Robust Adaptive Control of 3D Overhead Crane System

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Additional information is available at the end of the chapter

Abstract

In this chapter an adaptive anti-sway controller for uncertain overhead cranes is proposed. The system model including the system uncertainties and disturbances is introduced firstly. Next, the adaptive controller which can guarantee tracking the desired position of the trolley as well as the anti-sway of the load cable is established. In this chapter, the system is proven to be input-to-state stable (ISS) which is supported by Lyapunov technique. The proposed algorithm is verified by using Matlab/Simulink simulation tool. The simulation results shown that the presented controller gives the good performances (i.e., fast transient response, position tracking, and low swing angle) when there exist system parameters variation as well as input disturbances.

Keywords: adaptive anti-swing control, input-to-state stable (ISS), overhead crane system, robust control, stability analysis, uncertainties

1. Introduction

The overhead crane system is one of the important devices in the transportation field. It includes a trolley, a driving motor, and a cable to hang the load. In the overhead crane system, there are two variables need to be controlled (the trolley position and the swing angle) but it has only one control input (acting force on the motor). This characteristic makes the control design of the overhead crane system is more difficult than full actuated system. Moreover, the operation of the system is affected by some unexpected factors such as the change of cable length and load mass, input disturbances, external disturbances. For this reason, the controller design for overhead crane system is much more challenging and attracts the consideration of many researchers.

In recent years, many controllers have been applied to the overhead crane system to move the trolley to the destination as fast as possible with acceptable swing angle. In [1–3], the PID

controllers are used for the crane systems to give the good performances with simple construction. However, it is well known that PID controller is sensitive to noises and disturbances. In [4–6], the controllers based on linearized theory are introduced. Also, these controllers cannot guarantee the good performances for the system under condition of uncertain factors. In order to face with system uncertainties, many advanced controllers have been presented such as sliding mode controllers [7–13], fuzzy controllers [14–21], intelligent adaptive strategies [22] and so on.

It is well known that, robust adaptive controller is a suitable selection for the systems which are affected by working environment. In [23] an adaptive fuzzy controller is proposed for the overhead crane system to deal with nonlinear disturbances. In this scheme, the fuzzy logic controller is combined with adaptive algorithm to keep stabling for the system as well as to tune the free parameters. The given strategy is simple but robust to the variation of the system parameters (wire length and payload weight) and external disturbances. However, the stability of overall system is not presented. An adaptive sliding-mode anti-sway controller is shown in [24]. The purpose of this scheme is given the good performances for the crane system in the range of high-speed hosting motion. This algorithm includes two parts: sliding-mode controller and fuzzy observer. The first one is to keep the asymptotic stability of the sway dynamic, the other is to cope with the system uncertainties. This algorithm gives the robust anti-sway performance to overhead cranes regardless of hosting velocity and system uncertainties. The stability of the system is proven in analysis and simulation. In [25], a fuzzy sliding-mode control is incorporated with a fuzzy uncertainty observer. By this cooperation, the controller guarantees not only the anti-sway trajectory tracking of the nominal plant but also the robustness to system uncertainties as well as actuator nonlinearity. This scheme guarantees asymptotic stability and robust performances but it is quite complicated.

In this chapter a robust adaptive controller is introduced for 3D crane system. Firstly, the controller is designed based on the Euler-Lagrange model of the overhead crane system which includes the system uncertainties and external disturbances. Next, by using this controller, the error dynamic of the system is show in the form of state space model. Finally, the simulation is done to verify the effectiveness of the given algorithm. The simulation results show that the proposed controller guarantees the good tracking and no payload swing angle for the crane system even under the effect of parameters variation as well as external disturbances.

