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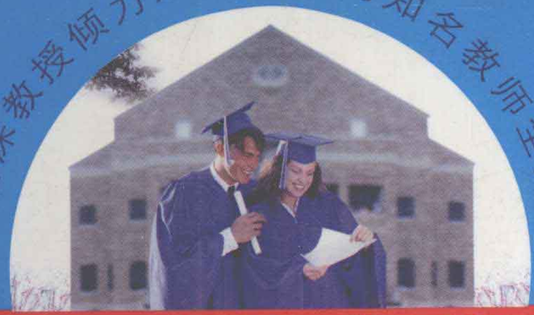


国外高校电子信息类优秀教材

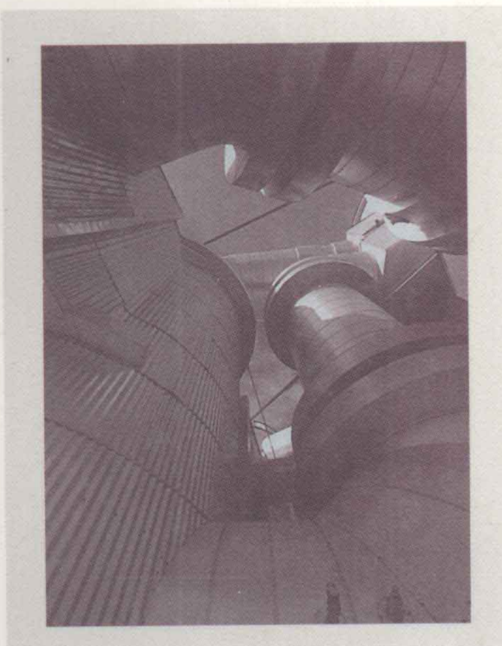
自适应控制

（第二版）

Adaptive Control

(Second Edition)

（英文影印版）



Karl Johan Åström　Björn Wittenmark 著

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内 容 简 介

本书为国外高校电子信息类优秀教材(英文影印版)之一。

本书综合地展现了自适应控制的全貌,并全面而精练地对自适应控制的理论与实现作了有深度的论述。针对第一版读者的反馈,作者在第二版中重新组织了书中的材料,使内容安排更加合理,易于教学。

本书适合作为自动化、控制专业高年级本科生和研究生教学用书。

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国外高校电子信息类优秀教材（英文影印版）

丛 书 编 委 会

To Bia, Emma, Ida, Johanna, Kalle, Kalle, Karin, and Karin

PREFACE

Adaptive control is a fascinating field for study and research. It is also of increasing practical importance, since adaptive techniques are being used more and more in industrial control systems. However, there are still many unsolved theoretical and practical issues.

• *Goal of the book* Our goal is to give an introduction and an overview of the theoretical and practical aspects of adaptive control.

Since knowledge about adaptive techniques is widely scattered in the literature, it is difficult for a newcomer to get a good grasp of the field. In the book we introduce the basic ideas of adaptive control and compare different approaches. Practical aspects such as implementation and applications are presented in depth. These are very important for the understanding of the advantages and shortcomings of adaptive control. This book has evolved from many years of research and teaching in the field.

After learning the material in the book a reader should have a good perspective of adaptive techniques, an active knowledge of the key approaches, and a good sense of when adaptive techniques can be used and when other methods are more appropriate.

• *The new edition* Adaptive control is a dynamic field of research and industrial applications. Much new knowledge has appeared which by itself motivates a new edition.

We have used the first edition of the book to teach to a wide variety of audiences, in regular university courses, courses to engineers in industry, and short courses at conferences. These experiences combined with advances in research, have shaped the major revisions made in the new edition. We have also benefited from feedback of students and colleagues in industry and universities, who have used the first edition of the book.

New chapters have been added, and the material has been reorganized. Most of the chapters have been substantially revised. In the revision we have also given more emphasis to the connection between different design methods in adaptive control. There is a major change in the way we deal with the theory. In the first edition we relied on mathematics from a wide variety of sources. In the new edition we have to a large extent developed the results from first principles. To make this possible we have made stronger assumptions in a few cases, but the material is now much easier to teach. The reorganization of the material also makes it easier to use the book for different audiences.

The first edition had two introductory chapters; they have now been compressed to one. In the first edition we started with model-reference adaptive systems following the historical tradition. In the second edition we start with parameter estimation and the self-tuning regulator. This has several advantages, one is that students can start to simulate and experiment with computer-based adaptive control at a much earlier state, another is that system identification gives the natural background and the key concepts required to understand many aspects of adaptive control.

