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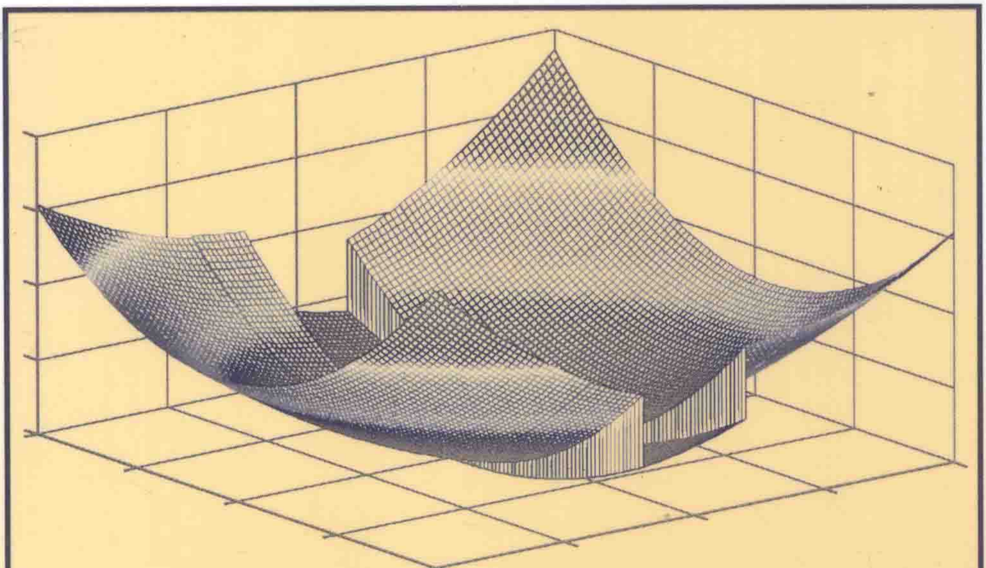
A Model-Based Approach



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Analysis and Synthesis of Fuzzy Control Systems

A Model-Based Approach

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A Model-Based Approach

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Preface

Fuzzy sets and systems have gone through significant development since the introduction of fuzzy set theory by L. A. Zadeh about four decades ago. They have found a great variety of applications ranging from control engineering, pattern recognition, signal processing, information processing, and machine intelligence to decision making, management, finance, medicine, robotics, and so on. In particular, fuzzy logic control (FLC) has become one of the most successful applications and has proven to be a popular control approach for many complex nonlinear systems or even nonanalytic systems. In many cases it has been suggested as an alternative approach to conventional control techniques.

Conventional fuzzy logic control developed in the 1970s to 1980s unfortunately suffers from a lack of tools for systematic stability analysis and controller design even though it has had great success in industrial applications. It has been recognized that conventional fuzzy logic control is fundamentally model free, which more or less is the essential cause of the problem. To address the difficulties encountered by conventional fuzzy logic control, many model-based fuzzy control approaches have been developed in the past decade.

In particular, the fuzzy dynamic model or the Takagi and Sugeno (T–S) fuzzy model-based approaches have been proposed and widely studied. This model is based on using a set of fuzzy rules to describe a nonlinear system in terms of a set of local linear models that are smoothly connected by fuzzy membership functions. This fuzzy modeling method offers an alternative approach to describing complex nonlinear dynamic systems. One of the most appealing features of T–S fuzzy models is that two kinds of knowledge, one the qualitative knowledge represented by fuzzy IF–THEN rules and the other the quantitative knowledge represented by local linear models, can be embedded into one model. In addition, T–S fuzzy models have a compatible structure with a two-level control system with the lower level providing basic feedback control and the higher level providing supervisory control or scheduling. By using T–S fuzzy models one can formulate these two kinds of knowledge or two-level systems into a unified mathematical framework. And more important, T–S fuzzy models provide a basis for the development of systematic approaches to stability analysis and controller design of fuzzy control systems in view of powerful conventional control theory and techniques.

