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Full Length Research Paper

A critical review of nonlinear fuzzy multiple time-delay interconnected systems using the Lyapunov criterion

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This paper reviews the development of fuzzy systems and the problem of time delay control in nonlinear systems. Based on this review, a fuzzy Lyapunov method defined in fuzzy blending quadratic Lyapunov functions is proposed from which to derive stability conditions. In the controller procedure, a parallel distributed compensation (PDC) scheme is utilized to construct a global fuzzy logic controller (FLC) by blending all linear local state feedback controllers. Furthermore, the multiple time-delay interconnected systems are considered in the nonlinear fuzzy systems.

Key words: Interconnected systems, fuzzy Lyapunov method, linear matrix inequality.

INTRODUCTION

In the past two decades, time delay issues in control systems have been discussed in a large number of studies. Hong and Hughes (2001) devoted efforts to the study of what factors like time delays can have on performance, or even stability, which are especially important when dealing with things like closed-loop control systems for lightly damped vibratory systems. The main focus of this paper is on the time-delayed rate feedback control of lightly damped single-degree-of-freedom harmonic oscillators. This subject has many interesting characteristics and must be treated carefully, even relatively simple situations. Many years ago, root loci were analyzed to provide a basis for stability conditions, and stability boundaries plotted to correct the results derived. It was explained in simple terms how to extend these results to a complete spacecraft from one structural mode to an arbitrary number of structural modes.

Vahidi and Eskandarian (2001) proposed a predictive control methodology for active vehicle suspension control, considering the effect of time delays as an inherent characteristic of active systems. With this method, at each time instant, the control signal is calculated. This is done by minimizing the performance index in terms of the predicted response within a finite prediction horizon. With the discrete predictive methodology, it is easier to formulate the results as a discrete-time control algorithm suitable for digital control rather than the widely used linear quadratic regulator method, and time delays can be more easily introduced in the formulation. Predictive control simulation results are compared with passive control results in this study. It has been shown that this method is capable of ameliorating the ride performance of a single-degree-of-freedom quarter-car model for a wide range of input frequencies in the presence of time delays. At the same time, it is possible to keep the maximum suspension travel below the maximum of passively controlled suspensions.

In the following year, Wang and Xu (2002) studied the global asymptotic stability of the equilibrium point of Hopfield neural networks with interneuron transmission delays. They derived some sufficient conditions related to the existence of a unique equilibrium point and its global asymptotic stability. Furthermore, Marzbanrad et al. (2002) studied a method for the optimal preview control of a vehicle suspension system traveling on a rough road. A three-dimensional seven degree-of-freedom car-riding model and several descriptions of the road surface roughness heights are used in the analysis, including haversine (hole/bump) and stochastic filtered white noise models. It is assumed that contact-less sensors affixed to the vehicle's front bumper measure the road surface height at specific distances. The sprung mass, tire deflection, suspension rattle space and control force required to optimize the suspension systems with respect to ride comfort and road holding preferences containing acceleration are considered. The performance and power demand of active, active and delay, and active and preview systems were evaluated and compared with those for the passive system. The results show that the optimal preview control ameliorated all aspects of the vehicle suspension performance while requiring less power. They also examined the effects of variations in the preview time and variations in the road condition.

In 2005, Marzban and Razzaghi (2005) presented a method using a hybrid function for finding the solution for time-delay systems. They presented the properties consisting of block-pulse functions plus the Taylor series of the hybrid functions. They based this method on expanding various time functions in the system as truncated hybrid functions. For the solution of algebraic equations they presented operational matrices for integration and delay which were utilized to simplifying the solution of time-delay systems. Illustrative examples were contained to demonstrate the validity and applicability of the technique.

Cai and Yang (2006) asserted that time delay inevitably exists in active control systems which may cause unsynchronized control forces. Time delays can not only degrade the performance of the control systems, but also result in the instability of the dynamic systems. The active vibration controllers (with time delays) for a flexible cantilever beam were studied and a method for treating the time delay was proposed. Dynamic equations for the control mode with time delays were first developed using independent modal space control, and then discretized and changed into a standard discrete form with no explicit time delays by augmenting the state variables. The continuous performance index was also changed into a discrete form and discrete optimal control algorithms designed in terms of the augmented state systems. Because time delay effects were incorporated in the mathematical model of the dynamic system throughout the control design and assumptions were made without approximations and in the control algorithm derivation, system stability was ensured. Furthermore, the extraction of modal coordinates from actual physical measurements and the transformation to actual control force from a modal one were presented. The feasibility and efficiency of the proposed control algorithm were demonstrated in numerical simulations showing that the vibration of the beam could be significantly suppressed using the proposed control algorithm. Instability could occur if time delays are neglected in the control design.

Subsequently, in order to solve the Takagi-Sugeno (TS) fuzzy model based time-delay dynamic equations (TSFMTDE) a shifted Chebyshev series approach was developed in Hsu and Chou (2007). Using only matrix algebra the new method simplifies the procedure of solving the TSFMTDE as a system of recursive formulae. An algorithm based on these recursive formulae, and containing only straightforward algebraic computation was also proposed. The computer implementation of the new approach was non-iterative, non-differential, non-integral, straightforward, and well-adapted. Two numerical examples were also provided. The first displays that the proposed method in terms of the shifted Chebyshev series may produce close-to-exact solutions. The second (nonlinear mass-spring-damper mechanical time-delays system with a fuzzy parallel-distributed-compensation controller) displays the application of the proposed approach.

In the study of Lu et al. (2009) discrete parameters via the precise integration method and derived time-delay discrete-time equations was obtained straight from the differential vibration equations for structures in state space. Then, a state vector expansion method was used to change these equations into ones which do not contain time-delay terms explicitly. Next, the order of this system was substantially lessened using the balanced reduction method to form a dominant subsystem which was expressed in terms of the eigenmodes of the state subspace with highest controllability. In order to reflect the effect of time delays, the controllers were then designed using the discrete time-delay optimal control theory, which includes the control terms not only of the current state but also of a few previous states. The order of the controller was very substantially lessened without causing any essential difference in the control effect by using the proposed method. A numerical example for a shear-type building was presented and the results displayed the effectiveness of the proposed method even when time delays were quite large.

There were also five other studies presenting the time delay issue in the Journal of Vibration and Control in the same year. Karkoub (2009) used pivoting guiders to deal with the robust control of the lateral movement of webs. Lateral shifting was generally a result of either processing the changes in the physical properties of the materials, or the variations of mechanical states of the machine. The lateral motion of a web system was usually disregarded; however, the lateral position has to be controlled to perform high productivity and ameliorate the product quality. A theoretical model was presented in terms of the assumption that the moving web was a beam with a very low thickness. This leads to a sixth-order transfer function with time delays. The time delays were the result of the non-collocation of the sensor and actuator. A robust control technique was used to control the web lateral shifting since there were many sources of errors. As well as the time delays, several controllers were synthesized using the mu-synthesis control design technique which accounts for modeling imperfections. Sturdy performance was achieved with the designed controllers and the closed-loop response was worthy even under extreme conditions.

