An Optimal Type-2 Fuzzy Sliding Mode Control of a Cylindrical Robotic Arm

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Abstract
In this paper, a type-2 fuzzy sliding mode control (T2-FSMC) is suggested for the trajectory tracking of a cylindrical robotic arm. By using Whale Optimization Algorithm (WOA), the parameters of the proposed controller are optimized. For robustness against external disturbance and parameter uncertainty, sliding mode control (SMC) is proposed. Type-2 fuzzy systems are designated by type-2 membership functions that can be very useful to handle uncertainties and minimize their effects. To improve the effectiveness of the SMC and type-2 fuzzy logic, can combine them and benefit from the advantages of both methods. Also, by utilizing the Lyapunov stability theorem closed-loop system stability is proved. The simulation results present the merits of the suggested controller.
Keywords: Cylindrical robotic arm, Type-2 fuzzy logic, Sliding mode control, Whale Optimization Algorithm

1. Introduction

Robot manipulators are widely utilized in automated industrial applications, for example, used in medical fields, machine manufacturing, and nuclear [1], [2]. By reducing working costs, and safely human working situations where repeated and perilous works are performed, these devices are utilized [3]. For better flexibility, accuracy, and productivity, it is needed to meticulously design robust controllers that can exactly command the robotic motion. Various robust control methods are designed for different robotic systems such as $H\infty$ control [4], adaptive control [5], fractional-order control (FO) [6], sliding mode control (SMC) [7]. Between the above robust controller methods, (SMC) is very popular and offers a switching function to control the nonlinear dynamic systems in presence of external disturbances and uncertainties that cause the generality and various applications of this control method [8].

Generally, the selection of proper gain to reduce uncertainties effect, warranty system stability, and prevent to cause chattering, is a major challenge. Recently, different solutions for the mentioned issue are suggesting such as neural network-based sliding mode control [9], higher-order SMC [10], fuzzy sliding mode control [11, 12], and type 2 fuzzy sliding mode control [13]. In recent research, the combination of fuzzy systems with sliding mode controllers have grown a lot of interest. Fuzzy sliding mode control (FSMC) has the merits of both techniques to improve the effectiveness of the control. In [14] fuzzy system has been combined with fractional sliding mode control for control rotor current of doubly-fed induction generator. In [15] design a robust adaptive fuzzy sliding mode controller for uncertain serial robotic manipulators is suggested. In order to improve control performance and handling uncertainties, T1-FLCs are upgraded to interval type-2 FLCs (IT2-FLC) that provide an extra degree of freedom by the footprint of uncertainty (FOU). In [16] for power-line inspection robot with unknown uncertainties and disturbances, an interval Type-2 Fuzzy Sliding Mode controller is proposed. Also, various applications of type-2 fuzzy SMC in robotic systems are offered in [17,18].

For organizing control rules and membership functions of an FLSs we need the experience or knowledge of an expert. For this aim, to tune the parameters of the FLSs we can utilize an optimization tool. Genetic optimization algorithm [19], Artificial Bee Colony (ABC) [20], Gray Wolf Optimization Algorithm (GWO) [21], Whale Optimization Algorithm (WOA) [22], Jaya Algorithm [23] are some of the optimization algorithms which widely used. In [24] Jaya optimization algorithm has been utilized for optimization of the membership function of the fuzzy sliding surface system. In [25], a genetic algorithm optimization approach was used to optimize the scaling factors of interval type-2 fuzzy PID controllers to control trajectory tracking a 5-degree of freedom redundant robot manipulator. Whale Optimization Algorithm (WOA) is one of the popular meta-heuristic algorithms based on the social behavior of whales. Recently, WOA has been used for the various aims of optimization applications. WOA is in the class of swarmed intelligence optimization approaches. The main merit of the WOA methodology in comparison to other published approaches is that the WOA method has not needed special algorithm parameters.