Many fundamental theoretical results on function approximation, stability analysis, and controller synthesis of T–S fuzzy systems have been developed during the past 10 years or so. In fact, it has been shown that T–S fuzzy models are universal function approximators in the sense that they are able to approximate any smooth nonlinear functions to any degree of accuracy in any convex compact region. This result provides a theoretical foundation for using T–S fuzzy models to represent complex nonlinear systems approximately. Based on T–S fuzzy models many approaches to systematic analysis and synthesis of fuzzy control systems have been developed. Moreover, it has been successfully demonstrated that conventional control technology and fuzzy logic control can be elegantly combined and further developed so that the disadvantages of conventional fuzzy logic control can be avoided and the horizon of conventional control technology can be greatly extended.

This book is devoted to systematic analysis and synthesis of model-based fuzzy control systems. It mainly consists of two parts: fuzzy system modeling and identification, describing how a nonlinear system can be represented by a T–S fuzzy model; and analysis and synthesis of T–S fuzzy model-based control systems, which is the main focus of the book. In addition, many chapters of the book also feature application simulation examples and numerical examples based on the software platform MATLAB®. The introduction in Chapter 1 gives a brief review of the varieties of fuzzy logic control and in particular T–S fuzzy model-based fuzzy logic control. Chapter 2 introduces the fundamental concepts of fuzzy sets, fuzzy logic, and fuzzy systems that enable the book to be self-contained and provide a basis for the developments in the later chapters. T–S fuzzy modeling and identification via nonlinear models or data are studied in Chapter 3, which is followed by stability analysis of T–S fuzzy systems in Chapter 4, stabilization controller synthesis in Chapter 5, robust H_∞ controller synthesis in Chapter 6, and observer and output feedback controller synthesis in Chapter 7. Robust controller synthesis of uncertain T–S fuzzy systems and time-delay T–S fuzzy systems are studied in Chapters 8 and 9, respectively, followed by fuzzy model predictive control in Chapter 10, robust fuzzy filtering in Chapter 11, and finally adaptive control of T–S fuzzy systems in Chapter 12.

The book can be used as a textbook for graduate students in a course of intelligent or fuzzy control, and also as a reference for scientists and engineers in the area of systems and control. The prerequisite knowledge required of readers includes basic theories of linear algebra, advanced calculus, control systems, and linear systems.

The completion of this project would have been impossible without the generous support of the many people involved. In particular, Professor Frank Lewis inspired the author to initiate this project. Many colleagues or students of the author, including N. W. Rees, Shuguang Cao, Zhixiu Han, C. K. Chak, Louis Wang, Cailian Chen, Tiejun Zhang, Bo Yang, Jianbin Qiu, He Huang, Yonghui Sun, Yuan Fan, and Cheng Song, have made various and significant contributions. In fact, some chapters in this book are adapted from joint publications of the author and his colleagues or students, and the author would like to take this opportunity to acknowledge their contributions. In addition, the author would like to acknowledge the contribution of Yanyan Shen and Jianbin Qiu who have carried out all the simulation studies contained in this book. The author is also grateful to LiMing Leong, Acquiring Editor; Yong Ling Lam, Assistant Editor; Iris Fahrer, Project Editor, and Jennifer Ahringer, Project Coordinator at Taylor & Francis for their assistance and generous support during the long project period.

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Dr. Feng is an IEEE Fellow and an associate editor of *IEEE Transactions on Automatic Control*, *IEEE Transactions on Fuzzy Systems*, and *Mechatronics*. He has served as an associate editor of *IEEE Transactions on Systems, Man, & Cybernetics, Part C, Control Theory and Applications*, and on the Conference Editorial Board, IEEE Control Systems Society.

