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Fast terminal sliding mode control for dual arm manipulators

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ABSTRACT

In this paper, present the recent advances in bimanual industrial manipulators have led to an increased interest in the specific problems pertaining to dual arm manipulation. This paper presents a control algorithm for dual arm robot that can move the object in a working plane both in translation and rotation ways. Different from other research that extend the control algorithms for a single robot to a dual arm robot because of fixed grasp assumption, this research has considered the frictional contact constraints to guarantee object grasping during moving of the object. Fast terminal sliding mode control (FTSMC) technique is used to design the controller and comparison to traditional and super-twisting sliding mode controls have been done. Simulations show the effectiveness and outperformance of the proposed control algorithm in comparison to considered sliding mode control techniques.

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1. INTRODUCTION

Due to high flexibility in maneuvring operations, dual arm manipulators exhibit many advantages in various applications. Intentionally designated to work in coordinated situations, the dual arm robot experience inherent strong kinematic and kinetic couplings making control problems of the robot arms difficult. When individual arms synchronously engage a task, the formation of closed-chain dynamics between the robot arms and manipulating objects results in complex scenarios for modelling and controlling processes.

The control problem of dual arm robots has attracted many researchers in recent years [1]. There have been many approaches applied to control dual arm robots, from traditional methods such as nonlinear feedback control [1], input-output linearization [2], [3], impedance control [4]–[7], hybrid force/motion control [8]–[13], to modern methods such as robust-adaptive control and intelligent control [14]–[24]. The traditional control methods are general model-based, require the knowledge of the robotic system structure and parameters. Thus, they are not effective in cases of model imprecision and unknown robot parameters. In order to cope with model uncertainty, intelligent control such as fuzzy control [14], [15] neural network [16], reinforcement learning control [17] have been applied to dual arm robot system. In addition, modified sliding control [18], intelligent control in combination with sliding mode control [19], [20] also are proposed to control dual arm robot. Such types of control techniques are straightforward generalizations from the single to multiple manipulator case, since with the assumption of fixed grasps, dynamic model uncertainties affect the dynamic response of the controlled system in an analogous fashion in both single and multiple manipulator cases. The problem of control dual arm robot becomes more complicated when the grasp conditions are considered as constraints when designing the controllers. Research by Hacioglu *et al*. [21], Nguyen and Vu [22] by using Coulomb law to model the frictional contact constraints, the dynamic model of a dual robot arm system has been developed. Then sliding mode control [21] and fuzzy sliding mode control [22] are applied to control the system. However, in the research, the dual robot can only translate the object in parallel to an axis. To provide flexible maneuvering ability for the dual arm robot, in this paper, an algorithm to control the dual arm robot that can manipulate the object with both translational and rotational motions using fast terminal sliding mode technique. In addition, fast terminal sliding mode control (FTSMC) is formulated to enhance tracking ability, convergent period and robustness against disturbances and then compared to traditional and super-twisting sliding mode control [23]–[25] to verify the effectiveness of the proposed control algorithm. The comparison analysis is performed based on processor-in-the-loop (PIL) simulations.

2. SYSTEM DYNAMICS

In this paper, a dual 2-degree of freedom (2DoF) robot system handing an object in a plane is considered [23]. The dual arm robot consists of two 2DoF planar robot arms with revolute joints and these two robot arms grasp a rectangular object. Figure 1 describes the system, in which, m_i, I_i, and L_i $(i = 1, 2, 3, 4)$ presents the mass, moment of inertia, and length of the related links, respectively; k_i is the distance from the center of mass of i^{th} link to the preceding joint and θ_i is the i^{th} joint angle. In addition, m is the object's mass; d_1 denotes the width of the rectangle load and d_2 denotes the distance between the bases of the two robot arms. In this system, the viscous frictions acting on all the joints in both robot arms that denoted by b_i $(i = 1, 2, 3, 4)$ are also considered. It is assumed that the robot arms work in the *xy*-plane and gravity acts in the negative *z*-direction.

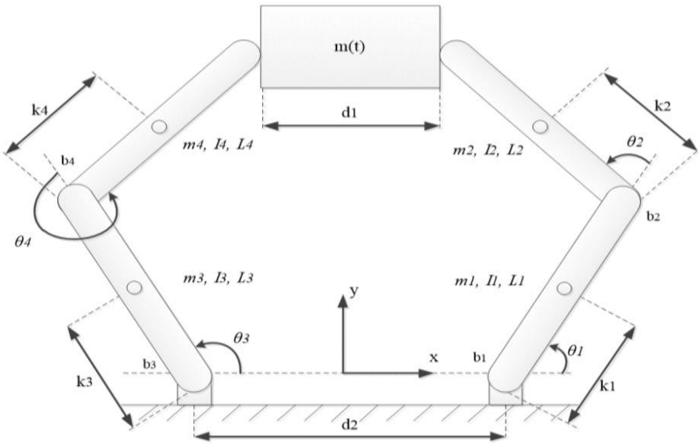

Figure 1. Physical model of the dual arm robot

To establish the dynamical model of the dual robot system, the system is considered as two separated robots with external forces at tips of the robots. The external forces are the interactive forces between the robot arms and the object as shown in Figure 2. The dynamical equations for the dual robot system are described as (1):

