

DESIGN OF FUZZY BASED VIRTUAL ACTUATOR FOR A CLASS OF NONLINEAR SYSTEMS

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Abstract. *The paper presents new conditions suitable in design of a virtual actuator for a class of continuous-time nonlinear systems represented by Takagi-Sugeno models, and measurable premise variables. Simulation results illustrate the design procedure and demonstrate the basic performances of the proposed control design method.*

Keywords

Actuator faults, fault tolerant control, fuzzy control, fuzzy virtual actuator, Takagi - Sugeno models.

1. Introduction

All technological systems are subject to faults, due to both component malfunctions and unforeseen external influences. The complexity of control systems requires fault tolerance schemes to provide control of the faulty system. Fault tolerant systems (FTS) are that the fruitful applications with potential significance for domains in which control of systems must proceed while the system is operative and testing opportunities are limited by operational conditions. The real problem is usually to fix the system with faults so that it can continue its mission for some time with some limitations of functionality.

The main task to be tackled in achieving fault tolerance is design of controllers with such suitable reconfigurable structure, which guarantees the stability, the satisfactory performance, and the plant operation economy in nominal operational conditions. To achieve the fault tolerance, used methods rely on employing on-line fault diagnosis schemes, which activate an alternative control - reconfigurable control structure - that is supposed to handle a fault. Among these structures can be quoted control systems with adaptation to faults, the virtual-based control structures, as well as the output control reconfiguration algorithms [1].

In order to solve the complexity problems, the

control reconfiguration has to satisfy the requirement that the control reconfiguration has to be performed on line after the fault has been detected [2], [3]. This requires simple and fast algorithms that work reliably without manual interventions and without the controller parameters tuning in a fault case. It is sufficient to store a parametric model of the system (including all faults) and a reconfiguration algorithm. The new control structure is generated on demand after the fault has been detected. Bibliographical reviews can be found in [4], [5], new developments in fault-tolerant control methods are presented e.g. in [2], [6], [7].

For nonlinear system design, various control schemes were introduced including exact feedback linearization and adaptive control. The technique of exact feedback linearization needs perfect knowledge of the nonlinear system and uses that knowledge to cancel the nonlinearities of the system. Since perfect knowledge of the system is almost impossible, the technique of exact feedback linearization cannot be generally used for nonlinear system control design. Also, adaptive control schemes, which were introduced to deal with nonlinear systems, exploit complicated parameter update laws and so the adaptive control algorithms posse hard limitations.

Since a generic controller design method 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 [8] the nonlinear system is represented as a collection of 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.

The main idea of the TS model-based controller

design is to derive control rules so as to compensate each rule of a fuzzy system, determining the local feedback gains [9]. It is known that the separate stabilization of these local models does not ensure the stability of the overall fuzzy model, and global design conditions have to be used to guarantee the global stability and control performance. Therefore, a range of stability conditions have been developed for TS fuzzy systems [10], most of them relying on the feasibility of an associated system of linear matrix inequalities (LMI) [11]. Therefore, the state control based on fuzzy TS systems model gives control structures, which can be designed using technique also based on equivalent LMIs. The idea behind this type of design is that the TS model based fuzzy control provides a user-friendly formalism for representing, implementing and achieving high-performance control structures [12].

This paper is concerned with the problem of the fuzzy virtual actuator design. Focusing on procedures for nonlinear dynamic system control, numerical example and system simulation are presented in advance.

2. On Takagi-Sugeno Fuzzy Models

The systems under consideration are one class of multi-input and multi-output nonlinear (MIMO) dynamic systems, represented in the state-space form as

$$\dot{q}(t) = a(q(t)) + Bu(t), \tag{1}$$

$$y(t) = Cq(t), \tag{2}$$

where $q(t) \in R^n$, $u(t) \in R^r$, $y(t) \in R^m$, are vectors of the state, input, and output variables, respectively, and $B \in R^{n \times r}$, and $C \in R^{m \times n}$ are real finite values matrices.