In this paper, an OT2-FSMC is suggested for the tracking control of a cylindrical robotic arm that by using an interval type-2 fuzzy logic system decreases the chattering phenomenon value. Also, the controller parameters have been optimized by WOA. The proposed controller achieves eliminates chattering and reduces tracking error and has good performance in uncertainty conditions. This paper is organized as follows: In Sect. II is expressing the dynamic of the cylindrical robotic arm. Design a conventional SMC is given in section III. In Sect. IV, represent the design of T2-FSMC. The WOA and parameters to be set are expressed in section V. In Sect. VI, the simulation of the proposed control method for cylindrical robotic arm. In Sect. VII, the conclusion is presented.

2. Robot dynamic description

The dynamic equation of n degrees of freedom robotic manipulator can be expressed as follows:

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$$M(q)\,\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau \quad (1)$$

where q shows the joint angles or link displacements of the manipulator, $G(q)$ are the gravity terms, $M(q)$ denotes the robot inertia matrix, and $C(q,\dot{q})$ shows the Coriolis terms. The cylindrical robotic arm is illustrated in Fig. 1. To obtain the mathematical model of the cylindrical robotic arm, the Euler Lagrangian technique is utilized. The cylindrical robotic arm dynamic is [18]:

$$\begin{aligned} &J_{13} + (m_2 + 4m_3)l_{c2}^2\ddot{\theta}_1 + 2(m_2 + 4m_3)l_{c2}\dot{\theta}_1\dot{l}_{c2} = \tau_1 \\ &(m_2 + 4m_3)\ddot{l}_{c2} - (m_2 + 4m_3)l_{c2}\dot{\theta}_1^2 = \tau_2 \\ &m_3\ddot{l}_{c3} - m_3 g = \tau_3 \end{aligned} \quad (2)$$

where τ_1, τ_2, and τ_3 are the torques utilized to motion the links 1, 2, and 3, respectively, $q_1 = \theta_1$ is the angle of the rotation joint, and $q_2 = l_{c2}$ and $q_3 = l_{c3}$ is the length that grows until the center of mass of the links 2 and 3, respectively.

$$\begin{aligned} &\ddot{q} = -M(q)^{-1}C(q,\dot{q})\dot{q} - M(q)^{-1}G(q) - d(t) + M(q)^{-1}\tau \\ &\ddot{q} = -(A + \Delta A)\dot{q} - (B + \Delta B)G(q) - d(t) + (B + \Delta B)\tau \end{aligned} \quad (3)$$

where $A = M(q)^{-1}C(q,\dot{q})$, $B = M(q)^{-1}$, $d(t)$disturbance, ΔA, ΔB are considered the existing uncertainties in the system and are bounded such that $\Delta Al \le \Delta A \le \Delta Au$,

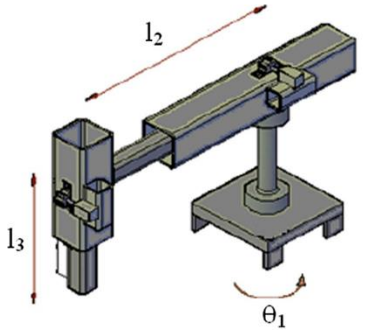

Fig. 1. Cylindrical robotic arm [13]

$\Delta Bl \le \Delta B \le \Delta Bu$ where l and u represents the lower and upper uncertainties values and:

$$M(q) = \begin{bmatrix} J_{13} + (m_2 + 4m_3)q_2^2 & 0 & 0 \\ 0 & m_2 + 4m_3 & 0 \\ 0 & 0 & m_3 \end{bmatrix}$$

$$C(q,\dot{q}) = \begin{bmatrix} (m_2 + 4m_3)q_2\dot{q}_2 & (m_2 + 4m_3)q_2\dot{q}_1 & 0 \\ -(m_2 + 4m_3)q_2\dot{q}_1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (4)$$

$$G(q) = \begin{bmatrix} 0 \\ 0 \\ -m_2 g \end{bmatrix}$$

3. Controller design

3.1. Sliding mode control

The proportional-integral-derivative (PID) sliding surface can be written as follows:

$$S(t) = K_p e(t) + K_i \int e(t)dt + K_d \dot{e}(t) \quad (5)$$

where, K_p, $K_i$and K_d are the n×n diagonal gain matrix and

$$e(t) = q_d(t) - q(t) \quad (6)$$

where, $q(t)$ is the actual trajectory and $q_d(t)$ is the desired trajectory. The objective of the sliding mode control is to compel error of tracking (e(t)) towards the sliding surface and then force error to the origin. Control law of SMC is the mixture of reaching control and equivalent control which is shown as $u(t) = u_{eq}(t) - u_r(t)$. By derivation of sliding surface with respect to time, achieve to equivalent control $u_{eq}(t)$:

$$\dot{S}(t) = K_p\dot{e}(t) + K_i e(t) + K_d\ddot{e}(t) = K_p\dot{e}(t) + K_i e(t) + K_d[\ddot{q}_d(t) + (A + \Delta A)\dot{q}(t) + (B + \Delta B)G(q) + d(t) - (B + \Delta B)u(t)] \quad (7)$$

Now without discussing disturbances and uncertainties, calculate equivalent control i.e, $d(t) = \Delta A = \Delta B = 0$

$$u_{eq} = (K_d B)^{-1}[K_p\dot{e} + K_i e(t) + K_d A\dot{q} + K_d BG(q)] \quad (8)$$

However, if unsought disturbances happen, so complementary control is needed to ensure the robustness of system. The complementary control with Lyapunov theory can be designed. The complementary control is reaching control. The Lyapunov function is selected as:

$$V(t) = \frac{1}{2}S(t)^2 \quad (9)$$

The sufficient condition for the stability analysis is:

$$\dot{V}(t) = S(t)\dot{S}(t) < -\eta.|S(t)| \quad (10)$$

where η is the positive value. The derivative of Eq. (10) is

$$\begin{aligned} S^T\dot{S} = {} & S^T\left(K_p\dot{e} + K_i e + K_d[\ddot{q}_d - \ddot{q}]\right) \\ = {} & S^T\Big\{K_p\dot{e} + K_i e \\ & + K_d\Big[\ddot{q}_d + (A + \Delta A)\dot{q} + (B + \Delta B)G(q) \\ & - (B + \Delta B)\left(u_{eq}(t) + u_r(t) + d(t)\right)\Big]\Big\} \\ = {} & S^T\{K_p\dot{e} + K_i e + K_d A\dot{q} + K_d BG(q) \\ & + K_d d(t) + K_d\Delta A\dot{q} + K_d\Delta BG(q)\} \\ & - |S^T\{K_d(B + \Delta B)(K_d B)^{-1}| \times [K_p\dot{e} + K_i e \\ & + K_d A\dot{q} + K_d BG(q) + u_r(t)]\} \end{aligned} \quad (11)$$

Simplification of Eq. (12) produces:

$$\begin{aligned} S^T\dot{S} = {} & S^T\{K_p[(\Delta A - A^{-1}B\Delta B)\dot{q} + (\Delta B - A^{-1}B\Delta B) \times G(q) \\ & + d(t)] - B^{-1}\Delta B\left(K_p\dot{e} + K_i e + K_d\ddot{q}\right)\} \\ & - S^T K_d \times (B + \Delta B)u_r(t) \\ \le {} & S^T\{K_p[|\Delta A - B^{-1}A\Delta B||\dot{q}| + |d(t)|] \\ & - |B^{-1}\Delta B| \times \left(K_p|\dot{e}| + K_i|e| + K_d|\ddot{q}|\right)\} \\ & - S^T K_d(B + \Delta B)u_r(t) \end{aligned} \quad (12)$$

Finally, the reaching control law is computed as:

$$\begin{aligned} u_r(t) = {} & \mathrm{sign}(S)[K_d(B + \Delta B_l)]^{-1}\{[|\Delta A_u - B^{-1}A\Delta B_l||\dot{q}| \\ & + K_d|d(t)|] - |B^{-1}\Delta B_u|(K_p|\dot{e}| + K_i|e| \\ & + K_d|\ddot{q}|)\} \end{aligned} \quad (13)$$

From Eq. (12) it is clear that $\dot{V} < 0$, so the error will converge to the equilibrium points. The reaching control term in SMC is given by

$$u_r(t) = K_r sign(S(t)) \quad (14)$$

where K_r explains the reaching control gain dependents with the upper limit of disturbances and uncertainties, and sign [.] is a sign function.