$$M(\bar{q})\ddot{\bar{q}} + C(\bar{q}, \dot{\bar{q}}) = \bar{\tau} + J(\bar{q})^T\bar{F} - \bar{b} + \bar{w} \tag{1}$$

where $\bar{q} = [\theta_1, \theta_2, \theta_3, \theta_4]^T$ is angular vector, $\bar{\tau} = [\tau_1, \tau_2, \tau_3, \tau_4]^T$ is torque input vector; $\bar{F} = [F_{1x}, F_{1y}, F_{2x}, F_{2y}]^T$ is external force vector; $\bar{b} = [b_1\dot{q}_1, b_2\dot{q}_2, b_3\dot{q}_3, b_4\dot{q}_4]^T$ is viscous friction vector (b_1, b_2, b_3, b_4 are friction coefficients at dual arm robot joints); $\bar{w} = [w_1, w_2, w_3, w_4]^T$ is external disturbance torque vector. The external force component can be calculated as (2)-(5):

$$F_{1x} = F_1 cos\varphi + F_{s1xy} sin\varphi \tag{2}$$

$$F_{1y} = F_1 sin\varphi - F_{s1xy} cos\varphi \tag{3}$$

$$F_{2x} = -F_2 cos\varphi + F_{s2xy} sin\varphi \quad (4)$$

$$F_{2y} = -F_2 sin\varphi - F_{s2xy} cos\varphi \quad (5)$$

where φ is object's rotational angle about z axis; F_1, F_2 are the forces that the robots apply to the object; and F_{s1xy}, F_{s2xy} are the friction forces between the arm tips and the load surface in xy plane.

In addition, $M(\bar{q})$ is inertia matrix, $C(\bar{q}, \dot{\bar{q}})$ is Coriolis matrix, $J(\bar{q})$ is Jacobian matrix, and they are calculated as following:

$$M(\bar{q}) = \begin{bmatrix} m_{11} & m_{12} & 0 & 0 \\ m_{21} & m_{22} & 0 & 0 \\ 0 & 0 & m_{33} & m_{34} \\ 0 & 0 & m_{43} & m_{44} \end{bmatrix}$$

where: $m_{11} = A_1 + A_2 + 2A_3 cos\theta_2; m_{12} = A_2 + A_3 cos\theta_2; m_{21} = A_2 + A_3 cos\theta_2; m_{22} = A_2; m_{33} = A_4 + A_5 + 2A_6 cos\theta_4; m_{34} = A_5 + A_6 cos\theta_4; m_{43} = A_5 + A_6 cos\theta_4; m_{44} = A_5$.

$$C(\bar{q}, \dot{\bar{q}}) = \begin{bmatrix} -A_3 sin\theta_2(\dot{\theta}_2^2 + 2\dot{\theta}_1\dot{\theta}_2) \\ -A_3\dot{\theta}_1\dot{\theta}_2 sin\theta_2 \\ -A_6 sin\theta_4(\dot{\theta}_4^2 + 2\dot{\theta}_3\dot{\theta}_4) \\ -A_6\dot{\theta}_3\dot{\theta}_4 sin\theta_4 \end{bmatrix}; J(\bar{q}) = \begin{bmatrix} n_{11} & n_{12} & 0 & 0 \\ n_{21} & n_{22} & 0 & 0 \\ 0 & 0 & n_{33} & n_{34} \\ 0 & 0 & n_{43} & n_{44} \end{bmatrix}$$

where: $n_{11} = -L_1 sin\theta_1 - L_2 sin(\theta_1 + \theta_2); n_{12} = -L_2 sin(\theta_1 + \theta_2); n_{21} = L_1 cos\theta_1 + L_2 cos(\theta_1 + \theta_2); n_{22} = L_2 cos(\theta_1 + \theta_2); n_{33} = -L_3 sin\theta_3 - L_4 sin(\theta_3 + \theta_4); n_{34} = -L_4 sin(\theta_3 + \theta_4); n_{43} = L_3 cos\theta_3 + L_4 cos(\theta_3 + \theta_4); n_{44} = L_4 cos(\theta_3 + \theta_4)$. Where $A_j (j = 1, 2, \ldots, 6)$ are the constant coefficients given by: $A_1 = m_1 k_1^2 + m_2 L_1^2 + I_1$; $A_2 = m_2 k_2^2 + I_2$; $A_3 = m_2 L_1 k_2$; $A_4 = m_3 k_3^2 + m_4 L_3^2 + I_3$; $A_5 = m_4 k_4^2 + I_4$; $A_6 = m_4 L_3 k_4$.

