International Journal of the Physical Sciences Vol. 6(19), pp. 4492-4501, 16 September, 2011
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS11.908
ISSN 1992 - 1950 ©2011 Academic Journals

Full Length Research Paper

A critical review of parallel distributed computing and the Lyapunov criterion for multiple time-delay fuzzy systems

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Accepted 13 July, 2011

This work reviews some important Lyapunov criterion results based on which we address the stability problems of multiple time-delay Takagi-Sugeno (T-S) fuzzy systems. A delay-dependent stability criterion is derived using the fuzzy Lyapunov method that will ensure the asymptotic stability of the multiple time-delay T-S fuzzy systems. Furthermore, the parallel distributed compensation (PDC) scheme is used to achieve a controller design for fuzzy systems.

Key words: Lyapunov, critical review, multiple time-delay system, PDC.

INTRODUCTION

Cao and Frank (2000, 2001) first considered using Tagagi-Sugeno (T-S) based fuzzy control for nonlinear time-delay systems. Moreover, the criteria for time-delay systems can be classified as delay-independent or delay-dependent, depending on whether the size of the delay is included in the criteria. Delay-dependent criteria are generally less conservative than delay-independent criteria in terms of practical utility. Most studies consider utilizing the single Lyapunov function for the fuzzy control stability conditions, which reduces the stability problem to a series of linear matrix inequality (LMI) problems in terms of a common Lyapunov function. Efficient interior-point algorithms are therefore available to solve LMI problems using the recently developed convex optimization technique (Nesterov and Nemirovsky, 1994). Increasing attention has recently been paid to Lyapunov functions for stability and stabilization problems (Tanaka et al., 2001, 2003). For example, in the past ten years, over fifty papers concerning the Lyapunov topic have been published in journal of vibration and control. In 2003, a direct adaptive neural network controller was developed for a model of an underwater vehicle (Kim and Inman, 2003). They derived a control law and a stable on-line adaptive law using the Lyapunov theory, where the tracking error converges to zero and the roundedness of the signals is guaranteed. Mazumder and Nayfeh (2003) analyzed the stability of a boost power-factor-correction (PFC) circuit using a hybrid model. Using concepts of discontinuous systems, they showed that the global existence of a smooth hyper surface for boosting the PFC circuit is not possible. Subsequently, they developed conditions for the local existence of each of the closed-loop systems using a Lyapunov function.

Derkhorenian et al. (2004) described the design and implementation of a nonlinear adaptive disturbance rejection approach for single-input-single-output linear-time-invariant uncertain systems subject to sinusoidal disturbances with unknown amplitude and frequency. The controller design was based on a single Lyapunov function incorporating both the error states and updating laws, and hence, global stability and improved transient performance are readily achieved. Choi et al. (2004) investigated the active vibration control of a translating tensioned steel strip in a zinc galvanizing line. The control objective is to suppress the transverse vibrations of the strip via boundary control. The correct boundary control law is derived based on the Lyapunov second method. It is revealed that a time-varying boundary force and suitable passive damping at the right boundary can successfully suppress the transverse vibrations. Roup and Bernstein (2004) considered adaptive stabilization for a class of linear time

-varying second-order systems. Lyapunov methods are used to prove global convergence of the system states. In the same year, a translational cantilevered Euler-Bernoulli beam operating with tip mass dynamics at its free end was used to study the effect of several damping mechanisms on the stabilization of the beam displacement. Specifically, a Lyapunov-based controller was developed utilizing a partial differential equation model of the translational beam to exponentially stabilize the beam displacement while the beam support is regulated to a desired set-point position (Dadfarnia et al., 2004). Urakubo et al. (2004) dealt with the attitude control of a rigid spacecraft with two reaction wheels. They derived a discontinuous state feedback law based on Lyapunov control wherein the control input was obtained by multiplying the gradient vector of the Lyapunov function by a matrix that is composed of a symmetrical matrix and an asymmetric one. Choura and Yigit (2005) proposed a control strategy for the simultaneous suppression and confinement of vibrations in linear time-varying structures. The proposed controller has time-varying gains and can also be used for linear time-invariant systems. The proposed control strategy can be applied for the rapid removal of vibration energy in sensitive parts of a flexible structure for safety or performance reasons. The stability of the closed-loop system was proven through a Lyapunov approach. In the same year, two robust nonlinear controllers were developed to control the rigid and flexible motions of a single-link robotic manipulator (Bazzi and Chalhoub, 2005). The controllers consist of a conventional sliding mode controller (CSMC) and a fuzzy sliding mode controller (FSMC). The parameters for the proposed FSMC are determined via fuzzy inference systems, and is designed based on two Lyapunov functions. In addition, mathematical models of aircraft systems always contain uncertain elements, which reflect the designer's lack of knowledge regarding some parameter values, disturbances and unmodeled dynamics (Ibrir and Botez, 2005).

