Multi-Agent Model Predictive Control
with Applications to Power Networks

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Multi-Agent Model Predictive Control
with Applications to Power Networks

Proefschrift

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Chapter 1

Introduction

In this chapter we present the background and the motivation for the research addressed in this thesis. In Section 1.1 we first introduce the type of systems that we consider: transportation networks in general, and power networks in particular. In Section 1.2 we then discuss controlling such systems and motivate the use of multi-agent control structures. In Section 1.3 the conceptual ideas of model predictive control are presented as strategy for the control agents to determine which actions to take, and various issues to be addressed in relation with model predictive control and multi-agent control structures for transportation networks are discussed. In Section 1.4 we discuss opportunities for the use of multi-agent model predictive control in the power networks of the future, and in Section 1.5 we conclude the chapter with an overview and road map of this thesis, and a list of the contributions to the state of the art.

Parts of this chapter have been published in [107].

1.1 Transportation networks

Transportation or infrastructure networks, like power distribution networks [82], traffic and transportation systems [33], water distribution networks [21], logistic operations networks [88], etc., are the corner stones of our 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. Recent examples illustrate this. E.g., the problems in the USA and Canada [141], Italy [139], Denmark and Sweden [43], The Netherlands, Germany, Belgium, and France [140], and many other countries [114, 148] due to power outages have shown that as power network operation gets closer to its limits, small disturbances in heavily loaded lines can lead to large black-outs causing not only huge economic losses, but also mobility problems as trains and metros may not be able to operate. Also, as road traffic operation gets closer to its limits, unexpected situations in road traffic networks can lead to heavy congestion. Not only the huge traffic congestion after incidents such as bomb alerts are examples of this, also the almost daily road-traffic jams due to accidents illustrate this convincingly.

Expanding the physical infrastructure of these networks could help to relieve the issues

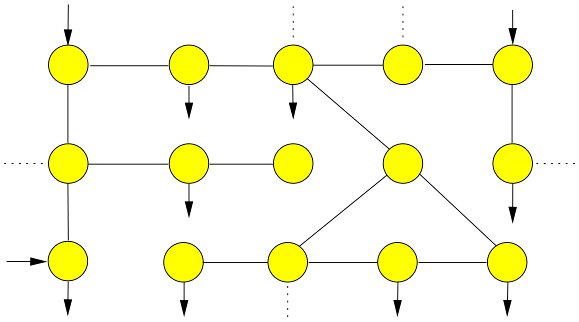


Figure 1.1: Generic transportation network. Commodity enters the network at sources (circles with an arrow pointing towards them), flows over links to other elements in the network that alter the flows (at each circle, and leaves the network at sinks (circles with an arrow pointing outward). Dotted lines represent connections with other parts of the network.

in transportation networks, although at extremely high costs. As alternative to spending this money on building new infrastructure, it is worth spending effort on investigating improved use of the existing infrastructure by employing intelligent control techniques that combine state-of-the-art techniques from fields like systems and control engineering [6], optimization [18], and multi-agent systems [147], with domain-specific knowledge.

The examples of networks just mentioned are only some particular types of networks within the much larger class of transportation networks. Common to transportation networks is that at a generic level they can be seen as a set of nodes, representing the components or elements of the network, and interconnections between these nodes. In addition, transportation networks have some sort of commodity, that is brought into the network at source nodes, that flows over links to sink nodes, and that is influenced in its way of flowing over the network by elements inside the network, as illustrated in Figure 1.1. Other characteristics that are common to transportation networks are:

- they typically span a large geographical area;
- they have a modular structure consisting of many subsystems;
- they have many actuators and sensors;
- they have dynamics evolving over different time scales.

In addition to this, transportation networks often contain both continuous (e.g., flow evolution) and discrete dynamics (e.g., on and off switching), and are therefore also referred to as hybrid systems [143]. This mixture of characteristics makes that transportation networks can show extremely complex dynamics.

Even though transportation networks differ in the details of commodity, sources, sinks, etc., it is worth to consider them in a generic setting. On the one hand, methods developed for generic transportation networks can be applied to a wide range of specific domains, perhaps using additional fine-tuning and domain-specific enhancements to improve the per-

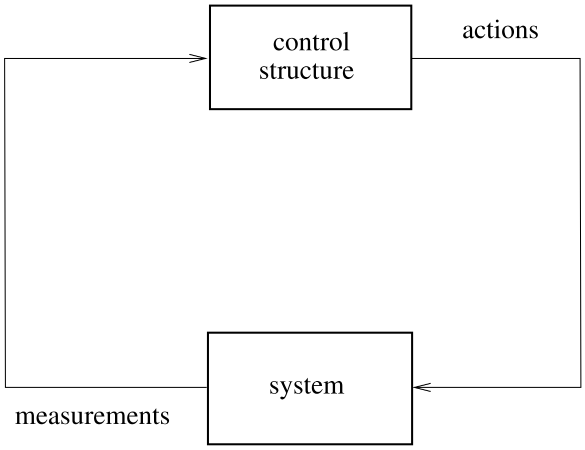


Figure 1.2: The relation between a general system and the control structure that controls the system.

formance. On the other hand, approaches specifically developed for a particular domain can be applied to other domains after having transfered them to the generic framework.

1.2 Control structures

There are many users, controllers, players, actors, and operators involved in the evolution of transportation networks. Each of these refers to entities that directly or indirectly change the way commodity is flowing. Different users may have different objectives, and these objectives may be conflicting. Objectives that users may have involve avoiding congestion of links, maximizing throughput, minimizing costs of control actions, minimizing travel times, etc. An example of conflicting objectives in a road traffic network is given by the objectives that the individual road users have on the one hand and road authority has on the other: The individual road users want to minimize the travel time to their destination, whereas the road authority wants to minimize overall network congestion [134]. An example in the domain of power networks is given by the objectives that the individual households have on the one hand and the government has on the other: The individual households aim at minimizing the costs on energy, whereas the government aims at maximizing usage of the perhaps more expensive green energy. Also, in power networks, it may sometimes be beneficial for the overall network performance to cut off certain parts of the network from electricity consumption in a controlled way in order to prevent large black-outs [142], even though individual consumers perhaps do not want this.

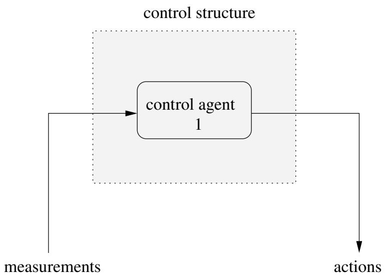
In order to formalize the operation of transportation networks, consider Figure 1.2. The figure illustrates the overall picture of a *system* on the one hand and a *control structure* on the other. The system is the entity that is under control, and the control structure is the entity that controls the system. Hence, the control structure is the concept used to indicate the structure that produces actuator settings. The control structure monitors the system by making measurements and based on these chooses control actions that are implemented on the system. The system evolves subject to these actions to a new state, which is again measured by the control structure. The control structure consists of one or more components, called *control agents*. These control agents try to determine settings for the actuators inside the system in such a way that their own objectives are met as closely as possible and any constraints are satisfied. In our case, the system consists of the transportation network, and the components of the control structure consists of all the users, controllers, operators, players, etc., from now on only referred to as the control agents.