Because the dynamical equations of the system contain the interaction forces between the robots and the object, it is necessary to determine the interaction forces in case of the system handles the object. As shown in Figures 2 and 3, forces F_1 and F_2 are exerted from the arm tips to the load at position (x_1, y_1) and (x_2, y_2), respectively. The object's center locates at (x_m, y_m) and it is rotated by φ around *z*-axis. The friction forces F_{s1xy} and F_{s2xy} are between the arm tips and the load surface in *xy* plane. The friction forces F_{s1z} and F_{s2z} dedicate the interaction between the arm tips and the load surface along z axis. Since in plane operation is considered, it can be supposed that:

$$F_{s1z} = F_{s2z} = \frac{mg}{2} \quad (6)$$

where g is gravitational acceleration. Using forward kinematics for the two arms, the positions of arm tips can be calculated as (7)-(10):

$$x_1 = \frac{d_2}{2} + L_1 cos\theta_1 + L_2 cos(\theta_1 + \theta_2) \quad (7)$$

$$y_1 = L_1 sin\theta_1 + L_2 sin(\theta_1 + \theta_2) \quad (8)$$

$$x_2 = -\frac{d_2}{2} + L_1 cos\theta_3 + L_2 cos(\theta_3 + \theta_4) \quad (9)$$

$$y_1 = L_1 sin\theta_3 + L_2 sin(\theta_3 + \theta_4) \quad (10)$$

Then the object's position can be calculated from robot tips and object's rotational angle as (11):

$$x_m = \frac{d_2}{2} + L_1 cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) - \frac{d_1}{2} cos\phi = -\frac{d_2}{2} + L_3 cos\theta_3 + L_4 \cos(\theta_3 + \theta_4) + \frac{d_1}{2} cos\phi \quad (11)$$

$$y_m = L_1 sin\theta_1 + L_2 sin(\theta_1 + \theta_2) - \frac{d_1}{2} sin\phi = L_3 sin\theta_3 + L_4 sin(\theta_3 + \theta_4) + \frac{d_1}{2} sin\phi \quad (12)$$

The object obtains the interaction forces $F_1, F_2, F_{s1xy}, F_{s2xy}$ in the xy plane from two robots. Therefore, the dynamic equations of the object are:

$$m\ddot{x}_m = -F_1 cos\phi + F_2 cos\phi - F_{s1xy} sin\phi - F_{s2xy} sin\phi \quad (13)$$

$$m\ddot{y}_m = -F_1 sin\phi + F_2 sin\phi + F_{s1xy} cos\phi + F_{s2xy} cos\phi \quad (14)$$

$$J\ddot{\phi} = (F_{s1xy} - F_{s2xy})\frac{d_1}{2} \quad (15)$$

from (13) and (14) we can obtain:

$$m(\ddot{x}_m sin\phi - \ddot{y}_m cos\phi) = -sin^2\phi(F_{s1xy} + F_{s2xy}) - cos^2\phi(F_{s1xy} + F_{s2xy}) \quad (16)$$

or:

$$F_{s1xy} + F_{s2xy} = m(\ddot{x}_m sin\phi_5 - \ddot{y}_m cos\phi_5) \quad (17)$$

Using (15) and (17) we can calculate the friction forces F_{s1xy} and F_{s2xy} as (18) and (19):

$$F_{s1xy} = [m(\ddot{x}_m sin\phi - \ddot{y}_m cos\phi) + \frac{2J\ddot{\phi}}{d_1}] \quad (18)$$

$$F_{s2xy} = [m(\ddot{x}_m sin\phi - \ddot{y}_m cos\phi) - \frac{2J\ddot{\phi}}{d_1}] \quad (19)$$

Next, we will calculate F_1, F_2. Substitute (18) and (19) into (13) we obtain:

$$\Delta F = F_2 - F_1 = m\frac{(1+sin^2\phi)\ddot{x}_m + sin\phi cos\phi \ddot{y}_m}{cos\phi} \quad (20)$$