Contents

1 Introduction to Fuzzy Logic Control

1.1 INTRODUCTION

Since their introduction by Professor L. A. Zadeh in his seminal works (Zadeh, 1965, 1968, 1971, 1973, 1975) in the early 1970s, fuzzy sets and fuzzy logic theory have found a great variety of applications in control engineering, power systems, telecommunication, consumer electronics, information processing, pattern recognition, signal processing, machine intelligence, qualitative modeling, decision making, management, finance, medicine, the chemical industry, motor industry, robotics, and so on (see, e.g., Babuska, 1998; Bellman and Zadeh, 1970; Bezdek et al., 1999; Bonissone et al., 1995; Koska, 1992; Lee, 1990a,b; Mendel, 1995; Pedrycs, 1993; Sugeno, 1985; Teodorescu, Jain, and Kandel, 1998; Zimmermann, 1991). In particular, fuzzy logic control, or fuzzy control for short, as one of the earliest applications of fuzzy sets and fuzzy logic theory, has become one of the most notable applications. In fact, fuzzy logic control has proven to be a successful control approach to many practical and industrial systems, especially to complex nonlinear systems or even nonanalytic systems, and has been widely accepted as an alternative or complementary approach to conventional control techniques in many engineering applications.

It is generally believed that the first real fuzzy logic control system was developed by Mamdani and Assilian (Mamdani, 1974; Mamdani and Assilian, 1975) and called a Mamdani-type or conventional fuzzy controller. Since its inception, fuzzy logic control has attracted great attention from both the academic and industrial communities. Many people have devoted considerable effort to both theoretical research and application techniques of fuzzy logic controllers. In particular, fuzzy logic control has been developed substantially since the 1980s and put to use in a variety of applications in industry. This widespread research and development is evidenced by a number of excellent books and tutorial articles on the topic; see, for example, Babuska (1998), Lee (1990a,b), Feng (2006), Mendel (1995), Palm, Driankov, and Hellendoorn (1996), Passino and Yurkovich (1998), Pedrycs (1993), de Silva (1995), Bezdek et al. (1999), Bonissone et al. (1995), Sala, Guerra, and Babuska (2005), Tanaka and Wang (2001), Wang (1994, 1997), Sugeno (1985), and Yager and Filev (1994).

Successful engineering application areas include, but are not limited to, power systems (Abdelazim and Malik, 2003; Flores et al., 2005; Guesmi, Adballah, and Toumi, 2004; Ko and Niimura, 2002); telecommunications (Aoul et al., 2004; Chen, Lee, and Guo, 2003a,b; Chen, Tsai, and Chen, 2003; Kandel et al., 1999; Lee and Lim, 2001; Zhang and Phillis, 1999); mechanical/robotic systems (Bai, Zhuang, and Roth, 2005; Baturone et al., 2004; Boukezzoula, Galichet, and Foulloy, 2004; Chang and Chen, 2005; Hagras, 2004; Hwang and Kuo, 2001; Li, Lee, and Cheng, 2004;

Santibanez, Kelly, and Llama, 2005; Sun and Er, 2004; Yang et al., 2004); automobiles (Bonissone et al., 1995; Huang and Lin, 2003; Lin and Hsu, 2004; Mar and Lin, 2001; Murakami and Maeda, 1985; Niasar, Moghbeli, and Kazemi, 2003; Sugeno and Nishida, 1985); industrial/chemical processes (Chen and Liu, 2005a; Frey and Kuntze, 2001; Horiuchi and Kishimoto, 2002; Juang and Hsu, 2005; King and Mamdani, 1977; Larsen, 1980; Ostergaard, 1977; Sugeno, 1985; Tani, Murakoshi, and Umano, 1996; Tong, Beck, and Latten, 1980; Umbers and King, 1980); aircraft (Chiu et al., 1991; Farinwata, Pirovolou, and Vachtsevanos, 1994; Kadmiry and Driankov, 2004; Larkin, 1985); motors (Barrero et al., 2002; Guillemin, 1996; Kim and Lee, 2000); medical services (Kwok et al., 2004; Seker et al., 2003; Zheng and Zhu, 2004); consumer electronics (Haruki and Kikuchi, 1992; Kumar, 2005; Lee and Bien, 1994; Lee et al., 1994; Nakagaki et al., 1994; Smith, 1994; Takagi, 1992; Wu and Sung, 1994); and other areas such as chaos control (S. S. Chen et al., 2005; Lian et al., 2001) and nuclear reactors (Boroushaki et al., 2003; Munasinghe, Kim, and Lee, 2005).

