International Journal of Advanced and Applied Sciences, 10(10) 2023, Pages: 166-173

Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: http://www.science-gate.com/IJAAS.html

Fuzzy nonsingular fast terminal sliding mode controller for a robotic system

Lafi Alnufaie *

Department of Electrical Engineering, Engineering College, Shaqra University, Shaqra, Saudi Arabia

ARTICLE INFO

Article history:
Received 25 May 2023
Received in revised form
16 September 2023
Accepted 6 October 2023

Keywords:
Robotic system control
Nonsingular fast sliding mode
Type-2 fuzzy logic
Adaptive fuzzy systems
Control system simulation

ABSTRACT

This study introduces an innovative control strategy utilizing a nonsingular fast sliding mode technique tailored for robotic systems. The core of this approach lies in the development of a type-2 fuzzy logic-based nominal model, meticulously designed to accurately approximate the dynamics of the real system while adeptly handling the variability in system parameters. This method marks a departure from conventional approaches by inferring the switch signal for type-2 adaptive fuzzy systems, a critical step in achieving superior tracking performance without the necessity for extensive knowledge of the system's upper bounds in uncertainties and external disturbances. The efficacy of the proposed control law is rigorously validated through a series of simulations, encompassing a variety of initial conditions and reference signals, thereby demonstrating its robust performance capabilities.

1. Introduction

Widely used in many applications, sliding mode control can be considered a very popular approach to ensure good tracking performance against external disturbances (Liang et al., 2022). Despite its simple design procedure and good tracking performance, sliding mode control has two major disadvantages. This first one is the chattering phenomena introduced by using the signum function in the control signal. The second disadvantage lies in its time convergence, which cannot be imposed. Several improvements have been proposed in the literature to reduce the chattering phenomena. In Vo and Kang (2019), the switching signal is smoothed by using a low-pass filter. An adaptive fuzzy system has been used by Hamzaoui et al. (2004) to substitute the switching control and, hence, to eliminate the chattering phenomenon. However, this improvement needs a tradeoff between the smoothness of the switching signal and tracking performance. Second-order sliding mode control has also presented a good solution to chattering but the design procedure is complex and requires a good knowledge of the studied system (Manceur et al., 2011).

Recently, terminal sliding mode control has been developed, where a nonlinear surface is used (Venkataraman and Gulati, 1993; Wang et al., 2016a). However, these kinds of controllers suffer from singularity problems due to the presence of terms with negative fractional powers (Boukattaya et al., 2018). This problem can be resolved by using a nonsingular terminal sliding mode controller (Boukattaya et al., 2018; Venkataraman and Gulati, 1993; Vo and Kang, 2019). Nevertheless, this improvement was obtained at the expense of the convergence time which becomes slower. Nonsingular fast terminal sliding mode controller has been developed to overcome singularity and to obtain fast convergence time (Jayaraman et al., 2022; Van et al., 2016; Wang et al., 2016b; Xu et al., 2021; Zhai et al., 2021). Thus, in this paper, we propose a nonsingular fast terminal sliding mode controller for a robotic system that guarantees finite-time convergence, fast speed when the states are far from the origin, avoidance of singularity, and without chattering. The main contribution of authors: (i) a type-2 fuzzy nominal model is elaborated to overcome the problem of knowledge of system parameters. Using type-2 fuzzy logic allows us to ensure a robust model against uncertainties. (ii) the switching control signal terms are calculated adaptive type-2 fuzzy systems used to avoid a well-knowledge of the upper bounds of both uncertainties

* Corresponding Author.
Email Address: lalnufaie@su.edu.sa
https://doi.org/10.21833/ijaas.2023.10.019
Corresponding author's ORCID profile:
https://orcid.org/0000-0003-2453-2637

and external disturbances, which are in general unknown.

The remainder of this paper is organized as follows. Section 2 is dedicated to introducing type-2 fuzzy systems. In Section 3, the problem statement of controlling a robotic system is treated. Section 4 is dedicated to the controller design and stability analysis. Simulation and results are given in Section 5 to show the effectiveness of the proposed approach. Finally, the conclusion is provided.

2. Interval type-2 fuzzy logic system

Fuzzy Logic Systems are known as universal approximators and have several applications in control design and identification. A type-1 fuzzy system consists of four major parts: fuzzifier, rule base, inference engine, and defuzzifier. A T2FLS is very similar to a T1FLS, the major difference being that the defuzzifier block of a type-1 fuzzy system is replaced by the output processing block in a type-2 fuzzy system, which consists of type-reduction followed by defuzzification as presented in Fig. 1 (Karnik et al., 1999; Li et al., 2016; Manceur et al., 2013).

In an interval type-2 fuzzy system, a triangular fuzzy set is defined by a lower and upper set as shown in Fig. 2.

