퍼지 및 지능시스템학회 논문지 2005, Vol. 15, No. 7, pp. 881-886

Power Series를 이용한 불확실성을 갖는 비선형 시스템의 지능형 디지털 재설계

Intelligent Digital Redesign for Uncertain Nonlinear Systems Using Power Series

성화창*, 박진배*, 고성현**, 주영훈**
Hwa Chang Sung*, Jin Bae Park*, Sung Hyun Go, and Young Hoon Joo**

* 연세대학교 전기전자공학과
** 군산대학교 전자정보공학부

요 약

본 논문은 복합 상태 공간에서의 퍼지 기반 제어기를 이용한 지능형 디지털 재설계의 전 역적 접근 방안에 대해 제안하고자 한다. 이산화를 통한 제어기 설계에 있어서 불확실성이 포함된 실시간 비선형 시스템에 대해 보다 효율적이고 안정적인 접근을 위해 TS 퍼지 모델이 사용되었다. 그리고 전 역적 접근을 위핸 방안으로서 문제를 볼록 최적화 관점으로 변환 후, 에러가 가질 수 있는 놈의 영역을 최소화 하여 상태 접합을 이루고자 하였다. 또한 power series를 사용함으로써 불확실성이 포함된 비선형 시스템을 보다 더 정확하게 분석하였다. 샘플링 기간이 충분히 작다면, 불확실 비선형 시스템의 실시간 시스템으로의 전환이 충분한 이유를 가지게 된다. 전 역적 접근을 통한 디지털로 제어된 시스템은 선형 행렬 부등식 형태로 바꾸어 시스템의 안정성을 보장하고자 하였다. 마지막으로 TS 퍼지 모델로 분석된 혼돈 Lorenz system에 적용함으로써 제안된 방법의 안정성과 효율성을 보장받게 된다.

Abstract

This paper presents intelligent digital redesign method of global approach for hybrid state space fuzzy-model-based controllers. For effectiveness and stabilization of continuous-time uncertain nonlinear systems under discrete-time controller, Takagi-Sugeno(TS) fuzzy model is used to represent the complex system. And global approach design problems viewed as a convex optimization problem that we minimize the error of the norm bounds between nonlinearly interpolated linear operators to be matched. Also, by using the power series, we analyzed nonlinear system's uncertain parts more precisely. When a sampling period is sufficiently small, the conversion of a continuous-time structured uncertain nonlinear system to an equivalent discrete-time system have proper reason. Sufficiently conditions for the global state-matching of the digitally controlled system are formulated in terms of linear matrix inequalities (LMIs). Finally, a TS fuzzy model for the chaotic Lorentz system is used as an example to guarantee the stability and effectiveness of the proposed method.

Key Words : Chaotic Lorentz system, uncertain nonlinear systems, intelligent digital redesign, T-S fuzzy model, power series.

1. Introduction

Many complex dynamical systems, including chaotic systems, comprise uncertain plants. So we have many technical problem to control the whole systems. The uncertainty about the plant arises from unmodelled dynamics, sensor noises, parameter variations, etc. Generally, complex dynamic systems should be described by a continuous-time and/or discrete-time uncertain framework. As advanced digital implements, represented computer and microprocessor, many analog systems are converted to digital systems. For digital simulation, digital control and digital implementation of a continuous-time uncertain linear system, it is necessary to find an equivalent discrete-time uncertain model. A digital implementation of the continuous-time controller is indeed very desirable when the designed continuous-time controller uses some recent and advanced control algorithm. So digital control of continuous-time systems have been more interest.

The efficient approach to design digital controller is called digital redesign, which was first proposed by Kuo. And Joo et la[10] first apply digital redesign technique to complex nonlinear systems, and we call this new approach to intelligent digital redesign. Intelligent digital redesign technique is that complex nonlinear system has analyzed by using Takagi-Sugeno (T-S) fuzzy model

접수일자 : 2005년 10월 21일
완료일자 : 2005년 12월 5일

which combines the fuzzy inference rules with some local linear state-space models for a global representation of the system dynamics. Lee et la[3] proposed new intelligent digital redesign of global approach for the TS fuzzy systems which are represented as a convex optimization problem of the norm distance between nonlinearly interpolated linear operators to be matched, and thus can be cast into LMI framework. But there has unsolved problem, which represented by uncertainty. Although, Chang et la[11] solve the uncertain nonlinear system by using intelligent digital redesign, but this method is not global approach. Because of uncertain exponential parts, it is too difficult to apply intelligent digital redesign technique which includes uncertain parts.

