Stabilizing Fuzzy Static Output Control for a Class of Nonlinear Systems

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Abstract—The paper presents new conditions suitable in design of a stabilizing static output controller for a class of continuous-time nonlinear systems represented by Takagi-Sugeno models, and measurable premise variables. Based on an enhanced Lyapunov inequality, the design conditions are outlined in the terms of linear matrix inequalities to possess a stable closed-loop system closest to optimal asymptotic properties. Simulation result illustrates the design procedure and demonstrates the performances of the proposed design method.

Index Terms—Takagi-Sugeno models, fuzzy output control, linear matrix inequalities, convex optimization.

I. INTRODUCTION

Since a generic method for design of a controller valid for all types of nonlinear systems has not been developed yet, an alternative to design a controller for nonlinear systems is e.g. fuzzy approach which benefits from the advantages of the approximation techniques approximating nonlinear system model equations. Using the Takagi-Sugeno (TS) fuzzy model [14] the nonlinear system is represented as a collection of the fuzzy rules, where each rule utilizes the local dynamics by a linear system model. Since TS fuzzy models can well approximate a large class of nonlinear systems, and the TS model based approach can apprehend the nonlinear behavior of a system while keeping the simplicity of the linear models, by employing the TS fuzzy model a control design methodology exploits fully advantage of the modern control theory, especially in the state space optimal and robust control.

During the last years, many tasks have been carried out to investigate the stability analysis and the design of static controller of TS systems (among others basic principles and results see e.g. in [7], [10], [11], [15], [18]). The main idea of the TS fuzzy model-based controller design is to derive control rules so as to compensate each rule of a fuzzy system, determining the local feedback gains. Unfortunately, it is also known that the separate stabilization with respect to local TS models does not ensure the stability of the overall system, and global design conditions have to be used to guarantee the global stability and control performance, using the control policy based on the parallel distributed compensator, where the control law shares the same fuzzy rules the TS system. In that way, a range of stability conditions have been developed for TS fuzzy systems [1], [5], [8], [11], [17], [19], relying mostly on the feasibility of an associated set of linear matrix inequalities (LMI) [2]. An important fact is that the stability problem is a standard feasibility problem with several LMIs, potentially reformulated such that the feedback gains can be solved numerically. In consequence, the state control, as well the static output feedback control based on fuzzy TS systems model, are realized in such structures which can be designed using technique based on LMIs.

The main contribution of the paper is to present modified design conditions for designing the fuzzy static output feedback control for continuous-time nonlinear MIMO systems approximated by a TS model, and using the measurable premise variables. Constructing the fuzzy model describing the behavior of given set of nonlinear dynamic systems, the Lyapunov synthesis approach is exploited to guarantee global stability of the system. The proposed design method extend the methodology given in [3], [6] but is constructed on an enhanced form of quadratic Lyapunov function [9], [16] to express such design condition in the form of LMIs. Comparing with standard LMI design conditions based on a quadratic Lyapunov matrix, which are particularly in the case of a large number of rules conservative, as a common symmetric positive definite matrix is used to verifying all Lyapunov inequalities, presented principle naturally extends the affine TS model properties using slack matrix variables to decouple Lyapunov matrix and the system matrices in LMIs. By this way, sufficient LMI design conditions were obtained by simply imposing an equivalent matrix to the Lyapunov matrix. Potentially, extra constraints can be imposed to the slack matrix variables, but increasing the conservativeness of the design conditions.

The remainder parts of this paper are organized as follows. In Section II the structure of TS model for considered class of nonlinear systems is briefly described, and some its properties are outlined. The static output feedback control design problem for systems with measurable premise variables is given in Section III where especially design conditions that guarantees global quadratic stability are formulated and proven. Section IV gives a numerical example to illustrate the effectiveness of the proposed approach, and to confirm the validity of the control scheme. The last section draws conclusions and some future directions.
II. TAKAGI-SUGENO FUZZY MODELS

The systems under consideration is one class of multi-input and multi-output nonlinear (MIMO) dynamic systems, represented in state-space form as
\[ \dot{q}(t) = a(q(t)) + Bu(t) \]  
\[ y(t) = Cq(t) \]
where \( q(t) \in \mathbb{R}^n, u(t) \in \mathbb{R}^r, y(t) \in \mathbb{R}^m \), are vectors of the state, input, and output variables, respectively, and \( B \in \mathbb{R}^{n \times r}, \) and \( C \in \mathbb{R}^{m \times n} \) are real finite values matrices.

