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Digital Fuzzy Control of Nonlinear Systems Using Intelligent Digital Redesign

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Abstract

In this paper, a novel and efficient global intelligent digital redesign technique for a Takagi-Sugeno (TS) fuzzy system is addressed. The proposed method should be notably discriminated from the previous works in that it allows us to globally match the states of the closed-loop TS fuzzy system with the pre-designed continuous-time fuzzy-model-based controller and those with the digitally redesigned fuzzy-model-based controller, and further to guarantee the stabilizability by the redesigned controller in the sense of Lyapunov. Sufficient conditions for the global state-matching and the stability of the digitally controlled system are formulated in terms of linear matrix inequalities (LMIs). The Duffing-like chaotic oscillator is simulated and demonstrated, to validate the effectiveness of the proposed digital redesign technique, which implies the safe applicability to the digital control system.

Key Words : TS fuzzy systems, intelligent digital redesign, linear matrix inequality, chaotic Duffing-like oscillator

1. Introduction

Dynamical behaviors of most physical systems are characterized by a set of differential equations in continuous-time setting. Viewed in a standpoint of control engineering, it is no wonder for researches to have focused on the development of various design techniques of continuous-time controllers. However, digital implementation of a controller is indeed quite desirable especially when the designed controller uses certain sophisticated and advanced control algorithms that require considerable amount of computation efforts. For this reason, digital control of continuous-time systems has been an active research branch in recent years.

A new efficient approach to designing digital controllers is called digital redesign, where an analog controller is first designed and then converted to an equivalent digital controller in the sense of state-matching [2-6,10]. It is noted that these digital redesign schemes basically work only for a class of linear systems. It has been highly eager to develop some intelligent digital redesign methodology for complex nonlinear systems, in which the first attempt was made by Joo *et al.* [2]. They synergetically merged together the fuzzy-model-based control and the digital redesign technique for a class of nonlinear systems. Chang *et al.* extended the intelligent digital redesign to uncertain TS fuzzy systems [3].

Although the intelligent digital redesign technique allows control engineers to enjoy the classical digital redesign techniques for nonlinear systems representable by Takagi-Sugeno (TS) fuzzy systems, it may lead to undesirable and/or inaccurate results. The majority among the reasons is that the redesigned digital control gain matrices are obtained by considering the local state-matching only for each sub-closed-loop system of the TS fuzzy system, which, in turn, obviously does not guarantee the global equivalence between the analogously controlled system and the digitally controlled counterpart. To overcome this weakness, a global state-matching should be embedded. However, it is also difficult to develop the global state-matching method in an analytic way, because of the highly complex and nonlinear interactions among the subsystems through the fuzzy inference rules, which is intrinsically the major obstacle in analysis and synthesis in fuzzy control. Regarding an extremely critical issue, the stability of the digital control system should be guaranteed when the intelligent digital redesign is used. Thus far, the above-mentioned critical issues on digital redesign have not been tackled, and thus be still open.

Motivated by the above concerns, this paper aims at the developing of a new intelligent digital redesign methodology for TS fuzzy systems with careful reflection of the global state-matching as well as the stability of the digital control system. The main contribution of this paper is the derivation of some sufficient conditions, in terms of linear matrix inequalities(LMIs), for the global intelligent digital redesign of the continuous-time TS fuzzy-model-based controller. The presented results should be expressly distinguished from the previous works in that i) the

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proposed methodology takes into account the global state-matching condition on the overall TS fuzzy system, not limited on the local one, and ii) the stabilizability using the digitally redesigned controller is indirectly examined. The Duffing-like chaotic oscillator is presented as an example for illustration, which was recently discovered [9], and therefore is interesting for control.

This paper is organized as follows: Section 2 briefly reviews the TS fuzzy systems. In Section 3, a new intelligent digital redesign methodology for TS fuzzy system is discussed. An intelligent design redesign and simulation results are included in Section 4. Finally closing remarks are drawn in Section 5.

