Multi-Agent Model Predictive Control
with Applications to Power Networks

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Proefschrift

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Chapter 6

Conclusions and future research

In this thesis we have discussed multi-agent model predictive control of transportation networks in general, and power networks in particular. We have discussed how control agents have to make decisions given different constraints on the type of systems they control, the actuators they can access, the information they can sense, and the communication and cooperation they can perform. In this chapter we summarize our main contributions and formulate future research directions.

6.1 Conclusions

Our main contributions with respect to the control approaches discussed are:

- **Serial versus parallel schemes.** In Chapter 2 we have formalized the dynamics of subnetworks as interconnected linear time-invariant systems, and defined their control using an MPC control agent for each subnetwork. We have discussed why the control agent has to communicate with neighboring agents about how the variables involved in interconnecting constraints evolve. Furthermore, we have surveyed several ways of how to perform such communication, and have proposed a novel serial scheme, which converges toward an overall optimal solution under convexity of the overall MPC control problem. It has hereby been assumed that the subnetworks have discrete-time linear time-invariant dynamics, involving only variables taking on continuous values, and that the control objectives can be formulated as affine or convex functions. We have contrasted the scheme with a related parallel scheme. Experiments have confirmed that the proposed approach can achieve performance close to overall performance.
- **Networked hybrid systems.** In Chapter 3 we have discussed issues related to modeling and control of hybrid systems, i.e., systems including both discrete and continuous elements. With respect to modeling of hybrid systems we have illustrated how discrete logic statements can be transformed into linear mixed-integer equality and inequality constraints. We have discussed issues arising in multi-agent control of interconnected hybrid systems and we have proposed an extension of the serial approach of Chapter 3 for control of such systems. This extension relaxes the assumptions

made on the original approach (i.e., discrete-time linear time-invariant dynamics for subnetworks with variables taking on continuous values, in combination with affine or convex objective functions) by allowing input variables to take on integer values instead of continuous values. Experiments using the proposed approach have given an indication that the proposed extension can resolve the discussed issues and can result in actions that give adequate performance.

- **Multi-layer control using MPC.** In Chapter 4 we have discussed MPC in multi-layer control. We have discussed the layered control of transportation networks using higher, medium, and lower-layer control, based on a time-scale decomposition of the dynamics. Then, we have focused in particular on issues related to the prediction model that a medium-layer MPC control agent uses and discussed why object-oriented modeling is suitable for constructing such a prediction model. Subsequently, we have proposed an MPC approach using such an object-oriented prediction model, or using a linearized approximation of such a model. To cope with the nonlinear, non-smooth, and costly-to-evaluate objective function of the MPC problem based on the object-oriented model, we have proposed the use of multi-start pattern search as optimization method. In experiments we have illustrated that the multi-start pattern search can outperform a state-of-the-art multi-start gradient-based approach. In addition, we have illustrated that using the MPC problem based on the linearized approximation of an object-oriented prediction model can result in significantly faster control, although at the price of reduced performance.

- **Overlapping subnetworks.** In Chapter 5 we have focused on the control by a higher-layer control agent. It is hereby assumed that at this higher layer the dynamics of the underlying control layers and physical network can be assumed instantaneous. We have discussed various ways of defining subnetworks, and have in particular focused on how subnetworks can be defined based on the influence that actuators of a control agent have. Using such influence-based subnetworks, it could happen that several subnetworks are overlapping. We have discussed issues that arise due to this overlap, and have proposed an approach for multi-agent control of overlapping subnetworks, using the nonlinear steady-state characteristics of the subnetworks as prediction models. Experiments have illustrated for a given example that the proposed approach can choose actions close to overall optimal actions.

We have considered several applications to which the proposed control approaches can be applied. Our main contributions with respect to these applications are:

- **Load-frequency control.** In Chapter 2 we have proposed the application of the serial MPC control scheme for a load-frequency control problem. Through experimental studies on a network consisting of 13 subnetworks, we have compared the serial scheme with the related parallel scheme and an overall scheme. The serial scheme showed to have preferable properties in terms of speed of convergence and quality of solutions. However, the parallel scheme outperformed the serial scheme in terms of total computation time. For the serial and the parallel schemes, the performance of the solutions obtained converged toward the performance of the solutions obtained by the overall scheme.

Furthermore, in Chapter 3 we have considered how the proposed extension of the serial scheme for interconnected hybrid systems performs when applied to the load-frequency control problem of Chapter 2, extended with discrete generation switching. We have illustrated that the approach has the potential to yield control actions that are overall optimal.