Considering that the number of the nonlinear terms in \( a(q(t)) \) is \( p \), there exists a set of nonlinear sector functions
\[ w_{ij}(\theta(t)), \ j = 1, 2, \ldots, k, \ l = 1, 2, \ldots, p \]
\[ w_{ij}(\theta(t)) = 1 - \sum_{l=1}^{k} w_{ij}(\theta(t)) \]
\[ w_{ij}(\theta(t)) = w_{ij}(\theta_i(t)) \]
where \( k \) is the number of sectors, and
\[ \theta(t) = [\ \theta_1(t) \ \theta_2(t) \ \cdots \ \theta_q(t) \ ] \]  
(4)
is the vector of premise variables. It is supposed that a premise variable represents any measurable variable, and can be a function of state variables or, in a simple case, it can be chosen as a state variable. It is supposed that the premise variables are not functions of the input vector \( u(t) \) to avoid a complicated defuzzification process.

Using a TS model, the conclusion part of a single rule consists no longer of a fuzzy set [11], but determines a function with state variables as arguments, and the corresponding function is a local function for the fuzzy region that is described by the premise part of the rule. Thus, using linear functions, a system state is described locally (in fuzzy regions) by linear models, and at the boundaries between regions an interpolation is used between the corresponding local models.

Given a pair of \( (q(t), u(t)) \) the final states of the systems are inferred as follows
\[ \dot{q}_i(t) = \frac{\sum_{h=1}^{k} \sum_{j=1}^{k} w_{ih}(\theta_i(t)) \cdots w_{pj}(\theta_j(t)) \Omega_{h...j}}{\sum_{h=1}^{k} \sum_{j=1}^{k} w_{ih}(\theta_i(t)) \cdots w_{pj}(\theta_j(t))} \]  
\[ \Omega_{h...j} = A_{h...j}q(t) + Bu(t) \]
where \( \Omega_{h...j} \) is the linear model associated with the \( (h \ldots j) \) combination of sector function indexes. It is evident that a general fuzzy model is achieved by fuzzy amalgamation of the linear systems models.

Thus, the set \( \{w_i(\theta(t))\}, \ i = 1, 2, \ldots, s, s = 2^k \) can be constructed from all combinations of sector functions, e.g. ordered as follows
\[ w_1(\theta(t)) = w_{11}(\theta_1(t)) \cdots w_{pk}(\theta_k(t)) \]
\[ w_s(\theta(t)) = w_{11}(\theta_1(t)) \cdots w_{pk}(\theta_k(t)) \]
which implies
\[ \dot{q}(t) = \frac{\sum_{i=1}^{s} w_i(\theta(t))\Omega_i(t)}{\sum_{i=1}^{s} w_i(\theta(t))} = \sum_{i=1}^{s} h_i(\theta(t))\Omega_i(t) \]
\[ \Omega_i = A_iq(t) + Bu(t) \]
(8)
(9)
where
\[ h_i(\theta(t)) = \frac{w_i(\theta(t))}{\sum_{i=1}^{s} w_i(\theta(t))} \]
(10)
is the averaging weight for the \( i \)-th rule, representing the normalized grade of membership (membership function). By definition, the membership functions satisfy the following convex sum properties
\[ 0 \leq h_i(\theta(t)) \leq 1, \sum_{i=1}^{s} h_i(\theta(t)) = 1 \forall i \in \{1, \ldots, s\} \]  
(11)
and the linear consequent equation represented by (9) is called a linear subsystem.

Assuming, the vector function \( a(q(t)) \) is bounded in sectors, i.e. in the fuzzy regions within the system will operate, and takes the value \( a(\theta) = 0 \), the fuzzy approximation of (1) leads to (8), (9) where \( A_i \in \mathbb{R}^{n \times n} \) is the Jacobian matrix of \( a(q(t)) \) with respect to \( q(t) = q_i \), and \( q_i \) is the center of the \( i \)-th fuzzy region described by the associated sector function from the set (3).

Assumption 1: The matrices \( B, C \) are the same for all local models.