It is assumed that $a(q(t))$ is a vector function, is bounded in associated sectors, i.e. in the fuzzy regions where it is assumed the system will operate within, and takes the value $a(0) = 0$. It is considered that the number of the nonlinear terms in the nonlinear part of the model $a(q(t))$ is p , and that there exists a set of nonlinear sector functions of these properties

$$\begin{cases} w_{lj}(\theta(t)), j = 1, 2, \dots, k, l = 1, 2, \dots, p \\ w_{1l}(\theta(t)) = 1 - \sum_{j=2}^k w_{lj}(\theta(t)) \\ w_{lj}(\theta(t)) = w_{lj}(\theta_j(t)) \end{cases}, \tag{3}$$

where k is the number of sector functions, and

$$\theta(t) = [\theta_1(t) \ \theta_2(t) \ \dots \ \theta_q(t)] \tag{4}$$

is the vector of premise variables. It is supposed in the next that premise variables are measurable, and a premise variable can represent the state variable.

Using a TS model, the conclusion part of a single rule consists no longer of a fuzzy set, 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.

Thus, the normalized aggregated function set $\{h_i(\theta(t)), i = 1, 2, \dots, s, s = 2^k\}$ can be constructed from all combinations of the sector functions which implies

$$\dot{q}(t) = \sum_{i=1}^s h_i(\theta(t))\Omega_i(t), \quad h_i(\theta(t)) = \frac{w_i(\theta(t))}{\sum_{i=1}^s w_i(\theta(t))}, \tag{5}$$

$$\Omega_i(t) = A_i q(t) + Bu(t), \tag{6}$$

where $h_i(\theta(t))$ is the i -th aggregated (normalized) membership function satisfying conditions

$$0 \leq h_i(\theta(t)) \leq 1, \quad \sum_{i=1}^s h_i(\theta(t)) = 1 \quad \forall i \in \{1, \dots, s\}. \tag{7}$$

Therefore, the approximation of (1) leads to (5), (6), where $A_i \in R^{n \times n}$ 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 set of sector functions (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

$$a(q(t)) = \sum_{i=1}^s h_i(\theta(t))A_i. \tag{8}$$

Now the TS fuzzy model for (1), (2) takes form

$$\dot{q}(t) = \sum_{i=1}^s h_i(\theta(t))(A_i q(t) + Bu(t)), \tag{9}$$

$$y(t) = Cq(t), \tag{10}$$

and can be interpreted as a combination of s linear sub-models through the set of normalized membership functions $\{h_i(\theta(t)), i = 1, 2, \dots, s\}$ to approximate the nonlinear system.

3. Stabilizing Fuzzy Controller

3.1. Standard Fuzzy Control Design

Considering (9), i.e.

$$\dot{q}(t) = \sum_{i=1}^s h_i(\theta(t))(A_i q(t) + Bu(t)), \quad (11)$$

and using the same set of membership function, the nonlinear fuzzy state controller is defined as

$$u(t) = -\sum_{j=1}^s h_j(\Theta(t)) K_j q(t). \quad (12)$$

Substituting (12) into (11) results in

$$\dot{q}(t) = \sum_{i=1}^s h_i(\theta(t))(A_i q(t) - \sum_{j=1}^s h_j(\theta(t))BK_j q(t)). \quad (13)$$

Since $\sum_{i=1}^s h_i(\theta(t)) = 1 \forall i \in \{1, \dots, s\}$ it yields

$$\dot{q}(t) = \sum_{i=1}^s \sum_{j=1}^s h_i(\theta(t))h_j(\theta(t))(A_i - BK_j) q(t). \quad (14)$$

The equilibrium of the fuzzy system (9), (10), controlled by the fuzzy controller (12) is globally asymptotically stable [2] if there exists positive definite matrix $X \in R^{n \times n}$ and matrices $Y_j \in R^{r \times n}$ such that

$$X = X^T > 0, \quad (15)$$

$$X A_i^T + A_i X - Y_j^T B^T - B Y_j < 0, \quad (16)$$

for $h_i(\Theta(t))h_j(\Theta(t)) \neq 0, \forall t \geq 0$, and $i, j = 1, 2, \dots, s$.

