Multi-Agent Model Predictive Control

with Applications to Power Networks

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Summary

Multi-Agent Model Predictive Control with Applications to Power Networks

Transportation networks, such as power distribution and transmission networks, road traffic networks, water distribution networks, railway networks, etc., are the corner stones of modern society. A smooth, efficient, reliable, and safe operation of these systems is of huge importance for the economic growth, the environment, and the quality of life, not only when the systems are pressed to the limits of their performance, but also under regular operating conditions. As transportation networks have to operate closer and closer to their capacity limits and as the dynamics of these networks become more and more complex, currently used control strategies can no longer provide adequate performance in all situations. Hence, control of transportation networks has to be advanced to a higher level using novel control techniques.

A class of transportation networks for which such new control techniques are in particular required are power networks. The structure of power networks is changing at several levels. At a European level the electricity networks of the individual countries are becoming more integrated as high-capacity power lines are constructed to enhance system security. At a national level power does not any longer only flow from the transmission network in the direction of the distribution network and onwards to the industrial sites and cities, but also in the other direction. Furthermore, at the local level controllable loads are installed, energy can be generated locally with small-scale generators, and energy can be stored locally using batteries. To still guarantee basic requirements and service levels and to meet the demands and requirements of the users while facing the changing structure of power networks, state-of-the-art control techniques have to be developed and implemented.

In this PhD thesis we propose several new control techniques designed for handling the emerging problems in transportation networks in general and power networks in particular. To manage the typically large size and distributed nature of the control problems encountered, we employ multi-agent approaches, in which several control agents each control their own part of the network and cooperate to achieve the best possible overall performance. To be able to incorporate all available information and to be able to anticipate undesired behavior at an early stage, we use model predictive control (MPC).

Next we give a summary of the control techniques proposed in this PhD thesis and the control problems from a particular class of transportation networks, viz. the class of power networks, to which we apply the proposed control techniques in order to assess their

performance.

Multi-agent model predictive control

In multi-agent control, control is distributed over several control agents. The control agents can be grouped according to the authority relationships that they have among each other. The result is a layered control structure in which control agents at higher layers have authority over control agents in lower layers, and control agents within a control layer have equal authority relationships. In multi-agent MPC, control agents take actions based on predictions that they make using a prediction model of the part of the overall system they control. At higher layers typically less detailed models and slower time scales are considered, whereas at lower layers more detailed models and faster time scales are considered.

In this PhD thesis the following control strategies for control agents at various locations in a control structure are proposed and discussed:

- For coordination of control agents within a control layer a novel serial scheme for multi-agent MPC is proposed and compared with an existing parallel scheme. In the approach it is assumed that the dynamics of the subnetworks that the control agents control are purely continuous and can be modeled with interconnected linear discrete-time time-invariant models in which all variables take on continuous values.

- In practice, the dynamics of the subnetworks may show hybrid dynamics, caused by both continuous and discrete dynamics. We discuss how discrete dynamics can be captured by systems of linear equalities and inequalities and how control agents can use this in their decision making. In addition, we propose an extension of the coordination schemes for purely continuous systems that deals with interconnected linear time-invariant subnetworks with integer inputs.

- For an individual control agent that determines set-points for control agents in a lower control layer, creating object-oriented prediction models is discussed. Such an object-oriented prediction model is then used to formulate an MPC control problem. We propose to use the optimization technique pattern search to solve the resulting MPC control problem. In addition, for efficiency reasons, we propose an MPC control strategy based on a linearization of the object-oriented prediction model.

- Commonly, subnetworks are defined based on already existing network regions. Such subnetworks typically do not overlap. However, when subnetworks are based on, e.g., regions of influence of actuators, then the subnetworks may be overlapping. For multiple control agents in a higher control layer, at which it can be assumed that the behavior of the underlying control layers is static, we propose an MPC strategy for control of overlapping subnetworks.

Multi-agent control problems in power networks

Power networks are a particular class of transportation networks and are subject to a changing structure. This changing structure requires the development of advanced control techniques in order to maintain adequate control performance. The control strategies proposed

in this PhD thesis are applied to and assessed on specific power domain control problems. In particular, we discuss the following power network problems and control approaches:

- We consider a distributed load-frequency control problem, which is the problem of maintaining frequency deviations after load disturbances close to zero. Control agents each control their own part of the network and have to cooperate in order to achieve the best possible overall network performance. The control agents achieve this by obtaining agreement on how much power should flow among the subnetworks. The serial and parallel MPC strategies are employed for this, both when the prediction models involve only continuous variables, and when the prediction models involve both continuous and discrete variables. In simulations we illustrate the performance that the schemes can obtain.

- In the near future households will be able to produce their own energy, store it locally, sell it to an energy supplier, and perhaps exchange it with neighboring households. We propose an MPC strategy to be used by a control agent controlling the energy usage in a household. This control agent takes into account expected energy prices, predicted energy consumption patterns, and the dynamics of the household, including dynamics of local energy generation and storage devices. For a given scenario of energy prices and consumption patterns, the performance that the control agent can achieve are illustrated.

- Voltage instability is a major source of power outages. To prevent voltage instability from emerging, a lower layer of control agents is installed in power networks at generation sites. These agents locally adjust generation to maintain voltage magnitudes. Such local control works well under normal operating conditions. However, under large disturbances such local control does not provide adequate performance. In such situations, the actions of the local control agents have to be coordinated. We propose an MPC control agent that has the task to coordinate the local control agents. The MPC strategy that the agent uses is based on either an object-oriented model of the power network or on a linearized approximation of this model. The object-oriented model includes a model of the physical network and the local control agents. We illustrate the performance of the MPC control agent using the object-oriented model or the linearized approximation via simulations on a dynamic 9-bus power network.

- Optimal power flow control is commonly used to improve steady-state power network security by improving the voltage profile, preventing lines from overloading, and minimizing active power losses. Using optimal power flow control, device settings for flexible alternating current transmission systems (FACTS) can be determined. We consider the situation in which there are several FACTS devices, each controlled by a different control agent. The subnetwork that each control agent considers consists of a region of influence of its FACTS device. Since the subnetworks are based on regions of influence, the subnetworks of several agents may be overlapping. We propose a coordination and communication scheme that takes this overlap into account. In simulation experiments on an adjusted 57-bus IEEE power network the performance of the scheme is illustrated.

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