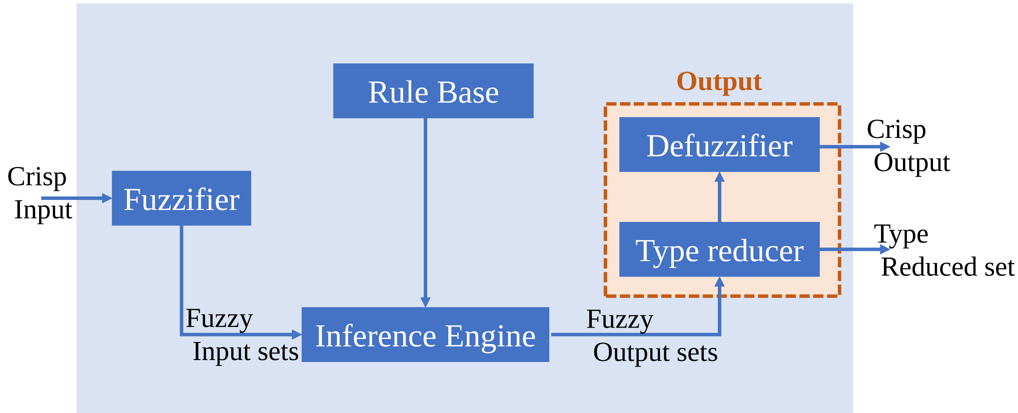

Fig. 1: Structure of a type-2 fuzzy logic system

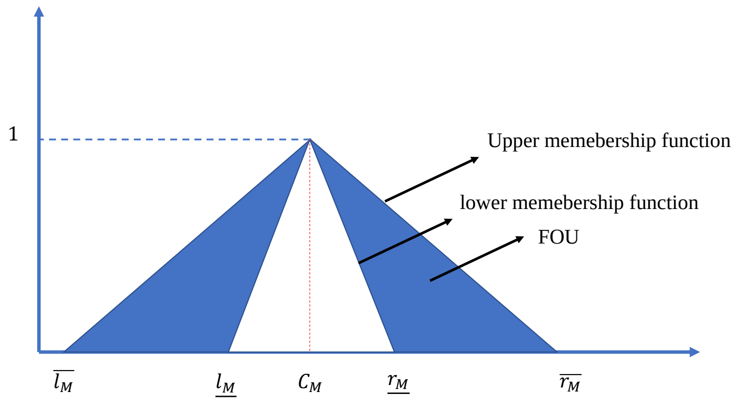

Fig. 2: Interval type-2 triangular fuzzy sets

It is clear that the interval type-2 fuzzy set is in a region bounded by an upper membership function and a lower membership function denoted as $\bar{\mu}_{\tilde{A}(x)}$ and $\underline{\mu}_{\tilde{A}}$ respectively and is named a foot of uncertainty (FOU) Assume that there are M rules in a type-2 fuzzy rule base, and each of them has the following form:

$$R^i: IF\ x_1\ is\ \tilde{F}_1^i\ and \dots and\ x_n\ is\ \tilde{F}_n^i\ THEN\ y\ is\ [w_l^i\ w_r^i]$$

where, $x_j\ j = 1,2, \dots, n$ and y are the input and output variables of type-2 fuzzy system, respectively, the $\tilde{F}_j^i$ is the type-2 fuzzy sets of antecedent parts and $[w_l^i\ w_r^i]$ is the weighting interval set in the consequent part the operation of type-reduction is to give a type-1 set from a type-2 set. In the meantime, the firing strength Fi for the ith rule can be an interval type-2 set expressed as:

$$F^i \equiv \left[\underline{f}^i, \bar{f}^i\right]$$

where,

$$\begin{cases} \underline{f}^i = \underline{\mu}_{\tilde{F}_1^i}(x_1) * \dots * \underline{\mu}_{\tilde{F}_n^i}(x_n) \\ \bar{f}^i = \bar{\mu}_{\tilde{F}_1^i}(x_1) * \dots * \bar{\mu}_{\tilde{F}_1^i}(x_n) \end{cases}.$$

In this work, the center of set type-reduction method is used to simplify the notation. Therefore, the output can be expressed as:

$y_{cos}(x) = [y_l\,; y_r]$

where, $y_{cos}(x)$ is also an interval type-1 set determined by left and most points (y_l and y_r), can be derived from the consequent centroid set $[w_l^i \; w_r^i]$ (either $\underline{w}^i$ or $\overline{w}^i$) and the firing strength $f^i \in F^i \equiv [\underline{f}^i, \overline{f}^i]$. The interval set $[w_l^i \; w_r^i]$ $(i = 1, \dots, M)$ should be computed or set first before the computation of $y_{cos}(x)$. Hence, left most point y_l and right most point y_r can be expressed as;

$$\begin{cases} y_l = \dfrac{\sum_{i=1}^{M} \underline{f}^i w_l^i}{\sum_{i=1}^{M} \underline{f}^i} \\ y_r = \dfrac{\sum_{i=1}^{M} \overline{f}^i w_r^i}{\sum_{i=1}^{M} \overline{f}^i} \end{cases} \tag{1}$$

Using the center of set type reduction method to compute y_l and y_r the defuzzified crisp output from an interval type-2 fuzzy logic system can be obtained according to the following equation:

$$y(x) = \frac{y_l + y_r}{2} \tag{2}$$

Which can be rewritten in the following vectorial form:

$$y(x) = \Psi^T(x).w \tag{3}$$

where, $\Psi^T(x)$ represents the regressive vector and w the consequent vector containing the conclusion values of the fuzzy rules.

