Time Delay Estimation Based Integral Sliding Mode and Super-Twisting Control for Robust Robot Trajectory Tracking

Tinhinane Bacha, Adem Manseur, and Chems Eddine Boudjdir

Abstract—This paper improved trajectory tracking control strategy for robotic manipulators, combining Time Delay Control (TDC), Integral Sliding Mode (ISM), and the Super-Twisting Algorithm (TDC-IS-STA). The Time Delay Control framework provides a model-free aspect by estimation of unknown nonlinear dynamics and external disturbances using previously measured system data, while the integral sliding surface eliminates the reaching phase and ensures robustness from the initial instant of operation. To further mitigate the chattering phenomenon inherent in classical sliding mode control, the Super-Twisting Algorithm is incorporated to generate a continuous control signal while preserving finite-time convergence and robust performance. The proposed controller is validated through numerical simulations performed in MATLAB/Simulink on a parallel Delta robot model under multiple operating scenarios .Comparative study against control approaches demonstrate that the proposed TDC-IS-STA strategy achieves superior tracking accuracy, reduced chattering in the actuator torque signals .

***Keywords*—Time Delay Control, Integral Sliding Mode, Super-Twisting Algorithm, Trajectory Tracking, Delta robot.**

Nomenclature

PID	Proportional Integral Derivative.
TDC	Time Delay Control.
TDE	Time Delay Estimation.
SMC	Sliding Mode Control.
ISM	Integral Sliding Mode.
STA	Super-Twisting Algorithm.

I. Introduction

In modern industrial automation, achieving high precision, repeatability, and fast dynamic response has become an essential requirement for many robotic applications. Parallel robotic structures [1] have attracted considerable attention due to their superior rigidity, high positioning accuracy, and enhanced load-to-weight ratio compared to conventional serial manipulators. Owing to these advantages, parallel robots are widely used in many applications [2] such as high-speed pick-and-place operations, assembly processes, and trajectory tracking tasks that require both accuracy and rapid motion.

The Delta robot is one of the most well-known parallel robotic structures [3, 4]. Due to its lightweight moving platform and parallel kinematic architecture, the Delta robot can achieve fast, accurate motions. Despite these advantages, controlling parallel manipulators remains challenging due to their highly nonlinear dynamics, strong coupling effects, parameter uncertainties, and sensitivity to external disturbances.

Traditional control approaches have been widely used in robotic systems because they are easy to implement and inexpensive. Among these approaches, PID have been extensively used in trajectory tracking applications [5, 6]. However, their performance tends to degrade when the robotic system operates under complex dynamics and uncertain conditions. In addition, these controllers rely on fixed tuned gains, which can become ineffective when system dynamics vary, thereby limiting tracking accuracy and robustness.

To improve trajectory tracking performance, several advanced control strategies have been proposed in the literature, including adaptive control [7], sliding mode control [8], and model-based [9]. Among these techniques, Time Delay Control (TDC) has received considerable attention due to its simple structure and reduced dependence on an accurate dynamic model. Using previously measured system data, TDC estimates unknown dynamics and disturbances, providing an efficient, model-free framework capable of achieving satisfactory tracking performance in nonlinear robotic systems.

Despite its effectiveness, the performance of TDC may deteriorate in the presence of Time Delay Estimation (TDE) errors, particularly under rapid dynamic variations and external disturbances.To overcome this limitation and enhance system robustness, TDC has been combined with various advanced control techniques [10–13], such as Sliding Mode Control (SMC). The Integral Sliding Mode (ISM) technique [14], in particular, has attracted considerable attention due to its ability to eliminate the reaching phase and ensure robustness from the initial instant of operation. By introducing an integral sliding surface, the system states are forced to evolve on the sliding manifold throughout

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the motion, resulting in improved disturbance rejection and enhanced tracking accuracy.

However, classical SMC still suffers from the chattering phenomenon caused by discontinuous switching control actions [15, 16]. This phenomenon produces high-frequency oscillations in the control signal that may lead to mechanical wear, actuator degradation, unwanted vibrations, and excitation of unmodeled dynamics.