The literature on the topic of fuzzy logic control is vast and many different approaches have been developed. Based on the features of fuzzy control rules, these approaches can be roughly classified into the following categories:

1. Conventional fuzzy control or Mamdani fuzzy control
2. Fuzzy proportional-integral-derivative (PID) control
3. Neuro–fuzzy control or fuzzy–neuro control
4. Fuzzy sliding mode control
5. Adaptive fuzzy control
6. Takagi–Sugeno model-based fuzzy control

However, this classification is neither unique nor exhaustive, and many other different classifications can also be employed. It should also be noted that overlapping among these classification categories is inevitable. For example, conventional fuzzy control can be adaptive, fuzzy PID control can be tuned by neuro–fuzzy systems, or neuro–fuzzy control can be adaptive in nature in many cases. A brief review of all these categories of fuzzy logic control approaches is presented next.

1.2 BRIEF REVIEW OF FUZZY LOGIC CONTROL

1.2.1 Conventional Fuzzy Control (Mamdani-Type Fuzzy Control)

Mamdani and Assilian developed the first real fuzzy control algorithm in the early 1970s (Mamdani, 1974; Mamdani and Assilian, 1975), where control of a small steam engine was considered. The fuzzy control algorithm basically consisted of a set of heuristic control rules, and fuzzy sets and fuzzy logic were used, respectively, to represent linguistic terms and to evaluate the control rules, called conventional fuzzy control or Mamdani-type fuzzy control. Since then similar fuzzy logic control algorithms have been developed for many different engineering processes. For example, Kickert and Lemke (1976) developed a fuzzy control algorithm for a warm-water plant, and Ostergaard (1977) presented another fuzzy control algorithm for a small-scale heat exchanger.

There were many other applications of conventional fuzzy control, including robot (Baturone et al., 2004; Uragami, Mizumoto, and Tanaka, 1976; Xiao et al., 2004; Yang et al., 2004), stirred tank reactor (King and Mamdani, 1977), traffic junction (Pappis and Mamdani, 1977), steel furnace (Kornblum and Tribus, 1970), cement kilns (Umbers and King, 1980), automobile (Bonissone et al., 1995; Murakami and Maeda, 1985; Sugeno and Nishida, 1985), wastewater treatment (Tong, Beck, and Latten, 1980), aircraft (Chiu et al., 1991; Larkin, 1985), missile autopilot (Farinwata, Pirovolou, and Vachtsevanos, 1994), motor (Guillemin, 1996), network traffic management and congestion control (Kandel et al., 1999; Lee and Lim, 2001), bioprocesses (Horiuchi and Kishimoto, 2002), fusion welding (Bingul, Cook, and Strauss, 2000), and so on. In addition, conventional fuzzy control was also widely used in various consumer electronic devices such as video cameras, washing machines, televisions, and sound systems in the late 1980s and early 1990s (Haruki and Kikuchi, 1992; Kumar, 2005; Lee and Bien, 1994; Lee et al., 1994; Nakagaki et al., 1994; Smith, 1994; Takagi, 1992; Wu and Sung, 1994).

These methods of conventional fuzzy control are essentially heuristic and model free. Conventional fuzzy logic control has been widely accepted by engineers in industry due to its simplicity and ease in understanding and implementation. The fuzzy control "IF–THEN" rules are often obtained based on an operator's control action or knowledge. It is thus obvious that the design method works well only in the cases where operators or their knowledge play an important or critical role in controlling the system. Even though the performance of such control schemes might be generally satisfactory in practice, the stability issue of the closed-loop fuzzy control systems is often not addressed and thus often criticized in the earlier development of these methods. Moreover, design of conventional fuzzy control systems suffers from a lack of systematic tools, which often leads to difficulty in controller design and inconsistency in performance of the closed-loop control systems. Thus great efforts have been devoted to issues of stability analysis and controller design of conventional fuzzy control systems, and various approaches have been developed.