3. Problem statement

Let us consider the dynamic equation of n degree-of-freedom robotic manipulators as follows:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q,\dot{q}) = \Gamma(t) + \Gamma_{ext}(t) \tag{4}$$

where, q, $\dot{q}$ and $\ddot{q} \in \mathbb{R}^n$ are the vectors of joint position, joint velocity, and joint acceleration, respectively. $M(q) \in \mathbb{R}^{n\times n}$ is a symmetric and positive definite inertia matrix, $C(q,\dot{q}) \in \mathbb{R}^{n\times n}$ is the matrix of centrifugal and Coriolis forces, $G(q) \in \mathbb{R}^n$ is the vector of gravitational forces, $\Gamma(t) \in \mathbb{R}^n$ is the vector of input joint torque and $\Gamma_{ext}(t) \in \mathbb{R}^n$ is the vector of unknown external disturbances.

For practical applications, it is impossible to know the exact dynamic model of the robotic manipulators. Hence, the above dynamic quantities can be expressed as:

$$\begin{aligned} M(q) &= M_0(q) + \Delta M(q) \\ C(q,\dot{q}) &= C_0(q,\dot{q}) + \Delta C(q,\dot{q}) \\ G(q) &= G_0(q) + \Delta G(q) \end{aligned} \tag{5}$$

where, $M_0(q)$, $C_0(q,\dot{q})$, $G_0(q)$ are the nominal values of $M(q)$, $C(q,\dot{q})$, $G(q)$ respectively and $\Delta M(q)$, $\Delta C(q,\dot{q})$, $\Delta G(q)$ are the uncertain parts of $M(q)$, $C(q,\dot{q})$, $G(q)$ respectively.

Using Eq. 5, the dynamic model of the robotic manipulators can be expressed as:

$$M_0(q)\ddot{q} + C_0(q,\dot{q})\dot{q} + G_0(q,\dot{q}) = \Gamma(t) + \delta(q,\dot{q},\ddot{q}) \tag{6}$$

where,

$$\delta(q,\dot{q},\ddot{q}) = \Gamma_{ext}(t) - \Delta M(q)\ddot{q} - \Delta C(q,\dot{q})\dot{q} - \Delta G(q).$$

Let's define the tracking error $e = q - q_d$ and its time derivative $\dot{e} = \dot{q} - \dot{q}_d$ where, q_d the desired trajectory. Then the error dynamic of the robotic manipulators with the uncertainties and disturbances can be written as:

$$\ddot{e} = f(e,\dot{e}) + g(e,\dot{e})\Gamma(t) + D(e,\dot{e}) \tag{7}$$

where,

$(e,\dot{e}) = -M_0^{-1}(q)[C_0(q,\dot{q})\dot{q} + G_0(q,\dot{q})] - \ddot{q}_d$, $g(e,\dot{e}) = M_0^{-1}(q)$

and

$D(e,\dot{e}) = M_0^{-1}(q)\,\delta(q,\dot{q},\ddot{q})$.

As given in [14], the upper bound of lumped uncertainty can be expressed as:

$$|D(e,\dot{e})| \le a_0 + a_1|q| + a_2|\dot{q}|^2 \tag{8}$$

where, b_0, b_1 and b_2 are positive scalars.

The next task is to develop a robust controller based on nonsingular fast terminal sliding mode control allowing tracking objectives (Feng et al., 2002; Van et al., 2016; Wang et al., 2016a).

4. Controller design

To design our controller, let's consider the following nonsingular terminal sliding surface:

$$S(t) = e + k_1|e|^{\alpha} sign(e) + k_2|\dot{e}|^{\beta}\, sign(\dot{e}) \tag{9}$$

where, k_1 and k_2 are positive constants, $1 < \beta < 2$ and $\alpha > \beta$.

The structure of this surface allows us to attain fast convergence of the tracking error to zero. Indeed, if the position of the initial value is far from the desired one, then the term $k_1|e|^{\alpha} sign(e)$ will be dominant, which leads to fast convergence. In the case where the system is near the desired trajectory, the term $k_2|\dot{e}|^{\beta}\, sign(\dot{e})$ must ensure a finite time convergence.

The time derivative of the sliding surface can be written as:

$$\dot{S}(t) = \dot{e} + \alpha.k_1|e|^{\alpha-1}\,\dot{e} + \beta.k_2|\dot{e}|^{\beta-1}.\ddot{e} \tag{10}$$

Our control law will be composed of two terms. The first one, named equivalent control $\Gamma_e(t)$, is dedicated to maintaining the system on the sliding surface. In the second term, $\Gamma_s(t)$ called switching signal, must force the system to converge to the sliding surface. Then, to design the equivalent control law $\Gamma_e(t)$, we consider that the system is on the surface ($S(t) = 0$) and remains on ($\dot{S}(t) = 0$). In this case, the system is considered insensitive to uncertainties and external disturbances (Truong et al., 2021; Vo and Kang, 2019).