3.2. Type 2 fuzzy sliding mode control

In cases that it is hard to calculate the right membership function of fuzzy sets, type-2 fuzzy sets are selected to clique uncertainties [20]. The structure of an IT2-FLS is illustrated in Fig. 2. In IT2-FLS the inference illustrated in **TABLE 1.** Fuzzy rules

Fig. 2. In IT2-FLS the inference engine output is a type-2 fuzzy set. Also, there is a type-reducer in the structure of

	e					
$\dot{e}$		NB	N	ZE	P	PB
	NB	M	S	VS	S	M
	N	B	M	S	M	B
	ZE	VB	B	M	B	VB
	P	B	M	S	M	B
	PB	M	S	VS	S	M

IT2-FLS that's its duty to convert the type-2 output sets obtained from the FLS to the type-1 fuzzy set. This act is called type reduction. Hence, the type-reduced sets are defuzzified to get a crisp output from a type-2 FLS. The structure of the sliding mode controller based on IT2-FLS is shown in Fig. 3. In the IT2-FSMC, the *lth* rule has the form as:

$$R^{(l)} :: If \;\; e(t) is\ \tilde{F}_e^l \;and\; \dot{e}(t) is\ \tilde{F}_{de}^l \;then\; K_r(t) is\ \tilde{F}_r^l$$

where, $\tilde{F}_e^l$ and $\tilde{F}_{de}^l$ are the input interval type-2 fuzzy sets, $\tilde{F}_r^l$ are the output interval type-2 fuzzy sets and l = 1,...,25 represents the fuzzy IF-THEN rules.

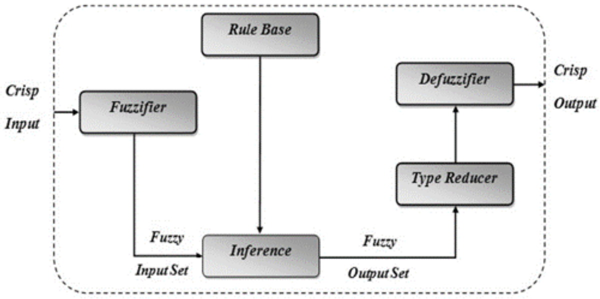

Fig. 2. Structure described the interval type-2 fuzzy logic controller [16]

The membership functions for the consequent and antecedent sets of the type-2 FLS system, i.e., the input and output membership functions, are illustrated in Figs. 4, 5, and 6. The rule base of the type-2 FLS is definite in Table: I. The firing set is given by:

$$F^l = \left[\underline{f}^l \;\overline{f}^l\right] \quad (15)$$

$$\underline{f}^l = \underline{\mu}_{\tilde{F}_e^l}\underline{\mu}_{\tilde{F}_{de}^l}, \overline{f}^l = \overline{\mu}_{\tilde{F}_e^l}\overline{\mu}_{\tilde{F}_{de}^l} \quad (16)$$

Note that $\underline{\mu}_{\tilde{F}_e^l}$ and $\underline{\mu}_{\tilde{F}_{de}^l}$ denote the lower membership grades and $\overline{\mu}_{\tilde{F}_e^l}$ and $\overline{\mu}_{\tilde{F}_{de}^l}$ denote the upper membership grades.

$$K_r^r = \frac{\sum_{l=1}^{R} \underline{f}^l \overline{K}_r^l + \sum_{l=R+1}^{M} \overline{f}^l \underline{K}_r^l}{\sum_{l=1}^{R} \underline{f}^l + \sum_{l=R+1}^{M} \overline{f}^l} \quad (17)$$

$$K_r^l = \frac{\sum_{l=1}^{L} \underline{f}^l \overline{K}_r^l + \sum_{l=L+1}^{M} \overline{f}^l \underline{K}_r^l}{\sum_{l=1}^{L} \overline{f}^l + \sum_{l=L+1}^{M} \underline{f}^l} \quad (18)$$