Several techniques have been proposed in the literature to reduce chattering, including boundary layer methods and saturation functions [16, 17]. While these methods can reduce high-frequency oscillations, they often decrease robustness and tracking performance. To overcome this limitation , the Super-Twisting Algorithm (STA), which belongs to the class of higher-order sliding mode techniques has emerged as an effective solution for chattering mitigation [18, 19]. Unlike classical SMC, the STA generates a continuous control signal while maintaining the robustness of sliding mode control. Furthermore, STA guarantees finite-time convergence of the sliding variable and its derivative, providing effective chattering mitigation. Consequently, combining integral sliding surfaces with the STA provides enhanced disturbance rejection, reduced chattering, and higher trajectory tracking accuracy.

Motivated by these advantages, this work proposes a robust model-free control strategy combining Time-Delay Control, Integral Sliding Mode, and the Super-Twisting Algorithm (TDC-IS-STA) for robotic manipulator trajectory tracking. The proposed approach does not require an accurate dynamic model and can be applied to robotic manipulators with arbitrary degrees of freedom (n-DOF). The integral sliding surface is introduced to improve disturbance rejection from the initial instant and enhance tracking precision, while the STA component is employed to suppress chattering and maintain robust performance in the presence of uncertainties and TDE errors. The proposed controller aims to achieve accurate and smooth trajectory tracking while ensuring robustness and stability under different operating conditions. Furthermore, the asymptotic stability of the closed-loop system is rigorously established using Lyapunov stability theory. In addition, a comparative study using a similar control approach is conducted on a parallel Delta robot to further demonstrate the effectiveness and applicability of the proposed method.

The remainder of this paper is organized as follows. Section II presents the fundamental concepts of TDC and ISM. Section III describes the proposed TDC-IS-STA control strategy and discusses its stability and convergence analysis. Section IV presents the simulation results and performance evaluation. Finally, Section V concludes the paper.

II. Brief Review of Time-Delay Control Based Super-Twisting Sliding Mode Controller

A. *Time-Delay Control*

Time Delay Control is a robust nonlinear control technique used to compensate unknown dynamics and external disturbances in uncertain systems by using information from a previous sampling instant. The main principle of TDC is that the nonlinear dynamics of the system do not change significantly during a very short time interval. Therefore, the unknown dynamics at the current time can be approximated by their delayed values. For an n-degree-of-freedom (n-DOF) robot manipulator, the dynamic model is expressed as:

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

Where $q \in \mathbb{R}^n$ denotes the vector of joint positions, while $M(q)$ corresponds to the inertia matrix of the manipulator. The term $C(q,\dot{q})\dot{q}$ describes the Coriolis and centrifugal forces, and $G(q)$ represents the gravitational effects acting on the robot. In addition, $d(t)$ includes external disturbances and model uncertainties, and τ defines the vector of control torques applied to the joints.

The dynamic behavior of the n-DOF robotic manipulator can be reformulated by introducing a nominal constant inertia matrix $\bar{M}$. By separating the nominal and uncertain parts of the inertia matrix, the system dynamics become

$$\bar{M}\ddot{q} + (M(q) - \bar{M})\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + d(t) = \tau \tag{2}$$

in which $\bar{M}$ is selected as a constant diagonal positive-definite matrix.Based on this decomposition, the manipulator dynamics can be rewritten in a compact representation as

$$\ddot{q}_t = \bar{M}^{-1}\tau_t + N_t \tag{3}$$

with the nonlinear uncertain term N_t defined by

$$N_t = -\bar{M}^{-1}\left[(M(q_t) - \bar{M})\ddot{q}_t + C(q_t,\dot{q}_t)\dot{q}_t \;\; + G(q_t) + d(t)\right]$$