2. Robust adaptive control system design

2.1. 3D overhead crane system modeling

Figure 1 shows the structure of the 3D overhead crane. The dynamic model of the overhead crane is as follows [26]:

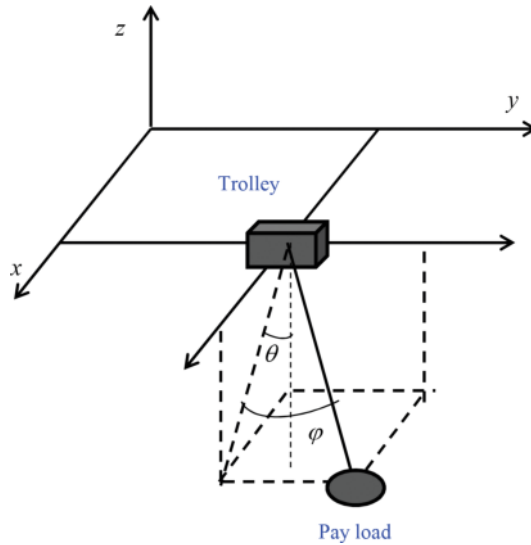$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau \tag{1}$$

where

Figure 1. Structure of 3D overhead crane.

$$M(q) = \begin{pmatrix} m_c + m_h & 0 & m_h l \cos\theta \cos\varphi & -m_h l \sin\theta \sin\varphi \\ 0 & m_c + m_h + m_x & m_h l \cos\theta \sin\varphi & m_h l \sin\theta \cos\varphi \\ m_h l \cos\theta \cos\varphi & m_h l \cos\theta \sin\varphi & m_h l^2 + J & 0 \\ -m_h l \sin\theta \sin\varphi & m_h l \sin\theta \cos\varphi & 0 & m_h l^2 \sin^2\theta + J \end{pmatrix} \tag{2}$$

$$C(q,\dot{q}) = \begin{pmatrix} 0 & 0 & -m_h l\dot\theta \sin\theta \cos\varphi - m_h l\dot\varphi \cos\theta \sin\varphi & -m_h l\dot\theta \cos\theta \sin\varphi - m_h l\dot\varphi \sin\theta \cos\varphi \\ 0 & 0 & -m_h l\dot\theta \sin\theta \sin\varphi + m_h l\dot\varphi \cos\theta \cos\varphi & m_h l\dot\theta \cos\theta \cos\varphi - m_h l\dot\varphi \sin\theta \sin\varphi \\ 0 & 0 & 0 & -m_h l^2 \dot\varphi \sin\theta \cos\theta \\ 0 & 0 & m_h l^2 \dot\varphi \sin\theta \cos\theta & m_h l^2 \dot\theta \sin\theta \cos\theta \end{pmatrix} \tag{3}$$

$$g(q) = \begin{pmatrix} 0 \\ 0 \\ m_h g l \sin\theta \\ 0 \end{pmatrix} \tag{4}$$

$$\tau = (u_1, u_2, 0, 0)^T, \quad q = (x, y, \theta, \varphi)^T. \tag{5}$$

In considering the system uncertainties, the model (1) is rewritten as the following:

$$M(q,d)\ddot{q} + C(q,\dot{q},d)\dot{q} + g(q,d) = D(u + n(q,\dot{q},\ddot{q},d,t)) \tag{6}$$

where

$$D = \begin{pmatrix} I_{2 \times 2} \\ 0 \end{pmatrix}, \boldsymbol{u} = (u_1, u_2)^T \tag{7}$$

The uncertain vector $d \in \mathbb{R}^4$ includes the unknown constants in the system model and $n(q, \dot{q}, \ddot{q}, d, t)$ is external disturbance. In the rest of this chapter, $n(q, \dot{q}, \ddot{q}, d, t)$ is shorten by $n(t)$.

Model (1) is rewritten as the following:

$$\underbrace{\begin{pmatrix} M_{11}(q,d) & M_{12}(q,d) \\ M_{21}(q,d) & M_{22}(q,d) \end{pmatrix}}_{M(q,d)} \underbrace{\begin{pmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{pmatrix}}_{\ddot{q}} + \underbrace{\begin{pmatrix} C_{11}(q,\dot{q},d) & C_{12}(q,\dot{q},d) \\ C_{21}(q,\dot{q},d) & C_{22}(q,\dot{q},d) \end{pmatrix}}_{C(q,\dot{q},d)} \underbrace{\begin{pmatrix} \dot{q}_1 \\ \dot{q}_2 \end{pmatrix}}_{\dot{q}} + \underbrace{\begin{pmatrix} g_1(q,d) \\ g_2(q,d) \end{pmatrix}}_{g(q,d)} = \begin{pmatrix} u+n \\ 0 \end{pmatrix} \tag{8}$$

