Received: Added at production | Revised: Added at production | Accepted: Added at production

DOI: xxx/xxxx

ARTICLE TYPE

Global Finite-Time Co-operative Control for Multiple Manipulators using Integral Sliding Mode Control

Mien Van*[1] | Shuzhi Sam Ge[2] | Dariusz Ceglarek[3]

[1]School of Electronics, Electrical Engineering and Computer Science, Queen's University Belfast, Belfast, United Kingdom

[2]Department of Electrical and Computer Engineering, National University of Singapore, Singapore

[3]Warwick Manufacturing Group, University of Warwick, Coventry, United Kingdom

Correspondence

*Mien Van. Email: m.van@qub.ac.uk

Summary

In this paper, a global finite-time co-operative control is first time proposed for co-operative multiple manipulators. The proposed control scheme is developed based on an integration between a finite-time disturbance observer (FTDO) and a finite-time integral sliding mode controller (FTISMC) to get a high robustness against the effects of the model uncertainties and disturbances in the system. The switching term of the integral sliding mode controller is reconstructed such that the desired sliding manifold can be convergent in a finite time. The nominal controller of the integral sliding mode control is developed based on an advanced backstepping control, namely finite-time backstepping control, which also provides a finite time convergence. The integration of the finite-time disturbance observer, finite-time switching term and the finite-time backstepping controller forms a new global finite-time integral sliding mode control. The effectiveness of the proposed approach is demonstrated based on a co-operative control of a dual two-link manipulators.

KEYWORDS:

Multiple Manipulators; Finite-time convergence; Integral sliding mode control; Backstepping control.

1 | INTRODUCTION

Robots have been widely applied in manufacturing sector to enhance the quality and quantity of the products [36], [24]. Initially, a single robot was designed to hold/carry objects independently without interacting with other robots. However, for handling/-carrying a long, large and heavy object, the use of single manipulator may not be sufficient. One solution for this problem is to re-design structure of single robot manipulator so that it suits for this particular application. However, this design procedure becomes complex and costly. An alternative solution for this issue is to use multiple simpler and cheaper robots. Due to this demand, co-operative control of multiple manipulators has been developed recently [46], [17].

However, the design of co-operative control of multiple manipulators faces many challenges compared to those for single robot because of the complex coupling effects in the motions between the robots and the handled object. To get a good tracking precision for the object, all manipulators need to provide high tracking performances. Actually, the lower tracking precision of a robot will possibly generate a huge tracking error for the whole system. Consequently, a huge internal force may be produced that can disturb the stability of the system and even damage the handled objects or manipulators themselves [13]. Therefore, it is necessary to enhance the tracking precision of robot manipulators [27]. Many solutions have been proposed to enhance the tracking performance of robot manipulators. In [45], a nonlinear feedback control has been investigated for multiple manipulators. In [25], a PD plus gravity compensation has been proposed. However, these approaches presumed a prior knowledge of the full dynamic model of the robot. Unfortunately, this assumption might not be applicable for the practical robot systems;

there always exist model uncertainties and disturbance in robot dynamics, which reduce the tracking performance of the robots significantly [39],[4].

To eliminate the uncertainties and disturbances' effects, many solutions have been explored. In the first approach, adaptive control techniques have been developed [2], [5], [9]. In the second approach, learning techniques have been proposed [8], [10], [16], [40], [14]. Alternative solutions based on disturbance observers have been recommended in [41], [38]. In [18], an reduced-order observer has been developed. However, these conventional disturbance observer did not provide finite time convergence. To obtain a finite time convergence of the disturbance estimate errors, a finite time disturbance observer based on a state estimation scheme have been developed [23], [15]. In these disturbance observers, the disturbance estimate can be reconstructed when the estimated states converged to the real states.

Due to its high robustness, sliding mode control (SMC) techniques have been utilized to suppress the effects of the uncertainties and disturbances in the system [29]. The conventional SMC has been utilized to improve the tracking control of a co-operative control of multiple manipulators [3]. Generally, the conventional SMC has two basic operaional stages. In the first stage, the origin of the system is driven to reach the predefined sliding surface. Then, in the second stage, the system is controlled to sustain its location in the sliding surface in infinite time. Unfortunately, the transition period in the first stage decreases the settling time of the system [12]. To eliminate this shortcoming, integral sliding mode control (ISMC) has been proposed [31], [32], [37]. In a comparison with its counterpart, i.e., the conventional SMC, the ISMC provides many prominant features [22]. First, no reaching phase is present. This property is helpful for many practical applications because it helps to guarantee the physical constraints of the system can be satisfied from the beginning of the operating point. Second, the ISMC suppresses the matched disturbances, yet it does not boosts the unmatched ones. Third, under the presence of matched uncertainties, the system response is matching with the response of the nominal system. However, the conventional ISMC does not provide a finite time convergence for the system. The property of finite time convergence is particularly useful for practical systems since it can guarantee the stability and convergence after a finite time and increase the tracking precision for the system [47], [42]. Due to this significance, finite time convergence has been studied extensively for many applications based on a new advanced SMC, namely terminal sliding mode control (TSMC) [44], [30], [35], [34]. However, the TSMC does not provide the three aforementioned desired properties like that of the ISMC. Another finite time controllers based on finite time backstepping control have been developed [26], [43]. However, like the conventional backstepping control such as [32], the finite time backstepping control possesses low robustness against uncertainties and disturbances compared to the sliding mode control approaches. This motivates us to develop a new controller that can combine the property of finite time backstepping control and integral sliding mode control to preserve the merit features of the two conventional approaches.

In this paper, in order to enhance the tracking performance of co-operative control of multiple manipulators, an integration between a new finite-time disturbance observer (FTDO) and a new finite-time integral sliding mode control (FTISMC) is proposed for the first time. First, a coupled dynamic model of the multiple manipulators and the handled object is derived. A FTDO is then developed to estimate the disturbance component in the system. Next, a FTISMC, which includes a finite-time switching term and a finite-time backstepping control, which is used as a nominal controller, is derived so that the system can achieve a finite time convergence. The finite time stability of the whole system is proved rigorously. Finally, the proposed method is applied for a co-operative control of a dual two-link manipulators system. In summary, the major contributions of this paper can be marked as follows:

- A finite-time disturbance observer is proposed. Compared to the conventional disturbance observers [41, 38], the proposed observer guarantees a finite time stability and convergence of the estimated disturbance errors (see section 4). The finite time convergence property of the proposed disturbance observer has a similar property as [23], [15], howerver the proposed disturbance observer is designed for estimating the disturbance observer directly (the disturbance observer is reconstructed based on a disturbance estimate component), while the approaches in [23], [15] reconstructed a disturbance estimate from a state observer.

- A finite-time integral sliding mode control (FTISMC) is first time explored for a co-operative control of multiple manipulators. Compared to the existing approaches such as PD controller [25], adaptive control techniques [2], [5], [9] and conventional SMC [3], the proposed method is superior since it has a strong robustness against the effects of the uncertainties and faults, eliminates the reaching phase and provides a finite time convergence. Compared to other integral sliding mode controllers such as [15], [6], [33], the proposed FTISMC has two major advantages: (1) it uses a dynamic model of the robots to reconstruct an integral sliding surface, so it can eliminate the reaching phase and provide high robustness, (2) it provides a finite time convergence, while the existing approaches, i.e., [15], [6], [33] cannot.

- Compared to the conventional integral sliding mode control [31], [32], [37], both the switching term and nominal controller of the proposed FTISMC provide a finite time convergence. Compared to other finite time controllers such as [1], [11], the proposed FTISMC provides two major unique features: (1) an integration between a finite time disturbance observer and FTISMC guarantees a global finite time convergence, (2) the proposed FTISMC integrates the merits of both integral sliding mode control and finite time controller, so it provides higher robustness and faster convergence and no reaching phase required.
- Compared to the conventional backstepping control [32], the developed finite-time backstepping control technique provides a finite time convergence. Compared to the finite-time backstepping control approaches such as [26], [43], the proposed approach in this paper is unique in the way that the finite time backstepping is used as a nominal controller and integrated with a finite time integral sliding mode control. Therefore, it preserves the advantages of the backstepping control and integral sliding mode control simultaneously, which provides much higher robustness compared to the existing finite time backstepping control, i.e., [26], [43].

The remainder of this paper is organized as follows. Section 2 introduces some preliminaries. Problem statement is described in section 3. Section 4 presents the design of the finite-time integral sliding mode control. The nominal controller of the integral sliding mode control based on finite-time backstepping control is presented in section 5. The effectiveness of the proposed approach is demonstrated in section 6. Section 7 provides conclusions and proposes future works.

2 | PRELIMINARIES

Consider the differential equation below

$$\dot{x}(t) = f(x(t)),\ f(0) = 0,\ x \in D,\ x(0) = x_0 \tag{1}$$

where $f : D \to \Re^n$ is continuous.

Definition 1. The system (1) is said to be global finite-time stable if the following two conditions are satisfied:
(i) It is globally asymptotically stable,
(ii) Any solution $x(t, x_0)$ converges to the origin at some finite time, i.e., $x(t, x_0) = 0$, $t \geq T(x_0)$, where $T(x_0)$ is the settling time function.