The control structure is a very general concept and can have many different shapes. A first important distinguishing feature between control structures is the number of control agents that constitute the control structure. E.g., the control structure can consist of a single control agent or multiple control agents. Some other properties in which control structures can differ are:

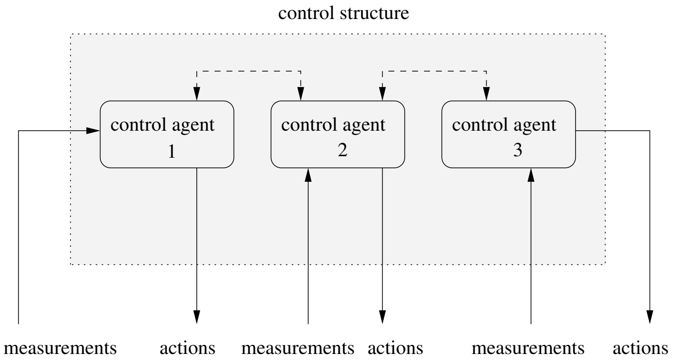
- the access that the control agents have to the sensors and actuators in the network,
- the communication that the control agents have among one another,
- the way in which the control agents process sensor data to obtain actions,
- the authority relations between the control agents,
- the beliefs, desires, and intentions of the control agents,
- etc.

Defining different types of control structures is difficult due to the large amount of properties that they can have. However, some general types of control structures can be identified, that have increasing complexity, that are commonly encountered in theory and practice, and that will also be of particular interest in the subsequent chapters:

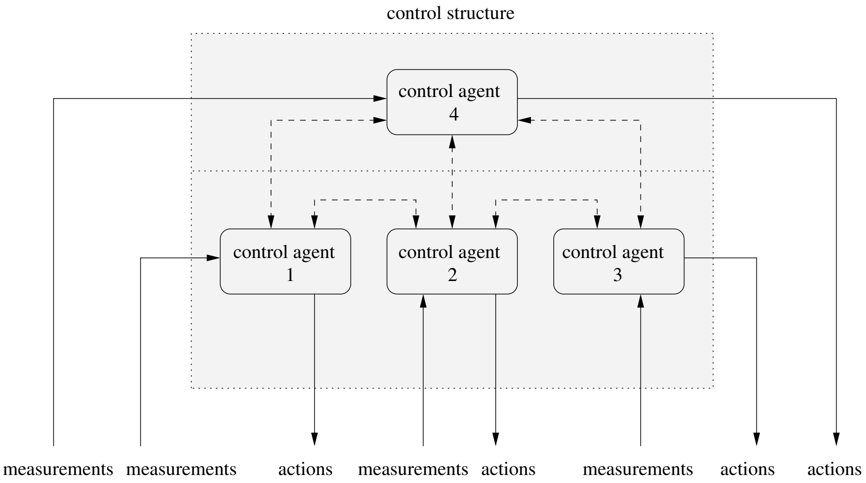
- When it is assumed that there is only one control agent, that has access to all actuators and sensors of the network and thus directly controls the physical network, then this control structure is referred to as an *ideal single-agent* control structure, as illustrated in Figure 1.3(a). The control structure is referred to as an ideal structure, since in principle such a control structure can determine actions that give optimal performance.
- When there are multiple control agents, each of them considering only its own part of the network and being able to access only sensors and actuators in that particular part of the network, then the control structure is referred to as a *multi-agent single-layer* control structure, as illustrated in Figure 1.3(b). If in addition the agents in the control structure do not communicate with each other, the control structure is *decentralized*. If the agents do communicate with each other, the control structure is *distributed*.
- When there are multiple control agents, and some of these control agents have authority over other control agents, in the sense that they can force or direct other control agents, then the control structure is a *multi-layer* control structure, as illustrated in Figure 1.3(c) A multi-layer control structure typically is present when one control agent determines set-points to a group of other control agents, that work in a decentralized or distributed way. Due to the authority relationship between agents or groups



(a) Single-agent control structure. The single control agent makes measurements of the system and provides actions to the network.



(b) Multi-agent single-layer control structure. Multiple control agents make measurements and provide actions to the network. Communication between the control agents is optionally present (dashed line).



(c) Multi-layer control structure. A higher-layer control agent can make measurements and provide actions to the network and can in addition direct or steer a lower control layer.

Figure 1.3: Some important types of control structures.

of agents, the multi-layer control structure can also be referred to as a supervisory control structure, or a hierarchical control structure.

1.2.1 Control structure design

Suppose that a particular network is given and that any control structure can be implemented on it. The question that then arises is the question of how it can be determined what the best control structure is. Unfortunately, theories for determining general control structures are lacking. However, motivations for preferring one type of control structure over another can be given.

Advantages of single-agent control structures are in general that they can deliver the best performance possible, and that they have been studied extensively in the literature, in particular for small-scale systems. However, there are several issues that complicate the use of single-agent control structures for large-scale transportation networks such as:

- undesirable properties with respect to robustness, reliability, scalability, and responsiveness;
- technical issues related to communication delays and computational requirements;
- commercial, legal, and political issues related to unavailability of information and restricted control access.

These reasons motivate the use of multi-agent control structures [135, 145, 147], which are expected to be able to deal or at least relieve these issues. Multi-agent control structures can in principle:

- improve robustness and reliability, since if one control agents fails, another can take over, and improve responsiveness, since the control agents typically use only local measurements and therefore can react quicker to changing situations;
- reduce communication delays, since the control agents operate locally and therefore solve problems that may be smaller, and since coomunication typically takes place among nearby control agents;
- deal with unavailability of information and restricted control access, since the control agents only require information of their own part of the network and since they determine actions only for their own part of the network.

However, typically multi-agent control structures have a lower performance than the performance of ideal single-agent control structures and implementing schemes that give desired performance is far from trivial.

An advantage of the decentralized over the distributed multi-agent single-layer control structures is that there is no communication between the controllers, resulting in lower computational requirements and faster control. However, this advantage will typically be at the price of decreased overall performance. The advantage of a distributed multi-agent single-layer control structure is therefore that improved performance can be obtained, although at the price of increased computation time due to cooperation, communication, and perhaps negotiation among control agents. However, even though improved performance can be obtained, the performance will still typically be lower than the performance of an ideal single-agent control structure.

