



Wiley, 2005  
ISBN 0-470-01167-X  
US\$145.00 (hardcover),  
ISBN 0-470-01168-8  
US\$72.00 (softcover),  
608 pages.

## Multivariable Feedback Control—Analysis and Design

by SIGURD SKOGESTAD  
and IAN POSTLETHWAITE

*Multivariable Feedback Control—Analysis and Design* approaches multi-input, multi-output feedback control design for linear systems using the paradigms, theory, and tools of robust control that have arisen during the past two decades. The book is aimed at graduate students and practicing engineers who have a basic knowledge of classical control design and state-space control

theory for linear systems. A basic knowledge of matrix theory and linear algebra is required to appreciate and digest the material offered.

This edition is a revised and expanded version of the first edition, which was published in 1996. The size of the book has been increased, not by the number of pages, which decreased from 559 to 574, but by a 20% increase in the page size. The revision has left intact the original style, approach, and goals. This edition contains revisions of almost all chapters, including minor corrections, improvements, and new material. In chapters 5 and 6, recent results on fundamental performance limitations have been added. Chapter 10 has been reorganized, while Chapter 12 on linear matrix inequalities is new. All Matlab programs have been updated and made compatible with the Robust Control Toolbox.

The book cohesively brings together three important conceptual achievements of the field of control: 1) multivariable feedback design, including a deep understanding of its achievements and limitations, 2) the concepts of uncertainty in plant behavior and uncertainty modeling as a natural part of a model-based approach to control design, and 3) the synthesis of feedback dealing with uncertainty models using  $H_\infty$  and  $\mu$ -synthesis tools. The book shows that the multivariable control design involves several phenomena not present in single-input, single output (SISO) control design, such as interaction among loops, directionality, and multivariable zeros. The incorporation of uncertainty in the design process can be seen as a major achievement, not only from a technical point of view but also as an educational issue. Uncertainty plays a major role in many fields of engineering, and the field of control is in the favorable position of having a theory available on how to make approximate uncertainty models and how to deal with them as part of the design of the feedback loop. The book teaches how to assemble the individual uncertainty models using the standard plant concept and shows that

control design with  $H_\infty$  and  $\mu$ -synthesis tools is suited for dealing with the uncertainty concepts.

These tools require a certain level of mathematics to define signal classes, norms, convexity, system factorizations, and the like, an effort well worth the price. The book provides the necessary insights and basic facts of knowledge, and yet the character of the book is design oriented, not mathematical. This format gives the book considerable strength. The main results are formulated with great precision in a theorem format, and a proof is included when the reasoning behind a proof amplifies understanding of the notions involved. Additional results are stated without proof, and reference is made to other sources such as [1]. This approach makes the book a fine example of how mathematical notions can be creatively used as building blocks in a design approach, where engineering students experience control design as a suite of mental steps.

Many examples and exercises are scattered throughout the text, and Matlab m-files are provided for the main computational steps. The frequency-domain specification of uncertainty and performance weights in the  $H_\infty$  and  $\mu$ -synthesis approaches take advantage of insights available in classical control design. As such, the concepts used in the book are easily grasped, and the use of classical control intuition is combined with computations that do the actual work. For almost all design steps discussed in the book, computational implementations are available in the Robust Control Toolbox.

The authors have a strong background in research in the theory and application of multivariable and robust control. Sigurd Skogestad's research work has concentrated on theoretical issues in the design of multivariable and robust control with applications to chemical reaction and separation processes. A second influence in the book is the successful British school of multivariable control at Manchester and Cambridge. The authors make clear that better theoretical understanding of key concepts of multivariable and robust control is the key toward better designs, and throughout the book this idea acts as a stimulus for the somewhat abstract and advanced ideas involved.

### CONTENTS

*Multivariable Feedback Control—Analysis and Design* begins with a chapter on classical control from a modern perspective, followed by a chapter dealing with basic properties of multivariable feedback systems. This chapter introduces many topics that are discussed more deeply in later chapters. The focus is on multivariable frequency response analysis using the singular value decomposition, sensitivity functions, relative gain analysis, and the role of multivariable right-half plane zeros. Two examples stress the relevance of input uncertainty in multivariable control.

