A T-S Model-Based Sliding Mode Control for Nonlinear System

Lotfi Chaouech, Abdelkader Chaari
Research Unit on Control, Monitoring and Safety of Systems (C3S)
High School of Sciences and Techniques of Tunis (ESSTT)
5 Avenue Taha Hussein, BP 56
1008 Tunis, Tunisia
{chaouech.lotfi, nabile.chaari}@yahoo.fr

ABSTRACT: *This paper proposes a new type of a sliding mode control algorithm based on Takagi-Sugeno fuzzy model for a class of nonlinear systems. Firstly, we choose the sliding surface which gives a good behaviour during sliding mode. It is formulated as an assignment of the poles of nonlinear system in a convex optimization area. Secondly, we design a nonlinear control law leading the state trajectory on the sliding surface in a finite time. Finally, a flexible joint manipulator is given to validate the theoretical results of our approach.*

Keywords: Variable Structure Control, Sliding Mode Control, Nonlinear Systems, T-S fuzzy Models, Robustness

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1. Introduction

TAKAGI–SUGENO (T-S) models [1] have recently become a powerful practical engineering tool for modeling and control of complex systems. In T-S fuzzy model, the nonlinear system can be approximated by the sum of several linear subsystems, because of the difficulty of designing a model that takes into account the full complexity of a nonlinear system. The basic principle of T-S is to represent the system as an interpolation of simple local Takagi-Sugeno models, by idea of sector nonlinearity. Each sub-model describes the behavior of the system in a limited part of the operating space. The local validity of sub-model is specified by an associated weighting function. The T-S models have been widely applied in many fields such as control [2]. Indeed, many control techniques have been reported, one of them is being the Variable Structure Control (VSC). This latter is a robust control strategy characterized by a sliding mode and its robustness with respect to parameter variations and external perturbations [3-4-5-6]. The sliding mode control (SMC) [11] is attained by designing the control laws which drive the system state to reach and remain on the intersection of a set of prescribed switching surfaces. When in the sliding mode, the system exhibits invariance properties, such as robustness to certain internal parameter variations and external disturbances.

Many approaches based on sliding mode control have been proposed to treat several control problems such as the uncertain systems with uncertainties type norm bounded [2-7-8-9]. However, a little number of works has been proposed on the sliding mode control of nonlinear systems based on Takagi-Sugeno fuzzy model [2-10].

The present work extends the results on hyperplane VSC design for nominal linear systems reported by Sellami et al. [8] to a class of nonlinear system described by a set of T-S model. Firstly, we design a robust fuzzy sliding mode surface. Secondly, once the fuzzy sliding mode surface has been fixed, we propose the control law method such that the global fuzzy model presents the desired dynamic characteristics.

This paper is organized as follows. In section II, a brief review of the T-S fuzzy modelling formulation is given. The proposed approach is detailed in section III and IV. A numerical example will be is presented in section V treated to validate the theoretical concepts. Finally, section VI summarizes the important features of proposed approach.

2. T-S Fuzzy Model

Consider a nonlinear system described by

$$\begin{cases} \dot{x}(t) = f(x(x)) + g(x(t))\, u(t) \\ y(t) = h(x(t)) \end{cases} \tag{1}$$

where $f(.)$, $g(.)$ and $h(.)$ are the nonlinear functions with appropriate dimensions, $x(t) \in \mathfrak{R}^{n}$ and $u(t) \in \mathfrak{R}^{m}$ are respectively the state and the input vectors.

The T-S modelling approach represents the behavior of the nonlinear system (1) by the interpolation of a set of linear sub-models. Each sub-model contributes to the global behavior of the nonlinear system through a weighting function $\mu_i(x(t))$. The system (1) can be represented with the Takagi-Sugeno fuzzy model (2), its i-th rule is given by [1]:

Model rule ***i***

IF $z_1(t)$ *is* M_{1i} and $z_p(t)$ is M_{pi}

$$\textbf{THEN} \begin{cases} \dot{x}(t) = A_i x(t) + B_i u(t) \\ y_i(t) = C_i x(t) \end{cases} \tag{2}$$

where $i = 1, 2, ...r$, M_{ji} is fuzzy set and r is the number of fuzzy rule. $A_i \in \mathfrak{R}^{n\times n}$, $B_i \in \mathfrak{R}^{n\times m}$. $z_1(t) \sim z_2(t)$ are known premise variable may be function of the states measurable. We will use $z(t)$ to denote the vector containing all the individual elements $z_1(t) \sim z_p(t)$.

