A Modified Adaptive Prescribed Performance Control Method for Motion Control Problems of Robotic Manipulators

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***Abstract*—This paper proposes a modified adaptive prescribed performance control method to solve motion control problems of robotic manipulators such as tracking accuracy, transient performance guarantee, convergence rate, and chattering phenomenon. A modified integral terminal sliding mode (ITSM) surface based on the error transformation and prescribed performance function (PPF) is generated to avoid singularity problems and to manage the convergence rate and steady-state of tracking errors within a predefined boundary of the control performance. Furthermore, an adaptive super-twisting reaching control (ASTwRC) law is applied to strengthen the robust performance and to deal with system uncertainties and harmful chattering. The stability of the developed controller is guaranteed using the Lyapunov theory. Several simulations on a 3-DOF robotic manipulator are implemented to investigate the effectiveness of the control solution proposal.**

***Index Terms*—prescribed performance control, robotic manipulators, super-twisting technique**

I. Introduction

Many control scientists and engineers have taken an interest in robot manipulators as nonlinear dynamically coupled MIMO systems [1] [2]. In non-linear systems such as robotics, surface vessels, inverted pendulums, and so on, operating under uncertain environments, sliding mode control (SMC) is a popular control method because it allows the controllers to be designed to compensate for the effects of disturbances and uncertainties [3] [4]. While the approach is claimed to be robust in the face of uncertain conditions, there are some drawbacks, such as the fact that only asymptotic stability is guaranteed, which means that accuracy is not high. Convergence rate and transient behavior are not guaranteed within a predefined prescribed performance. In addition to this, high-frequency control switching may lead to "chattering" of the controlled system, a type of dangerously high-frequency vibration [5].

For control systems, transient performance including settling time and maximum overshoot is regarded as a significant performance metric. Prescribed performance means that the tracking error should be confined to a minimal residual set, its convergence rate must not be lower than a constant, and the maximum overshoot must not exceed a prespecified value. Thus, the tracking error will satisfy both transient performance and steady-state performance [6].

There are various higher-order sliding mode (HOSM) methods that can be used to reduce chattering [7]–[9]. With these methods, the traditional SMC's advantages are maintained, while the chattering effect is significantly decreased, and higher-order precision is offered. As a special case of HOSM approaches, the characteristic of super-twisting control (STwC) algorithms provides smooth control signals and finite-time convergence for the controlled systems [8] [10] [11].

Different from traditional TSMCs that use tracking errors and the constrained model in the design of the ITSM surface and control law. Our controller uses a transformed error series and a modified unconstrained dynamic model of the robot based on prescribed performance control (PPC) in the control design to achieve the desired transient and control performance. An ASTwRC is applied to strengthen the robust performance and to deal with interior uncertainties, exterior disturbances, and harmful chattering. In addition, the control design eliminates the requirement of all uncertainty's upper boundary.

The rest of our article has the following outline. Section 2 presents the problem formulation. The development of the controller is stated in Section 3. Simulations are illustrated in Section 4. Section 5 is conclusions.

II. Problem Formulation

The dynamical equation of n-joint rigid robotic manipulators can be given as:

$$M(\theta)\ddot{\theta} + C_m(\theta,\dot{\theta})\dot{\theta} + g(\theta) + f_r(\dot{\theta}) + \tau_d = \tau, \quad (1)$$

where $\theta, \dot{\theta}, \ddot{\theta} \in R^n$ represents as the system's state vector. $M(\theta) \in R^{n\times n}$ is the inertia matrix, $C_m(\theta,\dot{\theta}) \in R^{n\times 1}$ represents as the matrix resulting from Coriolis and centrifugal forces, $g(\theta) \in R^{n\times 1}$ is the gravitational force vector, $f_r(\dot{\theta}) \in R^{n\times 1}$ is the friction

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vector, $\tau \in R^{n\times 1}$ is control torque vector, and $\tau_d \in R^{n\times 1}$ is disturbance vector.

