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Optimal Intelligent Digital Redesign for a Class of Fuzzy-Model-Based Controllers

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Abstract

In this paper, we develop an optimal intelligent digital redesign method for a class of fuzzy-model-based controllers, effective for stabilization of continuous-time complex nonlinear systems. Takagi-Sugeno (TS) fuzzy model is used to extend the results of the classical digital redesign technique to complex nonlinear systems. Unlike the conventional intelligent digital redesign technique reported in the literature, the proposed method utilized the recently developed LMI optimization technique to obtain a digitally redesigned fuzzy-model-based controller. Precisely speaking, the intelligent digital redesign problem is converted to an equivalent optimization problem, and the LMI optimization method is used to find the digitally redesigned fuzzy-model-based controller. A numerical example is provided to evaluate the feasibility of the proposed approach.

Key Words : Fuzzy-model-based controller, intelligent digital redesign, linear matrix inequality

I. Introduction and Problem Formulation

An intelligent digital redesign [4] was developed for the digital control of nonlinear systems by converting an continuous-time fuzzy-model-based controller into an equivalent digital one, whose main idea is to derive local digital control rules by the state-matching between the local rules of the continuous-time controlled system and those of the digitally controlled counterpart. In [4], one of the classical digital redesign methods, especially developed for linear systems [1,2,5,6], was adopted and extended to nonlinear systems by using TS fuzzy-model-based control method.

The main idea of the intelligent digital redesign method presented in their work is to digitally redesign each continuous-time fuzzy-model-based control rule so as to closely match the states of the closed-loop system formed by each control rule and plant rule. That is, the ith digital fuzzy control rule for the fuzzy-model-based controller is determined by applying the conventional digital redesign technique to the ith closed-loop system which is composed of the ith rule in the closed-loop TS fuzzy model and the fuzzy-model-based controller. Figure 1 shows the concept of the intelligent digital redesign method.

In this paper, a new technique for the intelligent digital redesign is proposed for optimal discretization of continuous-time fuzzy-model-based controllers while taking into account the closed-loop performance with LMI-based approach.

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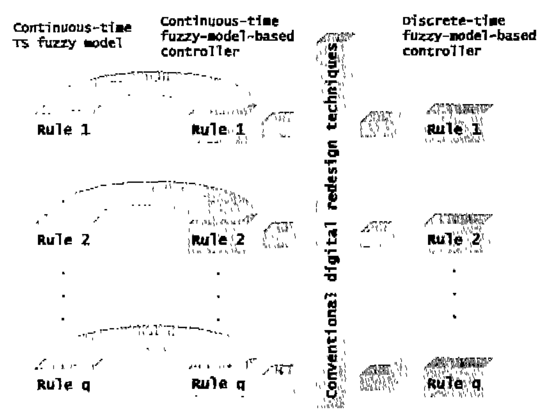

Fig. 1 Local intelligent digital redesign

Consider a continuous-time complex, multi-input and multi-output (MIMO) nonlinear system described by the following TS fuzzy model

(Σ_c):

IF-THEN form:

IF $z_1(t)$ is F_1^i and ... and $z_n(t)$ is F_n^i,

$$\text{THEN} \quad \dot{x}_c(t) = A_i x_c(t) + B_i u_c(t) \qquad i = 1, 2, \cdots, q \tag{1}$$

Dynamic form:

$$\dot{x}_c(t) = A(\mu(z(t)))x_c(t) + B(\mu(z(t)))u_c(t) \tag{2}$$

where F_j^i $(j = 1, 2, \cdots, n)$ is the fuzzy set of the jth premise variable, q is the number of fuzzy rules, $A_i \in R^{n\times n}$, $B_i \in R^{n\times m}$, $z_1(t), \cdots, z_n(t)$ are the premise variables and