Using both Lyapunov's direct method and the linear matrix inequality approach, Ibrir and Botez (2005) developed the controller design procedure, to obtain a definite feel for the stability analysis and robust control of aircraft systems with significant uncertainty. Zhang et al. (2005) presented a systematic procedure for deriving the model of a cable transporter system with arbitrarily varying cable lengths. The assumed mode method was used to obtain an approximate numerical solution for the governing equations by transforming the infinite - dimensional partial differential equations into a finite-dimensional discretized system. They proposed a Lyapunov controller, based directly on the governing partial differential equations, which can both dissipate the vibratory energy during the motion of the transporter and guarantee the attainment of the desired goal point. In 2006, Bowong and Kagou (2006) proposed a new adaptive feedback controller for linearizable chaotic systems with uncertainties. Based on the Lyapunov stability theory, the adaptation law is determined so as to tune the controller gains in order to track predetermined linearizing feedback control. They assert that this control method has a simple controller structure, high robustness against uncertainties and strong rejection of external disturbances. In the same year, an adaptive fuzzy sliding mode control scheme was presented.

Sadati and Talasaz’s proposed approach (2006), the switching functions are replaced by adaptive fuzzy control signals so as to satisfy the Lyapunov stability conditions. This adaptive fuzzy controller is believed to be able to improve the performance and also eliminate high frequency chattering in the control signals by preventing the application of large control gains where these are unnecessary, especially when the state trajectories are close to the sliding surfaces. In 2007, Dai and Chen (2007) analyzed the dynamic stability of a nonlinear cracked rotor system with asymmetrical viscoelastic supports. Nonlinear governing equations for the cracked rotor system subjected to periodic forces generated during machining are established. The linear and nonlinear dynamic stabilities of the system are investigated, utilizing the Lyapunov theory and the Floquet criterion. In the same year, Chen et al. (2007) proposed a design method for producing H-infinity control performance for structural systems using a T-S fuzzy model. A structural system with a tuned mass damper is modeled using a T-S type fuzzy model. Using the parallel distributed compensation (PDC) scheme, Chen et al. (2007) designed a nonlinear fuzzy controller for the tuned mass damper system. A sufficient stability condition for the control system can be derived in terms of Lyapunov theory. This control problem is reformulated to solve the linear matrix inequality (LMI) problem. Anac and Basdogan (2007) presented model validation techniques integrated with some design methodologies to predict the performance of micro systems. A two-dimensional micro scanner mirror was chosen for a case study to demonstrate the developed methodologies. The state space model was used for disturbance analysis performed using the Lyapunov approach to obtain the root mean square values of the mirror rotation angle under the effect of a disturbance torque. In 2008, analytical investigation was conducted to suppress the vibration of tall building structures in the presence of uncertainty in terms of structural dynamic characteristics (Amini and Vahdani, 2008). Three control algorithms consisting of probabilistic optimal control, fuzzy logic control and optimal control theories were combined to control system fluctuations and severe seismic excitations. A state-space reduced order model was constructed based on the dominant observable and controllable Gramians of Lyapunov equations in order to prevent a control matrix singularity and to achieve computational efficiency. Both types of active and semi-active control systems can be installed in buildings to reduce the seismic response (Amini and Vahdani, 2008).