The multi-agent multi-layer control structure provides the possibility to obtain a trade-off between system performance and computational complexity. A higher layer considers a larger part of the system and can therefore direct the lower control layer to obtain coordination. Such a multi-layer control structure can thus combine the advantages of the single-agent control structure with the multi-agent single-layer control structure, i.e., overall system performance with tractability. It is noted, however, that communication in a multi-agent multi-layer control structure is typically more complex than in a single-agent control structure and a multi-agent single-layer control structure.

Note that in practice often a particular control structure is already in place, and that the control structure cannot be redesigned from scratch. The question in this case is not so much the question of what control structure is best, but of how the currently existing control structure can be changed, such that the performance is improved. Of course here it has to be defined what the performance is, and in a control structure with control agents with conflicting objectives it may not be possible to reach consensus on this.

1.2.2 Assumptions for design and analysis

In this thesis we develop control strategies for several control structures. Due to the complexity of transportation networks, we have to narrow the scope of control problems that we will consider. Our focus will mostly be on the most fundamental of transportation network control problems: the operational control of transportation networks, in which amounts of commodity to be transported over the network are given, and controllers have to ensure that transport over the network can take place at acceptable service levels, while satisfying any constraints, both under normal and emergency operating conditions.

In order to make the analysis and the design of the control structures more tractable, assumptions have to be made, both on the network and the control structure. Assumptions relating to the network are made on the dynamics of the network, i.e., the way in which the components in the network function. E.g., the dynamics can be assumed to evolve over continuous time or in discrete-time, they can be assumed to involve only continuous dynamics, or both continuous and discrete dynamics, and they can be assumed to be instantaneous or not. In each chapter we explicitly point out which particular assumptions are made on the network.

With respect to the control structure, we assume in each of the following chapters that:

- the control agents are already present;
- the control agents control fixed parts of the network, and they can access actuators and sensors in these parts of the network;
- the control agents know what qualitative behavior is desired for the parts of the network they control;
- the control agents strive for the best possible overall performance of the network;
- the control agents can measure the state of the parts of the network that they control.

Under such assumptions it remains to be decided on how the agents in the control structure get from their measurements to actuator settings, i.e., what protocols, computations, and information exchanges take place inside the control structure. Assumptions on these are made in the subsequent chapters. In the following section we discuss the approach that we propose to be used by the control agents in a multi-agent control structure for transportation network control: model predictive control.

1.3 Model predictive control

To find the actions that meet the control objectives as well as possible, the control agents have to make a trade-off between the different available actions. In order to make the best decision and hence find the best actions, all relevant information about the consequences of choosing actions should be taken into account. For power networks, typical information that is available consists of forecasts on power consumption and exchanges [55], capacity limits on transmission lines, dynamics of components like generators, capacitor banks, transformers, and loads [82]. Furthermore, typically area-wide measurements of voltage magnitude and angles across the network can be made to provide an up-to-date status of the situation of the network. A particularly useful form of control for transportation network that in principle can use all information available is model predictive control (MPC) [27, 93].

1.3.1 Single-agent MPC

Over the last decades MPC (also knowns as receding horizon control or moving horizon control) has become an important strategy for finding control policies for complex, dynamic systems. MPC in a single-agent control structure has shown successful application in the process industry [93, 102], and is now gaining increasing attention in fields like amongst others power networks [49, 61], road traffic networks [58], railway networks [36], steam networks [94], supply chain management [146], food processing [130], mine planning [56], heat-exchanger networks [54], greenhouse control [123], and drug delivery [22].

Concept

MPC is a control strategy that is typically used in a discrete-time control context, i.e., control actions are determined in discrete control cycles of a particular duration which in itself is expressed in continuous time units[1]. From the beginning of one control cycle until the beginning of the next control cycle, the control actions stay fixed, i.e., a zero-order hold strategy is employed.

In each control cycle the MPC control agent uses the following information, as illustrated in Figure 1.4:

- an *objective function* expressing which system behavior and actions are desired;
- a *prediction model* describing the behavior of the system subject to actions;

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[1] Although usually the term control sample step is used to indicate the discrete step at which a control agent determines its actions, we refer to this as control cycle, since later on we will require control step to denote certain steps inside multi-agent MPC strategies.

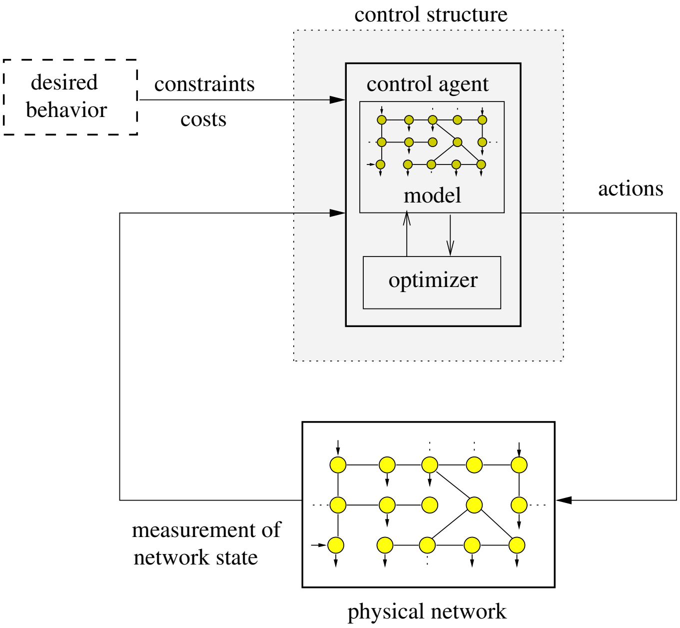

Figure 1.4: Single-agent MPC.

- possibly *constraints* on the states, the inputs, and the outputs of the system (where the inputs and the outputs of the system correspond to the actions and the measurements of the control agent, respectively);
- possibly known information about future disturbances;
- a *measurement* of the state of the system at beginning of the current control cycle.

The objective of the control agent is to determine those actions that optimize the behavior of the system and minimize costs as specified through the objective function. In order to find the actions that lead to the best performance, the control agent uses the prediction model to predict the behavior of the system under various actions over a certain prediction horizon, starting from the state at the beginning of the control cycle. Once the control agent has determined the actions that optimize the system performance over the prediction horizon, it implements the actions until the beginning of the next control cycle, at which point the control agent determines new actions over the prediction horizon starting at that point, using updated information. Hence, the control agent operates in a receding or rolling horizon fashion to determine its actions.

In general it is preferable to have a longer prediction horizon, since by considering a longer prediction horizon, the control agent can better oversee the consequences of its actions. At some length, however, increasing the length of the prediction horizon may not improve the performance, if transients in the dynamics may have become negligible. For computational reasons, determining the actions over a very long horizon typically is not tractable, and in addition due to potential uncertainty in the prediction model and in predictions of future disturbances, a smaller prediction horizon is usually considered. Hence, in practice, the prediction horizon should be long enough to cover the most important dynamics, i.e., those dynamics dominating the performance, and short enough to give tractable computations. It should hereby also be noted that if a prediction horizon is used that is too short, the system could arrive in states from which it cannot continue due to the presence of constraints, e.g., on the actions. The prediction horizon should thus have such a length that arriving in such states can be avoided.

