UDC 621.3.013 https://doi.org/10.20998/2074-272X.2025.1.05

H. Rahali, S. Zeghlache, B.D.E. Cherif, L. Benyettou, A. Djerioui

Robust adaptive fuzzy type-2 fast terminal sliding mode control of robot manipulators in attendance of actuator faults and payload variation

Introduction. *This study presents a robust control method for the path following problem of the PUMA560 robot. The technique is based on the Adaptive Fuzzy Type-2 Fast Terminal Sliding Mode Control (AFT2FTSMC) algorithm and is designed to handle actuator faults, uncertainties (such as payload change), and external disturbances. The* ***aim*** *of this study is to utilize the Fast Terminal Sliding Mode Control (FTSMC) approach in order to ensure effective compensation for faults and uncertainties, minimize tracking error, reduce the occurrence of chattering phenomena, and achieve rapid transient response. A novel adaptive fault tolerant Sliding Mode Control (SMC) approach is developed to address the challenges provided by uncertainties and actuator defects in real robotics tasks.* ***Originality.*** *The present work combined the AFT2FTSMC algorithm in order to give robust controllers for trajectory tracking of manipulator's robot in presence parameters uncertainties, external disturbance, and faults. We use an adaptive fuzzy logic system to estimate the robot's time-varying, nonlinear, and unfamiliar dynamics. A strong adaptive term is created to counteract actuator defects and approximation errors while also guaranteeing the convergence and stability of the entire robot control system.* ***Novelty.*** *The implemented controller effectively mitigates the chattering problem while maintaining the tracking precision and robustness of the system. The stability analysis has been conducted using the Lyapunov approach.* ***Results.*** *Numerical simulation and capability comparison with other control strategies show the effectiveness of the developed control algorithm.* References 53, table 1, figures 8.

Key words: **robot manipulator, type-2 fuzzy system, fast terminal sliding mode control, adaptive control.**

Вступ. *У роботі представлено надійний метод керування для проблеми слідування шляху робота PUMA560. Методика базується на алгоритмі адаптивного нечіткого типу 2 швидкого ковзного керування терміналом (AFT2FTSMC) і призначена для обробки несправностей приводу, невизначеностей (таких як зміна корисного навантаження) та зовнішніх завад.* ***Метою*** *статті є використання підходу швидкого ковзного режиму керування терміналом (FTSMC) для забезпечення ефективної компенсації помилок і невизначеностей, мінімізації помилок відстеження, зменшення виникнення явищ деренчання та досягання швидкої реакції на перехідні процеси. Розроблено новий адаптивний відмовостійкий підхід до керування ковзним режимом для вирішення проблеми, що пов'язана з невизначеністю та дефектами приводу в реальних роботах.* ***Оригінальність***. *Ця робота об'єднала алгоритм адаптивного нечіткого типу 2 і швидкого кінцевого ковзного режиму керування з метою створення надійних контролерів для відстеження траєкторії робота-маніпулятора в умовах невизначеності параметрів присутності, зовнішніх завад і несправностей. Використано систему адаптивної нечіткої логіки для оцінки змінної в часі нелінійної та невідомої динаміки робота. Створено сильний адаптивний термін для протидії дефектам приводу та помилкам апроксимації, а також для гарантії конвергенції та стабільності усієї системи керування роботом.* ***Новизна***. *Реалізований контролер ефективно пом'якшує проблему тріскання, зберігаючи при цьому точність відстеження та надійність системи. Аналіз стабільності проведено за підходом Ляпунова.* ***Результати***. *Чисельне моделювання та порівняння можливостей з іншими стратегіями керування показують ефективність розробленого алгоритму керування.* Бібл. 53, табл. 1, рис. 8.

Ключові слова: **робот-маніпулятор, нечітка система типу 2, швидке керування ковзним режимом терміналу, адаптивне керування.**

1. Introduction. After the beginning of robotics, robotic manipulators have been extensively utilized in industrial automation containing the medical and nuclear domains. Manipulator robot system control is a very hard mission, principally in reason to the existence of high nonlinearities, very strong coupling effects, uncertainties parameters, and external disturbances in this type of system [1]. Recently, a significant scientific endeavor has been dedicated to develop an efficient controller of robot manipulators. For example, PID controller [2, 3], intelligent control [4, 5], optimal control [6, 7]. In [8], a feedback linearization technique was employed to create an inverse dynamics control system for precise motion control of a manipulator robot and computed torque control has been also proposed in [9, 10], where this approach is performed by using feedback linearization method.

Several studies have suggested different approaches to develop robust controllers for accurately following a desired trajectory of a manipulator robot, even when there are external disturbances, uncertainties in the parameters, and defects [11, 12]. Sliding Mode Control (SMC) is a highly reliable control technique that has been widely employed in the motion control of robot manipulators due to its exceptional ability to handle uncertainty and external disturbances [13, 14]. This good property of SMC has been utilized in the Fault Tolerant Control (FTC) design [15, 16].

Numerous articles have proposed multiple alternatives to preserve the benefits and reduce or eliminate the drawbacks of the conventional SMC. The adoption of terminal SMC in [17, 18] aims to achieve finite-time convergence. Nevertheless, the conventional terminal SMC exhibits a singularity issue and provides a sluggish rate of convergence. To address the issue of SMC, researchers have devised two control methods: Fast Terminal SMC (FTSMC) and nonsingular terminal SMC [19–22]. The authors in [20, 23, 24] devised a method called Nonsingular Fast Terminal SMC (NFTSMC) to achieve both cancellation of singularities and rapid finite-time convergence. Two control methods PID based SMC (PID-SMC) and integral SMC, were introduced in [25, 26]. A second-order sliding mode controller is implemented based on a super twisting algorithm for higher performance and stability in dealing with parameter changes and external disturbances for a three-level inverter-fed permanent magnet synchronous motor proposed in [27]. To enhance the transient response of the conventional SMC, the utilization of the integral action within the PID controller is employed to enhance the transient responsiveness [28].

Several techniques have been suggested to reduce the chattering effect. In [29–31], a SMC has been developed utilizing a saturation function to address this issue. But this approach compromises the system's robustness to external disturbances, a high-order sliding mode controller is employed, with super-twisting algorithm tested for effectiveness and robustness [32]. A High-Order SMC

(HOSMC) approach proposed in [33, 34], effectively reduces chattering effect, but requires understanding the temporal derivative of sliding surfaces, which is not always accessible. The fuzzy logic control is chosen for its simplicity and reliability, demonstrating its ability to handle complex, nonlinear systems effectively through linguistic variables and heuristic reasoning [35].

To summarize, numerous approaches have been developed to address the shortcomings of classic SMC, but no literature exists that proposes a controller synthesis method that can collectively overcome all disadvantages of SMC. To achieve a reliable FTC system, SMC design must satisfy 4 essential requirements: chattering reduction, fast transient response, finite-time convergence, and compensation of uncertainties, external perturbations and faults.

Aim and objectives of the article. Motivated by the precedent problems, this work proposes a FTC to overcome the external perturbations effects, uncertainties and actuator faults for 3 Degrees of Freedom (3-DOF) manipulators robot utilizing Adaptive Fuzzy Type-2 Fast Terminal SMC (AFT2FTSMC). The main contribution of this study is the development of a single, resilient controller that starts with selecting a rapid nonlinear terminal sliding surface, this controller aims to minimize tracking errors, best performances and chattering reducing. In addition, an adaptive type-2 fuzzy system has been utilized in the synthesized controller, to identify the unknown nonlinear model of robots due to actuator faults and external disturbances.