or

$$\begin{cases} M_{11}(q,d)\ddot{q}_1 + M_{12}(q,d)\ddot{q}_2 + C_{11}(q,\dot{q},d)\dot{q}_1 + f_1(q,\dot{q},d) = u+n \\ M_{21}(q,d)\ddot{q}_1 + M_{22}(q,d)\ddot{q}_2 + f_2(q,\dot{q},d) = 0 \end{cases} \tag{9}$$

where

$$q = \begin{pmatrix} q_1 \\ q_2 \end{pmatrix}, q_1 = (x,y)^T, \quad q_2 = (\theta, \varphi)^T \tag{10}$$

$$f_1(q,\dot{q},d) = M_{12}(q,d)\ddot{q}_2 + C_{12}(q,\dot{q},d)\dot{q}_2 + g_1(q,d) \\ f_2(q,\dot{q},d) = C_{21}(q,\dot{q},d)\dot{q}_1 + C_{22}(q,\dot{q},d)\dot{q}_2 + g_2(q,d) \tag{11}$$

Because M(q, d) is positive definite matrix, M11(d, q) and M22(d, q) are invertible. From the second equation of (9), it can be obtained:

$$\ddot{q}_2 = -M_{22}(q,d)^{-1}\left[M_{21}(q,d)\ddot{q}_1 + f_2(q,\dot{q},d)\right] \tag{12}$$

Replacing Eq. (12) into Eq. (9) to get the following:

$$\begin{cases} M'(q,d)\ddot{q}_1 + C_{11}(q,\dot{q},d)\dot{q}_1 + f'(q,\dot{q},d) = u+n \\ M_{21}(q,d)\ddot{q}_1 + M_{22}(q,d)\ddot{q}_2 + f_2(q,\dot{q},d) = 0 \end{cases} \tag{13}$$

where

$$M'(q,d) = M_{11}(q,d) - M_{12}(q,d)M_{22}(q,d)^{-1}M_{21}(q,d) \\ f'(q,\dot{q},d) = f_1(q,\dot{q},d) - M_{12}(q,d)M_{22}(q,d)^{-1}f_2(q,\dot{q},d) \tag{14}$$

In this paper, the following assumptions are used:

- A1: $M'(\boldsymbol{q}, \boldsymbol{d})$ is quadratic positive definite for all d.
- A2: $\|\boldsymbol{n}(t)\|_\infty = \sup_t |\boldsymbol{n}(t)| = \delta$ where δ is finite scalar.

- A3: The relationship between the uncertainty d and the model is linear [27], i.e., the left side of Eq. (13) can be expressed as:

$$\begin{cases} M'(q,d)\ddot{q}_1 + C_{11}(q,\dot{q},d)\dot{q}_1 + f'(q,\dot{q},d) = F_1(q,\dot{q},\ddot{q}_1)d \\ M_{21}(q,d)\ddot{q}_1 + M_{22}(q,d)\ddot{q}_2 + f_2(q,\dot{q},d) = F_2(q,\dot{q},\ddot{q})d \end{cases} \tag{15}$$

2.2. Controller design

In this part, the following denotations are used:

$$\begin{aligned} &M' = M'(q,d), C_{11} = C_{11}(q,\dot{q},d), f' = f'(q,\dot{q},d) \\ &\widehat{M}' = M'\left(q,\widehat{d}\right), \widehat{C}_{11} = C_{11}\left(q,\dot{q},\widehat{d}\right), \widehat{f}' = f'\left(q,\dot{q},\widehat{d}\right) \\ &F_1 = F_1(q,\dot{q},\ddot{q}_1), F_2 = F_2(q,\dot{q},\ddot{q}_1) \end{aligned} \tag{16}$$

The role of the proposed controller in the system is to adapt to the constant uncertain d and robust with unknown function $n(t)$ so the error $e = q_r - q_1$, where q_r is the desired value of q_1, is bounded and converges asymptotically to 0.

The robust adaptive controller which satisfies the above requirements is obtained by the following theorem.