Assumption 2: The pair \( (a(q(t)), B) \) is locally controllable and \( B(C) \) is of full column (row) rank, where
\[ a(q(t)) = \sum_{i=1}^{s} h_i(\theta(t))A_i \]
(12)

Thus, the the entire TS fuzzy model of (1), (2) is reached by fuzzy blending of all consequents’ linear sub-models through the set of normalized membership functions \( \{h_i(\theta(t))\}, \ i = 1, 2, \ldots, s \), i.e.
\[ \dot{q}(t) = \sum_{i=1}^{s} h_i(\theta(t))(A_iq(t) + Bu(t)) \]
\[ y(t) = Cq(t) \]
(13)
(14)
Note, the aforementioned model does not include parameter uncertainties or external disturbances. It is supposed in the next that \( r = m \).

III. ENHANCED FUZZY STATIC OUTPUT CONTROL DESIGN

In the next, the fuzzy static output controller is designed using the concept of parallel distributed compensation, in which the fuzzy controller shares the same sets of normalized membership functions like the T-S fuzzy system model.
Definition 1: Considering (13), (14), and using the same set of membership function (11), the fuzzy static output controller is defined as
\[
 u(t) = -\sum_{j=1}^{s} h_j(\theta(t))K_jy(t) = -\sum_{j=1}^{s} h_j(\theta(t))K_jCq(t)
\]
(15)

Note that the fuzzy controller (15) is in general nonlinear.

Theorem 1: The equilibrium of the fuzzy system (13), (14) controlled by the fuzzy controller (15) is globally quadratically stable if there exist positive definite symmetric matrices \(U, V \in \mathbb{R}^{n \times n}\), a positive definite matrix \(T \in \mathbb{R}^{n \times n}\), and matrices \(N_j \in \mathbb{R}^{r \times n}\) such that
\[
 T > 0, \quad U = U^T > 0, \quad V = V^T > 0
\]
(16)
\[
 \begin{bmatrix}
 A_iV + VA_i^T + BN_jC + C^TN_j^TB - Y_{ij} \\
 T - U + A_iV + BN_jC \\
 \end{bmatrix} < 0
\]
(17)
\[
 \begin{bmatrix}
 Y_{11} & Y_{12} & \cdots & Y_{1s} \\
 Y_{12} & Y_{22} & \cdots & Y_{2s} \\
 \vdots & \vdots & \ddots & \vdots \\
 Y_{1s} & Y_{2s} & \cdots & Y_{ss} \\
 \end{bmatrix} > 0
\]
(18)

Thus, adding (24) as well as the transposition of (24) to (26), it yields
\[
 \dot{v}(q(t)) = q^T(t)Pq(t) + q^T(t)Pq(t) + \\
 \quad + \left( -q^T(t) \sum_{i=1}^{s} h_i(\theta(t))A_i - BK_jC \right)^T \left( S_iq(t) + S_2q(t) \right) + \\
 \quad + \left( q^T(t)S_1 + q^T(t)S_2 \right) \left( -\sum_{i=1}^{s} h_i(\theta(t))A_i - BK_jC \right)q(t) < 0
\]
(27)

Adding to (27), as well as subtracting from (27) the next term
\[
 \dot{v}_q(\theta(t)) = q^T(t)Z(\theta(t))q(t)
\]
(28)
where
\[
 Z(\theta(t)) = \sum_{i=1}^{s} \sum_{j=1}^{s} h_i(\theta(t))Y_{ij}X_{ij} > 0
\]
(29)
and \(X_{ij} = X_{ij}^T \in \mathbb{R}^{r \times n}, i, j = 1, 2, \ldots, s\) is the set of symmetric matrices, then it is obtained
\[
 \dot{v}(q(t)) = q^T(t)Pq(t) + \dot{q}^T(t)Pq(t) + \\
 \quad + \left( -q^T(t) \sum_{i=1}^{s} h_i(\theta(t))A_i - BK_jC \right)^T \left( S_iq(t) + S_2q(t) \right) + \\
 \quad + \left( q^T(t)S_1 + q^T(t)S_2 \right) \left( -\sum_{i=1}^{s} h_i(\theta(t))A_i - BK_jC \right)q(t) < 0
\]
(30)