For synthesis and control design, (1) is arranged in briefer form as:

$$\ddot{\theta} = h(\theta,\dot{\theta}) + d(\theta,\dot{\theta},t) + q(\theta)\tau, \quad (2)$$

where $h(\theta,\dot{\theta}) = M^{-1}(\theta)\big(-C_m(\theta,\dot{\theta})\dot{\theta} - g(\theta)\big)$, $q(\theta) = M^{-1}(\theta)$, and $d(\theta,\dot{\theta},t) = M^{-1}(\theta)\big(-f_r(\dot{\theta}) - \tau_d\big)$.

Define $u = \tau$ and $x = [x_1, x_2]^T$ where x_1, x_2 correspond to $\theta, \dot{\theta} \in R^n$. Then, (2) is described in the state space as:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = h(x,t) + d(x,t) + q(x,t)u' \end{cases} \quad (3)$$

where $h(x,t) \in R^n$ and $q(x,t) \in R^{n\times n}$ are smooth nonlinear vector fields, and $d(x,t) \in R^n$ denotes all uncertainty, including interior uncertainties and exterior disturbances.

The hypothesis here is that the proposed controller uses a transformed error series and a modified unconstrained dynamic model of the robot based on PPC in the control design to achieve the desired transient and control performance. Furthermore, the ASTwRC is applied to strengthen the robust performance and to deal with all uncertainty and harmful chattering.

The below assumption is necessary for control synthesis.

Assumption 1. Assume that $d(x,t)$ is bounded by the inequity below:

$$|d(x,t)| \le \delta, \quad (4)$$

where δ is a positive constant.

III. Integral Terminal Sliding Mode Control (ITSMC)

A. *The Modified ITSM Surface Based-the Tracking Error*

Let $e = x_1 - x_d$ and $\dot{e} = \dot{x}_1 - \dot{x}_d$ as the vector of the tracking error and velocity error, respectively, where x_d is the required route. Then, the modified ITSM based on the tracking error is proposed to remove singularity problems and obtain a fast convergence:

$$s = K_P e + \int_0^t (K_{I1} e + K_{I2}[\dot{e}]^{\varpi})\, d\iota + \dot{e}, \quad (5)$$

where ι is the time variable, $\varpi, K_P, K_{I1}, K_{I2}$ are user-designed positive constants, $0 < \varpi < 1$, $[e]^{\varpi} = |e|^{\varpi}\,\mathrm{sgn}(e)$, and $\mathrm{sgn}(e) = \begin{cases} 1 & \text{if } e > 0 \\ -1 & \text{if } e < 0. \\ 0 & \text{if } e = 0 \end{cases}$

B. *The ITSMC Design*

From (4), the error dynamics is expressed as:

$$\ddot{e}(t) = h(x,t) + d(x,t) + q(x,t)u - \ddot{x}_d. \quad (6)$$

The first derivative of (5) gives:

$$\dot{s} = K_P\dot{e} + K_{I1}e + K_{I2}[\dot{e}]^{\varpi} + \ddot{e}. \quad (7)$$

Substituting (6) into (7) gains:

$$\begin{aligned}\dot{s} = K_P\dot{e} + K_{I1}e + K_{I2}[\dot{e}]^{\varpi} + h(x,t). \\ +d(x,t) + q(x,t)u - \ddot{x}_d\end{aligned} \quad (8)$$

Therefore, the ITSMC torque is designed as:

$$\begin{cases} u = u_0 + u_r \\ u_0 = -q^{-1}(h(x,t) - \ddot{x}_d + K_P\dot{e} + K_{I1}e + K_{I2}[\dot{e}]^{\varpi}), \\ u_r = -q^{-1}(\delta + \gamma)\,\mathrm{sgn}(s) \end{cases} \quad (9)$$

where γ is positive constant.