The set of the control law gain matrices is given as

$$K_j = Y_j X^{-1}, \quad j = 1, 2, \dots, s. \quad (17)$$

4. Design of Fuzzy Based Nonlinear Virtual Actuator

Problem of the interest is to design an asymptotically stable fuzzy virtual actuator using Takagi – Sugeno fuzzy model of the nonlinear system (11).

An actuator fault is modeled by changing the input matrix B towards B_f . Columns of B_f that correspond to faulty actuators are scaled in case of actuator degradation, or set to zero in the case of actuator failure. The faulty dynamic system is now given by the set of equations

$$\dot{q}_f(t) = \sum_{i=1}^s h_i(\theta(t))(A_i q_f(t) + B_f u_f(t)), \quad (18)$$

$$y_f(t) = C q_f(t), \quad (19)$$

where $q_f(t) \in R^n, u_f(t) \in R^r, y_f(t) \in R^m$, are vectors of the state, input, and output variables, respectively, and $A_i \in R^{n \times n}, B_f \in R^{n \times r}, C \in R^{m \times n}$ are matrix parameters describing the faulty system. The controller is a nonlinear

fuzzy state feedback controller in the form (12).

The stabilization requires the reconfigured control loop to be stable while the signals of the controller are not affected by the fault. Since the idea of the reconfiguration is to make the faulty plant behaviour like the nominal plant ones, the state of the model of the nominal plant can be used as a reference. Thus, the fuzzy virtual actuator is given as

$$\dot{e}(t) = \sum_{i=1}^s \sum_{j=1}^s h_i(\theta(t))h_j(\theta(t))(A_i - B_f M_j) e(t) + Bu(t), \quad (20)$$

$$u_f(t) = \sum_{j=1}^s h_j(\theta(t)) M_j (q(t) - q_f(t)). \quad (21)$$

The structure of the reconfigured loop with a virtual actuator is in Fig. 1, where for simplicity

$$A = \sum_{i=1}^s h_i(\theta(t))A_i, \quad M = \sum_{j=1}^s h_j(\theta(t))M_j. \quad (22)$$

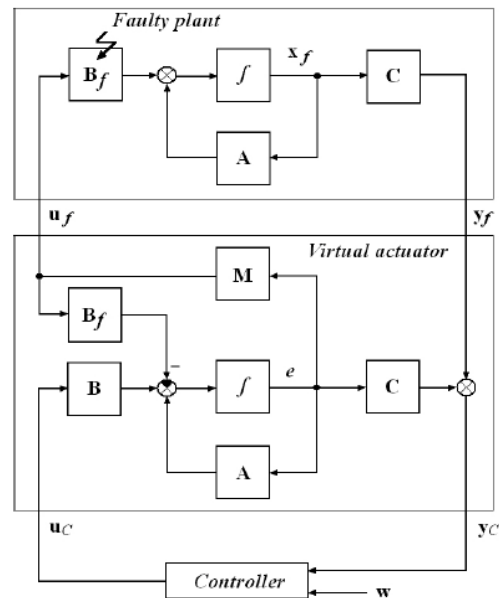


Fig. 1: Block diagram of the virtual actuator.

Theorem: The equilibrium of the system (11) with fuzzy virtual actuator is globally asymptotically stable if the pair $(a(q(t)), B_f)$ be robust stabilizable on the prescribed area of the premise variables and there exist positive definite symmetric matrix $X > 0, X \in R^{n \times n}$, and matrices $Z_j \in R^{n \times m}, j=1, 2, \dots, s$ such that

$$X = X^T > 0, \quad (23)$$

$$X A_i^T + A_i X - Z_j^T B_f^T - B_f Z_j < 0, \quad (24)$$

for $h_i(\theta(t))h_j(\theta(t)) \neq 0, \forall t \geq 0$, and $i, j = 1, 2, \dots, s$.