The values of the R and L are achieved by using the type reduction algorithm given in [19]. So, the defuzzified crisp output can be calculated as follows:

$$K_r = \frac{K_r^r + K_r^l}{2} \quad (19)$$

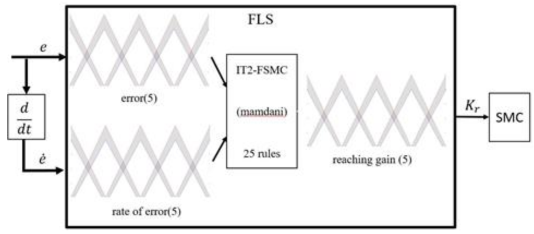

Fig. 3. Structure of IT2FL-SMC

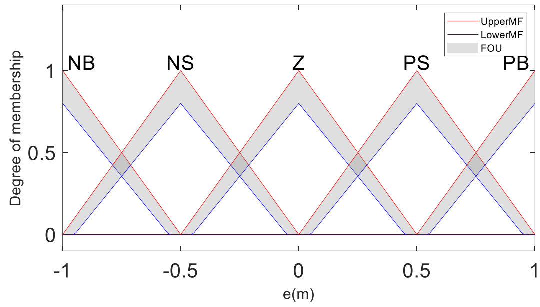

Fig. 4. The membership function of error

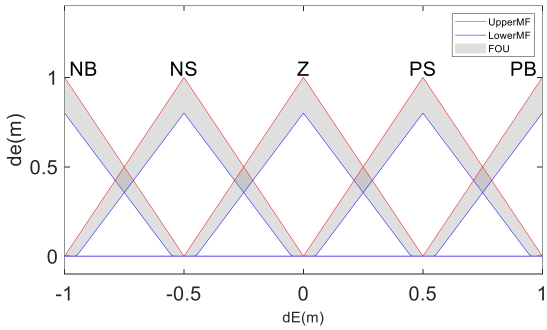

Fig. 5. The membership function of rate of error

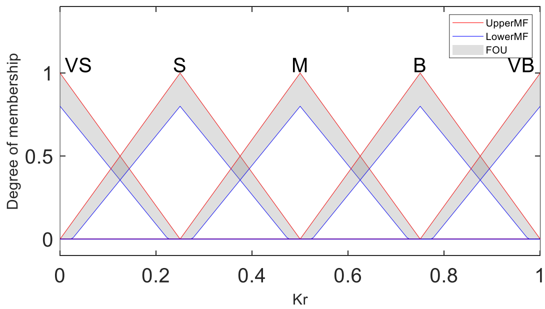

Fig. 6. The membership function of reaching gain

3.3. Optimal type 2 fuzzy sliding mode control

The main purpose of this part is to improve control performance by utilizing the whale optimization algorithm

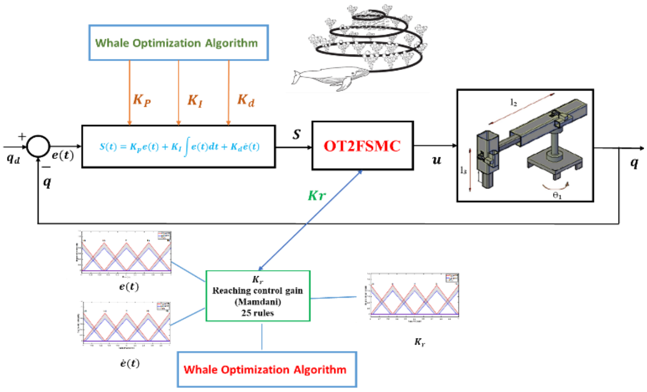

Fig. 7. The Optimal type 2 fuzzy sliding mode control structure

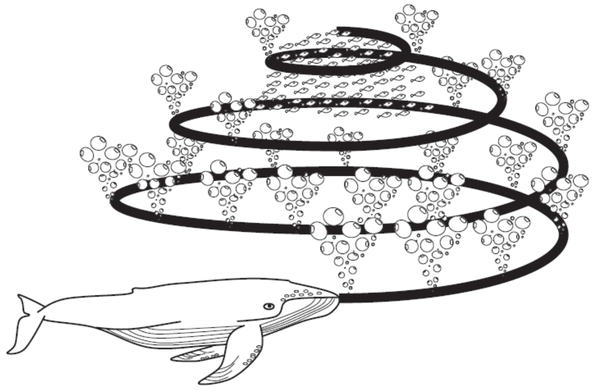

Fig. 8. Bubble-net feeding behavior of humpback whales [22]