Theorem: Consider the system Eq. (13), the following controller:

$$u = M'\left[\ddot{q}_r + K_1 e + K_2 \dot{e}\right] + C_{11}\dot{q}_1 + f' + s(t) \tag{17}$$

where $K_1 = \text{diag}(a), K_2 = \text{diag}\left(\sqrt{(a+1)a}\right), a > 0$, and

$$\begin{cases} \dot{v} = \left(M'\left(q,\widehat{d}\right)^{-1} F_1\right)^T (K_1, K_2)x \\ s(t) = F_1 v \end{cases} \tag{18}$$

in which $\widehat{d}$, which satisfies $\max\limits_{1 \le i \le n} \sum\limits_{j=1}^{n} \left|m'_{ij}\left(q,\widehat{d}\right)\right| \le \gamma, \forall q$ is representation of d, and $x = \text{col}(e,\dot{e})$.

will converge x to the neighborhood of the are $\mathcal{O}$:

$$\mathcal{O} = \left\{x \in \mathbb{R}^6 \mid |x| < \frac{\delta\gamma}{a}\right\} \tag{19}$$

Proof: Replacing Eq. (18) into Eq. (17), the following is obtained:

$$M'\ddot{q} + C_{11}\dot{q}_1 + f' = u + n = \widehat{M}'\left[\ddot{q}_r + K_1 e + K_2 \dot{e}\right] + \widehat{C}_{11}\dot{q}_1 + \widehat{f}' + s + n \tag{20}$$

which can be rewritten as:

$$\left(M' - \widehat{M}'\right)\ddot{q} + \left(C_{11} - \widehat{C}_{11}\right)\dot{q}_1 + \left(f' - \widehat{f}'\right) = \widehat{M}'/[\ddot{e} + K_1 e + K_2 \dot{e}] + s + n \tag{21}$$

By using A3, the above equation can be expressed as the following:

$$F_1\left(d - \widehat{d}\right) = \widehat{M}'[\ddot{e} + K_1 e + K_2 \dot{e}] + s + n \tag{22}$$

or

$$\ddot{e} = -K_1 e - K_2 \dot{e} + \left(\widehat{M}'\right)^{-1}\left[F_1\left(d - \widehat{d}\right) - s - n\right] \tag{23}$$

Equation (23) can be written in the state-space form as the following:

$$\dot{x} = \begin{pmatrix} 0 & I_{3\times3} \\ -K_1 & -K_2 \end{pmatrix} x + \begin{pmatrix} 0 \\ \left(\widehat{M}'\right)^{-1} \end{pmatrix}\left[F_1\left(d - \widehat{d}\right) - s - n\right]$$
$$= Ax + B\left[F_1\left(d - \widehat{d}\right) - s - n\right] \tag{24}$$

where

$$x = \begin{pmatrix} e \\ \dot{e} \end{pmatrix}, A = \begin{pmatrix} 0 & I_{3\times3} \\ -K_1 & -K_2 \end{pmatrix}, B = \begin{pmatrix} 0 \\ \left(\widehat{M}'\right)^{-1} \end{pmatrix} \tag{25}$$

Since K_1 and K_2 are symmetric positive definite matrices, matrix A is stable, it means that all the eigenvalues of A is located in the left side of the complex plane. Consequently, the linear reference model:

$$\dot{x}_m = Ax_m \tag{26}$$

is stable. Then, $x_m(t)$ is bounded and asymptotically converges to zero as $t \to \infty$ despite the initiative value $x_m(0)$.

Next step, it will be shown that, by using the controller Eq. (17) and auxiliary controller Eq. (18), the error $(x - x_m)$ is bounded and converges to the neighborhood of the area $\mathcal{O}$ defined in Eq. (19).

From Eqs. (24) and (26), the following is obtained:

$$\dot{x} - \dot{x}_m = A(x - x_m) + B\left[F_1\left(d - \widehat{d}\right) - s - n\right]$$
$$= A(x - x_m) + B(F_1 \Delta - n) \tag{27}$$

where $\Delta = d - \widehat{d} - v$.

