Large Scale Optimization and Control

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The project will develop basic theory and methodology for distributed optimization, learning and decision-making in large scale dynamic systems. This is essential to efficiently and reliably operate infrastructure networks for transportation, communications, data, electricity, heat and water, as well as smart cities and health care. The main research challenges are in the intersection between optimization, control, statistics, machine learning and economics.

Vision for the project

Background: Our modern society is critically dependent on large-scale networks for services such as energy supply, transportation and communications. The design and operation of such networks is becoming increasingly complex, due to their growing size, autonomy and heterogeneity. To address these difficulties, a systematic theory and methodology for large-scale optimization and control is needed. The project is addressing this challenge, building on leading academic expertise in related areas, in combination with strategic industrial and international partnerships.

Objective: New theory and methodology will be developed in the form of algorithms and analysis methods for dynamic operation of large scale systems. Optimization methods will be designed to operate in real time interaction with the physical environment. For scalable solutions, this means that data needs to processed in a distributed fashion, where local units for sensing, computation and actuation are coordinated via physical infrastructure as well as communication networks and broadcast technology. A relevant scenario is transmission and distribution of electrical power, where high penetration of wind and solar power needs to be balanced by flexible demand response triggered by economic incentives, with coupling to district heating networks and gas networks. Another scenario is traffic control, where efficient methodology is needed to coordinate routing and speed control for individual cars with conflict resolution at intersections and coordination of traffic flow at a higher level.

Connection to other WASP Projects:
Many other WASP projects are devoted to networks of autonomous systems, such as vehicles and robots, designed to interact with other agents in a complex environment. Here optimization is an important tool and scalability is a central issue. In particular, the project on Perception, Learning and Verification relies heavily on scalable methods for optimization. Another example is the project Autonomous Cloud which gives an implementation for methods developed in this project, while the Automated Transport Systems is focusing on an important application, where methods for large scale optimization and control play an important role.

Future Demonstrations: This project is closely related to the goals stated for the WASP WARA-CAT research arena. However, the truly large-scale aspects of the project will be hard to test in an artificial experimental environment. As a consequence, opportunities for full scale demonstrations will rely on collaborations with partners outside WASP, such as networks operators for traffic, power or district heating.

Research Challenges

Scalable optimization in a dynamic environment

Optimization is already a widely used technology for dynamic control. The premier example is Model Predictive Control based on centralized information, which is widely used, but far from scalable. On the other hand, there is also a rapid growth of algorithms designed for scalability, but not in the context of dynamical systems. The challenge is to combine the two, such that stability and dynamic performance can be guaranteed, even when the algorithmic dynamics of scalable optimization are strongly coupled with dynamics of physics, humans and communications.

Global versus local information

The theory for control and decision-making is relatively straightforward when full information about the system is available. Another widely studied case is where information is limited, but localized and fixed. This case is much more complicated to analyze, but good practical solutions often exist. Our challenge is to develop scalable methods for control based on propagation of partial information, with provable bounds on dynamic performance. In this setting, global broadcast information could be combined with local information kept for internal use.

Adaptation and Learning

The rapid growth of machine learning algorithms during the past decades has drastically changed the way we approach modeling and decision-making in autonomous systems. Most likely, this development has only just started. However, most of the learning theory has been developed without explicit regard for dynamics. For efficient integration of the new learning algorithms with control of dynamical systems we will build on established theory for adaptive control and systems identification, where stability and dynamic performance is explicitly taken into account.

Control through economic incentives

Many applications have a strong presence of independent decision-makers, responding to price variations and individual preferences. The integration and coordination of such decision-makers will be studied for a resource sharing network, where time-varying local demands are to be balanced by time-varying supplies elsewhere in the network. The actions of each node are governed by a desire to optimize a given utility function. In addition to local production and consumption, the exchange between nodes is limited by capacity constraints of the network links. Our objective is to understand and exploit the interaction between node demands and network dynamics. Privacy, security and fairness will be essential factors in evaluation of achievable performance.

Industrial Challenges

There are numerous industrial challenges relating to this project. ABB is selling hardware and software for automation of industrial processes, where optimization plays a key role. Industrial trends are increasingly facilitating integration and data exchange between low level control loops and high level process management and business decisions. This is increases the need for scalable optimization and control. Cloud technology (for example provided by Ericsson) stimulates this development further. Moreover, the "sharing economy" is creating new business models, where information exchange and price mechanisms enable more efficient solutions to many societal needs. For industry, this means new opportunities. At the same time, also the role of government is becoming increasingly complex, creating a demand for analytical tools as provided by this project.

Sub-projects

Large-Scale Optimization for Distributed Control
Shervin Parvini Ahmadi, LiU
This PhD project will investigate network topology such as hierarchical network structure, e.g. chordal graphs, for scalable and rigorous robustness analysis and the extension of this towards hierarchical and distributed control synthesis. We will also study how privacy affects the achievable performance and what amount of communication that is needed between different computational agents in order to achieve the most efficient overall computations. Relevant applications are within infrastructure networks for traffic, water, gas, electricity, and building control. In this project we primarily focus on applications within power grids. Contacts have been established with ABB Corporate Research in Switzerland.

Advanced real-time planning and decision making for autonomous systems
Kristoffer Bergman (industrial student), SAAB and LiU
This project aims at developing state-of-the-art real-time planning and decision making algorithms that we believe will play a key-role of the "intelligence" of future autonomous systems. We would like to, as far as possible, to work model based and minimize situation and platform specialization, as well as operator involvement. The algorithms should themselves find solutions, i.e., a sequence of decisions in time, to the given problems formulated in the form of a user-defined mission objective, constraints on behaviors and actions, and a model of relevant parts of the world (updated in real-time from observations and communication) where the platform acts.

Control using Distributed Information
Hamed Sadeghi, Lund University
Motivated by applications in infrastructure networks (mainly traffic and transportation) we are studying how network flows can be optimized using distributed controllers. Existing results for linear systems with an H-infinity objective will be generalized to accommodate non-linear flow constraints and other convex objectives. Tradeoffs between congestion reduction and shortest path solutions will be studied. During the initial phase, we will study how desirable static performance objectives can be met using distributed feedback. Objectives and constraints appearing in traffic and transportation networks will be emphasized. The next step is to design the dynamic properties of the distributed controllers, while keeping the static properties intact.

Integrated verification, optimization and learning
Fredrik Hagebring, academic PhD, Chalmers
This project focuses on combining formal verification and optimization in correct-by design control synthesis. The synthesis is based on specifications of the desired system behavior that may include performance, safety and liveness properties. Optimality in terms of cost, performance and energy is also crucial. To get a holistic view, correctness and optimality need to be further related. The goal is to obtain a unified framework that guarantees optimal and correct behavior of autonomous systems, including both controllable and uncontrollable/spontaneous dynamic behavior. Robustness concerning uncertainties and adaptation/learning based on changes in decisions and system behavior will be considered.