C. *Stability Analysis*

Substituting (9) into (8) yields:

$$\dot{s} = -(\delta + \gamma)\,\mathrm{sgn}(s) + d(x,t). \quad (10)$$

Consider Lyapunov function for stable validation of the controller as:

$$V = \tfrac{1}{2} s^T s. \quad (11)$$

Differentiating the time derivative of (11) and noting (10) gives:

$$\begin{aligned}\dot{V} &= s^T\dot{s} \\ &= s^T(-(\delta+\gamma)\,\mathrm{sgn}(s) + d(x,t)) \\ &\le d(x,t)s - \delta|s| - \gamma|s| \le -\gamma|s|.\end{aligned} \quad (12)$$

With the design parameter $\gamma > 0$, $\dot{V}$ is negative semidefinite, i.e., $\dot{V} \le -\gamma|s|$. It indicated that the convergence of s to zero is guaranteed according to Lyapunov theory.

Remark 1. Although, the control input (9) can provide a good control performance for the robot. However, the control design (9) depends on Assumption 1 which must know in advance the upper bound of all uncertainty. To solve the effect of all uncertainty, the design parameter δ is selected as a big value that leads to harmful chattering in the control system. Furthermore, convergence rate and transient behavior are not guaranteed within a predefined prescribed performance. To overcome the mentioned problems, a modified adaptive prescribed performance method is developed to guarantee tracking accuracy, transient performance, and convergence rate. The ASTwRC integrated into the proposed method eliminates the upper boundary requirement of uncertainty and reduces harmful chattering.

IV. Prescribed Performance Integral Terminal Sliding Mode Control (PP-ITSMC)

A. *PPF and Error Transformation*

Firstly, a PPF is selected as [6] to achieve the desired transient performance and stabilize the tracking error within a predefined steady boundary.

$$\psi(t) = (\psi_0 - \psi_\infty)\varepsilon^{-\mu t} + \psi_\infty \quad (13)$$

where ε is Euler's number. $\psi_0 > \psi_\infty > 0$ and μ are user-designed parameters.

The following condition is used to maintain the trajectory tracking error within a specified range:

$$-\delta_l\psi(t) < e(t) < \delta_u\psi(t), \forall t > 0, \qquad (14)$$

where δ_l and δ_u are positive parameters.

Then, a series of transformed errors is used to change the constrained dynamic model of the robot to an unconstrained one. Therefore, the error transformation is applied below.

$$e(t) = \psi(t)\sigma(\pi_1), \qquad (15)$$

where π_1 is the transformed error and $\sigma(\pi_1)$ is defined by:

$$\sigma(\pi_1) = \frac{\delta_u\varepsilon^{\pi_1} - \delta_l\varepsilon^{-\pi_1}}{\varepsilon^{\pi_1} + \varepsilon^{-\pi_1}}. \qquad (16)$$

Because the transformed error π_1 is bounded, it is calculated, as follows:

$$\pi_1 = \sigma^{-1}\left[\frac{e(t)}{\psi(t)}\right] = \frac{1}{2}\ln\frac{v(t)+\delta_l}{\delta_u - \varepsilon(t)}, \qquad (17)$$

whereas $v(t) = \frac{e(t)}{\psi(t)}$ is the normalized tracking error.

With $v(t) = \frac{e(t)}{\psi(t)}$, the first and second derivative of π_1 yields:

$$\begin{cases} \dot{\pi}_1 = \xi\left(\dot{e} - \frac{e\dot{\psi}}{\psi}\right) \\ \ddot{\pi}_1 = \dot{\xi}\vartheta_1(e,t) + \xi(\ddot{e} + \vartheta_2(e,t)) \end{cases}, \qquad (18)$$

where $\xi(e,t) = \frac{1}{2\psi}\left(\frac{1}{v+\delta_l} - \frac{1}{v-\delta_u}\right)$, $0 < \xi < \xi_M$, $\vartheta_1(e,t) = \left(\dot{e} - \frac{e\dot{\psi}}{\psi}\right)$, $\vartheta_2(e,t) = -\frac{\dot{e}\dot{\psi}}{\psi} - \frac{e\ddot{\psi}}{\psi} + \frac{e\dot{\psi}^2}{\psi^2}$, and $\dot{\xi} = -\frac{\dot{\psi}}{2\psi^2}\left(\frac{1}{v+\delta_l} - \frac{1}{v-\delta_u}\right) - \frac{\dot{e}\psi - e\dot{\psi}}{2\psi^3}\left(\frac{1}{(v+\delta_l)^2} - \frac{1}{(v-\delta_u)^2}\right)$.