Lemma 1. [44] Consider a smooth positive Lyapunov function $V(x)$ satisfied $\dot{V}(x) + \lambda_1 V(x) + \lambda_2 V^\gamma(x) \leq 0$ for any real numbers $\lambda_1 > 0$, $\lambda_2 > 1, 0 < \gamma < 1$, then the system converges in finite time. The settling time of the system (1) is given by

$$T(x_0) \leq \frac{1}{\lambda_1(1-\gamma)} \ln \frac{\lambda_1 V^{1-\gamma}(x_0) + \lambda_2}{\lambda_2} \tag{2}$$

where $V(x_0)$ is the initial value of $V(x)$.

3 | PROBLEM STATEMENT

3.1 | Problem statement

3.1.1 | Kinematics of the System

In this paper, a co-operative control of m n-DOF manipulators illustrated in Fig. 1 is considered. Let $x_i \in \Re^{n_i}$ be the end-effector pose of the ith manipulator, the kinematics of the ith manipulator, which describes the relationship between the position of the end-effector x_i and the joint angles q_i, can be described as

$$x_i = \phi_{e,i}(q_i) \tag{3}$$

The derivative of (3) yields

$$\dot{x}_i = J_{e,i}(q_i)\dot{q}_i \tag{4}$$

where $J_{e,i}(q_i) \in \Re^{n_i \times n_i}$ is the Jacobian of the manipulator.

Let x_0 be the centroid of the handled object. The relationship between the end-effector of the ith manipulator, i.e., x_i, and the centroid of the object, i.e., x_0, can be defined by

$$x_0 = \phi_i(x_i) \tag{5}$$

Differentiating (5) with respect to time, yields

$$\dot{x}_0 = J_i(x_i)\dot{x}_i \tag{6}$$

where $J_i(x_i)$ is the Jacobian matrix. Furthermore, differentiating (6) with respect to time, yields [13]:

$$\ddot{x}_0 = \dot{J}_i(x_i)\dot{x}_i + J_i(x_i)\ddot{x}_i \tag{7}$$

where $\dot{x}_i$ and $\ddot{x}_i$ are the velocity and acceleration of the end-effector of the i-th manipulator, respectively, $\dot{x}_0$ and $\ddot{x}_0$ are the velocity and acceleration of the mass center of the object, respectively.

3.1.2 | Dynamics of robot manipulators

In the joint space, the dynamics of the i-th manipulator is [16], [14]:

$$M_{r,i}(q_i)\ddot{q}_i + C_{r,i}(q_i, \dot{q}_i)\dot{q}_i + G_{r,i}(q_i) = \tau_{r,i} + J^T_{r,i}(q_i)F_{r,i} \tag{8}$$

where $\tau_{r,i} \in \mathfrak{R}^{n_i}$ is the joint torque, $q_i, \dot{q}_i, \ddot{q}_i \in \mathfrak{R}^{n_i}$ denotes the joint position, joint velocity, and joint acceleration, respectively, $M_{r,i}(q_i) \in \mathfrak{R}^{n_i \times n_i}$ denotes the symmetric positive definite inertia matrix, $C_{r,i}(q_i) \in \mathfrak{R}^{n_i \times n_i}$ is the Coriolis-centrifugal torque matrix, $G_{r,i} \in \mathfrak{R}^{n_i}$ denotes the gravity torque vector, $F_{r,i}$ is the force vector exerted on the end-effector of the ith manipulator, $n_i(i = 1, ..., m)$ denotes the number of ith manipulator's DOFs, and m is the number of manipulators.

From (4) and (8), the dynamics of the ith manipulator in the Cartesian space can be represented as:

$$M_i(q_i)\ddot{x}_i + C_i(q_i, \dot{q}_i)\dot{x}_i + G_i(q_i) = \tau_i + F_i \tag{9}$$

where,

$$\begin{aligned} M_i(q_i) &= J^{-T}_{r,i}(q_i)M_{r,i}(q_i)J^{-1}_{r,i}(q_i), \\ C_i(q_i, \dot{q}_i) &= J^{-T}_{r,i}(q_i)(C_{r,i}(q_i, \dot{q}_i) - M_{r,i}(q_i)J^{-T}_{r,i}\dot{J}_{r,i}(q_i))J^{-T}_{r,i}, \\ G_i(q_i) &= J^{-T}_{r,i}(q_i)G_{r,i}(q_i), \\ \tau_i &= J^{-T}_{r,i}(q_i)\tau_{r,i}, \\ F_i &= J^{-T}_{r,i}(q_i)J^T_{r,i}(q_i)F_{r,i}. \end{aligned} \tag{10}$$

Property 1. [8] The matrix $M_i(q_i)$ is symmetric and positive definite.

Property 2. [8],[16] The skew-symmetric matrix $2C_i(q_i, \dot{q}_i) - \dot{M}_i(q_i) \in \mathfrak{R}^{n_i \times n_i}$ satisfies that

$$x^T[\dot{M}_i(q_i) - 2C_i(q_i, \dot{q}_i)]x = 0, \forall x \in \mathfrak{R}^{n_i} \tag{11}$$

3.1.3 | Coupled Dynamics of Multiple Manipulators and the Handled Object

Under the input of the exerted force produced by m manipulators, the motion of the object is described by [16]

$$M_0(x_0)\ddot{x}_0 + C_0(x_0, \dot{x}_0)\dot{x}_0 + G_0(x_0) = F_0 - F_d \tag{12}$$

where F_d is the environmental force vector. Note that the environmental force is unknown, so it can be considered as an uncertainty/disturbance component in the system.

From (6), we also have

$$F_0 = -J(x_0)F_r \tag{13}$$

where $J(x_0) = diag(J_i(x_0)) \in \mathfrak{R}^{\bar{n} \times \bar{n}}$ and $F_r = [F_1^T, ..., F_m^T]^T$, here, $\bar{n} = \sum_1^m n_i$ is declared.

From (9), a compact form of the dynamic model of the m manipulators can be introduced as

$$M(q)\ddot{x} + C(q, \dot{q})\dot{x} + G(q) = \tau_r + F_r \tag{14}$$

From the results in (7), the coupled dynamics between manipulators and the handled object can be represented in a form below:

$$M(q)J(x_0)\ddot{x}_0 + \left(M(q)\dot{J}(x_0) + C(q, \dot{q})\right)\dot{x}_0 + G(q) = \tau_r + F_r \tag{15}$$

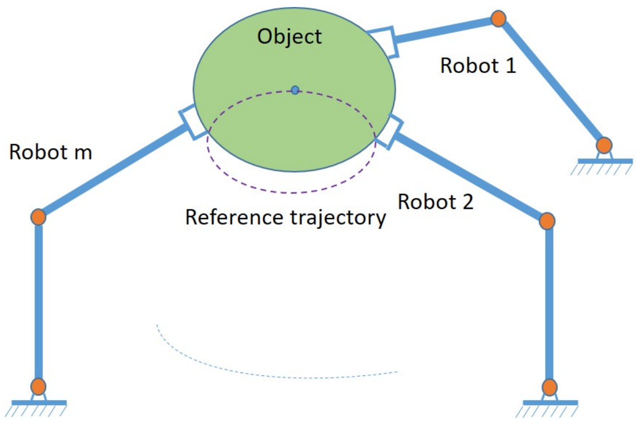

FIGURE 1 Multiple manipulators steer the object follows a desired trajectory

where $q = [q_1^T, ..., q_m^T]^T \in \Re^{\bar{n}}$, $J(x_0) = diag(J_i(x_0)) \in \Re^{\bar{n}\times\bar{n}}$, $M(q) = diag(M_i(q_i)) \in \Re^{\bar{n}\times\bar{n}}$, $C(q,\dot{q}) = diag(C_i(q_i,\dot{q}_i)) \in \Re^{\bar{n}\times\bar{n}}$, $\tau_r = [\tau_1^T, ..., \tau_m^T]^T \in \Re^{\bar{n}\times 1}$, and $\bar{n} = \sum_1^m n_i$.

By multiplying left side of (15) by $J^T(x_0)$, integrating equations (12) and (13), yields [16]

$$\Omega(q,x_0)\ddot{x}_0 + \Psi(q,\dot{q},x_0,\dot{x}_0) + \Gamma(q,x_0,\dot{x}_0) = \tau - F_d \tag{16}$$

where $\Omega(q,x_0) = J^T(x_0)M(q)J(x_0) + M_0 \in \Re^{\bar{n}\times\bar{n}}$, $\Psi(q,\dot{q},x_0,\dot{x}_0) = J^T(x_0)(M(q)\dot{J}(x_0) + C(q,\dot{q})J(x_0)) + C_0(x_0) \in \Re^{\bar{n}\times\bar{n}}$, $\Gamma(q,x_0,\dot{x}_0) = J^T(x_0)G(q) + G_0 \in \Re^{\bar{n}\times 1}$, and $\tau = J^T(x_0)\tau_r \in \Re^{\bar{n}\times 1}$.

