Second order sliding mode control based on extended state observer for double pendulum overhead cranes

Nguyen Dinh Hiep, Vo Nhat Huy, Nguyen Danh Huy, Hoang Thi Mai*

Hanoi University of Science and Technology, 1 Dai Co Viet, Hai Ba Trung, Hanoi, Vietnam.
*Corresponding author: mai.ht232216m@sis.hust.edu.vn
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ABSTRACT

This study proposes a second order sliding mode controller (SO-SMC) based on an extended state observer for a 3D crane system with a double pendulum effect and constant rope length. A second order sliding mode controller requires an accurate model of the system's parameters. However, in practice, model parameters and external disturbances are difficult to determine in detail. Therefore, the extended state observer is designed to estimate the system state variables and the total disturbance. Finally, a sliding mode controller is developed with the signals taken from the observer. The controller ensures stability according to Lyapunov function. Simulation results show that the proposed method ensures that the trolleys reach the desired trajectory while minimizing vibration even in the presence of disturbances and uncertain components.

Keywords: Double-pendulum Overhead cranes; Second order Sliding Mode Controller; Extended State Observer.

1. INTRODUCTION

Cranes are commonly used for transporting goods in industrial factories. Despite their many advantages, controlling crane movement remains a challenge for researchers. The crane system is an underactuated system, the dynamic model exhibits significant nonlinearity and is highly susceptible to external disturbances. The control objective is to move the load quickly to the desired position while minimizing the swing angle.

In practice, to control tracking grip and anti-oscillation, the proportional derivative (PD) controller is widely used due to the advantage of these approaches is convenience. However, these methods do not ensure rise-time, overshoot, settling time, and steady-state error of the position and anti-swing regulations. Therefore, based on the particle swarm optimization (PSO) algorithm or simulated annealing (SA), several proportional integral derivative (PID) control methods have been proposed [1]. For open-loop control methods, the commonly used approach is input shaping. Using this method [2], the input shaper is designed based on a complete nonlinear model which can reduce load swings better. In recent years, the sliding mode control (SMC) method [3] has been widely used in practice due to its advantages such as simplicity and efficiency.

In the practical operation of overhead cranes, many physical quantities cannot be directly measured, such as the state parameters and external disturbances. Therefore, other control methods are combined, such as fuzzy control method [4], neuron network [5]. Besides, the control algorithms based on the disturbance approximation observers have been studied and verified on cranes. For instance, high gain observer was proposed in [6] can well suppress the disturbance, with good control effect.

This study proposes a second order sliding mode controller based on extended state observer (ESO) to control the trolley to follow the desired trajectory and suppress payload oscillation, while also estimating certain system state variables and disturbance. The contribution of the study can be summarized as follows: (1) The ESO is designed to estimate certain system state variables and external disturbances. (2) The second order sliding mode controller is designed to ensure that the trolley follows the desired trajectory, and the payload is lifted with minimal oscillation.

2. PROBLEM

2.1. Dynamic model

The 3D crane system includes a double pendulum and a moving trolley as described in figure 1: x, y denotes the position of the trolley; θ_1, θ_2, θ_3, θ_4 represent the swing angles of the hook and the payload along the x and y axes, respectively; M_1 is the mass of the trolley, and M_2 is the sum of the mass of the trolley and the bridge; m_1 and m_2 are the masses of the hook and payload; l_1 is the length of the cable and l_2 is the distance from the hook to the payload. The driving forces along the x axis and the y axis are F_x, F_y; $\boldsymbol{\tau} = [F_x, F_y, 0, 0, 0, 0]^T$ is the force vector, with a state vector $\mathbf{q} = [x, y, \theta_1, \theta_2, \theta_3, \theta_4]^T$. F_{rx} and F_{ry} represent the axial friction force along x, y axis. The dynamic equation of the system is represented in matrix form similar to [7] as follows:

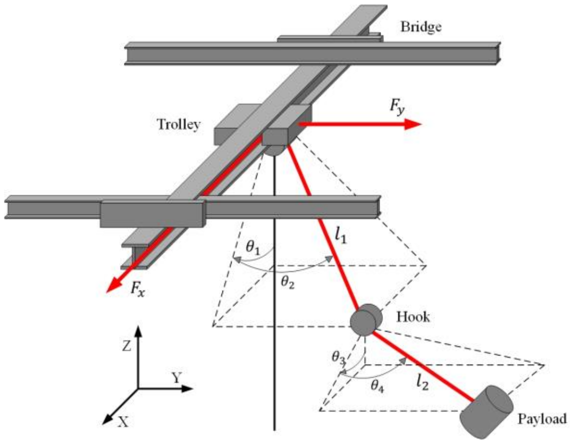

Figure 1. *System dynamic model.*

$$\mathbf{M(q)\ddot{q} + B(q,\dot{q})\dot{q} + C(q,\dot{q})\dot{q} + G(q) + W = \boldsymbol{\tau}} \quad (1)$$

where $\mathbf{M(q)} \in \mathbb{R}^{6\times6}$ is the mass matrix, $\mathbf{B(q,\dot{q})} \in \mathbb{R}^{6\times6}$ denotes vector friction, $\mathbf{C(q,\dot{q})} \in \mathbb{R}^{6\times6}$ is the inertial matrix, $\mathbf{G(q)} \in \mathbb{R}^{6\times1}$ is the vector gravity and $\mathbf{W} \in \mathbb{R}^{6\times1}$ is the external disturbance.

2.2. Extended state observer

In practice, controlling the crane system requires attention to disturbances affecting the system and the measurement of state variables, such as the velocity of swing angles. Therefore, the extended state observer (ESO) is designed to address all existing problems.

The state variables of the observer are defined as: $\mathbf{x_1 = q}$; $\mathbf{x_2 = \dot{q}}$ (2)

From equation (1), the system dynamic equation can be rewritten in the state space:

$$\begin{cases} \mathbf{\dot{x}_1 = x_2} \\ \mathbf{\dot{x}_2 = M^{-1}(q)\boldsymbol{\tau} - M^{-1}(q)(B(q,\dot{q})\dot{q} + C(q,\dot{q})\dot{q} + G(q) + W)} \end{cases} \quad (3)$$

Set $\mathbf{f_x(q,\dot{q},}t\mathbf{) = -M^{-1}(q)(B(q,\dot{q})\dot{q} + C(q,\dot{q})\dot{q} + G(q))}$ denotes the system's nonlinear parts; $\boldsymbol{\omega}_\mathbf{x}\mathbf{(q,\dot{q},}t\mathbf{) = -M^{-1}(q)W}$ is the disturbance affecting the system and $\mathbf{h_x(q,\dot{q},}t\mathbf{) = f_x(q,\dot{q},}t\mathbf{) + \boldsymbol{\omega}_x(q,\dot{q},}t\mathbf{)}$ is a total disturbance.

Equation (3) of the system can be rewritten as:
$$\begin{cases} \mathbf{\dot{x}_1 = x_2} \\ \mathbf{\dot{x}_2 = x_3 + M^{-1}(q)\boldsymbol{\tau}} \\ \mathbf{\dot{x}_3} = \vartheta(t) \end{cases} \quad (4)$$

where $\mathbf{x_3 = h_x(q,\dot{q},}t\mathbf{)}$ is the subsidiary state variable, $\vartheta(t)$ is the derivative of $\mathbf{h_x(q,\dot{q},}t\mathbf{)}$. The state variables $\mathbf{x}_i$ $(i = 1-3)$ are estimated by $\hat{\mathbf{x}}_i$ and the estimation errors are $\mathbf{e_i = x_i - \hat{x}_i}$. In this study, the linear extended state observer (LESO) is designed based on the following linear function as follows:

$$\begin{cases} \dot{\hat{\mathbf{x}}}_1 = \hat{\mathbf{x}}_2 + \dfrac{\beta_1}{\sigma}(\mathbf{x}_1 - \hat{\mathbf{x}}_1) \\ \dot{\hat{\mathbf{x}}}_2 = \hat{\mathbf{x}}_3 + \dfrac{\beta_2}{\sigma^2}(\mathbf{x}_1 - \hat{\mathbf{x}}_1) + \mathbf{u}_\mathbf{x} \\ \dot{\hat{\mathbf{x}}}_3 = \dfrac{\beta_3}{\sigma^3}(\mathbf{x}_1 - \hat{\mathbf{x}}_1) \end{cases} \tag{5}$$

where σ is a small positive constant; $\mathbf{u}_\mathbf{x} = \mathbf{M}^{-1}(\mathbf{q})\boldsymbol{\tau}$ is the force, torque applied on the system.