The index t refers to the current sampling instant. Since the exact nonlinear dynamics are generally difficult to obtain, the unknown term N_t is approximated using the (TDE) principle. Assuming that the system dynamics vary slowly over a sufficiently small delay interval L, the estimated nonlinear term can be expressed as

$$\hat{N}_t \approx N_{t-L} \tag{4}$$

which yields

$$\hat{N}_t = \ddot{q}_{t-L} - \bar{M}^{-1}\tau_{t-L} \tag{5}$$

The tracking objective is achieved by forcing the manipulator joints to follow a desired reference trajectory q_d. Accordingly, the position and velocity tracking errors are introduced as

$$\tilde{q}_t = q_{d,t} - q_t \tag{6}$$

and

$$\dot{\tilde{q}}_t = \dot{q}_{d,t} - \dot{q}_t \tag{7}$$

respectively,the estimation accuracy of the TDE approach is characterized through the time-delay estimation error defined by

$$\tilde{N} = \hat{N}_t - N_t \tag{8}$$

B. *Integral sliding surface*

The integral sliding surface is a sliding manifold that incorporates both the tracking error and its integral, ensuring improved robustness against system uncertainties and disturbances while eliminating the reaching phase. The integral sliding surface is defined as

$$s_t = \dot{\tilde{q}}_t + K_d\tilde{q}_t + K_p\int_0^t \tilde{q}_t \, d\tau \tag{9}$$

in which K_p and K_d denote positive definite gain matrices associated with the position and velocity tracking errors, respectively. Since the manipulator is initialized at the desired position, i.e.,

$$q(0) = q_d(0) \tag{10}$$

the initial tracking error is zero, $e(0) = 0$. Consequently, the sliding variable satisfies

$$s(0) = 0 \tag{11}$$

which ensures that the reaching phase will be eliminated.

III. Proposed control law and stability analysis

A. Control Design

The proposed TDC-IS-STA is given by :

$$\tau_t = \tau_{t-L} - \bar{M}\ddot{q}_{t-L} + \bar{M}\left(\ddot{q}_{d,t} + K_d\dot{\tilde{q}}_t + K_p\tilde{q}_t + u_{st}\right) \tag{12}$$

The terms τ_{t-L} and $\ddot{q}_{t-L}$ correspond to the delayed control input and delayed joint acceleration used in the Time Delay Control framework.

To enhance the robustness of the closed-loop system and attenuate the chattering effect, a Super-Twisting term u_{st} is incorporated into the control law.

The super-twisting algorithm is expressed as

$$u_{st} = k_1|s_t|^{1/2}\operatorname{sgn}(s_t) + v \tag{13}$$

with the auxiliary variable v governed by

$$\dot{v} = k_2\operatorname{sgn}(s_t) \tag{14}$$

B. proof of convergence

1— Proposition: For the n-DOF robotic manipulator described by (1),the tracking error converges asymptotically to zero under the proposed TDC-IS-STA control law defined in (12), thereby ensuring asymptotic tracking stability of the closed-loop system.

2— Proof: Differentiating (9) with respect to time yields

$$\dot{s}_t = \ddot{\tilde{q}}_t + K_d\dot{\tilde{q}}_t + K_p\tilde{q}_t \tag{15}$$

Since

$$\ddot{\tilde{q}}_t = \ddot{q}_{d,t} - \ddot{q}_t \tag{16}$$

then

$$\dot{s}_t = \ddot{q}_{d,t} - \ddot{q}_t + K_d\dot{\tilde{q}}_t + K_p\tilde{q}_t \tag{17}$$

Substituting (3) gives

$$\dot{s}_t = \ddot{q}_{d,t} + K_d\dot{\tilde{q}}_t + K_p\tilde{q}_t - N_t - \bar{M}^{-1}\tau_t \tag{18}$$

Multiplying the control law (12) by $\bar{M}^{-1}$ yields

$$\bar{M}^{-1}\tau_t = \bar{M}^{-1}\tau_{t-L} - \ddot{q}_{t-L} + \ddot{q}_{d,t} + K_d\dot{\tilde{q}}_t + K_p\tilde{q}_t + u_{st} \tag{19}$$

Using (5), (19) becomes

$$\bar{M}^{-1}\tau_t = -\hat{N}_t + \ddot{q}_{d,t} + K_d\dot{\tilde{q}}_t + K_p\tilde{q}_t + u_{st} \tag{20}$$

