General Conclusion

In this book, the main results concerning the quadratic stabilization of T–S fuzzy models have been presented. Using state feedback, static and dynamic output feedback controllers, the stabilization conditions formulated in LMI terms have been proposed. The main available results in the literature are recalled for T–S fuzzy systems with or without fixed delay, uncertain T–S fuzzy systems. Techniques for observer design have been presented. The problem of constrained nonlinear systems represented by fuzzy systems has been studied using positive invariance tools. Sufficient conditions of asymptotic stability have been obtained despite the presence of saturations on the control by using both common quadratic Lyapunov function and piecewise Lyapunov function. The used approach has been the one followed in [1] with like uncertain subsystems and upper bound subsystems. The obtained results has successfully been applied to two nonlinear systems with constrained control. This leads to the characterization of a common region of positive invariance and asymptotic stability of both ellipsoidal and polyhedral form. It has also been shown that a common Lyapunov function, when it exists, leads to less conservative region of positive invariance and asymptotic stability for constrained systems. Improved conditions of stabilizability are also presented. It has been shown that even if a piecewise Lyapunov function is used, no common region has been needed at all to guarantee the asymptotic stability of the fuzzy system despite the presence of constraints on the control. Hence, a set of LMIs has been proposed to built such stabilizing controllers.

Besides, stability analysis and design methods for nonlinear systems with actuator saturation have been studied. T–S fuzzy models with actuator saturation have been used to describe nonlinear systems. Two different methods have been used, one direct and one indirect to derive sufficient conditions of asymptotic stability of T–S fuzzy systems with saturated control. Finally, these design methodologies have been illustrated by their application to the stabilization of a balancing-up truck trailer. It has been shown that the indirect method leads to less conservative LMIs since it leads to larger stability domains. Further, to improve the obtained results, a composite quadratic Lyapunov function has been used to obtain sufficient conditions of asymptotic stability for discrete-time nonlinear system represented with a T–S fuzzy

A. Benzaouia and A. El Hajjaji, *Advanced Takagi–Sugeno Fuzzy Systems*,
Studies in Systems, Decision and Control 8, DOI: 10.1007/978-3-319-05639-5,

model. It has been shown in the literature that this piecewise Lyapunov function leads to better results in the sense that a common quadratic Lyapunov function may not exist, while a piecewise one exists. These conditions have been formulated in LMI constraints. A discrete-time nonlinear model representing the problem of parking in reverse gear of a vehicle with trailer has been studied.

A main control problem has also been studied in this book: stabilizing with static output PDC control (SOPDC). Two results of synthesis and design of static output feedback controllers for nonlinear systems described by T–S models have been investigated. A new development of the triple summing has been presented by Lemma 3.2. It has been shown that the SOPDC controller can be obtained easily using this lemma. A common quadratic Lyapunov function has been used to obtain sufficient conditions of asymptotic stability. Based on cone complementarity method, the design conditions have been formulated in LMI terms. Two discrete-time nonlinear models have been proposed for illustration. To avoid the constraining optimization problem, a technique has been proposed to relax the based cone complementarity approach result.

For discrete-time nonlinear positive systems which can be represented by positive T–S fuzzy models, sufficient conditions of stabilizability, using multiple Lyapunov functions, have been proposed. PDC and non-PDC control techniques have been investigated using LMI approach. The proposed approach has been illustrated on a physical plant model. These results can be improved by using other techniques of relaxation, such as slack variables and cone complementarity.

An important topic has been also considered in this book: Fuzzy systems with time-varying delay. Firstly, delay-dependent design of stabilizing fuzzy controllers for T–S fuzzy systems while imposing positivity in closed-loop has been investigated. The proposed method which has been used to reduce both the conservatism and the computational burden in [2], has been used to govern the closed-loop delayed system only in the positive orthant. Besides, the obtained delay-dependent stabilization conditions have been formulated in terms of LMIs without involving any tuning parameter. A memory feedback control has also been used in case delay matrices $A_{\tau i}$ are not nonnegative. The model of a real plant has been used to illustrate the proposed approaches.

Secondly, the obtained results have been extended to take account of actuator saturations.

The delay-dependent design of state feedback stabilizing fuzzy controllers for uncertain T–S fuzzy systems with time-varying delay has then been investigated in this book. An important contribution has been established, which allows to reduce the conservatism and the computational efforts in the same time. Three examples have been given to illustrate numerically that the obtained results are less conservative than the existing ones in the literature. In the same way, a new method for the H_∞ control for T–S fuzzy systems with time delay has been proposed. Less conservative results have been obtained by using fuzzy weighting-dependent approach without imposing any model transformation and any bounding technique for cross terms in the derivation process. Further, the problem of delay-dependent observer-based H_∞ control for T–S fuzzy systems with time-delay has been studied and design conditions has been formulated in strict LMIs. The designed observer-based H_∞ control is valid for both slowly and fast time-varying delays. An illustrative example has been given to demonstrate the use and merits of the present result. In addition, the problem of presence of saturation on the control has been considered by proposing two kinds of controllers:

- Unsaturating controllers which stabilize the system without tolerating saturation to take effect. These controllers work in a linear region of behavior.
- Saturating controllers which stabilize the system with tolerance of saturation.

Each result has been illustrated by an example to show the applicability and usefulness of the proposed methodology.

In order to obtain less conservative conditions, the controller designing tool based linear programming approach has been developed to deal with strong constraints as positivity or asymmetrical boundedness on the control for positive T–S fuzzy systems. An application to two tanks system has been presented. A comparative study has been performed to illustrate the advantage of LP technique approach in terms of conservatism reduction.

Stability and stabilization of discrete and continuous 2D nonlinear systems represented by T–S fuzzy models with PDC state feedback control have also been studied. Common quadratic and multiple Lyapunov functions have been considered to obtain sufficient conditions of asymptotic stabilization for this class of systems. Besides, non-PDC control has also been used for continuous 2D T–S fuzzy systems to obtain less conservative conditions of stabilizability. All the design conditions have been formulated in LMI terms. Nonlinear numerical examples have been proposed to illustrate the obtained results. The extension to 2D-delayed T–S fuzzy systems has also been investigated using multiple Lyapunov–Krasovskii functional to derive less conservative conditions. Numerical example has been presented to show the applicability of these results.

References

1. Cao SG, Rees NW, Feng G (1996) Stability analysis and design for a class of continuous-time fuzzy control systems. Int J Cont 64:1069–1088
2. Gassara H, El Hajjaji A, Chaabane M (2009) New delay-dependent stabilization conditions of T-S fuzzy systems with time varying delay. In: 17th IEEE Mediterranean conference on control automation, Thessaloniki, 24–26 June 2009

Index

A. Benzaouia and A. El Hajjaji, *Advanced Takagi–Sugeno Fuzzy Systems*,
Studies in Systems, Decision and Control 8, DOI: 10.1007/978-3-319-05639-5,

M

N

O

P

Q

R

S

T

U