Remark 1. Since $\mathbf{f}_\mathbf{x}, \dfrac{\partial \mathbf{f}_\mathbf{x}}{\partial t}, \dfrac{\partial \mathbf{f}_\mathbf{x}}{\partial \mathbf{x}_1}, \dfrac{\partial \mathbf{f}_\mathbf{x}}{\partial \mathbf{x}_2}$ are vectors and matrices containing parameters, position, velocity and acceleration of the crane system. These quantities and the actuator torque/force are limited. Therefore, there exist positive constants $k_m, l_m, p_m, b_1, b_2, b_3, u_m$ such that:

$$\|\mathbf{x}_1\| \le k_m, \|\mathbf{x}_2\| \le l_m, \|\dot{\mathbf{x}}_2\| \le p_m, \left\|\frac{\partial \mathbf{f}_\mathbf{x}}{\partial t}\right\| \le b_1, \left\|\frac{\partial \mathbf{f}_\mathbf{x}}{\partial \mathbf{x}_1}\right\| \le b_2, \left\|\frac{\partial \mathbf{f}_\mathbf{x}}{\partial \mathbf{x}_2}\right\| \le b_3, \|\mathbf{u}_\mathbf{x}\| \le u_m.$$

Assumption 1. The external disturbance $\boldsymbol{\omega}_\mathbf{x}$ is continuous and differentiable for its variables. Therefore, $\boldsymbol{\omega}_\mathbf{x}$ and its derivative $\dot{\boldsymbol{\omega}}_\mathbf{x}$ are bounded, which mean $\|\boldsymbol{\omega}_\mathbf{x}\| \le \bar{\boldsymbol{\omega}}_1$ and $\|\dot{\boldsymbol{\omega}}_\mathbf{x}\| \le \bar{\boldsymbol{\omega}}_2$ with $\bar{\boldsymbol{\omega}}_1$ and $\bar{\boldsymbol{\omega}}_2$ are positive constants.

Theorem 1. Consider the crane system in (4) and LESO in (5). According to **Remark 1** and **Assumption 1:** The estimation states will converge to the real states when $t \to \infty$, mean $\lim_{t\to\infty} |\mathbf{x}_\mathbf{i} - \hat{\mathbf{x}}_i| = 0$ with $i = 1 - 3$, if the coefficient $\beta_1, \beta_2, \beta_3$ are chosen to make matrix

$\mathbf{E} = \begin{bmatrix} -\beta_1 & 1 & 0 \\ -\beta_2 & 0 & 1 \\ -\beta_3 & 0 & 0 \end{bmatrix}$ a Hurwitz matrix and σ is a small positive constant.

Theorem 1 is proved similarly in [8].

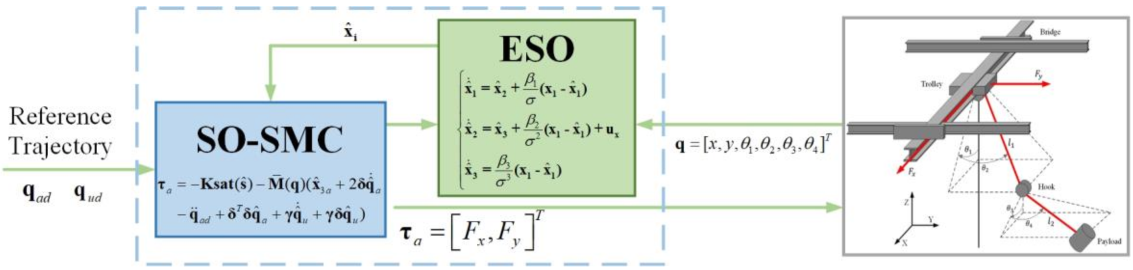

__Figure 2.__ Closed-loop control system diagram.

2.3. Second order sliding mode controller based on ESO

The overhead crane system under consideration is a system lacking an actuator mechanism. The state variables are divided into two subsystems: actuated states $\mathbf{q}_a = [x, y]^T$ and unactuated states $\mathbf{q}_u = [\theta_1, \theta_2, \theta_3, \theta_4]^T$. The dynamic equation of the system (1) is rewritten into two equations according to $\mathbf{q}_a$ and $\mathbf{q}_u$ as follows:

$$\begin{cases}\mathbf{M}_{11}(\mathbf{q})\ddot{\mathbf{q}}_a+\mathbf{M}_{12}(\mathbf{q})\ddot{\mathbf{q}}_u+\mathbf{B}_{11}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}_a+\mathbf{C}_{11}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}_a+\mathbf{C}_{12}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}_u+\mathbf{G}_1(\mathbf{q})+\mathbf{W}_{11}=\boldsymbol{\tau}_a\\ \mathbf{M}_{21}(\mathbf{q})\ddot{\mathbf{q}}_a+\mathbf{M}_{22}(\mathbf{q})\ddot{\mathbf{q}}_u+\mathbf{B}_{21}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}_a+\mathbf{C}_{21}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}_a+\mathbf{C}_{22}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}_u+\mathbf{G}_2(\mathbf{q})+\mathbf{W}_{21}=\mathbf{0}\end{cases} \quad (6)$$

From the two equations in (6), the actuated dynamics equation is derived and defined as:

$$\bar{\mathbf{M}}(\mathbf{q})\ddot{\mathbf{q}}_a+\bar{\mathbf{C}}_1(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}_a+\bar{\mathbf{C}}_2(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}_u+\bar{\mathbf{G}}(\mathbf{q})+\bar{\mathbf{W}}_1=\boldsymbol{\tau}_a \quad (7)$$

where: $\bar{\mathbf{M}}(\mathbf{q})=\mathbf{M}_{11}(\mathbf{q})-\mathbf{M}_{12}(\mathbf{q})\mathbf{M}_{22}^{-1}(\mathbf{q})\mathbf{M}_{21}(\mathbf{q})$;

$\bar{\mathbf{C}}_1(\mathbf{q},\dot{\mathbf{q}})=\mathbf{B}_{11}(\mathbf{q},\dot{\mathbf{q}})+\mathbf{C}_{11}(\mathbf{q},\dot{\mathbf{q}})-\mathbf{M}_{12}(\mathbf{q})\mathbf{M}_{22}^{-1}(\mathbf{q})\mathbf{C}_{21}(\mathbf{q},\dot{\mathbf{q}})$;

$\bar{\mathbf{C}}_2(\mathbf{q},\dot{\mathbf{q}})=\mathbf{B}_{21}(\mathbf{q},\dot{\mathbf{q}})+\mathbf{C}_{12}(\mathbf{q},\dot{\mathbf{q}})-\mathbf{M}_{12}(\mathbf{q})\mathbf{M}_{22}^{-1}(\mathbf{q})\mathbf{C}_{22}(\mathbf{q},\dot{\mathbf{q}})$;

$\bar{\mathbf{G}}(\mathbf{q})=\mathbf{G}_1(\mathbf{q})-\mathbf{M}_{12}(\mathbf{q})\mathbf{M}_{22}^{-1}(\mathbf{q})\mathbf{G}_2(\mathbf{q})$; $\bar{\mathbf{W}}_1=\mathbf{W}_{11}-\mathbf{M}_{12}(\mathbf{q})\mathbf{M}_{22}^{-1}(\mathbf{q})\mathbf{W}_{21}$.

Define $\mathbf{q}_{ad}=[x_d,y_d]^T$ and $\mathbf{q}_{ud}=[\theta_{1d},\theta_{2d},\theta_{3d},\theta_{4d}]^T=[0,0,0,0]^T$ are desired positions and swing angles of the system. State variables $\mathbf{q}_a,\mathbf{q}_u$ are estimated by $\hat{\mathbf{x}}_a=[\mathbf{z}_1(1),\mathbf{z}_1(2)]^T$, $\hat{\mathbf{x}}_u=[\mathbf{z}_1(3),\mathbf{z}_1(4),\mathbf{z}_1(5),\mathbf{z}_1(6)]^T$. The total disturbance is estimated by $\hat{\mathbf{x}}_{3a}=[\mathbf{z}_3(1),\mathbf{z}_3(2)]^T$.