In Wang and Wang (2009) the global exponential robust stability analysis problem for a class of uncertain distributed parameter control systems with time-varying delays was Considered. In the systems, the uncertain parameters were generated from modeling errors as well as parameter variations. The purpose of the study was to derive some easy to test conditions ao that the dynamics of the uncertain system would be globally exponentially robustly stable. A linear matrix inequality (LMI) approach was developed to set the desired sufficient states and global exponential sturdy stability so that the unsure distributed parameter control systems with time-varying delays could be simply checked by utilizing the numerically efficient Matlab LMI toolbox to employ a new Lyapunov-Krasovskii function. A numerical example was used to show the usefulness of the derived LMI-based stability conditions.

Li et al. (2009) developed a stochastic averaging technique for multi-time-delayed feedback control and wide-band random excitation for resonant and non-resonant quasi linear systems. The technique was then able to predict the reply of one and two degree-of-freedom linear oscillators with nonlinear damping. The results of a Monte Carlo simulation and comparison showed that the proposed technique produces quite a good result, even for long delay times, and that the time-delayed feedback control may lead to phenomenological bifurcation.

Xuan et al. (2009) designed a magnetic bearing system for the suppression of rotor vibration. The magnetic bearings could support the shaft without mechanical contacts, and could also control the rotational vibration. A digital controller, actuating amplifiers, and electromagnets composed the magnetic bearing system of position sensors. Time Delay Control (TDC) was utilized to control the vibration of a magnetic bearing system effectively. An optimal controller was proposed when uncertainty was found in the system, i.e., there was difficulty extracting detailed mathematical data, and there were external disturbances. For regulation of the rotor whirling motion, an observer with position information was used to obtain a feedback signal. A simulation was first performed to validate the efficiency of the proposed controller in restraining the whirling of the rotor. Experiments followed to guarantee its usefulness in the rotor rig with a magnetic actuator. The vibrating suppression was confirmed with TDC and its effect was compared with that of proportional and derivative controllers.

Chen and Cai (2009) designed a controller using a discrete optimal control method. Piezoelectric patches were used as actuators. They studied a method for the active control of a flexible cantilever beam with multiple time delays. First, modal orthogonality was used to obtain the condition equations for the controlled modes for a system with multiple time delays. After that, by a particular augmenting of the state variables, the condition equation was discretized and transformed into a standard form without any explicit time delays. A continuous performance index was also discretized into a standard discrete form. The standard discrete form was a function of the augmented conditions. In this way, a discrete controller could be designed in terms of the augmented system. Every step of the computation for the controller includes not only the current step of condition feedback but also a linear combination of some former control steps. The simulation results indicated that if the time delays were not treated, the system could suffer from instability when time delays were small. The proposed controller offered effective control with simultaneous compensation for delays. Furthermore, the proposed controller may possibly offer more effective control than the controller with no time delays.

A Takagi-Sugeno (T-S) fuzzy model approach combined with a parallel distributed compensation (PDC) scheme was proposed for time-delay control for the response of a tension leg platform (TLP) system subjected to an external wave force in Chen et al. (2009). By blending all local state feedback controllers, a global PDC-based fuzzy logic controller was constructed. A fuzzy-model-based control method was therefore developed which could attenuate the influence of the external wave force. The controller was evaluated though stability analysis. It was found that the linear matrix inequality (LMI) states guarantee the stability of the TLP system derived using Lyapunov theory. A simulation example was given to display the feasibility of the proposed fuzzy control approach. The example shows that the concept of half-circle fuzzy numbers can be displayed in fuzzy control and the proposed control method can be used in practical engineering problems for oceanic structures.

In the subsequent year, Tang et al. (2010) proposed the H infinity information control method for structural vibration suppression with control delays within a discrete-time framework. First, precise computation of matrix exponentials discretized the continuous-time system equation with control delays. The time-delay system was transformed into standard discrete forms without time delays by introducing an appropriate extended state vector. Then a controller was designed in terms of the discrete time H infinity full information control theory. The controller includes a regular closed feedback-loop and a feed-forward compensator, which utilizes external excitation signals gauged in real time. The feed-forward joined with feedback controller had better performance than feedback only controllers. The feedback loop of the deduced controller includes linear combinations of former control inputs outside of the current condition feedback terms. Thus, the proposed method was applicable to large time-delay cases. To consider the complexity of the changed system, a 2(N) algorithm was introduced to search the optimal attenuation level and evaluate the control law. The presented algorithm could be executed in parallel, which makes the design of H infinity controllers very easy. Finally, numerical simulations of a three-story structure control were completed. On the optimal attenuation level, time-delay effects were given to display that it was an important factor for system stability. The simulation demonstrated the feasibility and effectiveness of the proposed control method.

In the same year, Kuske (2010) studied the combined effect of different noise sources on systems with delays. Variation of material parameters or external (additive) noise can amplify vibrations via coherence resonance, while random variation of delay can suppress these vibrations in a model for machine tool vibrations, specifically regenerative chatter. In the system, a key feature was the interplay of the noise with several different inherent time scales: first, the short period of the intrinsic oscillations; second, the long time scale of their envelope, and the intermediate time interval for the variation of the delays. Optimizing the suppression of vibrations depends on understanding how these time scales and the bifurcation structure influence the joined effect of the noise sources. Then, this multiple-scale viewpoint supplies predictions for related types of stochastic dynamics in other systems with delays.

Yi et al. (2010) also examined the problem of feedback controller design using eigenvalue assignment with a single delay for linear time-invariant systems of linear delay differential equations (DDEs). Unlike ordinary differential equations (ODEs), DDEs have a limitless eigenspectrum, and it is not possible to assign all closed-loop eigenvalues. Although, they can assign a critical subset of them by a solution to linear systems of DDEs to the matrix Lambert W function. The solution had an analytical form expressed to the parameters of the DDE, like the condition transition matrix in linear ODEs. Therefore, one can extend controller design methods developed based on the solution form of systems of ODEs to systems of DDEs, containing the design of feedback controllers via eigenvalue assignment. They illustrated such an approach using some examples, and compared it with other existing methods.

In 2010, there were also some successful applications in time delay systems. For examples, Deshmukh (2010) proposed a geometric interpretation of the evolution of the linearized system approximate stability analysis of nonlinear delay differential algebraic equations (DDAEs) with periodic coefficients. Firstly, a numerical algorithm based on direct integration in terms of Chebyshev polynomials was derived for linear analysis by expansion. The proposed algorithm was shown to have deeper connections with and be computationally less bulky than the solution of the underlying semi-explicit system via a similarity transformation.

In another study, Robert and Gabor (2010) presented a closed-form calculation for the analysis of the period-doubling bifurcation in the time-periodic delay-differential equation model of interrupted machining processes like milling where nonlinearity is essentially nonsymmetric. Using the Lyapunov-Perron method, they showed the subcritical sense of this period-doubling bifurcation and approximated the emerging period-two oscillations for computing the center manifold by using the Poincare-Lyapunov calculation including analytical bifurcation at certain characteristic parameter values. Using a numerical continuation algorithm developed for time-periodic delay-differential equations they confirmed the existence of the unstable period-two oscillations around the stable stationary cutting.