Substituting (20) into (18) leads to

$$\dot{s}_t = \hat{N}_t - N_t - u_{st} \tag{21}$$

using the TDE estimation error given by (8), one obtains

$$\dot{s}_t = \tilde{N} - u_{st} \tag{22}$$

Substituting (13) and (14) into (22) gives

$$\dot{s}_t = -k_1|s_t|^{1/2}\operatorname{sgn}(s_t) - v - \int_0^t k_2\operatorname{sgn}(s_t) + \tilde{N} \tag{23}$$

By introducing the following state variables,

$$z_1 = s_t, \tag{24}$$

$$z_2 = -K_2\int_0^t \operatorname{sign}(s_t)\,d\tau + \tilde{N} \tag{25}$$

the system dynamics can be expressed as follows

$$\dot{z}_1 = -k_1|z_1|^{1/2}\operatorname{sign}(z_1) + z_2, \tag{26}$$

$$\dot{z}_2 = -k_2\operatorname{sign}(z_1) + \dot{\tilde{N}} \tag{27}$$

Defining

$$\zeta = \begin{bmatrix} |z_1|^{1/2}\operatorname{sign}(z_1) \\ z_2 \end{bmatrix} = \begin{bmatrix} \zeta_1 \\ \zeta_2 \end{bmatrix} \tag{28}$$

the subsequent expressions are derived as

$$\dot{\zeta}_1 = |z_1|^{-1/2}\left[-\frac{1}{2}k_1|z_1|^{1/2}\operatorname{sign}(z_1) + \frac{1}{2}z_2\right] \tag{29}$$

$$\dot{\zeta}_2 = |z_1|^{-1/2}\left[-k_2|z_1|^{1/2}\operatorname{sign}(z_1)\right] + \dot{\tilde{N}} \tag{30}$$

The aggregated uncertainty term $\tilde{N}$ is assumed to be continuously differentiable, and there exists a positive scalar δ_N satisfying

$$|\dot{\tilde{N}}| \le \delta_N, \tag{31}$$

which is globally bounded.

$$\begin{aligned} \dot{\zeta} &= \begin{bmatrix} \dot{\zeta}_1 \\ \dot{\zeta}_2 \end{bmatrix} \\ &= -|z_1|^{-1/2}\begin{bmatrix} \frac{1}{2}k_1 & -\frac{1}{2} \\ k_2 & 0 \end{bmatrix}\begin{bmatrix} \zeta_1 \\ \zeta_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \dot{\tilde{N}} \end{bmatrix} \end{aligned} \tag{32}$$

$$\dot{\zeta} = -|z_1|^{-1/2}A\zeta - \begin{bmatrix} 0 \\ \dot{\tilde{N}} \end{bmatrix} \tag{33}$$

where

$$A = \begin{bmatrix} \frac{1}{2}k_1 & -\frac{1}{2} \\ k_2 & 0 \end{bmatrix} \tag{34}$$

Consider the following Lyapunov function candidate

$$V_\zeta = \frac{1}{2}\zeta^T P\zeta, \tag{35}$$

where P denotes a positive definite matrix given by

$$P = \frac{1}{2}\begin{bmatrix} 4k_2 + k_1^2 & -k_1 \\ -k_1 & 2 \end{bmatrix} \tag{36}$$

It is positive definite if $k_2 > 0$ Taking the time derivative of V_ζ yields

$$\dot{V}_\zeta = \frac{1}{2}\dot{\zeta}^T P \zeta + \frac{1}{2}\zeta^T P \dot{\zeta} \tag{37}$$

Substituting $\dot{\zeta}$ into the previous equation gives

$$\dot{V}_\zeta = -|z_1|^{-1/2}\zeta^T P A \zeta + \zeta^T P \begin{bmatrix} 0 \\ \dot{\tilde{N}} \end{bmatrix} \tag{38}$$