Using Eq. 7, Eq. 10 can be rewritten as:

$$\dot{S}(t) = \dot{e} + \alpha.k_1|e|^{\alpha-1}\,\dot{e} + \beta.k_2|\dot{e}|^{\beta-1}.[f(e,\dot{e}) + g(e,\dot{e})\Gamma_e(t)] \quad (11)$$

Then the expression of equivalent control law can be expressed as:

$$\Gamma_e(t) = -g^{-1}(e,\dot{e}).[f(e,\dot{e}) + [\beta.k_2]^{-1}\,|\dot{e}|^{2-\beta}(1 + \alpha.k_1|e|^{\alpha-1})\,sign(\dot{e})] \quad (12)$$

Note that, we used the fact that $\dot{e} = |\dot{e}|.sign(\dot{e})$ to write Eq. 9 in a compact form.

Our next task is to determine the expression of the switching signal $\Gamma_s(t)$ allowing to force the system to reach the sliding surface in the presence of uncertainties and external disturbances.

In this case, Eq. 10 becomes:

$$\dot{S}(t) = \dot{e} + \alpha.k_1|e|^{\alpha-1}\,\dot{e} + \beta.k_2|\dot{e}|^{\beta-1}.[f(e,\dot{e}) + g(e,\dot{e})\Gamma(t) + D(e,\dot{e})] \quad (13)$$

Using Eq. 12, we can rewrite Eq. 10 as:

$$\dot{S}(t) = \dot{e} + \alpha.k_1|e|^{\alpha-1}\,\dot{e} + \beta.k_2|\dot{e}|^{\beta-1}.[f(e,\dot{e}) + g(e,\dot{e})\Gamma_e(t)] + \beta.k_2|\dot{e}|^{\beta-1}.[g(e,\dot{e})\Gamma_s(t) + D(e,\dot{e})] \quad (14)$$

According to the definition of the equivalent control, Eq. 14 can be simplified to:

$$\dot{S}(t) = \beta.k_2|\dot{e}|^{\beta-1}.[g(e,\dot{e})\Gamma_s(t) + D(e,\dot{e})]. \quad (14a)$$

To deduce the expression of $\Gamma_s(t)$ allowing the switching condition, we consider the following Lyapunov function:

$$V(t) = \tfrac{1}{2}S^2(t). \quad (15)$$

Differentiating $V(t)$ concerning time and using Eq. 15 lead to:

$$\dot{V}(t) = S(t).\beta.k_2|\dot{e}|^{\beta-1}.[g(e,\dot{e})\Gamma_s(t) + D(e,\dot{e})]. \quad (16)$$

Choosing $\Gamma_s(t)$ as:

$$\Gamma_s(t) = -g^{-1}(e,\dot{e})[k_{01}.S(t) + (k_{02} + a_0 + a_1|q| + a_2|\dot{q}|^2).sign(S(t))] \quad (17)$$

where, k_{01} and k_{02} are two positive scalars. The time derivative of the Lyapunov function becomes:

$$\begin{aligned}\dot{V}(t) &= S(t).\beta.k_2|\dot{e}|^{\beta-1}.[g(e,\dot{e})\Gamma_s(t) + D(e,\dot{e})]\\ &= \beta.k_2|\dot{e}|^{\beta-1}.[-k_{01}.S^2(t) - (k_{02} + a_0 + a_1|q| + a_2|\dot{q}|^2).|S(t)| + D(e,\dot{e})]\end{aligned} \quad (18)$$

Using the assumption in Eq. 8, we obtain the following inequality:

$$\dot{V}(t) \le \beta.k_2|\dot{e}|^{\beta-1}.[-k_{01}.S^2(t) - k_{02}.|S(t)|] \le 0 \quad (19)$$

Based on the Lyapunov theorem, the system converges asymptotically to the sliding surface and remains on.

To prove convergence in finite time, let us take up inequality in Eq. 20:

$$\dot{V}(t) \le -\beta.k_{01}.k_2|\dot{e}|^{\beta-1}.S^2(t) - \beta.k_{02}.k_2|\dot{e}|^{\beta-1}.|S(t)| \quad (20)$$

$$\dot{V}(t) = \frac{dV(t)}{dt} \le -\underbrace{2.\beta.k_{01}.k_2|\dot{e}|^{\beta-1}}_{\beta_1}.V(t) - \underbrace{\sqrt{2}\beta.k_{02}.k_2|\dot{e}|^{\beta-1}}_{\beta_2}.V^{\frac{1}{2}}(t). \quad (21)$$

Then we can obtain:

$$dt \le \frac{-dV(t)}{\beta_1.V(t)+\beta_2.V^{\frac{1}{2}}(t)} = -2.\frac{dV^{\frac{1}{2}}(t)}{\beta_1.V^{\frac{1}{2}}(t)+\beta_2}. \quad (22)$$

If we consider that the system converges to 0 at $t = t_r$ implies that:

$$\int_0^{t_r} dt \le \int_{V(0)}^{V(t_r)} \frac{-2.dV^{\frac{1}{2}}(t)}{\beta_1.V^{\frac{1}{2}}(t)+\beta_2} = \left[-\frac{2}{\beta_1}ln\left(\beta_1 V^{\frac{1}{2}}(t) + \beta_2\right)\right]_{V(0)}^{V(t_r)} \quad (23)$$

hence,

$$t_r \le \frac{2}{\beta_1}ln\left(\frac{\beta_1 V^{\frac{1}{2}}(0)+\beta_2}{\beta_2}\right) \quad (24)$$

Consequently, the control law $\Gamma(t) = \Gamma_e(t) + \Gamma_s(t)$, whose terms are defined by Eqs. 12 and 18, guarantee the asymptotic stability of the closed-loop system and the convergence of the tracking error in a finite time.