The material on self-tuning control has been expanded substantially by introducing an extra chapter. This has made it possible to give a strict separation between deterministic and stochastic self-tuners. This is advantageous in courses which are restricted to the deterministic case.

The chapter on model-reference adaptive control has been expanded substantially. The key results on stability theory are now derived from first principles. This makes it much easier to teach to students who lack a background in stability theory. A new section on adaptive control of nonlinear systems has also been added.

The reorganization makes the transformation from algorithms to theory much smoother. The chapter on theory now naturally follows the development of nonlinear stability theory. The presentation of the theory has been modified substantially. A new section on stability of time-varying systems has been added. This makes it possible to get a much better understanding of adaptation of feedforward gains. It also is a good transition to the nonlinear case. Material on the nonlinear behavior of adaptive systems has also been added. This adds substantially to the understanding of the behavior of adaptive systems.

The chapter on practical aspects and implementation has been rewritten completely to reflect the increased experience of practical use of adaptive control. It has been very rewarding to observe the drastically increased industrial use of adaptive control. This has influenced the revision of the chapter on applications. For example, adaptive control is now used extensively in automobiles.

Many examples and simulations are given throughout the book to illustrate ideas and theory. Numerous problems are also given. There are theoretical problems as well as problems in which computers must be used for analysis and simulations. The examples and problems give the reader good insight into properties, design procedures, and implementation of adaptive controllers. To maintain a reasonable size of the book we have also done careful pruning.

To summarize, new research and new experiences have made it possible to present the field of adaptive control in what we hope is a better way.

Outline of the Book

• ***Background Material*** The first chapter gives a broad presentation of adaptive control and background for its use. Real-time estimation, which is an essential part of adaptive control, is introduced in Chapter 2. Both discrete-time and continuous-time estimation are covered.

• ***Self-tuning Regulators and Model-reference Adaptive Systems*** Chapters 3, 4, and 5 give two basic developments of adaptive control: self-tuning regulators (STR) and model-reference adaptive systems (MRAS). Today we do not make a distinction between these two approaches, since they are actually equivalent. We have tried to follow the historical development by mainly treating MRAS in continuous time and STR in discrete time. By doing so it is possible to cover many aspects of adaptive regulators. These chapters mainly cover the ideas and basic properties of the controllers. They also serve as a source of algorithms for adaptive control.

• ***Theory*** Chapter 6 gives deeper coverage of the theory of adaptive control. Questions such as stability, convergence, and robustness are discussed. Stochastic adaptive control is treated in Chapter 7. Depending on the background of the students, some of the material in Chapters 6 and 7 can be omitted in an introductory course.

• ***Broadening the View*** Automatic tuning of regulators, which is rapidly gaining industrial acceptance, is presented in Chapter 8. Gain scheduling is discussed in Chapter 9. Even though adaptive controllers are very useful tools, they are not the only ways to deal with systems that have varying parameters. Since we believe that it is useful for an engineer to have several ways of solving a problem, alternatives to adaptive control are also included. Robust high-gain control and self-oscillating controllers are presented in Chapter 10.

• ***Practical Aspects and Applications*** Chapter 11 gives suggestions for the implementation of adaptive controllers. The guidelines are based on practical experience in using adaptive controllers on real processes. Chapter 12 is a summary of applications and description of some commercial adaptive controllers. The applications show that adaptive control can be used in many different types of processes, but also that all applications have special features that must be considered to obtain a good control system.

• ***Perspectives*** Finally, Chapter 13 contains a brief review of some areas closely related to adaptive control that we have not been able to cover in the book. Connections to adaptive signal processing, expert systems, and neural networks are given.

Prerequisites

The book is for a course at the graduate level for engineering majors. It is assumed that the reader already has good knowledge in automatic control and a basic knowledge in sampled data systems. At our university the course can be taken after an introductory course in feedback control and a course in digital control. The intent is also that the book should be useful for an industrial audience.

Course Configurations

The book has been organized so that it can be used in different ways. An introductory course in adaptive control could cover Chapters 1, 2, 3, 4, 5, 8, 11, 12, and 13. A more advanced course might include all chapters in the book. A course for an industrial audience could contain Chapters 1, parts of Chapters 2, 3, 4, and 5, and Chapters 8, 9, 11, and 12. To get the full benefit of a course, it is important to supplement lectures with problem-solving sessions, simulation exercises, and laboratory experiments.