3.2 | Control Objective

Let $\chi_1 = x_0$ and $\chi_2 = \dot{x}_0$, the dynamic model expressed in (16) can be represented in a state space form

$$\begin{aligned} \dot{\chi}_1 &= \chi_2 \\ \dot{\chi}_2 &= \Omega(q,x_0)^{-1}u + \Upsilon(q,\dot{q},x_0,\dot{x}_0) + \Theta \end{aligned} \tag{17}$$

where $u = \tau$ is the control input. $\Theta = -\Omega(q,x_0)F_d$ denotes the disturbance components. $\Upsilon(q,\dot{q},x_0,\dot{x}_0) = \Omega(q,x_0)^{-1}(-\Psi(q,\dot{q},x_0,\dot{x}_0) - \Gamma(q,x_0,\dot{x}_0))$ denotes the lumped known component.

Assumption 1. The unknown disturbance component is bounded by

$$|\Theta| \le \delta \tag{18}$$

where δ is a known constant.

Assumption 2. [13], [16] The object is not deformed under the force exerted by the arms.

Assumption 3. [13],[16] When the manipulators handle the object, no relative movement occurs between the end-effectors of the robots and the handled object.

Based on the assumptions, the objective of this paper is to design a finite-time integral sliding mode control so that the centroid of the object $x_0 = \chi_1$ can track the desired trajectory x_{0d} precisely, and that the tracking error can converge to zero in a finite time.

4 | DESIGN OF FINITE-TIME DISTURBANCE OBSERVER

Consider the following observer:

$$\dot{\hat{\chi}}_2 = \Omega(q,x_0)^{-1}u + \Upsilon(q,\dot{q},x_0,\dot{x}_0) + \hat{\Theta} \tag{19}$$

Substituting (17) into (19), we obtain the following error:

$$\dot{\tilde{\chi}}_2 = \tilde{\Theta} \tag{20}$$

where $\tilde{\chi}_2 = \chi_2 - \hat{\chi}_2$ and $\tilde{\Theta} = \Theta - \hat{\Theta}$. The disturbance observer can be designed as:

$$\begin{aligned}\hat{\Theta} &= \hat{e} + \varphi(\chi_2) + (\delta + \nu)\int sign(\dot{\tilde{\chi}}_2) + l\int \dot{\tilde{\chi}}_2^{\gamma_1} \\ \dot{\hat{e}} &= -\phi(\chi_2)\left(\Omega(q, x_0)^{-1}u + \Upsilon(q, \dot{q}, x_0, \dot{x}_0) + \hat{\Theta}\right)\end{aligned} \tag{21}$$

where $\varphi(\chi_2)$ is a linear function of χ_2 and $\phi(\chi_2) = (\partial\varphi(\chi_2)/\partial\chi_2)$ is a positive constant, ν is a small positive constant, and l is a positive constant, and $0 < \gamma_1 < 1$.

Differentiating (21) with respect to time, we have

$$\begin{aligned}\dot{\hat{\Theta}} &= \dot{\hat{e}} + \phi(\chi_2)(\dot{\chi}_2) + (\delta + \nu)sign(\dot{\tilde{\chi}}_2) + l\dot{\tilde{\chi}}_2^{\gamma_1} \\ &= -\phi(\chi_2)\left(\Omega(q, x_0)^{-1}u + \Upsilon(q, \dot{q}, x_0, \dot{x}_0) + \hat{\Theta}\right) + (\delta + \nu)sign(\dot{\tilde{\chi}}_2) + l\dot{\tilde{\chi}}_2^{\gamma_1} \\ &+ \phi(\chi_2)\left(\Omega(q, x_0)^{-1}u + \Upsilon(q, \dot{q}, x_0, \dot{x}_0) + \Theta\right) \\ &= \phi(\chi_2)\tilde{\Theta} + (\delta + \nu)sign(\dot{\tilde{\chi}}_2) + l\dot{\tilde{\chi}}_2^{\gamma_1}\end{aligned} \tag{22}$$

From (20) and (22), the disturbance observation error can be computed as

$$\begin{aligned}\dot{\tilde{\Theta}} &= -\phi(\chi_2)\tilde{\Theta} - (\delta + \nu)sign(\dot{\tilde{\chi}}_2) + \dot{\Theta} - l\dot{\tilde{\chi}}_2^{\gamma_1} \\ &= -\phi(\chi_2)\tilde{\Theta} - (\delta + \nu)sign(\tilde{\Theta}) + \dot{\Theta} - l\tilde{\Theta}^{\gamma_1}\end{aligned} \tag{23}$$

Consider a Lyapunov function candidate $V(\tilde{\Theta}) = \frac{1}{2}\tilde{\Theta}^2$. Combining the derivative of the Lyapunov function with the results in (23), we have

$$\begin{aligned}\dot{V} &= \tilde{\Theta}\dot{\tilde{\Theta}} \\ &= \tilde{\Theta}\left(-\phi(x_2)\tilde{\Theta} - (\delta + \nu)sign(\tilde{\Theta}) - \dot{\Theta} - l\tilde{\Theta}^{\gamma_1}\right) \\ &\leq -\phi(x_2)\tilde{\Theta}^2 - l\tilde{\Theta}^{\gamma_1 + 1} \\ &\leq -2\phi(x_2)V - 2^{\gamma_1 + 1}lV^{\frac{\gamma_1 + 1}{2}}\end{aligned} \tag{24}$$

Therefore, based on the result of Lemma 1, the finite time convergence of the disturbance estimation error is established. However, the estimation of (21) cannot be implemented since the term $\dot{\tilde{\chi}}_2$ is not available. Hence, in order to obtain a FTDO, a finite-time estimation of $\dot{\tilde{\chi}}_2$ is needed. To get the estimation, we employ a second-order non-recursive sliding mode differentiator [21]:

$$\begin{aligned}\dot{\zeta}_1 &= \zeta_2(t) - k_1|\zeta_1(t) - \tilde{\chi}_2|^{\beta_1} sign(\zeta_1(t) - \tilde{\chi}_2) \\ \dot{\zeta}_2 &= -k_2|\zeta_1(t) - \tilde{\chi}_2|^{\beta_2} sign(\zeta_1(t) - \tilde{\chi}_2)\end{aligned} \tag{25}$$

where $k_1, k_2 > 0$ and the exponents β_1 and β_2 are chosen such that: $\beta_i \in (0, 1), i = 1, 2$ and $\beta_1 = \beta$ and $\beta_2 = 2\beta - 1$, where β is a value within the interval $(1 - \epsilon, 1)$ and $\epsilon > 0$ is sufficiently small. The parameters $k_i, i = 1, 2$ are assigned such that the matrix:

$$A = \begin{bmatrix} -k_1 & 1 \\ -k_2 & 0 \end{bmatrix} \tag{26}$$

is Hurwitz.

When the differentiator (25) is converged, the following results are obtained:

$$\zeta_1 = \tilde{x}_2, \zeta_2 = \dot{\tilde{x}}_2 \tag{27}$$

Inserting the results in (27) into (21), the disturbance observer is finally designed as

$$\begin{aligned}\hat{\Theta} &= \hat{e} + \varphi(\chi_2) + (\delta + \nu)\int sign(\zeta_2) + l_3\int \zeta_2^{\gamma_1} \\ \dot{\hat{e}} &= -\phi(\chi_2)\left(\Omega(q, x_0)^{-1}u + \Upsilon(q, \dot{q}, x_0, \dot{x}_0) + \hat{\Theta}\right)\end{aligned} \tag{28}$$

Theorem 1. The disturbance observation error, i.e., $\tilde{\Theta} = \Theta - \hat{\Theta}$, under the proposed observer in (28) and the differentiator (25) converges to zero after a finite time.

Proof. Since the result in (27) is obtained after a finite time, the stability and convergence of the of the disturbance observer designed in (28) can be achieved as a similar way as in (24). This completes the proof.

5 | DESIGN OF FINITE-TIME INTEGRAL SLIDING MODE CONTROL

5.1 | Finite-time integral sliding mode control

Assumption 4. The disturbance estimation error $\tilde{\Theta}$ is bounded by

$$|\tilde{\Theta}| \leq \varsigma \tag{29}$$

where ς is a known constant.

In order to obtain the objective defined above, a finite-time integral sliding mode control (FTISMC) is designed in this section.

Denote $e = \chi_1 - x_{0d}$ as the trajectory tracking error. In order to get both the error, i.e., e, and the derivative of error, i.e., $\dot{e}$, converged to zero, the following filter is introduced:

$$s = \dot{e} + \lambda e \tag{30}$$

where λ is a design parameter.

Adding the derivative of (30) and the result in (17) yields

$$\begin{aligned} \dot{s} &= \ddot{e} + \lambda \dot{e} \\ &= \Omega(q, x_0)^{-1} u + \Upsilon(q, \dot{q}, x_0, \dot{x}_0) + \Theta - \ddot{x}_{0d} + \lambda \dot{e} \end{aligned} \tag{31}$$

The proposed sliding surface has a form below [31, 32]:

$$\begin{aligned} \sigma(t) &= s(t) - s(0) \\ &- \int_0^t \left(\Omega(q, x_0)^{-1} u_0 + \Upsilon(q, \dot{q}, x_0, \dot{x}_0) - \ddot{x}_{0d} + \lambda \dot{e} \right) dt \end{aligned} \tag{32}$$

where $s(0)$ is the initial value of the sliding surface s. Note that the designed sliding surface (32) can eliminate the reaching phase of the sliding mode. The nominal controller u_0 is used to stabilize the system in the presence of no uncertainty or disturbance ($\Theta = 0$), i.e., $\dot{s} = \Omega(q, x_0)^{-1} u + \Upsilon(q, \dot{q}, x_0, \dot{x}_0) - \ddot{x}_{0d} + \lambda \dot{e}$.

