

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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Preface

I owe a lot of thanks to ...

I have greatly appreciated ...

It has been a delight for me to work with ...

I acknowledge the efforts of ...

Rudy R. Negenborn,
Delft, December 2007.

Contents

Preface	v
1 Introduction	1
1.1 Transportation networks	1
1.2 Overview of this thesis	1
1.2.1 Thesis outline	1
1.2.2 Road map	2
1.2.3 Contributions	2
2 Serial versus parallel schemes	7
2.1 Introduction	7
2.2 Summary	7
3 Conclusions and future research	9
3.1 Conclusions	9
3.2 Future research	9
A Tables and Calculations	11
Bibliography	13
Glossary	13
Samenvatting	15
Summary	17
Curriculum vitae	19

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 ... In Section 1.2 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 [?].

1.1 Transportation networks

Transportation or infrastructure networks, like power distribution networks, traffic and transportation systems, water distribution networks, logistic operations networks, etc., are the corner stones of our modern society. . .

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.

Illustrations are subfigures are found in Figure 1.2(a), 1.2(b), and 1.2(c).

1.2 Overview of this thesis

1.2.1 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** ...
- In **Chapter 3** ...
- ...
- **Chapter 6** summarizes the results of this thesis and outlines directions for future research.

1.2.2 Road map

Figure 1.3 illustrates a grouping of the chapters in related subjects and an ordering in which the chapters can be read...¹

1.2.3 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 [? ?], and for a class of interconnected linear hybrid systems in [?] (see also Chapter 2).
- A coordinating MPC control strategy using an object-oriented prediction model has been proposed in [?], and using a linearized object-oriented prediction model in [?] (see also Chapter ...).
- A parallel scheme for multi-agent single-layer MPC for nonlinear overlapping sub-networks has been proposed in [?] (see also Chapter ...).

With respect to power network control our main contributions are:

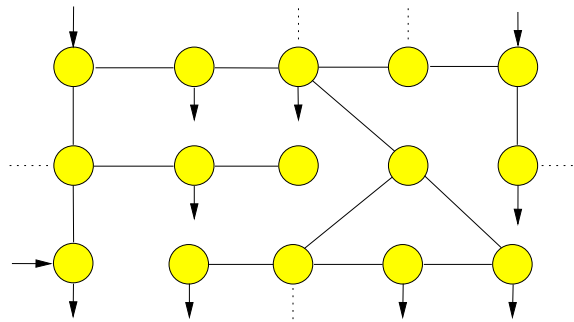
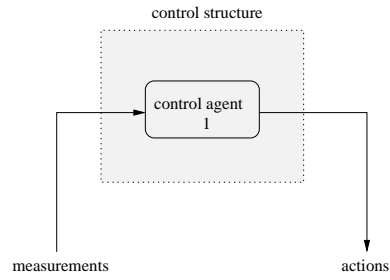
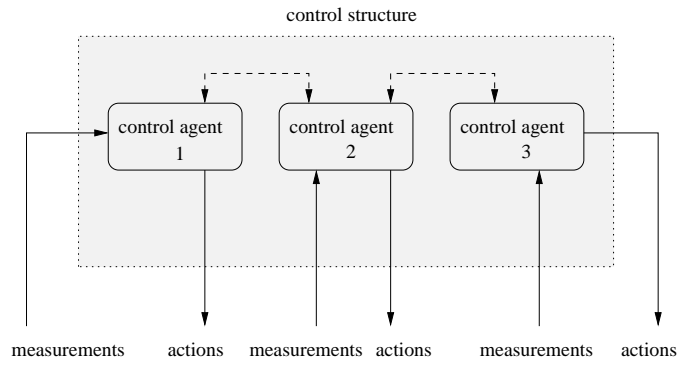


Figure 1.1: Generic transportation network.

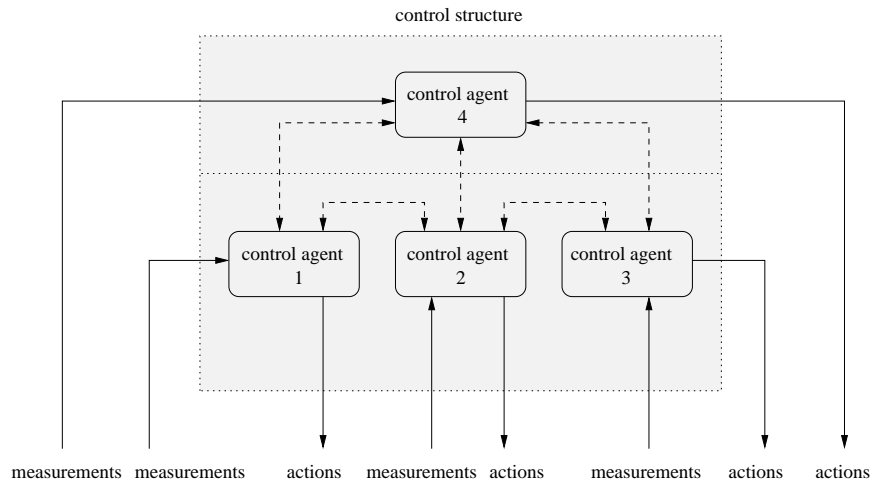
¹Footnotes are shown below figures/tables at the bottom of a page.



(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 1.2: Some important types of control structures.

