Preface

Networked control of multi-agent systems became the subject of intensive research nearly two decades ago and comprises still a rapidly expanding area with many sessions at international conferences, specific workshops, and special journal issues. The field has appeared when modern means of communication made it easy to connect system components whenever information links may contribute to improving the overall system performance. In the early times, research has been focussed on the imperfections of the data networks with packet losses opening the feedback loop and transmission delays endangering the stability of the control loop. However, an even more important aspect of networked control results from the flexibility of the digital communication systems to connect arbitrary components on demand, which makes novel control structures possible and poses fundamental research questions:

> Under what conditions should information be transferred from one control loop to another one?
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> What is the minimum requirement on the communication structure to solve a control problem at hand, and which additional communication links lead to a considerable improvement of the system performance?
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> In which way do the properties of the controlled subsystems aggregate to a collective behaviour of a networked overall system? How does this behaviour relate to the communication structure used?
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> How is it possible to ensure a required behaviour of a networked system that does not have any coordinating unit but gets its structure as the result of the self-organisation of the subsystems?

Several answers have been given to these and further questions and elaborate methods have been applied to technological and non-technological systems to evaluate them under practical restrictions. The methods are based on a combination of algebraic graph theory with systems analysis and controller design. They have appeared in numerous research papers and in a few survey articles and tutorials, and it is time to summarise their basic ideas in a textbook that makes the main lines understandable for learners.

This book concentrates on multi-agent systems, which consist of independent subsystems (agents). Cooperative controllers have to be found to make the agents satisfy a common goal. This problem concerns a wide range of applications, among others,

- formation control of robots and multirotors,
- vehicle platooning,

- synchronisation of oscillator networks,
- control of electrical power networks,
- load-balancing of microprocessors, and
- distributed averaging, estimation and state observation.

The examples, exercises and application studies of this book are taken from these fields (for a list, cf. pp. XIX – XXII).

Contents. The main goal of the book is to introduce analysis and design methods that deal with the new dynamical phenomena appearing in networked control systems. The common problem of all parts of the text can be posed as the question of how the properties of the controlled subsystems together with the interactions relate to the overall system behaviour and, consequently, how the communication structure of the controller should be chosen to make the overall system satisfy its performance specifications.

The book consists of three parts:

- **Part I – Introduction:** Chapter 1 characterises the field of networked control systems and summarises the main ideas of this text. Basic notions of algebraic graph theory, which sets the foundation for all structural investigations of networked systems, are introduced in Chapter 2.
- **Part II – Networked control with deterministic communication structures:** Consensus and synchronisation are explained in detail in Chapters 3 and 4 as two important phenomena encountered in networked systems. The methods for the design of the communication structure elaborated in Chapter 5 are based on an abstract model representing the information flow through the networked system.
- **Part III – Networked control with random communication structures:** Properties of graphs with random edges are surveyed in Chapter 6 and used for networked control in Chapter 7. They are also important for the self-organised networked systems considered in Chapter 8, where the agents change the communication structure of the overall system based on their local information. In event-triggered control described in Chapter 9 the components of a closed-loop system decide themselves when information has to be transferred to other parts of the system.

The classical questions of networked control on how the closed-loop performance deteriorates in case of packet losses or transmission delays brought about by the digital communication system are considered in several examples, particularly with respect to the stochastic stability of systems with a random structure, but they are not the main topic of this book.

Guiding principles. There are three central themes that spread over the whole text. First, *network thinking* provides the common methodological foundation for the solution of all analysis and design problems. Accordingly, the overall system is seen as a compound of coupled subsystems that gets its dynamics from the properties of the controlled agents and from the interconnection structure. From the viewpoint of the subsystems, the basic questions ask which properties the local controllers should give the isolated agents and which communication should bind the controlled agents to the overall system. This viewpoint contrasts with optimisation-oriented approaches that handle multi-agent systems from an overall systems viewpoint.