In this brief, we further develop a systematic method for the intelligent digital redesign of a hybrid state space TS fuzzy-model-based controller for sampled-data control of continuous- time complex dynamical systems by using Power series. Developing the uncertain nonlinear systems, we face the problem of exponential terms which has uncertain part. Genetic Power series are able to convert the exponential terms to easily forms, so the complex problems are solved.

This paper is organized as follows. Section 2 introduces a brief overview of a continuous time TS fuzzy model and its discretized form, sampled-data parts. In Section 3, we proposed the method of intelligent digital redesign of global approach so that we should solve the uncertain nonlinear parts. Then, in Section 4, the chaotic Lorenz system is used as a example for the proposed method. Funally, this paper concludes with Section 5.

2. Preliminaries

Consider a class of continuous-time nonlinear systems that contain parametric uncertainties, in the following form:

$$x(t) = f(x(t)) + \Delta f(x(t)) + (g(x(t)) + \Delta g(x(t)))u(t) \tag{1}$$

where $x(t) \in R^n$ is the state vector, $u(t) \in R^m$ is the control input vector, $f(x(t)) \in R^n$ and $g(x(t)) \in R^n$ are nonlinear vector functions, and $\Delta f(x(t))$, $\Delta g(x(t))$ are uncertain vector functions. This nonlinear system can be represented by a TS fuzzy model, also with parametric uncertainties. The TS fuzzy model which is a convenient and powerful tool to handle such nonlinear system is a combination of the fuzzy inference rules and some local linear uncertain systems. The ith rule of T-S fuzzy system is formulated in the following form:

IF – THEN Form :

R^i : *IF* $x_1(t)$ *is about* Γ_1^i *and ... and* $x_n(t)$ *is about* Γ_n^i

THEN $\dot{x}_c(t) = (A_i + \Delta A_i)x_c(t) + (B_i + \Delta B_i)u_c(t)$,

where $i = 1, 2, ..., q$,

Defuzzified Form :

$$\dot{x}(t) = \sum_{i=1}^{q} \mu_i(x(t))((A_i + \Delta A_i)x(t) + (B_i + \Delta B_i)u(t)),$$

where

$$\omega_i(x(t)) = \prod_{j=1}^{n} \Gamma^i{}_j(x_j(t)), \qquad \mu_i(x(t)) = \frac{\omega_i(x(t))}{\sum_{i=1}^{q}\omega_i(x(t))}, \tag{2}$$

where $\Gamma_j^i(x_j(t))$ is the grade of membership of $x_j(t)$ in Γ_j^i. Some basic properties of $\omega_i(t)$ are:

$$\omega_i(x(t)) \geq 0, \qquad \sum_{i=1}^{q}\omega_i(x(t)) > 0, \qquad i = 1, 2, \dots, q. \tag{3}$$

It is clear that

$$\mu_i(x(t)) \geq 0, \qquad \sum_{i=1}^{q}\mu_i(x(t)) = 1, \qquad i = 1, 2, \dots, q. \tag{4}$$

We use the following fuzzy-model-based controller structure which is represented by either of the following forms:

IF – THEN Form :

IF $z_1(t)$ is F_1^i and $\cdots$ *and* $z_n(t)$ is F_n^i

THEN $u_c(t) = -K_{ci}x_c(t)$, $\qquad i = 1, 2, ..., q$

Defuzzified Form :

$$u_c(t) = -K_c(\mu)x_c(t) \tag{5}$$

where K_{ci} are a feedback gain in the ith subspace, $K_c(\mu) = \sum_{i=1}^{q}\mu_i K_{ci}$. The resulting continuous-time closed-loop TS fuzzy system becomes

$$\dot{x}_c(t) = \sum_{i=1}^{q}\sum_{j=1}^{q}\mu_i(z(t))\mu_j(z(t))\{(A_i + \Delta A_i) + (B_i + \Delta B_i)K_{cj}\}x_c(t). \tag{6}$$