Chapter 4 on linear systems provides basic theory needed in the following chapters. For many readers this theory may be familiar material, but the selection of topics exactly

fits the needs of the book. Chapters 5 and 6 go into detail by treating achievable control performance, depending on uncertainty and robustness properties. This topic is first considered for SISO systems by building intuitive knowledge about the concepts involved, followed by a more technical treatment dealing with the multivariable case. These chapters discuss feedback limitations imposed by time delay, phase lag, right-half-plane zeros, unstable poles, input constraints, and uncertainty. Although the uninitiated reader may have the impression that feedback has only limitations, the development creates important background knowledge for control law design part as well as issues such as sensor and actuator placement, control structure design, controller implementation, and embedded control structures.

Chapters 7 and 8 discuss uncertainty modeling as well as the analysis of robust stability and robust performance. The generalized plant is a key concept in the analysis, and uncertainty is represented by real and complex perturbations. In the face of multiple perturbations, the structured singular value is shown to be the basic analysis tool. Using D-K iteration, the control analysis is extended to a control synthesis (design) step by solving a sequence of scaled  $H_\infty$  problems. Chapter 9 is on controller design concentrating on tradeoffs in feedback design. The  $H_\infty$  solution is given in several variants such as S/KS mixed sensitivity designs. Also linear quadratic Gaussian design followed by loop transfer recovery is discussed. Also included is the Glover/McFarlane approach to  $H_\infty$  loop-shaping design.

Although chapters 7–9 form the culmination of the book, there are four additional chapters with material that broadens the approach. Chapter 10 discusses control structure design, which is an important subject from an applications point of view but difficult to present coherently and systematically in a single chapter since an underlying theory of structure selection is not available. Yet the authors have done a remarkable job explaining control layers, configuration selection, decentralized control, and classical structures such as cascade control. In addition, relations between structure selection and performance limitation indicators such as right-half-plane zeros are discussed.

Chapter 11 considers model reduction, which is necessitated by the design methods presented in the book. In particular,  $\mu$  synthesis yields controllers whose order is the sum of the orders of the model and weighting functions, which is generally impractically high. Consequently, this chapter focuses on truncation and residualization of balanced forms, as well as on Hankel-norm reduction. Chapter 12 provides an introduction to linear matrix inequalities (LMIs), which arise in the synthesis procedures. Although the chapter is short, it provides a basic introduction to the theory and a single example. Chapter 13 discusses applied control design for three case studies, namely, helicopter flight control, gas turbine control, and distillation process control. The book contains appendices

on matrix theory, signal and system norms, and subjects such as linear fractional transformations.

## EVALUATION

*Multivariable Feedback Control—Analysis and Design* provides a well-balanced, effective, and efficient treatment of robust multivariable control, well suited for graduate students and for engineers in industry. The book concentrates on creating an understanding of the underlying concepts and then formulates the problem in mathematical terms. This approach works well and creates synergy between building intuitive understanding and exploiting theoretical insight. The Matlab routines available in the Robust Control Toolbox are expected to handle all computations necessary in the various design steps. Because the book can rely on this toolbox, there is no need to have much material on computational algorithms in the book, although some numerical issues are discussed, such as the necessity of proper scaling and conditioning of model representations. However, for larger industrial robust control problems in high dimensions, solving the numerical issues is the key to success.

Apart from being an excellent textbook, the book has several other merits that make it a valuable gem in the field of systems and control. The book combines high standards regarding precise formulations and mathematical correctness with being creatively design oriented and accessible for those having only a classical control background. The designs that the authors have in mind are full-scale industrial multivariable designs, where only the best concepts and tools bring success, and this message is heard throughout the book.

The contents of the book can already be viewed as “classical robust control design,” and the book has contributed substantially toward bringing the field of control to this point. Finally, the book sets a firm international standard for the level of a graduate course in multivariable robust control.

**Okko H. Bosgra**

## REVIEWER INFORMATION

*Okko H. Bosgra* obtained his M.S. degree with research diploma from Delft University of Technology, The Netherlands. From 1980–1985 he was professor of systems and control at Wageningen University, and since 1986 he has chaired the Mechanical Engineering Systems and Control Group at Delft University of Technology. Since 2003 he has held a joint appointment at Eindhoven University of Technology, The Netherlands. His research interests are in applications of robust control and system identification to the areas of process control and motion control.

## REFERENCE

[1] K. Zhou, J.C. Doyle, and K. Glover, *Robust and Optimal Control*. Englewood Cliffs, NJ: Prentice Hall, 1996.