The derivative of (32) provides

$$\begin{aligned} \dot{\sigma} &= \left(\Omega(q, x_0)^{-1} u + \Upsilon(q, \dot{q}, x_0, \dot{x}_0) + \Theta - \ddot{x}_{0d} + \lambda \dot{e} \right) \\ &- \left(\Omega(q, x_0)^{-1} u_0 + \Upsilon(q, \dot{q}, x_0, \dot{x}_0) - \ddot{x}_{0d} + \lambda \dot{e} \right) \end{aligned} \tag{33}$$

Theorem 2. Consider the system (17) and the sliding surface defined in (32). If the control input of the system is designed as

$$u = u_0 + u_s + u_d \tag{34}$$

where u_0 is used to control the nominal system, u_s is the switching term and it is designed as

$$u_s = -\Omega(q, x_0)(\varsigma + \epsilon) sign(\sigma) - k\sigma - l\sigma^{[\gamma_1]} \tag{35}$$

where the constant ϵ is chosen as a small value and δ is defined as in Assumption 1, k and l are positive constants, $0 < \alpha_1 < 1$, and $\sigma^{[\gamma_1]} = |\sigma|^{\gamma_1} sign(\sigma)$, and, the disturbance compensational term:

$$u_d = -\Omega(q, x_0)\hat{\Theta} \tag{36}$$

then, the sliding surface σ converges to zero in a finite time.

Proof. Inserting the result in (34) into (33):

$$\dot{\sigma} = \Omega(q, x_0)^{-1} u_s - \tilde{\Theta} \tag{37}$$

Inserting the composite controller (34) and (35) into (33), yields

$$\dot{\sigma} = -(\varsigma + \epsilon) sign(\sigma) - \tilde{\Theta} - k\sigma - l\sigma^{[\gamma_1]} \tag{38}$$

By defining a Lyapunov function candidate as $V = \frac{1}{2}\sigma^T \sigma$, the following result is obtained:

$$\begin{aligned} \dot{V} &= \sigma^T \dot{\sigma} \\ &= \sigma^T \left(-(\varsigma + \epsilon) sign(\sigma) - \tilde{\Theta} - k\sigma - l\sigma^{[\gamma_1]} \right) \\ &= -(\varsigma + \epsilon)|\sigma| - \tilde{\Theta}\sigma - k\sigma^T \sigma - l|\sigma|^{\gamma_1 + 1} \\ &\leq -2kV - 2^{\gamma_1 + 1} l V^{\frac{\gamma_1 + 1}{2}} \end{aligned} \tag{39}$$

Reflecting the result in (39) with the result in Lemma 1, it reaches a conclusion that the finite time convergence of the system is guaranteed. This completes the proof.

Remark 1. The sliding gain ς used in (35) was selected based on the Assumption 4. In the case that the bounded value ς is unknown, an adaptive technique can be employed to approximate the unknown bounded value online. There are some adaptive approaches existing in the literature that the interested readers can refer to, for example [32], [28], [19].

Remark 2. The switching term (35),which contains a '*sign*' function, provides chattering, which reduces the system performance significantly. To suppress this undesired symptom, a boundary method can be employed and that the switching term u_s can be re-designed as:

$$u_s = -\Omega(q, x_0)(\varsigma + \epsilon)\frac{\sigma}{|\sigma| + c} - k\sigma - l\sigma^{[\gamma_1]} \tag{40}$$

where the positive constant c is a design parameter.

5.2 | Design of nominal controller based on finite-time backstepping control

In order to obtain a global finite-time convergence for the system, the nominal controller u_0 needs to guarantee a finite time convergence. In this paper, a finite-time backstepping control is proposed to achieve this property.

From (17), the nominal system dynamics can be represented as

$$\begin{aligned}\dot{\chi}_1 &= \chi_2\\ \dot{\chi}_2 &= \Omega(q, x_0)^{-1}u_0 + \Upsilon(q, \dot{q}, x_0, \dot{x}_0)\end{aligned} \tag{41}$$

The finite-time backstepping control is designed step by step as follows:

Step 1: First, the tracking error is introduced as:

$$z_1 = \chi_1(t) - x_{0d}(t) \tag{42}$$

The following control system can be obtained from (42):

$$\dot{z}_1 = \alpha_1(t) - \dot{x}_{0d}(t) \tag{43}$$

In the above equation, $\dot{\chi}_1 = \alpha_1(t)$ is considered as a virtual control input. In order to stabilize the system (43), the virtual control input can be selected as:

$$\alpha_1(t) = -\kappa_1 z_1(t) + \dot{x}_{0d}(t) - l_1 z_1^{[\gamma_2]} \tag{44}$$

where κ_1 and l_1 are positive constants, $0 < \gamma_2 < 1$ and $z_1^{[\gamma_2]} = |z_1|^{\gamma_2} sign(z_1)$.

Step 2: The following error is introduced

$$z_2(t) = \chi_2(t) - \alpha_1(t) \tag{45}$$

Then, combining the derivative of (45) with the results in (44) and (10), yields

$$\begin{aligned}\dot{z}_2(t) &= \dot{\chi}_2(t) - \dot{\alpha}_1(t)\\ &= \Omega(q, x_0)^{-1}u_0 + \Upsilon(q, \dot{q}, x_0, \dot{x}_0) - \dot{\alpha}_1(t)\end{aligned} \tag{46}$$

Step 3: Consider a Lyapunov function candidate:

$$V(z_1, z_2) = \frac{1}{2}z_1^2 + \frac{1}{2}z_2^2 \tag{47}$$

Differentiating (47) with respect to time and integrating the results with the ones obtained in (46) and (43), yields

$$\begin{aligned}\dot{V}(z_1, z_2) &= z_1\dot{z}_1 + z_2\dot{z}_2\\ &= z_1\left(z_2(t) + \alpha_1(t) - \dot{x}_d(t)\right) + z_2(\Omega(q, x_0)^{-1}u_0 + \Upsilon(q, \dot{q}, x_0, \dot{x}_0)) - \dot{\alpha}_1(t)\end{aligned} \tag{48}$$

The nominal control input is selected as

$$u_0 = \Upsilon(q, \dot{q}, x_0, \dot{x}_0) + \Omega(q, x_0)(\dot{\alpha}_1 - z_1 - \kappa_2 z_2 - l_2 z_2^{[\gamma_2]}) \tag{49}$$

where the constants $\kappa_2 > 0$, $l_2 > 0$ and $z_2^{[\gamma_2]} = |z_2|^{\gamma_2} sign(z_2)$.

Theorem 3. Consider the nominal system (41). If the control input designed in (49) is used for the system (41), then, the tracking errors, i.e., z_1, z_2, converge to zero in a finite time.

Proof. Adding the control input (49) into (48), we obtain

$$\begin{aligned}\dot{V}(z_1,z_2) &\leq z_1\dot{z}_1 + z_2\dot{z}_2\\ &\leq z_1(-\kappa_1 z_1 - l_1 z_1^{[\gamma_2]}) + z_2(-\kappa_2 z_2 - l_2 z_2^{[\gamma_2]})\\ &\leq -\kappa_1 z_1^2 - \kappa_2 z_2^2 - l_1|z_1|^{\gamma_2+1} - l_2|z_2|^{\gamma_2+1}\\ &\leq -\sum_{i=1}^{2}\kappa_i z_i^2 - \sum_{i=1}^{2} l_i|z_i|^{\gamma_2+1}\\ &\leq -aV - bV^{\frac{\gamma_2+1}{2}}\end{aligned} \tag{50}$$

Refering the result in (50) with the result stated in Lemma 1, it can be concluded that the sliding errors, i.e., z_1 and z_2, converge to zero in a finite time. This completes the proof.

Remark 3. The controller (49) contains the derivative of the virtual control input α_1. From (44), when computing the derivative of the virtual control input α_1, it will appear the term $|z_1|^{\gamma_2-1}\dot{z}_1$, so it is singular when $z_1 = 0$ and $\dot{z}_1 \neq 0$. To avoid the singularity, a first-order differentiating technique below can be applied to compute the virtual input α_1 and the derivative of α_1:

$$\begin{aligned}\dot{\beta} &= z\\ z &= -l_1|\beta - \alpha|^{\frac{1}{2}} sign(\beta - \alpha_1) + \mu\\ \dot{\mu} &= -l_2 sign(\mu - z)\end{aligned} \tag{51}$$

where l_1 and l_2 are constants. β and $\dot{\beta}$ are the estimate of α_1 and its derivative. Further detail about the method to eliminate the singularity can be referred to [43].