$$z(t) = (z_1(t), z_2(t), \cdots, z_n(t))$$

$$A(\mu(z(t))) = \sum_{i=1}^{q} \mu_i(z(t)) A_i,$$
$$B(\mu(z(t))) = \sum_{i=1}^{q} \mu_i(z(t)) B_i$$
$$\mu(z(t)) = (\mu_1(z(t)), \mu_2(z(t)), \cdots, \mu_n(z(t)))$$
$$\mu_i(z(t)) = \frac{\omega_i(z(t))}{\sum_{i=1}^{q} \omega_i(z(t))}, \ \omega_i(z(t)) = \prod_{j=1}^{n} F_j^i(z_j(t))$$

and $F_j^i(z_j(t))$ is the grade of membership of $z_j(t)$ in F_j^i, with the degree of fulfillment of fuzzy rules given by

$$\mu_{i(z(t))} \geq 0, \ \sum_{i=1}^{q} \mu_i(z(t)) = 1 \quad (i = 1, 2, \cdots, q), \forall t$$

Let the state-feedback fuzzy-model-based control law (K_c) be

IF-THEN form:

IF $z_1(t)$ is F_1^i and ... and $z_n(t)$ is F_n^i,

$$\text{THEN } u_c(t) = -K_c^i x_c(t), \quad i = 1, 2, \cdots, q \tag{3}$$

Dynamic form:

$$u_c(t) = -K_c(\mu(z(t))) x_c(t) \tag{4}$$

where K_c^i is the feedback gain in the ith subspace and

$$K_c(\mu(z(t))) = \sum_{i=1}^{q} \mu_i(z(t)) K_c^i$$

The resulting closed-loop system becomes

$$\dot{x}_c(t) = (A(\mu(z(t))) - B(\mu(z(t))) K_c(\mu(z(t))) x_c(t) \tag{5}$$

Let the state equation of a continuous-time system which contains the same system matrices A_i and input matrices B_i of the system (1), with a different input, be represented by

(Σ_d):

$$\dot{x}_d(t) = A(\mu(z(t))) x_d(t) + B(\mu(z(t))) u_d(t) \tag{6}$$

where $u_d(t)$ is an $m \times 1$ piecewise-constant input function

$$u_d(t) = u_d(kT), \qquad \text{for } kT \leq t < (k+1)T \tag{7}$$

and T is the sampling period.
Let the digital control law (K_d) for the system in (6) be

IF-THEN form:

IF $z_1(t)$ is F_1^i and ... and $z_n(t)$ is F_n^i,

$$\text{THEN } \ u_d(kT) = -K_d^i x_d(kT), \quad i = 1, 2, \cdots, q \tag{8}$$

Dynamic form:

$$u_d(t) = -K_d(\mu(z(kT))) x_d(kT) \tag{9}$$

where K_d^i is the feedback gain in the ith subspace and

$$K_d(\mu(z(kT))) = \sum_{i=1}^{q} \mu_i(z(kT)) K_d^i$$

A zero-order hold is used in (9). The resulting closed-loop system becomes

$$\begin{aligned} \dot{x}_d(t) = A(\mu(z(t))) x_d(t) - B(\mu(z(t))) \\ K_d(\mu(zKT))) x_d(kT) \end{aligned} \tag{10}$$

The digital redesign problem can be stated as follows:
Problem 1: (Intelligent digital redesign) The intelligent digital redesign problem is to find the discrete-time fuzzy-model-based controller K_d in (8) or (9) from the continuous-time fuzzy-model-based control law K_c in (3) or (4) so that the states of the sampled-data system in (10) approximately match those of the analogously controlled system in (5) for $x_c(0) = x_d(0)$.
Alternatively, in the sense of optimality, Problem 1 can be rewritten as follows:
Problem 2: (Optimal intelligent digital redesign) Given continuous-time TS fuzzy model Σ_c, continuous-time fuzzy-model-based controller K_c, and sampling period T, design discrete-time fuzzy-model-based controller K_d to minimize the cost function defined by

$$J = \sum_{k=0}^{\infty} J(kT)$$

where

$$J(kT) = \frac{1}{2}(x_c(kT) - x_d(kT))^T Q(x_c(kT) - x_d(kT))$$

II. Optimal intelligent digital redesign

In this section, we develop an optimal state- matching intelligent digital redesign method by using LMI-based approach. The intelligent digital redesign is a procedure that converts a continuous-time fuzzy-model-based controller into an equivalent discrete-time fuzzy-model-based controller.