for online tuning of sliding surface gains. The block diagram structure of optimal type 2 fuzzy sliding mode control is denoted in Fig7. It is worth mentioning that whales are intelligent animals with special hunting behaviors that underlie the development of the WOA algorithm [21]. Humpback whales are using their own special unique hunting style named the bubble net feeding technique. Now, the mathematical model of spiral bubble-net, encircling prey, encouraging movement, and scanning for prey is presented. This behavior can be expressed following equations

$$\vec{D} = \left|\vec{C} - \overrightarrow{X(t)^*} - \overrightarrow{X(t)}\right| \qquad (20)$$

$$\vec{X}(t+1) = \overrightarrow{X(t)^*} - \vec{A}.\vec{D} \qquad (21)$$

where $\vec{C}$ and $\vec{A}$ show coefficient vectors, $\vec{X}$ denotes the position vector, $\overrightarrow{X^*}$ denotes the best solution of position vector, the current iteration is shown by t and | | denotes the absolute value. The vectors $\vec{A}$ and $\vec{C}$ can be obtained following as:

$$\vec{A} = 2\vec{a}.\vec{r} - \vec{a} \qquad (22)$$

$$\vec{C} = 2.\vec{r} \qquad (23)$$

In which $\vec{r}$ is a random vector in [0,1] and $\vec{a}$ is linearly reduced from 2 to 0 over the course of iterations. A spiral-based equation which is between the place of prey and whale to mimic the helix-shaped move that is related to humpback whales can be written as follows:

$$\vec{X}(t+1) = \vec{\acute{D}}.e^{bl}.cos(2\pi l) + \vec{X}^*(t) \qquad (24)$$

$$\vec{\acute{D}} = \left|\vec{X}^*(t) - \vec{X}(t)\right| \qquad (25)$$

In which *b* denotes a constant for the logarithmic spiral shape, *d* represents the distance between i_{th} whale to the best solution and *l* is a random number in [-1,1]. The Bubble-net feeding behavior of humpback whales are illustrated in Fig7. In order to prey, A vector can be used for exploration aim which is a random value less than -1 or larger than 1. So, exploration applies by the two mentioned conditions as follows:

$$\vec{D} = \vec{C}.\vec{X}_{rand} - \vec{X} \qquad (26)$$

$$\vec{X}(t+1) = \vec{X}_{rand} - \vec{A}.\vec{D} \qquad (27)$$

where rand denotes a random whale position vector which is selected from the current population. The concept of this approach is, search to attain the best solution and to elude defeat solutions. In this reasearch, we use the whale optimization algorithm for adjusting IT2-FSMC parameters. Adjustable parameters are:

- K_p, K_i and K_d
- Input type-2 fuzzy sets
- Output type-2 fuzzy sets

The objective function is commonly suggested as a function of tracking errors, therefore in this study the offered cost function is following as:

$$f(x) = \sqrt{\int_0^{20} e^2} \qquad (28)$$

4. Simulations and results

The simulation results by using MATLAB 2021 have been operating. The robot's nominal parameters can be shown in Table 2. The system uncertainties are:

$$\underline{m}_{1,2,3} < m_{1,2,3} < \overline{m}_{1,2,3} \qquad (29)$$

$$\underline{J}_{1,2,3} < J_{1,2,3} < \overline{J}_{1,2,3} \qquad (30)$$

the lower and upper bounds of uncertainty are 4% lower and 4% upper than the nominal value, respectively. By using the WOA, adjusted parameters of T2FSMC. The optimal PID sliding surface gain are $Kp = diag$ ([7:41; 8:25; 6:66]); $Ki = diag$ ([43:69; 41:12; 48:69]) and $Kd = diag$ ([0:2; 0:5; 0:3]). The membership functions of optimal type-2 FLS are shown in Fig. 9, 10 and 11. From Figs.12 ~ 14, it can be shown that the output of the cylindrical robotic arm follows the desired trajectories; also, it is shown that the OT2-FSMC better results than T2-FSMC because the T2-FSMC output signals are better following the references than the output signal of the other controller. In Figs.15 ~ 17 control signals of the cylindrical robotic arm links are illustrated. As expected, the chattering effects are generated in SMC whereas in T2FSMC and OT2FSMC chattering effects have been reduced.

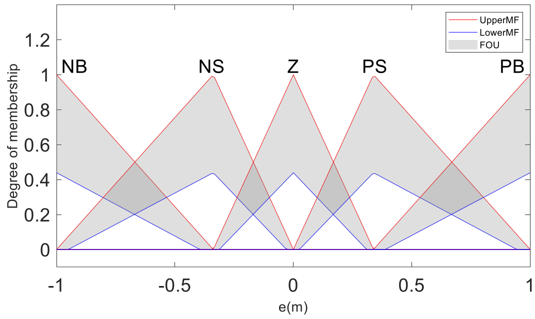

Fig. 9. The optimal membership function of error

TABLE 2. Parameters of a cylindrical arm

Parameter	Value	Unit
$l_{1,2,3}$	[0.3,0.3,0.2]	m
$m_{1,2,3}$	[0.46,0.32,0.32]	kg
$J_{1,2,3}$	[0.04624,0.02545,0.03616]	$Kg.m^2$