Using the notation
\[
 q^{*T}(t) = \left[ q^T(t) \quad \dot{q}^T(t) \right]
\]
(31)
the inequality (30) can be compactly rewritten as
\[
 \dot{v}(q(t)) = \sum_{i=1}^{s} \sum_{j=1}^{s} h_i(\theta(t))Y_{ij}X_{ij}q(t) < -q^T(t)Z(\theta(t))q(t) < 0
\]
(32)
where
\[
 P^*_{ij} = \left[ -S_i(A_i - BK_jC) - (A_i - BK_jC)^T S_{ij} \right] \left[ P + S_1 - S_2(A_i - BK_jC) \right] 2S_2
\]
(33)
It is evident, \(P^*_{ij}\) must be negative definite and \(Z(\theta(t))\) has to be positive definite since (32) has to be negative. Since \(r = m_i\), it is possible to set \(BK_jC = BK_jMM^{-1}C = BN_jCS_1\)
(34)

where
\[
 K_jM = N_j, \quad M^{-1}C = CS_1
\]
(35)
and \(M \in \mathbb{R}^{m \times m}\) is a regular square matrix. Inserting (35) into (33) results in
\[
 P^*_{ij} = \left[ P + S_1 - S_2(A_i - BN_jCS_1) \right] 2S_2
\]
(36)
where
\[
\Phi_{ij} = -X_{ij} - 
S_1(A_i - BN_jCS_1) - (A_i - BN_jCS_1)^T S_1
\]  
(37)

Defining the congruence transform matrix as follows
\[
T = \begin{bmatrix}
S_1^{-1} & S_2^{-1}
\end{bmatrix}
\]  
(38)

and pre-multiplying left-hand and right-hand side of (36) by \( T \) gives
\[
\begin{bmatrix}
\Pi_{ij} \\
S_2^{-1}PS_1^{-1} + S_2^{-1} - (A_iS_1^{-1} - BN_jC) - 2S_2^{-1}
\end{bmatrix} < 0
\]  
(39)

where
\[
\Pi_{ij} = S_1^{-1} \Phi_{ij} S_1^{-1} = -S_1^{-1} X_{ij} S_1^{-1} - (A_iS_1^{-1} - BN_jC) - (A_iS_1^{-1} - BN_jC)^T
\]  
(40)

and using the notations
\[
T = S_2^{-1}PS_1^{-1}, \quad V = -S_1^{-1}, \quad U = -S_2^{-1}, \quad Y_{ij} = VX_jV
\]  
(41)

then (39) implies (17).

Since (30) is conditioned by (29), then with respect to (41) it so also yields
\[
Z_v(\theta(t)) = VZ(\theta(t))V = \sum_{i=1}^s \sum_{j=1}^s h_i(\theta(t))h_j(\theta(t)) Y_{ij} > 0
\]  
(42)

where \( \{ Y_{ij} = Y_{ij}^T \in R^{n \times n}, i, j = 1, 2, \ldots, s \} \) is the set of symmetric matrices.

Writing \( Z_v(\theta(t)) \) as follows
\[
0 < Z_v(\theta(t)) = \begin{bmatrix}
h_1(\theta(t)) \\
h_2(\theta(t)) \\
\vdots \\
h_s(\theta(t))
\end{bmatrix}^T \begin{bmatrix}
Y_{11} & Y_{12} & \cdots & Y_{1s} \\
Y_{12} & Y_{22} & \cdots & Y_{2s} \\
\vdots & \vdots & \ddots & \vdots \\
Y_{1s} & Y_{2s} & \cdots & Y_{ss}
\end{bmatrix} \begin{bmatrix}
h_1(\theta(t)) \\
h_2(\theta(t)) \\
\vdots \\
h_s(\theta(t))
\end{bmatrix}
\]  
(43)

then (43) implies (18).

Moreover, (35) gives
\[
MC = CS_1^{-1} = -CV
\]  
(44)

then pre-multiplying the right side of (44) by \( C^T \) gives
\[
CVC^T = -MCC^T
\]  
(45)

and
\[
M = -CVC^T(C^TC)^{-1} = -CVC^{\leq 1}
\]  
(46)

Evidently, (35), (46) imply (19)–(21), respectively. This concludes the proof.

This principle naturally extends the affine TS model principle, and by introducing the slack matrix variables \( U, V \) into the LMI s the system matrices are decoupled from the equivalent Lyapunov matrix \( T \). Note, the above presented inequalities are linear matrix inequalities, the equivalent Lyapunov matrix \( T \) is positive definite, but not symmetric.