The primary objective of this work is to assess the effectiveness of modern control techniques in regulating the joint positions of a manipulator robot. Secondly, implement and validate the proposed command.

The Lyapunov approach was utilized for stability demonstration, with the work's contributions being highlighted by:

1) The design utilizes a fast nonlinear terminal sliding surface for improved control precision, finite-time convergence and fast transient response.

2) Stability analysis was proved according to the Lyapunov criterion, in which all adaptive laws were generated.

3) Compared to other control strategies suggested in the literature, such as computed torque control [9, 10], PID [2, 3], PID-SMC [25, 26], and conventional NFTSMC proposed in [20, 23, 24]. The proposed control strategy demonstrates the best performance when there is a defective.

In comparison with control strategies developed in [33–44] the following points encapsulate the work's contributions.

A complicated internal model based on passive FTC has been developed in [36, 37]. This control approach does not provide accurate trajectory tracking in the event of significant faults. The objective of this work is to use robust AFT2FTSMC for robot manipulators in the presence of payload changes.

The developed fast nonlinear terminal sliding surface outperforms studies in [38, 39] of best performances and exhibits robustness against actuator fault effects.

In contrast to [38–40], the controller synthesis in the work that is being described is independent of the robot manipulators' dynamic model. In our case, we supposed that the inertia matrix, Coriolis matrix, centrifugal forces, gravity terms are unknown.

In contrast to the control approach described in [41, 42], where the time delay identification it is adopted to estimate the unknown dynamics model. This study employs type-2 fuzzy systems to detect the uncertainties and nonlinear functions included in the model of robot manipulators. It also utilizes the FTSMC concept to develop a FTC controller that does not rely on time delay detection.

In [43] a complicated FTC strategy based on the association of SMC and nonlinear observer has been developed. Regrettably, this control technique requires a nonlinear observer, which will increase the intricacy and computing time. In this work, a robust FTC control has been developed without requiring a complex observer and can give good faults tolerance.

The authors in [33–35] proposed a HOSMC; this control algorithm has shown to be efficient to minimize the chattering effect, but requires the acquaintance of temporal derivative of sliding surfaces and it is sensible to actuator faults.

However, the suggested control technique effectively addresses the issue of chattering and successfully achieves optimal trajectory tracking even in the presence of external disturbances, uncertainties and actuator defects.

In [44], an adaptive fuzzy sliding control strategy has been proposed for 3-DOF manipulator robot, the results proved a favorable tracking performance with chattering phenomenon elimination, but this work did not deal the fault effects, but the proposed control strategy can give the best trajectory tracking in faulty operation.

The originality of our work was to combine the performance of fuzzy logic, the flexibility of adaptive control, and the robustness of sliding mode for the definition of a robust control structure tolerant to faults, achieving the best stability/performance ratios and speed/performance in the context of controlling a robot manipulator.

A novel adaptive fault tolerant SMC approach is developed to address the challenges provided by uncertainties and actuator defects in real robotics tasks. This method does not rely on prior knowledge of uncertainties and external disturbances unlike most of the methods known from the literature.

2. Robot manipulator dynamic modeling.

2.1 Robot manipulator dynamic modeling in healthy condition. The PUMA 560 robots are a 3-DOF robot arm, this type of robot is extensively utilized in industrial application. The configuration of PUMA 560 robots is presented in Fig. 1.

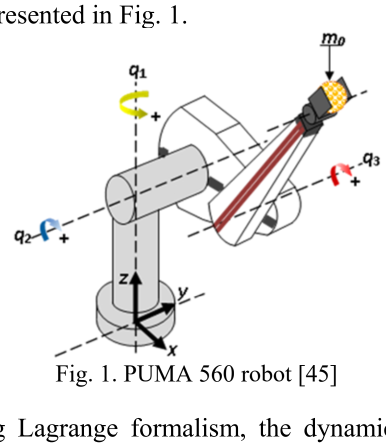

Fig. 1. PUMA 560 robot [45]

Using Lagrange formalism, the dynamic model of PUMA 560 robot is given as:

$$M(q)\,q''+V_m(q,q')q'+G(q)+u_{m0}=u+\tau_d\,, \quad (1)$$

where q = $[q_1, q_2, q_3]^T$ is the joint position vector; q' = $[q_1', q_2', q_3']^T$ is the joint velocity vector; q'' = $[q_1'', q_2'', q_3'']^T$ is the joint acceleration vector; u = $[u_1, u_2, u_3]^T$ is the joint input torque vector; $M(q)$ is the symmetric positive definite matrix of inertial accelerations; $V_m(q, q')$ is the matrix of Coriolis and centrifugal forces; $G(q)$ is the state varying vector of gravity terms; u is the motor torques; τ_d is the external disturbances; u_{m0} is the vector of torque due to the payload m_0 obtained by [45]:

$$u_{m0}=m_0 J^T(q)\left[J(q)q''+J'(q,q')q'+g\right], \quad (2)$$

with $g = [0\ 0\ 9.81]^T$ and J is the Jacobian matrix, equation (1) can be rewritten as:

$$M(q)\,q''+V_m(q,q')q'+G(q)=u+E(q,q',q''), \quad (3)$$

with $E(q,q',q'')=\tau_d-u_{m0}$.

2.2 Robot manipulator dynamic modeling in faulty condition. In robotic manipulators, defeat in the actuators can be generated by various reasons such as defeat in power supply systems. The dynamic model of robot manipulator in faulty condition is given by:

$$M(q)\,q''+V_m(q,q')q'+G(q)=u_f+E(q,q',q''), \quad (4)$$

where:

$$u_f = u + U_0, \quad (5)$$

where u_f is the motor torques in faulty condition; u is the motor torques; U_0 is the actuator fault component.

Substituting (5) in (4), the dynamic model in (3) is rearranged as:

$$q''=[M]^{-1}[u-V_m(q,q')q'-G(q)]+\vartheta(q,q',q''), \quad (6)$$

with:

$$\vartheta(q,q',q'')=[M]^{-1}[U_0+E(q,q',q'')],$$

where $\vartheta(q, q', q'')$ is the uncertainties component, which include payload variations and actuator faults effects.

3. Robust FTC using AFT2FTSMC. The dynamic model (6) can be expressed in the state space form by:

$$\begin{cases} x_1' = x_2; \\ x_2' = [M]^{-1}\left[u-V_m(q,q',q'')-G(q)\right]+\vartheta(q,q',q''); \\ y = x_1, \end{cases} \quad (7)$$

where $x_1 = [q_1\ q_2\ q_3]^T$ is the state vector; $x_2 = (q'_1\ q'_2\ q'_3)^T$.

The tracking error variable e_1 is defined by:

$$e_1 = q_d - x_1, \quad (8)$$

where $q_d = [q_{1d}\ q_{2d}\ q_{3d}]^T$ is desired signal.

The time derivative of (8) is computed by:

$$e_1' = q_d' - x_2 .$$

The global fast dynamic terminal sliding surface is given by [46–48]:

$$s=e_1'+\lambda e_1+\beta e_1^{m_1/n_1}=q_d'-x_2+\lambda e_1+\beta e_1^{m_1/n_1}, \quad (9)$$

where s is the global fast dynamic terminal sliding surface; λ, β, m_1, n_1 are the positive constants ($m_1<n_1$).