2. Preliminaries

Consider the following TS fuzzy rules

Plant Rule i :

$$\begin{aligned} &\text{IF } z_1(t) \text{ is } \Gamma_1^1 \cdots z_n(t) \text{ is } \Gamma_1^n \\ &\text{THEN } \dot{x}_c(t) = A_i x_c(t) + B_i u_c(t) \end{aligned} \qquad (1)$$

where Γ_j^i $(j=1,\cdots,n, i=1,\cdots,q)$ is the fuzzy set, Rule i denotes the ith fuzzy inference rule. The defuzzified output of this TS fuzzy system (1) is represented as follows :

$$\dot{x}_c(t) = \sum_{i=1}^{q} \mu_i(z(t))\,(A_i x_c(t) + B_i u_c(t)) \qquad (2)$$

where

$$\mu_i(x(t)) = \omega_i(z(t)) / \sum_{i=1}^{q} \omega_i(z(t))$$

$\omega_i(z(t)) = \prod_{j=1}^{n} \Gamma_j^i(z_j(t))$, in which $\Gamma_j^i(z_j(t))$ is the grade of membership of $z_j(t)$ in Γ_j^i..

Throughout this paper, a well-designed continuous-time state-feedback TS fuzzy-model-based control law is assumed to be pre-designed, which will be used in redesigning the digital control law. The controller rule is formed by :

Controller Rule i

$$\begin{aligned} &\text{IF } z_1(t) \text{ is } \Gamma_1^1 \cdots z_n(t) \text{ is } \Gamma_1^n \\ &\text{THEN } u_c(t) = K_i x_c(t) \end{aligned}$$

The defuzzified output of the controller rules is given by

$$u_c(t) = \sum_{i=1}^{q} \theta_i(z(t)) K_c^i x_c(t) \qquad (3)$$

The global closed-loop continuous-time TS fuzzy system is

$$\dot{x}_c(t) = \sum_{i=1}^{q} \sum_{j=1}^{q} \theta_i(z(t))\theta_j(z(t))\,(A_i + B_i K_c^j) x_c(t) \qquad (4)$$

3. New Intelligent Digital Redesign

This section first investigates the discretization of the continuous-time TS fuzzy systems, and then the new global intelligent digital redesign method by using a convex optimization technique is presented.

3.1 Discretization of the Continuous- Time TS Fuzzy Systems

Consider the sampled-data control system as follows :

$$\dot{x}_d(t) = \sum_{i=1}^{q} \theta_i(z(t))(A_i x_d(t) + B_i u_d(t)) \qquad (5)$$

where $u_d(t) = u_d(kT)$ is the piecewise-constant control input vector to be determined in the time interval $[kT, kT+T)$, $T>0$ is a sampling period, and the subscript 'd' implies the sampled-data digital control, while the subscript 'c' denotes the continuous-time analog control. For the sampled-data control of the continuous-time TS fuzzy system, we employ the digital TS fuzzy-model-based controller. Let the fuzzy rule of the digital control law for the system (5) take the following form :

Controller Rule i

$$\begin{aligned} &\text{IF } z_1(kT) \text{ is } \Gamma_1^1 \cdots z_n(kT) \text{ is } \Gamma_1^n \\ &\text{THEN } u_c(t) = K_i x_c(kT) \end{aligned} \qquad (6)$$

for $\forall t \in [kT, kT+T)$, where K_d^i is the digital feedback gain matrix to be redesigned in the ith rule, and the overall control law is given by

$$u_d(t) = \sum_{i=1}^{q} \theta_i(z(kT)) K_d^i x_d(kT) \qquad (7)$$

for $\forall t \in [kT, kT+T)$. The sampled-data control system definitely includes the samplers and the holding devices, which makes the controller synthesis and the analysis of the system quite complicated and difficult to handle. Thus, it is more convenient and natural to convert the continuous-time system into discrete one and then design a suitable controller. There are a few methods for discretizing a linear time-invariant (LTI) continuous-time system. Unfortunately, these discretization methods cannot be directly applied for the discretization of the continuous-time TS fuzzy system, since the defuzzifed output of the TS fuzzy system is not LTI but implicitly time-varying [3]. Moreover, it is further desired to maintain the polytopic structure of the discretized TS fuzzy system for the construction of the digital fuzzy-model-based controller. At this point, we need a mathematical foundation for the discretization of the continuous-time TS fuzzy system.