Given a pair of $[x(t), u(t), z(t)]$, the final output of the fuzzy system is inferred by using the center of gravity method for defuzzification

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^{r} h_i(z(t))\,(A_i x(t) + B_i u(t)) \\ y(t) = \sum_{i=1}^{r} h_i(z(t))\, C_i x(t) \end{cases} \tag{3}$$

Here h_i are calculated as follow:

$$h_i(z(t)) = \frac{w_i(z(t))}{\sum_{i=1}^{r} w_i(z(t))} \tag{4}$$

where w_i is given by:

$$w_i(z(t)) = \prod_{j=1}^{p} M_{ji}(z_j(t)) \tag{5}$$

$h_i(z(t))$ is regarded as the normalized weight of each model rule and $M_{ji}(z_j(t))$ is the grade of membership of $z_j(t)$ in M_{ji}. The membership values h_i have to satisfy the following conditions

$$\begin{cases} \sum_{i=1}^{r} h_i(x(t)) = 1 \\ 0 \leq h_i(x(t)) \leq 1 \forall\, i \in \{1, 2, ..., r\} \end{cases} \tag{6}$$

Our objective is to achieve $x(t) - x_d(t) \to 0$ as $t \to \infty$, where $x_d(t)$ is the desired state vector under the following assumptions:

***Assumption* 1**: The matrix B_i has full rank.

***Assumption* 2**: Each linear sub-system of the global model is controllable if $rank\,(V_i) = n$ with $V_i = [B_i, A_i B_i, ..., A_i^{n-1} B_i]$ for $i = 1,..., r$

3. Design of Fuzzy SMC Control Law

We can always design the SMC u_i for each subsystem of (3) such that $S_i = \bigcap_{j=1}^{l} S_j = \{x \in R^n : C_i x = 0\}$ are usually intersecting hyper-planes passing through the state space origin. The sliding mode occurs when the state reaches and remains in the intersection S^i of the l hyper-planes. Geometrically, the subspace S^i is the null space (or Kernel) of C_i.

Differentiating S^i with respect the time

$$\dot{S}^i = C_i \dot{x} = 0 \tag{7}$$

From (3) and (7), we get:

$$\dot{S}^i = C_i A_i x(t) + C_i B_i u_i(t) = 0 \tag{8}$$

if $(C_i B_i)^{-1}$ exists, then

$$u_{eq,i} = -(C_i B_i)^{-1} C_i A_i x = -k_i x \tag{9}$$

with

$$k_i = (C_i B_i)^{-1} C_i A_i \tag{10}$$

As a result, the dynamics $\dot{x} = (I - B_i (C_i B_i)^{-1} C_i) A_i x$ describes the motion on the sliding surface which is independent of the actual value of the control and depends only on the choice of the matrix C_i.

In order to achieve our objective, we choose the sliding surface that gives good behaviour during the sliding mode, and the reaching step in which we select the control to ensure that the reaching condition is met.

3.1 Design of fuzzy Sliding Surface

The canonical form used in [13] for **VSC** design can be applied for all the local models in order to select the gain matrix C_i.

***Assumption* 3**: There exists an $(n \times n)$ eorthogonal transformation matrix T_i such that $Y = T_i x$ and $T_i B_i = \begin{bmatrix} 0 \\ B_{2,i} \end{bmatrix}$ where B_i has null rank m and $B_{2,i}$ is non-singular.

The transformed state variable vector is defined as

$$Y = T_i x \tag{11}$$

The state equation becomes

$$Y = T_i A_i T_i^T Y + T_i B_i u \tag{12}$$

The sliding condition is

$$C_i x = C_i T_i^T Y = 0 \quad \text{with} \quad C_i T_i^T = [C_{1,i} C_{2,i}] \tag{13}$$

If the transformed state is partitioned as $Y^T = [Y_{1,i}^T Y_{2,i}^T]$, with $Y_{1,i} \in R^{n-m}$ and $Y_{2,i} \in R^m$ such as

$$T_i A_i T_i^T = \begin{bmatrix} A_{11,i} & A_{12,i} \\ A_{21,i} & A_{22,i} \end{bmatrix} \tag{14}$$

Then the system is given by

$$\begin{cases} \dot{Y}_1 = A_{11,i} Y_1 + A_{12,i} Y_2 \\ \dot{Y}_2 = A_{21,i} Y_1 + A_{22,i} Y_2 + B_{2,i} u \end{cases} \tag{15}$$

***Assumption* 4**: $C_i B_i$ non singular implies that $C_{2,i}$ must also be non singular and the condition defining the sliding mode is:

$$\begin{cases} Y_2 = -C_{2,i}^{-1} C_{1,i} Y_1 = -F_i Y_1 \\ F_i = C_{2,i}^{-1} C_{1,i} \end{cases} \tag{16}$$

with F_i is matrix of dimension $m \times (n-m)$ and the order of the uncertain system is $(n-m)$.

The sliding mode is governed by the following system equations

$$\begin{cases} \dot{Y}_1 = A_{11,i} Y_1 + A_{12,i} Y_2 \\ Y_2 = -F_i Y_1 \end{cases} \tag{17}$$

where Y_2 playing the role of a state feedback control.

The closed loop system is

$$\dot{Y}_1 = (A_{11,i} - A_{12,i} F_i)\, Y_1 \tag{18}$$

This indicates that the design of a stable sliding mode requires the selection of gain matrix F_i such that $\Psi_i = A_{11,i} - A_{12,i} F_i$ has $(n-m)$ left-half-plane eigen-values.