Abdel-Rohman et al. (2010) stated that it is necessary to introduce additional damping in order to increase the critical wind speed, to avoid the problem of galloping with flexible suspension bridges. One feasible method of introducing additional damping to suspension bridges is to use semi-active tuned mass damper control mechanisms. The time delays used in generating the active control action due to the actuator's dynamics are, however, a major practical problem which may destabilize the semi-active controlled structure. They investigated effect of the time delays on the stability of a semi-active controlled suspension bridge, showing that when the time delays for a semi-active controlled suspension bridge were considered, the critical wind speed would always be less than that shown when the time delays were neglected. The reduction in the critical wind speed due to time delays might cause the suspension bridge to run at normal wind speeds. They discussed how to compensate for the time delay effect in order to ensure galloping suppression. Two methods were used to treat the time delay compensation: they first used a truncated Taylor's series in terms of the current control action and its derivatives to methodologically express the delayed control action; the second method expressed the delayed control action as feedback of the delayed condition variables. Both methods were based on a linear model derived from the actual nonlinear model. The controlled reply considering the delay was obtained by applying the designed active control to the actual nonlinear model. Using a numerical example, the results of both methods of time delay compensation were discussed and compared.

Han et al. (2010) also studied the cause of parameter mismatch on lag synchronization in chaotic systems with time delays within the framework of a master-slave configuration. It may be seen that lag synchronization of coupled systems may be quite weak in the presence of small parameter mismatches. After rigorous theoretical analysis, the error bound of lag-synchronization arising from the parameter mismatches was also estimated. Numerical simulations on a Lu oscillator were presented to verify the theoretical results.

Chen (2010) presented a fuzzy robust control design for a system under external excitations which combined H infinity control performance with Tagagi-Sugeno (T-S) fuzzy control for the control of delayed nonlinear structural systems. The nonlinear fuzzy controller was designed in terms of parallel distributed compensation plans. The controller design problem was reformulated as an LMI problem as obtained from the Lyapunov theory. This robust method was designed to conquer the modeling error that can happen between delayed nonlinear structural systems with T-S fuzzy models. The stability of a delayed nonlinear structural system under external excitation is ensured by given the fuzzy-model-based H infinity control and the stability conditions. Furthermore, the delayed nonlinear structural system was equipped with a tuned mass damper designed as a result of the first mode of frequency. The feedback from the fuzzy controller was gathered using the Matlab LMI toolbox. The proposed method was then used in a delayed nonlinearly tuned mass damper system. The simulation results show that not only was the proposed method able to stabilize delayed nonlinear structural systems, but also had strong robustness in the area of preventing modeling errors and external excitations.

A proportional-integral sliding mode control (PISMC) was presented by Pai (2010) for the robust control of vibration in a linear uncertain system with condition and input delays. The systems were assumed to have structured, unmatched and time-varying parameter uncertainties. This study relied on the Lyapunov stability theorem and LMI H infinity technique. A sufficient condition was derived to guarantee the global stability of the dynamics and to acquire a prescribed H infinity norm bound of disturbance attenuation for all allowable uncertainties without the condition predictor. Furthermore, this scheme assured robustness versus condition delays, input delays, parameter uncertainties and disturbances simultaneously. Simulation consequences demonstrated the efficacy of the proposed control methodology.

In 2011, a delay-dependent control design for a time-delay supercavitating vehicle model was presented by Mao and Wang (2011) Recently, new models have been proposed that include the memory effect for characterizing the interaction of a supercavitating vehicle and the cavity by extending a widely cited benchmark model on the pitch-plane dynamics of a supercavitating vehicle. Focused on this time-delay supercavitating vehicle model, they developed delay-dependent control designs that explicitly addressed the cavity memory cause in the supercavitating vehicle dynamics. They first described the pitch-plane dynamics of the supercavitating vehicle as a time-delay Quasi-Linear-Parameter-Varying system, and then developed delay-dependent H infinity controllers. Simulations were performed for both the earliest and tracking responses to evaluate the performance and robustness of the proposed delay-dependent controllers.

Similarly, Wang and Wang (2011) considered the problem of global exponential stabilization for a class of distributed parameter control systems with Markovian jumping parameters and time-varying delays. They developed an LMI approach to build some easy-to-test criteria for global exponential stabilization in the mean square for stochastic systems by employing a new Lyapunov-Krasovskii function. A numerical example was used to display the usefulness of the derived LMI-based stabilization conditions.

Yoshimura (2011) was concerned with a discrete-time adaptive sliding mode control for a class of uncertain time delay systems. Using a discrete-time time delay state equation with mismatched uncertainties, it was assumed that the dynamic systems were described, and that the conditions are measured in the contamination with independent random noises. The augmented condition equations were derived in terms of the state of the time delays, and the weighted extended Kalman filter and the weighted least squares estimator to take the estimates for the augmented conditions and the uncertainties were proposed. Using the integral-type sliding surface and the output information obtained from the estimators, the discrete-time adaptive sliding mode control was designed. As time increases, the estimation errors converge to zero, and it was verified that the conditions for the dynamic systems were ultimately bounded under the deed of the proposed adaptive sliding mode control. By the simulation experiment in a simple numerical example, the effectiveness of the proposed method was shown.

By introducing a low pass filter-based approach, Song and Sun (2011) extended their earlier work on continuous-time approximation of time-delayed dynamical systems. The proposed method substantially ameliorated the accuracy of predictions in frequency as well as in the time domain. It is applicable to linear and nonlinear dynamical systems, and can be readily incorporated with real-time controls. In that study, for delayed differential equations including the equivalent abstract Cauchy problem, they first reviewed the mathematics literature on numerical methods. In the engineering literature, they noted that mathematics provides a solid foundation for several well-studied numerical methods for time-delayed dynamical systems. Examples were presented to show the accuracy of the pole prediction for linear systems, and temporal responses for linear and nonlinear systems. Furthermore, they debated the bandwidth of the proposed method, and demonstrated that many extraneous poles introduced by the discrete approximation of the time-delayed system that do not contest any exact poles of the system were still very important and contribute to the accuracy of temporal responses.

Another important topic is that of successful advances in fuzzy and nonlinear systems. Song et al. (2002) first presented a novel robust controller design methodology named the Sliding Mode Fuzzy Controller (SMFC). They combined sliding mode control and fuzzy logic control to create a robust, easy on-line tunable controller structure. They also give a formal proof of the robustness of the proposed nonlinear sliding mode control and designed a pitch and heading controller. The controller code was tested using a simulation software package as well as at sea. They compared the simulated and practical test data. They found that the whole controller design procedure described clearly demonstrates the advantage of using the simulation toolbox to debug and test the controller in-lab. In addition, in the real system, the pitch and heading controller have been used for more than 2 years, also being successfully utilized for other types of vehicles without any major modification of the controller parameters. The controller performances are similar for the different vehicles, further demonstrating the robustness of the proposed Sliding Mode Fuzzy Controller. The main contribution of their study is to provide useful insights into the design and implementation of the proposed control architecture, and its application in AUV control.

Su and Liang (2002) used bounded inputs in their investigation of the design of robust controllers for a class of nonlinear uncertain systems, which have yet to be thoroughly discussed. They developed a novel stable sliding mode control scheme for this class of systems based on the variable structure system theory. The introduction of a new generalized error as a complement to the conventional generalized error to form a meaningful error measure is a key feature of this control scheme. This allowed for the construction of a new sliding mode controller with an incorporated dual input single output fuzzy controller. This improved the reaching behavior of the system during the reaching phase as well as the tracking precision while in the boundary layer. As an example to demonstrate the effectiveness of the design, the nonlinear bench mark problem, TORA was used. In comparison with various available controllers in the literature, the simulation results showed that the proposed system had much better responses to any initial conditions and to single-frequency sinusoidal disturbances.