Assumption 1 : The firing strength of the ith rule, $\theta_i(z(t))$ is approximated by their values at time kT, that is,

$$\theta_i(z(t)) \approx \theta_i(z(kT)), \text{ for } kT \le t < kT+T. \quad (8)$$

Consequently, the nonlinear matrices, $\sum_{i=1}^{q}\theta(z(t))A_i$ and $\sum_{i=1}^{q}\theta(z(t))B_i$ can be approximated as constant matrices $\sum_{i=1}^{q}\theta(z(kT))A_i$, and $\sum_{i=1}^{q}\theta(z(kT))B_i$, respectively, over any interval $[kT, kT+T)$. If a sufficiently small sampling period $T>0$ is chosen, Assumption 1 is reasonable.

Theorem 1 : The dynamical nonlinear behavior of the digital TS fuzzy system (5) can be efficiently approximated by

$$x_d(kT+T) \approx \sum_{i=1}^{q}\theta(z(kT))(G_i x_d(kT)+H_i u_d(kT)) \quad (9)$$

where $G_i = \exp(A_i T)$ and $H_i = (G_i - I)A_i^{-1}B_i$.

Proof : See [3].

The discretized TS fuzzy system (9) possesses the discretization error whose order of $O(T^2)$, which is tolerable under the choice of a sufficiently small sampling period, and vanishes as $T \to 0$. Notice that the error induced in this discretization procedure is smaller than the first-order truncated Taylor series expansion of (5). Henceforth, the discretized version of the closed-loop system with (5) and (7) is constructed of the form :

$$x_d(kT+T) = \sum_{i=1}^{q}\sum_{j=1}^{q}\theta_i(z(kT))\theta_j(z(kT))\left(G_i + H_i K_d^j\right)x_d(kT) \quad (10)$$

Cororally 1 : The controlled TS fuzzy system (4) also can be approximately discretized

$$x_c(kT+T) \approx \sum_{i=1}^{q}\sum_{j=1}^{q}\theta_i(z(kT))\theta_j(z(kT))\Phi_{ij}x_c(kT) \quad (11)$$

where $\Phi_{ij} = \exp\left((A_i + B_i K_c^j)T\right)$

Proof : It can be proved by Theorem 1.

3.2 New Intelligent Digital Redesign Based on Global State-Matching Concept

For practical digital implementation of the pre-developed continuous-time fuzzy-model-based controller, one desires to convert it into an equivalent digital controller. Furthermore, it is highly required to maintain the control performance in the sense of state-matching. Our goal is to develop an intelligent digital redesign technique for TS fuzzy systems so that the global dynamical behavior of (5) with the digitally redesigned fuzzy-model-based controller may retain that of the closed-loop TS fuzzy system with the existing continuous-time TS fuzzy-model-based controller as well as the stability of the digitally controlled TS fuzzy system is secured. To the end, we formulate the following global intelligent digital redesign

Problem 1 : Given well-designed gain matrices K_c^i for the stabilizing continuous-time TS fuzzy-model-based controller (3), ***redesign*** the gain matrices K_d^i, $i=1,\cdots,q$., for the digital fuzzy-model-based control law (7) such that the following design objectives are sufficiently satisfied :

(i) The state of the digitally controlled continuous-time TS fuzzy system (5) is globally matched with that of the continuous-time closed-loop TS fuzzy system (4) at every sampling time instances $t=kT$, $k=1,2,\ldots$, as closely as possible.

(ii) The digitally controlled TS fuzzy system is globally asymptotically stable.