The sliding surface is defined as follows: $\mathbf{s}=\dot{\tilde{\mathbf{q}}}_a+\boldsymbol{\delta}\tilde{\mathbf{q}}_a+\boldsymbol{\gamma}\tilde{\mathbf{q}}_u$ (8)

where $\tilde{\mathbf{q}}_a=\mathbf{q}_a-\mathbf{q}_{ad}=[x-x_d,y-y_d]^T$ and $\tilde{\mathbf{q}}_u=\mathbf{q}_u-\mathbf{q}_{ud}=[\theta_1,\theta_2,\theta_3,\theta_4]^T$ are the errors from the desired values; $\boldsymbol{\delta}=\mathrm{diag}(\delta_1,\delta_2)$ and $\boldsymbol{\gamma}=\begin{bmatrix}\gamma_1 & 0 & \gamma_3 & 0\\ 0 & \gamma_2 & 0 & \gamma_4\end{bmatrix}$ are the design parameters.

The sliding surface is based on the observer, state variables $\hat{\mathbf{x}}_a$ and $\hat{\mathbf{x}}_u$ are defined as:

$$\hat{\mathbf{s}}=(\dot{\hat{\mathbf{x}}}_a-\dot{\mathbf{q}}_{ad})+\boldsymbol{\delta}(\hat{\mathbf{x}}_a-\mathbf{q}_{ad})+\boldsymbol{\gamma}(\hat{\mathbf{x}}_u-\mathbf{q}_{ud})=-\dot{\mathbf{e}}_a-\boldsymbol{\delta}\mathbf{e}_a-\boldsymbol{\gamma}\mathbf{e}_u+\mathbf{s} \quad (9)$$

where $\mathbf{e}_a=\mathbf{q}_a-\hat{\mathbf{x}}_a=[e_1(1),e_1(2)]^T$ and $\mathbf{e}_u=\mathbf{q}_u-\hat{\mathbf{x}}_u=[e_1(3),e_1(4),e_1(5),e_1(6)]^T$.

The second order sliding mode controller based on the ESO is proposed as follows:

$$\boldsymbol{\tau}_a=-\mathbf{K}\mathbf{sign}(\hat{\mathbf{s}})-\bar{\mathbf{M}}(\mathbf{q})\left(\hat{\mathbf{x}}_{3a}+2\boldsymbol{\delta}\dot{\hat{\mathbf{q}}}_a-\ddot{\mathbf{q}}_{ad}+\boldsymbol{\delta}^T\boldsymbol{\delta}\hat{\mathbf{q}}_a+\boldsymbol{\gamma}\dot{\hat{\mathbf{q}}}_u+\boldsymbol{\gamma}\boldsymbol{\delta}\hat{\mathbf{q}}_u\right) \quad (10)$$

with $\hat{\mathbf{q}}_a=\hat{\mathbf{x}}_a-\mathbf{q}_{ad}$ and $\hat{\mathbf{q}}_u=\hat{\mathbf{x}}_u-\mathbf{q}_{ud}$ are the errors between the observed and set values.

To reduce chattering, $\mathbf{sign}(\hat{\mathbf{s}})$ function should be replaced by a saturation function, as follows:

$\mathbf{sat}(\hat{\mathbf{s}})=\begin{cases}1 & ,\text{if } |\hat{\mathbf{s}}/p|>1\\ \hat{\mathbf{s}}/p & ,\text{if } |\hat{\mathbf{s}}/p|<1\end{cases}$, constant p indicates the thickness of the boundary layer.

The Lyapunov function is chosen as: $V=\frac{1}{2}\mathbf{s}^T\mathbf{s}$ (11)

The derivative of the Lyapunov function with respect to time t is as follows:

$$\dot{V}=-\mathbf{s}^T\bar{\mathbf{M}}^{-1}(\mathbf{q})\mathbf{K}\mathbf{sat}(-\dot{\mathbf{e}}_a-\boldsymbol{\delta}\mathbf{e}_a-\boldsymbol{\gamma}\mathbf{e}_u+\mathbf{s})+\mathbf{s}^T(-\boldsymbol{\delta}\mathbf{s}+\ddot{\mathbf{e}}_a+2\boldsymbol{\delta}\dot{\mathbf{e}}_a+\boldsymbol{\gamma}\dot{\mathbf{e}}_u+\boldsymbol{\delta}^2\mathbf{e}_a+\boldsymbol{\delta}\boldsymbol{\gamma}\mathbf{e}_u) \quad (12)$$

According to **Theorem 1**, the observation errors will converge to zero, meaning that $|e_i(t)|\to 0$. Therefore, (12) can be rewritten as: $\dot{V}\approx-\mathbf{s}^T\bar{\mathbf{M}}^{-1}(\mathbf{q})\mathbf{K}\mathbf{sat}(\mathbf{s})-\mathbf{s}^T\boldsymbol{\delta}\mathbf{s}$ (13)