Remark 4. In the literature, there are some more issues needed to be considered further when designing controller for co-operative control of multiple manipulators. For example, the input and output constraints of the system should be considered as in the approaches [16], [14]. The interaction between the handled object and the unknown environment should be investigated as in [14], etc. However, solving these properties are not focused in this paper. The major contribution of this paper is to propose a finite-time controller for the co-operative control of multiple manipulators system with enhanced capability on disturbance rejection. The interested readers are recommended for the mentioned papers, i.e., [16],[14], for solving the discussed issues.

Remark 5. In the literature, many finite time/fixed time control methods have been proposed for nonlinear systems, for example [7, 20]. However, compared to the existing approaches, the proposed approach has three major advantages: (1) the proposed approach is designed based on an integral sliding mode control so it eliminates the reaching phase and provides higher robustness agaisnt uncertainties and disturbance, (2) the proposed approach provides a global finite time convergence, (3) the design procedure is simple and straightforward. However, it has a disadvantage is that the controller requires an knowledge of dynamic model.

6 | RESULTS AND DISCUSSIONS

In this section, the performance of the proposed approach is illustrated. The two homogeneous manipulators handling and steering an object is used in this simulation study, as shown in Fig. 2. The parameters of the dual manipulators are selected as the same values, as depicted in Table 1, and each manipulator has a force sensor to measure external forces.

The dual manipulators are supposed to handle and steer a cube object with the the parameters shown in Table 1. The center of the object are subjected to track the following trajectory:

$$\begin{bmatrix} x_{0d}\\ y_{0d}\\ \theta_{0d}\end{bmatrix} = \begin{bmatrix} 0.2\cos(0.1t)\\ 0.2\sin(0.1t)\\ 0\end{bmatrix} \tag{52}$$

where x_{0d} and y_{0d} and θ_{0d} are the desired trajectory of the object. The following parameters are selected to model dynamics of the object:

TABLE 1 Parameters of the Manipulator

Parameters	Descriptions	Value
m_{i1}	Mass of link 1	$2.00kg$
m_{i2}	Mass of link 2	$1.00kg$
l_{i1}	Length of link 1	$0.3m$
l_{i2}	Length of link 2	$0.3m$
I_{i1}	Inetia of link 1	$0.047kg\dot{m}^2$
I_{i2}	Inertia of link 2	$0.0021kg\dot{m}^2$
l_0	Length of cube object	0.1
m_0	Mass of cube object	$0.2kg$
I_0	Mass of cube object	$0.2kg\dot{m}^2$

$$M_0 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix}, C_0 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix}, G_0 = \begin{bmatrix} 0 \\ -9.8 \\ 0 \end{bmatrix}.$$

Denotes q_{11} and q_{12} as the first, the second joint angles, and x_1 and y_1 are the position in the Cartesian space, respectively, of the first manipulator. Correspondingly, the definitions for the second manipulators are q_{21}, q_{22}, x_2 and y_2, respectively. The kinematic model is described by

$$\begin{bmatrix} x_1 \\ y_1 \end{bmatrix} = \begin{bmatrix} l_1\cos(q_{11}) + l_2\cos(q_{11}+q_{12}) \\ l_1\sin(q_{11}) + l_2\sin(q_{11}+q_{12}) \end{bmatrix} + \begin{bmatrix} b_1 \\ 0 \end{bmatrix},$$

$$\begin{bmatrix} x_2 \\ y_2 \end{bmatrix} = \begin{bmatrix} l_1\cos(q_{21}) + l_2\cos(q_{21}+q_{22}) \\ l_1\sin(q_{21}) + l_2\sin(q_{21}+q_{22}) \end{bmatrix} + \begin{bmatrix} b_2 \\ 0 \end{bmatrix},$$ where $[b_1, 0]^T$ and $[b_2, 0]^T$ are the position of the bases of two manipulators. Therefore, the Jacobian matrices are computed as

$$J_{e,1}(q) = \begin{bmatrix} J_{e,1_1}(q) & J_{e,1_2}(q) \end{bmatrix}, \text{ where, } J_{e,1_1}(q) = \begin{bmatrix} -l_1\sin(q_{11}) - l_2\sin(q_{11}+q_{12}) \\ l_1\cos(q_{11}) - l_2\cos(q_{11}+q_{12}) \end{bmatrix}, J_{e,1_2}(q) = \begin{bmatrix} -l_2\sin(q_{11}+q_{12}) \\ l_2\cos(q_{11}+q_{12}) \end{bmatrix}, \text{ and}$$

$$J_{e,2}(q) = \begin{bmatrix} J_{e,2_1}(q) & J_{e,2_2}(q) \end{bmatrix}, \text{ where, } J_{e,2_1}(q) = \begin{bmatrix} -l_1\sin(q_{21}) - l_2\sin(q_{21}+q_{22}) \\ l_1\cos(q_{21}) - l_2\cos(q_{21}+q_{22}) \end{bmatrix}, J_{e,2_2}(q) = \begin{bmatrix} -l_2\sin(q_{21}+q_{22}) \\ l_2\cos(q_{21}+q_{22}) \end{bmatrix}.$$

The Jacobian matrix between the end-effectors and the object is $J_0(x_0) = diag(J_1(x_0), J_2(x_0))$, where:

$$J_1(x_0) = \begin{bmatrix} 1 & 0 & \frac{l_0}{2}\sin(\theta) \\ 0 & 1 & -\frac{l_0}{2}\cos(\theta) \end{bmatrix},$$

$$J_2(x_0) = \begin{bmatrix} 1 & 0 & -\frac{l_0}{2}\sin(\theta) \\ 0 & 1 & \frac{l_0}{2}\cos(\theta) \end{bmatrix}.$$

The ith ($i = 1$ and 2) manipulator is simulated using the following dynamical parameters:

$$M_{r,i} = \begin{bmatrix} p_{i1} + 2p_{i2}\cos(q_{i2}) & p_{i3} + p_{i2}\cos(q_{i2}) \\ p_{i3} + p_{i2}\cos(q_{i2}) & p_{i3} \end{bmatrix},$$

$$C_{r,i} = \begin{bmatrix} -p_{i2}\sin(q_{i2})\dot{q}_{i2} & -p_{i2}\sin(q_{i2})\dot{q}_{i2} \\ p_{i2}\sin(q_{i2})(\dot{q}_{i1} + \dot{q}_{i2}) & 0 \end{bmatrix},$$

$$G_{r,i} = \begin{bmatrix} (m_{i1}l_{c2} + m_{i2}l_{i1})g\cos(q_{i1}) + m_{i2}l_{c2}g\cos(q_{i1}+q_{i2}) \\ m_{i2}l_{c2}g\cos(q_{i1}+q_{i2}) \end{bmatrix}^T,$$ where $p_{i1} = m_{i1}l_{c1}^2 + m_{i2}(l_{i1}^2 + l_c2^2) + I_{i1} + I_{i2}$; $p_{i2} = m_{i2}l_{i1}l_{c2}$; $p_{i3} = m_{i2}l_{c2}^2 + I_{i2}$.

The environmental force is modeled as $F_d = [0.2\sin(t), 0.2\cos(t), 0]^T$.

First, we verify the effectiveness of the proposed FTDO. The parameters of the disturbance observer are slected as $\phi(\chi_2) = diag(5,5,5)$, $\delta + \nu = 15$, $l = 10$, $\gamma_1 = 0.75$ for the FTSMC, the parameters of the second-order non-recursive sliding mode differentiator in (25) are selected as $\beta = 0.8, k_1 = 20, k_2 = 210$. The estimation performance of the proposed disturbance observer is illustrated in Fig. 3. From Fig. 3, it can be seen that the disturbance observer provides very high accurate disturbance estimation.