Noting (3) and (18), dynamic model of the robot can now be described as new dynamic:

$$\begin{cases} \dot{\pi}_1 = \pi_2 \\ \dot{\pi}_2 = \dot{\xi}\vartheta_1(e,t) + \xi\begin{pmatrix} q(x,t)u + \vartheta_2(e,t) \\ -\ddot{x}_d + h(x,t) + d(x,t) \end{pmatrix} \end{cases}. \qquad (19)$$

B. The Modified ITSM Surface Based-the Transformed Error

The modified ITSM surface based on the transformed error is proposed to avoid singularity problems and to manage the convergence rate and steady-state of tracking errors within a predefined boundary of the control performance:

$$s = K_P\pi_1 + \int_0^t (K_{I1}\pi_1 + K_{I2}[\dot{\pi}_1]^{\varpi})\, d\iota + \dot{\pi}_1. \qquad (20)$$

C. The Proposed PP-ITSMC

Performing the same calculation steps as (6) – (8), we gain:

$$\dot{s} = K_P\dot{\pi}_1 + K_{I1}\pi_1 + K_{I2}[\dot{\pi}_1]^{\varpi} + h(x,t) + d(x,t) + q(x,t)u - \ddot{x}_d. \qquad (21)$$

Therefore, the proposed control torque is designed as:

$$\begin{cases} u = -q^{-1}(x,t)\xi^{-1}(u_0 + u_{ar}) \\ u_0 = \dot{\xi}\vartheta_1(e,t) + \xi(\vartheta_2(e,t) - \ddot{x}_d + h(x,t)) \\ \quad + K_P\dot{\pi}_1 + K_{I1}\pi_1 + K_{I2}[\dot{\pi}_1]^{\varpi} \\ u_{ar} = \alpha_1(t)[s]^{\frac{1}{2}} + \alpha_2(t)s \\ \quad + \int_0^t (\alpha_3(t)[s]^0 + \alpha_4(t)s)\, d\iota \end{cases}, \qquad (22)$$

where the gains $\alpha_m(t)$ $(m = 1,2,3,4)$ are attained by:

$$\alpha_1(t) = \alpha_{10}\sqrt{\phi_0(t)}; \alpha_3(t) = \alpha_{30}\phi_0(t);$$
$$\alpha_2(t) = \alpha_{20}\phi_0(t); \alpha_4(t) = \alpha_{40}\phi_0^2(t), \qquad (23)$$

and positive parameters α_{m0} that satisfy: $4\alpha_{30}\alpha_{40} \geq (8\alpha_{30} + 9\alpha_{10}^2)\alpha_{20}^2$.

The $\phi_0(t)$ is adopted by rule below:

$$\dot{\phi}_0(t) = \begin{cases} \eta & \text{if } |s| \geq \delta_s \\ 0 & \text{otherwise} \end{cases}, \qquad (24)$$

where δ_s is positive constant.

D. Stability Analysis

With the proposed control law (22), (21) becomes

$$\begin{aligned} \dot{s} &= \xi d(x,t) - u_{ar} \\ &= \xi d(x,t) - \alpha_1(t)[s]^{\frac{1}{2}} - \alpha_2(t)s \\ &\quad - \int_0^t (\alpha_3(t)[s]^0 + \alpha_4(t)s)\, d\iota. \end{aligned} \qquad (25)$$

Consequently, dynamic (25) is stated in the following formula:

$$\begin{cases} \dot{s} = -\alpha_1(t)[s]^{\frac{1}{2}} - \alpha_2(t)s - \kappa \\ \dot{\kappa} = -\alpha_3(t)[s]^0 - \alpha_4(t)s + \dot{\xi}\dot{d}(x,t) \end{cases} \qquad (26)$$

where $\kappa = -\int_0^t (\alpha_3(t)[s]^0 + \alpha_4(t)s)\, d\iota + \xi d(x,t)$. Assume that there exists some unknown scalar $\delta_d \geq 0$such that $\left|\dot{\xi}\dot{d}(x,t)\right| \leq \delta_d$ [11].