The time derivative of (9) is given as:

$$s'=q_d''+\left(\lambda+\beta\frac{m_1}{n_1}e_1^{(m_1-n_1)/n_1}\right)e_1'+ \\ +[M(q)]^{-1}[V_m(q,q')q'+G(q)]-[M(q)]^{-1}u-\vartheta(q,q',q''), \quad (10)$$

where s' is the time derivative of s.

Define the following Lyapunov function as:

$$V=\frac{1}{2}[M(q)]s^2\,, \quad (11)$$

where V is the Lyapunov's function.

The time derivative of (11) is calculated by:

$$V'=[M(q)]ss'-\frac{1}{2}[M'(q)]^{-1}[M(q)]^2 s^2\,, \quad (12)$$

where V' is the time derivative of Lyapunov's function.

Substituting (10) in (12) yields:

$$V'=s\left(\begin{array}{l} q_d''+\left(\lambda+\beta\frac{m_1}{n_1}e_1^{(m_1-n_1)/n_1}\right)e_1'+ \\ +\dfrac{[M(q)]^{-1}[V_m(q,q')q'+G(q)]-\vartheta(q,q',q'')}{[M(q)]^{-1}}- \\ -\dfrac{1}{2}[M'(q)]^{-1}[M(q)]^2 s-u \end{array}\right). \quad (13)$$

The control law u is extracted by:

$$u=\frac{1}{[M(q)]^{-1}}\left(\begin{array}{l} q_d''+\left(\lambda+\beta\frac{m_1}{n_1}e_1^{(m_1-n_1)/n_1}\right)e_1'+ \\ +[M(q)]^{-1}[V_m(q,q')q'+G(q)]- \\ -\dfrac{1}{2}[M'(q)]^{-1}[M(q)]^2 s-\vartheta(q,q',q'') \end{array}\right)+\alpha s\,, \quad (14)$$

where $\alpha = \mathrm{diag}[\alpha_1\ \alpha_2\ \alpha_3]>0$.

Using (14), it can be checked that:

$$V'\le-\alpha s^2<0\,. \quad (15)$$

If we considered a free of payload variations and without actuator defects, i.e., $\vartheta(q, q', q'') = 0$, the ideal control law is written as:

$$u=\frac{1}{[M(q)]^{-1}}(q_d''+(\lambda+\beta\frac{m_1}{n_1}e_1^{(m_1-n_1)/n_1})e_1'+ \\ +[M(q)]^{-1}[V_m(q,q')q'+G(q)]-\frac{1}{2}[M'(q)]^{-1}[M(q)]^2 s)+\alpha s. \quad (16)$$

The functions $M(q)$, $V_m(q, q')$ and $G(q)$ are unknown and $\vartheta(q, q', q'')$ expression which include actuator faults effects and payload variations are different to zero ($\vartheta(q, q', q'') \neq 0$), in this work an adaptive type fuzzy-2 system has been utilized to treat this problematic. The developed method concern the online identification of the ideal control law given by global fast dynamic terminal sliding mode control using fuzzy type-2 inference system where the fuzzy parameters are adapted.

The ideal control law presented in (16) can be rewritten as [49]:

$$u = u_b + \alpha s, \quad (17)$$

where u_b is the real control law:

$$u_b=\frac{1}{[M(q)]^{-1}}(q_d''+(\lambda+\beta\frac{m_1}{n_1}e_1^{(m_1-n_1)/n_1})e_1'+ \\ +[M(q)]^{-1}[V_m(q,q')q'+G(q)]-\frac{1}{2}[M'(q)]^{-1}[M(q)]^2 s). \quad (18)$$

To synthesis an adaptive control law, we suppose that each component of the control law $u_b = [u_{b1}\ u_{b2}\ u_{b3}]^T$ can be identified by a type-2 fuzzy as:

$$\hat{u}_{bj}=W_j^T(e_1(j),e_1'(j))\Theta_j\,. \quad (19)$$

Let us denote: $\Theta = [\Theta_1^T\ \Theta_2^T\ \Theta_3^T]^T$ and

$(e_1, e_1') = diag[W_1(e_1(1), e_1'(1))W_2(e_1(2), e_1'(2))W_3(e_1(3), e_1'(3))]$, therefore, we can write:

$$\hat{u}_b = W^T(e_1, e_1')\Theta, \qquad (20)$$

where Θ denotes adapted vector parameters; $W(X)$ is the average basis functions obtained by fuzzy type-2 system where each basis function is obtained by the average of corresponded left and right basis functions.

The real control law u_b is expressed by:

$$u_b = W^T(e_1, e_1')\Theta^* + \varepsilon, \qquad (21)$$

where Θ^* is the optimal parameter; $\varepsilon = [\varepsilon_1\ \varepsilon_2\ \varepsilon_3]^T$ is the identification error that guaranty that $|\varepsilon| \le \bar{\varepsilon}$, where $\bar{\varepsilon}$ is positive constant.

The adaptive control law applied to the robot is expressed as [49]:

$$u = u_a + u_r + u_p, \qquad (22)$$

where:

1) $u_{a,j}$ is the fuzzy type-2 adaptive control term which is designed in order to identified the ideal global fast dynamic terminal sliding mode control law u_b in (21) given as:

$$u_a = \hat{u}_b = W^T(e_1, e_1')\Theta, \qquad (23)$$

where $W^T(e_1, e'_1)$ is the average basis functions obtained by fuzzy type-2 system where each basis function is given by the average of corresponded left and right basis functions and Θ is the adjusted vector parameters given by:

$$\Theta' = \gamma \cdot s \cdot W^T(e_1, e_1') - \sigma_1\Theta, \qquad (24)$$

where $\gamma = diag[\gamma_1\ \gamma_2\ \gamma_3]>0$, $\sigma_1 = diag[\sigma_{1,1}\ \sigma_{1,2}\ \sigma_{1,3}]>0$, $s = q_d' - x_2 + \lambda e_1 + \beta e_1^{m_1/n_1}$ and $\Theta(0) = 0$.

2) u_r is the robust control term are added to minimize both the effects of fuzzy type-2 identification error and uncertainties expressed as [50]:

$$u_r = \hat{\varepsilon}\tanh(s/\chi), \qquad (25)$$

with $\hat{\varepsilon} = diag[\hat{\varepsilon}_1\ \hat{\varepsilon}_2\ \hat{\varepsilon}_3]$,

$$\hat{\varepsilon}' = \eta s \tanh(s/\chi) - \sigma_2\hat{\varepsilon}, \qquad (26)$$

with $\eta = diag[\eta_1\ \eta_2\ \eta_3]>0$, $\sigma_2 = diag[\sigma_{2,1}\ \sigma_{2,2}\ \sigma_{2,3}]>0$, $\chi>0$ and $\hat{\varepsilon}_j(0) = 0$.

3) $u_{p,j}$ is given by:

$$u_p = \alpha s, \qquad (22)$$

where $\alpha = diag[\alpha_1\ \alpha_2\ \alpha_3]>0$.