To handle the object effectively, the following conditions must be satisfied:

$$F_{s1xy}^2 + F_{s1z}^2 \leq (\mu F_1)^2 \quad (21)$$

$$F_{s2xy}^2 + F_{s2z}^2 \leq (\mu F_2)^2 \quad (22)$$

where μ is dry friction coefficient of the object. Since the direction of the forces F_1 and F_2 are always perpendicular and toward the object, the friction force equation that results in a positive signed solution for both F_1 and F_2should be considered. Therefore, there are two situations corresponding the relation between F_1 and F_2 needs to be taken into account. In the first case, when $F_1 > F_2$ (i.e. $\Delta F > 0$), using (21). If the two forces are equal, F_1 and F_2 can be calculated as (23) and (24):

$$F_1 = \frac{1}{\mu}\sqrt{F_{s1xy}^2 + F_{s1z}^2} \quad (23)$$

$$F_2 = F_1 + \Delta F \quad (24)$$

where F_{s1xy}, F_{s1z} and ΔF are calculated using (18), (6) and (20) respectively. In the second situation, if $F_2 \leq F_1$ (i.e. $\Delta F \leq 0$), using (22) with equal case, F_1 and F_2 can be calculated as (25) and (26):

$$F_2 = \frac{1}{\mu}\sqrt{F_{s2xy}^2 + F_{s2z}^2} \quad (25)$$

$$F_1 = F_2 - \Delta F \tag{26}$$

where F_{s2xy}, F_{s2z} and ΔF are calculated using (19), (6) and (20) respectively. For summary, the dynamical model of the dual arm robot system includes two 2DoF robot arms that handles an object is expressed in (1) with external forces F_1, F_{s1xy} for the first arm and F_2, F_{s2xy} for the second arm are calculated using (23) (or (26)), (18), (24) (or (25)), and (19), respectively.

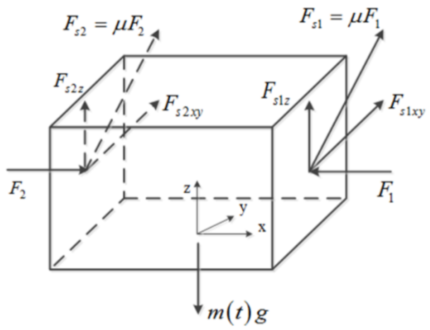

Figure 2. Contact forces between dual robot arm and the object

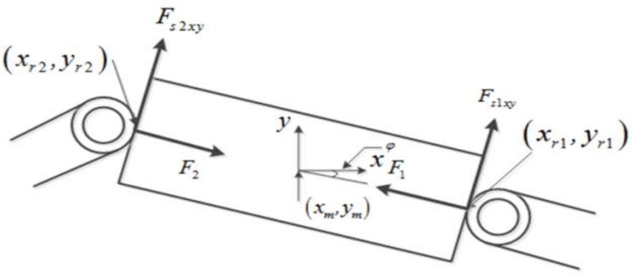

Figure 3. Contact forces between dual robot arm and the object in xy plane

3. FAST TERMILAL SLIDING MODE CONTROL FOR DUAL ARM ROBOT

In this paper we apply the FTSMC [24] for dual robot arm. The FTMSC is expected to overcome the various problems of normal sliding mode control such as asymptotic convergence, chattering. Moreover, the converge time of system states to zero can be managed by selecting the appropriate controller parameters.

3.1. Fast terminal sliding mode control

Consider a second order nonlinear system as following:

$$\dot{e}_1 = e_2 \tag{27}$$

$$\dot{e}_2 = f(e) + g(e)u + d(t) \tag{28}$$

where $e = [e_1, e_2]$ is system state vector, $f(e), g(e)$ are smooth functions, $d(t)$ denotes the uncertainties and $|d(t)| \leq L$, where L is a positive constant. The fast sliding surface is selected as (29):

$$s = \dot{e}_1 + \alpha_0 e_1 + \beta_0 e_1^{q_0/p_0} \tag{29}$$

where α_0, β_0 and q_0, p_0 $(q_0 < p_0)$ are positive odd numbers. The fast sliding mode controller is designed as (30):

$$u(t) = -\frac{1}{g(e)}\left(f(e) + \alpha_0 \dot{e}_1 + \beta_0 \frac{d}{dt} e_1^{q_0/p_0} + \varphi s + \gamma s^{q/p}\right) \tag{30}$$

where $\phi > 0, \gamma > 0$ and q, p are positive odd numbers. To confirm the stability of the system with the fast sliding mode controller, the Lyapunov function is chosen as (31):

$$V = \frac{1}{2}s^2 \tag{31}$$

From (29) we have:

$$\dot{s} = \ddot{e}_1 + \alpha_0\dot{e}_1 + \beta_0\frac{d}{dt}e_1^{q_0/p_0} = f(e) + g(e)u + d(t) + \alpha_0\dot{e}_1 + \beta_0\frac{d}{dt}e_1^{q_0/p_0} \tag{32}$$