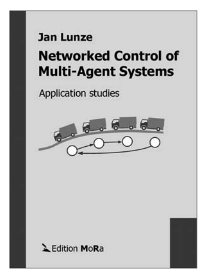
The second leading idea concerns the *design of the communication structure* as the primary problem when creating networked controllers. It considers the communication structure as the subject of a design process rather than a given constraint. Since modern data networks provide the flexibility to choose the communication links according to the performance requirements, control engineers need systematic ways to find out which structures are necessary, reasonable or even optimal. One of the main questions is how to combine the models representing the information flow through the network with the dynamical models describing the state evolution of the agents. Chapter 5 introduces an appropriate way, which is particularly useful for vehicle platooning for which it leads to new conditions that guarantee collision avoidance.

Third, in the absence of a coordinating unit, the agents have to make their decisions based on their local information. Consequently, the communication structure appears as a result of the *self-organisation* of the overall system. Chapter 8 elaborates this point in depth, but other chapters contribute to this guiding principle as well. In particular, in event-triggered control in Chapter 9 the event generators decide upon their current information when to send or to request information to or from other subsystems and adapt the communication structure accordingly.

Didactical concept. This textbook introduces the ideas of networked control systems in a self-contained way. The focus is laid on a rigorous understanding of the dynamical phenomena appearing in networks of dynamical systems. The main results are summarised in theorems, algorithms, marked sentences and formulas highlighted by boxes. The text also gives extensive mathematical and systems-theoretical interpretations and illustrates the results by numerous examples from various application domains. Figures with block diagrams and graphs show the structure and the behaviour of networked systems. Every chapter ends with a *summary of the main results*, a survey about the most influential papers of the field, hints to more general subjects along the line of the chapter, and current research questions.

Numerous examples and exercises illustrate the fascinating and challenging field of networked control systems. The exercises are classified as follows:

- **Exercises** (without an asterisk) help to understand the material just presented. They can be solved in analogy to the examples.
- **Exercises marked by an asterisk** apply the methods to a larger numerical or practical example. Their solutions are given in Appendix 1. The readers are encouraged first to try to solve the exercises themselves before going to the solution section in the appendix.
- **Application studies** go beyond the material presented. They should illustrate that the methods of this textbook are applicable even if some assumptions have to be released or if the problems are posed in a broader context. The main ideas of the application studies are included in this textbook, but a comprehensive description of the problems and their solutions have been moved to a supplementary booklet[1].



[1] Jan Lunze: *Networked Control of Multi-Agent Systems: Application Studies*, Edition **M**o**R**a 2022

Exercises with numerical calculations, which can be solved by using MATLAB, are marked with the symbol .

The required background includes competence in linear algebra and in systems and control theory on the level of graduate students. Appendices review some basics in probability theory, systems theory and matrix theory and give hints how to analyse graphs with MATLAB.

The text has been used for one-semester graduate courses on networked systems at the Ruhr-University Bochum, Germany, and at several PhD schools, at the 2020 International Graduate School on Control of the European Embedded Control Institute, and at seminars in industry.

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Last, but not least, I thank my daughter KATRIN who has convinced me during a 35 km hiking tour through the Belgian *Les Hautes Fagnes* that a textbook about a novel subject needs a novel way of marketing.

Second edition. The new version of the book presents, besides many revised parts, new material about the robustness of synchronised systems (Section 4.8) and numerous additional examples and exercises. The application studies have been extended and its description is collected in a supplementary booklet.

A few new symbols are used, in particular, $\boldsymbol{A}_{\mathcal{G}}$ for the adjacency matrix to distinguish it from the matrix $\boldsymbol{A}$ of the agent models. The synchronisation errors, the disagreement vector and the local control errors are all set-up in the same way like the synchronisation error $\delta(t) = \boldsymbol{x}_{\rm s}(t) - \boldsymbol{x}(t)$ as the difference between the synchronous state trajectory and the current state (in this order). The delay measure introduced in Chapter 5 is denoted by $\varDelta$ to avoid confusion with the disturbance $D(s)$.

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The webpage `www.editionmora.de/ncs` offers additional material including the MATLAB scripts for generating numerous figures of this book and further teaching instructions.