The set of the control law gain matrices is given as

$$M_j = Z_j X^{-1}, \quad j = 1, 2, \dots, s. \quad (25)$$

Proof: Introducing the error between the state vector of the nominal and faulty system in the form

$$e(t) = q(t) - q_f(t), \quad (26)$$

then using TS fuzzy model (11) and (18), and taking the time derivative of $e(t)$ it can be directly obtained

$$\dot{e}(t) = \sum_{i=1}^s h_i(\theta(t)) \sum_{j=1}^s h_j(\theta(t)) (A_i - B_f M_j) e(t) + B u_c(t), \quad (27)$$

The equations (11), (12), and (27) can be expressed in the matrix form

$$\begin{bmatrix} \dot{x}(t) \\ \dot{e}(t) \end{bmatrix} = \sum_{i=1}^s h_i(\theta(t)) \sum_{j=1}^s h_j(\theta(t)) \begin{bmatrix} A_i - B K_j & 0 \\ -B K_j & A_i - B_f M_j \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}. \quad (28)$$

It is evident from (28) that the separation principle can be used and to design separately the fuzzy controller and the fuzzy virtual actuator.

Since autonomous error dynamics of the closed loop system with fuzzy virtual actuator is given by

$$\dot{e}(t) = \sum_{i=1}^s h_i(\theta(t)) \sum_{j=1}^s h_j(\theta(t)) (A_i - B_f M_j) e(t), \quad (29)$$

defining the Lyapunov function of the form

$$v(e(t)) = e^T(t) P e(t) > 0, \quad (30)$$

where $P = P^T \in R^{n \times n}$, $P > 0$ is asymmetric positive definite matrix, then the Lyapunov function derivative takes the form

$$\dot{v}(e(t)) = \sum_{i=1}^s h_i(\theta(t)) \sum_{j=1}^s h_j(\theta(t)) e^T(t) P_v e(t) < 0, \quad (31)$$

where

$$P_v = P(A_i - B_f M_j) + (A_i - B_f M_j)^T P. \quad (32)$$

Thus, (31) implies that (29) is asymptotically stable if

$$P(A_i - B_f M_j) + (A_i - B_f M_j)^T P < 0, \quad (33)$$

for $h_i(\theta(t)) h_j(\theta(t)) \neq 0, \forall t \geq 0$, and $i, j = 1, 2, \dots, s$.

Since P is a regular matrix, then pre-multiplying left-hand side and right-hand side of (33) by P^{-1} gives

$$(A_i - B_f M_j) P^{-1} + P^{-1} (A_i - B_f M_j)^T < 0, \quad (34)$$

$$A_i P^{-1} + P^{-1} A_i^T - B_f M_j P^{-1} - P^{-1} M_j^T B_f^T < 0, \quad (35)$$

respectively. Then, with the notations

$$P^{-1} = X, \quad M_j P^{-1} = Z_j, \quad (36)$$

(35) implies (24). This concludes the proof.

5. Illustrative Example

The nonlinear dynamics of the system (1), (2) is represented by the six order model with the parameters

$$A(\theta) = \begin{bmatrix} 0 & 1 & 0 & 0,05 & 0 & 0,05 \\ 2 & -x_3(t) & 0,08 & 0,01 & 0,08 & 0,01 \\ 0 & 0,05 & 0 & -p(t) & 0 & 0,05 \\ 0,08 & 0,01 & -2 & 0,5 & 0,08 & 0,01 \\ 0 & 0,05 & 0 & 0,05 & 0 & 1 \\ 0,08 & 0,01 & 0,08 & 0,01 & p(t) & -2 \end{bmatrix}$$

$$B^T = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}, \quad C = I_{6 \times 6}$$

where the matrices B, C are the same for all local models.

The interpretation of the nonlinear system in a TS fuzzy system gives

$$A_i = \begin{bmatrix} 0 & 1 & 0 & 0,05 & 0 & 0,05 \\ 2 & -1b_i & 0,08 & 0,01 & 0,08 & 0,01 \\ 0 & 0,05 & 0 & -1c_k & 0 & 0,05 \\ 0,08 & 0,01 & -2 & 0,5 & 0,08 & 0,01 \\ 0 & 0,05 & 0 & 0,05 & 0 & 1 \\ 0,08 & 0,01 & 0,08 & 0,01 & 1c_k & -2 \end{bmatrix}$$

with the associations

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

Evidently, vector of the premise variables can be chosen as follows

$$\theta(t) = [\theta_1(t) \quad \theta_2(t)] = [q_3(t) \quad p(t)],$$

and the premise variables $p(t) \in (0,3)$ and $q_3(t) \in (-1,4)$ are bounded on the prescribed sectors.