Replace (30) into the above equation, then we have:

$$\dot{s} = -\varphi s - \gamma s^{p/q} + d(t) \tag{33}$$

Thus,

$$\dot{V} = s\dot{s} = -\varphi s^2 - \gamma s^{(q+p)/q} + sd(t) \tag{34}$$

by choosing $\gamma \geq |\frac{1}{s^{p/q}}|L$, then:

$$\gamma \geq |\frac{1}{s^{p/q}}|L \geq \frac{1}{s^{p/q}}d(t) \tag{35}$$

Since q and p are odd numbers, $q + p$ is an even number, then $S^{(q+p)/p} \geq 0$. Multiple both sides of (35) with $S^{(q+p)/p}$ we obtain:

$$\gamma s^{(q+p)/q} \geq sd(t) \tag{36}$$

Therefore,

$$\dot{V} = -\varphi s^2 - \gamma s^{(q+p)/q} + sd(t) \leq 0 \tag{37}$$

The system is asymptotic stable. In addition, from the fast sliding surface (29), it can be seen that the system state attain equilibrium $e_1 = 0$ from initial state $e_1(0) \neq 0$ in a finite time ts with:

$$t_s = \frac{p}{\alpha_0(p_0-q_0)} ln\frac{\alpha_0 e_1(0)^{(p_0-q_0)/p_0}+\beta_0}{\beta_0} \tag{38}$$

Moreover, from the fast-sliding surface (29), when the system is in the sliding surface, i.e. $s = 0$, we have:

$$\dot{e}_1 = -\alpha_0 e_1 - \beta_0 e_1^{q_0/p_0} \tag{39}$$

When the state e_1 is far away from the origin, the convergent time is decided by the fast terminal attraction equation $\dot{e}_1 = -\beta_0 e_1^{q_0/p_0}$. When the state $e_1$approaches the origin $e_1 = 0$, the convergent time is determined by exponential convergence equation $\dot{e}_1 = -\alpha_0 e_1$. Accordingly, the state can converge to equilibrium point speedily and precisely.

3.2. Fast terminal sliding mode control for dual arm robot

In this section we will design the FTSMC for dual arm robot. From (1) we have:

$$\ddot{\bar{q}} = M^{-1}(\bar{q})[-C(\bar{q},\dot{\bar{q}}) + J(\bar{q})^T\bar{F} - \bar{b} + \bar{\tau} + \bar{w}] \tag{40}$$

Let the desired angular vector be $\bar{q}_d = [\theta_{1d}, \theta_{2d}, \theta_{3d}, \theta_{4d}]$. Set new state variables $\bar{e}_1 = \bar{q} - \bar{q}_d$, $\bar{e}_2 = \dot{\bar{e}}_1$. Then from (40) we can obtain the system with new state variables as (41) and (42):

$$\dot{\bar{e}}_1 = \bar{e}_2 \tag{41}$$

$$\dot{\bar{e}}_2 = M^{-1}(\bar{q})[-C(\bar{q},\dot{\bar{q}}) + J(\bar{q})^T\bar{F} - \bar{b} + \bar{\tau} + \bar{w}] - \ddot{\bar{q}}_d \tag{42}$$

like (41) and (42) can be rewritten as (43) and (44):

$$\dot{\bar{e}}_1 = \bar{e}_2 \quad (43)$$

$$\dot{\bar{e}}_2 = f(\bar{e}) - \ddot{\bar{q}}_d + g(\bar{e})\bar{\tau} + \bar{d}(t) \quad (44)$$

where, $\bar{e} = [\bar{e}_1, \bar{e}_2]^T$, $f(\bar{e}) = M^{-1}(\bar{q})[-C(\bar{q}, \dot{\bar{q}}) + J(\bar{q})^T\bar{F} - \bar{b}]$, $g(\bar{e}) = M^{-1}(\bar{q})$, and $\bar{d}(t) = M^{-1}\bar{w}$. Choose the fast-sliding surface as (45):

$$\bar{s} = \dot{\bar{e}}_1 + \alpha_0\bar{e}_1 + \beta_0\bar{e}_1^{q_0/p_0} \quad (45)$$

where α_0, β_0 and q_0, p_0 $(q_0 < p_0)$ are positive odd numbers. Then, the fast-sliding mode controller for this system is,

$$\bar{\tau} = -\frac{1}{g(\bar{e})}\left(f(\bar{e}) - \ddot{\bar{q}}_d + \alpha_0\dot{\bar{e}}_1 + \beta_0\frac{d}{dt}\bar{e}_1^{q_0/p_0} + \varphi\bar{s} + \gamma\bar{s}^{q/p}\right) \quad (46)$$

where $\phi > 0, \gamma > 0$ and q, p are positive odd numbers.