Consider the first objective of Problem 1. Comparing (10) with (11), to obtain $x_c(kT+T) = x_d(kT+T)$ under the assumption of $x_c(kT) = x_d(kT)$, it is necessary to determine the digital control gain matrices K_d^i such that following matrix equality constraints are satisfied

$$\Phi_{ij} = G_i + H_i K_d^j, \; i,j = 1,2,\ldots,q \quad (12)$$

Then, the state $x_d(t)$ closely matches the state $x_c(t)$ globally at each sampling time instance, $t=kT, k=1,2,\ldots$, provided that their initial conditions are equivalent, i.e., $x_c(0) = x_d(0) = x_0$.

Remark 1 : Equations (12) may be solved for matrices K_d^i if the dimension of the state vector is not larger than the dimension of the control input vector and H_i, $i=1,2,\cdots,q.$, is nonsingular, which is unusual even if in a LTI system. In case of LTI system setting, to avoid such awkwardness, a variety of techniques for finding the approximate solution to (12) have been developed [2-6,10]. Notice that Joo et al. [2], and Chang et al. [3] adopted one of them in TS fuzzy system setting, which just allows the local state-matching. In addition, it should be emphasized that the equalities (12) are hardly met in general cases of TS fuzzy-model-based control, since each variable K_d^i should satisfy q different matrix equality constraints (12). Besides, it is commonly believed that the stability analysis of the sampled-data TS fuzzy system is difficult to directly examine because of the hybridism of the system state.

In order to resolve these difficulties, we relax Problem 1 and find K_d^i using an alternative suboptimal way-numerical optimization technique. Our key idea is to find K_d^i for which the norm distance between Φ_{ij} and $G_i + H_i K_d^i$ is minimized as small as possible, and to consider the stability condition for the discretized version of the controlled sampled-data TS fuzzy system, which is widely commute in this context [7,8]. Henceforth, Problem 1 can be reformulated as follows :

Problem 2 : Given a well-designed gain matrices for the stabilizing continuous-time TS fuzzy-model-based controller (3), find gain matrices K_d^i, $i=1,\ldots,q.$, for the digital fuzzy-model-based control law (6) such that the following constraints are satisfied :

(i) Minimize gamma subject to $|\Phi_{ij}-G_i-H_iK_d^j|<\gamma$ inthe sense of the induced 2-norm measure, where $i,j=1,2,\ldots,q$.

(ii) The discretized closed-loop system (10) is globally asymptotically stable in the sense of Lyapunov criterion.

Notice that Problem 2 is the constrained convex optimization problem, hence can be effectively solved by formulating in terms of LMIs and using the extremely efficient and powerful numerical algorithms. The main results of this paper are summarized as follows :

Theorem 2 : If there exist symmetric positive definite matrices Q, symmetric positive semi-definite matrix O, matrices F_i and a possibly small positive scalar gamma such that the following generalized eigenvalue problem (GEVP) has solutions

$\min_{Q,O,F_i}\ \gamma$ subject to

$$\begin{bmatrix} -\gamma Q & * \\ \Phi_{ij}Q-G_iQ-H_iF_j & -\gamma I\end{bmatrix}<0 \quad i,j=1,2,\ldots,q. \tag{12}$$

$$\begin{bmatrix} -Q+(q-1)O & * \\ G_iQ+H_iF_i & -Q\end{bmatrix}<0 \quad i=1,2\ldots,q. \tag{13}$$

$$\begin{bmatrix} -Q-O & * \\ \dfrac{G_iQ+H_iF_j+G_jQ+H_jF_i}{2} & -Q\end{bmatrix}<0 \tag{14}$$

$i=1,\ldots,q-1.,\ j=i+1,\ldots,q.$

where $K_i=F_iQ^{-1}$, then, the state $x_d(t)$ of the continuous-time TS fuzzy system (5) controlled via the redesigned digital fuzzy-model-based controller (6) closely match the state $x_c(t)$ of the continuous-time stable TS fuzzy system (4). Furthermore, the discretized sampled-data TS fuzzy system (10) is globally asymptotically stabilizable in the sense of Lyapunov stability criterion, where $*$ denotes the transposed element in symmetric positions.