Subtituting P

$$\dot{V}_{\zeta 1} = -|z_1|^{-1/2}\zeta^T Q \zeta + \dot{\tilde{N}} \begin{bmatrix} -\frac{k_1}{2} & 1 \end{bmatrix} \zeta \tag{39}$$

$$\dot{V}_\zeta \leq -|z_1|^{-1/2}\zeta^T Q_\delta \zeta \tag{40}$$

where

$$Q = A^T P + P A = \frac{k_1}{2}\begin{bmatrix} 2k_2 + k_1^2 & -k_1 \\ -k_1 & 1 \end{bmatrix} \tag{41}$$

and

$$Q_\delta = \frac{k_1}{2}\begin{bmatrix} 2k_2 + k_1^2 - \delta_N & -k_1 - \frac{\delta_N}{k_1} \\ -k_1 - \frac{\delta_N}{k_1} & 1 \end{bmatrix} \tag{42}$$

if the gains satisfy

$$k_1 > 0, \qquad k_2 > \frac{\delta_N(\delta_N + 3k_1^2)}{2k_1^2}, \tag{43}$$

Then, it follows that

$$z_1 \to 0, \qquad z_2 \to 0 \quad \text{as} \quad t \to \infty,$$

which implies that

$$s_t \to 0, \qquad \tilde{q}_t \to 0 \quad \text{asymptotically as} \quad t \to \infty.$$

IV. Simulation Results and Disscusion

In this section, the effectiveness of the proposed control strategy is investigated through numerical simulations carried out in MATLAB/Simulink on a parallel Delta robot model shown in Fig. 1. The Delta robot represents a suitable platform for validating advanced trajectory tracking controllers due to its highly nonlinear coupled dynamics and its capability to operate at high speeds [3]. Detailed formulations of the inertia matrix M, Coriolis and centrifugal matrix C, and gravity vector G are available in [20].

A. Simulation Setup

The reference trajectory adopted for the simulations follows a semi-elliptical path. The motion starts from the point $(0.25,\ 0,\ -0.43)$ and ends at $(-0.25,\ 0,\ -0.43)$. To demonstrate the performance of the proposed controller, referred to as TDC+IS+STA, comparative analyses are performed with two additional control approaches: the controller introduced in (3) and the Time Delay Estimation based Integral Sliding controller (TDE+IS) described by Equation (44). The comparison focuses on the tracking capability and robustness of each control strategy under identical operating conditions.

The control input associated with the TDE+IS approach can be written as

$$\tau_t = -\bar{M}\ddot{q}_{t-L} + \tau_{t-L} + \bar{M}\left(\ddot{q}_d + K_d\dot{\tilde{q}}_t + K_p\tilde{q}_t + K_s\,\mathrm{sgn}(s_t)\right) \tag{44}$$

while K_p, K_d, and K_s represent positive control gains related to the proportional, derivative, and switching actions, respectively.

The simulations are presented under three distinct scenarios.

B. Scenario 1: Nominal Trajectory Tracking

The first simulation case focuses on nominal operating conditions in order to analyze the tracking capability of the different controllers under moderate motion requirements. In this scenario, the desired joint trajectory is executed within $t = 0.8$ s. In the TDE+IS scheme, the saturation function is employed in place of the signum function within the integral sliding surface in order to smooth the control input and avoid the chattering phenomenon. Several simulation tests were performed in order to tune the controller parameters and achieve satisfactory tracking performance. Based on these numerical experiments, The optimal set of control gains is shown in Table 1.

Table. I
Controller Parameters

Controller	Parameters	Values
TDC+IS	K_p, K_d, K_s $\bar{M}$	1800, 1800, 1460 0.0003
TDC+IS+STA	K_p, K_d, k_1, k_2 $\bar{M}$	1800, 1800, 700, 100 0.0003

