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Qing Gao

Universal Fuzzy Controllers for Non-affine Nonlinear Systems

Doctoral Thesis accepted by
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To my parents
for raising me to have a sense of whimsy.
To my wife
for appearing in my life as a real beauty.

Supervisor's Foreword

It has long been a significant concern about the feasibility of fuzzy control design for nonlinear systems, despite the countless contribution made on fuzzy-model-based nonlinear control in recent decades. The universal fuzzy controller's problem, which was proposed in the early 1990s, offers an intelligent insight by investigating the existence of a fuzzy control law when a non-fuzzy controller can stabilize a nonlinear system under consideration.

I congratulate the author on contributing this very complete framework on the problem of universal fuzzy control, which puts together all the author's key findings in his Ph.D. study. A fantastic feature of this book is that discussion is given in context of general non-affine nonlinear systems, which makes the work applicable widely. This book is definitely a very self-contained work, covering important issues including universal function approximation, controller synthesis and universality discussion of the controllers. Readers can grasp the full picture without referring much to the sea of references.

Hong Kong, China
June 2016

Prof. Gang Feng

Preface

Analysis and synthesis of nonlinear systems is complicated. This is mainly because the nonlinear differential equation's description normally provides limited knowledge about the system behaviour, or from another perspective, nonlinear dynamics are often hard to understand and formulate. What embody this truth in control theory are the great difficulties we face in searching for a suitable Lyapunov candidate for a complex nonlinear system. As a result, one has to restart the machine when dealing with a different nonlinear plant and, what is embarrassing is he/she cannot even guarantee that the control task can be accomplished! So it is natural to question about the existence of any systematic way of analyzing nonlinear systems.

Approaches-based Takagi-Sugeno (T-S) fuzzy models, also known as dynamic fuzzy models, tend be a fantastic solution to the issue we concerned. T-S fuzzy-model-based nonlinear control has been very successful in recent decades, which is witnessed by the large volume of research papers and books published. It is amazing that by using T-S fuzzy models and quadratic-type Lyapunov functions, analysis and synthesis of any smooth nonlinear systems, at least theoretically, can be solved by finding solutions to a convex optimization problem, and the design procedure has been systematic! However, it is very difficult to choose the right fuzzy rules, including the right number and suitable interpolation points, such that the convex optimization problem is feasible and the original nonlinear system is well modelled at the same time. In practice, this is done using a trial-and-error way of design. So how good are T-S fuzzy-model-based control approaches? This book is trying to express a viewpoint that, the feasibility of T-S fuzzy-model-based approaches is as good as their non-fuzzy counterpart, which is exciting regarding the ease of designing fuzzy controllers.

My aim in this book is to present the unified framework of a new fuzzy-model-based nonlinear control approach, including modelling, control design and universality discussion. The picture is drawn in the context of general deterministic/stochastic non-affine nonlinear systems, control of which most classical engineers would feel to be a tough job. We consider two different cases, i.e.

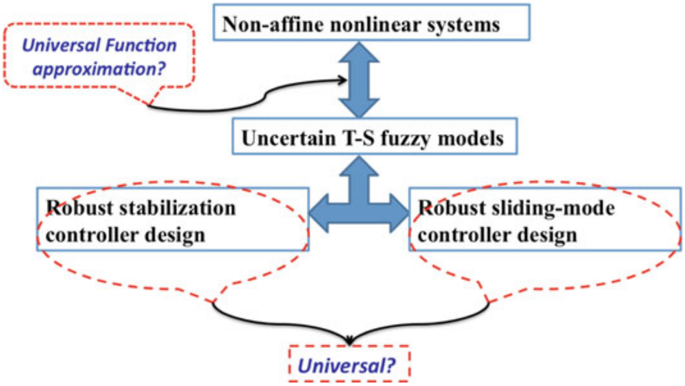

Fig. 1 Sketch of the theory

stabilization controller and sliding-mode controller design. However, the ideas among them are very same and can be extended to various cases.

The key theory of this book is as illustrated in Fig.1.

The book contains two parts. Part I concerns universal fuzzy stabilization controllers while Part II concerns universal fuzzy integral sliding-mode controllers. Both are given for deterministic/stochastic non-affine nonlinear systems.

Chapter 2 considers the universal fuzzy model and the universal fuzzy controller problems for non-affine nonlinear systems based on a class of generalized T-S fuzzy models. It is noted that the commonly used T-S fuzzy models, where the premise variables are only dependent on the system state variables, are only able to approximate affine nonlinear systems to any degree of accuracy on any compact set. In Chap. 2, a class of generalized T-S fuzzy models, where the premise variables are dependent on both the systems state vector x and the system control input u, is shown to be universal function approximators to non-affine nonlinear systems. A constructive procedure for obtaining T-S fuzzy approximation models of non-affine nonlinear systems is also provided. This kind of generalized T-S fuzzy models is then shown to be universal fuzzy models for non-affine nonlinear systems under some sufficient conditions. Then an approach to robust stabilization fuzzy controller design of the generalized T-S fuzzy model, or equivalently, semi-global stabilization fuzzy controller of the non-affine nonlinear system is developed. It is noted that, with the control input included in the premise part of fuzzy rules, the commonly used parallel distributed compensation (PDC) control scheme, whose local models are given by static-state feedback controllers, cannot be directly applied in control design of the generalized T-S fuzzy model. Thus a fuzzy controller in the form of *dynamic parallel distributed compensation* (DPDC) is employed instead. Based on this kind of dynamic fuzzy controllers, the results of universal fuzzy controllers for a class of exponentially stabilizable nonlinear systems and a class of asymptotically stabilizable nonlinear systems are given. Constructive procedures to obtain the universal fuzzy controllers are also provided.