3.2 Determination of the gain matrix F_i

To determine the matrix C_i and the gain F_i, the method of the **LMI** seems to us very effective. Indeed to improve the performance of the control law and the response of system. We select to place the poles in a defined area [14], called area **LMI** who will allow us to obtain from good result. For that we propose to choose all the eigen-values of the matrix in an area defined by equation (14) such that is stable and its eigen-values are localised in:

- Conic sector centred at (0, 0) with inner angle θ
- Disc of radius r, and centre $(q, 0)$
- Vertical strip $\lambda(\Psi_i) \prec \sigma$

Chilali and Gahinet [14] have proven that the following inequalities will describe these regions

$$\begin{bmatrix} (P_i\Psi_i + \Psi_i^T P_i)s & -(P_i\Psi_i - \Psi_i^T P_i)c \\ (P_i\Psi_i + \Psi_i^T P_i)c & (P_i\Psi_i - \Psi_i^T P_i)s \end{bmatrix} \prec 0 \tag{19}$$

$$\begin{bmatrix} -rP_i & P_i\Psi_i - qP_i \\ \Psi_i^T P_i - qP_i & -rP_i \end{bmatrix} \prec 0 \tag{20}$$

$$P_i\Psi_i + \Psi_i^T P_i - 2\sigma P_i \prec 0 \tag{21}$$

where $s = \sin\theta$ and $c = \cos\theta$

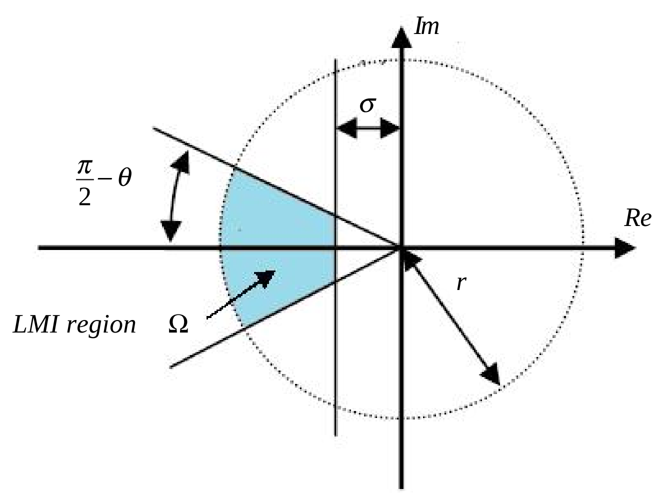


Figure 1. The damping sector Ω for root clustering

Once the stabilizing matrix F_i is determined, the matrix C_i can be obtained by

$$C_i = [\, F_i \; I_m \,]\, T_i \tag{22}$$

4. Control Law Design

Once the existence problem has been solved that is the matrix has been determined, attention must be turned to solving the reachability problem. This involves the selection of a feedback control function $u(x)$ which ensures that trajectories are directed towards the switching surface from any point in the state space.

The proposed control law consists of the sum of a linear control law $u_{L,i}$ and a nonlinear part $u_{N,i}$, which has the following form:

$$u(x) = L_i x + \rho \frac{N_i x}{\| M_i x \| + \delta} = u_{L,i} + u_{N,i} \tag{23}$$

where L_i is an $m \times n$ matrix, the null spaces of the matrices N_i, M_i; and C_i are coincident, and δ is a small positive constant to replace the discontinuous component by a smooth nonlinear function, yielding chattering-free system response. ρ is a design parameter.

Starting from the transformed state $[Y_{1,i}^T \; Y_{2,i}^T]^T$, we form a second transformation $T_{2,i} : \Re^n \rightarrow \Re^n$ such that:

$$z = T_{2,i}\, Y = [z_1^T \; z_2^T\,]^T \tag{24}$$

with $z_1 \in \Re^{n-m}$ and $z_2 \in \Re^m$ where

$$T_{2,i} = \begin{bmatrix} I_{n-m} & 0 \\ F_i & I_m \end{bmatrix} \tag{25}$$

$$T_{2,i}^{-1} = \begin{bmatrix} I_{n-m} & 0 \\ -F_i & I_m \end{bmatrix} \tag{26}$$

Then the state variables z_1 and z_2 are

$$\begin{cases} z_1 = Y_1 \\ z_2 = F_i Y_1 + Y_2 \end{cases} \tag{27}$$

The transformed system is given by

$$\begin{cases} \dot{z}_1 = \Sigma_{1,i} z_1 + \Sigma_{2,i} z_2 \\ \dot{z}_2 = \Sigma_{3,i} z_1 + \Sigma_{4,i} z_2 + B_{2,i} u_i \end{cases} \tag{28}$$

with

$$\begin{cases} \Sigma_{1,i} = A_{11,i} - A_{12,i} F_i \\ \Sigma_{2,i} = A_{12,i} \\ \Sigma_{3,i} = F_i \Sigma_{1,i} - A_{22,i} F_i + A_{21,i} \\ \Sigma_{4,i} = A_{22,i} + A_{12,i} F_i \end{cases} \tag{29}$$