Proof : Introducing a free matrix variable X, we have

$$\begin{aligned}|\Phi_{ij}-G_i-H_iK_d^j|_2 &< \hat{\gamma} \\ &= \hat{\gamma}\frac{1}{|X^TX|_2}\cdot|X^TX|_2 \\ &= \gamma|X^TX|_2\end{aligned} \tag{15}$$

where $\gamma=\dfrac{\hat{\gamma}}{|X^TX|_2}$ is a positive scalar and X has a full column rank, accordingly X^TX is symmetric and positive definite. Without loss of generality, one can choose P as X^TX, which is reasonable since we know that P is definitely bounded from (13) and (14), and symmetric and positive definite. From the fact of $|\cdot|_2=\sqrt{\lambda_{\max}((\cdot)^T(\cdot))}$, the following inequality holds

$$(\Phi_{ij}-G_i-H_iK_d^j)^T(\Phi_{ij}-G_i-H_iK_d^j)<\gamma^2P$$

Using Schur complement, () can be represented LMIs of the form :

$$\begin{bmatrix} -\gamma P & * \\ \Phi_{ij}-G_i-H_iK_d^j & -\gamma I\end{bmatrix}<0 \tag{16}$$

Further applying Congruence transformation to (16) with $diag[P^{-1}\ I]$, and denoting $F_i=K_d^iP^{-1}$ yields (12). The remaining LMIs (13) and (14) directly follow from the standard Lyapunov stability criterion for the discrete-time TS fuzzy system, and in turn, applying Schur complement and Congruence transformation. This completes the proof.

Remark 2 : It should be distinguished from the *local intelligent digital redesign* in [2] in that the newly proposed intelligent digital redesign approach tries to match the states of the global dynamical systems, not local ones, and incorporates the stability conditions of the discretized closed-loop system with the digitally redesign fuzzy-model-based controller.

4. Intelligent Digital Redesign and Control for the Duffing-like Chaotic Oscillator

To visualize the theoretical analysis and design, an example is included here for illustration. More precisely, the digital control problem of the Duffing-like chaotic oscillator using the new intelligent digital redesign technique proposed in this paper is

presented. Consider the following Duffing-like chaotic oscillator [8] :

$$\ddot{y}(t)-ay(t)+by(t)|y(t)|=\varepsilon(-\zeta\dot{y}(t)+c\sin(\omega t)) \tag{17}$$

where $a=1.1, b=1$, and $c=21$ are some positive constants, $\zeta=3$, and $\varepsilon=0.1$ are small positive constants for chaos to emerge. The trajectory of this system is shown in Fig. 1, which is chaotic and irregular. Now, the analytic TS fuzzy system of (17) is given by

Rule 1 IF $x_1(t)$ is about Γ_1^1
THEN $\dot{x}_c(t)=A_1x_c(t)+B_1u_c(t)$

Rule 2 IF $x_1(t)$ is about Γ_1^2
THEN $\dot{x}_c(t)=A_2x_c(t)+B_2u_c(t)$

where

$$A_1=\begin{bmatrix}0&1&0&0\\a&-\varepsilon\zeta&\varepsilon c&0\\0&0&0&\omega\\0&0&-\omega&0\end{bmatrix}, A_2=\begin{bmatrix}0&1&0&0\\a-bM&-\varepsilon\zeta&\varepsilon c&0\\0&0&0&\omega\\0&0&-\omega&0\end{bmatrix}$$

Since the mathematical equations of the original Duffing-like chaotic oscillator and its TS fuzzy system are same, one can easily expect that their trajectories are identical. For design of a suitable fuzzy-model-based controller, the input matrices are assumed to be $B_1=B_2=[0\ 1\ 1\ 0]^T$

which preserve the controllability of the system. From Theorem 3 in [1], we get the well-designed gain matrices for the continuous-time fuzzy-model-based controller as follows:

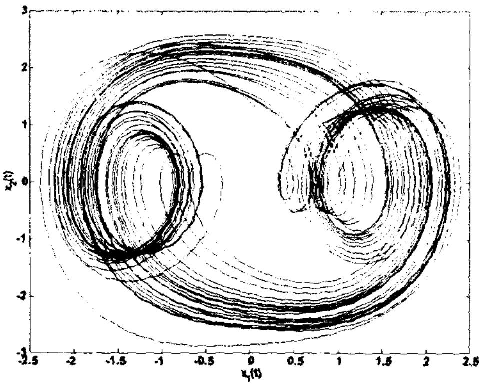

Fig. 1. The trajectory of the uncontrolled Duffing-like chaotic oscillator.

$$K_c^1 = [-9.1263\ \ -2.6634\ \ -1.3199\ \ 0.0400]$$
$$K_c^2 = [-8.3869\ \ -3.5096\ \ -0.7655\ \ -0.3501]$$

Applying Theorem 2 yields the digitally redesigned fuzzy-model-based control gain matrices, for the sampling period $T=0.3$ sec., as

$$K_d^1 = [-4.4147\ \ -2.0323\ \ -1.2822\ \ -0.3181]$$
$$K_d^2 = [-3.9342\ \ -2.2794\ \ -1.0726\ \ -0.4246]$$

Other available intelligent digital redesign method [2] is also simulated for comparison purpose. The initial value is $x_c(0)=x_d(0)=x_0=[1\ 0\ 0\ 1]^T$ and simulation time is 6 sec.. For the qualitative comparison of the performance of the proposed intelligent digital redesign technique with other method, we define the following performance measure [4].

$$P=\sum_{i=1}^{4}\left(\int_0^6 |x_{ci}(t)-x_{di}(t)|dt\right) \qquad (18)$$

The time response of the simulation is shown in Fig. 2. Control input is activated at $t=1.2$ sec. which reports the excellence of the proposed method minutely. It should be strongly stressed that the controlled trajectory by the proposed method closely match that of the original controlled trajectory, whereas the local intelligent digital redesign method yields a poor state-matching. It is because the proposed method provides the global state-matching of the global TS fuzzy system, while the other method only tries to match the states in the local subsystem of the TS fuzzy system. The performance measures of two methods regarding the state-matching concretely validate the superiority of the proposed method.

Another relatively longer sampling period $T=0.6$ sec. is chosen, so as to emphasize the superiority of the proposed method to other method in the angle of the stabilizability and control performance. Figure 3 shows the trajectories of two digitally controlled system. As clearly shown in the Fig. 3, the redesigned digital fuzzy-model-based controller by the proposed method not only drives the trajectories to the

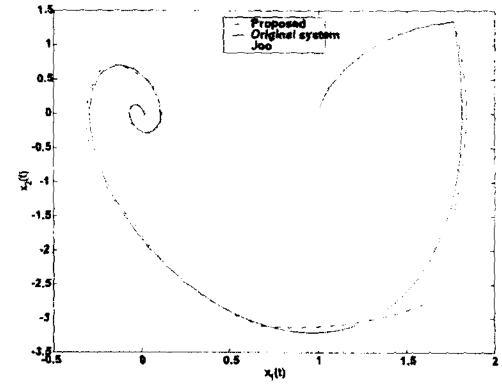

Fig. 2. The comparison of the trajectories of the controlled Duffing-like chaotic oscillator. (sampling period is $T=0.3$ sec.

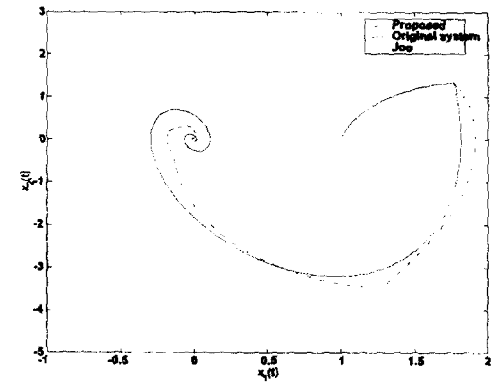

Fig. 3. The comparison of the trajectories of the controlled Duffing-like chaotic oscillator. (sampling period is $T=0.6$ sec.

Table 1. Comparison of the performance P of the proposed method with that of other method in various sampling periods T.