Kaddissi et al. (2009) studied the control of an electrohydraulic active suspension, based on a combination of backstepping and integrator forwarding. The goal is to control and reduce the car's vertical motion and keep it at zero. The active suspension model is highly nonlinear and non-differentiable due to the hydraulic components, especially the servovalve and the hydraulic actuator, whose chamber volume varies during extension and retraction. Therefore, a powerful control strategy is required. In such cases, Lyapunov-based control strategies are the most suitable because they offer a lot of maneuverability in building an analytical control signal (Kaddissi et al., 2009). In the same year, Asokanthan and Wang (2009) studied the instabilities in a MEMS gyroscope subjected to angular rate fluctuations. For the purpose of acquiring stability conditions, when the angular rate input is subject to small periodic intensity fluctuations, the dynamic behavior of periodically perturbed linear gyroscopic systems should be studied in detail. An asymptotic approach based on the method of averaging has been employed for this purpose, and closed-form conditions for the onset of instability due to parametric resonances have been obtained. A numerical approach based on the Floquet-Lyapunov theory is employed for validating the analytical stability predictions. Wang and Wang (2009) considered the global exponential robust stability analysis problem for a class of uncertain distributed parameter control systems with time-varying delays. The uncertain parameters are generated from modeling errors as well as parameter variations in the systems. The purpose for addressing this problem is to derive easy-to-test conditions such that the dynamics of the uncertain system will be globally exponentially robustly stable. A new Lyapunov-Krasovskii function was developed by employing, a linear matrix inequality (LMI) approach to establish the desired sufficient conditions. Global exponential robust stability for uncertain distributed parameter control systems with time-varying delays can be easily checked by utilizing the numerically efficient Matlab LMI toolbox. Moreover, modeling and robust controller designs for horizontal vibrations of high-speed elevators were discussed (Feng et al., 2009). Based on the theory of rigid body dynamics, they modeled the horizontal vibrations about an elevator cage. The motion of the elevator cage is resolved into translation and rotation around the center of mass of the cage. Taking account of the characteristics of nonlinearity, parameter uncertainties and external disturbances of the elevator cage, a robust controller can be designed using Lyapunov's method (Feng et al., 2009).

Chen et al. (2010) proposed a combining a T-S fuzzy model approach with a parallel distributed compensation (PDC) scheme for time-delay control of the response of a tension leg platform (TLP) system subjected to an external wave force. A global PDC-based fuzzy logic controller is constructed by blending all local state feedback controllers. A method of fuzzy-model-based control is thereby developed which can attenuate the influence of the external wave force. The controller can be evaluated in terms of stability analysis and the LMI conditions guaranteeing the stability of the TLP system derived via Lyapunov theory. In the same year, Dogan and Morgul (2010) considered the motion of a two-link flexible arm with a nonuniform cross section. They proposed a novel control scheme which consists of a dominant control law together with a parallel controller and showed that with the proposed controller, the control objectives are satisfied. The stability analysis is based on the Lyapunov approach and LaSalle's invariance principle extended to infinite-dimensional systems.

Furthermore, Robert and Gabor (2010) proved the subcritical sense of this period-doubling bifurcation. They approximated the emerging period-two oscillations by using the Lyapunov-Perron method to compute the center manifold and by calculating the Poincare-Lyapunov constant of the bifurcation analytically at certain characteristic parameter values. The existence of the unstable period-two oscillations around the stable stationary cutting was confirmed using a numerical continuation algorithm developed for time-periodic delay-differential equations. In another work Li et al. (2010) adopted the adaptive fuzzy sliding mode (AFSM) control algorithm to actively control nonlinear structural vibration. Since the AFSM control algorithm needs the full state feedback of the structure, a dynamic neural network (DNN) observer is proposed, considering the nonlinearity of the structure. The neural network weights are adapted on-line, so no off-line learning is required. Furthermore, no exact knowledge of structural nonlinearities is needed. Li et al. (2010) established a weight training algorithm based on Lyapunov stability theory in the presence of modeling errors. Moreover, Yoshimura (2010) proposed an adaptive discrete sliding mode control (SMC) for mechanical systems with mismatched uncertainties. The uncertainties are expressed in a parameterized form, and the estimates for the states and the uncertainties are taken by using the proposed weighted least squares estimator (WLSE). The proposed adaptive discrete SMC is constructed on the basis of the estimates obtained by the proposed WLSE. It can be verified using the Lyapunov method so that the estimation error equation is asymptotically stable and the mechanical systems are ultimately bounded under the action of the proposed adaptive discrete SMC. Zhao et al. (2010) was also concerned with the problem of robust H-infinity reliable load-dependent control design for a class of semi-active seat suspension systems. A four degree-of-freedom human body model was considered in order to investigate the control strategy more precisely. It is assumed that the human body mass resides in an interval and can be measured online. The load - dependent approach is based on a parameter-dependent