(30)

4.1 Design of the linear fuzzy control law $u_{L,i}$

The linear control law $u_{L,i}$ is obtained by taking $z_1 = \dot{z}_2 = 0$, which is defined as

$$u_{L,i}(x) = -B_{2,i}^{-1} [\, \Sigma_{3,i} (\Sigma_{4,i} - \Sigma_{4,i}^*)] T_{2,i} T_i x = L_i x$$

with

$$L_i = -B_{2,i}^{-1} [\Sigma_{3,i} (\Sigma_{4,i} - \Sigma_{4,i}^*)] T_{2,i} T_i \tag{31}$$

where $\Sigma_{4,i}^{*} \in R^{m\times m}$ is a matrix such that its eigen-values are in the left half complex plane.

4.2 Design of the non-linear fuzzy control law $u_{N,i}$

$$V_{2,i}(z_2) = \frac{1}{2} z_2^T P_{2,i} z_2 \tag{32}$$

where $P_{2,i}$ is a positive definite matrix solution of

$$P_{2,i}\Sigma_{4,i}^{*} + \Sigma_{4,i}^{*T} P_{2,i} I_m = 0 \tag{33}$$

with $P_{2,i} z_2 = 0$ if and only if $z_2 = 0$

By differentiating (32), we obtain

$$\dot{V}_{2,i}(z_2) = -\frac{1}{2} \dot{z}_2^T P_{2,i} z_2 + \frac{1}{2} z_2^T P_{2,i} \dot{z}_2 \tag{34}$$

and taking $P_{2,i}\Sigma_4^{*} = -\left(\frac{I_m}{2}\right)$, (34) begin

$$\dot{V}_{2,i}(z_2) = \frac{1}{2} \| z_2 \|^2 + z_2 P_{2,i} B_{2,i} u_{N,i} \tag{35}$$

Using equation (23), the following equation can be obtained:

$$z_2 P_{2,i} u_{N,i} = -\rho \frac{P_{2,i} z_2}{\| P_{2,i} z_2 \| + \delta} B_{2,i}^{-1} \tag{36}$$

then, the existence of $\dot{V}_{2,i}(z_2) < 0$ is provided.

Finally, using T_i et $T_{2,i}$, we find

$$N_i = -B_{2,i}^{-1} [0 \;\; P_{2,i}] \, T_{2,i} T_i \tag{37}$$

$$M_i = [0 \;\; P_{2,i}] \, T_{2,i} T_i \tag{38}$$

5. Numerical Application

We consider the single link robot with flexible joint (Figure 2). This benchmark problem is investigated as a case study for the control method proposed in this paper.

The single link flexible joint manipulator and its dynamics given as [12]

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \dot{x}_3 = x_4 \\ \dot{x}_4 = \dfrac{MgL}{I} \sin x_1 \left[x_2^2 + \dfrac{MgL}{I} \cos x_1 + \dfrac{k}{I} \right] + \left(x_3 + \dfrac{MgL}{I} \sin x_1 \right) \left[\dfrac{MgL}{I} \cos x_1 + \dfrac{k}{I} + \dfrac{k}{J} \right] + \dfrac{k}{IJ} u \end{cases}$$

where I is the link inertia moment, J is the motor inertia moment and M is the link mass. k is the joint elastic constant, is the L distance from the axis of the rotation to the link center of mass, g ($9.8 ms^{-2}$) is the gravitational acceleration and u control input.

We assume that $I = 1 Kgm^2$, $J = 1 Kgm^2$, $M = 1 Kg$ and $k = 1 Nm^{-1}$ for the simplicity of calculation.

Figure 4 is the surface viewer, which defines the relationship between 2 inputs of the $x_1(t)$ and $x_1(t)$ with 1 output.

The membership functions for the states are shown in Figure 3. The fuzzy rules can be obtained by linearizing the nonlinear equation at the point $[x_1, x_2] = [-\pi, 0, \pi]$as follows