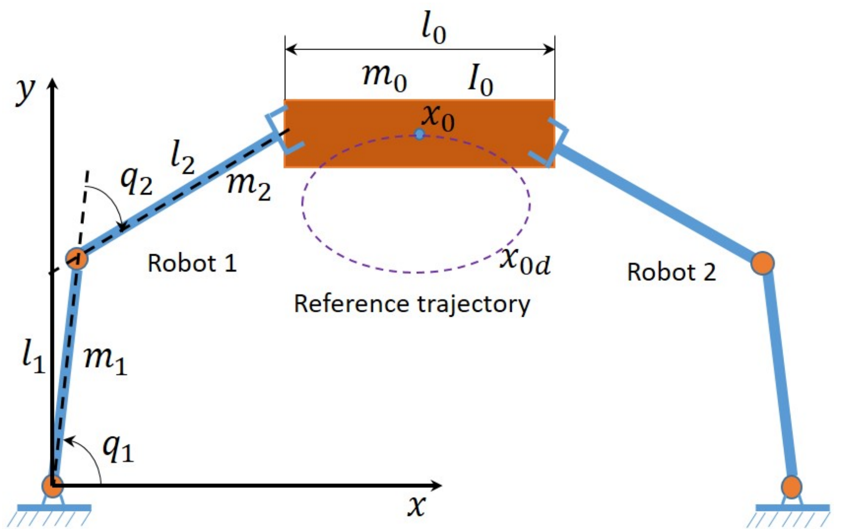

FIGURE 2 Multiple manipulators steer the object follows a desired trajectory

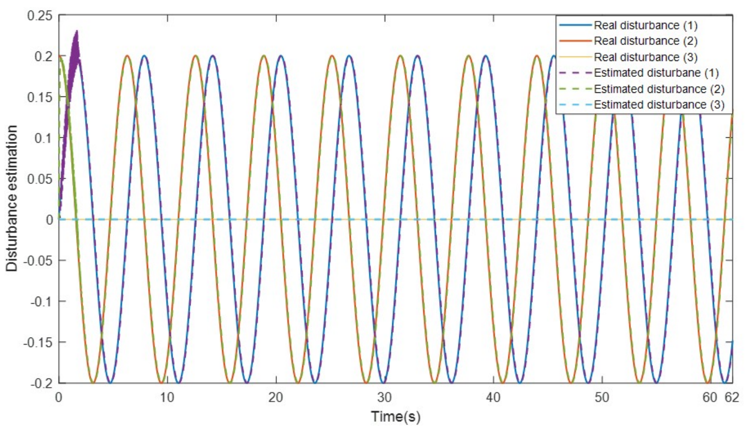

FIGURE 3 Time history of disturbance estimation

In the next, the tracking performance of the proposed method is verified. In order to demonstrate the superior performance of the proposed approach, it is compared with other state-of-the-art control technique, which is being used for co-operative control of multiple manipulators, including PD+gravity compensation (PD+G) and computed torque control (CTC). The design of the PD+G and the CTC can be designed as in Appendix A andB , respectively. The parameters of the PD+G controller are selected as $K_p = 10$ and $K_d = 20$, and the parameters of the CTC are selected as $K_p = 10$ and $K_d = 20$. The parameters of the proposed FTISMC are selected as: for the switching term: $\varsigma + \epsilon = 0.5$, $c = 2.5$, $k = 10$, $\gamma_1 = 0.75$, $l = 12$, and for the finite-time backstepping controller: $\kappa_1 = \kappa_2 = 0.2$, $l_1 = l_2 = 100$ and $\gamma_2 = 0.75$. These parameters are selected based on a trial and error procedure based on a computer simulation.

The tracking performance of the three controllers, i.e., PD+G, CTC and FTISMC, are shown in Fig. 4. The detail tracking errors of the PD+G, CTC and the FTISMC are also shown in Figs. 5, 6 and 7, respectively. From Figs. 4, 5, 6 and 7, it can be seen that the PD+G controller provides poor tracking performance for the system in the presence of the disturbance F_d; the tracking error is big, as shown in Figs. 4 and 5. The CTC provides a slightly better performance than the PD+G, as shown in Figs. 4 and 6. In contrast, the proposed FTISMC tackles the effects of the disturbance F_d very well; the tracking errors converge to zero very quickly, as shown in Fig 7. The time history of the sliding surface σ of the FTISMC is shown in Fig. 8. From Fig. 8, it can be seen that the reaching phase is almost eliminated. It means the sliding surface σ converges to zero from beginning.

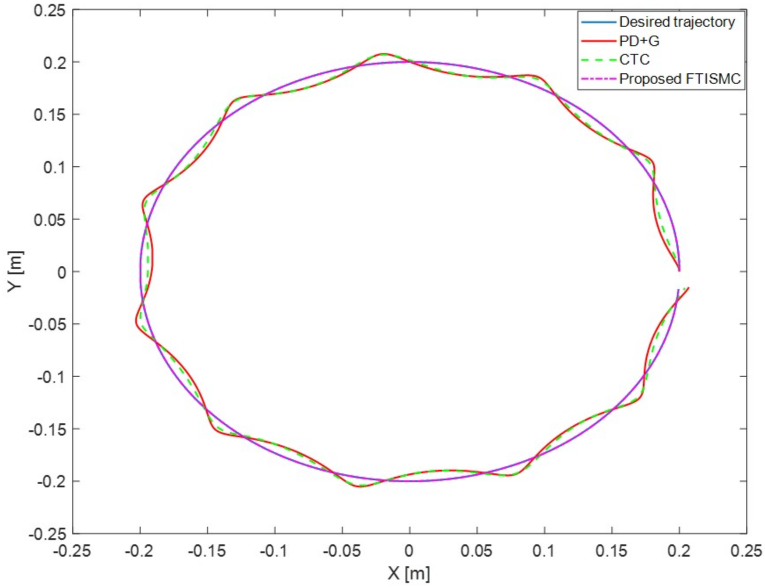

FIGURE 4 Comparison in tracking performance between three controllers, i.e., PD+G, CTC and FTISMC

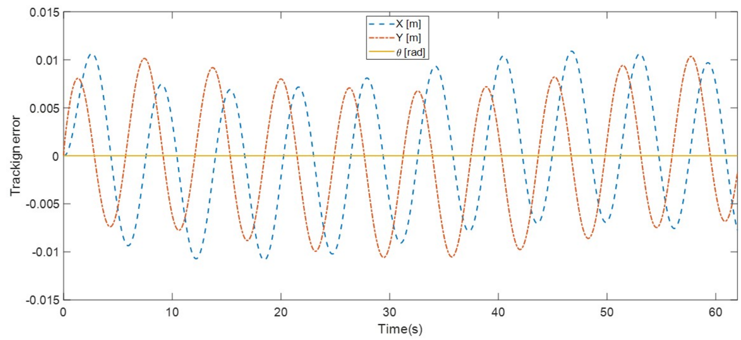

FIGURE 5 Tracking errors of the system under the PD+G controller

The individual control efforts of the three controllers, i.e., PD+G, CTC and FTISMC, are shown in Figs. 9, 10 and 11, respectively. Note that τ_1 and τ_2 are the forces acting on the object to track the desired trajectory x_0 and y_0, while τ_3 is the torque acting on the object to track the desired θ_0. From these figures, it can be observed that the controllers provide smooth control efforts.

7 | CONCLUSIONS AND FUTURE WORKS

In this paper, a new global finite-time convergent control method has been introduced for co-operative control of multiple manipulators based on an integration between a finite-time disturbance observer and a finite-time integral sliding mode control technique. Different from the conventional integral sliding mode control, both the nominal controller and the switching term of the proposed finite-time integral sliding mode control technique provide finite time stability and convergence. This design strategy is significant for practical applications since it suppresses the effects of the uncertainties and disturbances very well thanks to the property of the integral sliding mode control, and provides finite time convergence for the system and improves the

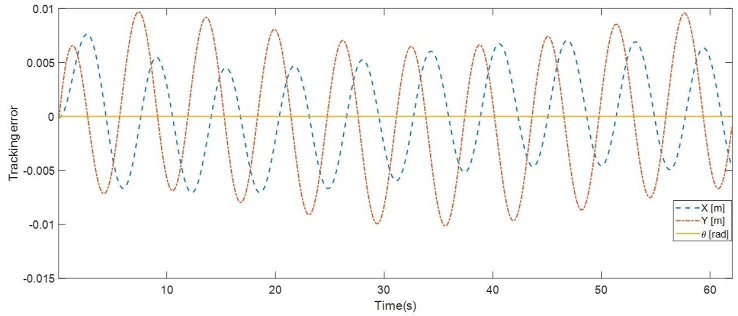

FIGURE 6 Tracking errors of the system under the CTC controller

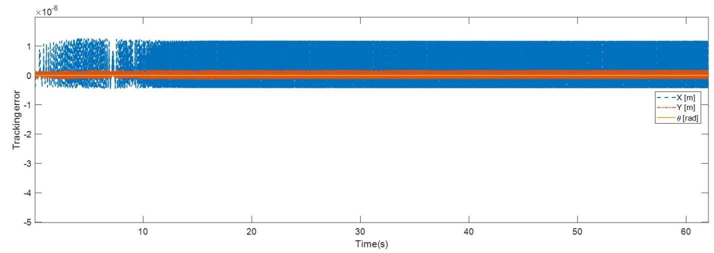

FIGURE 7 Tracking errors of the system under the FTISMC controller

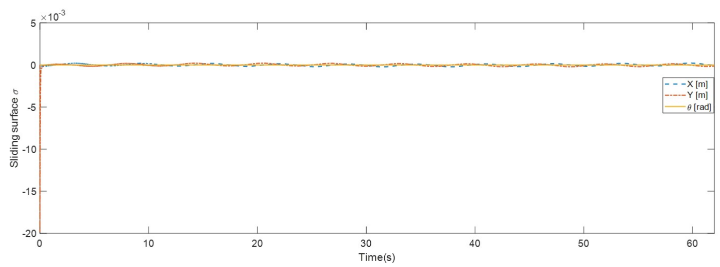

FIGURE 8 Time history of the sliding surface σ of the FTISMC controller

tracking performance of the system thanks to the characteristics of the finite-time controller. The simulation results conducted on co-operative control of dual two-link manipulators demonstrates the effectiveness of the suggested method.

In future works, the constraints on inputs and outputs of the system will be studied and solved. The problem of co-operative control of multiple manipulators and deformed object will be investigated as well.

ACKNOWLEDGMENTS

This work was supported by the Natural Environment Research Council [grant number NE/V008080/1] and the UK Engineering and Physical Sciences Research Council (EPSRC) grant EP/V062158/1: “Made Smarter Innovation - Research Centre for Smart, Collaborative Industrial Robotics".