4. PROCESSOR-IN-THE-LOOP BASED SIMULATIONS AND COMPARISON

To verify the effectiveness of the proposed control method, we preform simulations of the dual arm robot in accordance with conventional sliding mode control, super-twisting sliding mode control and the proposed FTSMC. In PIL simulation, the controller is embedded in target hardware TI C2000 F38377s. The robot parameters (as shown in Figure 1) are given in Table 1.

Table 1. Robot parameters

Parameter	Value	Parameter	Value
L_1	0.5 m	L_3	0.5 m
L_2	0.4 m	L_4	0.4 m
m_1	5 kg	m_3	5 kg
m_2	4 kg	m_4	4 kg
I_1	0.1 kgm^2	I_3	0.1 kgm^2
I_2	0.08 kgm^2	I_4	0.08 kgm^2
k_1	0.25 m	k_3	0.25 m
k_2	0.2 m	k_4	0.2 m
b_1	100 Ns/m^2	b_3	100 Ns/m^2
b_2	100 Ns/m^2	b_4	100 Ns/m^2
d_1	0.2 m	D_2	0.4 m
m	5 kg	*Object size*	0.2×0.1 m

The simulation scenario is as following: the first joints of two robots are placed at [0.2; 0] for the first robot and [-0.2; 0] for the second robot. The initial joint angle vector is $\theta = [0; 3\pi/4; \pi; -3\pi/4]^T$. Then, the initial positions of the first and the second arm's tips are [0.42; 0.28] and [-0.42;0.28] respectively. The object has a rectangle form with the center point is located at [0; 0.4]. Initially, to grasp the object, the first arm's tip will proceed to [0.1; 0.4] and the second arm's tip will travel to [-0.1; 0.4] as depicted in Figure 4.

Secondly, the dual arm robot will translate the object's center to [0.2; 0.7] without rotating the object. It means that the first arm's tip will move to [0.3; 0.7] and the second arm's tip will move to [0.1; 0.7]; as shown in Figure 5. And finally, the robot will drive the object's center point to [0.3; 0.5] while rotate the object about 45 degrees. It means that the first arm's tip will move to [0.37; 0.43] and the second arm's tip will shift to [0.23; 0.57]; as in Figure 6. To verify the effectiveness of FTSM control, we do the simulation for the system with disturbance. Supposing that the disturbance is sinusoidal type vector that is expressed as:

$$\bar{w} = [\sin 1\,0\pi t \; \sin 2\,0\pi t - \sin 1\,0\pi t - \sin 2\,0\pi t]^T$$

Three control algorithms including SMC, super-twisting and FTSM are applied to the system. The simulation results of the system with disturbance are shown in Figures 7-9. It can be seen that the system is stable with good position tracking performance. The considered controllers can reject the effect of the disturbance to the stability and the system’s performance. Once again, FTSM outperforms the conventional SMC and super-twisting slide mode controllers.

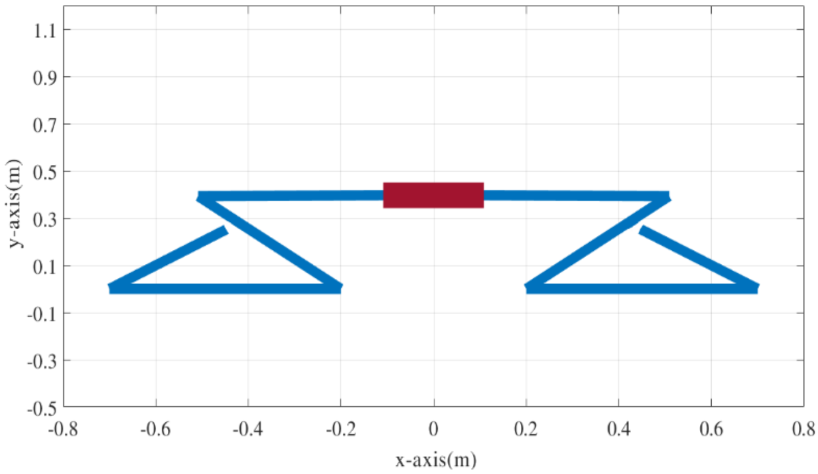

Figure 4. The begin and the final positions of the dual arm robot in the first stage