MPC Algorithm

Summarizing, a control agent in a single-agent control structure using MPC to determine its actions performs at each control cycle the following:

1. Measure the current state of the system.
2. Determine which actions optimize the performance over the prediction horizon by solving the following optimization problem:

   minimize the objective function in terms of actions over the prediction horizon
   subject to the dynamics of the whole network over the prediction horizon,
   the constraints on, e.g., ranges of actuator inputs and link capacities,
   the measurement of the initial state of the network at the beginning
   of the current control cycle.

3. Implement the actions until the next control cycle, and return to step 1.

Advantages and issues

Advantages of MPC are that in principle it can take into account all available information and that it can therefore anticipate undesirable situations in the future at an early stage. Additional advantages of MPC are [93]:

- its explicit way of handling constraints on actions, states, and outputs;
- its ability to operate without intervention for long periods;
- its ability to adapt to slow changes in the system parameters;
- its ability to control systems with multiple inputs and multiple outputs;
- its relatively easy tuning procedure;
- its built-in robustness properties.

However, there are also some issues that have to be addressed before a control agent using an MPC strategy can be implemented successfully:

- the control goals have to be specified;
- the prediction model has to be constructed;

- the measurement of the system state has to be available;
- a solution approach has to be available that can solve the MPC optimization problem;
- the solution approach has to be tractable.

Basic issues, e.g., stability and robustness, have extensively been studied for MPC in single-agent control structures [102], in particular for linear time-invariant systems. For other classes of systems there are still many open issues. E.g., tractability issues of MPC for nonlinear and discrete-event systems, and for systems in which variables take on discrete values, still deserve attention. E.g., in [106] we propose one approach to make the MPC problem for a system modeled as a Markov decision process more tractable and to deal with changing system dynamics by including experience using reinforcement learning. Another class of systems for which there are still many open questions are hybrid systems, i.e., systems including both continuous and discrete dynamics. This class of systems currently receives significant attention in MPC research and will be considered in more detail in Chapters 3 and 4.

1.3.2 Multi-agent MPC

As mentioned in the previous section, in a multi-agent control structure, there are multiple control agents, each of them controlling only its own subnetwork, i.e., a part of the overall network. Multi-agent MPC issues have been investigated since the 90s in [1, 2, 12, 25, 28, 38, 41, 48, 53, 72, 74, 75, 77, 117, 129, 144].

In multi-agent MPC, multiple control agents in the control structure use MPC, but now they first measure the subnetwork state, then they determine the best actions over the predicted subnetwork evolution, and then they implement actions. Although this may seem like a straightforward extension of single-agent MPC at first sight, when considering the details it is not.

The actions that an agent in a multi-agent control structure takes influence both the evolution of the subnetwork it controls, and the evolution of the subnetworks connected to its subnetwork. Since the agents in a multi-agent control structure usually have no global overview and can only access a relatively small number of sensors and actuators, predicting the evolution of a subnetwork over a horizon involves even more uncertainty than when a single agent is employed. In addition, when a control agent in a multi-layer control structure provides set-points to another agent, this supervisory control changes the way in which the other agent chooses its actions, and thus the higher-layer control agent changes the performance of the system. Hence, the interactions between the agents make multi-agent MPC involved.

Under the assumption that the control agents strive for an optimal overall network performance, the challenge in implementing such a multi-agent MPC strategy comes from ensuring that the actions that the individual agents choose result in a performance that is as good as when a hypothetical single-agent control structure in which all information is available would be used.

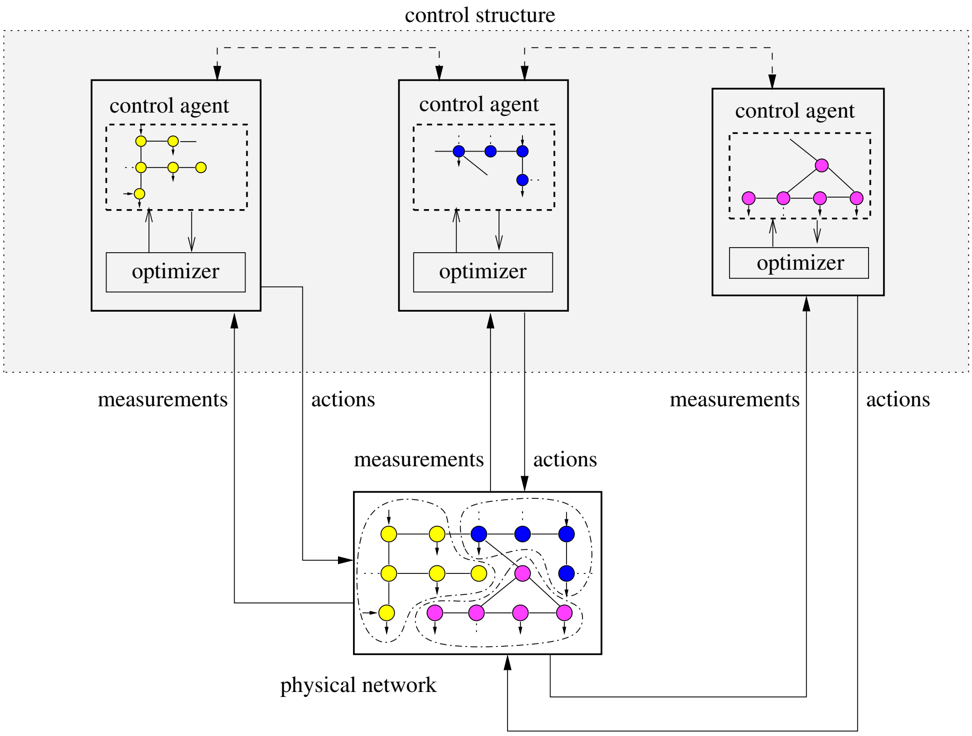

Figure 1.5: Multi-agent single-layer MPC.

Multi-agent single-layer MPC

In the multi-agent single-layer control structure each control agent only has information gathering and action capabilities that are restricted to that part of the network that a particular control agent controls, as illustrated in Figure 1.5. The challenge in implementing multi-agent single-layer MPC comes from predicting the dynamics of the subnetwork, since as mentioned, its evolution is influenced by the other agents. The underlying problem of MPC for multi-agent control structures can therefore be seen as optimization over a distributed simulation.