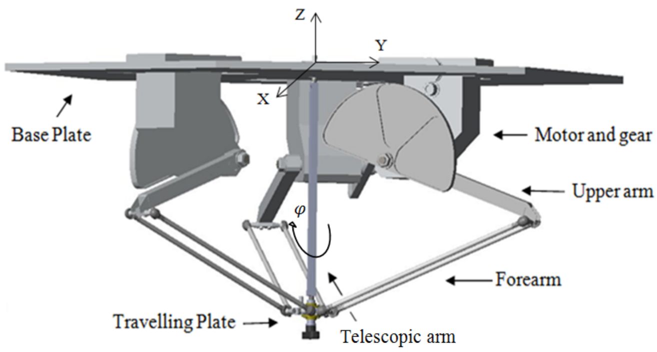

Fig. 1: Delta robot structure

Fig. 2: Trajectory tracking in the task space

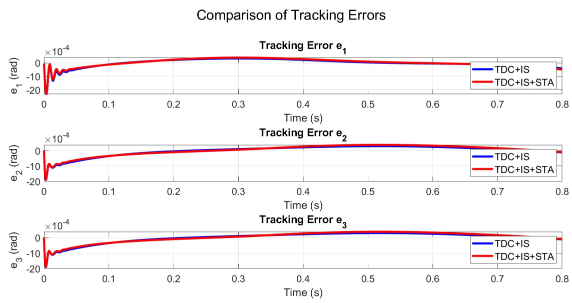

Fig. 3: Tracking errors in scenario 1 for each joint using TDC+IS and TDC+IS+STA.

The simulation results presented in Fig. 2, Fig. 3 and Fig. 4 indicate that all considered controllers are capable of achieving satisfactory trajectory tracking while maintaining relatively smooth control torques.The relatively small performance improvement observed in Scenario 1 is expected because it involves a low-cadence, slow trajectory, which imposes relatively mild dynamic demands on the controllers. However, the proposed control strategy provides superior tracking precision compared with the other approaches. This improvement is confirmed by the lower Root Mean Square (RMS) tracking errors reported in Table II.

C. Scenario 2: High-Speed Motion Condition

The second simulation scenario investigates a more aggressive operating condition intended to assess the robustness and dynamic response of the compared control methods under fast trajectory execution. For this case, the desired joint motion is completed within a shorter duration of $t = 0.2\,\mathrm{s}$. Such rapid movements generate stronger transient effects and increase the difficulty of the tracking task due to the highly nonlinear dynamics of the robotic system. As illustrated in Fig. 5, the tracking errors of the TDC+IS+STA controller remain bounded and converge faster compared to the standard TDC+IS approach, demonstrating improved robustness under high-cadence operating conditions. Furthermore, the control torque profiles shown in Fig. 6 confirm that the TDC+IS+STA controller produces smoother torque signals with reduced chattering, which is particularly advantageous for practical implementation on real robotic systems.

D. Scenario 3: Composite Semi-Elliptical Three-Dimensional Trajectory

In the third simulation study, the controllers are evaluated using a more complex three-dimensional composite semi-elliptical trajectory, as illustrated in Fig. 7. This scenario is designed to examine the capability of the proposed approach to accurately track spatial motions involving simultaneous variations along multiple axes. The objective of this test is to validate the effectiveness of the control strategy for realistic robotic operations requiring smooth and precise 3D trajectory tracking under nonlinear coupled dynamics. As illustrated in Fig. 8, the tracking errors of the TDC+IS+STA controller remain bounded and exhibit faster convergence compared to the standard TDC+IS approach, particularly at the trajectory transition point, demonstrating improved robustness under complex spatial motion conditions. Furthermore, the control torque profiles shown in Fig. 9 confirm that the TDC+IS+STA controller produces smoother torque signals with significantly reduced chattering across all three joints, which is particularly advantageous for practical implementation on real robotic systems.

Fig. 4: Control torque in scenario 1 for each joint using TDC+IS and TDC+IS+STA.

Fig. 5: Tracking errors in scenario 2 for each joint using TDC+IS and TDC+IS+STA.

RMS TRACKING ERRORS FOR THE COMPARED CONTROLLERS

Table. II
RMS TRACKING ERRORS FOR SCENARIO 1 (rad)

Controller	Joint 1	Joint 2	Joint 3
TDC+IS	3.463×10^{-4}	3.587×10^{-4}	3.587×10^{-4}
TDC+IS+STA	3.423×10^{-4}	3.583×10^{-4}	3.583×10^{-4}

Table. III
RMS TRACKING ERRORS FOR SCENARIO 2 (rad)

Controller	Joint 1	Joint 2	Joint 3
TDC+IS	0.0056	0.0069	0.0069
TDC+IS+STA	0.0044	0.0047	0.0047