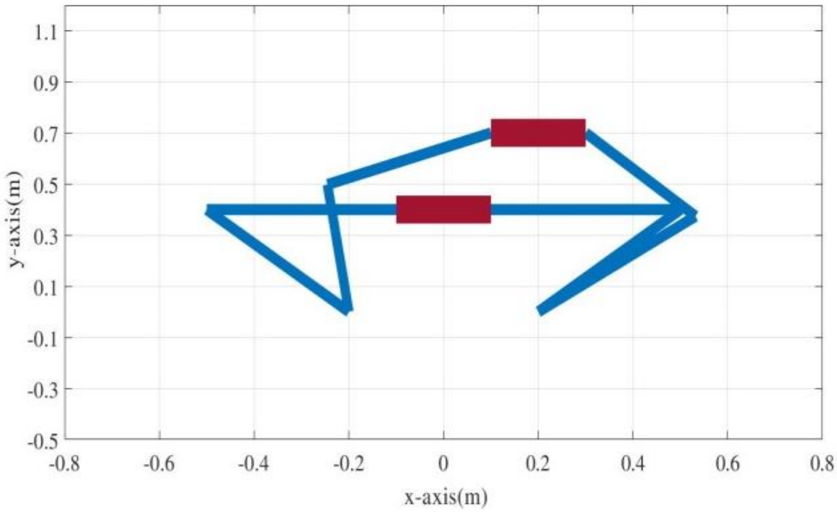

Figure 5. The begin and the final positions of the dual arm robot in the second stage

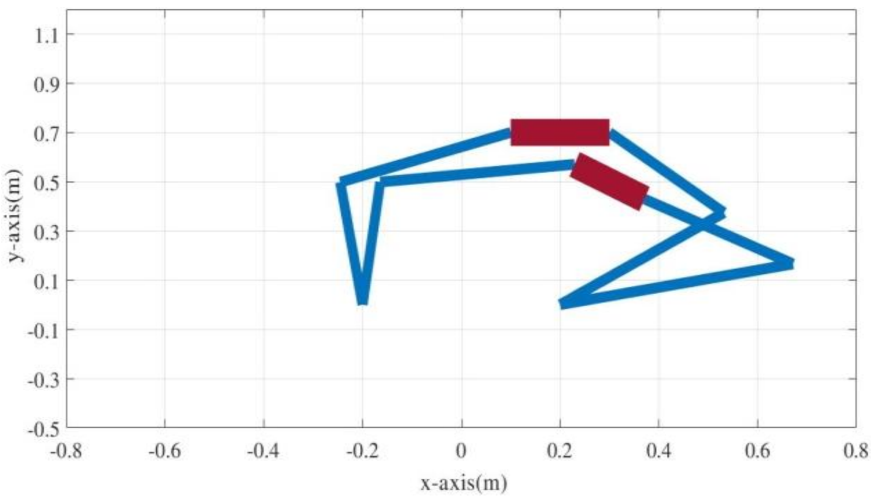

Figure 6. The begin and the final positions of the dual arm robot in the second stage