Simulation Tools

Computer simulation is an indispensible tool for understanding the behavior of adaptive systems. Most of the simulations in the book are done by using the interactive simulation package Simnon, which has been developed at our department. Simnon is available for IBM-PC compatible computers and also for several workstations and mainframe computers. Further information can be obtained from SSPA Systems, Box 24001, S-400 22 Göteborg, Sweden, e-mail: simnon@sspa.se. The macros used in the simulations are available for anonymous FTP from `ftp.control.lth.se`, directory `/pub/books/adaptive_control`. Adaptive systems can of course also be simulated using other tools.

Supplements

An instructor's manual with solutions to the problems is available through the publisher.

Wanted: Feedback

As teachers and researchers in automatic control, we know the importance of feedback. We therefore encourage all readers to write to us about errors, misunderstandings, suggestions for improvements, and also about what may be valuable in the material we have presented.

Acknowledgments

During the years we have done research in adaptive control and written the book, we have had the pleasure and privilege of interacting with many colleagues throughout the world. Consciously and subconsciously, we have picked up material from the knowledge base called adaptive control. It is impossible to mention everyone who has contributed ideas, suggestions, concepts, and examples, but we owe you all our deepest thanks. The long-term support of our research on adaptive control by the Swedish Board of Industrial and Technical Development (NUTEK) and by the Swedish Research Council for Engineering Sciences (TFR) are gratefully acknowledged.

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Finally, we want to thank some people who, more than others, have made it possible for us to write this book. Leif Andersson has been our TEXpert. He and Eva Dagnegård have been invaluable when solving many of the TEX problems. Eva Dagnegård and Agneta Tuszynski have done an excellent job of typing many versions of the manuscript. Most of the illustrations have been done by Britt-Marie Carlsson and Doris Nilsson. Without all their patience and understanding of our whims, there would never have been a final book. We also want to thank the staff at Addison-Wesley for their support and professionalism in bookmaking.

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CONTENTS

CHAPTER 1

WHAT IS ADAPTIVE CONTROL?

1.1 INTRODUCTION

In everyday language, "to adapt" means to change a behavior to conform to new circumstances. Intuitively, an adaptive controller is thus a controller that can modify its behavior in response to changes in the dynamics of the process and the character of the disturbances. Since ordinary feedback also attempts to reduce the effects of disturbances and plant uncertainty, the question of the difference between feedback control and adaptive control immediately arises. Over the years there have been many attempts to define adaptive control formally. At an early symposium in 1961 a long discussion ended with the following suggestion: "An adaptive system is any physical system that has been designed with an adaptive viewpoint." A renewed attempt was made by an IEEE committee in 1973. It proposed a new vocabulary based on notions like self-organizing control (SOC) system, parameter-adaptive SOC, performance-adaptive SOC, and learning control system. However, these efforts were not widely accepted. A meaningful definition of adaptive control, which would make it possible to look at a controller hardware and software and decide whether or not it is adaptive, is still lacking. However, there appears to be a consensus that a constant-gain feedback system is not an adaptive system.

In this book we take the pragmatic attitude that *an adaptive controller is a controller with adjustable parameters and a mechanism for adjusting the parameters*. The controller becomes nonlinear because of the parameter adjustment mechanism. It has, however, a very special structure. Since general nonlinear systems are difficult to deal with, it makes sense to consider special classes of nonlinear systems. An adaptive control system can be thought of as having two loops. One loop is a normal feedback with the process and the controller. The other loop is the parameter adjustment loop. A block diagram

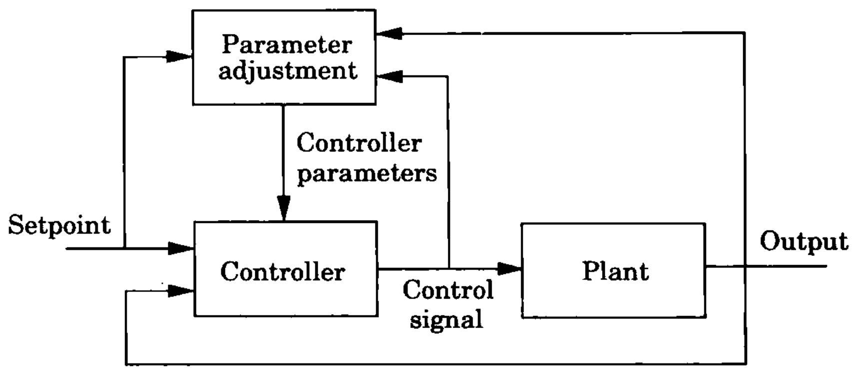

Figure 1.1 Block diagram of an adaptive system.

of an adaptive system is shown in Fig. 1.1. The parameter adjustment loop is often slower than the normal feedback loop.