3.1 Stability demonstration. The Lyapunov function is given by:

$$V = \frac{1}{2}M^{-1}(q)s^2 + \frac{1}{2\gamma}\tilde{\Theta}^T\tilde{\Theta} + \frac{1}{2\eta_j}\tilde{\varepsilon}^T\tilde{\varepsilon}, \qquad (28)$$

where $\tilde{\varepsilon}$ and $\tilde{\Theta}$ are the identification errors given as:

$$\tilde{\varepsilon} = \varepsilon^* - \hat{\varepsilon}, \qquad (29)$$

where $\hat{\varepsilon}$ is the estimate of ε^*;

$$\tilde{\Theta} = \Theta^* - \Theta. \qquad (30)$$

The time derivative of (28) yields:

$$V' = s(u_b - u) + \frac{1}{\gamma}\tilde{\Theta}^T\tilde{\Theta}' + \frac{1}{\eta}\tilde{\varepsilon}^T\tilde{\varepsilon}'. \qquad (31)$$

Substituting (21), (22), (23) and (27) in (31) yields:

$$V' \le s\left(W^T(e_1, e_1')\Theta^* + \varepsilon - W^T(e_1, e_1')\Theta - u_r - \alpha s\right) + \\ + \frac{1}{\gamma}\tilde{\Theta}^T\tilde{\Theta}' + \frac{1}{\eta}\tilde{\varepsilon}^T\tilde{\varepsilon}'. \qquad (32)$$

The optimal parameters vector Θ^* and ε^* are slowly time varying, therefore the time derivative of estimation error will be:

$$\tilde{\varepsilon}' = -\hat{\varepsilon}' \quad \text{and} \quad \tilde{\Theta}' = -\Theta'. \qquad (33)$$

Substituting (33) in (32) and taking account (30) we obtain:

$$V' \le -\alpha s^2 + sW^T(e_1, e_1')\tilde{\Theta} + s(\varepsilon - u_r) - \\ -\frac{1}{\gamma}\tilde{\Theta}^T\Theta' - \frac{1}{\eta}\tilde{\varepsilon}^T\hat{\varepsilon}'. \qquad (34)$$

By introducing (24) and (26) into (34), yield:

$$V' \le -\alpha s^2 + s(\varepsilon - u_r) + \\ + \frac{\sigma_1}{\gamma}\tilde{\Theta}^T\Theta - \frac{1}{\eta}\tilde{\varepsilon}\eta s \tanh\left(\frac{s}{\chi}\right) + \frac{\sigma_2}{\eta}\tilde{\varepsilon}\hat{\varepsilon}. \qquad (35)$$

Substituting (29) in (35) we obtain:

$$V' \le -\alpha s^2 + s(\varepsilon - u_r) + \frac{\sigma_1}{\gamma}\tilde{\Theta}^T\Theta - \\ -\varepsilon^* s \tanh\left(\frac{s}{\chi}\right) + \varepsilon_j^* s \tanh\left(\frac{s}{\chi}\right) + \frac{\sigma_2}{\eta}\tilde{\varepsilon}\hat{\varepsilon}. \qquad (36)$$

Or equivalently:

$$V' \le -\alpha s^2 + \frac{\sigma_1}{\gamma}\tilde{\Theta}^T\Theta - \varepsilon^* s \tanh\left(\frac{s}{\chi}\right) + \\ + \hat{\varepsilon} s \tanh\left(\frac{s}{\chi}\right) + \frac{\sigma_2}{\eta}\tilde{\varepsilon}\hat{\varepsilon} - su_{r,j} + |s|\varepsilon^*. \qquad (37)$$

By introducing (25) into (37), yields:

$$V' \le -\alpha s^2 + \frac{\sigma_1}{\gamma}\tilde{\Theta}^T\Theta + |s|\varepsilon_j^* - \varepsilon^* s \tanh\left(\frac{s}{\chi}\right) + \frac{\sigma_2}{\eta}\tilde{\varepsilon}\hat{\varepsilon}. \qquad (38)$$

Let the inequality given as follows for any value of $\zeta > 0$ [50]:

$$|s| - s\tanh\left(\frac{s}{\chi}\right) \le \zeta\chi = \varsigma, \qquad (39)$$

with ζ is the constant that confirms $\zeta = e^{-(\zeta+1)}$, i.e. $\zeta = 0.2785$.

Equation (39) is changed as:

$$V' \le -\alpha s^2 + \varepsilon^*\varsigma + \frac{\sigma_1}{\gamma}\tilde{\Theta}^T\Theta + \frac{\sigma_2}{\eta}\tilde{\varepsilon}\hat{\varepsilon}. \qquad (40)$$

By using young's inequality, we obtain: (27)

$$\frac{\sigma_1}{\gamma}\tilde{\Theta}^T\Theta \le -\frac{\sigma_1}{2\gamma}\tilde{\Theta}^T\Theta + \frac{\sigma_1}{2\gamma}\tilde{\Theta}^{*T}\Theta^*. \qquad (41)$$

$$\frac{\sigma_2}{\eta}\tilde{\varepsilon}^T\hat{\varepsilon} \le -\frac{\sigma_2}{2\eta}\tilde{\varepsilon}^2 + \frac{\sigma_2}{2\eta}\left|\varepsilon^*\right|^2. \qquad (42)$$

By introducing (41) and (42) into (40), yields:

$$V' \le -\alpha s^2 + \varepsilon^*\varsigma - \frac{\sigma_1}{2\gamma}\tilde{\Theta}^T\Theta + \frac{\sigma_1}{2\gamma}\tilde{\Theta}^{*T}\Theta^* - \\ -\frac{\sigma_2}{2\eta}\tilde{\varepsilon}^2 + \frac{\sigma_2}{2\eta}\left|\varepsilon^*\right|^2. \qquad (43)$$

Let's specify:

$$c = \min\{\sigma_1, \sigma_2, 2\alpha\}. \qquad (44)$$

So (43) becomes:

$$V' \le -cV + \rho, \qquad (45)$$

with:

$$\rho = \varepsilon^*\varsigma + \frac{\sigma_1}{2\gamma}\tilde{\Theta}^{*T}\Theta^* + \frac{\sigma_2}{2\eta}\left|\varepsilon^*\right|^2. \qquad (46)$$

By integrating (46), we find that:

$$V(t) \le V(0)e^{-ct} + \rho/c. \quad (47)$$

Using (45) it can be demonstrated that the developed control algorithm of PUMA 560 robot presented in (22) is stable despite the existence of payload uncertainties and actuator faults consequently the tracking errors converge to zero. The proposed control scheme is showed in Fig. 2.

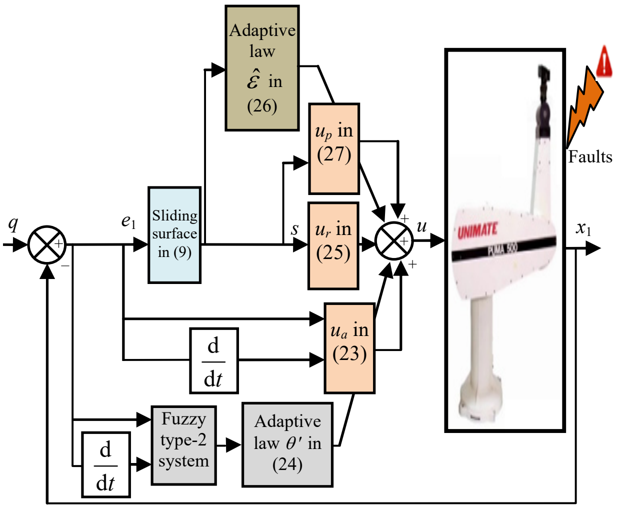

Fig. 2. Proposed adaptive control algorithm

4. Simulation results. The developed control method has been carried out by numerical simulation using MATLAB/Simulink environment in order to prove the efficiency of tracking capability of the three joints (q_1, q_2, q_3), where payload uncertainties and actuator faults are taken into account.