- **Household energy control.** In Chapter 3 we have used the transformations for discrete dynamics to derive a model for a household equipped with its own power generation and storage capabilities. As a first step toward a control structure in which multiple control agents, each representing a single household, jointly control the energy usage in a district, we have then proposed MPC for control of a single household using this model. In its decision making, the control agent uses expected energy consumption profiles and electricity export prices. We have illustrated that the MPC control agent can adequately take into account the discrete dynamics and yield a reduction in operational costs.

- **Emergency voltage control.** In Chapter 4 we have considered a control agent in a medium control layer of a power network that provides set-points to a lower control layer with the aim of preventing voltage collapses. For the MPC formulation of the higher-layer control agent based on the object-oriented model, using experiments we have illustrated the that multi-start pattern can outperform a multi-start state-of-the-art gradient-based method and we have illustrated that the voltage collapses can be prevented from occurring. For the MPC problem based on the linearized model, we have illustrated the performance of the control and related this performance to the quality of the predictions of the linearized model under faults of varying magnitude.

- **FACTS-based optimal flow control.** In Chapter 5, we have considered the problem of control of overlapping subnetworks using FACTS devices on an adjusted version of the IEEE 57-bus power network. We have illustrated how the region of influence of an actuator varies depending on the sensitivity threshold used, and we have applied the control approach proposed for control of overlapping subnetworks. Simulations have illustrated that the proposed approach has the potential to achieve fast convergence to actuator values that are overall optimal.

6.2 Future research

In principle, a multi-agent control approach for a transportation network will have to integrate solutions to each of the issues discussed in this thesis. However, even then several issues remain unsolved or can be investigated further. With respect to the control approaches addressed in this thesis, some challenging issues that require future research are:

- **Serial versus parallel schemes.** With respect to the serial multi-agent MPC scheme as discussed in Chapter 2, analytical bounds on the rate of convergence should be derived to give guarantees on the speed at which decisions are made. In addition, ways to speed up the decision making should be investigated, e.g., by forming groups and control agents that cooperate in coalitions.

- **Networked hybrid systems.** In Chapter 3, the transformations that have been used to transform discrete logic into linear constraints yielded a large number of binary variables. Research should address how the number of binary variables can be reduced. This may be done, e.g., by reformulating the underlying discrete logic, or by examining for which discrete dynamics it is strictly necessary to explicitly include these discrete dynamics; it may be the case that some discrete dynamics have a negligible effect on the continuous dynamics (e.g., dynamics appearing further away on a prediction horizon) and that these discrete dynamics therefore can be neglected or approximated with continuous dynamics. For the proposed extension of the serial MPC scheme for hybrid systems, it should be investigated formally whether and under which assumptions the scheme is guaranteed to converge to an overall optimal solution. In addition, it should be investigated how exactly the penalty coefficient should be increased, and with what value this should be done. Furthermore, it should be investigated what the range of systems is for which the proposed approach could work, and if for a larger range of systems combinations between techniques from distributed integer and distributed real optimization could be useful.

- **Multi-layer control using MPC.** With respect to Chapter 4, the performance loss when using the MPC control problem based on the linearized prediction model due to the approximation of the linearization should be further investigated. In addition, the solution techniques should be extended to deal with both continuous and discrete variables, such that hybrid systems can be controlled. Furthermore, analysis has to be done regarding the performance of the proposed approach for a medium-layer control agent when the model of the medium-layer control agent is an abstraction of the dynamics of the physical network and lower control layer. Model order reduction techniques may be used to determine which dynamics have to be taken into account by a medium-layer control agent, and which may be removed. In addition, topological reduction techniques may be used to determine which dynamics a medium-layer control agent can aggregate in order to obtain a simplified model. Furthermore, it has to be determined how control agents using MPC in a lower control layer should be taken into account by a higher-layer control agent, and how ultimately multiple MPC control agents in a higher layer should control multiple MPC control agents in a lower layer. Techniques such as those discussed in Chapters 2 and 5 may be extended to obtain agreement between control agents at different layers about certain variables. The techniques of Chapters 2 and 5 for the control agents in the lower control layer should be mixed with similar techniques to obtain coordination between lower and medium control layers.

- **Overlapping subnetworks.** For Chapter 5, the quality of the predictions made with subnetworks based on the influence of actuators under different sensitivity parameter values should be analyzed formally. In addition, investigation has to be performed on the assumptions under which the scheme proposed for control of overlapping subnetworks converges, and what the quality of the solutions obtained is. The scheme should be extended to include dynamic models, instead of only steady-state models, and to be able to deal with time-varying subnetworks, instead of fixed subnetworks.