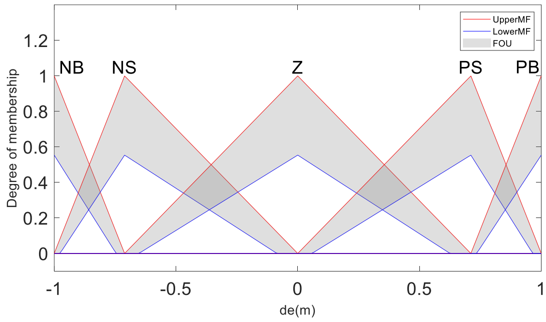

Fig. 10. The optimal membership function of rate of error

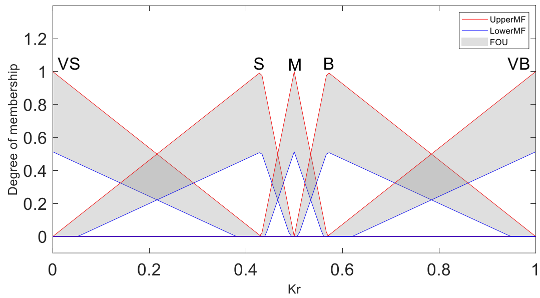

Fig. 11. The optimal membership function of reaching gain

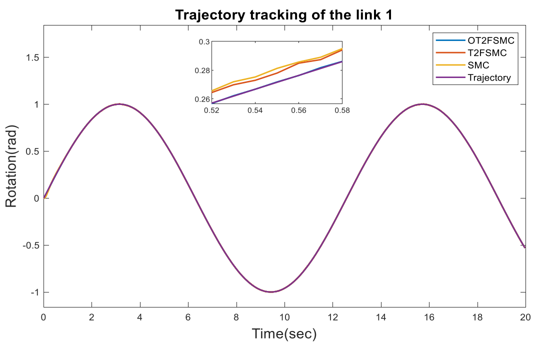

Fig. 12. Trajectory tracking performance of the link 1

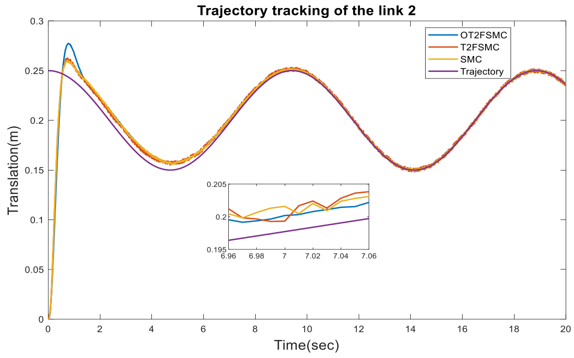

Fig. 13. Trajectory tracking performance of the link 2

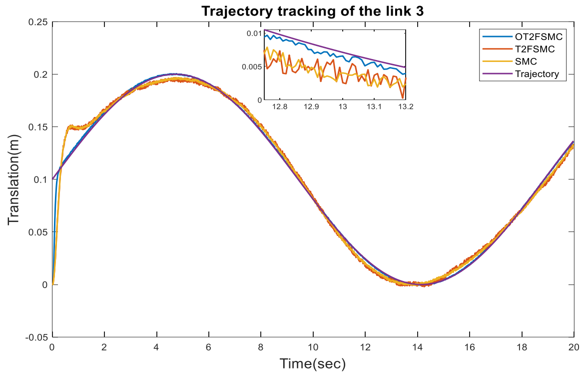

Fig. 14. Trajectory tracking performance of the link 3

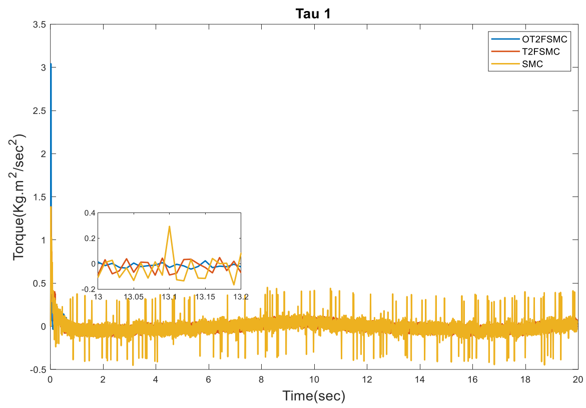

Fig. 15. Control signal of the link 1

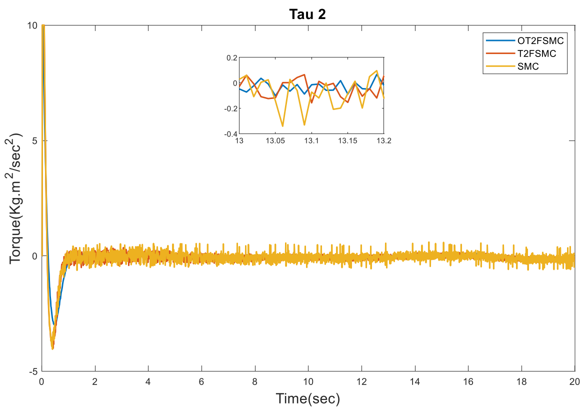

Fig. 16. Control signal of the link 2

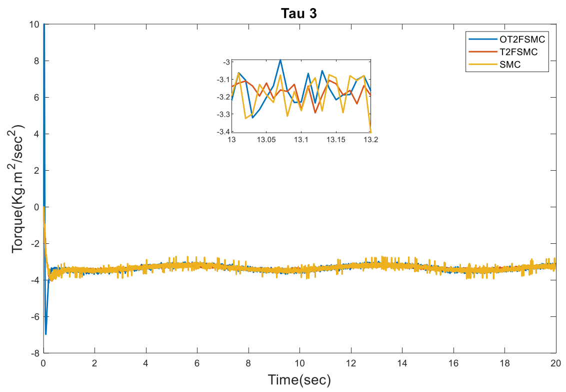

Fig. 17. Control signal of the link 3

5. Conclusion

In the presented paper, an OT2-FSMC is offered for the tracking control of a cylindrical robotic arm that by using a type-2 fuzzy logic system decreases the chattering phenomenon value. The parameters of the proposed controller are tuned by utilizing the whale optimization algorithm. Due to simulation results can be concluded the merits of the suggested controller compared to other controllers in reducing tracking error, decreasing chattering effects, and robustness against uncertainty.

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