Nevertheless, it is very difficult if not possible to know the exact values of the scalars a_0, a_1 and a_2. To overcome this problem, we propose to approximate them by three adaptive type-2 fuzzy systems $\hat{a}_0 = \Psi^T(e,\dot{e}).w_0$, $\hat{a}_1 = \Psi^T(e,\dot{e}).w_1$ and $\hat{a}_2 = \Psi^T(e,\dot{e}).w_2$. According to the universal approximation theorem, there exists an optimal value of type-2 fuzzy systems we can write:

$$\begin{aligned} a_0 &= \Psi^T(e,\dot{e}).w_0^*\\ a_1 &= \Psi^T(e,\dot{e}).w_1^*\\ a_2 &= \Psi^T(e,\dot{e}).w_2^*\end{aligned} \quad (25)$$

where, w_0^*, w_1^* and w_2^* represent the optimal values of w_0, w_1 and w_2 respectively. Consequently, the control laws become:

$$\begin{aligned} &\Gamma(t) = \Gamma_e(t) + \Gamma_s(t) \\ &\Gamma_e(t) = -g^{-1}(e,\dot{e}).\left[f(e,\dot{e}) + [\beta.k_2]^{-1}\,|\dot{e}|^{2-\beta}(1+\alpha.k_1|e|^{\alpha-1})\,sign(\dot{e})\right] \\ &\Gamma_s(t) = -g^{-1}(e,\dot{e})[k_{01}.S(t) + (k_{02} + \hat{a}_0 + \hat{a}_1|q| + \hat{a}_2|\dot{q}|^2).sign(S(t))] \end{aligned} \quad (26)$$

These modified control laws allow to ensure convergence to the reference trajectory in a finite time.

To deduce the adaptation laws of the three adaptive fuzzy systems, we consider the new Lyapunov function:

$$V(t) = \frac{1}{2}S^2(t) + \beta.k_2\left(\frac{1}{2\gamma_0}(w_0 - w_0^*)^2 + \frac{1}{2\gamma_1}(w_1 - w_1^*)^2 + \frac{1}{2\gamma_2}(w_2 - w_2^*)^2\right). \quad (27)$$

Using the control laws in Eq. 27 and the following adaptation laws:

$$\begin{aligned} &\dot{w}_0 = \gamma_0\Psi^T(e,\dot{e}).|S(t)|.|\dot{e}|^{\beta-1} \\ &\dot{w}_1 = \gamma_1\Psi^T(e,\dot{e}).|S(t)|.|\dot{e}|^{\beta-1}|e|. \\ &\dot{w}_2 = \gamma_0\Psi^T(e,\dot{e}).|S(t)|.|\dot{e}|^{\beta} \end{aligned} \quad (28)$$

And following the same mathematical development used previously, the time derivative of the Lyapunov function in Eq. 28 becomes:

$$\dot{V}(t) \leq \beta.k_2|\dot{e}|^{\beta-1}.[-k_{01}.S^2(t) - k_{02}.|S(t)|] \leq 0 \quad (29)$$

Thus, the convergence of the closed-loop system to the reference trajectory in a finite time is guaranteed.

5. Simulation and results

To show the performances of the performances of the proposed approach, we consider a one-link robot, shown in Fig. 3, whose dynamics equation is given by:

$$ml^2\ddot{q} + mglcos(q)\dot{q} + mglsin(q) = \Gamma + \Gamma_{ext}(t)$$

with

$$m_1 = 1Kg; l_1 = 1m; g = 9.8ms^{-2}$$

To construct the type-2 fuzzy nominal model, we consider that the position q is constrained within $\left[-\frac{\pi}{2};\frac{\pi}{2}\right]$, which leads to 3 fuzzy rules. Each one of them gives the relation between the equilibrium point and the corresponding local model. Then, each rule uses a type2 fuzzy set in the antecedent part to describe the equilibrium point and the consequent part in the corresponding local model. Using the product as an interference engine, the method of center set for the reduction type and center of gravity for defuzzification, the output fuzzy system will be giving the type-2 fuzzy nominal model.

Fig. 4 gives the angular position and velocity for two initial positions. The convergence to zero in a finite time is well shown in Fig. 5. To illustrate the efficiency of the proposed approach we have used a more complex trajectory $q_q = 0.5\cos((t) + 0.5\sin(2t)$. Fig. 6 gives the angular position and velocity for two initial values. These results show also good tracking performances and convergence to the reference trajectory in a finite time. Furthermore, the control signal is given in Fig. 7 the elimination of the chattering phenomenon and the smooth control signal. We can conclude that the proposed approach ensures high tracking precision, fast response, singularity avoidance, and strong robustness to external disturbances and modeling uncertainties.