Since $\mathbf{M}$ is a positive definite symmetric matrix and its inverse, and $\mathbf{K}$ is a diagonal matrix with positive coefficients, it follows that $\dot{V} \le 0$. Thus, according to Barbalat's lemma: $\lim_{t\to\infty} V = 0$, which lead to $\lim_{t\to\infty} s = 0$. Therefore, the sliding surface is asymptotically stable. In practice, under the influence of gravity, the rotational angles $\theta_1, \theta_2, \theta_3, \theta_4$ will converge to zero, or errors $\tilde{\mathbf{q}}_u \to 0$. Therefore, $\dot{\tilde{\mathbf{q}}}_a + \boldsymbol{\delta}\tilde{\mathbf{q}}_a \to 0$, which mean $\tilde{\mathbf{q}}_a \to 0$ and the controller helps the system to track the reference trajectories.

3. SIMULATION AND RESULT

In this section, several simulations are conducted to evaluate the results of the proposed control method. The design parameters include: $M_1 = 6.1\,\text{kg}$, $M_2 = 15.6\,\text{kg}$, $m_1 = 2\,\text{kg}$, $m_2 = 0.6\,\text{kg}$, $l_1 = 0.5\,\text{m}$, $l_2 = 0.4\,\text{m}$, $g = 9.8\,\text{m/s}^2$, $\mathbf{K} = \text{diag}(1;1)$, $F_{rx} = F_{ry} = 0.1\,\text{Nm/s}$, $\boldsymbol{\delta} = diag(3;3)$, $\boldsymbol{\gamma} = \begin{bmatrix} -0.5 & 0 & -0.5 & 0 \\ 0 & -0.5 & 0 & -0.5 \end{bmatrix}$, $\beta_1 = \text{diag}(40;40;40;40;40;16)$, $\beta_2 = \text{diag}(20;20;20;20;20;20)$, $\beta_3 = 120 \times \text{diag}(1;1;1;1;1;2)$, $\sigma = 0.08$ and $p = 0.001$. Simulation was conducted using MATLAB/Simulink software. Figure 3 shows that the trolley's motion trajectory along the x and y axes closely follows the desired trajectory, which is a fifth-degree polynomial function moving from the initial position $[0,0]$ to $[2,3]$ m. The control signals remain within a moderate range throughout the motion. The swing angles of the hook and payload are very small, not exceeding 0.1 rad, indicating that the payload is lifted with minimal oscillation. Additionally, figure 3 also illustrates the actual total disturbance components of the system. Figure 4 shows the errors of the state variables, with the x and y deviation errors converging to zero in about 2 seconds, while those of the swing angles require approximately 25 seconds. Figure 5 shows the velocity errors, where the x and y velocity deviations also converge to zero within 2 seconds, and the swing angle velocity errors require approximately 30 seconds. Figure 6 illustrates the total disturbance errors, which approach zero in roughly 30 seconds.