2.1 Digital modeling of sampled-data TS fuzzy models

The exact solution of the sampled-data TS fuzzy model Σ_d at $t = kT + T$, where $T > 0$ is the sampling period, is given by

$$x_d(kT+T) = \tilde{G} x_d(kT) + \tilde{H} u_d(kT), \quad kT \leq t < kT + T \tag{11}$$

where

$$\tilde{G} = \Phi(\mu(z(kT+T)), \mu(z(kT)))$$
$$\tilde{H} = \int_{kT}^{kT+T} \Phi(\mu(z(kT+T)), \mu(z(\tau))) B(\tau) d\tau$$

$\Phi(\mu(z(kT+T)), \ \mu(z(kT))) = \Psi(\mu(z(kT+T))) \Psi(\mu(z(kT)))$ is the state transition matrix of the continuous-time TS

fuzzy model, and Ψ is the fundamental matrix of $\dot{x}_d = A(\mu(z(t)))x_d$ which is nonsingular for all t.
The exact evaluation of the state transition matrix $\Phi(\cdot, \cdot)$ is very difficult, if not impossible, since the TS fuzzy model is actually a nonlinear or, at least, linear parameter varying (LPV) system. One may try to get the state transition matrix by using a power series expansion for $\Phi(\cdot, \cdot)$, which is called the Peano-Baker formular [7]. This method requires that $A(\mu)$ and $\int_{kT}^{kT+T} A(\mu)d\tau$ commute, which does not hold in many cases [7-8]. To resolve this problem we select a set of discrete-time points, kT, with the following assumption:
Assumption 1: The sampling period T is sufficiently small so that during any interval $[kT\ kT+T]$ the degree of fulfillment of the ith rule $\mu_i(t)$ can be approximated by $\mu_i(kT)$. Consequently, $A(\mu(z(t)))$, $B(\mu(z(t)))$, and $K_c(\mu(z(t)))$ are approximated by $A(\mu(z(kT)))$, $B(\mu(z(kT)))$, and $K_c(\mu(z(kT)))$ during any interval $[kT\ kT+T]$.
With Assumption 1, in the time interval $kT \le t < kT+T$, $\tilde{G}$ and $\tilde{H}$ have the following representations:

$$\begin{aligned}\tilde{G}(kT) &= \exp(A(kT)T)\\ \tilde{H}(kT) &= \int_{kT}^{kT+T} \exp(A(kT)(kT+T-\tau))B(kT)d\tau\\ &= [\tilde{G}(kT)-I]A(kT)^{-1}B(kT)\end{aligned} \tag{12}$$

In order to obtain a feasible discrete-time TS fuzzy model, nonlinear matrices $\tilde{G}(kT)$ and $\tilde{H}(kT)$ are approximated as follows:

$$\begin{aligned}\tilde{G}(kT) &= \exp\Big(\sum_{i=1}^{q}\mu_i(z(kT))A_iT\Big)\\ &= I+\sum_{i=1}^{q}\mu_i(z(kT))A_iT+O(T^2)\\ &\cong \sum_{i=1}^{q}\mu_i(z(kT))(I+A_iT)\\ &\cong \sum_{i=1}^{q}\mu_i(z(kT))\exp(A_iT)\\ &= \sum_{i=1}^{q}\mu_i(z(kT))G_i\end{aligned} \tag{13}$$

and

$$\begin{aligned}\tilde{H}(kT) &= [G(kT)-I]A(kT)^{-1}B(kT)\\ &= [A(kT)T+O(T^2)]A(kT)^{-1}B(kT)\\ &\cong B(kT)T = \sum_{i=1}^{q}\mu_i(z(kT))B_iT\\ &\cong \sum_{i=1}^{q}\mu_i(z(kT))[\exp(A_iT)-I](A_i)^{-1}B_i\\ &= \sum_{i=1}^{q}\mu_i(z(kT))H_i\end{aligned} \tag{14}$$

where

$$G_i = \exp(A_iT), \quad H_i = [G_i - I]^{-1}(A_i)^{-1}B_i$$

Substituting (13) and (14) into (11) yields

$$x_d(kT+T) \cong Gx_d(kT) + Hu_d(kT), \quad \text{for } kT \le t < kT+T \tag{15}$$

where

$$G = \sum_{i=1}^{q}\mu_i(z(kT))G_i, \quad G_i = \exp(A_iT)$$
$$H = \sum_{i=1}^{q}\mu_i(z(kT))H_i, \quad H_i = [G_i - I]^{-1}(A_i^{-1})B_i$$