Next we discuss the discretization of the continuous-time T-S fuzzy system. Consider a class of T-S fuzzy system governed by

$$\dot{x}_d(t) = \sum_{i=1}^{q}\mu_i(z(t))\{(A_i + \Delta A_i)x_d(t) + (B_i + \Delta B_i)u_d(t)\}. \tag{7}$$

where $u_d(t) = u_d(kT)$ is the piecewise- constant control input vector to be determined in the time interval $[kT, kT+T)$, where $T > 0$ is a sampling period. For the digital control of the continuous-time TS fuzzy system, the digital fuzzy-model-based controller is employed. Let the fuzzy rule of the digital control law for the system (7) take the following form:

R^i : IF $z_1(kT)$ is about Γ_1^i and ... and $z_n(kT)$ is about Γ_1^i

THEN $u_d(t) = K_d{}^i x_d(kT)$ (8)

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

$$u_d(t) = \sum_{i=1}^{q}\mu_i(z(kT))K_d{}^i x_d(kT) \tag{9}$$

for $t \in [kT, kT+T)$.

The digital redesign problem is to find digital controller gains from the analog gains by using close matching theorem. Thus it is necessary to convert the TS fuzzy system into discrete-time version for derivation of the state-matching condition. But the defuzzifed output of the TS fuzzy system, which is above mentioned, is not LTI but implicitly time-varing [2]. Also, it is further desired to maintain the polytopic structure if the discretized TS fuzzy system for the construction of the digital fuzzy-model-based controller. These reasons prevent to discretize the closed-loop TS fuzzy system, so we need appropriate assumption.

Assumption 1[3]: Assume that the firing strength of the ith rule, $\mu_i(z(t))$ is approximated by its value at time kT, that is

$$\mu_i(z(t)) \approx \mu_i(z(kT))$$

for $t \in [kT, kT+T)$. Consequently, the nonlinear matrices $\sum_{i=1}^{q} \mu_i(z(t))A_i$ and $\sum_{i=1}^{q} \mu_i(z(t))B_i$, respectively, over any interval $[kT, kT+T)$. If a sufficiently small sampling period T is chosen, Assumption 1 is reasonable.

Thanks to Assumption 1, we efficiently derive the discretization of TS fuzzy system (7),

$$x_d(kT+T) = \sum_{i=1}^{q}\sum_{j=1}^{q} \mu_i(z(kT))\mu_j(z(kT))(\hat{G} + \hat{H}_i k_{d_j})x_d(kT) \tag{10}$$

where

$$\hat{G} = \exp(A_i + \Delta A)T,$$
$$\hat{H} = \int_0^T e^{(A+\Delta A)\tau}(B+\Delta B)d\tau = (\hat{G} - I_n)(A_0 + \Delta A)^{-1}(B + \Delta B)$$

The pointwise dynamical behavior of the continuous-time closed-loop TS fuzzy system (6) cam also be approximately discretized as

$$x_c(KT+T) = \sum_{i=1}^{q}\sum_{j=1}^{q} \mu_i(z(t))\mu_j(z(t))\Phi_{ij}x_c(kT) \tag{11}$$

where $\Phi_{ij} = \exp\{((A_i + \Delta A) + (B_i + \Delta B)K_c^{\ j})T\}$

And $\Delta A_i, \Delta B_i$ are the unknown and possibly time-varing matrices representing the uncertainties of the system. Since the plant rules have time-varying uncertain matrices, it is not easy to design the controller gain matrices. In order to find these gain matrices, K_i, we should remove the uncertain matrices under some reasonable assumptions.