Issues To make accurate predictions of the evolution of the subnetwork, a control agent requires the current state of its subnetwork, a sequence of actions over the prediction horizon, and predictions of the evolution of the interconnections with other subnetworks. The predictions of the evolution of the interconnections with other subnetworks are based on the information communicated with the neighboring control agents. In Chapter 2 we classify how existing approaches implement this. One particular class of methods aims at achieving cooperation among control agents in an iterative way in which in each control cycle control agents perform several iterations consisting of local problem solving and communication.

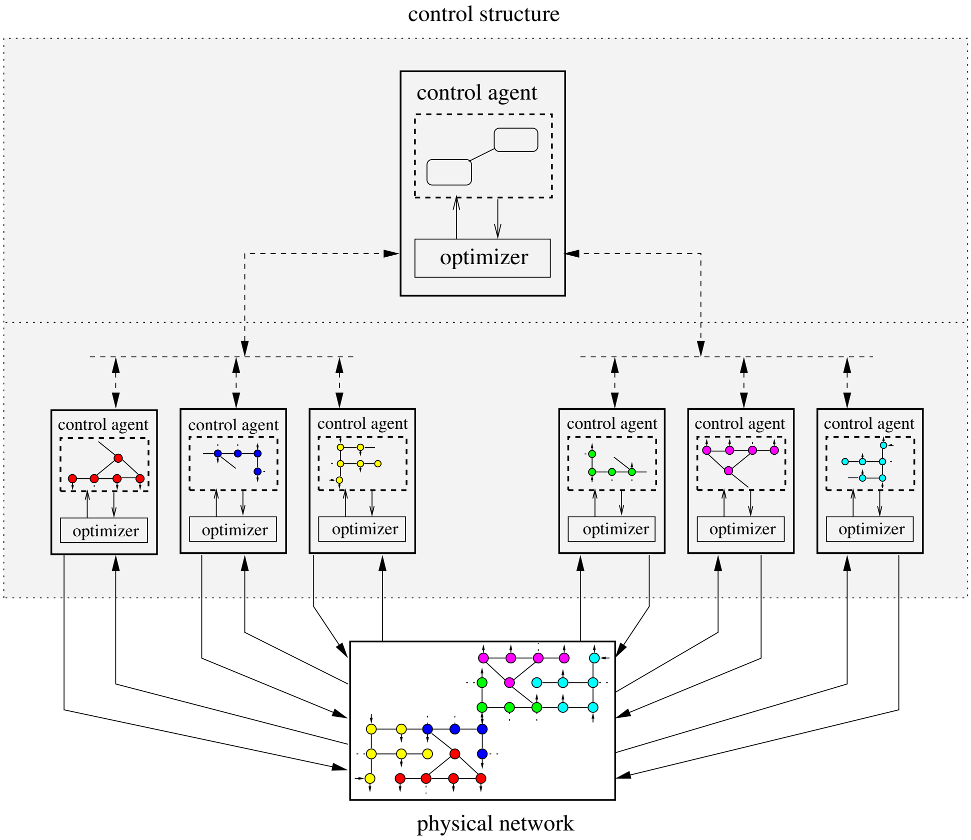

Figure 1.6: Multi-agent multi-layer MPC.

In each iteration agents obtain information about what the plans of neighboring agents are. Ideally at the end of the iterations the agents have found actions that lead to overall optimal performance. In Chapter 2 we discuss such schemes.

As is the case with MPC for single-agent control structures, having both continuous and discrete dynamics causes computational problems. In transportation networks this combination is commonly encountered, and it is therefore relevant to study models that take this into account. In Chapter 3 such models and MPC for multi-agent single-layer control structures for these models are considered.

A further complicating issue arises when the subnetworks that the agents control are overlapping. Existing strategies assume that the subnetworks that the control agents control are non-overlapping. However, in some applications the subnetworks considered by the control agents are overlapping. In Chapter 5 this issue is further addressed.

Multi-agent multi-layer MPC

In the multi-layer multi-agent MPC case there are multiple control layers in the control structure, i.e., there are authority relationships between the agents in the sense that some agents provide set-points or directions to other agents. The agents at higher layers typically consider a larger region of the network and consider slower time scales than agents in lower layers. Figure 1.6 illustrates this.

MPC can also be used by a control agent in a higher layer of the control structure. This higher-layer control agent can then coordinate the lower layer, which may consist of control agents using multi-agent single-layer MPC, or of control agents that use alternative control strategies. The higher-layer control agent then coordinates the lower control layer by enforcing penalty terms, providing additional constraints, or providing set-points. The advantage of the higher-layer control agent is in particular clear when the control agents of the lower layer are working decentralized, i.e., not communicating with one another.

Issues An important issue to be addressed when designing MPC for multi-agent multi-layer control structures is the choice of the prediction model that the higher-layer control agent uses. A higher-layer control agent has to be able to make relevant predictions of the physical system, but since the physical system is under control of the lower-control layer, the lower control layer has to be taken into account by the higher-layer control agent as well. In addition, the prediction model that the higher-layer control agent uses will typically involve both continuous and discrete elements, since it has to consider a larger part of the network than lower-layer agents. This makes the resulting MPC control problem more complex, and efficient ways have to be found to solve it efficiently. In Chapter 4 we address these issues.

1.4 Power networks

In this thesis we develop MPC for multi-agent control structures. In order to illustrate the performance of the developed techniques we use problems from the domain of power networks.

1.4.1 Physical power networks

Power networks [82, 92, 128] are large transportation networks consisting of a large number of components. The dynamics of the power network as a whole are the result of the interactions between the individual components. The generators produce power that is injected into the network on the one side, while the loads consume power from the network on the other. The distribution of the power in the network is dictated by Kirchhoff's laws and influenced by the settings of the generators, loads, transformers, and potentially also by capacitor banks and FACTS devices. This ensemble of components together produces an evolution over time of active and reactive power, and voltage magnitudes and angles. Power networks do not only exhibit continuous dynamics, but also discrete dynamics. Discrete dynamics in power networks appear due to discrete events triggered by on and off switching of generators and loads, breaking of transmission lines, discrete switching logic inside transformers, saturation effects in generators, etc. Hence, power networks are large-scale hybrid systems with complex dynamics.

1.4.2 Future power networks

Power networks are evolving towards a new structure. Conventionally, in power networks, power was generated in several large power generators. This power was then transported through the transmission and distribution network to the location where it was consumed, e.g., households and industry. Power flows were relatively predictable, and the number of control agents was relatively low. Due to the ongoing deregulation in the power generation and distribution sector in the U.S. and Europe, the number of players involved in the generation and distribution of power has increased significantly. In the near future the number of source nodes of the power distribution network will even further increase as also large-scale industrial suppliers and small-scale individual households will start to feed electricity into the network [73].

