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 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. 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?

What is the minimum requirement on the communication structure to solve a control problem at hand, and how can additional communication links lead to a considerable improvement of the system performance?

In which way do the properties of controlled subsystems aggregate to a collective behaviour within a networked overall system and how does this behaviour relate to the communication structure used?

Is it possible to ensure a reasonable 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 and estimation.

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

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 the 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. Methods for the design of the communication structure are based on an abstract model representing the information flow through the networked system, which is elaborated in Chapter 5.

• 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.

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 result of a design process rather than as a given constraint. As 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 central 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 different 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 in the main text. 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.

- **Exercises with two asterisks** go beyond the material presented in the main text. They should illustrate that the methods of this textbook are applicable even if some assumptions are released or if the problems are posed in a broader context. There is no unique solution of them, but the main ideas presented in Appendix 1 illustrate the scope of the extensions that they stimulate.

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 a one-semester graduate course on networked systems at the Ruhr-University Bochum, Germany. Former versions were presented at several PhD schools and in seminars in industry.

Acknowledgements. I am very grateful to my former and current PhD students for many interesting discussions about the field: TORSTEN SCHLAGE, DANIEL LEHMANN, OZAN DEMIR, CHRISTIAN STÖCKER, ANDREJ MOSEBACH, RENÉ SCHUH, ALEXANDER SCHWAB, KAI SCHENK, PHILIPP WELZ, MICHAEL SCHWUNG and MARKUS ZGORZELSKI. Most of them have made valuable comments on earlier versions of my manuscript. As this textbook has to concentrate on the basic ideas of multi-agent systems, it can only mention our most advanced research results in the notes-and-references sections.

I have profited from many discussions within common projects or at conferences and workshops, in particular, with LARS GRÜNE (Bayreuth), OLIVER JUNGE (München), MAURICE HEEMELS (Eindhoven), KARL HENRIK JOHANSSON (Stockholm), and with further colleagues and PhD students of the former Priority Programme on “Control Theory of Digitally Networked Dynamic Systems” of the German Research Foundation.

Many thanks are due to Ms. ANDREA MARSCHELL who has drawn and re-drawn many figures. She has given approximately 200 block diagrams and graphs a uniform style and layout.

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.

Comments on this book are welcome: Lunze@atp.rub.de

Bochum, in February 2019

JAN LUNZE

The webpage www.atp.rub.de/Buch/NCS of the Institute of Automation and Computer Control, Ruhr-University Bochum, Germany offers additional material including the MATLAB scripts for generating numerous figures of this book and further teaching instructions.