Lyapunov function. Chen (2010) also presented a fuzzy robust control design which combines H-infinity control performance with Tagagi-Sugeno (T-S) fuzzy control for the control of delayed nonlinear structural systems under external excitations. They designed a nonlinear fuzzy controller based on parallel distributed compensation schemes. The controller design problem is reformulated as an LMI problem as derived from the Lyapunov theory. Lee et al. (2010) focused on the development of triangular fuzzy numbers, the revising of triangular fuzzy numbers, and the constructing of a half-circle fuzzy number model, which can be utilized to perform more plural operations. Similarly, Pai (2010) presented a proportional-integral sliding mode control methodology for the robust control of vibrations in a linear uncertain system with state and input delays. The systems were assumed to have structured, unmatched and time-varying parameter uncertainties. Based on the Lyapunov stability theorem and LMI H-infinity technique, a sufficient condition was derived to guarantee the global stability of the dynamics and achieve a prescribed H-infinity normal bound of disturbance attenuation for all admissible uncertainties without the state predictor.

Chen et al. (2011) discussed the stability analysis of a genetic algorithm-based (GA-based) H-infinity adaptive fuzzy sliding model controller (AFSMC) for a nonlinear system. Lyapunov's direct method can be used to ensure the stability of the nonlinear system. In the same year, Gabale and Sinha (2011) provided a methodology for a reduced order controller design for nonlinear dynamic systems with time-periodic coefficients. The proposed methodology is quite general in the sense that it can easily be modified for nonlinear systems with constant coefficients. The equations of motion are represented by quasi-linear differential equations in state space, containing a time-periodic linear part and nonlinear monomials of states with periodic coefficients. The Lyapunov-Floquet (L-F) transformation is used to transform the time-varying linear portion of the system into a time-invariant form. Lin et al. (2011) also considered the modeling of a TLP system via the Lyapunov method. In terms of the stability analysis, the linear matrix inequality conditions guaranteeing the stability of the TLP system can be derived from fuzzy Lyapunov theory. McCullough et al. (2011) also considered a Lyapunov treatment of swarm coordination under conflict. A Newtonian dynamics-based double integrator model is taken into account, as well as a control strategy using the relative positions and velocities of opposing swarm members. This control was introduced so as to achieve stability and to ensure the capture of the evaders by the pursuers. For the sake of simplicity only swarms with equal membership strengths and equal mass are considered in the present document. This effort begins with a set of suggested interaction force profiles, which are functions of local vectors. To formulate a robust control law, Lyapunov-based stability analysis was used (McCullough et al., 2011). Njah (2011) designed active controllers based on the Lyapunov stability theory and the Routh-Hurwitz criteria. They were designed to completely synchronize two parametrically and externally excited Phi(6) Van der Pol oscillators, Phi(6) Duffing oscillators and a Phi(6) Van der Pol oscillator with a Phi(6) Duffing oscillator in the triple-well configuration of the Phi(6) potential. Furthermore, they considered global exponential stabilization for a class of distributed parameter control systems with Markovian jumping parameters and time-varying delay (Wang and Wang, 2011). By employing a new Lyapunov-Krasovskii function, an LMI approach was developed to establish some easy-to-test criteria for global exponential stabilization in the mean square for stochastic systems (Wang and Wang, 2011). In a recent effort, Kozic et al. (2011) investigated the stochastic stability of narrow moving bands under random tension fluctuation utilizing the concept of the Lyapunov exponent. Galerkin's method was used to reduce the partial differential equations of motion for a corresponding ordinary differential equation with randomly varying stiffness. They obtained explicit stability conditions based on the asymptotic expansion series for a two-dimensional linear stochastic system. Moreover, advanced techniques in soft computing and artificial intelligence have been successfully applied to a variety of fields, such as robot manipulation (Hsiao et al., 2005a, 2005b, 2005c, 2005d, 2005e; Chen et al., 2011a, 2011b; Chen and Huang, 2011; Shih et al., 2011a, 2011b; Lee et al., 2011), engineering applications (Lu, 2003; Amini and Vahdani, 2008; Chang et al., 2008; Chen, 2006; Chen et al., 2008d, 2008e; Trabia et al., 2008; Tu et al., 2008; Yang et al., 2008a; Shih et al., 2010b; Yeh and Chen, 2010), architectural engineering (Chen et al., 2004; Chen et al., 2010i; Hsieh et al., 2006; Chen, 2010a, 2010b, 2010c; Hsu et al., 2010; Chen cy, 2010; Chen cy, 2011a; b; c; d; Chen, 2011c, 2011d; Chen et al., 2011c, 2011d; Liu et al., 2011; Tang et al., 2011), satellite observations (Lin et al., 2009a, 2009b; Lin and Chen, 2010b; Lin and Chen, 2011; Yeh et al., 2011), marine research (Chen et al., 2005a, 2005b; Chen et al., 2006a, 2006b, 2006c; Chen et al., 2007a, 2007b, 2007c, 2007d, 2007e, 2007f; Chen et al., 2008a, 2008b, 2008c; Tseng et al., 2009; Chen, 2009b, 2009c; Chen et al., 2009c; Chen, 2010d; Chen, 2011a, 2011b, 2011c), network optimization (Chen et al., 2009g; Chen and Chen, 2010b; Shih et al., 2010a, 2010c; Kuo et al., 2010; Kuo et al., 2011; Kuo and Chen, 2011a, 2011b), system development (Chen, 2009a; 2010c; Chen et al., 2009a, 2009b, 2009d, 2009e, 2009f; Chen et al., 2010a, 2010c, 2010d, 2010f; Lin and Chen, 2010a; Shih et al., 2011d; Tseng et al., 2011), educational improvement (Chen et al., 2010b; Shih et al., 2010d; Shen et al., 2011; Shih et al., 2011c) and management in the leisure and tourism industries (Yildirim et al., 2009; Zhao et al., 2009; Tsai et al., 2008; Yang et al., 2008b; Yeh et al., 2008; Chen and Chen, 2010a; Chen et al., 2010e, g, h; Lee et al., 2010a, 2010b; Chiang et al., 2010;