Table. IV
RMS TRACKING ERRORS FOR SCENARIO 3 (rad)

Controller	Joint 1	Joint 2	Joint 3
TDC+IS	7.265×10^{-4}	1.622×10^{-4}	1.608×10^{-4}
TDC+IS+STA	5.592×10^{-4}	1.776×10^{-4}	1.752×10^{-4}

V. CONCLUSION

This paper presented a robust model-free trajectory tracking control strategy based on the combination of Time Delay Control, Integral Sliding Mode, and the Super-Twisting Algorithm for robotic manipulators. The proposed TDC-IS-STA approach enhances tracking accuracy while reducing the chattering phenomenon commonly associated with conventional sliding mode methods. By integrating the integral sliding surface and the super-twisting algorithm within the TDC framework, the controller ensures improved robustness against parameter uncertainties, external disturbances, and TDE errors. In addition, a Lyapunov stability analysis was conducted to guarantee the stability and convergence of the closed-loop system. The effectiveness of the proposed method was investigated on a parallel Delta robot under different operating conditions and complex three-dimensional trajectories. Comparative results demonstrated superior tracking performance, smoother control signals, and enhanced robustness compared to existing approaches. These results confirm the suitability of the proposed strategy for high-performance robotic applications involving nonlinear and uncertain dynamics.

Fig. 6: Control torque in scenario 2 for each joint using TDC+IS and TDC+IS+STA.

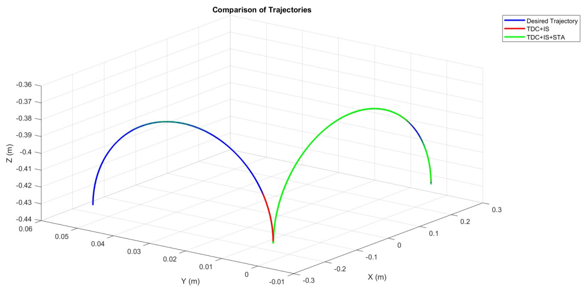

Fig. 7: trajectory tracking in the task space for scenario 3

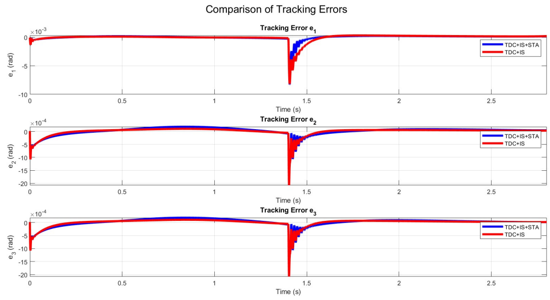

Fig. 8: Tracking errors in scenario 3 for each joint using TDC+IS and TDC+IS+STA.

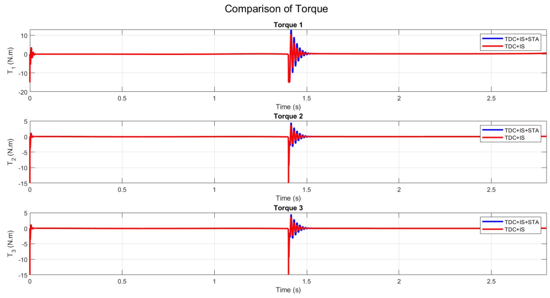

Fig. 9: Control torque in scenario 3 for each joint using TDC+IS and TDC+IS+STA.

References

[1] H. D. Taghirad, *Parallel Robots: Mechanics and Control*, 2nd ed. Boca Raton, FL: CRC Press, 2026.

[2] Z. Zhang, Z. Shao, Z. You, X. Tang, B. Zi, G. Yang, C. Gosselin, and S. Caro, "State-of-the-art on theories and applications of cable-driven parallel robots," *Frontiers of Mechanical Engineering*, vol. 17, no. 3, p. 37, 2022.

[3] N. Cretescu, M. Neagoe, and R. Saulescu, "Dynamic analysis of a delta parallel robot with flexible links and joint clearances," *Applied Sciences*, vol. 13, no. 11, p. 6693, 2023.