As a consequence, the structure of the power distribution network is changing from a hierarchical top-down structure into a much more decentralized system with many generating sources and distributing agencies. This multi-player structure thus results in a system with many interactions and interdependencies. In addition, the following interesting developments are taking or will take place:

- At a European scale the electricity networks of the individual countries are becoming more integrated as high-capacity power lines are constructed to enhance system security [132]. The national network operators will have to cooperate and coordinate more at a European scale to operate the power network in a desirable way.
- At a national scale 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 can also flow from the industrial sites and cities to the distribution network and into the transmission network [73]. The network flows will vary more and it will therefore be necessary to improve the coordination of decentralized local controllers, and to improve the cooperation between power regions.
- At the local scale loads at consumption nodes become controllable and it becomes possible to store energy using batteries [73]. In addition, groups of households can become independent of the large electricity suppliers by arranging energy exchanges among each other.

Hence, to still guarantee basic requirements and service levels, such as voltage levels, frequency, bounds on deviations, stability, elimination of transients, etc., and to meet the demands and requirements of the users, new control techniques have to be developed and implemented. These control techniques have to be adaptive and online as the input patterns and demands may vary over time.

1.4.3 Opportunities for multi-agent control

The developments outlined above offer many new opportunities for multi-agent control. In this thesis we deal in particular with and propose new solutions for control problems inspired by the following power domain control problems:

- distributed load-frequency control of non-overlapping power areas (Chapters 2 and 3);

- distributed FACTS devices control for security of overlapping power areas (Chapter 5);
- supervisory emergency voltage control for coordination of a layer of decentralized controllers (Chapter 4);
- decentralized control of electricity and heat usage in households (Chapter 3).

The first three problems aim at improving the operational control of power networks, ensuring adequate system performance under normal and emergency operating conditions. Here, system security is the main issue, and economical objectives are less important. The last problem aims more at economical optimization, and assumes the system operations to be reliable.

1.5 Overview of this thesis

1.5.1 Thesis outline

In this thesis current issues in model predictive control (MPC) in multi-agent control structures with applications to control problems in power networks are discussed and new solutions are proposed. This thesis is organized as follows:

- In **Chapter 2** communication and decision making schemes for multi-agent MPC are discussed, with a particular focus on serial versus parallel schemes. A novel serial scheme for multi-agent MPC is proposed and compared with an existing parallel scheme. The emphasis is on networks modeled as interconnected linear time-invariant subnetworks, a basic, yet important class of networks. The theory developed is applied to the load-frequency control problem in power networks.
- In **Chapter 3** multi-agent MPC for networked hybrid systems is studied. Translating discrete phenomena like saturation into systems of inequalities is discussed, and an extension of the schemes of Chapter 2 for dealing with interconnected linear time-invariant subnetworks with both real and integer inputs is proposed. A decentralized MPC controller for household optimization is constructed, and the load-frequency control problem of Chapter 2 is extended by including discrete switching of power generation.
- In **Chapter 4** the focus is on multi-layer multi-agent control. Creating object-oriented prediction models to construct models of complex systems is discussed, and a medium-layer MPC controller is proposed that uses such a model to determine set points for a lower decentralized control layer. The theory is applied to a voltage collapse problem in a nine-bus dynamic power network.
- In **Chapter 5** higher-layer multi-agent MPC for controlling networks in which the subnetworks are overlapping is proposed. Conventional approaches assume non-overlapping subnetworks, in which control objectives and system dynamics can be clearly assigned to individual subnetworks. An extension of a recently developed scheme for multi-agent MPC is proposed for situations in which the subnetworks are

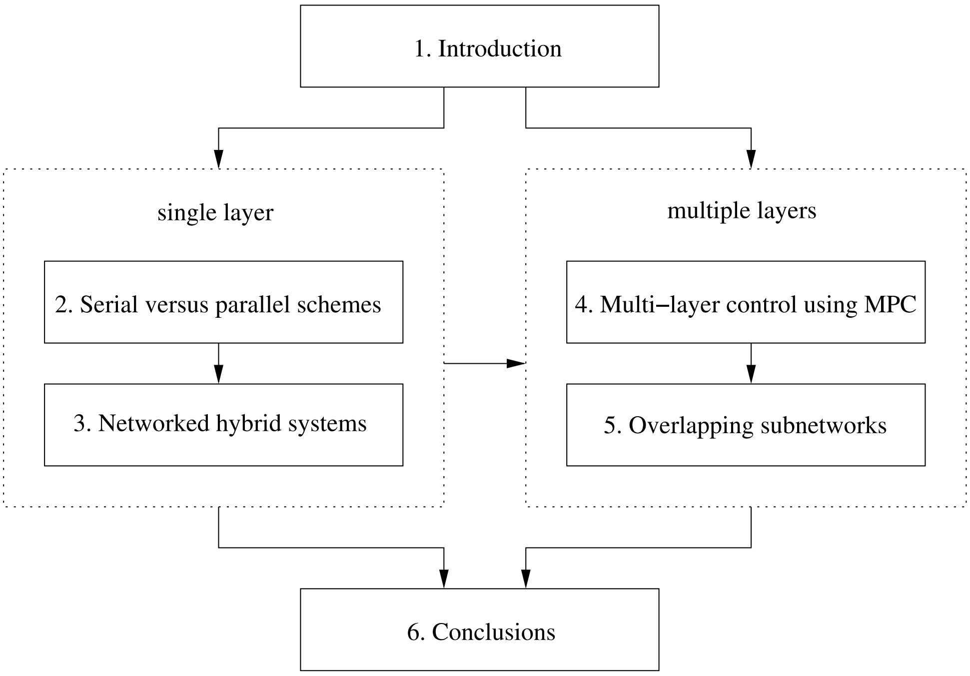

Figure 1.7: Road map. Arrows indicate read before *relations.*

overlapping. The developed scheme is used for FACTS-controlled optimal power flow control.

- **Chapter 6** summarizes the results of this thesis and outlines directions for future research.

1.5.2 Road map

Figure 1.7 illustrates a grouping of the chapters in related subjects and an ordering in which the chapters can be read. It is suggested to read the chapters in the order as they appear in the thesis. Chapter 1 contains a general introduction to the topics in this thesis, and is therefore suggested to be read first. Chapters 2 and 3 focus both on issues related to control by control agents that have equal authority relationships, and therefore operate in a single layer. In addition, the schemes discussed in these chapters assume that subnetworks are non-overlapping. Chapters 4 and 5 focus on issues related to control by control agents with different authority relationships, and therefore operate in multiple layers. In addition, in Chapter 5 it is assumed that subnetworks are overlapping. It is therefore suggested to read Chapters 2 and 3 before Chapters 4 and 5. Chapter 6 summarizes the results of this thesis and gives directions for future research. This chapter can be read after the other chapters.