In addition to these topics, more general fundamental further future research directions consist of:

- **Scalability.** It remains to be addressed how the convergence speed of the approaches discussed changes when applied to control structures with large numbers of control agents. If the approaches do not scale well, then ways to make them scalable should be investigated, e.g., by clustering control agents in groups in combination with coordination between the groups.

- **Robustness.** It should be investigated how robust the discussed approaches are against modeling errors and noise. In addition the control schemes that we have discussed silently assume that the decision making is done instantaneously or that at least the information used to initiate the decision making at a particular control cycle is valid also at moment at which actions are actually implemented. Future research should address how the schemes could be made robust to delays. In addition, fault-tolerance against failing control agents is still an unsolved issue.

- **Non-cooperative agents.** When some of the control agents are not cooperative the control agents may not be able to reach agreement on which actions to take. It should be investigated how the cooperative agents could deal with this and if they could, e.g., manipulate the non-cooperative control agents in order to reach the cooperative objectives. It would hereby be interesting to related concepts from multi-agent MPC to concepts from the field of non-cooperative game theory [11], such as Stackelberg games [11] and inverse Stackelberg games [64, 134].

- **Alternative control methodologies.** The techniques that have been discussed in this thesis should be compared with alternative, non-MPC-based techniques (both from the field of control engineering and from the field of computer science), to determine the advantages and disadvantages of each. In this way possibly new techniques can be proposed, combining the best of several techniques.

With respect to the applications discussed in this thesis, future research directly related to these applications consists of:

- **Load-frequency control.** The models that are used for the load-frequency control problem in Chapters 2 and 3 could be extended to more adequately represent the dynamics of the power networks, e.g., by including more detailed models of generators and loads, and by modeling explicitly the presence of tie-line power control devices. In addition, the model representing the physical network could be replaced by a continuous-time nonlinear model, instead of the currently used discrete-time linearized model. Furthermore, forecasts about expected power flows between subnetworks could be included, such the MPC strategy can be exploit at an early time expected changes in power flows.

- **Household energy control.** The model of a single household in Chapter 3 could be extended by including, e.g., disposable loads, i.e., load shedding within a household. In addition, the control problem could be reformulated to include variable gas and electricity export prices, and to schedule when consumption and generation should take place. Furthermore, several households could be connected to one another, allowing energy to be exchanged between neighboring households. The control problem could then be extended such that the control agents of the households cooperatively optimize their energy usage. The models of the individual households will then depend on variables of other households. The control agents will have to reach agreement on the values of these variables in order to successfully implement MPC. It should be investigated how the proposed scheme in Section 3.4 for control of interconnected hybrid subnetworks performs on such a system of interconnected households. Moreover, from the practical point of view, steps toward implementation in practice can be made by first implementing the household control agents on a laboratory setup and then implementing the household control agents in physical households.

- **Emergency voltage control.** With respect to the emergency voltage control scenario in Chapter 4, it would be interesting to further investigate the range of situations in which the MPC control agent using the linearized prediction model performs adequately and would be a good replacement for the control agent using the nonlinear prediction model. In addition, a larger benchmark network could be constructed after which the extended control approaches proposed for future research could be applied. In this larger benchmark network, control agents are used to control parts of the network using MPC, and a higher-layer control agent coordinates these MPC control agents. Furthermore, it would be interesting to investigate the potential of the proposed approach for emergency voltage control within large industrial sites.
- **FACTS-based optimal flow control.** The way in which the subnetworks based on the influence of the FACTS devices change under varying network conditions should be investigated. In addition, instead of considering steady-state characteristics of the power network under consideration in Chapter 5, dynamics could be included, e.g., in the generators and loads, to more adequately model the dynamics of the network.

In addition, future general application-oriented research should investigate the use of the discussed approaches in other fields besides power networks. In this respect, the following future research directions should be considered:

- **Model development and validation.** The control schemes that we have discussed all require a model that adequately represents the dynamics of the system. For application of the approaches discussed on practical examples, models will have to be constructed and validated. It will then also have to be investigated which quantities can be measured in practice, and which quantities will have to be estimated.
- **Alternative application domains.** The application of the control approaches presented in this thesis is not restricted to the applications from the domain of power networks only. Domains in which the control approaches presented could be applied include not only transportation networks, such as water distribution networks, road traffic networks, railway networks, gas distribution networks, etc., but also the process industry (e.g., for multi-agent control of production lines), supply chains (e.g., for multi-agent control of stocks), and autonomous guided or flying vehicles. Investigation of the application of the approaches discussed in this thesis to these domains will give interesting insights into the similarities and dissimilarities between the operation of transportation networks.

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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.