6. Conclusion

A novel robust control law based on a nonsingular fast sliding mode technique for a robotic system is developed. the main contribution lies in exploiting the agility of type-2 fuzzy logic to overcome the limits of classical control. Indeed, we elaborate firstly a type-2 fuzzy nominal model allowing us to approximate at best the real system with precise knowledge. Secondly, the developed switching signal allowing fast convergence to the origin uses an adaptive type-2 fuzzy system to avoid the knowledge of the upper bound of both uncertainties and external disturbances. The adaptation laws of these parameters are deduced from the stability analysis. Several simulation results have been given to show the performances of the proposed approach. Our next task is to apply this method in real-time on a robot with three degrees of freedom.

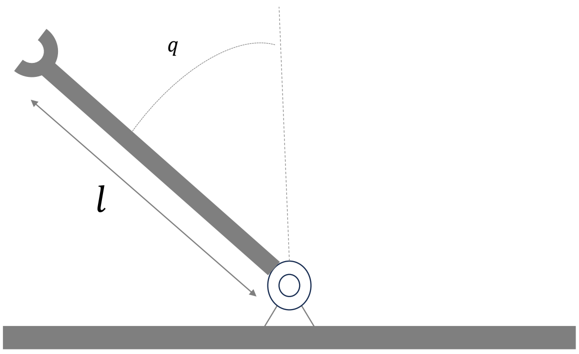

Fig. 3: one link robot manipulator

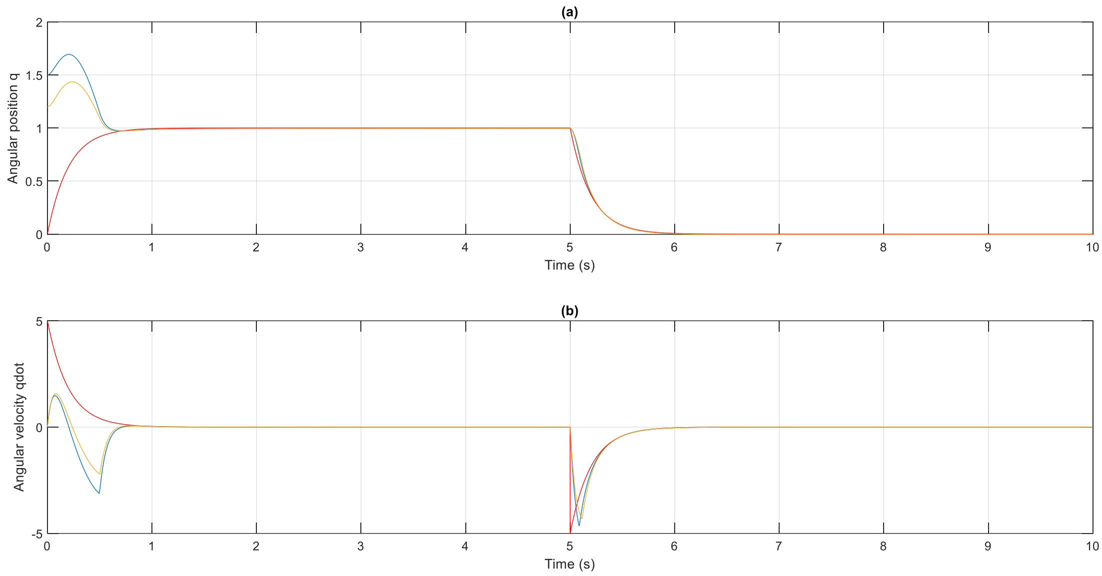

Fig. 4: Outputs of the system: (a) Angular position (b) Angular velocity

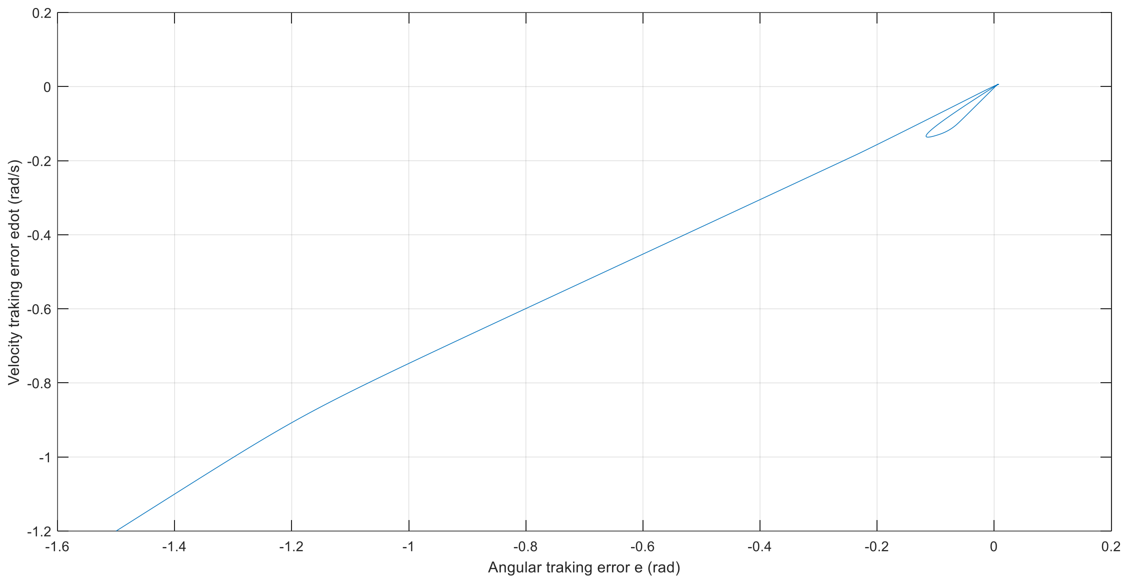

Fig. 5: Error phase plane

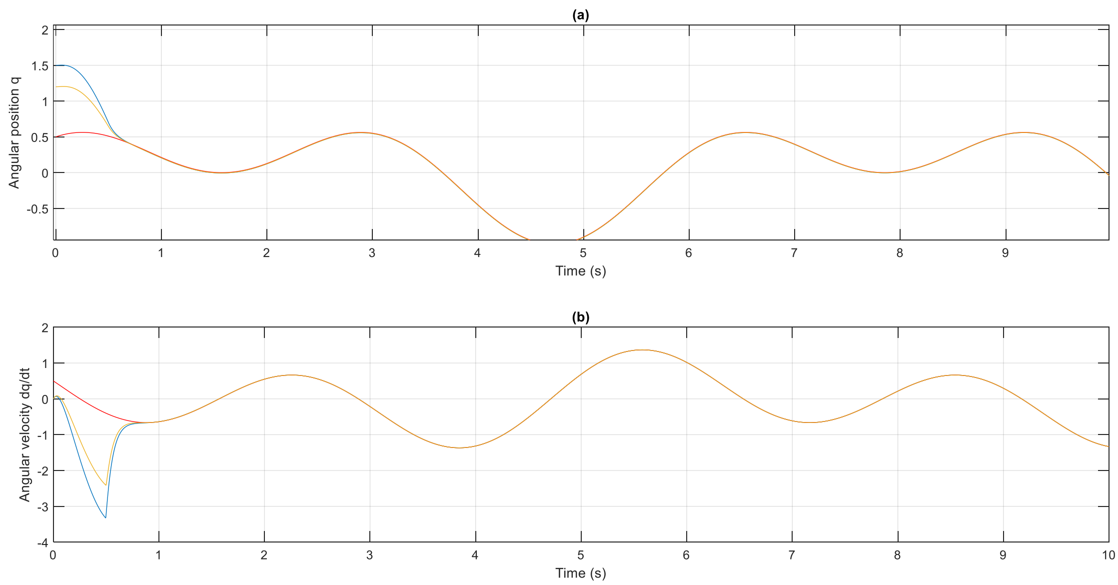

Fig. 6: Outputs of the system: (a) Angular position (b) Angular velocity

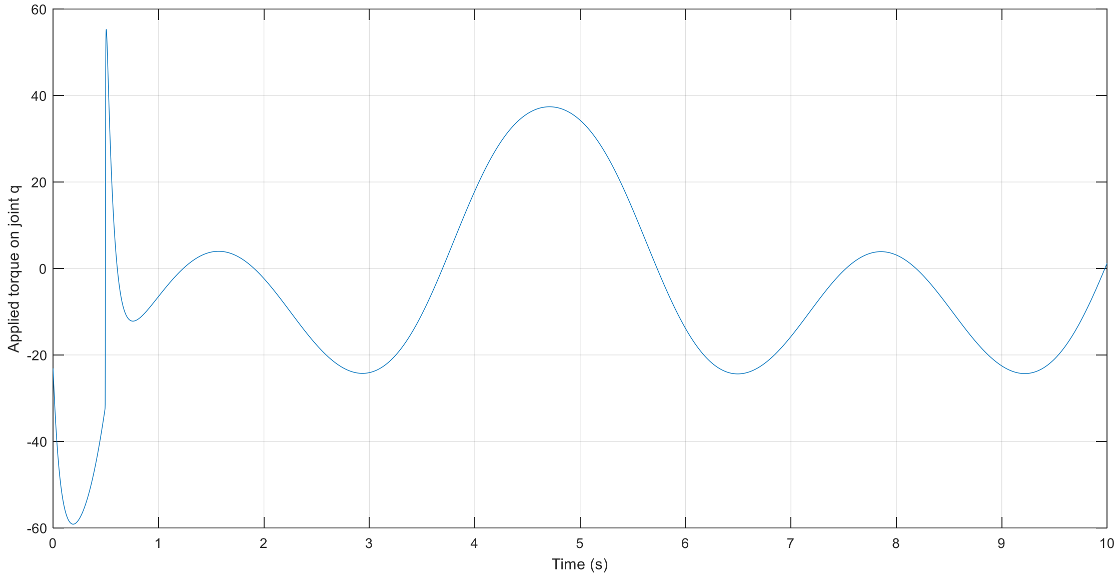

Fig. 7: Applied control signal

List of symbols

q	Angular position of joint
$\dot{q}$	Angular velocity of joint
$\ddot{q}$	Angular acceleration of joint
$M(q)$	Inertia matrix
$C(q, \dot{q})$	Matrix of centrifugal and Coriolis forces
$G(q)$	Vector of gravitational forces
$\Gamma(t)$	Vector of gravitational forces
$\Gamma_{ext}(t)$	Vector of unknown external disturbances