Assumption 2[11]: The uncertainty matrices ΔA_i and ΔB_i are norm bounded and have the following structures:

$$[\Delta A_i \quad \Delta B_i] = D_i F_i(t)[E_{i1} \quad E_{i2}]$$

where D_i, E_{i1}, and E_{i2} are predetermined constant real matrices of appropriate dimensions, which represent the structures of the system uncertainties, and $F_i(t) \in R^{i \times j}$ is an unknown matrix function with Lebesque-measurable elements and satisfies

$$F_i^{\mathrm{T}}(t)F_i(t) \le I.$$

In addition, we also note that the uncertain matrices ΔA_i and ΔB_i can be represented in an interval form ΔA_i^I and ΔB_i^I, where $\Delta A_i^I = [\Delta \underline{A}_i, \Delta \overline{A}_i]$ and $\Delta B_i^I = [\Delta \underline{B}_i, \Delta \overline{B}_i]$. The interval arithmetic preliminaries can be found in [12], [4].

3. Main Result

In this section, we develop the continuous-time fuzzy-model-based controller design algorithm and derive an intelligent digital redesign procedure by global state matching in a hybrid state-space setting. Our goal is to develop an intelligent digital redesign technique for TS fuzzy systems so that the global dynamical behavior of (10) with the digitally redesigned fuzzy-model-based controller may retain that of the closed-loop TS fuzzy system with the existing analog fuzzy-model-based controller, andthe stability of the digitally controlled TS fuzzy system is secured. To achieve this goal, we must contain two condition, the one is 'stability' and the other is ' gain matching '.

Stability problem are linked the discretization of digitally redesigned TS fuzzy model. By using the method of the sense of Lyapunov criterion, the digitally controlled T-S fuzzy system (10) are guaranteed globally asymptotically stable. The concrete problems are following:

Problem 1-1 (Stability problem[3]): If there exist symmetric positive definite matrix Q, symmetric positive-semidefinite matrix O, constant matrices F_i, following 2 equations are proper reasons:

$$\begin{bmatrix} -Q + (q-1)O & * \\ \hat{G}_i Q + \hat{H}_i U_i & -Q \end{bmatrix} < 0, \qquad i, j = 1, 2, \ldots, q. \tag{12}$$

$$\begin{bmatrix} -Q - O & * \\ \dfrac{\hat{G}_i Q + \hat{H}_i U_j + \hat{G}_j Q + \hat{H}_j U_i}{2} & -Q \end{bmatrix} < 0, \quad i = 1, \ldots, q-1, \; j = i+1, \ldots, q \tag{13}$$

where $\hat{G} = \exp(A + \Delta A)T$,

$$\hat{H} = \int_0^T e^{(A+\Delta A)\tau}(B+\Delta B)d\tau = (\hat{G} - I_n)(A_0 + \Delta A)^{-1}(B_0 + \Delta B)$$

And the other is to design an equivalent digital fuzzy-model-based controller from the continuous-time counterpart, so we take a global digital redesign approach.

Problem 2(γ- Suboptimal Global Intelligent Digital Redesign Problem) [3] : Given a well-constructed gain matrices K_{ci} for the stabilizing analog fuzzy-model-based controller (11), find gain matrices .. for the digital fuzzy-model-based control law (10) such that the following constraints are satified.

Minimize γ subject to $\|\Phi_{ij} - G_i - H_i K_d^j\| < \gamma$, $i, j = 1, 2, \dots, q$, in the sense of the induced 2-norm distance measure.

$$\begin{bmatrix} -\gamma Q & * \\ \Phi_{ij}Q - \hat{G}Q - \hat{H}U_j & -\gamma I \end{bmatrix} < 0 \quad (14)$$

where $\Phi_{ij} = \exp\{((A_i + \Delta A) + (B_i + \Delta B)K_c^j)T\}$.

Notice that intelligent digital redesign problems become a convex optimization problem, so those are numerically solved by formulation in terms of LMIs, Theorem 1 and Theorem 2. But there are critical problems in these equations. The exponential uncertainty terms G_i, H_i, and Φ_{ij} are too complicated to solve, so we need another theorem, the solutions of both exponential and uncertainty. The distinct theorems are followed:

Theorem 1: The exponential uncertainty terms which included the equation (14) are solved by

$$\hat{G}_i \approx I_n + (A_i + \Delta A_i)T \quad (15)$$

$$\hat{H}_i \approx (B_i + \Delta B_i)T \quad (16)$$

$$\Phi_{ij} \approx I_n + (A_i + \Delta A_i)T + (B_i + \Delta B_i)K_c^j T \quad (17)$$