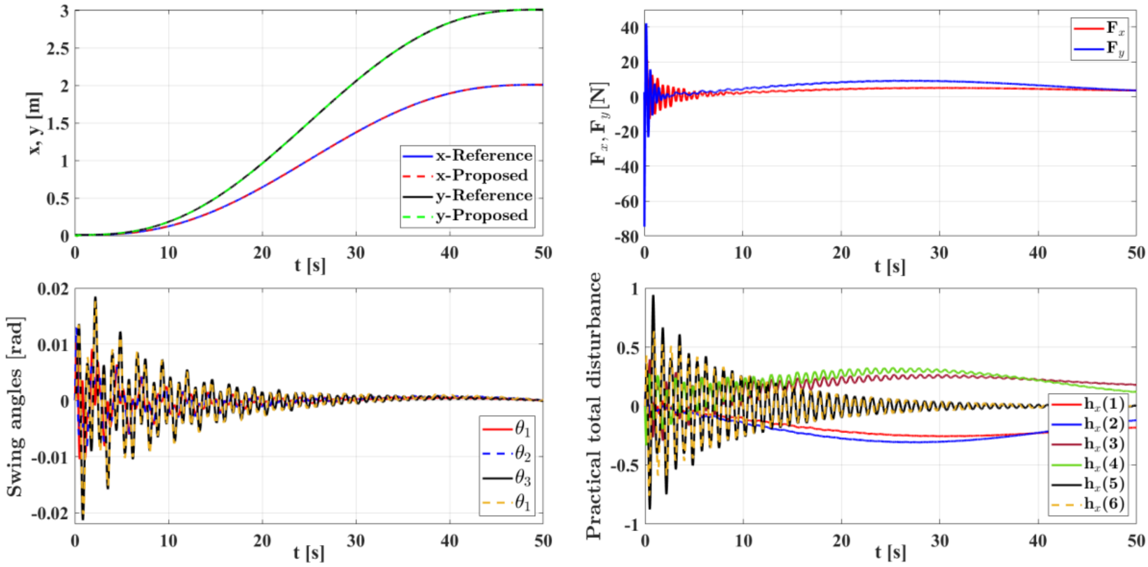

Figure 3. *Control of trajectory tracking along the x, y axes; input control signals F_x, F_y; swing angles of hook, payload and total disturbance.*