Simulation studies are finally presented to show the advantages of the proposed approaches.

The techniques involved in Chap. 2 include universal function approximation, quadratic Lyapunov functions, Lyapunov stability theory, and inverse Lyapunov theorem. It is noted that many new approaches proposed in the book originate from the results in Chap. 2. This chapter plays a fundamental role in the whole book.

Chapter 3 extends the results given in Chap. 2 to stochastic non-affine nonlinear systems case. It is noted that there are different views or interpretations on descriptions of stochastic fuzzy systems. In Chap. 3, the underlying mechanism of stochastic fuzzy system is first discussed and a stochastic generalized fuzzy model with new stochastic fuzzy rule base is then given. Based on their function approximation capability, these kind of stochastic generalized fuzzy models are shown to be universal fuzzy models for stochastic non-affine nonlinear systems under some sufficient conditions. An approach to stabilization controller design for stochastic non-affine nonlinear systems is then developed through their stochastic generalized T-S fuzzy approximation models. Then the results of universal fuzzy controllers for two classes of stochastic nonlinear systems, along with constructive procedures to obtain the universal fuzzy controllers, are also provided. Finally, an inverted pendulum example is presented to illustrate the effectiveness of the proposed approach.

Chapter 4 is concerned with SMC design of both deterministic and stochastic uncertain T-S fuzzy systems with a constant time delay. A novel fuzzy dynamic sliding-mode control (DSMC) approach is developed. A key feature of the proposed DSMC approach is that the sliding surface function is defined to be linearly dependent on both system state vector x and control input vector u. By employing a sliding-mode controller with a fuzzy dynamic feedback control term, it is shown that the sliding mode can be achieved in finite time and the stability of the sliding motion can be guaranteed in terms of LMIs. It is also shown that with the proposed DSMC approaches, those two restrictive assumptions in most existing fuzzy SMC works have been removed. Simulation results are provided to show the effectiveness and advantages of DSMC over the existing fuzzy SMC approaches.

Chapter 5 is devoted to the so-called universal fuzzy integral sliding-mode controller problem for non-affine nonlinear systems. A novel dynamic integral sliding-mode control (DISMC) scheme is developed, aiming to remove the assumption that all subsystems of the T-S fuzzy models share the same input matrix, which is required in most existing fuzzy ISMC approaches. It is shown that the sliding mode can be achieved and maintained since the initial time, and moreover the stability of the resulting sliding motion can be guaranteed in terms of LMIs. Moreover, the corresponding integral sliding surface and the sliding-mode controller can be obtained simultaneously. Then based on the proposed DISMC approach, the results of universal fuzzy integral sliding-mode controllers for a class of exponentially stabilizable nonlinear systems and a class of asymptotically stabilizable nonlinear systems are given. Constructive procedures to obtain the universal fuzzy integral sliding-mode controllers are also provided. Simulation results illustrating the effectiveness and advantages of DISMC over the existing fuzzy ISMC approaches are finally presented.

Chapter 6 extends the results in Chap. 5 to the case of stochastic non-affine nonlinear systems. In particular, the assumption that the stochastic perturbation can be ignored during the sliding mode, which is required in most existing ISMC approaches for stochastic systems, is removed. It is shown that the trajectories of the closed-loop control system can be kept on the sliding surface almost surely since the initial time, and the resulting sliding motion is stochastically stable if a set of LMIs is feasible. Moreover, the corresponding integral sliding surface and the sliding-mode controller can be obtained simultaneously. Then based on the proposed DISMC approach, the results of universal fuzzy integral sliding-mode controllers for a class of stochastically exponentially stabilizable nonlinear systems and a class of stochastically asymptotically stabilizable nonlinear systems are given. Constructive procedures to obtain the universal fuzzy integral sliding-mode controllers are also provided. Simulation results from an inverted pendulum example are finally presented to show the effectiveness and advantages of the proposed approaches.

The final chapter is a brief summary of the contribution and some future research topics.

In order to understand this book, it is necessary to have a sound knowledge of nonlinear control systems, especially Lyapunov theory. Knowledge of fuzzy systems and stochastic differential equations help understanding the work better but can also be learned from the content. This book is primarily designed to be a reference book, which is useful to engineers for both theory research and real applications. And I truly hope this work would help attract more new researchers into the area of fuzzy control.

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My deepest gratitude goes first and foremost to my Ph.D. supervisors, Prof. Gang Feng and Prof. Yong Wang. They always keep vivid view on my research work and give me constructive suggestions on each important stage during my research, at the same time leaving me enough freedom to explore myself. What I have learnt from them include not only the knowledge which is embodied in this book, but also the training on solid research, from which I will continue benefiting all my life. Professor Jianbin Qiu from Harbin Institute of Technology is another important person I wish to thank, who introduced me into this area and guided me like a supervisor.

I wish to express my sincere gratitude to my parents and my sisters. Their encouragement and support have helped me to overcome various difficulties in my life and finish my doctoral study. Their lifelong love is the most precious gift to me in all my life. Finally, special appreciation goes to my dearest wife, Dr. Tingting Gang. Without her altruistic care, love, encouragement and patience all the time, I would not have been able to finish this work.

Hong Kong
June 2016

Qing Gao

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