Model Based Fuzzy Control

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Fuzzy Gain Schedulers and Sliding Mode Fuzzy Controllers

With 86 Figures

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Foreword

Despite the excitement about its capabilities, and its success in some challenging applications, fuzzy control is still young and hence some important questions arise: In what situations, or for what applications, is fuzzy control superior to conventional control methods? Is it possible to combine some of the best ideas from the conventional methods with ideas from fuzzy control to provide more effective control solutions? How do we measure the success or failure of the methods? For many applications, simulations and experimental evaluations are not sufficient to verify the behavior of a control system, and in such situations there is a need for mathematical analysis of closed-loop system properties such as stability, performance, and robustness to determine whether a fuzzy control system is successful. Verification of such properties may be especially important for "safety-critical applications" (e.g., an aircraft or nuclear power plant) where the engineer must gain as much confidence in the closed-loop system as is possible before implementation.

Conventional control focuses on the use of models to construct controllers for dynamical systems. Fuzzy control focuses on the use of heuristics in the construction of a controller. While each of these seemingly disjoint approaches uses some ideas from the other, there has been relatively little work on how to more closely combine them to exploit the best characteristics of each. This book helps to remedy this problem by providing schemes that allow for the incorporation of heuristics and mathematical models. It also provides important ideas on how to marry some very successful conventional control ideas (e.g., sliding mode control and gain scheduling) with ideas from fuzzy control. While the past lack of focus on the use of mathematical models in fuzzy control systems development resulted in researchers ignoring mathematical analysis of stability, the basic approach used allows the authors to confront this important problem.

Overall, this book makes important steps toward bridging the apparent gap between fuzzy and conventional control. I would expect the techniques studied here to be quite useful for a wide range of challenging applications and would expect these ideas to form a foundation on which more research in this promising area will be based.

Columbus, Ohio, USA, 1996 *Kevin M. Passino*

Preface

During the past few years two principally different approaches to the design of fuzzy logic controllers (FLC) have emerged: heuristics based design and model based design.

The main motivation for the heuristics based design is given by the fact that many industrial processes are still controlled in one of the following two ways:

- The process is controlled manually by an experienced operator.
- The process is controlled by an automatic control system which needs additional manual on-line "trimming" from an experienced operator.

In both cases it is enough to translate the operator's manual control algorithm in terms of a set of fuzzy if-then rules in order to obtain an equally good, or an even better, wholy automatic control system incorporating an FLC. This implies that the design of an FLC can only be done *after* a "control algorithm" already exists.

In the first case, the existing control algorithm may consist of sequential and/or parallel manual control actions performed by the operator upon a process whose mathematical model is either impossible to derive or of negligible utility for cost related reasons. In this case the FLC simply makes explicit the existing manual control knowledge, and consequently automates the use of this knowledge thus becoming a part of the closed loop system. In the second case, the existing control algorithm is a conventional control algorithm in need of additional manual "trimming". An FLC is then again used to automate the manual "trimming" algorithm employed by the operator and thus acts as a supervisor to the conventional closed loop system already in place.

It is admitted in the literature on fuzzy control that the heuristics based design is very difficult to apply to multiple-input/multiple-output control problems, which represent the largest part of challenging industrial process control applications. Furthermore, the heuristics based design lacks systematic and formally verifiable tuning techniques, and studies of stability, performance, and robustness can only be done via extensive simulations. Last but not least, there is a lack of systematic and easily verifiable knowledge acquisition techniques via which the qualitative knowledge about the process and/or available manual control algorithm can be extracted.

The above difficulties faced by the heuristics based design explain the recent surge of interest in the derivation of *black box* fuzzy models of the plant under control, in terms of the identification of a set of fuzzy if-then rules, by the use of conventional identification techniques, neural networks, genetic algorithms, or a mixture of these techniques.

This interest in the identification of fuzzy models is accompanied by a similar surge of interest in the model based design of fuzzy controllers. Model based fuzzy control uses a given conventional or fuzzy open loop model of the plant under control in order to derive the set of fuzzy if-then rules constituting the corresponding FLC. Interest then centers on the stability, performance, and robustness analysis of the resulting closed loop system involving a conventional model and an FLC, or a fuzzy model and an FLC. The major objective of model based fuzzy control is to use existing conventional linear and nonlinear design and analysis methods for the design of such FLCs that have better stability, performance, and robustness properties than the corresponding non-fuzzy controllers designed by the use of these same techniques. How to achieve this objective in terms of the design and analysis of sliding mode fuzzy controllers and fuzzy gain schedulers is the subject of this book.

