Nonsingular Fast Terminal Sliding Mode Controller for a Robotic System: A Fuzzy Approach

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ABSTRACT

This study presents a combination of Type-2 fuzzy logic and nonsingular fast sliding mode technique to design a robust controller for a robotic system. The control law is composed of two signals. The first one called equivalent control law is dedicated to maintaining the system on the sliding surface and then converges to zero. Since the system is uncertain, a Type-2 fuzzy nominal model was constructed, deduced from linear local models, which allows a good approximation of the real robotic system. The second signal, whose objective is to force the system to attain the sliding surface, is deduced from stability analysis using Lyapunov theory. Several simulations were conducted to evaluate the efficiency of the proposed approach, showing good tracking performance for different reference signals despite the presence of uncertainties and external disturbances.

Keywords-robotic system; nonsingular fast terminal sliding mode control

I. INTRODUCTION

Sliding mode control is a very popular approach to ensure good tracking performance against external disturbances [1-5]. Despite its simple design procedure and good tracking performance, it has two major disadvantages. The first one is the chattering phenomenon 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 to reduce chattering phenomena [1, 6-8]. However, these methods need a trade-off between the smoothness of the switching signal and tracking performance. Second-order sliding mode control has presented a good solution to chattering, but the design procedure is complex and requires a good knowledge of the studied system [9]. Recently, terminal sliding mode control was proposed, where a nonlinear surface is used to guarantee a finite time convergence to the origin of the phase plan. However, these types of controllers suffer from the singularity problem due to the presence of terms with negative fractional powers [10-12]. This problem can be resolved by using a nonsingular terminal sliding mode controller [13]. Nevertheless, this improvement was obtained at the expense of the convergence time, which became slower. A nonsingular fast terminal sliding mode controller was developed to overcome singularity and obtain a fast convergence time [14]. This paper proposes a Type-2 fuzzy nonsingular fast terminal sliding mode controller for a robotic system, guaranteeing finite-time convergence, fast speed when the states are far from the origin, avoidance of singularity, and no chattering. The design procedure consists of two major steps. In the first step, a nominal model was designed using a Type-2 fuzzy system, exploiting linear local models, which allows the construction of a nominal model too close to the real system. This model was used to design the equivalent control law, whose mission is to maintain the system on the sliding surface and slide on to zero. The second step aimed to establish the switching signal on the sliding surface despite the presence of external disturbances and uncertainties.

II. INTERVAL TYPE-2 FUZZY LOGIC SYSTEMS

Fuzzy logic systems are known as universal approximators and have several applications in control design and identification. A Type-1 Fuzzy Logic System (T1FLS) consists of four major parts: fuzzifier, rule base, inference engine, and defuzzifier. A Type-2 Fuzzy Logic System (T2FLS) is very similar to a T1FLS [15-16], and the major structure difference is that the defuzzifier block of a T1FLS is replaced by the output processing block, which consists of type-reduction followed by defuzzification. In an interval T2FLS, a triangular fuzzy set is defined by a lower and upper set, as shown in Figure 2.

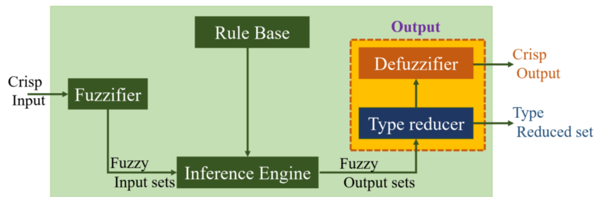

Fig. 1. Structure of a T2FLS.

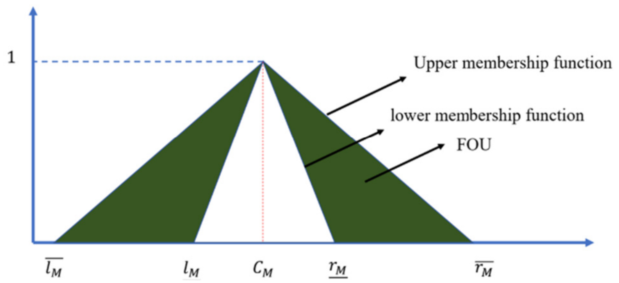

Fig. 2. Interval T2FLS sets.