According to [11], it indicated that $s = 0$ and $\kappa = 0$ will be achieved in a finite time moment.

V. SIMULATIONS

This paper uses a 3 DOF robot manipulator shown in Fig. 1 to verify the effectiveness of the PP-ITSMC. The detailed design parameters of the robot as well as the description of kinematics and dynamics can be found in the article [12] [13]. In addition, the PP-ITSMC also demonstrated its exceptional features through a performance comparison with the ITSMC (9). Table I reports the selected control parameters for two control methods.

TABLE I. CONTROL PARAMETER SELECTION FOR TWO CONTROL METHODS

Description	Symbol	Value
ITSMC (9)	$\varpi, K_P, K_{I1}, K_{I2}, \delta, \gamma$	$0.5, 20, 0.02, 0.01, 16, 0.1$
PP-ITSMC (22)	$\delta_l, \delta_u, \mu, \psi_0, \psi_\infty$	$1, 1, 10, [0.34, 0.15, 0.3]^T, [0.005, 0.005, 0.005]^T$
	$\varpi, K_P, K_{I1}, K_{I2}$	$0.5, 20, 0.02, 0.01$
	$\eta, \delta_s, \alpha_{01}, \alpha_{02}, \alpha_{03}, \alpha_{04}$	$30, 0.01, 10, 10, 30, 200$

The robot's task is to follow a configured trajectory below.

$$\begin{cases} x = 0.85 - 0.01t \\ y = 0.2 + 0.2\sin(0.5t) \quad (\mathrm{m}) \\ z = 0.7 + 0.2\cos(0.5t) \end{cases} \tag{27}$$

To simulate the influence of interior uncertainties and exterior disturbances, these terms are assumed as $\Delta M(\theta) = 0.3M(\theta)$, $\Delta C(\theta,\dot{\theta}) = 0.3C(\theta,\dot{\theta})$, $\Delta G(\theta) = 0.3G(\theta)$, $\tau_d(t) = \begin{bmatrix} 6\sin(2t) + 2\sin(t) + 4\sin(t/2) + 3[\theta_1]^{0.8} \\ 5\sin(2t) + 2\sin(t) + 1\sin(t/2) + 2[\theta_2]^{0.8} \\ 7\sin(2t) + 2\sin(t) + 3\sin(t/3) + 3[\theta_3]^{0.8} \end{bmatrix}$ (N.m) , and $f_r(\dot{\theta}) = \left[0.01[\dot{\theta}_1]^0 + 2\dot{\theta}_1, 0.01[\dot{\theta}_2]^0 + 2\dot{\theta}_2, 0.01[\dot{\theta}_3]^0 + 2\dot{\theta}_3\right]^T$ (N.m)

Transient performance and trajectory tracking performance and are shown in Figs. 2 – 4. It is observed that the PP-ITSMC has transient performance and convergence rate within a predefined boundary. Then, the tracking errors are still maintained in high accuracy when the time goes to infinity. The PP-ITSMC achieves superior accuracy and faster convergence than the ITSMC, as shown in Figs. 3 and 4. Under the effects of uncertain components, the PP-ITSMC also proves that it can cope with these influences without the control performance reduction.

Figure 1. A 3-DOF manipulator Model.