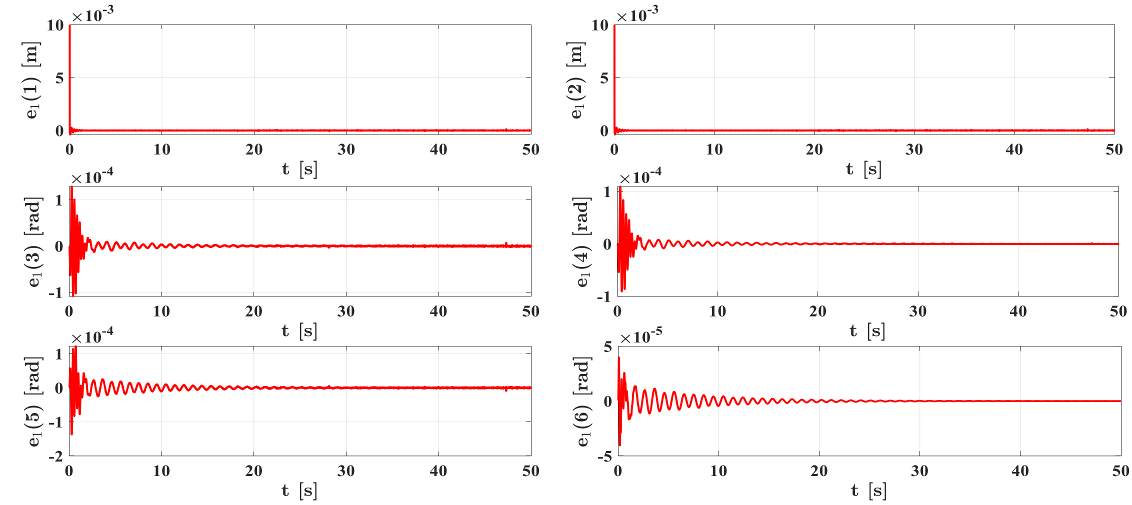

Figure 4. *Observer errors of state variables.*

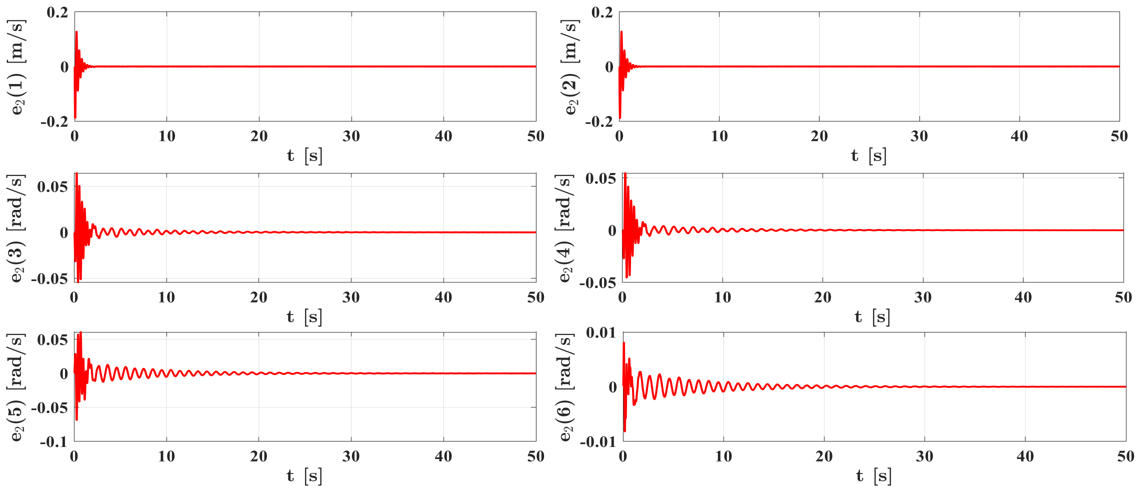

Figure 5. *Observer errors of variables' velocities.*

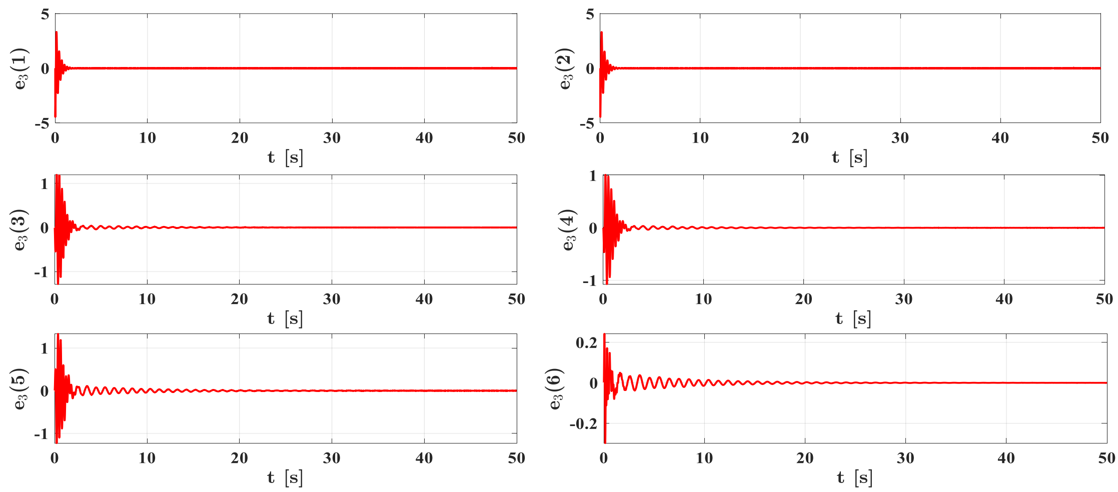

Figure 6. *Observer errors of total disturbance.*

4. CONCLUSIONS

This study proposes a second order sliding mode control method based on an extended state observer (ESO) for a 3D crane system. In this controller, the state variables and total disturbance are estimated by the linear extended state observer (LESO). The second order sliding mode controller is designed to ensure that the trolley follows the desired trajectory, and the load is lifted with minimal oscillation. The controller is guaranteed to be stable in a closed loop and its performance is validated through simulation results.

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TÓM TẮT

Điều khiển chế độ trượt bậc hai kết hợp bộ quan sát trạng thái mở rộng cho hệ thống cầu trục con lắc kép

Nghiên cứu này tập trung thiết kế bộ điều khiển trượt bậc hai dựa trên bộ quan sát trạng thái mở rộng cho hệ thống cầu trục 3D với hiệu ứng con lắc kép và chiều dài dây không đổi. Bộ điều khiển trượt bậc hai yêu cầu mô hình trạng thái của hệ thống chính xác, tuy nhiên, trong thực tế thông số mô hình và nhiễu tác động bên ngoài khó có thể xác định cụ thể. Vì vậy, bộ quan sát trạng thái mở rộng được thiết kế để ước lượng các biến trạng thái của hệ thống và nhiễu tổng. Cuối cùng, bộ điều khiển trượt được phát triển với đầu vào được lấy từ các tín hiệu của bộ quan sát đảm bảo tính ổn định theo tiêu chuẩn Lyapunov. Các kết quả mô phỏng cho thấy phương pháp đề xuất đảm bảo cầu trục vận hành theo quỹ đạo mong muốn và đồng thời hạn chế được hiện tượng rung lắc ngay cả khi có sự xuất hiện của nhiễu và các thành phần bất định.

Từ khoá: Cầu trục 3D với hiệu ứng con lắc kép và chiều dài dây không đổi; Bộ điều khiển trượt bậc hai; Bộ quan sát trạng thái mở rộng.