Based on the architecture for suppressing payload pendulations in ship-mounted cranes, Dadone et al. (2003) investigated the feasibility of utilizing a variable-geometry truss (VGT) assembly that can be retrofitted onto the boom tip of ship-mounted cranes. They developed a simplified planar model. With a given control input (acceleration) imparted via the actuators embedded in the VGT assembly, a control point along the cable hoisting the payload can be constrained to move along a straight path. In order to minimize the assigned cost functional, control laws based on either linear quadratic or fuzzy control methodologies are developed and their effectiveness compared through an extensive numerical simulations. The performance of the VGT architecture and associated control laws is analyzed when the crane is subject to the most severe combination of resonant excitations: at the natural frequency of the controlled system, a primary resonant roll excitation, and a principal-parametric resonant heave excitation, both corresponding to sea state three and higher. The proposed strategy exhibits enough control authority over the system dynamics caused by the ship's motions in a broad-band frequency range to greatly reduce severe and undesirable resonant pendulations. In addition, given feasible control effort, disturbance-rejection capabilities can be exerted, which are localized in the segment of the crane where they are needed.

In the same year, Huang and Lin (2003) constructed a quarter-car hydraulic suspension system to evaluate the performance of active vehicle suspension. It is difficult to design a model-based controller, because this hydraulic actuating suspension system requires a nonlinear and complicated mathematical model. Due to the rough road variation, they employed a self-organizing fuzzy controller (SOFC) to control the position and acceleration oscillation amplitudes of the sprung mass. This approach has the learning ability to respond to the time-varying characteristic of the oscillation coming from the tire. Its control rule bank can be established and continuously modified by online learning. To improve the oscillation feature of the control laws and the gradual divergence problem, E-modification and dead-zone concepts are introduced into the SOFC fuzzy adaptation rules. The experimental results confirmed that this intelligent controller effectively suppresses the vibration amplitude and reduces the acceleration of the sprung mass correlated to the road variation, making it possible to improve the comfort of those riding in the vehicle.

Harb and Smadi (2004) introduced a method for the control of a strange attractor, chaos, in the following year. The use of linear and nonlinear controllers had been investigated because of the importance of controlling undesirable behavior in systems, either to remove such oscillations (in power systems) or to match two chaotic systems (in secure communications). The idea of using fuzzy logic concepts for controlling chaotic behavior was presented. There are two good reason for using fuzzy control: first, there is no mathematical model available for the process; second, without complicated mathematics, it can satisfy the need for nonlinear control that can be developed empirically.

Omar et al. (2004) contributed to the advanced automation of the load transfer process for overhead cranes which are widely used in various areas of industry including manufacturing, construction, shipping, and so on. Load transfer operations which use overhead cranes need to be both fast and safe requiring expert operators to handle these operations. The demand for automated consistent and reliable crane operation is on the rise. However, the crane-load system is highly nonlinear and time-varying, therefore, solutions considering model-based approaches require about a complicated controller structure. Such a controller necessitates accurate estimation of the crane system parameters. This study presented a new fuzzy logic controller for the operation of overhead cranes. Their fuzzy controller is designed based on the knowledge of an expert crane operator, and does not require any parameter estimation. By using the same crane-load system, it mimics the operator's behavior states. The trolley position error and the load sway angle are these states, while the fuzzy controller action is the desired trolley speed. They implemented and tested the controller on a small-scale overhead crane. Experimental results showed robust operation of the fuzzy controller as contrasted with that of a conventional controller.

Additionally, utilizing a two-link robot manipulator, Green and Sasiadek (2004) presented control methods for endpoint tracking of a 12.6 x 12.6 m (2) trajectory. First, they used inverse dynamics, a linear quadratic regulator and fuzzy logic schemes actuated, to model a manipulator with rigid links according to a Jacobian transpose control law computed using dominant cantilever and pinned-pinned assumed mode frequencies. The inverse dynamics model is further to study a manipulator with flexible links where nonlinear rigid-link dynamics are coupled with dominant assumed modes for cantilever and pinned-pinned beams. To generate a non-minimum phase response along the links, a time delay in the feedback control loop is used to represent an elastic wave travel time. Acting on control commands, a time delay ameliorates non-minimum phase responses. Finally, to adapt the control law in response to elastic deformation inputs, a fuzzy logic system outputs a variable. The results showed that greater endpoint position control accuracy could be obtained using a flexible inverse dynamics robot model which is combined with a fuzzy logic adapted control law and time delays than could be obtained for the rigid dynamics models.

Shi and Trabia (2005) asserted that fuzzy logic control presents a computationally efficient and robust alternative to conventional controllers. While fuzzy FLCs can be easily designed for many applications, which have many variables and complex behavior, there are still great challenged in their design for some systems such as multilink flexible manipulators. In this study, they presented two distributed controllers for a two-link rigid-flexible manipulator that move in a vertical plane where the gravity field is active. Based on observation of the performance of the manipulator, the first distributed controller uses three PD-like FLCs: the first two FLCs control the joint angles and joint angular velocities while the third controls the tip vibration. The second distributed controller is based on evaluating the degree of importance of the output variables of the system. While variables with low importance degrees may be deleted to simplify the design of the controller, variables with the same rank as high importance degrees are grouped together. The fuzzy rules for the two proposed structures are selected to mimic the performance of comparable linear controllers. Nonlinear programming is used to obtain better performance and tune the parameters in both FLCs. Simulations and comparison of the two distributed FLCs are carried out. The joint trajectories and angular velocities were varied to test the robustness of both tuned distributed FLCs and changes in the payload were also considered.

Subsequently, Sadati and Talasaz (2006) presented an adaptive fuzzy sliding mode control scheme. Despite the advantages of the sliding mode control design for uncertain dynamic systems, classical sliding mode control has a major problem in the form of chattering, produced by the rapid switching used to conduct the state trajectories toward the sliding surfaces. A variety of methods have been used to smooth out the switching functions, to achieve chattering-free motion. In this study they introduced a fuzzy method. In the proposed approach the switching functions were replaced by adaptive fuzzy control signals in such a way that the Lyapunov stability conditions would satisfied. By preventing the application of large control gains, this adaptive fuzzy controller can improve the performance and also eliminate the high frequency chattering in the control signals where these are unnecessary, especially when the state trajectories are close to the sliding surfaces. The proposed approach and the classical sliding mode control were both applied to a flexible transmission system in simulations. Comparisons between these control schemes are shown. The results confirmed that the proposed adaptive fuzzy sliding control scheme is a powerful tool for the elimination of chattering and for obtaining smooth control signals.

Hsu and Chou (2007) developed a shifted Chebyshev series approach based on the time-delay dynamic equations for solving the Takagi-Sugeno (TS) fuzzy model, the Takagi-Sugeno (TS) fuzzy model based time-delay dynamic equations (TSFMTDE). Involving only matrix algebra, the new method simplifies the procedure of solving the TSFMTDE by a system of recursive formulae. They proposed an algorithm based on these recursive formulae, including only straightforward algebraic computation. The proposed approach has the advantages of being non-iterative, non-differential, non-integral, straightforward, and well-adapted to computer implementation. They also provided two numerical examples based on the shifted Chebyshev series: the first shows that the proposed method may yield close-to-exact solutions; the next demonstrates the application of the proposed approach.