Cycloidal desired trajectories are considered to the three joints of PUMA 560 robot defined as:

$$q_{dj}(t)=\begin{cases} q_{dj}(0)+\dfrac{D_j}{2\pi}\left[2\pi\dfrac{t}{t_f}-\sin\left(2\pi\dfrac{t}{t_f}\right)\right] \text{for } 0\le t\le t_f; \\ q_{dj}(t_f) \text{ for } t>t_f, \end{cases} \quad (48)$$

where $q_{dj}(t)$ is the cycloidal desired trajectory, j = 1,..., 3; $D_j = q_{dj}(t_f) - q_{dj}(0)$, and t_f is the final time of robot motion.

In addition, a comparative study with other state-of-the-art control methodology has been carried out, the input variables (e_1, e'_1) of the fuzzy type-2 system in (23) are decomposed into five linguistic variables on the normalized intervals [–1, 1] with five type-2 Gaussian membership functions. In order to verify the efficiency of the proposed control to versus actuator faults, we supply the following abrupt faults:

$$U_0 = \begin{cases} 150 \ \text{N}\cdot\text{m} & t = 2\ \text{s}; \\ 120 \ \text{N}\cdot\text{m} & t = 2\ \text{s}; \\ 230 \ \text{N}\cdot\text{m} & t = 3\ \text{s}. \end{cases}$$

In addition, the payload mass m_0 varies in the interval from 10 kg to 2 kg, where it is showed in Fig. 3, and additional external disturbances τ_d are supposed varied in the time as:

$$\tau_d = \begin{cases} 10\sin(t) + 5\sin(200\pi t); \\ 5\cos(2t) + 5\sin(200\pi t); \\ 5\cos(2t) + 5\sin(200\pi t). \end{cases}$$

The initial conditions of the three joints are $q(0)$ = [–45 –130 125]^T deg. Three joints trajectory tracking are showed in Fig. 4, where it is remarked that, the positions for joints 1, 2, and 3 given by the control method proposed in [38, 51, 52] are deviated from their desired trajectory as depicted in Fig. 4, which show the insufficiency of this control strategy in faulty condition.

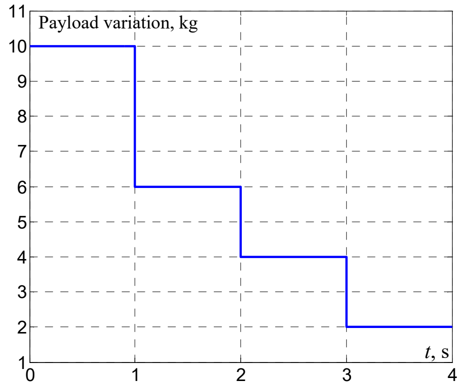

Fig. 3. Payload variation

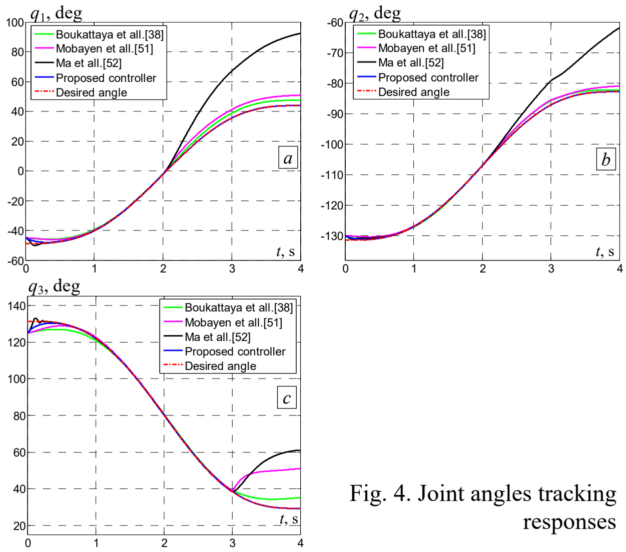

Fig. 4. Joint angles tracking responses

Figure 5 presents the joint tracking error for joints 1, 2, and 3, respectively. In Fig. 5, it is noted that in faulty operation, the proposed control give a smallest tracking error in compared to the proposed control in [38, 51, 52].

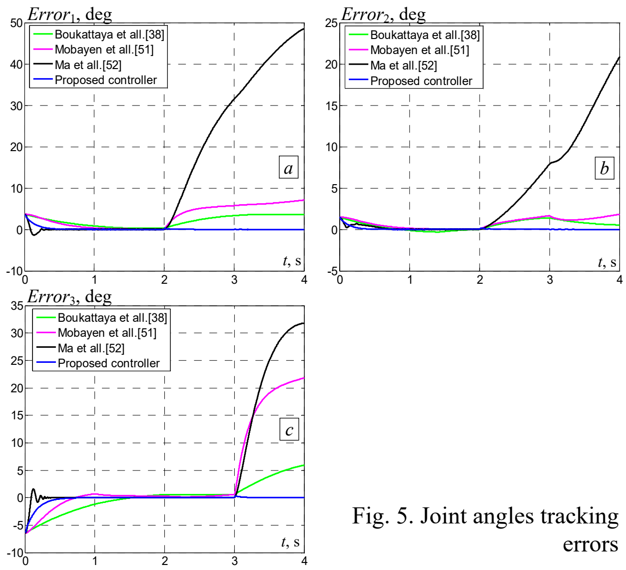

Fig. 5. Joint angles tracking errors

It is noted also from Fig. 6, that the proposed control strategy give lower control efforts with smooth signal, this can be checked by the integral square of control input values (ISV) in Table 1. The trajectory tracking of the robot in Cartesian space under the proposed controller and the proposed control in [38, 51, 52], are indicated in Fig. 7. It is remarked that the proposed control achieved a good tracking in compared to other controllers.

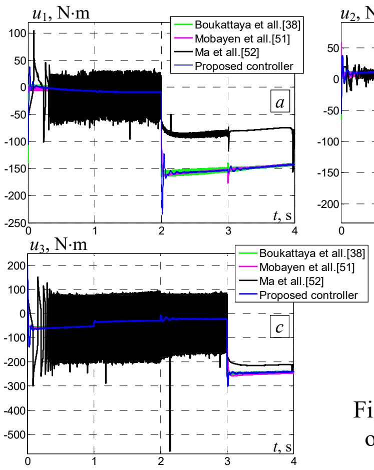

Fig. 6. Control input signal of the proposed controller

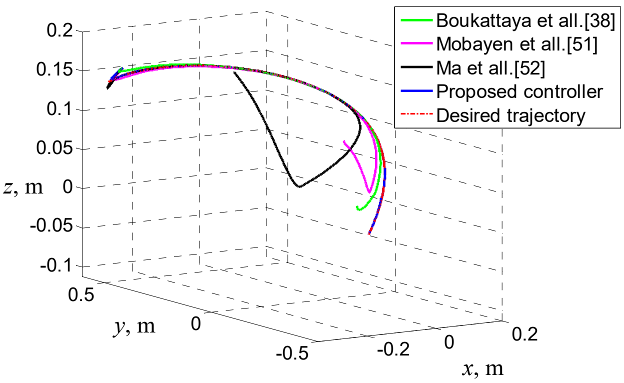

Fig. 7. Performed trajectory in Cartesian space

5. Quantitative comparison. In this section a quantitative comparison will be addressed in order to well illustrate the comparison between 4 control strategies, for this purpose an integral absolute error (IAE), integral square error (ISE), integral time absolute error (IATE) and ISV. The IAE, ISE and IATE are utilized as error tracking measured and ISV denotes energy consumption [53]. The IAE, ISE, IATE and ISV criteria are defined as:

$$IAE = \int_0^{t_f} |e_1(t)| \mathrm{d}t \, ; \quad (50) \qquad ISE = \int_0^{t_f} e_1^2(t) \mathrm{d}t \, ; \quad (51)$$

$$IATE = \int_0^{t_f} t|e_1(t)| \mathrm{d}t \, ; \quad (52) \qquad ISV = \int_0^{t_f} u_1^2(t) \mathrm{d}t \, . \quad (53)$$

From the quantitative comparison results presented in Table 1 and Fig. 8, it is confirmed that performance indices (IAE, ISE, IATE) values of the proposed controller are lower compared with the existing control [38, 51, 52]. In addition, comparing the control inputs (energy consumption), it is remarked that the proposed control strategy also give superior control input performance as shown in Table 1 and Fig. 8.