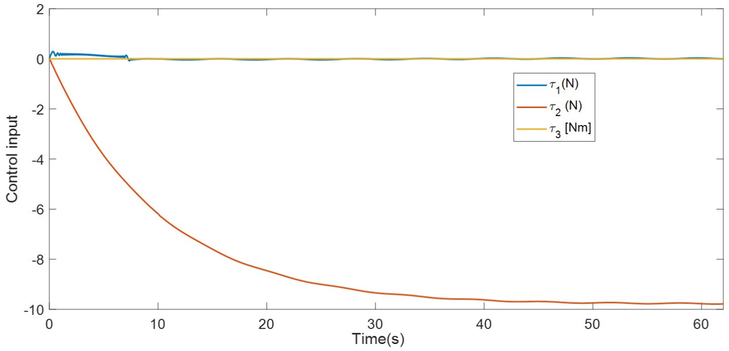

FIGURE 9 Control inputs of the PD+G controller

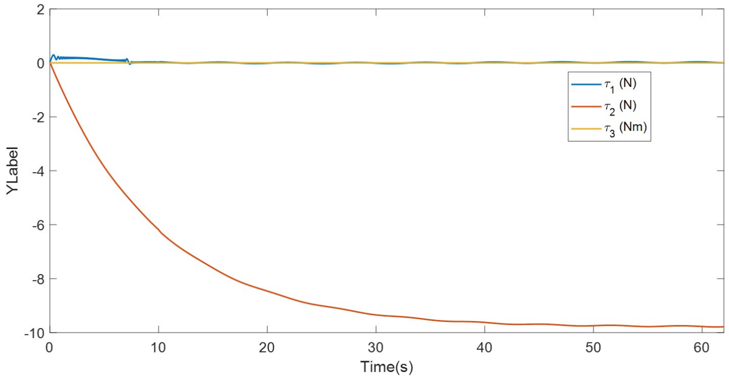

FIGURE 10 Control inputs of the CTC controller

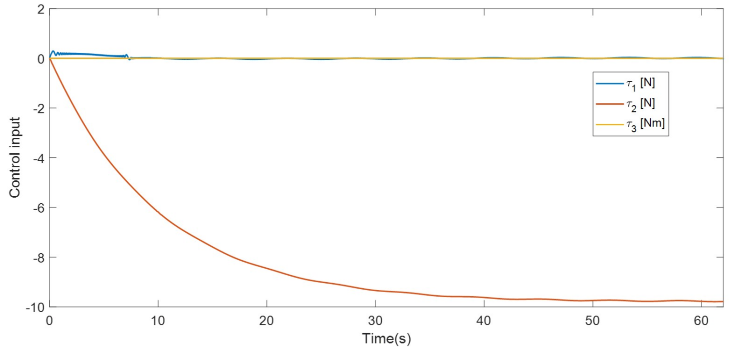

FIGURE 11 Control inputs of the proposed FTISMC controller

Author contributions

Conceptualization: Mien Van,methodology: Mien Van and Shuzhi Sam Ge; software: Mien Van; validation: Mien Van; formal analysis: Mien Van, Shuzhi Sam Ge and Dariusz Ceglarek;Others: Mien Van, Dariusz Ceglarek. All authors have read and agreed to the submited version of the manuscript.

Financial disclosure

None reported.

Conflict of interest

The authors declare no potential conflict of interests.

□

APPENDIX

A THE PD PLUS GRAVITY COMPENSATION

The PD plus gravity compensation (PD+G) can be designed for the coupled system (33) as [25]

$$\tau = K_p e_q + K_d \dot{e}_q + \Gamma(q, x_0, \dot{x}_0) \tag{A1}$$

where,

$$e_q = x_{0d} - x_0 \tag{A2}$$

where K_p and K_d are the proportional and derivative gains.

B COMPUTED TORQUE CONTROLLER

The computed torque controller (CTC) can be designed for the coupled system (33) as

$$\begin{aligned}\tau =& \Omega(q, x_0) \left(\ddot{x}_{0d} + K_p e_q + K_d \dot{e}_q \right) \\ &+ \Psi(q, \dot{q}, x_0, \dot{x}_0) + \Gamma(q, x_0, \dot{x}_0)\end{aligned} \tag{B3}$$

where,

$$e_q = x_{0d} - x_0 \tag{B4}$$

where K_p and K_d are the proportional and derivative gains.

References

[1] Z. Cao, Y. Niu, and J. Song, *Finite-time sliding-mode control of markovian jump cyber-physical systems against randomly occurring injection attacks*, IEEE Transactions on Automatic Control **65** (2020), no. 3, 1264–1271.

[2] C.-S. Chiu, K.-Y. Lian, and T.-C. Wu, *Robust adaptive motion/force tracking control design for uncertain constrained robot manipulators*, Automatica **40** (2004), no. 12, 2111 – 2119.

[3] Chun-Yi Su and Y. Stepanenko, *Adaptive sliding mode coordinated control of multiple robot arms attached to a constrained object*, IEEE Transactions on Systems, Man, and Cybernetics **25** (1995), no. 5, 871–878.

[4] W. E. Dixon, *Adaptive regulation of amplitude limited robot manipulators with uncertain kinematics and dynamics*, IEEE Transactions on Automatic Control **52** (2007), no. 3, 488–493.

[5] Dong Sun and J. K. Mills, *Adaptive synchronized control for coordination of multirobot assembly tasks*, IEEE Transactions on Robotics and Automation **18** (2002), no. 4, 498–510.

[6] H. Du et al., *Integral sliding mode tracking control for heavy vehicle electro-hydraulic power steering system*, IEEE/ASME Transactions on Mechatronics (2020), 1–1.

[7] P. Du et al., *Nonsingular finite-time event-triggered fuzzy control for large-scale nonlinear systems*, IEEE Transactions on Fuzzy Systems (2020), 1–1.

[8] S. S. Ge, T. H. Lee, and C. J. Harris, *Adaptive neural network control of robotic manipulators*, World Scientific, London, 1998.

[9] W. Gueaieb, S. Al-Sharhan, and M. Bolic, *Robust computationally efficient control of cooperative closed-chain manipulators with uncertain dynamics*, Automatica **43** (2007), no. 5, 842 – 851.

[10] W. Gueaieb, F. Karray, and S. Al-Sharhan, *A robust hybrid intelligent position/force control scheme for cooperative manipulators*, IEEE/ASME Transactions on Mechatronics **12** (2007), no. 2, 109–125.

[11] Y. Guo et al., *Robust saturated finite-time attitude control for spacecraft using integral sliding mode*, Journal of Guidance, Control, and Dynamics **42** (2019), no. 2, 440–446.

[12] M. T. Hamayun, C. Edwards, and H. Alwi, *Design and analysis of an integral sliding mode fault-tolerant control scheme*, IEEE Transactions on Automatic Control **57** (2012), no. 7, 1783–1789.

[13] W. He et al., *Disturbance observer-based neural network control of cooperative multiple manipulators with input saturation*, IEEE Transactions on Neural Networks and Learning Systems (2019), 1–12.

[14] L. Kong et al., *Adaptive fuzzy control for coordinated multiple robots with constraint using impedance learning*, IEEE Transactions on Cybernetics **49** (2019), no. 8, 3052–3063.

[15] B. Li et al., *Finite-time disturbance observer based integral sliding mode control for attitude stabilisation under actuator failure*, IET Control Theory & Applications **13** (2019), no. 1, 50–58.

[16] Y. Li et al., *Admittance-based adaptive cooperative control for multiple manipulators with output constraints*, IEEE Transactions on Neural Networks and Learning Systems (2019), 1–12.

[17] Z. Li and C. Su, *Neural-adaptive control of single-master-multiple-slaves teleoperation for coordinated multiple mobile manipulators with time-varying communication delays and input uncertainties*, IEEE Transactions on Neural Networks and Learning Systems **24** (2013), no. 9, 1400–1413.

[18] H. Liang et al., *Event-triggered fuzzy bipartite tracking control for network systems based on distributed reduced-order observers(revised manuscript of tfs-2019-1049)*, IEEE Transactions on Fuzzy Systems (2020), 1–1.

[19] Y. Liu et al., *A novel finite-time adaptive fuzzy tracking control scheme for nonstrict feedback systems*, IEEE Transactions on Fuzzy Systems **27** (2019), no. 4, 646–658.

[20] Y. Pan et al., *Singularity-free fixed-time fuzzy control for robotic systems with user-defined performance*, IEEE Transactions on Fuzzy Systems (2020), 1–1.

[21] W. Perruquetti, T. Floquet, and E. Moulay, *Finite-time observers: Application to secure communication*, IEEE Transactions on Automatic Control **53** (2008), no. 1, 356–360.

[22] J. Qin et al., *Fault-tolerant cooperative tracking control via integral sliding mode control technique*, IEEE/ASME Transactions on Mechatronics **23** (2018), no. 1, 342–351.

[23] H. Rabiee, M. Ataei, and M. Ekramian, *Continuous nonsingular terminal sliding mode control based on adaptive sliding mode disturbance observer for uncertain nonlinear systems*, Automatica **109** (2019), 108515.

[24] S. M. M. Rahman and R. Ikeura, *Weight-prediction-based predictive optimal position and force controls of a power assist robotic system for object manipulation*, IEEE Transactions on Industrial Electronics **63** (2016), no. 9, 5964–5975.