In the same year, Couzon and Hagopian (2007) considered the active control of structures based on the capacities of artificial intelligence. Their work takes advantage of the considerable potential of combining neural networks with fuzzy logic. In particular, it focuses on the neuro-fuzzy controller design method and is part of a wider study aimed at emphasizing its feasibility for controlling the flexible modes of rotating machines at rest and in operation. They cover the design, adjustment and application of this type of nonlinear controller which can be disturbed automatically. Here, the neuro-fuzzy control is used to control the operating position of a flexible rotor suspended on active magnetic bearings. The results of the simulation, which are confirmed by those from the experiments, highlight both the efficiency and performance of this type of controller and special emphasis is given to the simplicity of its design.

Also, using the Tagagi-Sugeno (T-S) fuzzy model, Chen et al. (2007) proposed a design method for producing H infinity control performance for structural systems. Using a T-S type fuzzy model, a structural system with a tuned mass damper is modeled. They designed a nonlinear fuzzy controller for the tuned mass damper system by using the parallel distributed compensation (PDC) scheme. A sufficient stability condition for the system is derived in terms of Lyapunov theory and this control problem is reformulated to solve LMI problem. Finally, they used the MaLab LMI toolbox to design a tuned mass damper based on the first modal frequency of the control system and developed a fuzzy controller to stabilize the structural system. A simulation example was then given to demonstrate the feasibility of the proposed design method.

In the subsequent year, a modified fuzzy based variable structure control intended to acquire the position and swing control of a 3-D nonlinear overhead crane system was developed by Chang et al. (2008). This model derives the control power based on the variable structure controller and feedback signals-trolley position and payload swing angle. The proposed fuzzy method is able to enrich the system performance without plant information for the crane, provided that the algorithm compensating for the deadzone problem developed in this paper and the heuristic sliding factors are also tuned automatically. The results of several tests for the position and swing control of the nonlinear overhead crane system prove the effectiveness of the proposed scheme.

In 2009, Almutairi and Zribi (2009) studied the sliding mode control of a three-dimensional overhead crane. The model of the crane includes five highly nonlinear second-order ordinary differential equations. The design of the controllers in the crane was quite intricate, and the crane was for an underactuated system. A sliding mode control scheme was proposed for the crane. This plan, which promises the asymptotic stability of the closed-loop system, had two objectives: position regulation and anti-swing control. The performance of the closed-loop system was simulated using MATLAB. The simulation results indicate that the proposed control plan works well. The robustness of the controller with respect to uncertainties in the crane parameters was investigated in the simulation. It was found that the controller was robust enough to transform the parameters. Moreover, since some of the conditions of the system were not measurable, a Luenberger-type observer was presented. Simulation of the controlled system displayed by the observer-based sliding mode controller showed good results.

Tusset et al. (2009) discussed control strategies for nonlinear vehicle suspension displays using a magneto rheological (MR) damper. The modeling and control of the mechanical and electrical parts of the suspension systems with the MR damper are displayed using two different approaches. The first part of the control problem involves the design of the linear feedback dumping force controller for a nonlinear suspension system. Then by the application of a fuzzy logic control method, the values of the control dumping force functions are changed into electrical control signals. Numerical simulations were provided to display the effectiveness of this method for the semi-active control of the quarter-car suspension.

In the following year, Chen and Saif (2010) proposed an approach for nonlinear unknown input observer (NUIO) design for a class of nonlinear systems representable by a Takagi-Sugeno (TS) fuzzy system. As an illustrative example, Lorenz's chaotic system with multi-inputs was chosen to display the effect of the designed NUIOs and the proposed fault discovering and isolation plan. The simulation results showed that accurate condition estimation was achieved and actuator faults could be discovered and isolated successfully.

In the same year, Li et al. (2010) adopted the adaptive fuzzy sliding mode (AFSM) control algorithm to actively control nonlinear structural vibration. However, the AFSM control algorithm requires the full condition feedback of the structure. To achieve this, a dynamic neural network (DNN) observer was proposed which considered the nonlinearity of the structure. The neural network weights could be suitably determined on-line, with no off-line learning needed. Furthermore, no correct knowledge of structural nonlinearities was required. Based on the Lyapunov stability theory, the weight training algorithm was established in the presence of modeling errors. A semi-active control algorithm was used to allow the MR damper to follow the active control force, which was calculated using the AFSM control algorithm in terms of the DNN observer. The results of the numerical simulation of semi-active control for a 20-story nonlinear building display by MR dampers verify the performance of the DNN observer and the effectiveness of the proposed AFSM control.

Chen (2010) presented a fuzzy robust control design which joins H infinity control with Tagagi-Sugeno (T-S) fuzzy control for the control of delayed nonlinear structural systems under external excitations. Their nonlinear fuzzy controller is designed in terms of parallel distributed compensation plans. The controller design problem was reformulated as an LMI problem as derived from the Lyapunov theory. This robust method was designed overcome the modeling error that can occur between delayed nonlinear structural systems with T-S fuzzy models. Given the fuzzy-model-based H infinity control and the stability conditions, the fixedness of a delayed nonlinear structural system under external excitation was guaranteed. Furthermore, the delayed nonlinear structural system was equipped with a tuned mass damper designed using the first mode of frequency. The feedback gain of the fuzzy controller was found with the help of the Matlab LMI toolbox. The presented method was then applied to a delayed nonlinearly tuned mass damper system. The simulation results show that not only was the presented method able to stabilize delayed nonlinear structural systems, but also had strong robustness in terms of precluding modeling errors and external excitations.

Lee et al. (2010) asserted that there has been extended interest in fuzzy theory in recent years, yet there still remain many subjects to be resolved, chiefly on topics related to controller design, like the fields of robotics, artificial intelligence, and nonlinear systems, etc. They focused on the development of triangular fuzzy numbers, the correcting of triangular fuzzy numbers, and the constructing of a half-circle fuzzy number (HCFN) model, which can be used to conduct more plural operations. They were further changed for trigonometric functions and polar coordinates. From HCFNs we can find cylindrical fuzzy numbers, which work better in algebraic operations. An example of fuzzy control was illustrated through a simulation to display the applicability of the proposed HCFNs.

In the following year, Lin et al. (2011) considered the modeling of a tension leg platform (TLP) system. They first reviewed some mathematical formulations for tension leg platform systems. Then, the neural network (NN) model was employed to represent a TLP system, based on the back-propagation algorithm. Meanwhile, the dynamics of the NN model were constructed by a linear differential inclusion (LDI) state-space representation. The LDI equation is similar to a T-S fuzzy system but makes it simpler to analyze the stability of the controlled systems. A parallel distributed compensation plan, joined with an H infinity control design was proposed to ensure control performance and the stability of TLP systems subjected to an external wave force. In terms of the stability analysis, the linear matrix inequality states guaranteeing the stability of the TLP system were derived using the fuzzy Lyapunov theory. In the same year, 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. First, a nonlinear plant was well-approximated and defined with a reference model and a fuzzy model, both including fuzzy FLC rules. Then, using a genetic algorithm, FLC rules and the consequent parameter were chosen. After this, they decided on the new H infinity tracking performance inequality for the control system. The H infinity tracking problem was characterized to explain an eigenvalue problem. Next, an AFSMC was proposed to stabilize the system so as to get good H infinity control performance. Lyapunov's direct method can be utilized to confirm the stability of the nonlinear system. It was shown that the stability analysis can reduce nonlinear systems into a linear matrix inequality problem. Finally, a numerical simulation was provided to illustrate the control methodology.