In **Chapter 1** we introduce the basic notions and concepts in fuzzy control, the basic types of FLCs treated in the book, the major types of nonlinear control problems, and the existing methods for model based design and analysis of nonlinear control systems relevant for model based fuzzy control. We finally discuss informally the motivation for the design of fuzzy gain schedulers and fuzzy sliding mode controllers.

In Section 1.1 of this introductory chapter we present the basic fuzzy control related concepts used throughout the book involving the notions of a fuzzy state, fuzzy input, fuzzy output variables, and fuzzy state space.

In Section 1.2 we present the basic types of FLCs whose model based design and analysis is our subject. These include different types of Takagi–Sugeno FLCs (TSFLC) and the sliding mode FLC (SMFLC). We describe the open loop models used for the design of the different types of FLCs and the form of the fuzzy rules constituting these FLCs. We also present the control schemes incorporating an FLC that are relevant for model based fuzzy control.

In Section 1.3 we first describe the two basic types of nonlinear control problems considered in the book, namely nonlinear regulation and nonlinear tracking. Then, we discuss the specifications of the desired behavior of nonlinear closed loop systems in terms of stability, robustness, accuracy, and response speed.

In Section 1.4 we present the major existing methods for the model based design and analysis of nonlinear control systems and identify those of them whose fuzzy counterparts (with appropriate modifications) concern us.

In Section 1.5 we introduce and discuss informally the motivation for two basic types of FLCs, namely the Takagi–Sugeno FLC and the sliding mode FLC.

In **Chapter 2** we describe computation with an FLC and its formal description as a static nonlinear transfer element and thus provide the background knowledge needed to understand control with an FLC. We show the relationship between conventional and rule-based transfer elements and establish the compatibility between these two conceptually different, in terms of representation, types of transfer elements. We also introduce the basic stability concepts used in the model based design and analysis of FLCs.

In Section 2.1 we describe the computational structure of an FLC involving the computational steps of input scaling, fuzzification, rule firing, defuzzification, and output scaling.

In Section 2.2 we present the sources of nonlinearity in the computational structure of an FLC by relating them to particular computational steps.

In Section 2.3 we describe the relationship between conventional transfer elements and rule-based transfer elements. We show the gradual transition from a conventional transfer element to a crisp rule-based transfer element, and finally to a fuzzy rule-based transfer element. We also describe the computational structure of Takagi–Sugeno FLCs.

In Section 2.4 we present the stability concepts used in the model based design and analysis of an FLC including Lyapunov-linearization and the Lyapunov direct method for autonomous and nonautonomous systems.

In **Chapter 3** we make use of the similarity between the so-called diagonal form FLC and a sliding mode controller (SMC) to redefine a diagonal form FLC in terms of an SMC with boundary layer (BL).

In Section 3.1 we describe the control law of an SMC for an n-th-order SISO nonlinear nonautonomous system and its design for a tracking control problem with and without an integrator term.

In Section 3.2 we describe in detail the diagonal form FLC for a second order SISO nonlinear autonomous system and derive the similarities between the control law of a diagonal form sliding mode FLC and the control law of an SMC with BL.

In Section 3.3 we describe the design of the control law of a sliding mode FLC for an n-th-order SISO system for the tracking control problem, with and without integrator term.

In Section 3.4 we discuss the tuning of input scaling factors of a sliding mode FLC. In Section 3.5 we give an example of a force adapting manipulator arm for the design of a sliding mode FLC. In Section 3.6 we extend the sliding mode FLC design method to MIMO systems.

In **Chapter 4** we present the design methods for each of the different types of Takagi–Sugeno FLCs outlined in Chap. 1.

In Section 4.1 we present the Takagi–Sugeno FLC-1. We confine ourselves only to the presentation of the form of the open loop system, the form of the Takagi–Sugeno FLC-1, the form of the closed loop system and its stability properties, and an outline of a trial-and-error type of design method.

In Section 4.2 and 4.3 we present in detail the design of the Takagi–Sugeno FLC-2 and its use in local stabilization and tracking of a nonlinear autonomous system. With respect to local stabilization, a Takagi–Sugeno FLC-2 is able to stabilize a nonlinear autonomous system around *any* operating point without the need to change its gains. With respect to tracking, the FLC-2 performs gain scheduling on *any* reference state trajectory under the restriction that the reference state trajectories are slowly time varying.

In **Chapter 5** we illustrate in detail the design of fuzzy sliding mode controllers and fuzzy gain schedulers on a MIMO control problem concerning the control of a two-link robot arm.