**Theorem 2:** The equilibrium of the fuzzy system (13), (14) controlled by the fuzzy controller (15) is globally quadratically stable if there exist positive definite symmetric matrices \( T, V \in R^{n \times n} \), a positive scalar \( \delta \in R \) and matrices \( N_j \in R^{p \times n} \) such that
\[
T - \delta V + AV + BN_jC < 0
\]  
(47)

\[
\begin{bmatrix}
Y_{11} & Y_{12} & \cdots & Y_{1s} \\
Y_{12} & Y_{22} & \cdots & Y_{2s} \\
\vdots & \vdots & \ddots & \vdots \\
Y_{1s} & Y_{2s} & \cdots & Y_{ss}
\end{bmatrix} > 0
\]  
(48)

for \( h_i(\theta(t))h_j(\theta(t)) \neq 0, \ i, j = 1, 2, \ldots, s \).

The set of control law gain matrices is given by (19)–(21).

**Proof:** Now, instead of the notations (41), there are used in (39) the next substitutions
\[
V = -S_1^{-1}, \quad \delta V = -S_2^{-1}, \quad \delta > 0
\]  
(49)

\[
T - S_2^{-1}PS_1^{-1} = \delta VPV, \quad Y_{ij} = VX_jV
\]  
(50)

respectively. It is evident that with (50), (51) then (39) implies (48), where \( T \) is a symmetric positive definite matrix. This concludes the proof. ■

Note, (48) are LMI s only if \( \delta \) is a prescribed constant which can be considered as a tuning parameter. Considering \( \delta \) as a LMI variable, (48) are bilinear matrix inequalities (BMI).

**IV. ILLUSTRATIVE EXAMPLE**

The nonlinear dynamics of the hydrostatic transmission was taken from [4] and this model was used in control design and simulation.

The hydrostatic transmission dynamics is represented by a nonlinear fourth order state-space model
\[
\begin{align*}
q_1(t) &= -a_{11}q_1(t) + b_{11}u_1(t) \\
q_2(t) &= -a_{22}q_2(t) + b_{22}u_2(t) \\
q_3(t) &= a_{31}q_1(t)p(t) - a_{33}q_3(t) - a_{34}q_2(t)q_4(t) \\
q_4(t) &= a_{43}q_2(t)q_3(t) - a_{44}q_4(t)
\end{align*}
\]

where \( q_1(t) \) is the normalized hydraulic pump angle, \( q_2(t) \) is the normalized hydraulic motor angle, \( q_3(t) \) is the pressure difference [bar], \( q_4(t) \) is the hydraulic motor speed [rad/s], \( p(t) \) is the speed of hydraulic pump [rad/s], \( u_1(t) \) is the normalized control signal of the hydraulic pump, and \( u_2(t) \) is the normalized control signal of the hydraulic motor. It is supposed that the external variable \( p(t) \), as well as the second state variable \( q_2(t) \) are measurable. In given working point the parameters are
\[
\begin{align*}
a_{11} &= 7.6923 \\
a_{22} &= 4.5455 \\
a_{33} &= 7.6054 \times 10^{-4} \\
a_{31} &= 0.7877 \\
a_{34} &= 0.9235 \\
b_{11} &= 1.8590 \times 10^3 \\
a_{43} &= 12.1967 \\
a_{44} &= 0.4143 \\
b_{22} &= 1.2879 \times 10^3
\end{align*}
\]
Since the variables \( p(t) \in (105,300) \) and \( q_2(t) \in (0.0001,1) \) are bounded on the prescribed sectors then vector of the premise variables can be chosen as follows

\[
\theta(t) = [ \theta_1(t) \quad \theta_2(t) ] = [ q_2(t) \quad p(t) ]
\]

Thus, the set of nonlinear sector functions

\[
w_{11}(q_2(t)) = \frac{b_1 - q_2(t)}{b_1 - b_2}, \quad b_1 = 0, \quad b_2 = 1
\]

\[
w_{12}(q_2(t)) = \frac{q_2(t) - b_2}{b_1 - b_2} = 1 - w_{11}(q_2(t))
\]

\[
w_{21}(p(t)) = \frac{c_1 - p(t)}{c_1 - c_2}, \quad c_1 = 105, \quad c_2 = 300
\]

\[
w_{22}(p(t)) = \frac{p(t) - c_2}{c_1 - c_2} = 1 - w_{21}(p(t))
\]

implies the next set of normalized membership functions

\[
h_1(q_2(t),p(t)) = w_{11}(q_2(t))w_{21}(p(t))
\]

\[
h_2(q_2(t),p(t)) = w_{12}(q_2(t))w_{21}(p(t))
\]

\[
h_3(q_2(t),p(t)) = w_{11}(q_2(t))w_{22}(p(t))
\]

\[
h_4(q_2(t),p(t)) = w_{12}(q_2(t))w_{22}(p(t))
\]