***Rule* 1 IF** x_1 is about 0 and x_2 is about 0, **THEN**

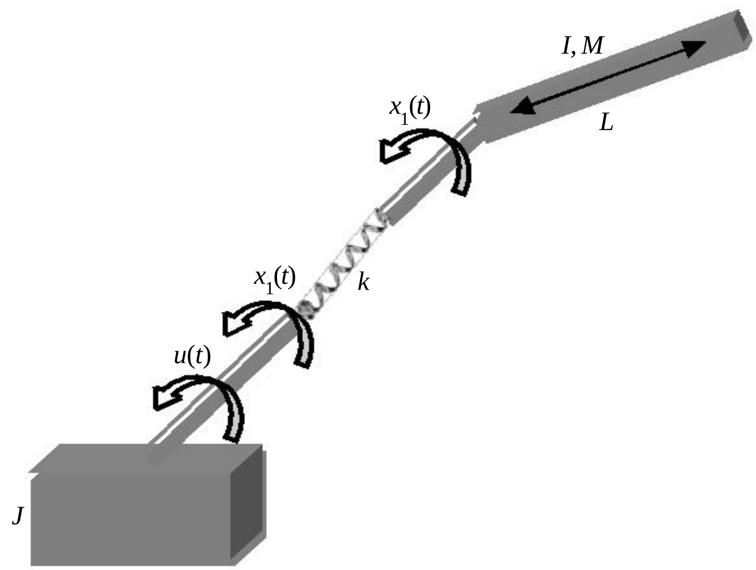


Figure 2. A flexible joint mechanism

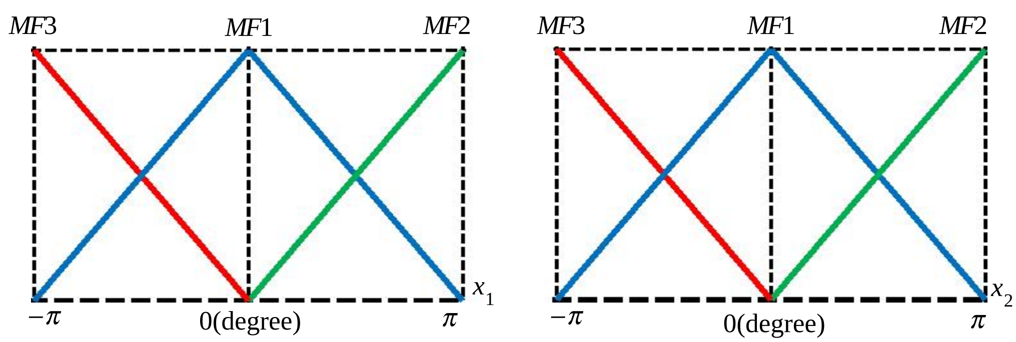


Figure 3. Membership functions

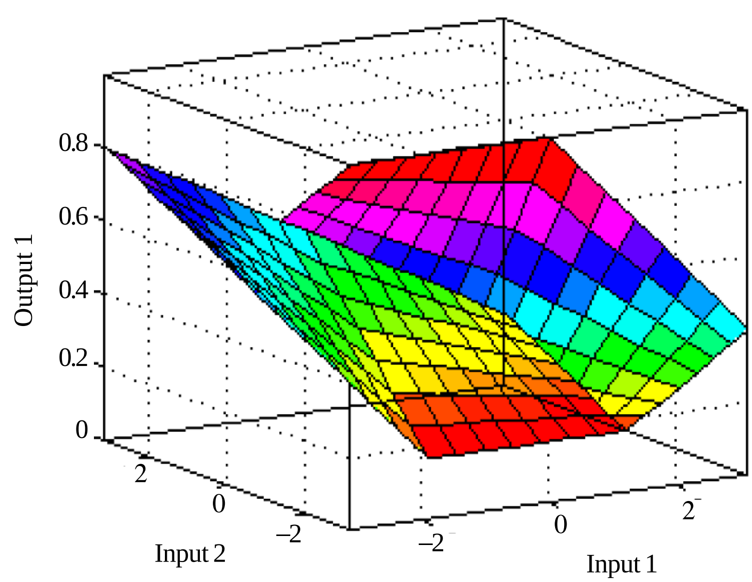


Figure 4. Surface viewer

$$\dot{x}(t) = A_1 x(t) + B_1 u(t)$$

***Rule* 2 IF** x_1 is about 0 and x_2 is about π, **THEN**

$$\dot{x}(t) = A_2 x(t) + B_2 u(t)$$

***Rule* 3 IF** x_1 is about 0 and x_2 is about $-\pi$, **THEN**

$$\dot{x}(t) = A_3 x(t) + B_3 u(t)$$

***Rule* 4 IF** x_1 is about π and x_2 is about 0 , **THEN**

$$\dot{x}(t) = A_4 x(t) + B_4 u(t)$$

***Rule* 5 IF** x_1 is about π and x_2 is about π, **THEN**

$$\dot{x}(t) = A_5 x(t) + B_5 u(t)$$

***Rule* 6 IF** x_1 is about π and x_2 is about $-\pi$, **THEN**

$$\dot{x}(t) = A_6 x(t) + B_6 u(t)$$

***Rule* 7 IF** x_1 is about $-\pi$ and x_2 is about 0 , **THEN**

$$\dot{x}(t) = A_7 x(t) + B_7 u(t)$$

Rule* 8 *If x_1 is about $-\pi$ and x_2 is about π, **THEN**

$$\dot{x}(t) = A_8 x(t) + B_8 u(t)$$

***Rule* 9 IF** x_1 is about $-\pi$ and x_2 is about $-\pi$, **THEN**

$$\dot{x}(t) = A_9 x(t) + B_9 u(t)$$

where

$$A_1 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -9.8 & 0 & -11.8 & 0 \end{bmatrix}, A_2 = A_3 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 86.9 & 0 & -11.8 & 0 \end{bmatrix},$$

$$A_4 = A_7 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 9.8 & 0 & 7.8 & 0 \end{bmatrix}$$

$$A_5 = A_6 = A_8 = A_9 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 86.9 & 0 & 7.8 & 0 \end{bmatrix}, B_i = [0 \;\; 0 \;\; 0 \;\; 1]^T, i = 1, 2, ..., 9$$