Proof) The general power series are these form:

$$\exp(A_i T) = I_n + A_i T + A_i^2 \frac{T^2}{2} + \cdots \quad (18)$$

As the above Power series, the equation (15) and (17) is easily defined, but the control of second and the bigger terms are very difficult. In this brief, we assume that these terms are approximate 0, when sampling time should be sufficiently small. And equation (16) is that,

$$\begin{aligned} \hat{H}_i &= (\hat{G}_i - I_n)(A_i + \Delta A_i)^{-1}(B_i + \Delta B_i) \\ &\approx (I_n + (A_i + \Delta A_i)T - I_n)(A_i + \Delta A_i)^{-1}(B_i + \Delta B_i) \\ &\approx (A_i + \Delta A_i)(A_i + \Delta A_i)^{-1}(B_i + \Delta B_i)T \\ &= (B_i + \Delta B_i)T \end{aligned}$$

The exponential terms are easily defined by Power series, but the uncertainty term ΔA_i, ΔB_i are still discussed. Following Lemma can help us to solve these difficulties.

Lemma 1 [2] : Given constant symmetric matrices $N, O,$ and L of appropriate dimensions, the following two inequalities are equivalent:

(a) $O > 0$, $N + L^T O L < 0$,

(b) $\begin{bmatrix} N & L^T \\ L & -O^{-1} \end{bmatrix} < 0$ or $\begin{bmatrix} -O^{-1} & L \\ L^T & O \end{bmatrix} < 0.$

Lemma 2 [2] : Given constant matrices D and E, and a symmetric constant matrix S of appropriate dimensions, the following inequality holds:

$$S + DFE + E^T F^T D^T < 0,$$

where F satisfies $F^T F \le I$, if and only if for some $\varepsilon > 0$,

$$S + [\varepsilon^{-1}E^T \quad \varepsilon D]\begin{bmatrix} \varepsilon^{-1}E \\ \varepsilon D^T \end{bmatrix} < 0.$$

Lemma 1 is one of the most basic and popular tool in converting nonlinear matrix inequalities to LMI. And by introducing Lemma 2, we deal with the uncertain nonlinear system more and easily. By applying these Lemma, we have following Theorem.

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

$$\underset{Q,\,O,\,F_i}{\text{Minimize}} \quad \gamma \quad \text{subject to}$$

$$\begin{bmatrix} -Q + (q-1)O & * & * & * \\ Q + A_i QT + B_i F_j T & -Q & * & * \\ E_{1i}QT + E_{2i}F_j T & 0 & -\varepsilon_{ii} I & * \\ 0 & 2 * D_i^T & 0 & -\varepsilon_{ii} I \end{bmatrix} < 0 \quad (19)$$

$$\begin{bmatrix} -Q - O & * & * & * \\ Q + \frac{1}{2}(A_i Q + B_i F_j + A_j Q + B_j F_i)T & -Q & * & * \\ \frac{1}{2}(E_{1i}Q + E_{2i}F_j + E_{1j}QT + E_{2j}F_i)T & 0 & -\varepsilon_{ii} I & * \\ 0 & D_i^T + Dj^T & 0 & -\varepsilon_{ii} I \end{bmatrix} < 0 \quad (20)$$

$$\begin{bmatrix} -\gamma Q & * & * & * \\ B_i K_c^j QT - B_i F_j T & -\gamma I & * & * \\ E_{2i} T K_c^j - E_{2i} T F_j & 0 & -\varepsilon_{ii} I & * \\ 0 & 2 * D_i^T & 0 & -\varepsilon_{ii} I \end{bmatrix} < 0 \quad (21)$$

The LMI form, (19) and (20) are solution of stability problem and the equation of (21) is the state matching terms.

