analysis, which provides economic incentives for the wide adoption of renewable technologies.

2 Research plans

My long term research objective is to develop mathematical tools and numerical algorithms for the estimation, control, and optimization of energy systems. I will leverage tools from my past work and develop new research directions.

2.1 Self-calibrated sensor networks for monitoring air quality in cities

Rapid improvement in our understanding of urban air quality relies on advances in sensing technology. Sensors have been deployed at street level to collect real-time data of the city's environment and activities. Mounting sensors in a cost-effective way subject to constraints introduced by city policies, privacy concerns, and physical limitations is a challenging but important problem.

My research interest in this project is to develop mathematical tools for the optimal design of self-calibrated sensor networks. First, the sensor placement problem will be studied in the 3D domain with the grid of streets and a specified range of height to monitor pollutants. In contrast to estimation problems in 2D domains, the complexity of the mathematical models for 3D estimation problems is orders of magnitude larger. New algorithms are thus required to process large data sets in real time. Second, conflicting objectives such as the number of sensors and the accuracy of estimation in sensorless streets must be addressed. Pollutants differ significantly in their physical properties (e.g., lighter gases such as ozone tend to rise, while heavier gases such as CO_2 tend to sink). The challenge to design the sensor network is to balance accuracy among dozens of different pollutants in addition to the aforementioned constraints. Third, the tradeoff between the network topology and the estimation accuracy must be quantified numerically. The design tools also need to be extensible in order to adjust to city-specific features such as weather patterns, architectures, and natural terrain.

One important outcome of this work would be to integrate the mathematical models and numerical algorithms in the *Array of Things*, an urban sensing project developed at Argonne National Laboratory in partnership with the City of Chicago.

2.2 Dynamic wind power forecasting using Bregman divergences

State-of-the-art forecasting systems for wind energy employ a two-step optimization procedure. First, the forecast systems integrate a large number of forecasting models and perform a regression analysis to remove bias from each model. Second, the forecasting systems assign weights to models based on the training data over a given period of time, and generate a consensus forecasting using the weighted models. This two-step calculation is performed weekly, typically over a ninety-day period of data for the entire North America [11].

Traditionally, least-squares estimation is the primary choice to quantify the performance of forecasting models. This measure, while computationally inexpensive, is highly sensitive to outliers. Dhillon and Tropp [12] demonstrated that Bregman divergences are appealing alternative measures because they are robust to outliers in addition to possessing other desired properties in learning theory. The price to pay is that Bregman divergences are computationally expensive and efficient numerical algorithms are yet to be developed.

Motivated by recent progress in proximal algorithms, I intend to study the wind energy forecasting problem using Bregman divergences. I will show that this problem can be dealt with within the proximal operator framework. In my earlier work, I have used proximal algorithms for the design of sparse feedback gains [1]. My objective in this project is to develop scalable algorithms for Bregman divergences and demonstrate their advantages in wind power forecasting over least-squares estimation.

2.3 Multilevel approach to nonlinear optimization

Many challenging problems in energy systems can be formulated as large-scale nonlinear optimization problems. Specific types of nonlinear constraints that capture the underlying physics give rise to different problem classes, such as PDE-constrained problems, mixed-integer problems, and stochastic problems. While these problem classes traditionally require customized algorithms that exploit specific structures, a multilevel framework has emerged as a unifying theme behind several state-of-the-art algorithms. With its roots in multigrid methods for solving elliptic PDEs, the multilevel approach has become one of the most effective methods for PDE-constrained optimization [13].

One advantage of the multilevel framework is that it provides the flexibility for hybrid algorithms. Most derivative-based optimization methods rely on the first-order or the second-order derivative information throughout the entire algorithmic design. My philosophy is that one should exploit both first- and second-order information, whenever appropriate, in order to successfully tackle these challenging problems. The multilevel approach builds a hierarchy of approximated problems with different levels of accuracy. At coarse levels where problem sizes are small, one takes advantage of robustness and accuracy of second-order methods; and at fine levels where problem sizes are large, one designs first-order methods given the problem structure in hands.

I believe that such a flexible framework is most suitable for end-users to trade off between solution optimality and computational resources in practice, and the multilevel framework has great potential to transform practical optimization in the next 10 years.

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