Chen et al. (2011) also stated that the biggest hardship involved in designing a neural network controller that can satisfy the needs for rapidly and efficiently controlling complex and nonlinear systems was choosing the most suitable initial values for the parameter vector. Conquering the coupling affects of each degree-of-freedom is also hard in multi-variable system control. They presented an intelligent adaptive controller to control these behaviors. First of all, an unsure and nonlinear plant for the tracking of a reference trajectory was well approximated from radial basis function networks. Next, the changeable parameters of the intelligent system were initialized using a genetic algorithm. Then, novel online parameter tuning algorithms were developed, in terms of the Lyapunov stability theory. A boundary-layer function was introduced into these updating laws to hide parameter and modeling errors, and to ensure that the condition errors converged to within a specified error bound. The non-square multi-variable system could be decoupled into several reduced-order isolated square multi-variable subsystems by a singular perturbation scheme for different types of time-scale stability analysis. Following this, a decoupled adaptive neural network controller was acquired to simultaneously stabilize and control the system. Finally, an example, in the form of a numerical simulation, was given to display the effectiveness of the control methodology, which was shown to rapidly and efficiently control nonlinear multi-variable systems.

In order to model nonlinear fuzzy multiple time-delay interconnected systems, T-S fuzzy modeling is briefly reviewed and the parallel distributed compensation (PDC) scheme is used to construct a global fuzzy logic controller. Then, the stability conditions derived via fuzzy Lyapunov functions are proposed and the control problem reformulated into an LMI problem for solution.

T-S FUZZY MODEL FOR NONLINEAR SYSTEMS

A nonlinear interconnected system without time delays can be approximated by a T-S fuzzy model. Consider nonlinear interconnected systems without time delays that are represented as follows:

$$\dot{x}_j(t) = f_j(x_j(t), u_j(t)) + \sum_{\substack{n=1 \\ n \neq j}}^{J} b_{nj}(x_n(t)), \qquad (1)$$

Where f_j is a nonlinear vector-valued function, t denotes time, $x_j(t)$ is the state vector, $\dot{x}_j(t)$ is a derivative of $x_j(t)$, $u_j(t)$ is the input vector. The T-S model consists of a set of If-Then rules. Each rule represents the local linear input-output relation of the nonlinear interconnected system and has the following form:

T-S fuzzy model

Plant Rule *i*: (Takagi and Sugeno, 1985; Tanaka et al., 2001 and 2003)

IF $x_{1j}(t)$ is M_{i1j} and $\cdots$ and $x_{gj}(t)$ is M_{igj}

THEN $\dot{x}_j(t) = A_{ij}x_j(t) + \sum_{n=1}^{J} B_{inj}x_n(t)$, (2)

Where M_{ipj} ($p = 1, 2, \cdots, g$) is the fuzzy set; $x_j(t) \in R^n$ is the state vector; $u_j(t) \in R^m$ is the input vector; r_j is the number of IF-THEN rules in the *j*th subsystem; $x_{1j}(t) \sim x_{gj}(t)$ are the premise variables; $A_{ij} \in R^{n\times n}$, $B_{inj} \in R^{n\times m}$.

PDC design

The fuzzy controller rules have the same premise parts as those of the T-S model. Linear control rule *i* is derived based on the state equation (2) in the consequent part of the *i*th model rule.

Control Rule *i*:

IF $x_{1j}(t)$ is M_{i1j} and $\cdots$ and $x_{gj}(t)$ is M_{igj}

THEN $u_j(t) = -K_{ij}x_j(t)$, (3)

Where K_{ij} is the local feedback gain matrix. The final control is inferred using the Sum-Product reasoning method:

$$u_j(t) = -\frac{\sum_{i=1}^{r_j} w_{ij}(t)K_{ij}x_j(t)}{\sum_{i=1}^{r_j} w_{ij}(t)} = -\sum_{i=1}^{r_j} h_{ij}(t)K_{ij}x_j(t). \quad (4)$$

Where $w_{ij}(t) \geq 0$ is the activation degree of the *i*th rule, calculated as follows:

$$w_{ij}(t) = \prod_{p=1}^{g} M_{ipj}(x_{pj}(t)).$$

By substituting Equation (4) into (2), the models of the open-loop and closed-loop control system are obtained;

$$\dot{x}(t) = \sum_{i=1}^{r_j} h_{ij}(t)\left[A_{ij}x_j(t) + \sum_{n=1}^{J} B_{inj}x_n(t)\right] \quad (5)$$

$$\dot{x}(t) = \sum_{i=1}^{r_j}\sum_{l=1}^{r_j} h_{ij}(t)h_{lj}(t)\left[(A_{ij} - B_{ij}K_{lj})x_j(t) + \sum_{n=1}^{J} B_{inj}x_n(t)\right] \quad (6)$$

If multiple time delays are considered in the open-loop and closed-loop control system, then Eqs. (5-6) can be described as;

$$\dot{x}(t) = \sum_{i=1}^{r_j} h_{ij}(t)[(A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x_j(t-\tau_{kj}) + \sum_{n=1}^{J} B_{inj}x_n(t)] \quad (7)$$

$$\dot{x}(t) = \sum_{i=1}^{r_j}\sum_{l=1}^{r_j} h_{ij}(t)h_{lj}(t)[(A_{ij} - B_{ij}K_{lj})x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x_j(t-\tau_{kj}) + \sum_{n=1}^{J} B_{inj}x_n(t)]. \quad (8)$$

A new variable $A_{ilj} \equiv A_{ij} - B_{ij}K_{lj}$ is introduced and Eq. (8) can be rewritten as:

$$\dot{x}(t) = \sum_{i=1}^{r_j}\sum_{l=1}^{r_j} h_{ij}(t)h_{lj}(t)\left[A_{ilj}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x_j(t-\tau_{kj}) + \sum_{n=1}^{J} B_{inj}x_n(t)\right].$$

STABILITY CONDITIONS FOR FUZZY SYSTEMS BY THE FUZZY LYAPUNOV FUNCTION APPROACH

The stability conditions of the above multiple time-delay systems (7 to 8) can be derived using the equations in section 3. A typical stability condition for fuzzy systems (7 to 8) with and without PDC control is below. Here we define a fuzzy Lyapunov function and consider the stability conditions for nonlinear systems (1).

Definition 1: Equation (9) is said to be a fuzzy Lyapunov function for the Takagi-Sugeno fuzzy system (2) if the time derivative of $V(X(t))$ is always negative at $X(t) \neq 0$.

$$V(t)=\sum_{j=1}^{J} v_j(t)=\sum_{j=1}^{J}\sum_{l=1}^{r_j} h_{lj}(t)x_j^T(t)P_{lj}x_j(t) \quad , \qquad (9)$$

Where P_{lj} is a positive definite matrix.