1.5.3 Contributions

Main contributions

The main contributions of the research described in this PhD thesis with respect to model predictive control and multi-agent systems are the following:

- A serial scheme for multi-agent single-layer MPC has been proposed for interconnected linear time-invariant systems in [109, 112], and for a class of interconnected linear hybrid systems in [108] (see also Chapters 2 and 3).
- A coordinating MPC control strategy using an object-oriented prediction model has been proposed in [113], and using a linearized object-oriented prediction model in [110] (see also Chapter 4).
- A parallel scheme for multi-agent single-layer MPC for nonlinear overlapping subnetworks has been proposed in [69] (see also Chapter 5).

With respect to power network control our main contributions are:

- A solution approach for distributed load-frequency control has been proposed for continuous problems in [109, 112], and for hybrid problems in [108] (see also Chapters 2 and 3).
- A decentralized MPC controller for optimization of energy consumption in households has been proposed in [68] (see also Chapter 3).
- Two solution approaches for coordinating decentralized controllers for emergency voltage control have been proposed in [110] and [113] (see also Chapter 4).
- A solution approach for FACTS-based security control in overlapping power areas has been proposed in [69] (see also Chapter 5).

Contributions to the state-of-the-art

Besides our main contributions, the research involved in this PhD thesis has resulted in additional contributions to the state-of-the-art in the following ways:

- A unified framework of multi-agent MPC strategies has been proposed in [107] (see also Chapter 2).
- A parallelization of the serial multi-agent MPC scheme has been proposed in [111].
- The integration of multi-level, in particular bi-level, control and multi-agent MPC has been discussed in [90].
- Challenges for process system engineering in transportation network control have been identified in [89].
- An MPC controller for Markov decision processes using experience to decrease computational requirements has been proposed in [106].

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Samenvatting

Multi-Agent Modelgebaseerd Voorspellend Regelen met Toepassingen in Elektriciteitsnetwerken

Transportnetwerken, zoals elektriciteitsnetwerken, verkeersnetwerken, spoornetwerken, waternetwerken, etc., vormen de hoekstenen van onze moderne samenleving. Een soepele, efficiënte, betrouwbare en veilige werking van deze netwerken is van enorm belang voor de economische groei, het milieu en de leefbaarheid, niet alleen wanneer deze netwerken op de grenzen van hun kunnen moeten opereren, maar ook onder normale omstandigheden. Aangezien transportnetwerken dichter en dichter bij hun capaciteitslimieten moeten werken, en aangezien de dynamica van dergelijke netwerken alsmaar complexer wordt, wordt het steeds moeilijker voor de huidige regelstrategieën om adequate prestaties te leveren onder alle omstandigheden. De regeling van transportnetwerken moet daarom naar een hoger niveau gebracht worden door gebruik te maken van nieuwe geavanceerde regelstrategieën.

Elektriciteitsnetwerken vormen een specifieke klasse van transportnetwerken waarvoor nieuwe regelstrategieën in het bijzonder nodig zijn. De structuur van elektriciteitsnetwerken is aan het veranderen op verschillende niveaus. Op Europees niveau worden de elektriciteitsnetwerken van individuele landen meer en meer geïntegreerd door de aanleg van transportlijnen tussen landen. Op nationaal niveau stroomt elektriciteit niet langer alleen van het transmissienetwerk via het distributienetwerk in de richting van bedrijven en steden, maar ook in de omgekeerde richting. Daarnaast wordt op lokaal niveau regelbare belasting geïnstalleerd en kan energie lokaal gegenereerd en opgeslagen worden. Om minimumeisen en -serviceniveaus te kunnen blijven garanderen, moeten *state-of-the-art* regeltechnieken ontwikkeld en geïmplementeerd worden.

In dit proefschrift stellen wij verschillende regelstrategieën voor die erop gericht zijn om de opkomende problemen in transportnetwerken in het algemeen en elektriciteitsnetwerken in het bijzonder het hoofd te bieden. Om het grootschalige en gedistribueerde karakter van de regelproblemen te beheersen gebruiken wij *multi-agent* aanpakken, waarin verschillende regelagenten elk hun eigen deel van het netwerk regelen en samenwerken om de best mogelijke netwerkbrede prestaties te behalen. Om alle beschikbare informatie mee te kunnen nemen en om vroegtijdig te kunnen anticiperen op ongewenst gedrag maken wij gebruik van modelgebaseerd voorspellend regelen (MVR). In de regelstrategieën die wij in dit proefschrift voorstellen, combineren wij multi-agent aanpakken met MVR. Hieronder volgt een overzicht van de regelstrategieën die wij voorstellen en de regelproblemen uit de specifieke klasse van elektriciteitsnetwerken, waarop wij de voorgestelde regelstrategieën toepassen.

Multi-agent modelgebaseerd voorspellend regelen

In een multi-agent regeling is de regeling van een systeem gedistribueerd over verschillende regelagenten. De regelagenten kunnen gegroepeerd worden aan de hand van de autoriteitsrelaties die tussen de regelagenten gelden. Een dergelijke groepering resulteert in een gelaagde regelstructuur waarin regelagenten in hogere lagen meer autoriteit hebben over regelagenten in lagere lagen en waarin regelagenten in dezelfde laag dezelfde autoriteitsrelaties met betrekking tot elkaar hebben. Gebaseerd op de ideeën van MVR bepalen in multi-agent MVR de regelagenten welke actie zij nemen aan de hand van voorspellingen. Deze voorspellingen maken zij met behulp van voorspellingsmodellen van die delen van het algehele systeem die zij regelen. Daar waar de regelagenten in hogere lagen typisch minder gedetailleerde modelen en langzamere tijdschalen beschouwen, beschouwen regelagenten op lagere regellagen typisch meer gedetailleerde modelen en snellere tijdschalen. In dit proefschrift worden de volgende regelstrategieën voorgesteld en bediscussieerd:

- Voor de coördinatie van regelagenten in een regellaag wordt een nieuw serieel schema voor multi-agent MVR voorgesteld en vergeleken met een bestaand parallel schema. In de voorgestelde aanpak wordt aangenomen dat de dynamica van de deelnetwerken alleen uit continue dynamica bestaat en dat de dynamica van het algehele netwerk gemodelleerd kan worden met verbonden lineaire tijdsinvariante modellen, waarin alle variabelen continue waarden aannemen.

- In de praktijk komt het regelmatig voor dat deelnetwerken hybride dynamica vertonen, veroorzaakt door zowel continue als discrete dynamica. We bediscussiëren hoe discrete dynamica gevat kan worden in modellen bestaande uit lineaire vergelijkingen en ongelijkheden en hoe regelagenten dergelijke modellen kunnen gebruiken bij het bepalen van hun acties. Daarnaast stellen wij een uitbreiding voor van de coördinatieschema's voor continue systemen naar systemen met continue en discrete variabelen.