Table 1

Quantitative comparison under external disturbances, payload variation and actuator

Control scheme	IAE			ISE		
	Joint 1	Joint 2	Joint 3	Joint 1	Joint 2	Joint 3
Ref. [38]	8.16	2.45	8.15	23.14	2.27	30.95
Ref. [51]	12.61	3.14	19.55	65.93	3.83	318.87
Ref. [52]	57.99	16.94	21.85	2.07	210.51	558.25
Proposed controller	0.5323	0.2155	1.016	0.9763	0.1484	3.233
Control scheme	IATE			ISV		
	Joint 1	Joint 2	Joint 3	Joint 1	Joint 2	Joint 3
Ref. [38]	19.53	5.61	16.61	277	1447.5	5067.1
Ref. [51]	34.41	7.76	61.75	202.28	1301.6	5587.9
Ref. [52]	189.31	56.78	77.59	4455.1	2439	7870
Proposed controller	0.122	0.08	0.26	189.76	1122.4	4926.1

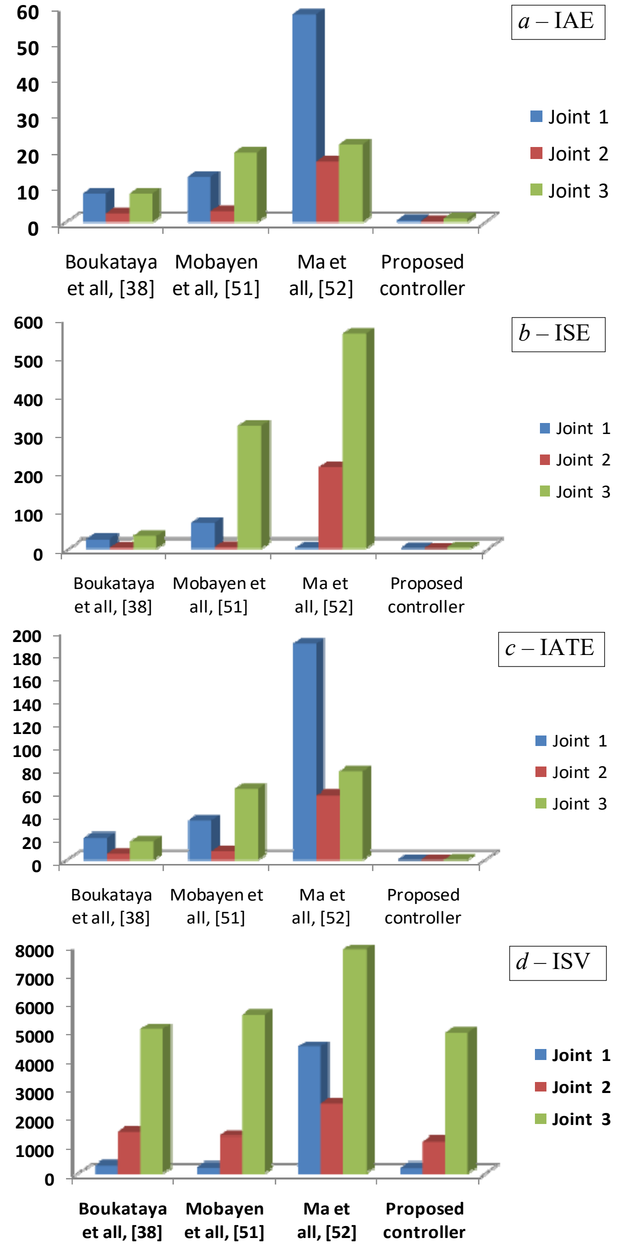

Fig. 8. Histogram of performance indices (IAE, ISE, IATE, ISV)

6. Conclusions. This work proposed a novel adaptive control strategy for path following of 3 degrees of freedom robot manipulators in the existence of uncertainties (payload variation), external disturbances, and actuator faults.

The developed approach associates an adaptive fuzzy type-2 control and FTSMC. The proposed control algorithm is characterized by the integration of advantages of SMC, adaptive fuzzy type-2 control, and FTSMC. By utilizing only one powerful controller can supply several benefits such as faults and uncertainties compensation, small tracking error, chattering phenomenon reducing, and fast transient response. In addition, the proposed controller can supply globally asymptotic stability, where it has been demonstrated by the Lyapunov theory.

The proposed control law in this paper has been applied to the PUMA560 robot and compared with other developed controllers. The numerical simulation results demonstrate the upper tracking capability of the developed control methodology in the attendance of external perturbations, uncertainties, and actuator faults. Finally, as future work, the measurement noises and sensor defects effects will be taken into account. In addition, an optimization algorithm will be addressed in order to give the optimal values of the developed controller.

Conflict of interest. The authors declare that there is no conflict of interest.

REFERENCES

1. Capisani L.M., Ferrara A., Magnani L. Second order sliding mode motion control of rigid robot manipulators. *2007 46th IEEE Conference on Decision and Control*, 2007, pp. 3691-3696. doi: https://doi.org/10.1109/CDC.2007.4434473.

2. Wen Yu, Rosen J. Neural PID Control of Robot Manipulators With Application to an Upper Limb Exoskeleton. *IEEE Transactions on Cybernetics*, 2013, vol. 43, no. 2, pp. 673-684. doi: https://doi.org/10.1109/TSMCB.2012.2214381.

3. Su Y., Muller P.C., Zheng C. Global asymptotic saturated PID control for robot manipulators. *IEEE Transactions on Control Systems Technology*, 2010, vol. 18, no. 6, pp. 1280-1288. doi: https://doi.org/10.1109/TCST.2009.2035924.

4. Tayebi A., Abdul S., Zaremba M.B., Ye Y. Robust Iterative Learning Control Design: Application to a Robot Manipulator. *IEEE/ASME Transactions on Mechatronics*, 2008, vol. 13, no. 5, pp. 608-613. doi: https://doi.org/10.1109/TMECH.2008.2004627.

5. Wang M., Yang A. Dynamic Learning From Adaptive Neural Control of Robot Manipulators With Prescribed Performance. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 2017, vol. 47, no. 8, pp. 2244-2255. doi: https://doi.org/10.1109/TSMC.2016.2645942.

6. Duchaine V., Bouchard S., Gosselin C.M. Computationally Efficient Predictive Robot Control. *IEEE/ASME Transactions on Mechatronics*, 2007, vol. 12, no. 5, pp. 570-578. doi: https://doi.org/10.1109/TMECH.2007.905722.

7. Feng Lin, Brandt R.D. An optimal control approach to robust control of robot manipulators. *IEEE Transactions on Robotics and Automation*, 1998, vol. 14, no. 1, pp. 69-77. doi: https://doi.org/10.1109/70.660845.