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

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

where x_j, $j = 1, 2, \dots, n$, and y are the input and output variables of the T2FLS, respectively, $\tilde{F}_j^i$ is the Type 2 fuzzy sets of antecedent part, 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 F^i for the i-th rule can be an interval Type-2 set expressed as:

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

where:

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

This study used the center of the set type-reduction method 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 the left and right-most points (y_l and y_r), which 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 before the computation of $y_{cos}(x)$. Therefore, the left-most point y_l and the right-most point y_r can be expressed as [17]:

$$\begin{cases} y_l = \frac{\sum_{i=1}^{M} \underline{f}^i w_l^i}{\sum_{i=1}^{M} \underline{f}^i} \\ y_r = \frac{\sum_{i=1}^{M} \overline{f}^i w_r^i}{\sum_{i=1}^{M} \overline{f}^i} \end{cases} \quad (1)$$

Using the center of set type reduction method to compute y_l and y_r the defuzzified crisp output from an interval T2FLS can be obtained according to:

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

which can be rewritten in the following vectorial form:

$$y(x) = \Psi^T(x).w \quad (3)$$

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

III. PROBLEM STATEMENT

Let's consider the dynamic equation of n Degree-of-Freedom (DoF) robotic manipulators as follows:

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

where q, $\dot{q}$ and $\ddot{q} \in \mathbb{R}^n$ are the vector 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.

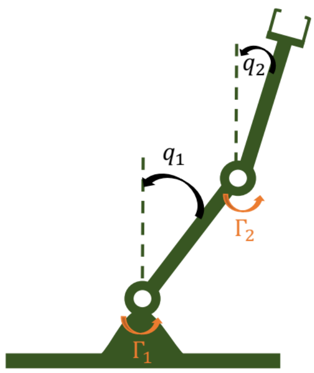

Fig. 3. Two link robot manipulators (2 DoFs).

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

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

where $M_0(q)$, $C_0(q,\dot{q})$, and $G_0(q)$ are the nominal values and $\Delta M(q)$, $\Delta C(q,\dot{q})$, $\Delta G(q)$ are the uncertain parts of $M(q)$, $C(q,\dot{q})$, and $G(q)$, respectively. Using (5), the dynamic model of the robotic manipulators can be expressed as:

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

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 is the desired trajectory. The error dynamic of the robotic manipulators with the uncertainties and disturbances can be written as:

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

where:

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

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

As given in [13], the upper bound of lumped uncertainty can be expressed as:

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

where a_0, a_1 and a_2 are positive scalars. The next task is to develop a robust controller based on Nonsingular Fast Terminal Sliding Mode Control (NFTSMC) allowing tracking objectives.

IV. CONTROLLER DESIGN

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

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

where k_1 and k_2 are positive constants, and:

$1 < \beta < 2$ and $\alpha > \beta$

The structure of this surface allows to attain fast convergence of the tracking error to zero. If the position's initial value is far from the desired one, then the term $k_1|e|^{\alpha}\mathrm{sign}(e)$ will be dominant, leading 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:

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

The control law is composed of two terms. The first one, named equivalent control $\Gamma_e(t)$, is dedicated to maintaining the system on the sliding surface. The second term $\Gamma_s(t)$, called the switching signal, must force the system to converge to the sliding surface. Then, to design the equivalent control law $\Gamma_e(t)$, it is considered 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 [1]. Using (7), (10) can be rewritten as:

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

The equivalent control law can be expressed as:

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

Note that, $\dot{e} = |\dot{e}|.\mathrm{sign}(\dot{e})$ was used to write (9) in a compact form. The 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, (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 (12), (10) can be rewritten as:

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

According to the definition of the equivalent control, (14) can be simplified to:

$$\dot{S}(t) = \beta.k_2|\dot{e}|^{\beta-1}.[g(e,\dot{e})\Gamma_s(t) + D(e,\dot{e})] \quad (15)$$

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

$$V(t) = \tfrac{1}{2}S^2(t) \quad (16)$$

Differentiating $V(t)$ for time and using (15) lead to:

$$\dot{V}(t) = S(t).\beta.k_2|\dot{e}|^{\beta-1}.[g(e,\dot{e})\Gamma_s(t) + D(e,\dot{e})] \quad (17)$$

Choosing $\Gamma_s(t)$ as:

$$\Gamma_s(t) = -g^{-1}(e,\dot{e})[k_{01}.S(t) + (k_{02} + a_0 + a_1|q| + a_2|\dot{q}|^2).\mathrm{sign}(S(t))] \quad (18)$$

where k_{01} and k_{02} are two positive scalars.

The time derivative of the Lyapunov function becomes:

$$\dot{V}\,(t) = S(t)\,\beta.k_2|\dot{e}|^{\beta-1}.[g(e,\dot{e})\Gamma_s(t) + D(e,\dot{e})]$$
$$= \beta.k_2|\dot{e}|^{\beta-1}.[-k_{01}.S^2(t) - (k_{02} + a_0 + a_1|q| + a_2|\dot{q}|^2).|S(t)| + D(e,\dot{e})] \quad (19)$$

Using the assumption (8), the following inequality is obtained:

$$\dot{V}(t) \le \beta.k_2|\dot{e}|^{\beta-1}.[-k_{01}.S^2(t) - k_{02}.|S(t)|] \le 0 \quad (20)$$

Based on the Lyapunov theorem, the system converges asymptotically to the sliding surface and remains on. To prove convergence in finite time, let's take up inequality (20):

$$\dot{V}(t) \le -\beta.k_{01}.k_2|\dot{e}|^{\beta-1}.S^2(t) - \beta.k_{02}.k_2|\dot{e}|^{\beta-1}.|S(t)| \quad (21)$$

$$\dot{V}(t) \le -\underbrace{2\beta k_{01}.k_2|\dot{e}|^{\beta-1}}_{\beta_1}.V(t) - \underbrace{\sqrt{2}\beta k_{02}.k_2|\dot{e}|^{\beta-1}}_{\beta_2}.V^{\frac{1}{2}}(t) \quad (22)$$

and then:

$$dt \le \frac{-dV(t)}{\beta_1.V(t)+\beta_2.V^{\frac{1}{2}}(t)} = -2.\frac{dV^{\frac{1}{2}}(t)}{\beta_1.V^{\frac{1}{2}}(t)+\beta_2} \quad (23)$$

Integrating inequality (23) and after some mathematical manipulation, the following can be obtained:

$$t_c \le \frac{2}{\beta_1}ln\left(\frac{\beta_1.V^{\frac{1}{2}}(0)+\beta_2}{\beta_2}\right)$$

It can be concluded that the time convergence to zero is finite.

V. SIMULATION AND RESULTS

To evaluate the performance of the proposed approach, a two-link robot was considered, as shown in Figure 3, whose dynamics equation is given by [14]:

$$\begin{bmatrix} M_{11}(q) & M_{12}(q) \\ M_{21}(q) & M_{22}(q) \end{bmatrix}\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} + \begin{bmatrix} C_{11}(q,\dot{q}) & C_{12}(q,\dot{q}) \\ C_{21}(q,\dot{q}) & C_{22}(q,\dot{q}) \end{bmatrix}\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} G_1(q) \\ G_2(q) \end{bmatrix} = \begin{bmatrix} \Gamma_1(t) \\ \Gamma_2(t) \end{bmatrix} + \begin{bmatrix} \Gamma_{ext1}(t) \\ \Gamma_{ext2}(t) \end{bmatrix}$$

where:

$M_{11}(q) = (m_1 + m_2)l_1^2$

$M_{12}(q) = M_{21}(q) = m_2 l_1 l_2(\sin(q_1)\sin(q_2) + \cos(q_1)\cos(q_2))$

$M_{22}(q) = m_2 l_2^2$

$C_{11}(q,\dot{q}) = -m_2 l_1 l_2(\cos(q_1)\sin(q_2) - \sin(q_1)\cos(q_2))\dot{q}_2$

$C_{21}(q,\dot{q}) = -m_2 l_1 l_2(\cos(q_1)\sin(q_2) - \sin(q_1)\cos(q_2))\dot{q}_1$

$C_{11}(q,\dot{q}) = C_{22}(q,\dot{q}) = 0$

$G_1(q) = -(m_1 + m_2)l_1 g.\sin(q_1)$

$G_2(q) = -m_2 l_2 g.\sin(q_2)$

$m_1 = m_2 = 1Kg; l_1 = l_2 = 1m; g = 9.8ms^{-2}$

To construct the Type 2 fuzzy nominal model, the positions q_1 and q_2 were considered to be constrained within $\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$, which leads to nine fuzzy rules. Each of them gives the relation between the equilibrium point and the corresponding local model. Then, each rule uses a Type-2 fuzzy set in the antecedent part to describe the equilibrium point and the consequent part of the corresponding local model. Using the product as an interference engine, the center set for the reduction type, and the center of gravity for defuzzification, the output fuzzy system will give the Type-2 fuzzy nominal model. Figures 4 to 6 show the results obtained for sinusoidal reference trajectories ($q_{1d}(t)$=sin(t), $q_{2d}(t)$=cos(t)) and the system subjected to both uncertainties (10% of nominal values of the system) and external disturbances in the form:

$\Gamma_{ext}(t) = 0.2\sin(t) + 0.1\sin(2t)$

Figure 7 shows another reference trajectory considered to demonstrate the performance of the proposed approach. This case also demonstrates the convergence of the system outputs towards the reference trajectories, confirming the previous conclusion.

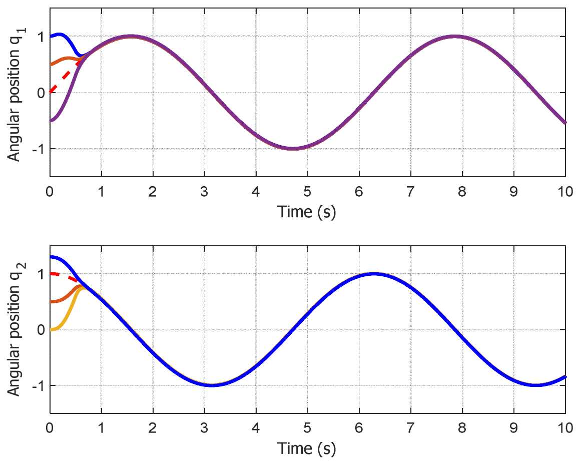

Fig. 4. Angular position tracking.

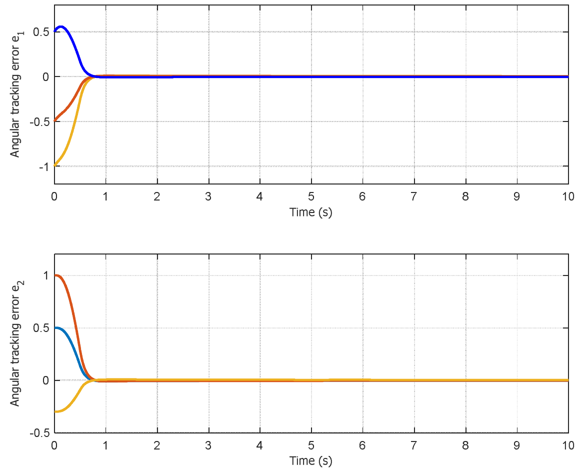

Fig. 5. Angular position tracking error.