- Voor een individuele regelagent die richtpunten bepaalt voor regelagenten in een lagere regellaag wordt het opzetten van object-georiënteerde voorspellingsmodellen bediscussieerd. Een dergelijk object-georiënteerd voorspellingsmodel wordt dan gebruikt om een MVR-regelprobleem te formuleren. Wij stellen voor om de optimalisatietechniek *pattern search* te gebruiken om het resulterende MVR-regelprobleem op te lossen. Daarnaast stellen wij omwille van de efficiëntie een MVR-regelstrategie voor die gebaseerd is op een gelineariseerde benadering van het object-georiënteerde voorspellingsmodel.

- Regelmatig worden deelnetwerken gedefinieerd op basis van reeds bestaande netwerkregio's. Dergelijke deelnetwerken overlappen meestal niet. Als deelnetwerken echter gebaseerd worden op bijvoorbeeld invloedsgebieden van actuatoren, dan kunnen de deelnetwerken overlappend zijn. Wij stellen een regelstrategie voor voor het regelen van overlappende deelnetwerken door regelagenten in een hogere regellaag.

Multi-agent regelproblemen in elektriciteitsnetwerken

Elektriciteitsnetwerken vormen een specifieke klasse van transportnetwerken waarvoor de ontwikkeling van geavanceerde regeltechnieken noodzakelijk is om adequate prestaties te behalen. De regelstrategieën die in dit proefschrift worden voorgesteld worden daarom aan de hand van toepassing op specifieke regelproblemen uit elektriciteitsnetwerken geëvalueerd. In het bijzonder worden de volgende regelproblemen besproken:

- We beschouwen een gedistribueerd *load-frequency* probleem, wat het probleem is van het dicht bij nul houden van frequentie-afwijkingen na verstoringen. Regelagenten regelen elk hun eigen deel van het netwerk en moeten samenwerken om de best mogelijke netwerkbrede prestaties te behalen. Om deze samenwerking te bewekstellingen gebruiken de regelagenten de seriële of de parallele MVR-strategieën. We beschouwen zowel samenwerking gebaseerd op voorspellingsmodellen die alleen continue variabelen bevatten, als met gebruikmaking van voorspellingsmodellen die zowel continue als ook discrete variabelen bevatten. Met behulp van simulaties illustreren we de prestaties die de schema's kunnen behalen.

- In de nabije toekomst zullen huishoudens de mogelijkheid hebben om hun eigen energie lokaal te produceren, lokaal op te slaan, te verkopen aan een energie-aanbieder en mogelijk uit te wisselen met naburige huishoudens. We stellen een MVR-strategie voor die gebruikt kan worden door een regelagent die het energiegebruik in een huishouden regelt. Deze regelagent neemt in zijn regeling verwachte energieprijzen, voorspelde energieconsumptiepatronen en de dynamica van het huishouden mee. We illustreren de prestaties die de regelagent kan behalen voor een gegeven scenario van energieprijzen en consumptiepatronen.

- Spanningsinstabiliteiten vormen een belangrijke bron van elektriciteitsuitval. Om te voorkomen dat spanningsinstabiliteiten ontstaan is lokaal bij generatielokaties een laag van regelagenten geïnstalleerd. Een dergelijke lokale regeling werkt onder normale omstandigheden goed, maar levert ten tijde van grote verstoringen geen adequate prestaties. In dergelijke situaties moeten de acties van de lokale regelagenten gecoördineerd worden. Wij stellen een MVR-regelagent voor die tot taak heeft deze coördinatie te realiseren. De voorgestelde MVR-strategie maakt gebruik van ofwel een object-georiënteerd model van het elektriciteitsnetwerk ofwel van een benadering van dit model verkregen na linearisatie. We illustreren de prestaties die behaald kunnen worden met behulp van simulaties op een dynamisch 9-bus elektriciteitsnetwerk.

- Regeling gebaseerd op *optimal power flow* (OPF) kan gebruikt worden om in transmissienetwerken de *steady-state* spanningsprofielen te verbeteren, het overschrijden van capaciteitslimieten te voorkomen, en vermogensverliezen te minimaliseren. Een type apparaat waarvoor met behulp van OPF-regeling actuatorinstellingen bepaald kunnen worden zijn *flexible alternating current transmission systems* (FACTS). Wij beschouwen een situatie waarin verschillende FACTS-apparaten aanwezig zijn en elk FACTS-apparaat geregeld wordt door een regelagent. Elke regelagent beschouwt als zijn deelnetwerk dat deel van het netwerk dat zijn FACTS-apparaat kan beïnvloeden. Aangezien de deelnetwerken gebaseerd zijn op beïnvloedingsregio's kunnen verschillende deelnetwerken overlappend zijn. Wij stellen een coördinatie- en communicatieschema voor dat kan omgaan met een dergelijke overlap. Via simulatiestudies op een aangepast elektriciteitsnetwerk met 57 bussen illustreren we de prestaties.

Rudy R. Negenborn

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.

Rudy R. Negenborn

Curriculum vitae

Rudy R. Negenborn was born on June 13, 1980 in Utrecht, The Netherlands. He finished his pre-university education (*VWO*) in 1998 at the Utrechts Stedelijk Gymnasium, Utrecht, The Netherlands. After this, Rudy Negenborn started his studies in Computer Science at the Utrecht University, Utrecht, The Netherlands. He received the title of *doctorandus* (comparable with Master of Science) in Computer Science, with a specialization in Intelligent Systems, *cum laude* from this university in 2003. For his graduation project, he performed research on Kalman filtering and robot localization. The research involved in this project was carried out during a one-year visit to the Copenhagen University, Denmark, and was supervised by Prof.Dr.Phil. P. Johansen and Dr. M. Wiering.

Since 2004, Rudy Negenborn has been working on his PhD project at the Delft Center for Systems and Control of Delft University of Technology, The Netherlands. The research of his PhD project has been on multi-agent model predictive control with applications to power networks, and has been supervised by Prof.dr.ir. B. De Schutter and Prof.dr.ir. J. Hellendoorn. During his PhD project, Rudy Negenborn obtained the DISC certificate for fulfilling the course program requirements of the Dutch Institute for Systems and Control. Furthermore, he cooperated with and spent time at various research groups, including the Hybrid System Control Group of Supélec, Rennes, France, and the Power Systems Laboratory and Automatic Control Laboratory of ETH Zürich, Zürich, Switzerland.

Rudy Negenborn's more fundamental research interests include multi-agent systems, hybrid systems, distributed control, and model predictive control. His more applied research interests include applications to transportation networks in general, and power networks in particular.

Since 2004, Rudy Negenborn has been a member of the DISC and of The Netherlands Research School for Transport, Infrastructure, and Logistics (TRAIL). Moreover, from 2004 until 2007, Rudy Negenborn fulfilled the positions of public relations representative and treasurer in the board of Promood, the representative body of the PhD candidates at Delft University of Technology.