Choosing the Lyapunov function as the following:

$$V = \frac{1}{2}\left[(x - x_m)^T P(x - x_m) + \Delta^T \Delta\right] \tag{28}$$

The derivative of V can be expressed as:

$$\dot{V} = \frac{1}{2}\left[(A(x - x_m) + B(F_1\Delta - n))^T P(x - x_m) + (x - x_m)^T P(A(x - x_m) + B(F_1\Delta - n))\right]$$

$$+ \Delta^T \dot{\Delta} \tag{29}$$

$$= \frac{1}{2}(x - x_m)^T (A^T P + PA)(x - x_m) + \Delta^T\left[(BF_1)^T P(x - x_m) - \dot{v}\right] - (x - x_m)^T PBn$$

or

$$\dot{V} = -(x - x_m)^T Q(x - x_m) + \Delta^T\left[(BF_1)^T P(x - x_m) - \dot{v}\right] - (x - x_m)^T PBn \tag{30}$$

where

$$Q = -\frac{1}{2}(A^T P + PA)$$

$$= -\frac{1}{2}\left[\begin{pmatrix} 0 & -K_1 \\ I_{3\times3} & -K_2 \end{pmatrix}\begin{pmatrix} 2K_1K_2 & K_1 \\ K_1 & K_2 \end{pmatrix} + \begin{pmatrix} 2K_1K_2 & K_1 \\ K_1 & K_2 \end{pmatrix}\begin{pmatrix} 0 & I_{3\times3} \\ -K_1 & -K_2 \end{pmatrix}\right] \tag{31}$$

$$= \begin{pmatrix} K_1^2 & 0 \\ 0 & K_2^2 - K_1 \end{pmatrix} = \mathrm{diag}(a^2)$$

is a symmetric positive definite matrix.

By choosing:

$$\dot{v} = (BF_1)^T P(x - x_m) = \left[\begin{pmatrix} 0 \\ \left(\widehat{M}'\right)^{-1} F_1 \end{pmatrix}\right]^T \begin{pmatrix} 2K_1K_2 & K_1 \\ K_1 & K_2 \end{pmatrix}(x - x_m)$$

$$= \left(\left(\left(\widehat{M}'\right)^{-1} F_1\right)^T K_1, \left(\left(\widehat{M}'\right)^{-1} F_1\right)^T K_2\right)(x - x_m) \tag{32}$$

$$= \left(\left(\widehat{M}'\right)^{-1} F_1\right)^T (K_1, K_2)(x - x_m)$$

then

$$\dot{V} = -(x - x_m)^T Q(x - x_m) - (x - x_m)^T PBn \tag{33}$$

Both Eqs. (32) and (33) are always feasible with any initial values of x_m. For the simplicity, the initial value of x_m is chosen at $x_m(0) = 0$. Consequently, this leads to the following:

$$\dot{v} = \left(\left(\widehat{M}' \right)^{-1} F_1 \right)^T (K_1, K_2) x \tag{34}$$

and

$$\begin{aligned} \dot{V} &= -x^T Q x - x^T PB n = -a^2 |x|^2 - x^T PB n \\ &\leq -a^2 |x|^2 + \|PB\| \delta |x| \leq a[-a|x| + \gamma \delta] |x| \end{aligned} \tag{35}$$

This implies that as $\frac{\gamma \delta}{a} < |x|$, i.e. when $x(t)$ is steel on the outside of the area $\mathcal{O}$, $\dot{V} < 0$ so the change of $|x(t)|$ is monotonous decrease. This completely proves that by using the proposed controller, the trajectory x will converge to the neighborhood of the area $\mathcal{O}$.

3. Simulation verification

In order to verify the effectiveness of the proposed controller, a simulation is setup based on the MATLAB/Simulink tool. The parameters of the overhead crane system are as follow:

$m_c = 10$ kg, $m_h = 10$ kg, $m_x = 5$ kg, $l = 1.2$ m, $g = 9.8$ m/s^2.

The simulation is carried out under the three cases:

Case 1: The system parameters are nominal, no input disturbances.

Case 2: The system parameters are variation (150%), no input disturbances.

Case 3: The system parameters are nominal, existing input disturbances.