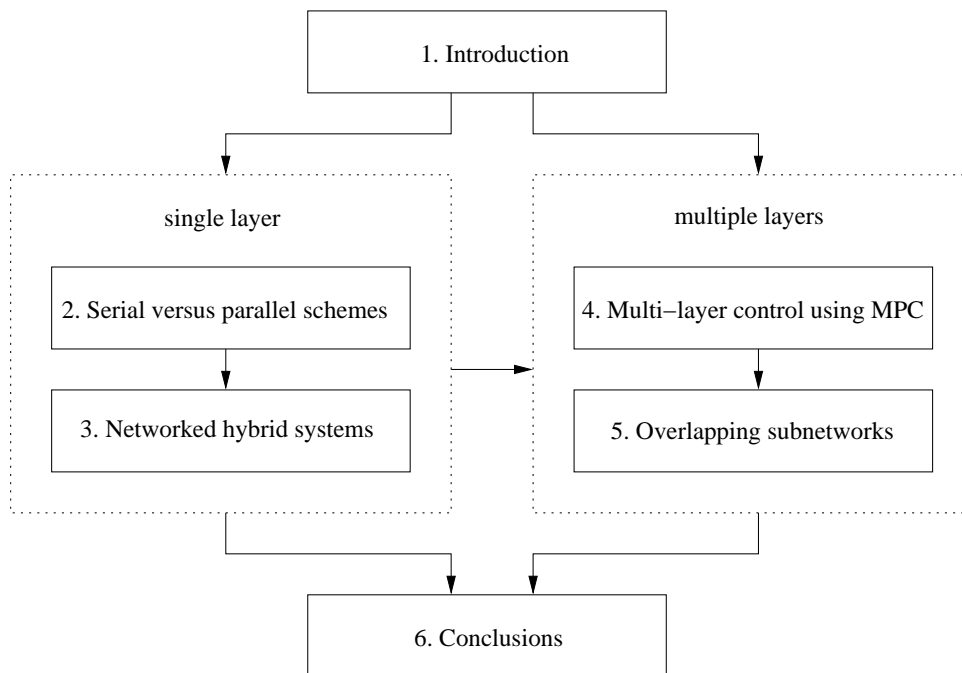


Figure 1.3: Road map. Arrows indicate read before relations.

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

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

Chapter 2

Serial versus parallel schemes

In this chapter we consider multi-agent single-layer MPC, in which the network is divided into several non-overlapping subnetworks, and each subnetwork is controlled by one control agent.

2.1 Introduction

...
In calligraphic style we write the following: *ABCDEFGHJ!*. Note that by enabling the use of `usepackage{pslatex}` in the class file `trailthesis.cls`, the calligraphic font is changed.

2.2 Summary

In this chapter we have considered multi-agent single-layer MPC for the control of transportation networks. We have started with formalizing the dynamics of the subnetworks...
In Chapter ... we extend the serial method to situations in which the problem of controlling the transportation network cannot be formulated as a convex problem...

Chapter 3

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. . .

3.1 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. . .
- **Networked hybrid systems.** In Chapter . . . we have discussed issues related to modeling and control of hybrid systems, i.e., systems including both discrete and continuous elements. . .
- . . .

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. . .
- **Household energy control.** In Chapter . . . we have used the transformations for discrete dynamics to derive a model for a household equipped with its own power generation and storage capabilities. . .
- . . .

3.2 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...

- ...

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...

- ...

Appendix A

Tables and Calculations

Here comes the appendix.

Glossary

Conventions

The following conventions are used in this thesis for notation and symbols:

- A lower case character typeset in boldface, e.g., \mathbf{x} , represents a column vector.
- The number of elements in a vector \mathbf{x} is indicated by $n_{\mathbf{x}}$.
- ...

List of symbols and notations

Below follows a list of the most frequently used symbols and notations in this thesis. Symbols particular to power network applications are explained only in the relevant chapters.

A	system matrices of linear time-invariant models
B	input matrices of linear time-invariant models
E₁	matrices of mixed-logical dynamic models

List of abbreviations

The following abbreviations are used in this thesis:

AVR	Automatic Voltage Regulator
DAE	Differential-Algebraic Equations
FACTS	Flexible Alternating-Current Transmission System
MPC	Model Predictive Control
...	...

Samenvatting

Multi-Agent Modelgebaseerd Voorspellend Regelen met Toepassingen in Elektriciteitsnetwerken

Transportnetwerken, zoals elektriciteitsnetwerken, verkeersnetwerken, spoornetwerken, waternetwerken, etc., vormen de hoekstenen van onze moderne samenleving. . .

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. . .

Multi-agent modelgebaseerd voorspellend regelen

In een multi-agent regeling is de regeling van een systeem gedistribueerd over verschillende regelagenten. . . In dit proefschrift worden de volgende regelstrategieën voorgesteld en besproken:

- 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 praktijk komt het regelmatig voor dat deelnetwerken hybride dynamica vertonen, veroorzaakt door zowel continue als discrete dynamica. . .
- . . .

Multi-agent regelproblemen in elektriciteitsnetwerken

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. . .
- 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. . .
- . . .

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...

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...

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... 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 practice, the dynamics of the subnetworks may show hybrid dynamics, caused by both continuous and discrete dynamics...
- ...

Multi-agent control problems in power networks

Power networks are a particular class of transportation networks and are subject to a changing structure... 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...
- 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...

- Idots

Rudy R. Negenborn

Curriculum vitae

Rudy R. Negenborn was born on June 13, 1980 in Utrecht, The Netherlands. . .