Tsai and Chen, 2010; Tsai and Chen, 2011). To the best of the author's knowledge, there are few existing results related to delay-dependent criteria for multiple time-delay fuzzy systems via fuzzy Lyapunov methods. In this work, the fuzzy Lyapunov approach is used to derive a stability condition for the stability analysis of multiple time-delay fuzzy systems. A delay-dependent stability criterion is proposed. This study uses a generalization (Tanaka et al., 2001, 2003). Based on the criteria given in this work, a parallel distributed compensation (PDC) control design is presented in order to stabilize the multiple time-delay T-S fuzzy systems.

SYSTEM DESCRIPTION AND PRELIMINARY PROBLEM

It is assumed that a continuous multiple time-delay fuzzy system can be described by fuzzy IF-THEN rules as follows:

Plant rule *i*

IF $z_1(t)$ is M_{i1} and $\cdots$ and $z_g(t)$ is M_{ig}

THEN $\dot{X}(t)=A_iX(t)+\bar{A}_iX(t-\tau_n)+B_iU(t)$ (1)

where τ_n is the multiple time delay of *n*; $i=1,2,\cdots,r$. *r* is the number of IF-THEN rules. M_{ip} ($p=1,2,\cdots,g$) is the fuzzy set, $X(t)\in R^n$ is the state vector, $U(t)\in R^m$ is the control input vector; $z_1(t)\sim z_g(t)$ are the premise variables and $(A_i,\bar{A}_i,B_i)$ is the *i*th subsystem of the system (Equation 1), where $A_i\in R^{n\times n}$, $B_i\in R^{n\times m}$ and $E_i\in R^{n\times m}$. It is assumed that the pair (*x*(*t*), *u*(*t*)) is a controllable pair and given a pair of (*x*(*t*), *u*(*t*)), the final output of the aforementioned system is inferred to be the following:

$$\dot{X}(t)=\frac{\sum_{i=1}^{r}w_i(t)[A_iX(t)+\bar{A}_iX(t-\tau_n)+B_iU(t)]}{\sum_{i=1}^{r}w_i(t)},$$

$$\dot{X}(t)=\sum_{i=1}^{r}h_i(t)\{A_iX(t)+\bar{A}_iX(t-\tau_n)+B_iU(t)\} \quad (2)$$

where w_i is the activation degree of the *i*th rule, calculated as follows:

$$w_i(t)=\prod_{p=1}^{g}M_{ip}(z_p(t)) \quad (3)$$

and

$$h_i(t)=\frac{w_i(t)}{\sum_{i=1}^{r}w_i(t)} \quad (4)$$

$M_{ip}(z_p(t))$ is the grade of membership of $z_p(t)$ in M_{ip}. It is assumed that $w_i(t)\ge 0$, $i=1,2,\cdots,r$;

