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Robust Control Systems

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Theory and Case Studies

With 221 Figures

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For my family:

Gabriela, Gisela and Julia

Preface

Control engineering is an exciting and challenging field within the engineering sciences, because by its very nature it is a multidisciplinary subject and because it plays a critical role in many practical technical applications. To be more specific: control theory brings together such different fields as electrical, mechanical and chemical engineering and applied mathematics. It plays a major role in engineering applications of all kinds of complexity. This may be a dc motor, a robot arm, an aircraft, a satellite, a power plant or a plant for the chemical industries such as a distillation column. On the other hand, the developments in the last two or three decades have shown that control engineering requires very solid skills in applied mathematics and therefore has become highly attractive for applied mathematicians, too.

The most fundamental idea of control theory is to change the dynamical behavior of a technical system (the "plant") by a device called the "controller" such that the dynamics gets certain desired properties. In almost all cases, the controller design is done by building a mathematical model, which can be emulated on a computer and serves as the basis for controller synthesis. It is obvious that the model represents the real system only up to a certain degree of accuracy. Despite this, the controller has to work for the real system as well as for the model; in other words, it has to be "robust" against errors in the mathematical model. Robustness has always played a key role in control theory, right from the beginning, but a considerable amount of theoretical research was necessary to find analysis and synthesis tools which work satisfactorily also for complex plants. In particular, this holds for plants with several inputs and outputs.

The intention of this textbook is to give a self-contained introduction to control theory which emphasizes the modern aspects concerning the design of controllers having prescribed performance and robustness properties. No prior knowledge about control theory is required; the most important facts from classical control are concisely presented in Chaps. 2–4. They are formulated in the light of the modern theory in order to get an early understanding of its most important ideas. The book is written at a graduate level for students of electrical or mechanical engineering sciences or of applied mathematics and may also serve as a reference for control practitioners.

During the last two decades, control theory has changed its character: although it is a well-established branch of the engineering sciences, it may also be viewed as a discipline of applied mathematics. This is a point which deserves some attention. Almost all control theory methods require some mathematics, and this is also true for the methods based on the Nyquist stability criterion presented in every undergraduate course, but for these the mathematical reasoning can be kept at a moderate level. Even for a complex plant, the role of the controller parameters is well understood and controller design can successfully be done step by step by an engineer who is experienced and has a good intuition.

For modern methods which use $\mathcal{H}_\infty$ optimization or the structured singular value μ the situation is more involved. Probably most people who see the conditions characterizing $\mathcal{H}_\infty$ suboptimal controllers for the first time will find them messy and hard to understand. In fact, there is no way to make these conditions plausible by intuitive engineering reasoning. The only way to accept them as natural and reasonable is to study the complete rigorous mathematical proofs. On the other hand, the application of the more advanced methods, where the weights for performance and the uncertainty structure are specified, requires again a solid engineering experience and intuition.

For the preparation of a textbook dealing with an advanced presentation of control theory, these considerations have some strong implications. In particular, there are only two possibilities concerning the proofs, namely to skip them all or to present them in full detail. Skipping them all would be an admissible way for students or practitioners who are only interested in applications, since the use of the methods, which means mainly to apply the commercial software, does not require a very detailed knowledge of the theory standing behind it. On the other hand, for readers who wish to get a deeper understanding of modern control theory, this possibility is unsatisfactory, and for this reason I have decided to present the modern theory completely as far as it is needed. A study of the theory requires a basic knowledge of linear algebra and analysis and in particular some familiarity with the mathematical way of thinking.

In the introduction it is shown how both kinds of readers can gain benefit from this book. In this context it must be emphasized that a large portion of the text is devoted to elementary examples and advanced case studies. The elementary examples answer questions like: How can a $\mathcal{H}_\infty$ or a μ controller for a simple second order SISO plant without or with uncertainty be compared with a conventional PID controller? The case studies are carried out in full detail and show how the modern methods can be applied to advanced problems. They make intensive use of MATLAB, in particular of the Control Systems Toolbox and the μ-Analysis and Synthesis Toolbox.

The main reason for writing this book was the following. There are many excellent textbooks which present control theory based on the Nyquist criterion and on elementary state space methods. On the other side, there are a lot of highly specialized books which report on recent developments described in the original literature. Books which present the modern theory in detail without being a research monograph or a research-oriented book are comparatively rare. It is in this sense that the present book should be understood. Its philosophy is to treat advanced theory only so far as commercial software is available in which the new algorithms are programmed.

The most fundamental theoretical parts of the book deal with $\mathcal{H}_\infty$ synthesis using two Riccati equations and robustness based on the structured singular value μ. They are written in the spirit of the famous monograph of Zhou, Doyle, and Glover [112]. A completely different approach to $\mathcal{H}_\infty$ synthesis is based on linear matrix inequalities (LMIs) and will also be presented here. A book treating $\mathcal{H}_\infty$ theory and robustness by LMIs in much greater detail is Dullerud and Paganini [37]. An (incomplete) list of further important books on advanced control theory in the sense discussed above, but with somewhat different intentions to that of this book, is Burl [17], Sanchez-Pena and Sznaier [80], Skogestad and Poslethwaite [92], and Trentelman, Stoorvogel, and Hautus [97].

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