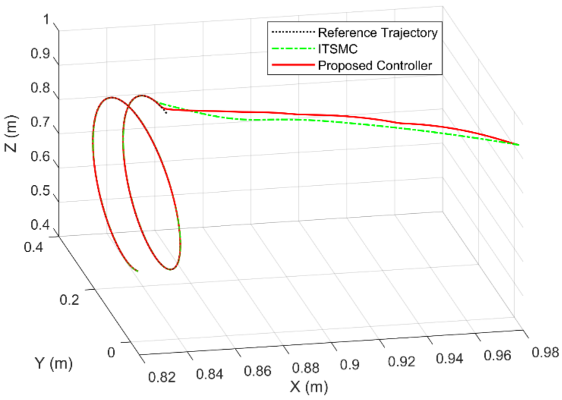

Figure 2. Required route and actual route under ITSMC and PP-ITSMC

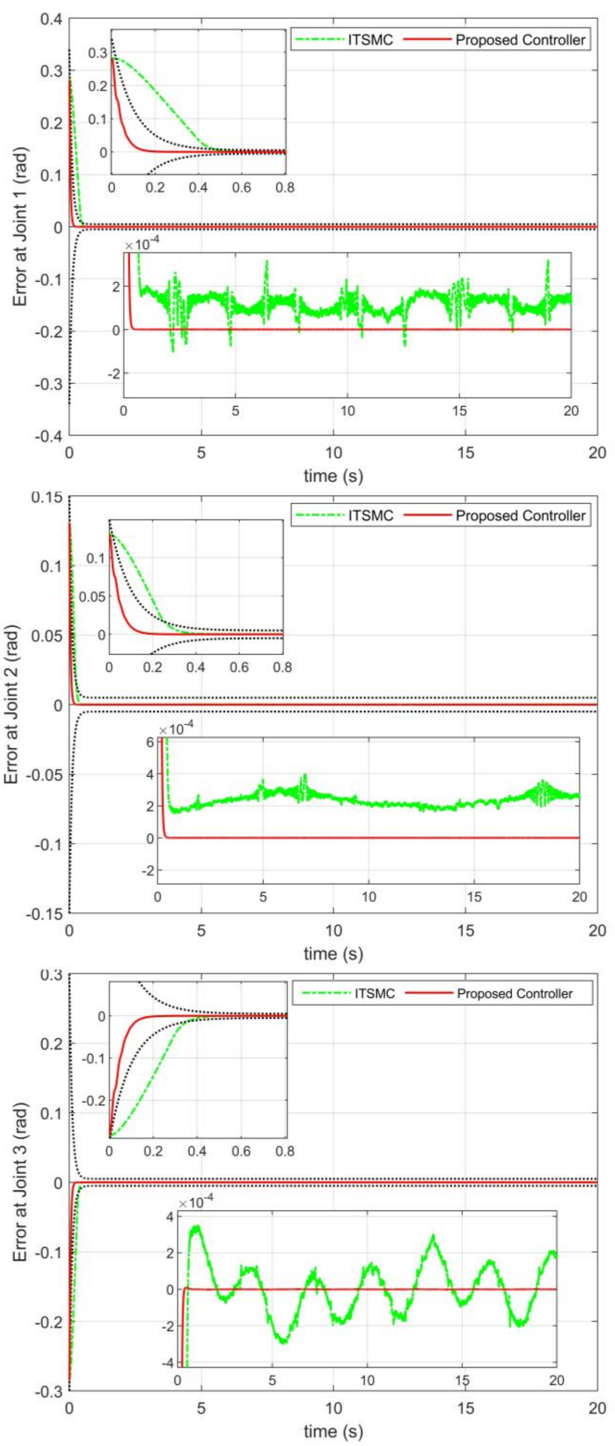

Figure 3. Time histories of the tracking errors at each Joint

The coefficient of adaptation at each joint is illustrated in Fig. 5. Once the tracking error is stable, it is observed that these will quickly become constants. Therefore, it eliminates the requirement of all uncertainty's upper boundary. According to Fig. 5, even though the coefficient of adaptation at joints is relatively large, the proposed PP-ITSMC provides a smooth control torque without chattering for the sake of STwC, as shown in Fig. 6. By contrast, the control torque from the ITSMC displayed a severe chattering behavior due to the large sliding gain of the reaching law.