The closed-loop dynamics is

$$x_d(kT+T) \cong (G(\mu(z(kT))) - H(\mu(z(kT)))K_d(\mu(z(kT))))x_d(kT) \tag{16}$$

2.2 Digital modeling of continuous-time TS fuzzy models

In this subsection, we will present the digital modeling of the continuous-time TS fuzzy model. Before the discussion, let us introduce the following two lemmas which will be essential for our discussion.
Lemma 1: For the sufficiently small sampling period T, the digital model of the closed-loop system (5) is denoted by

$$x_c(kT+T) = \sum_{i=1}^{q}\sum_{j=1}^{q}\mu_i\mu_j\Phi_c^{ij}(\mu(z(kT+T)), \mu(z(kT)))x_c(kT) \tag{17}$$

where Φ_c^{ij} is the state transition matrix of

$$A_c^{ij} = A_i - B_iK_c^j.$$

Proof: The proof can be directly inferred from the results of the previous section. Q. E. D.
Lemma 2: For the sufficiently small sampling period T, the state transition matrix Φ_c of the closed- loop linear system

$$\dot{x}_c = (A-BK)x_c \tag{18}$$

is approximated by

$$\Phi_c \cong \Big(I_n + \frac{1}{2}HK_c\Big)^{-1}\Big(G - \frac{1}{2}HK_c\Big) \tag{19}$$

Proof: The state transition matrix of (18) is given by

$$\Phi_c = \exp((A-BK_c)T)$$

and the digital model is

$$x_c(kT+T) = \Phi_c x_c(kT) \tag{20}$$

From [1], for the sufficiently small sampling period T, the digital model of the analogously controlled system in (18) is also approximated by

$$x_c(kT+T) \cong \Big(I_n + \frac{1}{2}HK_c\Big)^{-1}\Big(G - \frac{1}{2}HK_c\Big)x_c(kT) \tag{21}$$

From (20) and (21), we can conclude that

$$\Phi_c \cong \left(I_n+\frac{1}{2}HK_c\right)^{-1}\left(G-\frac{1}{2}HK_c\right)$$

This completes the proof. Q. E. D.

The result on the digital modeling of the continuous-time controlled TS fuzzy model is now summarized in the following fact:

Fact 1: With Assumption 1 and the above two lemmas, the digital model of the analogously controlled TS fuzzy model (5) is denoted by

$$x_c(kT+T) \cong \sum_{i=1}^{q}\sum_{j=1}^{q}\mu_i\mu_j\left[I_n+\frac{1}{2}H_iK_c^j\right]^{-1}\left[G_i-\frac{1}{2}H_iK_c^j\right]x_c(kT) \quad (22)$$

Proof: From Lemma 1, we obtain

$$x_c(kT+T) = \sum_{i=1}^{q}\sum_{j=1}^{q}\mu_i\mu_j\Phi_c^{ij}(\mu(z(kT+T)),\ \mu(z(kT)))x_c(kT) \quad (23)$$

and from Lemma 2, we can note the following:

$$\Phi_c^{ij} \cong \left[I_n+\frac{1}{2}H_iK_c^j\right]^{-1}\left[G_i-\frac{1}{2}H_iK_c^j\right],\quad i,j=1,2,\cdots,q$$

where Φ_c^{ij} is the state transition matrix of the system $\dot{x}=(A_i-B_iK_c^j)$. This completes the proof.