In addition to a heuristic approach provided by Braae and Rutherford (1979) for stability analysis of fuzzy control systems, a key idea of most approaches is to consider a fuzzy controller as a nonlinear controller and embed the stability or control design problem of fuzzy control systems into conventional nonlinear system stability theory. The typical approaches include describing function approach (Kickert and Mamdani, 1978), cell-state transition (Kang, 1993), Lure's system approach (Cho, Kim, and Lim 1993; Melin and Vidolov, 1994), Popov's theorem (Furutani, Saeki, and Araki, 1992), circle criterion (Opitz, 1993; Ray and Majumder, 1984; Singh, 1992), conicity criterion (Espada and Barreiro, 1999), sliding mode control (Hwang and Lin, 1992), and hyperstability (Calcev, Gorez, and De Neyer, 1998; Opitz, 1993), among others. However, a general theory for systematic stability analysis and controller synthesis of conventional fuzzy control systems is still out of reach and remains a challenging task for the fuzzy control community.

1.2.2 Fuzzy PID Control

It is well known that conventional proportional-integral-derivative controllers are still one of the most widely adopted methods in industry for various control applications. PID controllers have a number of distinctive advantages such as their simple structure, ease of design, and low cost of implementation in comparison to many other control methods. However, PID controllers might not perform satisfactorily or as desired if the system to be controlled is highly nonlinear or uncertain, or if the control performance specification is very demanding. On the other hand, fuzzy control has long been known for its ability to handle nonlinearities and uncertainties through the use of fuzzy set theory. It is thus believed that a better control system to take advantage of PID control and fuzzy control can be achieved by adequately integrating these two techniques. Considerable effort has been devoted to the course of this development and many significant results have been obtained. The resulting controllers are usually called fuzzy PID controllers.

It is noted that the name "fuzzy PID control" has been widely used in the literature with a variety of meanings. A particular example is the definition by Hu, Mann, and Gosine (2001). It is suggested that if the resulting control action from a fuzzy controller is in the scope of proportional-integral-derivative concepts like a conventional PID controller, then the fuzzy controller is called a fuzzy PID controller. Generally, this type of fuzzy PID controller is able to perform as well as conventional PID controllers if designed properly. However, the relative high cost of setting up a fuzzy control system would usually keep one from replacing conventional PID controllers with this type of controller. It should be noted that with this definition, the conventional fuzzy controller developed by Mamdani and Assilian (1975) would be classified as a two-input fuzzy PI controller, and this would not be in accordance with the original idea of fuzzy PID control. Instead, a more generally accepted definition is more or less relevant to integrating fuzzy logic control and PID control techniques. A typical example is that the controllers have the structure of PID controllers but with the gains implemented by fuzzy logic theory. This type of fuzzy PID controller is generally classified as "gain-scheduling" (He et al., 1993a,b; Zhao, Tomizuka, and Isaka, 1993) type fuzzy PID controllers, for the reason that controller gains change as the operating condition or dynamics of a system varies.

These gain-scheduling fuzzy PID controllers have gained wide acceptance by industry because they take advantage of both conventional PID control and fuzzy control techniques. In fact, this type of fuzzy PID control has indeed received much more attention and has had great success in industrial applications. It has also been shown that many fuzzy PID controllers are nonlinear PID controllers and perform much better than conventional PID controllers in most cases.

Other topics of interest relevant to fuzzy PID control include tuning of fuzzy PID parameters (Mann, Hu, and Gosine, 2001; Mudi and Pal, 1999; Woo, Chung, and Lin, 2000; Xu, Hang, and Liu, 2000), optimal fuzzy PID controller based on a genetic algorithm (Hu, Mann, and Gosine, 1999; Tang et al., 2001), realization of conventional PID controllers by fuzzy control methods (Mizumoto, 1995), improved robust fuzzy PID controller with optimal fuzzy reasoning (Li et al., 2005), and