A control engineer should know about adaptive systems because they have useful properties, which can be profitably used to design control systems with improved performance and functionality.

A Brief History

In the early 1950s there was extensive research on adaptive control in connection with the design of autopilots for high-performance aircraft (see Fig. 1.2). Such aircraft operate over a wide range of speeds and altitudes. It was found that ordinary constant-gain, linear feedback control could work well in one operating condition but not over the whole flight regime. A more sophisticated controller that could work well over a wide range of operating conditions was therefore needed. After a significant development effort it was found that gain scheduling was a suitable technique for flight control systems. The interest in adaptive control diminished partly because the adaptive control problem was too hard to deal with using the techniques that were available at the time.

In the 1960s there were much research in control theory that contributed to the development of adaptive control. State space and stability theory were introduced. There were also important results in stochastic control theory. Dynamic programming, introduced by Bellman, increased the understanding of adaptive processes. Fundamental contributions were also made by Tsypkin, who showed that many schemes for learning and adaptive control could be described in a common framework. There were also major developments in system identification. A renaissance of adaptive control occurred in the 1970s, when different estimation schemes were combined with various design methods. Many applications were reported, but theoretical results were very limited.

In the late 1970s and early 1980s, proofs for stability of adaptive systems appeared, albeit under very restrictive assumptions. The efforts to merge ideas

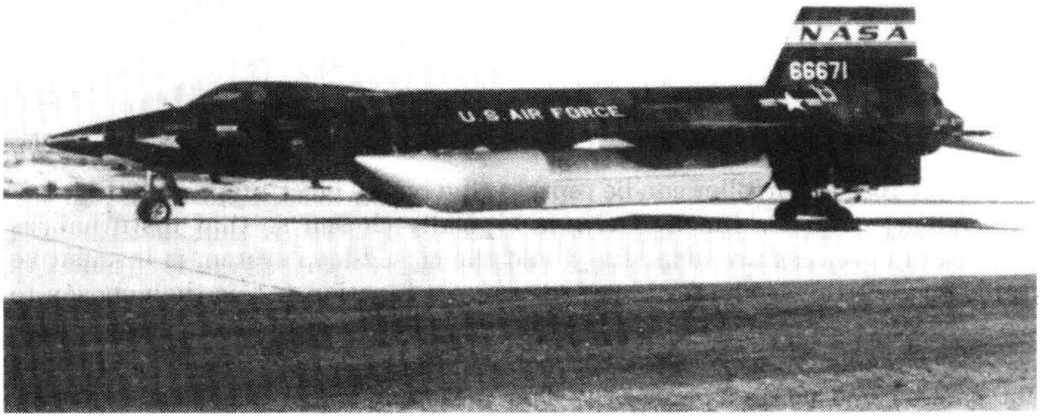

Figure 1.2 Several advanced flight control systems were tested on the X-15 experimental aircraft. (By courtesy of Smithsonian Institution.)

of robust control and system identification are of particular relevance. Investigation of the necessity of those assumptions sparked new and interesting research into the robustness of adaptive control, as well as into controllers that are universally stabilizing. Research in the late 1980s and early 1990s gave new insights into the robustness of adaptive controllers. Investigations of nonlinear systems led to significantly increased understanding of adaptive control. Lately, it has also been established that adaptive control has strong relations to ideas on learning that are emerging in the field of computer science.

There have been many experiments on adaptive control in laboratories and industry. The rapid progress in microelectronics was a strong stimulation. Interaction between theory and experimentation resulted in a vigorous development of the field. As a result, adaptive controllers started to appear commercially in the early 1980s. This development is now accelerating. One result is that virtually all single-loop controllers that are commercially available today allow adaptive techniques of some form. The primary reason for introducing adaptive control was to obtain controllers that could adapt to changes in process dynamics and disturbance characteristics. It has been found that adaptive techniques can also be used to provide automatic tuning of controllers.

1.2 LINEAR FEEDBACK

Feedback by itself has the ability to cope with parameter changes. The search for ways to design a system that are insensitive to process variations was in fact one of the driving forces for inventing feedback. Therefore it is of interest