Thus, the set of nonlinear sector functions

$$w_{11}(q_3(t)) = \frac{b_1 - q_3(t)}{b_1 - b_2}, \quad b_1 = -1, \quad b_2 = 4,$$

$$w_{12}(q_3(t)) = \frac{q_3(t) - b_2}{b_1 - b_2} = 1 - w_{11}(q_3(t)),$$

$$w_{21}(p(t)) = \frac{c_1 - p(t)}{c_1 - c_2}, \quad c_1 = 0, \quad c_2 = 3,$$

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

implies the next set of normalized membership functions

$$h_1(q_3(t), p(t)) = w_{11}(q_3(t)) w_{21}(p(t)),$$

$$h_2(q_3(t), p(t)) = w_{12}(q_3(t)) w_{21}(p(t)),$$

$$h_3(q_3(t), p(t)) = w_{11}(q_3(t)) w_{22}(p(t)),$$

$$h_4(q_3(t), p(t)) = w_{12}(q_3(t))w_{22}(p(t)),$$

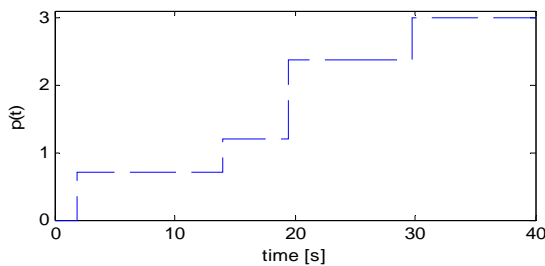


Fig. 2: Time response of $p(t)$.

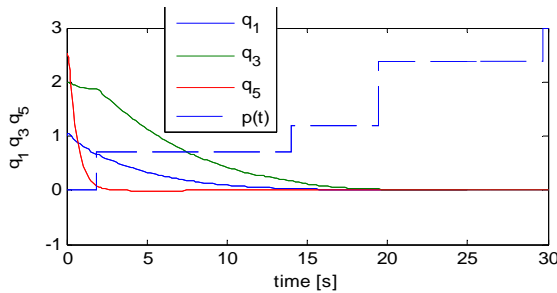


Fig. 3: Response of the fault-free system with fuzzy state controller.

5.1. Fuzzy Control Design

Thus, solving (15), (16) with respect to the LMI matrix variables X and $Y_j, j = 1,2,3,4$ using Self-Dual-Minimization (SeDuMi) package for Matlab, then according to (17) the matrices K_1, K_2, K_3, K_4 were obtained as

$$K_1 = \begin{bmatrix} 7,093 & 15,609 & 0,421 & -0,068 & 0,101 & 0,061 \\ 0,216 & -0,131 & -5,342 & 9,275 & 0,735 & 0,040 \\ -0,077 & 0,192 & 0,319 & 0,897 & 27,764 & 13,995 \end{bmatrix}$$

$$K_2 = \begin{bmatrix} 7,017 & 15,340 & 0,413 & -0,058 & 0,166 & 0,094 \\ 0,196 & -0,158 & -5,314 & 9,202 & 0,772 & 0,059 \\ -0,073 & 0,184 & 0,316 & 0,867 & 27,084 & 13,579 \end{bmatrix}$$

$$K_3 = \begin{bmatrix} 7,108 & 15,642 & 0,435 & -0,121 & -0,203 & -0,121 \\ 0,183 & -0,221 & -5,473 & 9,622 & 0,919 & 0,134 \\ -0,113 & 0,057 & 0,300 & 0,933 & 27,474 & 13,804 \end{bmatrix}$$

$$K_4 = \begin{bmatrix} 6,947 & 15,107 & 0,413 & -0,071 & 0,137 & 0,065 \\ 0,211 & -0,153 & -5,415 & 9,471 & 0,859 & 0,114 \\ -0,109 & 0,083 & 0,281 & 0,992 & 27,807 & 14,003 \end{bmatrix}$$

Figure 3 gives the simulation result of the fuzzy control for the fault-free systems, and to show the effectiveness of the fuzzy state control application for the nonlinear systems, where external signal $p(t)$ was from prescribed sector (see Fig. 2).