Method	Sampling periods T (second)			
	0.3	0.4	0.6	1.2
Joo et. al[2]	2.427	4.628	12.375	Unstable
Ours	2.079	3.382	6.314	24.187

origin, but also matches the trajectories of the original system much closely. However, the other controller gives the deteriorated state-matching performance. The performance measures of simulations with various sampling periods are tabulated in Table 1. It indicates that the proposed method outperforms that by Joo [2]. Furthermore, it should be stressed that the proposed method always guarantees the stability of the controlled system, while the other may fail to stabilize the system, especially for relatively longer sampling period, which is the another major advantage of the proposed method. This is because the proposed method incorporates the stability criterion in the redesign condition, whereas the other approach does not.

5. Conclusions

In this paper, a novel and reliable intelligent digital redesign methodology has been presented for the sampled-data control of the continuous-time TS fuzzy systems. Unlike other methods, the proposed method utilized an efficient numerical convex optimization algorithm. This powerful and flexible tool allows us to derive the global state-matching condition for the overall TS fuzzy system, which is the major factor that improves the performance of intelligent digital redesign. In addition, the stability condition of the controlled system via the digitally redesigned fuzzy-model-based controller was successfully incorporated in the proposed digital redesign condition. The simulation results indicates the great potential for reliable and safe engineering applications of realistic digital control.

References

[1] K. Tanaka, T. Ikeda, and H. O. Wang, "Fuzzy Regulators and Fuzzy Observers: Relaxed Stability Conditions and LMI-Based Designs," *IEEE Trans. on Fuzzy Systems*, vol. 6, no. 2, pp. 250-265, 1998.

[2] Y. H. Joo, G. Chen, and L. S. Shieh, "Hybrid State-Space Fuzzy Model-Based Controller with Dual-Rate Sampling for Digital Control of Chaotic Systems," *IEEE Trans. on Fuzzy Systems*, vol. 7, pp. 394-408, Aug. 1999.

[3] W. Chang, J. B. Park, Y. H. Joo, and G. Chen, "Design of Sampled-data Fuzzy-model-based Control Systems by Using Intelligent Digital Redesign," *IEEE Trans.* on Circ. and Syst. 1 to appear, 2001.

[4] H. J. Lee, J. B. Park and G. Chen, "Robust Fuzzy Control of Nonlinear Systems with Parametric Uncertainties," *IEEE Trans. on Fuzzy Systems*, vol. 9, no. 2, pp. 369-379, April, 2001.

[5] J. Xu, G. Chen, and L. S. Shieh, "Digital Redesign for Controlling Chaotic Chua's Circuit," *IEEE Trans. on Aero. & Electro.*, vol. 32, no. 8, pp. 1488-99, Oct., 1996.

[6] L. S. Shieh, J. L. Zhang, and J. W. Sunkel, "A New Appoach to Digital Redesign of Continuous-time Controllers," Contr. Theory and Advanced Technology, vol. 8, pp. 37-57, 1992.

[7] D. A. Lawrence, "Analysis and Design of Gain Scheduled Sampled-data Control Systems," Automatica, vol. 37, pp. 1041-1048, 2001.

[8] W. T. Baumann, "Discrete-time Control of Continuous-time Nonlinear Systems," Proc. of Conf. on Infor. Sci. and Syst., pp. 119-124, Baltimore, MD, 1989.

[9] K.-S. Tang, K. F. Man, G.-Q, Zhong, and G. Chen, "Generating Chaos via 저저," *IEEE Trans.* on Circ, and Syst.-1, vol. 48, no. 5, pp. 636-641, May, 2001.

[10] L.S. Shieh, W.M. Wang, M.K. Appu Panicker, "Design of PAM and PWM Digital Controllers for Cascaded Analog Systems," ISA Trans., vol. 37, pp. 201-213, 1998.

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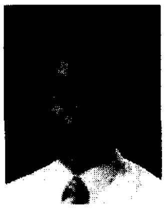

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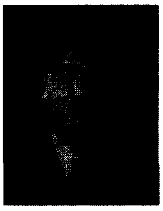

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