4. Computer Simulation

In this section, we discuss the exact TS fuzzy modeling of the chaotic Lorenz system and prove the effectiveness and stabilization of the proposed intelligent digital redesign method. The dynamics of the controlled chaotic Lorenz system is described by

$$\frac{d}{dt}\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} -\sigma x + \sigma y \\ \gamma x - y - xz \\ xy - bz \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad (22)$$

where $\sigma, \gamma, b > 0$ are parameters (σ is the Prandtl number, γ is the Rayleigh number, and b is a scaling constant). We further assume that system parameters σ, γ and b have additive uncertainites, i.e., $\sigma = \sigma_0 + \Delta\sigma$, $\gamma = \gamma_0 + \Delta\gamma$, $b = b_0 + \Delta b$ and the initial condition parameter is tha $(\sigma_0, \gamma_0, b_0) = (10, 28, (8/3))$, where the uncertain parameters are all bounded within 30% of their nominal values.

The corresponding TS fuzzy model of the system in is expressed as follows [5]:

$$\begin{aligned} &IF\ x\ is\ F_1^i, \\ &THEN\ \dot{x}_c(t) = (A_{0i} + \Delta A_i)\, x_c(t) + Bu_c(t), \quad i = 1, 2 \end{aligned} \tag{23}$$

where $x_c = [\, x\ y\ z]^T$

$$A_{01} = \begin{bmatrix} -\sigma_0 & \sigma_0 & 0 \\ \gamma_0 & -1 & -M_1 \\ 0 & M_1 & -b_0 \end{bmatrix}, \quad A_{02} = \begin{bmatrix} -\sigma_0 & \sigma_0 & 0 \\ \gamma_0 & -1 & -M_2 \\ 0 & M_2 & -b_0 \end{bmatrix}$$

and $\Delta A_i = D_i F_i E_{i1}$ is given by

$$D_1 = D_2 = \begin{bmatrix} -0.3 & 0 & 0 \\ 0 & 0.3 & 0 \\ 0 & 0 & 0.3 \end{bmatrix}$$

$$E_{11} = E_{21} = \begin{bmatrix} \sigma_0 & -\sigma_0 & 0 \\ \gamma_0 & 0 & 0 \\ 0 & 0 & b_0 \end{bmatrix}$$

or

$$\Delta A_i \in \Delta A_i' = \begin{bmatrix} \pm 0.3 & \pm 0.3 & 0 \\ \pm 8.4 & 0 & 0 \\ 0 & 0 & \pm 0.8 \end{bmatrix}, \quad i = 1, 2.$$

The membership functions are

$$F_1^1 = \frac{-x + M_2}{M_2 - M_1}, \quad F_1^2 = \frac{x - M_1}{M_2 - M_1} \tag{24}$$

and $(M_1, M_2) = (-20, 30)$

For digital simulation of the chaotic Lorenz systems, we first gather the gain of digital system. In Theorem 2, we change the problem of state matching and stability to LMI framework, so we approach the solution of Lorenz model more easily. The digital gain are following.

표 1. 디지털 이득
Table 1. Digital Gain

F{1}	7.2351	16.5052	0.2199
F{2}	7.2333	16.5047	-0.1911

For proving the effectiveness and stability of the proposed method, we need the comparison of two systems. The results are follows.

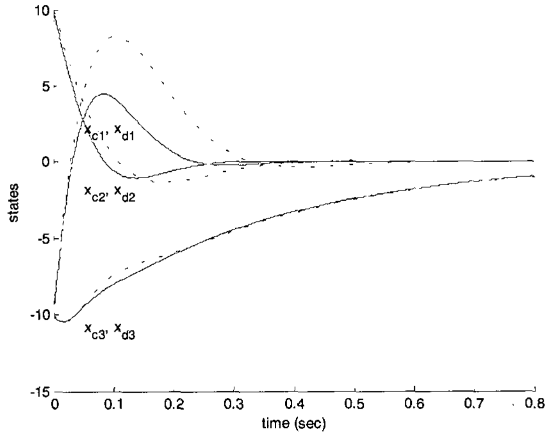

Fig. 1. States of the controlled Lorenz system with T=0.01(Dotted line: continuous-time system, Solid line: digital system)