Using **LMI** feasibility problem (19) to (21), the eigen-values of the sliding motion represented by the system matrix F_i were required to lie in the intersection of the following regions

- A conic sector symmetric about the real axis, with inner angle $\theta = \frac{\pi}{8}(rad)$
- A circle of centre (0,0) and radius10
- A vertical upper bound at $\sigma = -3.5$

$$F_i = [180,6534 \quad -17,8599 \quad -99,5267], \quad \text{for } i = 1, 2, ..., 9$$

$$C_i = [-180,6534 \quad -99,5267 \quad -17,8599 \quad -1], \quad \text{for } i = 1, 2, ..., 9$$

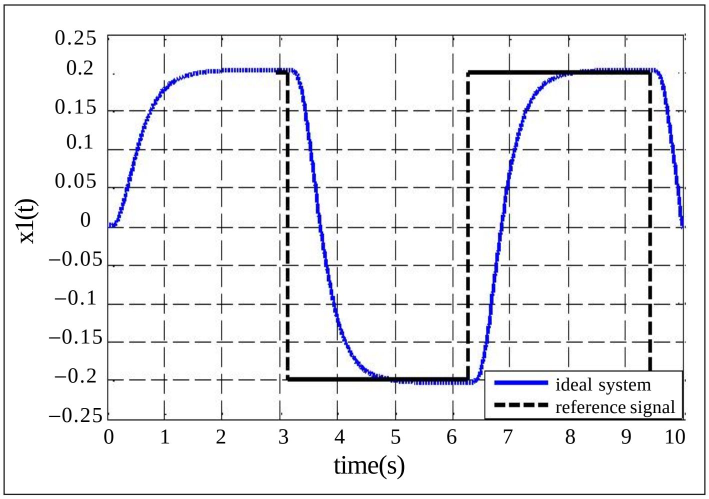
We get for $\Sigma^*_{4,i} = \{-30\}$, $\rho_i = 28$ and $\delta_i = 0.001$the following results:

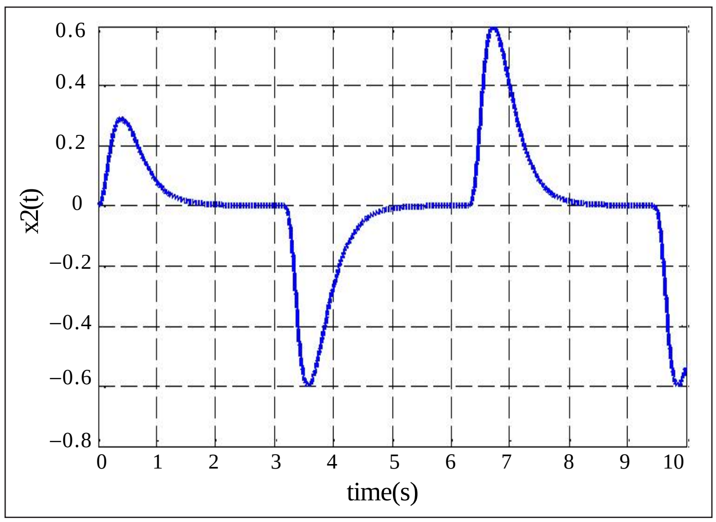
$$L_1 = 10^3[-5,4098 \quad -3,1665 \quad -0,6235 \quad -0,0479]$$

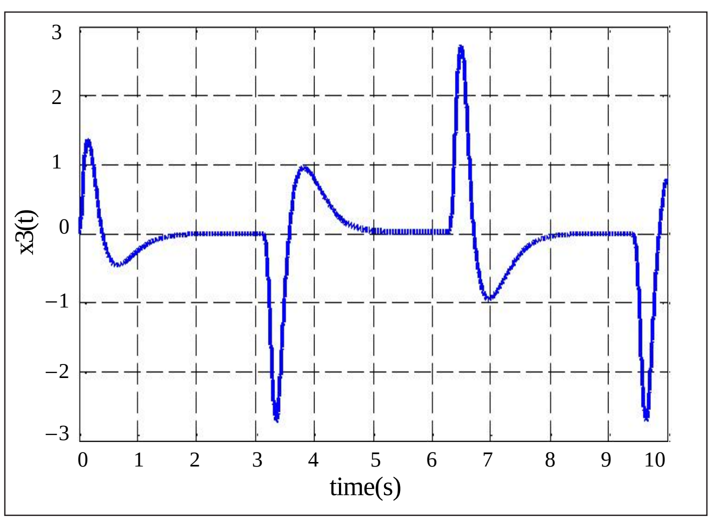
$$L_2 = L_3 = 10^3[-5,5065 \quad -3,1665 \quad -0,6235 \quad -0,0479]$$