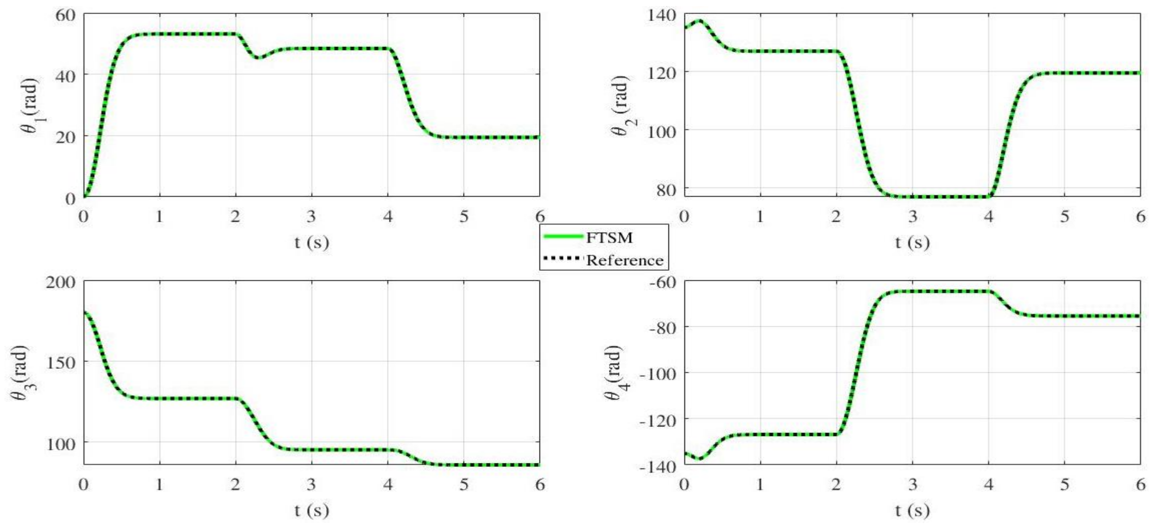

Figure 7. Angular positions of dual arm robot's joints in case of disturbance

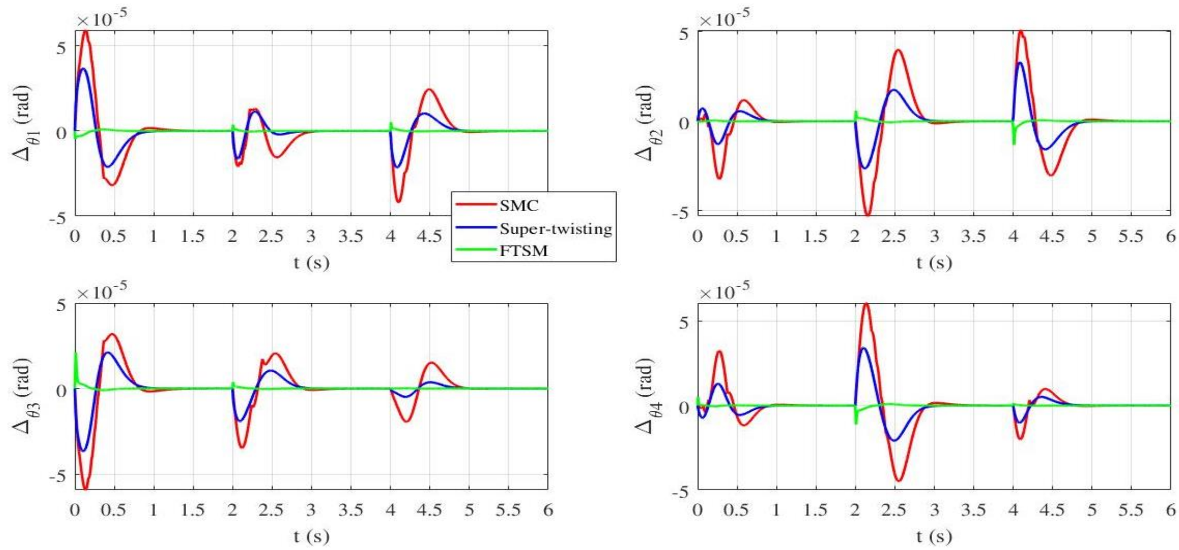

Figure 8. Position error in case of SMC, super-twisting and FTSM control in case of with disturbance

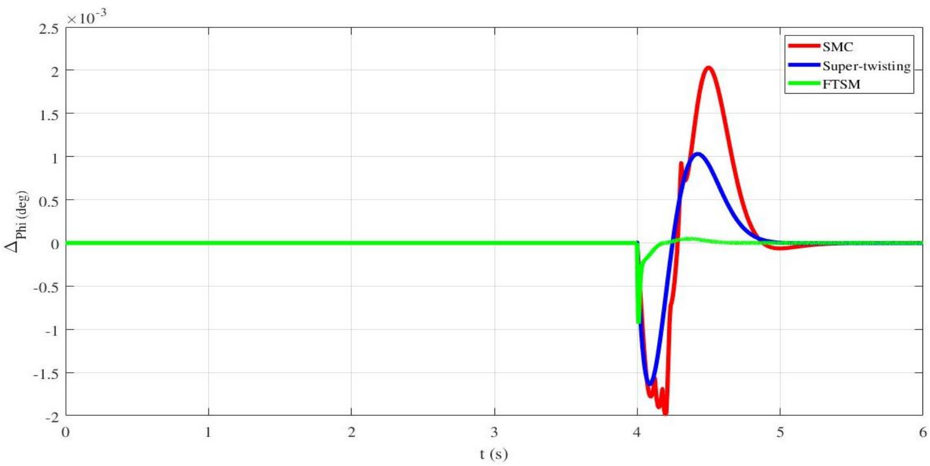

Figure 9. Object rotation angular error in case of SMC, super-twisting and FTSM control in case of with disturbance

5. CONCLUSION AND FURTHER STUDY

In this paper, a position control of a dual arm robot moving an object in a working plane is presented. The dynamic of dual arm robot with frictional contact constraint are considered and the FTSMC algorithm is developed that allow the robot to both translate and rotate the object. The comparison of the proposed controller to traditional and super-twist sliding mode controllers has been done and it is shown that the proposed algorithm outperforms the traditional and super-twisting sliding mode controls. In the near future, the multi arm robot system to moving object in a 3D space is considered. In addition, experimental implementation should be done in order to verify the effectiveness of the proposed control algorithm in the real world.

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