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1. Introduction to Model Based Fuzzy Control

A *fuzzy logic controller* (FLC) defines a *static nonlinear control law* by employing a set of *fuzzy if-then rules*, or *fuzzy rules* for short. The if-part of a fuzzy rule describes a fuzzy region in the state space. The then-part of a fuzzy rule specifies a control law applicable within the fuzzy region from the if-part of the same fuzzy rule. During control with an FLC a point in the state space is affected to a different extent by the control laws associated with all the fuzzy regions to which this particular point in the state space belongs.

The subject of this book is the model based design (synthesis) and analysis of FLCs, or in short, *model based fuzzy control.* Model based fuzzy control deals with the design of the set of fuzzy rules given a conventional, nonlinear open loop model of the system under control (a plant, or a process) and the consequent stability, robustness, and performance analysis of the resulting closed loop system. This is contrary to the *heuristic approach* to FLC design where the set of fuzzy rules is derived via a knowledge acquisition process and reflects the heuristic (shallow) knowledge of an experienced system operator. It is admitted in the literature on fuzzy control [5] that this approach is difficult to apply to *multiple-input/multiple-output* (MIMO) control problems. Though successfully applied in a wide range of basically *single-input/single-output* (SISO) control problems, the heuristic approach lacks systematic and verifiable tuning techniques, and studies of stability, robustness, and performance can only be done via extensive simulation.

In the design, we are given a nonlinear model of the plant to be controlled and some specifications of closed loop behavior, and the task is to construct an FLC, that is a set of fuzzy rules, so that the closed loop system meets these specifications. In the analysis, a nonlinear closed loop system involving an FLC is assumed to have been designed, and the task is to study its behavior in terms of certain characteristic features. In practice, design and analysis are interleaved and the design of a nonlinear controller is in effect an iterative process of analysis and design.

In Sect. 1.1 of this introductory chapter we first present the basic FLC related concepts to be used throughout the book involving the notions of a *fuzzy state, fuzzy input, fuzzy output variables*, and *fuzzy state space.*

In Sect. 1.2 we present the basic types of FLCs whose model based design and analysis are the subject of this book. These include different types of *Takagi–Sugeno* FLCs (TSFLC) and the *sliding mode* FLC (SMFLC). We describe the open loop models used for the design of the different types of FLCs and the form of the fuzzy rules constituting these FLCs. We also present the control schemes incorporating FLCs that are relevant for model based fuzzy control.

In Sect. 1.3 we first describe the two basic types of nonlinear control problems considered in the book, namely nonlinear regulation and nonlinear tracking. Then, we discuss the specifications of the desired behavior of nonlinear closed loop systems in terms of *stability*, *robustness*, *accuracy*, and *response speed*.

In Sect. 1.4 we present the major existing methods for the model based design and analysis of nonlinear control systems and identify those whose fuzzy counterparts (with appropriate modifications) are the subject of this book.

In Sect. 1.5 we introduce and discuss informally the motivation for the two basic types of FLCs that are the subject of this book, namely the Takagi-Sugeno FLC and the sliding mode FLC.

1.1 Fuzzy Concepts in Model Based Fuzzy Control

The essential feature of the notion of a *state* for a dynamical system is that it should contain all information about the past history of the system that is relevant for its future behavior. That is, if the state at a given instant of time is known, then its subsequent evolution can be predicted without any knowledge as to what has previously happened with the system. This means that when ordinary differential equations are used, the definition of the state must involve enough variables for all the equations to be of first order in the time-derivative. The dependent variables in these equations are called *state variables*, and they are usually denoted by $x_1, x_2, \ldots, x_n$, where n is the *order of the system*. Each state variable x_i is a function of time and takes pointwise, or *crisp values* in the domain of the reals and is thus called a *crisp state variable*.

Besides the crisp state variables, the equations also contain a number of externally specified variables which represent the driving forces acting upon the system from outside of the same system. These are known as *input variables* and are denoted as $u_1, u_2, \ldots, u_m$, where m is usually, though not necessarily, less than n. Each input variable is also a function of time and takes crisp values in the domain of reals and is thus called a *crisp input variable*. For ease of notation the crisp state and input variables are assembled into the so-called *state vectors* and *input vectors* $\mathbf{x} = (x_1, x_2, \ldots, x_n)^T$ and $\mathbf{u} = (u_1, u_2, \ldots, u_m)^T$ respectively. We will call these vectors *crisp state vectors* and *crisp input vectors*.