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

Boukattaya M, Mezghani N, and Damak T (2018). Adaptive nonsingular fast terminal sliding-mode control for the tracking problem of uncertain dynamical systems. ISA Transactions, 77: 1-19. https://doi.org/10.1016/j.isatra.2018.04.007 **PMid:29699696**

Feng Y, Yu X, and Man Z (2002). Non-singular terminal sliding mode control of rigid manipulators. Automatica, 38(12): 2159-2167. https://doi.org/10.1016/S0005-1098(02)00147-4

Hamzaoui A, Essounbouli N, and Zaytoon J (2004). Fuzzy sliding mode control with a fuzzy switching function for non-linear uncertain multi-input multi-output systems. Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, 218(4): 287-297. https://doi.org/10.1177/095965180421800404

Jayaraman B, Gaurav K, Giri DK, and Ghosh AK (2022). Nonsingular fast terminal sliding mode flight control of a subscale aircraft. In the American Institute of Aeronautics and Astronautics SciTech 2022 Forum, San Diego, USA. https://doi.org/10.2514/6.2022-0751

Karnik NN, Mendel JM, and Liang Q (1999). Type-2 fuzzy logic systems. IEEE Transactions on Fuzzy Systems, 7(6): 643-658. https://doi.org/10.1109/91.811231

Li P, Ma J, and Zheng Z (2016). Robust adaptive sliding mode control for uncertain nonlinear MIMO system with guaranteed steady state tracking error bounds. Journal of the Franklin Institute, 353(2): 303-321. https://doi.org/10.1016/j.jfranklin.2015.11.005

Liang X, Wang H, and Zhang Y (2022). Adaptive nonsingular terminal sliding mode control for rehabilitation robots. Computers and Electrical Engineering, 99: 107718. https://doi.org/10.1016/j.compeleceng.2022.107718

Manceur M, Essounbouli N, and Hamzaoui A (2011). Second-order sliding fuzzy interval type-2 control for an uncertain system with real application. IEEE Transactions on Fuzzy Systems, 20(2): 262-275. https://doi.org/10.1109/TFUZZ.2011.2172948

Manceur M, Menhour L, Essounbouli N, and Hamzaoui A (2013). MIMO sliding fuzzy type-2 control with manipulating approaching phase. In 10th IEEE International Conference on Networking, Sensing and Control, IEEE, Evry, France: 479-485. https://doi.org/10.1109/ICNSC.2013.6548786

Truong TN, Vo AT, and Kang HJ (2021). A backstepping global fast terminal sliding mode control for trajectory tracking control of industrial robotic manipulators. IEEE Access, 9: 31921-31931. https://doi.org/10.1109/ACCESS.2021.3060115

Van M, Ge SS, and Ren H (2016). Finite time fault tolerant control for robot manipulators using time delay estimation and continuous nonsingular fast terminal sliding mode control. IEEE Transactions on Cybernetics, 47(7): 1681-1693. https://doi.org/10.1109/TCYB.2016.2555307 **PMid:28113571**

Venkataraman S and Gulati S (1993). Control of nonlinear systems using terminal sliding modes. The Journal of Dynamic Systems, Measurement, and Control, 115(3): 554-560. https://doi.org/10.1115/1.2899138

Vo AT and Kang HJ (2019). A chattering-free, adaptive, robust tracking control scheme for nonlinear systems with uncertain dynamics. IEEE Access, 7: 10457-10466. https://doi.org/10.1109/ACCESS.2019.2891763

Wang H, Man Z, Kong H, Zhao Y, Yu M, Cao Z, and Do MT (2016a). Design and implementation of adaptive terminal sliding-mode control on a steer by wire equipped road vehicle. IEEE Transactions on Industrial Electronics, 63(9): 5774-5785. https://doi.org/10.1109/TIE.2016.2573239

Wang Y, Gu L, Xu Y, and Cao X (2016b). Practical tracking control of robot manipulators with continuous fractional-order nonsingular terminal sliding mode. IEEE Transactions on Industrial Electronics, 63(10): 6194-6204. https://doi.org/10.1109/TIE.2016.2569454

Xu Z, Huang W, Li Z, Hu L, and Lu P (2021). Nonlinear nonsingular fast terminal sliding mode control using deep deterministic policy gradient. Applied Sciences, 11(10): 4685. https://doi.org/10.3390/app11104685

Zhai J and Xu G (2020). A novel non-singular terminal sliding mode trajectory tracking control for robotic manipulators. IEEE Transactions on Circuits and Systems II: Express Briefs, 68(1): 391-395. https://doi.org/10.1109/TCSII.2020.2999937