[25] Y. Ren et al., *Biomimetic object impedance control for dual-arm cooperative 7-dof manipulators*, Robotics and Autonomous Systems **75** (2016), 273 – 287.

[26] X. Tang, D. Zhai, and X. Li, *Adaptive fault-tolerance control based finite-time backstepping for hypersonic flight vehicle with full state constrains*, Information Sciences **507** (2020), 53–66.

[27] T. Tarn, A. Bejczy, and X. Yun, *Design of dynamic control of two cooperating robot arms: Closed chain formulation*, *Proceedings. 1987 IEEE International Conference on Robotics and Automation*, vol. 4, 7–13.

[28] B. Tian et al., *Adaptive finite-time attitude tracking of quadrotors with experiments and comparisons*, IEEE Transactions on Industrial Electronics **66** (2019), no. 12, 9428–9438.

[29] V. Utkin, *Sliding Modes on Control and Optimization*, Berlin, Germany: Springer-Verlag, 1992.

[30] M. Van, *An enhanced robust fault tolerant control based on an adaptive fuzzy pid-nonsingular fast terminal sliding mode control for uncertain nonlinear systems*, IEEE/ASME Transactions on Mechatronics **23** (2018), no. 3, 1362–1371.

[31] M. Van, *Adaptive neural integral sliding-mode control for tracking control of fully actuated uncertain surface vessels*, International Journal of Robust and Nonlinear Control **29** (2019), no. 5, 1537–1557.

[32] M. Van, *An enhanced tracking control of marine surface vessels based on adaptive integral sliding mode control and disturbance observer*, ISA Transactions **90** (2019), 30 – 40.

[33] M. Van and S. S. Ge, *Adaptive fuzzy integral sliding mode control for robust fault tolerant control of robot manipulators with disturbance observer*, IEEE Transactions on Fuzzy Systems (2020), 1–1.

[34] M. Van, S. S. Ge, and H. Ren, *Finite time fault tolerant control for robot manipulators using time delay estimation and continuous nonsingular fast terminal sliding mode control*, IEEE Transactions on Cybernetics **47** (2017), no. 7, 1681–1693.

[35] M. Van, M. Mavrovouniotis, and S. S. Ge, *An adaptive backstepping nonsingular fast terminal sliding mode control for robust fault tolerant control of robot manipulators*, IEEE Transactions on Systems, Man, and Cybernetics: Systems **49** (2019), no. 7, 1448–1458.

[36] M. Van et al., *Fault diagnosis in image-based visual servoing with eye-in-hand configurations using kalman filter*, IEEE Transactions on Industrial Informatics **12** (2016), no. 6, 1998–2007.

[37] J. Wang et al., *Integral sliding mode control using a disturbance observer for vehicle platoons*, IEEE Transactions on Industrial Electronics (2019), 1–1.

[38] Wen-Hua Chen, *Disturbance observer based control for nonlinear systems*, IEEE/ASME Transactions on Mechatronics **9** (2004), no. 4, 706–710.

[39] B. Xiao and S. Yin, *Exponential tracking control of robotic manipulators with uncertain dynamics and kinematics*, IEEE Transactions on Industrial Informatics **15** (2019), no. 2, 689–698.

[40] C. Yang et al., *Finite-time convergence adaptive fuzzy control for dual-arm robot with unknown kinematics and dynamics*, IEEE Transactions on Fuzzy Systems **27** (2019), no. 3, 574–588.

[41] Z. Yang, Y. Fukushima, and P. Qin, *Decentralized adaptive robust control of robot manipulators using disturbance observers*, IEEE Transactions on Control Systems Technology **20** (2012), no. 5, 1357–1365.

[42] J. Yu, P. Shi, and L. Zhao, *Finite-time command filtered backstepping control for a class of nonlinear systems*, Automatica **92** (2018), 173 – 180.

[43] J. Yu, P. Shi, and L. Zhao, *Finite-time command filtered backstepping control for a class of nonlinear systems*, Automatica **92** (2018), 173–180.

[44] S. Yu et al., *Continuous finite-time control for robotic manipulators with terminal sliding mode*, Automatica **41** (2005), no. 11, 1957 – 1964.

[45] X. Yun, *Nonlinear feedback control of two manipulators in presence of environmental constraints*, *Proceedings, 1989 International Conference on Robotics and Automation*, 1252–1257 vol.2.

[46] Yun-Hui Liu, Yangsheng Xu, and M. Bergerman, *Cooperation control of multiple manipulators with passive joints*, IEEE Transactions on Robotics and Automation **15** (1999), no. 2, 258–267.

[47] Z.-L. Zhao and Z.-P. Jiang, *Finite-time output feedback stabilization of lower-triangular nonlinear systems*, Automatica **96** (2018), 259 – 269.

AUTHOR BIOGRAPHY

bioM.jpg

Mien Van. Dr Mien Van is a Lecturer(Assistant Professor) in Robotics and Control Engineering at Queen's University Belfast. Prior to joining Queen's, he was a Senior Research Fellow in the College of Engineering, Mathematics and Physical Sciences at the University of Exeter from 2018 to 2019 and held a number of academic positions with the National University of Singapore and University of Warwick, UK from 2015 to 2018. He received his Ph.D. degree in Robotics and Control Engineering from the School of Electrical Engineering, University of Ulsan, South Korea, in 2015. He has authored and co-authored over 55 journals and conference papers. He is listed among top 2% of the world's leading scientists for the single year 2019. Dr Van is an Associate Editor of the International Journal of Control, Automation and Systems, and Topic Editor of the journal Sensors.

bioG.jpg

Shuzhi Sam Ge. Prof. Shuzhi Sam Ge is with the Department of Electrical and Computer Engineering, and the Director with the Social Robotics Laboratory of Smart Systems Institute, The National University of Singapore, Singapore. He is the Honorary Director of Institute for Future (IFF), Qingdao University, Qingdao as well. He received the Ph.D. degree from the Imperial College London, London, U.K., in 1993, and the B.Sc. degree from the Beijing University of Aeronautics and Astronautics, Beijing, China, in 1986. He has (co)-authored seven books, and over 300 international journal and conference papers. He is the Editorin-Chief, International Journal of Social Robotics, Springer. He has served/been serving as an Associate Editor for a number of flagship journals including IEEE Transactions on Automatic Control, IEEE Transactions on Control Systems Technology, IEEE Transactions on Neural Networks, IEEE Transaction on SMC-Systems, and Automatica. He also serves as a book Editor of the Taylor & Francis Automation and Control Engineering Series. At IEEE Control Systems Society, he served/serves as Vice President for Technical Activities, 2009-2010, Vice President of Membership Activities, 2011- 2012, Member of Board of Governors of IEEE Control Systems Society, 2007-2009. He is also a Fellow of IFAC, IET, and SAEng. His current research interests include robotics, adaptive control, intelligent systems and artificial intelligence.

bioD.jpg

Dariusz Ceglare Prof. Dariusz Ceglarek is EPSRC Star Recruit Research Chair at WMG, University of Warwick, UK, and a Fellow of the College International pour la Recherche en Productique (CIRP). Previously, he was Professor with tenure in the Department of Industrial & Systems Engineering at University of Wisconsin, Madison. He received his Ph.D. in Mechanical Engineering from University of Michigan-Ann Arbor in 1994. His research focusses on smart manufacturing, closed-loop quality control; data mining/AI for root cause analysis across design, manufacturing and service. He has mentored numerous post-doctoral fellows, and PhD and Masters students. Several of his former Post-doctorate fellows and graduated PhD students are professors or associate professors at universities in the US, UK, Australia, Korea, and India. His research has created impact on digital manufacturing technologies, predictive modelling in automotive assembly systems and quality control. He has been PI/co-PI on research grants of over $41 funded by: US (NSF, NIST); UK (EPSRC, InnovateUK, APC and HVM Catapult); and EU (FP7, Marie Curie) and industry. He has published over 200 papers, received several Best Paper Awards; and is listed by Stanford University among Top 2% of the world's leading scientists and among Top-1.1% within subfield 'Industrial Engineering and Automation'. He has received numerous awards including the 2018 Jaguar LandRover's (JLR) 'Innovista' Award for the WMG-JLR collaborative project 'Laser Welded Lightweight Aluminium Door for SUV' as the most innovative project in category of 'piloted technologies'; his EU Factory-of-the-Future RLW Navigator programme was selected as a success story by the EC in 2015. He received the 2007 UK EPSRC Star Award given to 'exceptional senior faculty, recognised international leader in his research field', the US NSF 2003 CAREER Award; 1999 Outstanding Research Scientist Award from University of Michigan; the 1998 Dell K. Allen Outstanding Young Manufacturing Engineer of the Year Award from the SME. He has served on numerous Editorial Boards and is an Associate Editor (Europe) of the ASTM Smart and Sustainable Manufacturing Systems Journal. Prof. Ceglarek served as Chair of the Quality, Statistics and Reliability Section of INFORMS; Program Chair for the ASME Design-for-Manufacturing Life Cycle Conferences, Assoc. Editor of the IEEE Transactions on Automation Science and Engineering, and of the ASME Trans, Journal of Manufacturing Science & Engineering.