The transformation of nonlinear differential equation systems into a TS fuzzy system in standard form gives

\[
A_i = \begin{bmatrix}
-a_{11} & 0 & 0 & 0 \\
0 & -a_{22} & 0 & 0 \\
a_{31}c_k & 0 & -a_{31} & -a_{34}b_l \\
0 & 0 & a_{34}b_l & -a_{44}
\end{bmatrix}, \quad B = \begin{bmatrix}
a_{11} & 0 \\
0 & b_2 \\
0 & 0 \\
0 & 0
\end{bmatrix}, \quad C^T = \begin{bmatrix}
0 & 0 \\
0 & 1 \\
1 & 0 \\
0 & 0
\end{bmatrix}
\]

with the associations

\[
i = 1 \leftarrow (l = 1, k = 1) \quad i = 2 \leftarrow (l = 2, k = 1)
\]

\[
i = 3 \leftarrow (l = 1, k = 2) \quad i = 4 \leftarrow (l = 2, k = 2)
\]

Thus, solving (47), (48) with respect to the LMI matrix variables \( T, V, N_i, j = 1,2,3,4 \) and with \( \delta = 10 \) and \( Y_{ij} = 0 \ \forall i,j = 1,2,3,4 \) then, using Self–Dual–Minimization (SeDuMi) package for Matlab [13], the feedback gain matrix design problem was feasible with the results

\[
T = \begin{bmatrix}
0.0082 & 0.0000 & -0.1065 & -0.0021 \\
0.0000 & 3.9527 & 0.0001 & -0.0001 \\
-0.1065 & 0.0001 & 2.4732 & -0.6421 \\
-0.0021 & -0.0001 & -0.6421 & 7.7690
\end{bmatrix}
\]

\[
V = \begin{bmatrix}
0.0006 & 0.0000 & -0.0071 & -0.0004 \\
0.0000 & 0.2073 & 0.0000 & 0.0000 \\
-0.0071 & 0.0000 & 0.1645 & -0.1036 \\
-0.0004 & 0.0000 & -0.1036 & 0.8043
\end{bmatrix}
\]

\[
K_1 = \begin{bmatrix}
0.00000001 & 0.00021460 \\
0.00381356 & 0.00000017
\end{bmatrix}
\]

\[
K_2 = \begin{bmatrix}
0.00000001 & 0.00021460 \\
0.00382179 & 0.00000008
\end{bmatrix}
\]

which rise up a stable set of closed-loop subsystems. It can be seen that with an enough precision the used design conditions imply the approximately equal control gain matrices. Comparing with design methods proposed in [3], [6], the fuzzy control is so less conservative and quadratically stable.

The conditions in simulations were specified for the system in the forced regime, where

\[
u(t) = \sum_{j=1}^{s} h_j(\theta(t))(-K_jCq(t) + Ww(t))
\]

\[
w^T(t) = \begin{bmatrix}
0.5 \\
0.3
\end{bmatrix}, \quad q(0) = 0, \quad p(t) = 105
\]

\[
W = \begin{bmatrix}
0 & 0.000215 \\
0.007258 & 0
\end{bmatrix}
\]

Fig. 1 shows the simulation result for the system with zero initial state.

V. CONCLUDING REMARKS

New approach to static output control design for a class of continuous-time T-S fuzzy systems have been presented in this paper. This is achieved by application of TS fuzzy model relating to multi-model approximation structure and an enhanced Lyapunov inequality. Presented version is derived in terms of optimization over LMI constraints using standard LMI numerical optimization procedures to manipulate the global stability of the system.

The global quadratic stability of the closed-loop system, solved in the sense of enhanced Lyapunov inequality, was formulated considering measurable premise variables. Since the stability conditions based on the standard form of the quadratic Lyapunov function are very conservative as a common symmetric positive definite matrix verifying all Lyapunov inequalities is required, the presented principle, naturally exploiting the affine properties of TS fuzzy models and strictly decoupling the Lyapunov matrix and the system parameter matrices in the resulting LMIs, significantly reduces the conservativeness in the fuzzy control design. Simulation example has been given to
illustrate the validity and applicability of the proposed approach.

It is significant to extend the approach to the case for fuzzy systems with parametric perturbations, as well as to combine it e.g. with sliding mode control principle. These problems are included into the future authors’ work directions in presented field.

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REFERENCES