$$\sum_{i=1}^{r}w_i(t)>0 \quad (5)$$

For all *t*. Therefore,

$$h_i(t)\ge 0,\quad i=1,2,\cdots,r;$$

and

$$\sum_{i=1}^{r}h_i(t)=1, \quad (6)$$

for all *t*. We use the parallel distributed compensator (PDC) concept to synthesize fuzzy control laws for the stabilization of time-delayed T-S fuzzy systems. The idea of this type of fuzzy controller rules is based on the same premise as those of the T-S model. Therefore, we can use linear control design techniques to design the feedback gains to compensate each rule in the T-S fuzzy model using a PDC scheme, also called T-S fuzzy control in this paper. The linear control rule *i* is derived based on the state of Equation 2 in the consequent part of the *i*th model rule.

Control rule *i*

IF $z_1(t)$ is M_{i1} and $\cdots$ and $z_g(t)$ is M_{ig}

THEN $U(t)=-K_iX(t)$, (7)

where $i=1,2,\cdots,r$. *r* is the number of IF-THEN rules and K_i is the local feedback gain matrix. The final control *U* is inferred using the Sum-Product reasoning method.

$$U(t)=-\frac{\sum_{i=1}^{r}w_i(t)K_iX(t)}{\sum_{i=1}^{r}w_i(t)}. \quad (8)$$

By substituting Equation 8 into Equation 2, the following model of a closed-loop control system is obtained:

$$\dot{X}(t)=\sum_{i=1}^{r}\sum_{l=1}^{r}h_i(t)h_l(t)\{(A_i-B_iK_l)X(t)+\bar{A}_iX(t-\tau_n)\}. \quad (9)$$

FUZZY LYAPUNOV FUNCTION APPROACH

A fuzzy Lyapunov function is defined herein, and the stability conditions for time-delay T-S fuzzy systems described in Equation 9 are considered.

Definition 1

Equation 10 is said to be a fuzzy Lyapunov function for the T-S fuzzy system if the time derivative of $V(X(t))$ is always negative at $X(t)\neq 0$.

$$V(X(t))=\sum_{i=1}^{r}h_i(t)X^T(t)P_iX(t) \quad (10)$$

where P_i is a positive definite matrix. The fuzzy Lyapunov function contains the time derivative of the premise membership functions by sharing the same membership functions with the T-S fuzzy model. Therefore, the time derivative of the premise membership functions needs to be handled. This study adopted an upper bound for the time derivative, that is, $\left|\dot{h}_\rho(t)\right|\leq\phi_\rho$, to ensure that the term of the time derivative $\dot{h}_\rho(t)$ can be solved numerically. Before a typical stability condition for time-delay T-S fuzzy system (Equation 9) is proposed, some useful concepts are given below:

Lemma 1

Hsiao et al. (2005): For any *A*, $B\in \boldsymbol{R}^n$ and for any symmetric positive definite matrix $G\in \boldsymbol{R}^{n\times n}$ or $\boldsymbol{R}$, we have:

$$-2A^TB\leq A^TGA+B^TG^{-1}B. \quad (11)$$

Lemma 2

Wang et al. (1996): The point of equilibrium in a closed-loop fuzzy system $\dot{X}(t)=\sum_{i=1}^{r}\sum_{l=1}^{r}h_i(t)h_l(t)\{(A_i-B_iK_l)X(t)\}$ is asymptotically stable in the large if there exists a common positive definite matrix *P* such that:

$$(A_i-B_iK_l)^TP+P(A_i-B_iK_l)<0, \text{ for } P=P^T>0, \quad (12)$$

and

$$i,l=1,2,\cdots,r. \quad (13)$$

Lemma 2 gives a sufficient condition for ensuring asymptotic stability of a closed-loop fuzzy system

$$\dot{X}(t)=\sum_{i=1}^{r}\sum_{l=1}^{r}h_i(t)h_l(t)\{(A_i-B_iK_l)X(t)\}. \quad (14)$$

Based on the aforementioned inequalities, a stability condition can be generalized using the fuzzy Lyapunov method as follows:

Theorem 1

The fuzzy system (Equation 9) is stable in the large if there exist common positive definite matrices $P_1,\ P_2,\ \cdots,\ P_r$ such that inequality $\left|\dot{h}_\rho(t)\right|\leq\phi_\rho$ is satisfied and

$$\sum_{\rho=1}^{r}\phi_\rho P_\rho+(A_j-B_jK_l)P_i+P_i(A_j-B_jK_l)+R+P_i\bar{A}_jR^{-1}\bar{A}_j^TP_i<0 \quad (15)$$

Where

$$\Delta=(A_j-B_jK_l)P_i+P_i(A_j-B_jK_l), \quad (16)$$

with $P_i=P_i^T>0$, for $i,j,l=1,2,\cdots,r$.