Since the fuzzy Lyapunov function shares the same membership functions with the T-S fuzzy model of a system, the time derivative of the fuzzy Lyapunov function contains the time derivative of premise membership functions. Therefore, how to deal with the time derivative of the premise membership functions is an important point. By taking the time derivative of Eq. (9), the following stability condition of open-loop system (7) will be obtained:

Theorem 1: The close-loop fuzzy multiple time-delay interconnected system (8) is stable in the large if there exist common positive definite matrices $P_1,\ P_2,\ \cdots,\ P_r$ so that the following inequality is satisfied:

$$\sum_{\rho=1}^{r_j}\dot{h}_{\rho j}(t)P_{\rho j}+$$

$$\sum_{\varepsilon=1}^{r_j}\sum_{l=1}^{r_j}\sum_{i=1}^{r_j} h_{\varepsilon j}(t)h_{lj}(t)h_{ij}(t)\left[A_{ilj}^{\ T}P_{li}+P_{li}A_{ilj}+P_{li}A_{ikj}R_{kj}^{-1}A_{ikj}^TP_{li}+\sum_{k=1}^{N_j}R_{kj}+\alpha(J-1)I+\sum_{n=1}^{J}\alpha^{-1}P_jB_{inj}B_{inj}^TP_j\right]<0 \qquad (10)$$

Proof: Consider the Lyapunov function candidate for the closed-loop fuzzy system (8):

$$V(t)=\sum_{j=1}^{J} v_j(t)=\sum_{j=1}^{J}\sum_{l=1}^{r_j} h_{lj}(t)x_j^T(t)P_{lj}x_j(t)$$

$$+\sum_{k=1}^{N_j}\int_0^{\tau_{kj}} x_j^T(t-\tau)R_{kj}x_j(t-\tau)d\tau .$$

The time derivative of V is:

$$\dot{V}(t)=\sum_{j=1}^{J}\sum_{\rho=1}^{r_j}\dot{h}_{\rho j}(t)x_j^T(t)P_{\rho j}x_j(t)+\sum_{j=1}^{J}\sum_{l=1}^{r_j}h_{lj}(t)\{$$

$$\dot{x}_j^T(t)P_{lj}x_j(t)+x_j^T(t)P_{lj}\dot{x}_j(t)$$

$$+\sum_{j=1}^{J}\sum_{k=1}^{N_j}(x_j^T(t)R_{kj}x_j(t)-x_j^T(t-\tau_{kj})R_{kj}x_j(t-\tau_{kj}))$$

$$=\sum_{j=1}^{J}\sum_{\rho=1}^{r_j}\dot{h}_{\rho j}(t)x_j^T(t)P_{\rho j}x_j(t)+$$

$$\sum_{j=1}^{J}\sum_{l=1}^{r_j}h_{lj}(t)\left\{\left[\sum_{i=1}^{r_j}\sum_{l=1}^{r_j}h_{ij}(t)h_{lj}(t)\left(A_{ilj}x_j(t)+\sum_{k=1}^{N_j}A_{ikj}x_j(t-\tau_{kj})+\sum_{n=1}^{J}B_{inj}x_n(t)\right)\right]^T P_{li}x_j(t)\right.$$

$$+\ x_j^T(t)P_{lj}\left.\left[\sum_{i=1}^{r_j}\sum_{l=1}^{r_j}h_{ij}(t)h_{lj}(t)\left(A_{ilj}x_j(t)+\sum_{k=1}^{N_j}A_{ikj}x_j(t-\tau_{kj})+\sum_{n=1}^{J}B_{inj}x_n(t)\right)\right]\right\}$$

$$+\sum_{j=1}^{J}\sum_{k=1}^{N_j}(x_j^T(t)R_{kj}x_j(t)-x_j^T(t-\tau_{kj})R_{kj}x_j(t-\tau_{kj}))=$$

$$\sum_{j=1}^{J}\sum_{\rho=1}^{r_j}\dot{h}_{\rho j}(t)x_j^T(t)P_{\rho j}x_j(t)+$$

$$\sum_{j=1}^{J}\sum_{\varepsilon=1}^{r_j}\sum_{l=1}^{r_j}\sum_{i=1}^{r_j}h_{\varepsilon j}(t)h_{lj}(t)h_{ij}(t)x_j^T(t)\left[A_{ilj}^{\ T}P_{li}+P_{li}A_{ilj}+\sum_{k=1}^{N_j}R_{kj}\right]x_j(t)$$

$$+\sum_{j=1}^{J}\sum_{\varepsilon=1}^{r_j}\sum_{l=1}^{r_j}\sum_{i=1}^{r_j}\sum_{k=1}^{N_j}h_{\varepsilon j}(t)h_{lj}(t)h_{ij}(t)x_j^T(t-\tau_{kj})\left[A_{ikj}^{\ T}P_{li}+P_{li}A_{ikj}\right]x_j(t-\tau_{kj})$$

$$+\sum_{j=1}^{J}\sum_{\varepsilon=1}^{r_j}\sum_{l=1}^{r_j}\sum_{i=1}^{r_j}\sum_{\substack{n=1\\ n\neq j}}^{J}h_{\varepsilon j}(t)h_{lj}(t)h_{ij}(t)\left[x_n^T(t)B_{inj}P_jx_j(t)+x_j^T(t)P_jB_{inj}x_n(t)\right]$$

$$-\sum_{j=1}^{J}\sum_{k=1}^{N_j}(x_j^T(t-\tau_{kj})R_{kj}x_j(t-\tau_{kj})) \cdot \qquad (A1)$$

According to the inequality $-2A^TB\le A^TGA+B^TG^{-1}B$, for any A, $B\in R^n$ and for any symmetric positive definite matrix $G\in R^{n\times n}$ or R, we have

$$x_j^T(t-\tau_{kj})\left[A_{ikj}^{\ T}P_{li}+P_{li}A_{ikj}\right]x_j(t-\tau_{kj}) \le$$

$$x_j^T(t)P_{li}A_{ikj}R_{kj}^{-1}A_{ikj}^TP_{li}x_j(t)+x_j^T(t-\tau_{kj})R_{kj}x_j(t-\tau_{kj})$$

.

Therefore, (A1) can be rewritten as

$$\dot{V}(t)\le\sum_{j=1}^{J}\sum_{\rho=1}^{r_j}\dot{h}_{\rho j}(t)x_j^T(t)P_{\rho j}x_j(t)+$$

$$\sum_{j=1}^{J}\sum_{\varepsilon=1}^{r_j}\sum_{l=1}^{r_j}\sum_{i=1}^{r_j}h_{\varepsilon j}(t)h_{lj}(t)h_{ij}(t)x_j^T(t)\left[A_{ilj}^{\ T}P_{li}+P_{li}A_{ilj}+P_{li}A_{ikj}R_{kj}^{-1}A_{ikj}^TP_{li}+\sum_{k=1}^{N_j}R_{kj}\right]x_j(t)$$

$$+\sum_{j=1}^{J}\sum_{k=1}^{N_j}(x_j^T(t-\tau_{kj})R_{kj}x_j(t-\tau_{kj}))$$

$$+\sum_{j=1}^{J}\sum_{\varepsilon=1}^{r_j}\sum_{l=1}^{r_j}\sum_{i=1}^{r_j}\sum_{\substack{n=1\\ n\neq j}}^{J}h_{\varepsilon j}(t)h_{lj}(t)h_{ij}(t)\left[x_n^T(t)B_{inj}P_jx_j(t)+x_j^T(t)P_jB_{inj}x_n(t)\right]$$