5.2. The Failure of the Actuator

As can see in Fig. 4, if the actuator failure occurs, the nominal fuzzy controller is not be able to stabilize the

system. To stabilize the system, the fuzzy virtual actuator has to be incorporated into the control.

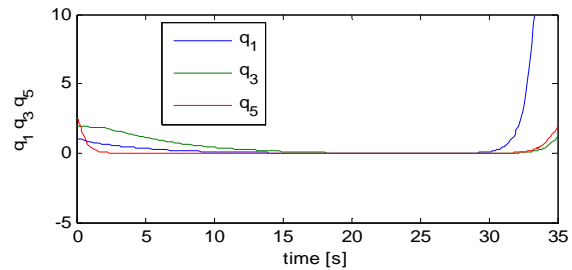


Fig. 4: Response of the system with the first actuator fault ($t_f = 26$ s).

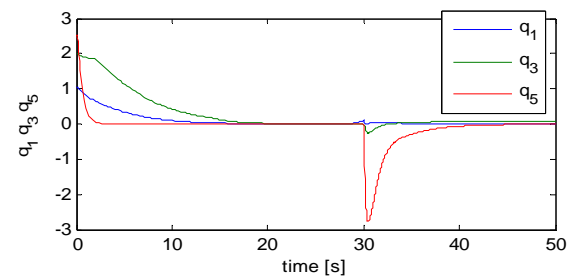


Fig. 5: Response of the system with the first actuator fault ($t_f = 26$ s) and fuzzy virtual actuator action starting at $t_{va} = 30$ s.

5.3. Fuzzy Virtual Actuator Design

If the first actuator fault occurs, the matrix B is changed into matrix B_f as follow

$$B_f^T = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Thus, solving (23), (24) with respect to the LMI matrix variables X and $Z_j, j = 1,2,3,4$ using Self-Dual-Minimization (SeDuMi) package for Matlab the next matrix parameter M_1, M_2, M_3, M_4 were obtained

$$M_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0,088 & 0,056 & 0,03 & 0,007 & -0,001 & 0,001 \\ 1,284 & 0,801 & 0,047 & 0,033 & -0,002 & 0,01 \end{bmatrix} \times 10^4$$

$$M_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0,088 & 0,056 & 0,03 & 0,007 & -0,001 & 0,001 \\ 1,284 & 0,801 & 0,047 & 0,033 & -0,002 & 0,01 \end{bmatrix} \times 10^4$$

$$M_3 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0,088 & 0,056 & 0,03 & 0,007 & -0,001 & 0,001 \\ 1,284 & 0,801 & 0,047 & 0,033 & -0,002 & 0,01 \end{bmatrix} \times 10^4$$

$$M_4 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0,088 & 0,056 & 0,03 & 0,007 & -0,001 & 0,001 \\ 1,284 & 0,801 & 0,047 & 0,033 & -0,002 & 0,01 \end{bmatrix} \times 10^4$$

and was applied in the fuzzy virtual actuator design.

Simulation results (Fig. 5.) show on the effectiveness of the fuzzy virtual actuator application for faulty nonlinear systems.

The presented results show that the nonlinear fuzzy controlled system with the failure of an actuator can be stabilized using the fuzzy virtual actuator.

6. Conclusion

The paper presents new conditions suitable in design of a fuzzy virtual actuator for a class of continuous-time nonlinear systems represented by Takagi-Sugeno models, and measurable premise variables. Simulation results show on the effectiveness the fuzzy state controller application for the nonlinear systems. If after the actuator failure the fuzzy controller is not able to stabilize the system, the faulty system can be stabilized by incorporating the fuzzy virtual actuator into the control structure. The presented results show that such instable nonlinear system with an actuator failure can be stabilized using the fuzzy controller and fuzzy virtual actuator.

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