$$L_4 = L_5 = L_6 = L_7 = L_8 = L_9$$

$$= 10^3 [-5,4294 \quad -3,1665 \quad -0,6431 \quad -0,0479]$$







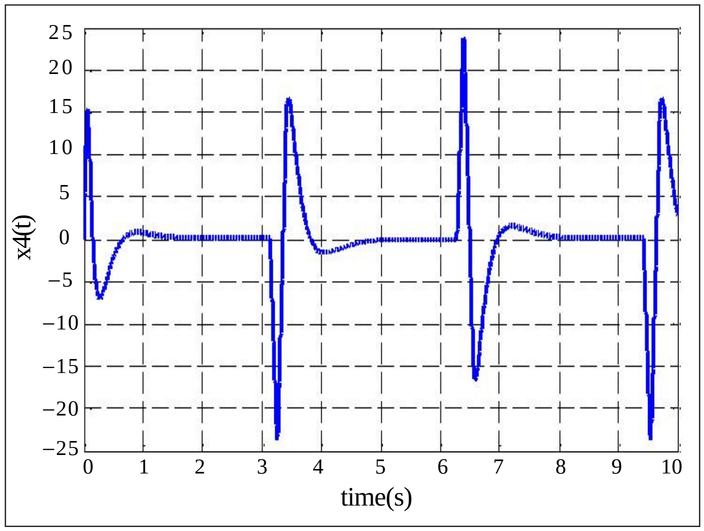


Figure 5. The evolution of state variables

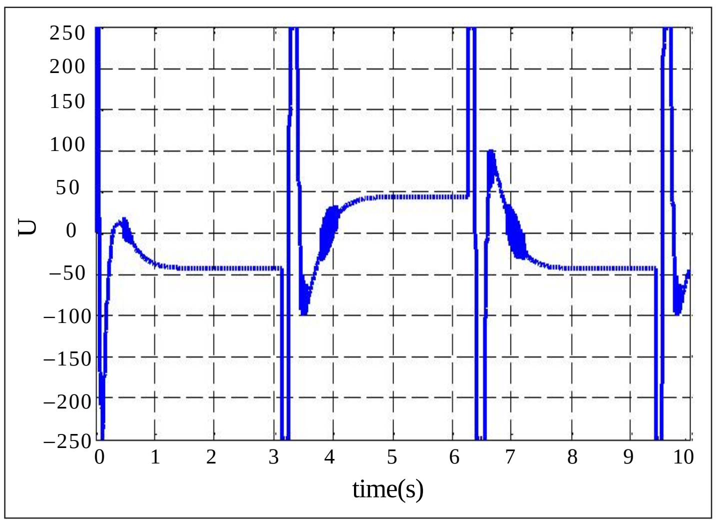


Figure 6. Evolution of the control *u*

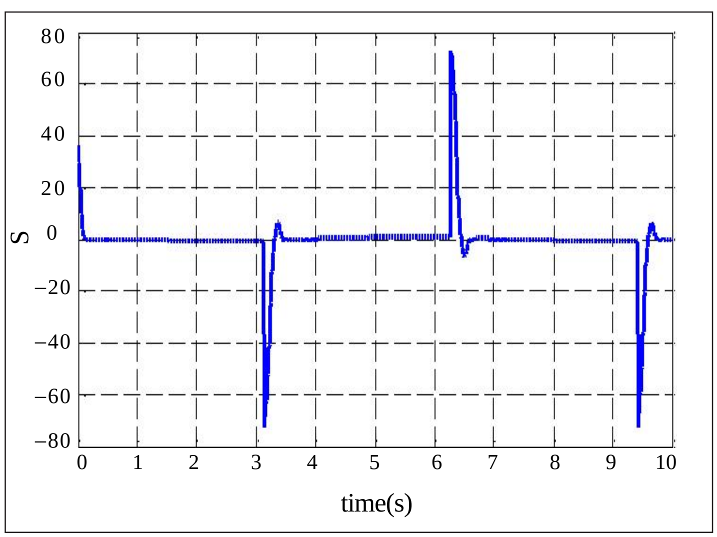


Figure 7. The sliding surface *S*

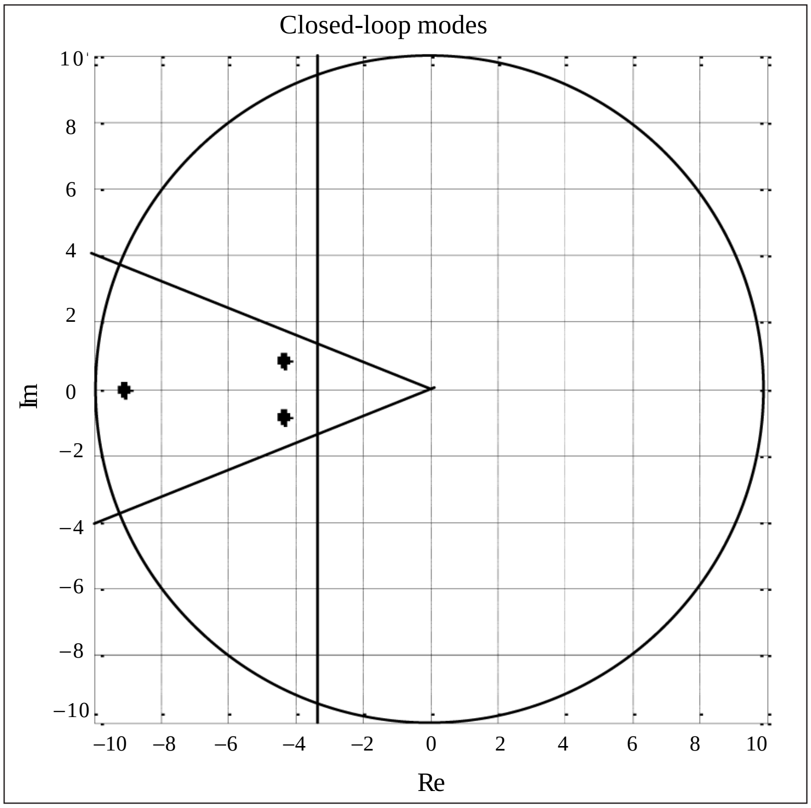


Figure 8. Closed-loop modes

$$M_i = [-3{,}0109 \quad -1{,}6588 \quad -0{,}2977 \quad -0{,}0167], \quad \text{for } i = 1, 2, ..., 9$$

$$N_i = [-3{,}0109 \quad -1{,}6588 \quad -0{,}2977 \quad -0{,}0167], \quad \text{for } i = 1, 2, ..., 9$$

The robustness of the proposed sliding mode control law is shown Figures 5 and 6. A similar analysis can be seen also in Figures 7 and 8.

6. Conclusion

A sliding mode control design approach for nonlinear-time invariant systems has been proposed in two steps. The first step consists in the synthesis of the sliding surface which gives a good behaviour during the sliding mode. It corresponds to the study of the problem of existence. In the second step, a nonlinear control scheme is introduced. It provides a bounded motion about the ideal sliding mode. Numerical simulation has been presented showing the efficiency and the robustness of the proposed method.

References

[1] Takagi, T., Sugeno, *M*. (1985). Fuzzy identification of systems and its application to modeling and control, *IEEE Trans. On System*, *Man and Cybernetics*, 15 (1) 116–132.

[2] Lotfi, C., Oussama, S., Abdelkader, C. (2013). Sliding Mode Control of Nonlinear Uncertain System Based on Takagi-Sugeno Fuzzy Model, *International Conference on Electrical Engineering and Software Applications*, Tunis March.

[3] Emelyanov, S. V. (1967). Variable structure control systems, Moscow, Nauka.

[4] Utkin, V. I. (1977). Variable structure systems with sliding mode, *IEEE Trans. On Auto. Cont*, 26 (2) 212-222.