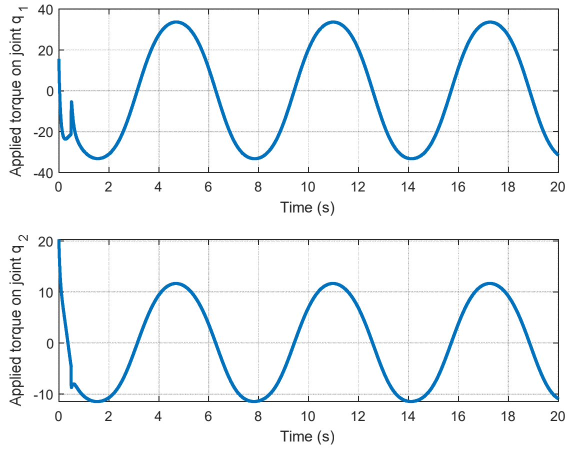

Fig. 6. Applied control signals.

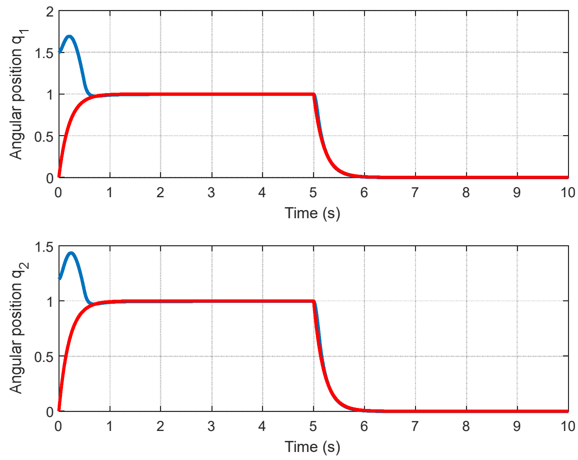

Fig. 7. Angular position tracking.

To further demonstrate the performance of the proposed approach, a comparative study was conducted with a Fuzzy Sliding Mode Control (FSMC) [2] and a Terminal Sliding Mode Controller (TSMC) [18] in terms of the Mean Square value of the Tracking Error (MSTE) defined as:

$$e_i = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\|e_i(k)\|^2} \quad ,i = 1,2$$

Table I shows the obtained MSTE values after using each method. As can be seen, the proposed approach obtained a smaller MSTE, demonstrating its better performance than the two other control methods.

TABLE I. MSTE VALUES

	Joint 1 (rad)	Joint 2 (rad)
FSMC	0.045	0.06
TSMC	0.04	0.055
Proposed method	0.025	0.035

Thus, it can be concluded that the proposed approach ensures high tracking precision, fast response, singularity avoidance, and strong robustness to external disturbances and modeling uncertainties.

VI. CONCLUSION

This study proposed a Type-2 fuzzy nonsingular fast terminal sliding mode controller for a robotic system. In the first step, the equivalent control law was elaborated based on a Type-2 fuzzy nominal model, which allows a good approximation of the real robotic system. This made it possible to effectively exploit human expertise in the behavior of the system, the flexibility of Type-2 fuzzy logic, and its ability to better consider uncertainties compared to other classical modeling methods. In the second step, Lyapunov theory was used to study the stability of the closed-loop system and deduce the expression of the switching signal. The designed control law, composed of two terms, was mathematically proven to lead to robustness against uncertainties and external disturbances, in addition to its convergence to the reference trajectories in a finite time. To demonstrate the performance of the proposed approach in terms of robustness and tracking, a simulation was conducted for sinusoidal trajectories with different initial positions and square reference signals. The results and the comparative study with other approaches demonstrated the superiority of the proposed approach in terms of MSTE. In the future, the implementation of this approach will be simplified by reducing the number of parameters and simplifying the expression of the switching signal.

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