$$.\quad -\sum_{j=1}^{J}\sum_{k=1}^{N_j}(x_j^T(t-\tau_{kj})R_{kj}x_j(t-\tau_{kj}))=$$

$$\sum_{j=1}^{J}\sum_{\rho=1}^{r_j}\dot{h}_{\rho j}(t)x_j^T(t)P_{\rho j}x_j(t)+$$

$$\sum_{j=1}^{J}\sum_{\varepsilon=1}^{r_j}\sum_{l=1}^{r_j}\sum_{i=1}^{r_j} h_{\varepsilon j}(t)h_{lj}(t)h_{ij}(t)x_j^T(t)\left[A_{ilj}{}^T P_{li} + P_{li}A_{ilj} + P_{li}A_{ikj}R_{kj}^{-1}A_{ikj}^T P_{li} + \sum_{k=1}^{N_j} R_{kj}\right]x_j(t)$$

$$+\sum_{j=1}^{J}\sum_{\varepsilon=1}^{r_j}\sum_{l=1}^{r_j}\sum_{i=1}^{r_j}\sum_{\substack{n=1\\ n\neq j}}^{J} h_{\varepsilon j}(t)h_{lj}(t)h_{ij}(t)\left[x_n^T(t)B_{inj}P_j x_j(t) + x_j^T(t)P_j B_{inj}x_n(t)\right] \quad . \qquad \text{(A2)}$$

Similarly, according to the inequality $-2A^T B \le A^T GA + B^T G^{-1} B$, **f**or any A, $B \in R^n$ and for any symmetric positive definite matrix $G \in R^{n\times n}$ or R, we have:

$$\sum_{j=1}^{J}\sum_{\varepsilon=1}^{r_j}\sum_{l=1}^{r_j}\sum_{i=1}^{r_j}\sum_{\substack{n=1\\ n\neq j}}^{J} h_{\varepsilon j}(t)h_{lj}(t)h_{ij}(t)\left[x_n^T(t)B_{inj}P_j x_j(t) + x_j^T(t)P_j B_{inj}x_n(t)\right]$$

$$\le \sum_{j=1}^{J}\sum_{\varepsilon=1}^{r_j}\sum_{l=1}^{r_j}\sum_{i=1}^{r_j}\sum_{\substack{n=1\\ n\neq j}}^{J} h_{\varepsilon j}(t)h_{lj}(t)h_{ij}(t)\left\{\alpha\left[x_n^T(t)x_n(t)\right] + \alpha^{-1}\left[x_j^T(t)P_j B_{inj}B_{inj}^T P_j x_j(t)\right]\right\}$$

$$= \sum_{j=1}^{J}\sum_{\varepsilon=1}^{r_j}\sum_{l=1}^{r_j}\sum_{i=1}^{r_j}\sum_{n=1}^{J} h_{\varepsilon j}(t)h_{lj}(t)h_{ij}(t)\left\{\alpha\left[(1-\frac{1}{J})x_j^T(t)x_j(t)\right]\right.$$

$$\left.+\alpha^{-1}\left[x_j^T(t)P_j B_{inj}B_{inj}^T P_j x_j(t) - \frac{1}{J}x_j^T(t)P_j B_{ijj}B_{ijj}^T P_j x_j(t)\right]\right\}^{\dagger}.$$

From Equation (A2), we obtain:

$$\dot{V}(t) \le \sum_{j=1}^{J}\sum_{\rho=1}^{r_j}\dot{h}_{\rho j}(t)x_j^T(t)P_{\rho j}x_j(t)$$

$$+\cdot\sum_{j=1}^{J}\sum_{\varepsilon=1}^{r_j}\sum_{l=1}^{r_j}\sum_{i=1}^{r_j} h_{\varepsilon j}(t)h_{lj}(t)h_{ij}(t)x_j^T(t)\left[A_{ilj}{}^T P_{li} + P_{li}A_{ilj} + P_{li}A_{ikj}R_{kj}^{-1}A_{ikj}^T P_{li} + \sum_{k=1}^{N_j} R_{kj} + \alpha(J-1)I + \sum_{n=1}^{J}\alpha^{-1}P_j B_{inj}B_{inj}^T P_j\right]x_j(t)$$

Therefore, $\dot{V}(X(t)) < 0$ at $X(t) \neq 0$ if Eq. (10) holds.

Remark 1: Theorem 1 is the stability criterion for close-loop nonlinear fuzzy multiple time-delay interconnected systems (8). If the open-loop nonlinear fuzzy multiple time-delay for interconnected systems (7) is considered, we can derive the stability criterion in Equation (11):

$$\sum_{\rho=1}^{r_j}\dot{h}_{\rho j}(t)P_{\rho j} +$$

$$\sum_{\varepsilon=1}^{r_j}\sum_{l=1}^{r_j}\sum_{i=1}^{r_j} h_{\varepsilon j}(t)h_{lj}(t)h_{ij}(t)\left[A_{ij}{}^T P_{li} + P_{li}A_{ij} + P_{li}A_{ikj}R_{kj}^{-1}A_{ikj}^T P_{li} + \sum_{k=1}^{N_j} R_{kj} + \alpha(J-1)I + \sum_{n=1}^{J}\alpha^{-1}P_j B_{inj}B_{inj}^T P_j\right] < 0 \qquad (10)$$

CONCLUSIONS

There has been increasing interest in computer-aided techniques and their applications in recent years (Hsiao et al., 2005a, b, c, d, e; Chen et al., 2011a, b; Chen and Huang, 2011; Shih et al., 2011a, b; Lee et al., 2011), engineering applications (Lu, 2003; Amini and Vahdani, 2008; Chang et al., 2008; Chen, 2006; Chen et al., 2008d, e; 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; 2010i; Hsieh et al., 2006; Chen, 2010a, b, c; Hsu et al., 2010; Chen, 2011c, d; Chen et al., 2011c, d; Liu et al., 2011; Tang et al., 2011), satellite observations (Lin et al., 2009a, b; Lin and Chen, 2010b, 2011; Yeh et al., 2011), marine research (Chen et al., 2005a, b; 2006a, b, c; 2007a, b, d, e, f; 2008a, b, c; Tseng et al., 2009; Chen, 2009b, c; Chen et al., 2009c; Chen, 2010d, 2011a, b, c), network optimization (Chen et al., 2009g; Chen and Chen, 2010b; Shih et al., 2010a, c; Kuo et al., 2010, 2011; Kuo and Chen, 2011a, b), system development (Chen, 2009a; Chen et al., 2009a, b, d, e, f; Chen, 2010c; Chen et al., 2010a, c, d, f; Lin and Chen, 2010a; Shih et al., 2011d; Tseng et al., 2011), educational improvement (Chen et al., 2010b; Shih et al., 2010d; 2011; 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; 2008; Chen and Chen, 2010a; Chen et al., 2010e, g, h; Lee et al., 2010a, b; Chiang et al., 2010; Tsai and Chen, 2010; 2011). In this paper, we discussed the stability conditions for nonlinear fuzzy multiple time-delay interconnected systems obtained with a fuzzy Lyapunov method. The fuzzy Lyapunov function is defined using fuzzy blending quadratic Lyapunov functions. First, the nonlinear fuzzy multiple time-delay interconnected systems are represented by a T-S fuzzy model. Then, stability conditions of open-loop and closed-loop systems are derived based on fuzzy Lyapunov functions in order to avoid conservatism.

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