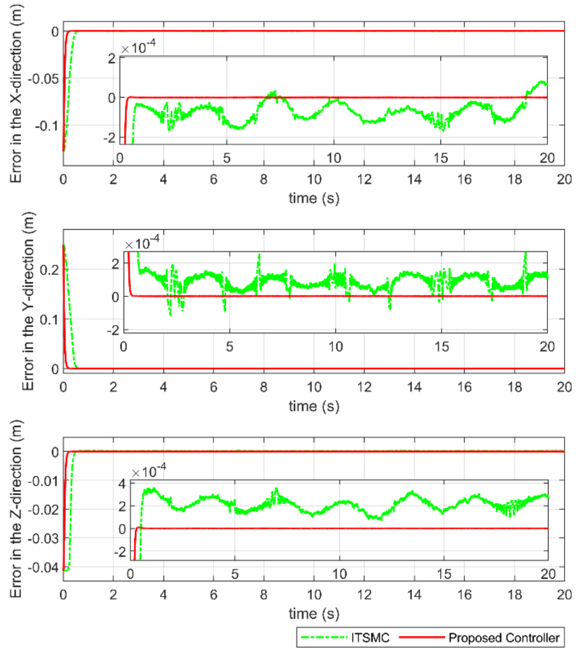

Figure 4. Time histories of X-axis errors, Y-axis errors, and Z-axis errors.

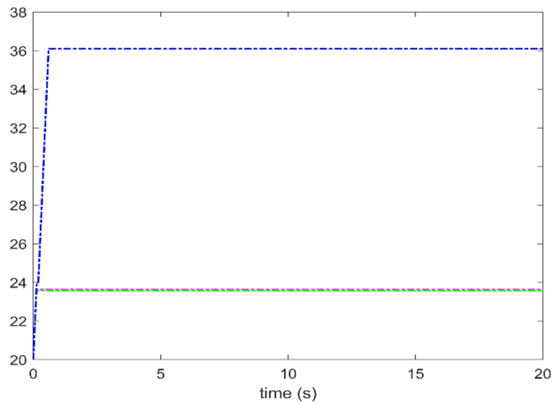

Figure 5. Coefficients of adaptation at each Joint.

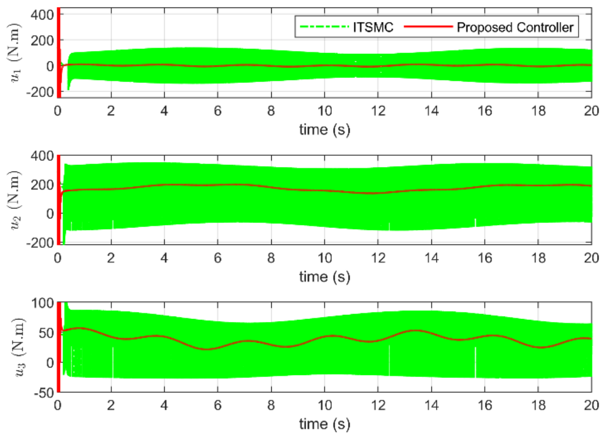

Figure 6. Control Torques of the ITSMC and the PP-ITSMC.

VI. Conclusion

This paper developed a PP-ITSMC to handle motion control problems of robotic manipulators such as tracking accuracy, transient performance guarantee, convergence speed, and chattering phenomenon. A modified ITSM surface based on the transformation error and performance function was constructed to avoid singularity problems and manage the convergence rate and steady-state of tracking errors within a predefined boundary of the control performance. With integrated ASTwRC into the proposed PP-ITSMC, its robustness and accuracy were enhanced expressively. Furthermore, it cleared the upper boundary requirement of uncertainty and reduced harmful chattering. The stability of the developed controller was guaranteed using the Lyapunov theory. Several simulations on a 3-DOF robotic manipulator were implemented to prove the effectiveness of the developed control solution.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, methodology, validation, writing—original draft preparation, and writing—review and editing, A.T.V.; software, visualization, and resources, T.N.T.; supervision, funding acquisition, and project administration, H.-J.K.; formal analysis, investigation, and data curation, T.N.T., and H.-J.K. The published version of the manuscript has been read and approved by all authors.

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