Proof of Theorem 1

Consider the Lyapunov function candidate for the fuzzy system (Equation 9):

$$V(X(t))=\sum_{i=1}^{r}h_i(t)X^T(t)P_iX(t)+\int_0^{\tau}X^T(t-\tau_n)RX(t-\tau_n)d\tau \quad (17)$$

The time derivative of *V* is

$$\dot{V}(X(t))=\sum_{\rho=1}^{r}\dot{h}_\rho(t)X^T(t)P_\rho X(t)+\sum_{i=1}^{r}h_i(t)\{\dot{X}^T(t)P_iX(t)+X^T(t)P_i\dot{X}(t)\}$$
$$+X^T(t)RX(t)-X^T(t-\tau_n)RX(t-\tau_n)$$

$$=+X^T(t)RX(t)-X^T(t-\tau_n)RX(t-\tau_n)$$
$$+\sum_{i=1}^{r}h_i(t)\left\{\sum_{j=1}^{r}\sum_{l=1}^{r}h_j(t)h_l(t)[(A_j-B_jK_l)X(t)+\bar{A}_jX(t-\tau_n)]^TP_iX(t)\right.$$

$$+X^T(t)P_i\sum_{j=1}^{r}\sum_{l=1}^{r}h_j(t)h_l(t)[(A_j-B_jK_l)X(t)+\overline{A}_jX(t-\tau_n)]\Bigg\} \quad (18)$$

Based on Lemma 1 and (Equation 18), we have:

$$\dot{V}(X(t))\le\sum_{\rho=1}^{r}\dot{h}_\rho(t)X^T(t)P_\rho X(t)+X^T(t)[P_i\overline{A}_jR^{-1}\overline{A}_j^TP_i]X(t)$$

$$+\sum_{i=1}^{r}\sum_{j=1}^{r}\sum_{l=1}^{r}h_i(t)h_j(t)h_l(t)X^T(t)\{(A_j-B_jK_l)P_i+P_i(A_j-B_jK_l)+R\}X(t) \quad (19)$$

$$\le\sum_{i=1}^{r}\sum_{j=1}^{r}\sum_{l=1}^{r}h_i(t)h_j(t)h_l(t)X^T(t)\Bigg\{\sum_{\rho=1}^{r}\phi_\rho P_\rho+(A_j-B_jK_l)P_i+P_i(A_j-B_jK_l)+R$$

$$+P_i\overline{A}_jR^{-1}\overline{A}_j^TP_i\Bigg\}X(t)\ . \quad (20)$$

Based on Theorem 1, $\dot{V}(X(t))<0$ at $X(t)\neq 0$.

Remark 1

Since condition of Equation 15 implies that condition of Equation 16 can be negative that is, $\Delta<0$, then $\dot{V}(X(t))<0$ when $\tau=0$ under single Lyapunov function. This means that the closed-loop T-S fuzzy system $\dot{X}(t)=\sum_{i=1}^{r}\sum_{l=1}^{r}h_i(t)h_l(t)\{(A_i-B_iK_l)X(t)\}$ is asymptotically stable if disturbances and time delays are not considered. This stability condition of Theorem 1 can be reduced to that of Lemma 2.

CONCLUSIONS

This study presents a criterion for multiple time-delay T-S fuzzy systems based on the fuzzy Lyapunov method, which is defined in terms of fuzzy blending quadratic Lyapunov functions. The delay-dependent stability criterion is derived in terms of the fuzzy Lyapunov method to guarantee the stability of multiple time-delay T-S fuzzy systems.

ACKNOWLEDGEMENTS

The author acknowledges the financial support from the National Science Council of Taiwan, R.O.C., under project number NSC 98-2221-E-366-006-MY2, NSC 100-2221-E-022-013-MY2, NSC 100-2628-E-022-002-MY2. The author is also most grateful for the constructive suggestions of the anonymous reviewers all of which has led to the making of several corrections and suggestions that have greatly aided us in the presentation of this paper.

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