2.3 LMI-based intelligent digital redesign by state-matching

In order to design a digital fuzzy-model-based controller, the continuous-time fuzzy-model-based controller has to be discretized so that the states $x_d(t)$ at $t=kT$ with the resulting digital fuzzy- model-based controller closely match those with the original continuous-time fuzzy-model-based controller.

Unlike the traditional method in [4], in this paper, we propose an alternative way to digitally redesign a continuous-time fuzzy-model-based controller with LMI-based approach.

Let us consider the following augmented system in the ith subspace

$$\dot{z}(t) = \sum_{i=1}^{q}\sum_{j=1}^{q}\mu_i\mu_j\overline{A}_{ij}z(t) - \overline{B}_i\overline{K}_jz(kT) \quad (24)$$

where

$$z(t)=\begin{bmatrix} x_c \\ x_d \end{bmatrix},\quad \overline{A}_{ij}=\begin{bmatrix} A_i-B_iK_c^j & 0_{n\times n} \\ 0_{n\times n} & A_i \end{bmatrix},$$

$$\overline{B}_i=\begin{bmatrix} 0_{n\times m} \\ B_i \end{bmatrix},\quad \overline{K}_j=[0_{m\times n}\ K_d^j]$$

By using (15) and (22), digital model of (24) is given by

$$z(kT+T) = \sum_{i=1}^{q}\sum_{j=1}^{q}\mu_i\mu_j(\overline{G}_{ij}-\overline{H}_i\overline{K}_j)z(kT) \quad (25)$$

where

$$z(kT)=\begin{bmatrix} x_c(kT) \\ x_d(kT) \end{bmatrix}$$

$$\overline{G}_{ij}=\begin{bmatrix} (I_n+\frac{1}{2}H_iK_c^j)^{-1}(G_i-\frac{1}{2}H_iK_c^j) & 0_{n\times n} \\ 0_{n\times n} & G_i \end{bmatrix}$$

$$\overline{H}_i=\begin{bmatrix} 0_{n\times m} \\ H_i \end{bmatrix},\quad \overline{K}_j=[0_{m\times n}\ K_d^j]$$

We define the following cost function as in Problem 2.

$$J=\sum_{k=0}^{\infty}J(kT) \quad (26)$$

where [2]

$$\begin{aligned} J(kT) &= \frac{1}{2}(x_c(kT)-x_d(kT))^TQ(x_c(kT)-x_d(kT)) \\ &= \frac{1}{2}[x_c(kT)^T\ x_d(kT)^T]\begin{bmatrix} Q & -Q \\ -Q & Q \end{bmatrix}\begin{bmatrix} x_c(kT) \\ x_d(kT) \end{bmatrix} \\ &= z(kT)^T\overline{Q}z(kT) \end{aligned}$$

Therefore, the digital redesign problem is converted to the standard discrete-time controller design problem. That is, the problem is to find K_d minimizing the cost function (26).

The main result of this paper is summarized in the following theorem.

Theorem 1: The digital controller K_d in (8) or (9) is a digitally redesigned controller if there exist a symmetric positive definite matrix Γ, a matrix L, and a matrices $\overline{F}_i=\overline{K}_i\Gamma$, such that the following LMI's are satisfied.

$$\Gamma>0 \quad (27)$$

$$\begin{bmatrix} \Gamma-(q-1)L & * & * \\ \overline{Q}^{1/2}\Gamma & I & * \\ \overline{G}_{ii}\Gamma-\overline{H}_iF_i & 0 & \Gamma \end{bmatrix}>0,\quad i=1,2,\cdots,q \quad (28)$$

$$\begin{bmatrix} \Gamma+L & * & * \\ \overline{Q}^{1/2} & I & * \\ \frac{1}{2}(\overline{G}_{ij}\Gamma-\overline{H}_iF_j+\overline{G}_{ij}\Gamma-\overline{H}_jF_i) & 0 & \Gamma \end{bmatrix}>0,\quad i<j \quad (29)$$

If above inequalities has feasible solutions $\Gamma_i>0$, L, and F_i, then the digital controller K_d^i is given by

$$K_d^i=F_i\Gamma_{i2}^{-1} \quad (30)$$

where $\Gamma_{i2}\in R^{n\times 2n}$ and satisfies

$$\Gamma=\begin{bmatrix} \Gamma_{i1} \\ \Gamma_{i2} \end{bmatrix} \quad (31)$$

Proof: It follows directly by combining Theorem 6 in [11] and Theorem Theorem 1 in [12]. Q. E. D.