8. Morecki A., Knapczyk J. *Basics of Robotics: Theory and Components of Manipulators and Robots*. Springer, 1999. 580 p.

9. Vidyasagar M. *Robot Dynamics and Control*. Wiley, 1989. 336 p.

10. Jansen H.V., Tas N.R., Berenschot J.W. *Encyclopedia of Nanoscience and Nanotechnology*. Addison-Wisley, 1989.

11. Ferrara A., Incremona G.P. Design of an Integral Suboptimal Second-Order Sliding Mode Controller for the Robust Motion Control of Robot Manipulators. *IEEE Transactions on Control Systems Technology*, 2015, vol. 23, no. 6, pp. 2316-2325. doi: https://doi.org/10.1109/TCST.2015.2420624.

12. Jin M., Kang S.H., Chang P.H., Lee J. Robust Control of Robot Manipulators Using Inclusive and Enhanced Time Delay Control. *IEEE/ASME Transactions on Mechatronics*, 2017, vol. 22, no. 5, pp. 2141-2152. doi: https://doi.org/10.1109/TMECH.2017.2718108.

13. Utkin V. *Sliding Modes on Control and Optimization*. Springer, 1992. 286 p.

14. Abed K., Zine H.K.E. Intelligent fuzzy back-stepping observer design based induction motor robust nonlinear sensorless control. *Electrical Engineering & Electromechanics*, 2024, no. 2, pp. 10-15. doi: https://doi.org/10.20998/2074-272X.2024.2.02.

15. Xiao B., Hu Q., Zhang Y. Adaptive Sliding Mode Fault Tolerant Attitude Tracking Control for Flexible Spacecraft Under Actuator Saturation. *IEEE Transactions on Control Systems Technology*, 2012, vol. 20, no. 6, pp. 1605-1612. doi: https://doi.org/10.1109/TCST.2011.2169796.

16. Liang Y.-W., Xu S.-D., Liaw D.-C., Chen C.-C. A Study of T–S Model-Based SMC Scheme With Application to Robot Control. *IEEE Transactions on Industrial Electronics*, 2008, vol. 55, no. 11, pp. 3964-3971. doi: https://doi.org/10.1109/TIE.2008.2005138.

17. Chen G., Song Y., Guan Y. Terminal Sliding Mode-Based Consensus Tracking Control for Networked Uncertain Mechanical Systems on Digraphs. *IEEE Transactions on Neural Networks and Learning Systems*, 2018, vol. 29, no. 3, pp. 749-756. doi: https://doi.org/10.1109/TNNLS.2016.2636323.

18. Xu Q. Piezoelectric Nanopositioning Control Using Second-Order Discrete-Time Terminal Sliding-Mode Strategy. *IEEE Transactions on Industrial Electronics*, 2015, vol. 62, no. 12, pp. 7738-7748. doi: https://doi.org/10.1109/TIE.2015.2449772.

19. Wang H., Man Z., Kong H., Zhao Y., Yu M., Cao Z., Zheng J., Do M.T. Design and Implementation of Adaptive Terminal Sliding-Mode Control on a Steer-by-Wire Equipped Road Vehicle. *IEEE Transactions on Industrial Electronics*, 2016, vol. 63, no. 9, pp. 5774-5785. doi: https://doi.org/10.1109/TIE.2016.2573239.

20. Zheng J., Wang H., Man Z., Jin J., Fu M. Robust Motion Control of a Linear Motor Positioner Using Fast Nonsingular Terminal Sliding Mode. *IEEE/ASME Transactions on Mechatronics*, 2015, vol. 20, no. 4, pp. 1743-1752. doi: https://doi.org/10.1109/TMECH.2014.2352647.

21. Madani T., Daachi B., Djouani K. Modular-Controller-Design-Based Fast Terminal Sliding Mode for Articulated Exoskeleton Systems. *IEEE Transactions on Control Systems Technology*, 2017, vol. 25, no. 3, pp. 1133-1140. doi: https://doi.org/10.1109/TCST.2016.2579603.

22. Solis C.U., Clempner J.B., Poznyak A.S. Fast Terminal Sliding-Mode Control With an Integral Filter Applied to a Van Der Pol Oscillator. *IEEE Transactions on Industrial Electronics*, 2017, vol. 64, no. 7, pp. 5622-5628. doi: https://doi.org/10.1109/TIE.2017.2677299.

23. Van M., Ge S.S., Ren H. Finite Time Fault Tolerant Control for Robot Manipulators Using Time Delay Estimation and Continuous Nonsingular Fast Terminal Sliding Mode Control. *IEEE Transactions on Cybernetics*, 2017, vol. 47, no. 7, pp. 1681-1693. doi: https://doi.org/10.1109/TCYB.2016.2555307.

24. Xu S.S.-D., Chen C.-C., Wu Z.-L. Study of Nonsingular Fast Terminal Sliding-Mode Fault-Tolerant Control. *IEEE Transactions on Industrial Electronics*, 2015, vol. 62, no. 6, pp. 3906-3913. doi: https://doi.org/10.1109/TIE.2015.2399397.

25. Parra-Vega V., Arimoto S., Yun-Hui Liu, Hirzinger G., Akella P. Dynamic sliding PID control for tracking of robot manipulators: theory and experiments. *IEEE Transactions on Robotics and Automation*, 2003, vol. 19, no. 6, pp. 967-976. doi: https://doi.org/10.1109/TRA.2003.819600.

26. Incremona G.P., Ferrara A., Magni L. MPC for Robot Manipulators With Integral Sliding Modes Generation. *IEEE/ASME Transactions on Mechatronics*, 2017, vol. 22, no. 3, pp. 1299-1307. doi: https://doi.org/10.1109/TMECH.2017.2674701.

27. Oualah O., Kerdoun D., Boumassata A. Super-twisting sliding mode control for brushless doubly fed reluctance generator based on wind energy conversion system. *Electrical Engineering & Electromechanics*, 2023, no. 2, pp. 86-92. doi: https://doi.org/10.20998/2074-272X.2023.2.13.

28. Van M., Ge S.S., Ren H. Robust Fault-Tolerant Control for a Class of Second-Order Nonlinear Systems Using an Adaptive