[5] Ryan, E. P., Corless, M. (1984). Ultimate boundedness and asymptotic stablity of a class uncertain dynamicall systems via continuous and discontinuous feedback control, *IMAJ of Mathematics and Control Information,* 1, p. 223-242.

[6] Filippov, M. (1960). Equations différentielles à second membre discontinu. *Journal de mathématiques*, 51 (1) 99-128.

[7] Spurgeon, S. K., Davies, R. (1993). A nonlinear control strategy for robust sliding mode performance in the presence of unmatched uncertainty, *International Journal of Control*, 57 (5) 1107-1123.

[8] Sallemi, A., Arzelier, D., M'hiri, R., Zrida, J. (2007). A sliding mode control approach for systems subjected to a norm-bounded uncertainty, *International Journal of Robust and Nonlinear Control*, 17 (4) 327-346.

[9] Torchani, B., sallemi, A., Hiri, R. M., Germain. Garcia, (2010). Saturated systems with sliding mode control, *International Journal of Sciences and Technique of Automatic control & computer engineering IJ-STA*, 4 (1)1208-1219.

[10] Ming, Y., Yi, J., Liu, Y., Wei, J. X., Huang, X. (2009). Sliding Mode Control Algorithm Based on T-S Fuzzy Model for a Class of Nonlinear Systems, *In*: Proceeding of the IEEE International Conference on Automation and Logistics Shenyang, China August.

[11] Utkin, V. I. (1992). *Sliding modes in control optimization*, Springer, Berlin.

[12] Hyun, C., Park, C., Kim, S. (2010). Takagi–Sugeno fuzzy model based indirect adaptive fuzzy observer and controller design, *Information Sciences*, 180, p. 2314-2327.

[13] Dorling, C. M., Zinober, A. (1986). Two approaches to hyperplane design multivariable variable structure control systems, *International Journal of Control*, 44 (1) 65–82.

[14] Chilali, M., Gahinet, *P*. (1996). H.V design with Pole Placement constraints: An LMI Approach. *IEEE Transactions on Automatic Control*, 41 (3) 358-367, March.