Remark 1: When solving the above LMIs, one must notice that $\overline{K}_i$ has a structure. That is,

$$\overline{K}_i=[0\ \blacksquare]$$

where ■ means no restriction on the particular matrix entry. Then, if we add the convex constraints

$$F_i=[0\ \blacksquare],\quad \Gamma_i=\begin{bmatrix} \blacksquare & 0 \\ 0 & \blacksquare \end{bmatrix}$$

We get $\overline{K}_i=F_i\Gamma_i^{-1}$ with the desired structure.

III. Simulation results and discussion

In order to show the effectiveness of the proposed method in designing an digital FMBC, we consider the following TS fuzzy model

Rule 1: IF x_1 is F_1^1, THEN $\dot{x}_c = A_1 x_c + B_1 u_c$
Rule 2: IF x_2 is F_1^2 THEN $\dot{x}_c = A_2 x_c + B_2 u_c$ (32)

where

$$A_1 = \begin{bmatrix} 0 & 1 \\ 17.2941 & 0 \end{bmatrix},\ A_2 = \begin{bmatrix} 0 & 1 \\ 9.36 & 0 \end{bmatrix}$$
$$B_1 = [0\ \ -0.1765]^T,\ B_2 = [0\ \ -0.0052]^T$$

and the membership functions are given by

$$F_1^1(x_1(t)) = \max(\min(\frac{x_1+1.57}{1.57}, \frac{1.57-x_1}{1.57}), 0)$$
$$F_1^2(x_1(t)) = 1 - F_1^1(x_1(t))$$

For digital control, sampling time T is 0.04 (sec). The continuous-time feedback gains are found to be $K_c^1 = [-120.7\ \ 22.7]$ and $K_c^2 = [-2551.6\ \ -764]$ with stability checked. Applying Theorem 1, the digitally redesigned gains are

$$K_d^1 = [-470.8053\ \ -146.5924],$$
$$K_d^2 = 1.0 \times 10^3 [-1.8244\ \ -0.6114].$$

The closed-loop responses of the analog controller, the digital controller by other intelligent digital redesign method [4], and the proposed method is shown in Fig. 2. As expected, the system is well stabilized and the states of the closed-loop system are closely match those of the original continuous-time controlled system and the performance of the proposed method is superior to that of the conventional method.

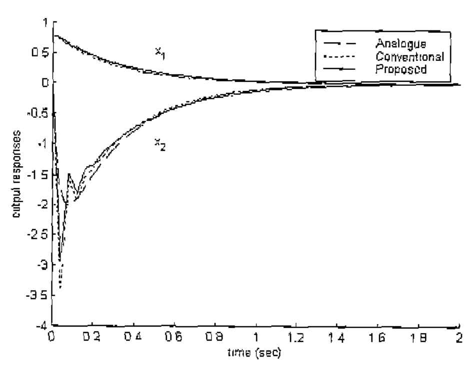

Fig. 2. The comparison of the states

IV. Conclusion

In this paper, we have presented a intelligent digital redesign methodology with LMI-based approach for digital control of complex and nonlinear systems such as the inverted pendulum, robot systems, etc. TS fuzzy model is used in the proposed design procedure to model the complex, nonlinear dynamic system and then the parallel distributed compensation technique is applied for the design of a fuzzy-model-based controller. The continuous- time fuzzy-model-based controller design problem is formulated in terms of LMIs. The intelligent digital redesign problem is then converted into the equivalent optimization problem taking into account the inter-sampling behavior, from which the powerful LMI optimization technique is adopted to design a discrete-time fuzzy-model-based controller. The overall design procedure is based on the so-called local intelligent digital redesign technique. Simulation results on the nonlinear numerical example have convincingly shown the feasibility and effectiveness of the developed digital redesign method.

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