[4] I. Bonev, "Delta parallel robot—the story of success," *ParalleMIC*, May 2001.

[5] T. Hägglund and J. L. Guzmán, "Give us PID controllers and we can control the world," *IFAC PapersOnLine*, vol. 58, no. 7, pp. 103–108, 2024.

[6] S. Amrane, C. E. Boudjedir, and D. Boukhetala, "Fractional-order pd control of a parallel delta robot: Experimental results," *ENP Engineering Science Journal*, vol. 5, no. 2, pp. 7–11, 2025.

[7] L. Wang, Z. Lu, X. Liu, K. Liu, and D. Zhang, "Adaptive control of a parallel robot via backstepping technique," *International Journal of Systems, Control and Communications*, vol. 1, no. 3, pp. 312–324, 2009.

[8] A.Kihal, C.E.Boudjedir, B.Talbi, A.Sahli, and A.Krama, "Adaptive model-free sliding mode control for boost converter with flexibility to varying operating conditions," *Journal of Electrical Engineering*, vol. 77, no. 1, pp. 77–88, 2026.

[9] J. A. Rossiter, *Model-Based Predictive Control: A Practical Approach*, ser. CRC Press Control Series. Boca Raton, FL: CRC Press, 2003.

[10] Y. Wang, J. Chen, K. Zhu, B. Chen, and H. Wu, "Time-delay control of cable-driven robots with adaptive fractional-order nonsingular terminal sliding mode," *IEEE Access*, vol. 7, pp. 157 716–157 726, 2019.

[11] S. Han, H. Wang, Y. Tian, and N. Christov, "Time-delay estimation based computed torque control with robust adaptive RBF neural network compensator for a rehabilitation exoskeleton," *ISA Transactions*, vol. 97, pp. 171–181, 2020.

[12] C. E. Boudjedir, "A widely-practical model-free prescribed time control for trajectory tracking of n-dof robot manipulators," *European Journal of Control*, p. 101396, 2025.

[13] S. Kim and J.-H. Suh, "A study on robust control scheme using prescribed performance-based time delay control and rbf neural network," *IEEE Access*, vol. 13, pp. 180 513–180 522, 2025.

[14] C. E. Boudjedir, M. Bouri, and D. Boukhetala, "An enhanced adaptive time delay control-based integral sliding mode for trajectory tracking of robot manipulators," *IEEE Transactions on Control Systems Technology*, vol. 31, no. 3, pp. 1042–1050, 2023.

[15] A. Rehan, I. Boiko, and Y. Zweiri, "Chaotic chattering in sliding mode control systems," *IEEE Transactions on Automatic Control*, vol. 69, no. 11, pp. 7925–7931, 2024.

[16] J. Guldner and V. I. Utkin, "The chattering problem in sliding mode systems," in *Proceedings of the 14th International Symposium of Mathematical Theory of Networks and Systems (MTNS)*, Perpignan, France, June 2000.

[17] A. Sahamijoo, F. Piltan, M. H. Mazloom, M. R. Avazpour, H. Ghiasi, and N. B. Sulaiman, "Methodologies of chattering attenuation in sliding mode controller," *International Journal of Hybrid Information Technology*, vol. 9, no. 2, pp. 11–36, 2016.

[18] H. Saied, A. Chemori, M. Bouri, M. E. Rafei, and C. Francis, "Feedforward super-twisting sliding mode control for robotic manipulators: Application to pkms," *IEEE Transactions on Robotics*, vol. 39, no. 4, pp. 3167–3184, 2023.

[19] I.-L. G. Borlaug, K. Y. Pettersen, and J. T. Gravdahl, "The generalized super-twisting algorithm with adaptive gains," *International Journal of Robust and Nonlinear Control*, vol. 32, no. 13, pp. 7240–7270, 2022.

[20] C. E. Boudjedir, M. Bouri, and D. Boukhetala, "Iterative learning control for trajectory tracking of a parallel delta robot," *at-Automatisierungstechnik*, vol. 67, no. 2, pp. 145–156, 2019.

VI. Biography

Authors' Biographies

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