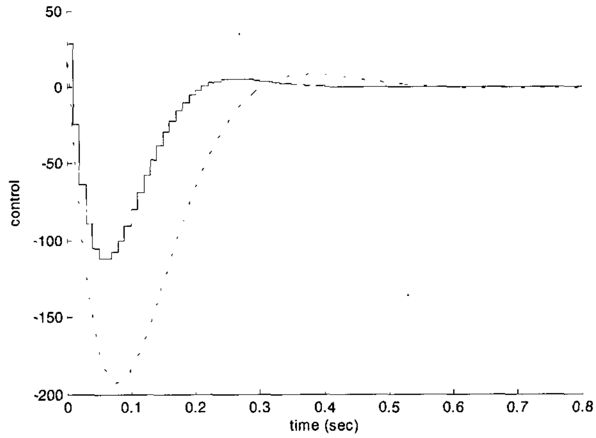

Fig. 2. Control input with T=0.01(Dotted line: continuous-time system, Solid line: digital system)

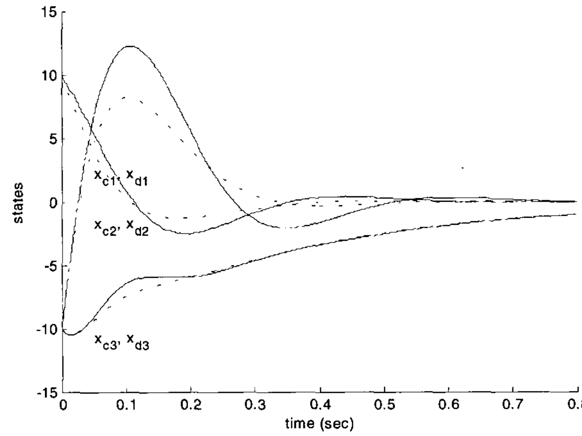

Fig. 3. States of the controlled Lorenz system with T=0.02 (Dotted line: continuous-time system, Solid line: digital system)

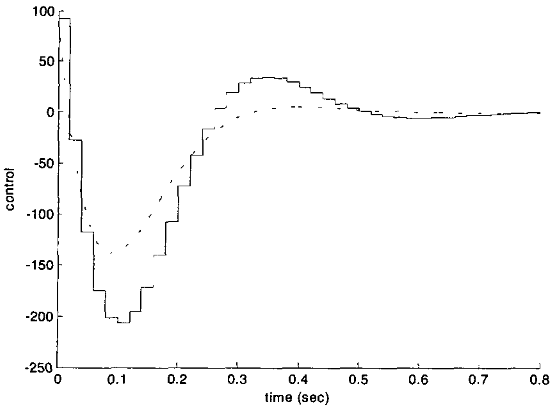

그림 4. T=0.02 일 때, 제어 입력

Fig. 4. Control input with T=0.02(Dotted line: continuous-time system, Solid line: digital system)

5. Conclusion

In this paper, we represent intelligent digital redesign method of global approach for uncertain nonlinear which analyzed by hybrid state space fuzzy-model-based controllers. For effectiveness and stabilization of continuous-time uncertain nonlinear systems under discrete-time controller, we use TS fuzzy model. Thank to these fuzzy model, we are easily construct the solution of nonlinear system. Also, by applying Taylor series to whole system, the uncertainty terms are easily defined. Finally, for LMI framework, we gather the gain of digital controller. The effectiveness and stability of proposed systems are guaranteed by applying the develop method to Chaotic Lorenz system.

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저 자 소 개

성화창(Hwa Chang Sung)

2005 : 연세대학교 전기전자공학과 졸업.

2005~현재 : 연세대학교 대학원 전기전자 공학과 석사과정

Phone : 02-2123-2773

Fax : 02-362-4539

E-mail : casfirspear@control.yonsei.ac.kr

박진배(Jin Bae Park)

제 15권 5호(2005년 10월호) 참조

고성현(Sung Hyun Go)

1998년 : 군산대학교 전파공학과 졸업

2000년 : 군산대학교 전파공학과 석사

2004년 : 군산대학교 전자정보공학부 박사 수료

2005년 3.2~현재 : 군산대학교 전자정보 공학부 겸임교수

1997. 11~현재 : 이지시스템(주) 대표이사

관심분야 : 멀티미디어 시스템, 전파통신, 초고속통신망, 유비쿼터스, 임베디드 시스템.

주영훈(Young Hoon Joo)

제 15권 5호(2005년 10월호) 참조