Third-Order Sliding Mode Control. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 2016, vol. 47, no. 2, pp. 221-228. doi: https://doi.org/10.1109/TSMC.2016.2557220.
29. Lilly J.H., Liang Yang. Sliding mode tracking for pneumatic muscle actuators in opposing pair configuration. *IEEE Transactions on Control Systems Technology*, 2005, vol. 13, no. 4, pp. 550-558. doi: https://doi.org/10.1109/TCST.2005.847333.
30. Chen J.-Y. Expert SMC-based fuzzy control with genetic algorithms. *Journal of the Franklin Institute*, 1999, vol. 336, no. 4, pp. 589-610. doi: https://doi.org/10.1016/S0016-0032(97)00077-X.
31. Tondu B. *Artificial Muscles for Humanoid Robots, Humanoid Robots: Human-like Machines*, 2007. Book edited by Matthias Hackel, pp. 89-122, Itech, Vienna, Austria.
32. Braikia K., Chettouh M., Tondu B., Acco P., Hamerlain M. Improved Control Strategy of 2-Sliding Controls Applied to a Flexible Robot Arm. *Advanced Robotics*, 2011, vol. 25, no. 11-12, pp. 1515-1538. doi: https://doi.org/10.1163/016918611X579510.
33. Van M., Kang H.-J., Suh Y.-S. Second Order Sliding Mode-Based Output Feedback Tracking Control for Uncertain Robot Manipulators. *International Journal of Advanced Robotic Systems*, 2013, vol. 10, no. 1, pp. 1-9. doi: https://doi.org/10.5772/55060.
34. Guezi A., Bendaikha A., Dendouga A. Direct torque control based on second order sliding mode controller for three-level inverter-fed permanent magnet synchronous motor: comparative study. *Electrical Engineering & Electromechanics*, 2022, no. 5, pp. 10-13. doi: https://doi.org/10.20998/2074-272X.2022.5.02.
35. Aissaoui M., Bouzeria H., Benidir M., Labed M.A. Harmonics suppression in high-speed railway via single-phase traction converter with an LCL filter using fuzzy logic control strategy. *Electrical Engineering & Electromechanics*, 2024, no. 2, pp. 16-22. doi: https://doi.org/10.20998/2074-272X.2024.2.03.
36. Bonivento C., Gentili L., Paoli A. Internal model based fault tolerant control of a robot manipulator. *2004 43rd IEEE Conference on Decision and Control (CDC)*, 2004, vol. 5, pp. 5260-5265. doi: https://doi.org/10.1109/CDC.2004.1429643.
37. Bonivento C., Gentili L., Paoli A. Fault Tolerant Tracking of a Robot Manipulator: An Internal Model Based Approach. *Systems and Control: Foundations and Applications*, 2006, no. 9780817643836, pp. 271-287. doi: https://doi.org/10.1007/0-8176-4470-9_15.
38. Boukattaya M., Mezghani N., Damak T. Adaptive nonsingular fast terminal sliding-mode control for the tracking problem of uncertain dynamical systems. *ISA Transactions*, 2018, vol. 77, pp. 1-19. doi: https://doi.org/10.1016/j.isatra.2018.04.007.
39. Yi S., Zhai J. Adaptive second-order fast nonsingular terminal sliding mode control for robotic manipulators. *ISA Transactions*, 2019, vol. 90, pp. 41-51. doi: https://doi.org/10.1016/j.isatra.2018.12.046.
40. Mondal S., Mahanta C. Adaptive second order terminal sliding mode controller for robotic manipulators. *Journal of the Franklin Institute*, 2014, vol. 351, no. 4, pp. 2356-2377. doi: https://doi.org/10.1016/j.jfranklin.2013.08.027.
41. Van M., Ge S.S., Ren H. Finite Time Fault Tolerant Control for Robot Manipulators Using Time Delay Estimation and Continuous Nonsingular Fast Terminal Sliding Mode Control. *IEEE Transactions on Cybernetics*, 2017, vol. 47, no. 7, pp. 1681-1693. doi: https://doi.org/10.1109/TCYB.2016.2555307.
42. Van M., Do X.P., Mavrovouniotis M. Self-tuning fuzzy PID-nonsingular fast terminal sliding mode control for robust fault tolerant control of robot manipulators. *ISA Transactions*, 2020, vol. 96, pp. 60-68. doi: https://doi.org/10.1016/j.isatra.2019.06.017.
43. Xiao B., Yin S., Gao H. Reconfigurable Tolerant Control of Uncertain Mechanical Systems With Actuator Faults: A Sliding Mode Observer-Based Approach. *IEEE Transactions on Control Systems Technology*, 2018, vol. 26, no. 4, pp. 1249-1258. doi: https://doi.org/10.1109/TCST.2017.2707333.
44. Amer A.F., Sallam E.A., Elawady W.M. Adaptive fuzzy sliding mode control using supervisory fuzzy control for 3 DOF planar robot manipulators. *Applied Soft Computing*, 2011, vol. 11, no. 8, pp. 4943-4953. doi: https://doi.org/10.1016/j.asoc.2011.06.005.
45. Guendouzi A., Boubakir A., Hamerlain M. Higher order sliding mode control of robot manipulator. *The Ninth International Conference on Autonomic and Autonomous Systems (ICAS 2013)*, 2013, pp. 61-66.
46. Xinghuo Yu, Man Zhihong. Fast terminal sliding-mode control design for nonlinear dynamical systems. *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, 2002, vol. 49, no. 2, pp. 261-264. doi: https://doi.org/10.1109/81.983876.
47. Chen M., Wu Q.-X., Cui R.-X. Terminal sliding mode tracking control for a class of SISO uncertain nonlinear systems. *ISA Transactions*, 2013, vol. 52, no. 2, pp. 198-206. doi: https://doi.org/10.1016/j.isatra.2012.09.009.
48. Xiong J.-J., Zhang G.-B. Global fast dynamic terminal sliding mode control for a quadrotor UAV. *ISA Transactions*, 2017, vol. 66, pp. 233-240. doi: https://doi.org/10.1016/j.isatra.2016.09.019.
49. Yacef F., Bouhali O., Hamerlain M., Rizoug N. Observer-based Adaptive Fuzzy Backstepping Tracking Control of Quadrotor Unmanned Aerial Vehicle Powered by Li-ion Battery. *Journal of Intelligent & Robotic Systems*, 2016, vol. 84, no. 1-4, pp. 179-197. doi: https://doi.org/10.1007/s10846-016-0345-0.
50. Bounar N., Boulkroune A., Boudjema F., M'Saad, M., Farza M. Adaptive fuzzy vector control for a doubly-fed induction motor. *Neurocomputing*, 2015, vol. 151, part 2, pp. 756-769. doi: https://doi.org/10.1016/j.neucom.2014.10.026.
51. Mobayen S., Tchier F., Ragoub L. Design of an adaptive tracker for n -link rigid robotic manipulators based on super-twisting global nonlinear sliding mode control. *International Journal of Systems Science*, 2017, vol. 48, no. 9, pp. 1990-2002. doi: https://doi.org/10.1080/00207721.2017.1299812.
52. Ma Z., Sun G. Dual terminal sliding mode control design for rigid robotic manipulator. *Journal of the Franklin Institute*, 2018, vol. 355, no. 18, pp. 9127-9149. doi: https://doi.org/10.1016/j.jfranklin.2017.01.034.
53. Li T.-H.S., Huang Y.-C. MIMO adaptive fuzzy terminal sliding-mode controller for robotic manipulators. *Information Sciences*, 2010, vol. 180, no. 23, pp. 4641-4660. doi: https://doi.org/10.1016/j.ins.2010.08.009.

Received 27.06.2024
Accepted 18.08.2024
Published 02.01.2025

H. Rahali [1], *Doctor of Electrotechnical,*
S. Zeghlache [2], *Doctor of Electrotechnical, Professor,*
B.D.E. Cherif [1], *Doctor of Electrotechnical,*
L. Benyettou [1], *Doctor of Electrotechnical, Professor,*
A. Djerioui [1], *Doctor of Electrotechnical, Professor,*
[1] Laboratory of Electrical Engineering,
Faculty of Technology, University of M'Sila, Algeria,
e-mail: hilal.rahali@univ-msila.dz (Corresponding Author);
[2] Laboratory of Signals and Systems Analysis,
Faculty of Technology, University of M'Sila, Algeria.

How to cite this article:
Rahali H., Zeghlache S., Cherif B.D.E., Benyettou L., Djerioui A. Robust adaptive fuzzy type-2 fast terminal sliding mode control of robot manipulators in attendance of actuator faults and payload variation. *Electrical Engineering & Electromechanics*, 2025, no. 1, pp. 31-38. doi: https://doi.org/10.20998/2074-272X.2025.1.05