The destination positions for all cases are 1.5 m for x-axis and 2 m for y-axis, the controller gains are as follow:

$$K_1 = \begin{bmatrix} 5 & 0 \\ 0 & 5 \end{bmatrix}, \quad K_2 = \begin{bmatrix} 5.48 & 0 \\ 0 & 5.48 \end{bmatrix} \tag{36}$$

The simulation results are shown in **Figures 2–4**. In each figure, the a part is result for the x-axis and the b part is for y-axis. In addition, from top to bottom are the waveforms of trolley position, payload swing angle, and control signal, respectively.

It can be seen from **Figure 2** that, in the case of system is certainty (Case 1), the trolley reaches the destination point after 3 sec in x-axis and 4 sec in y-axis, the steady state errors are
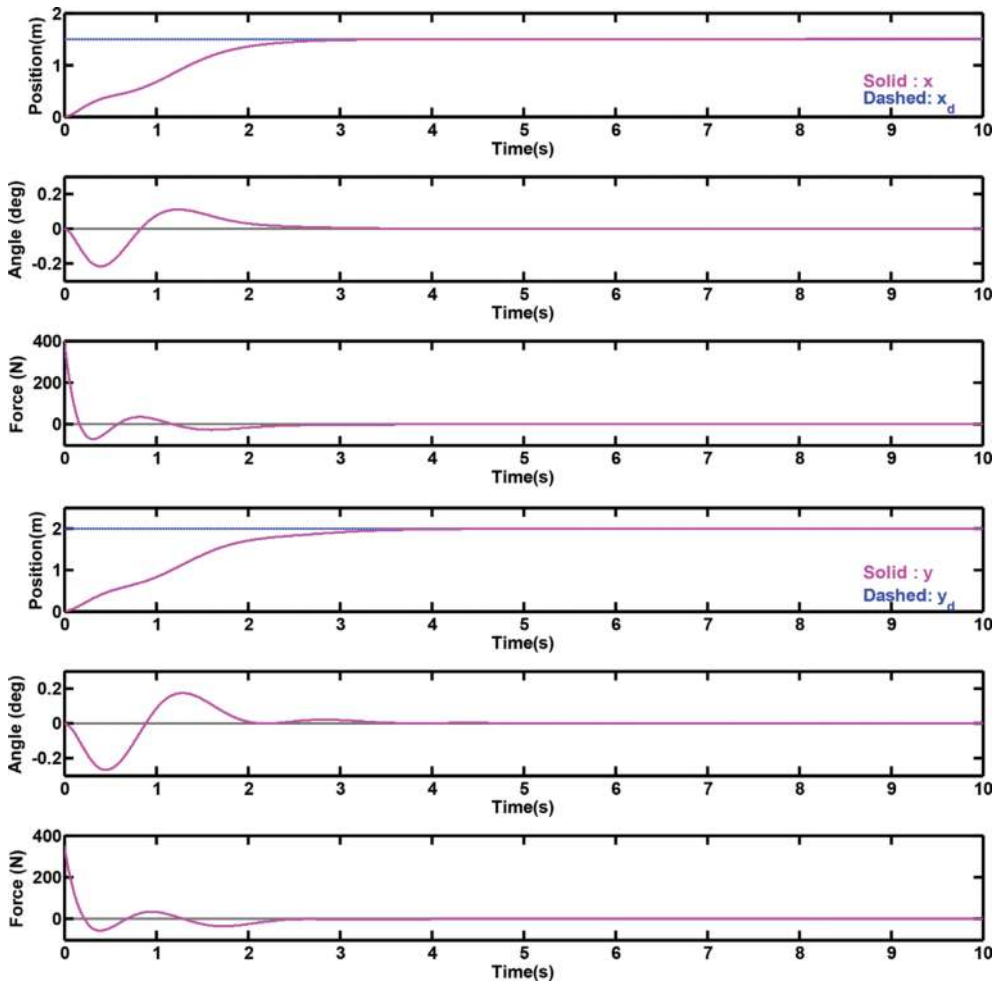
Figure 2. Simulation result of the robust adaptive controller for the case of certain system parameters.

negligible, and the payload swing quickly disappears as the trolleys finish their movements. In the **Figure 3** (Case 2), the system parameters are 150% variation but the results are nearly unchanged, i.e. the transient time is less than 5 sec, the maximum swing angle is smaller than 0.3 deg. and it is kept almost zero at the steady state.

Figure 4 is the waveform of the system under the condition of existing the external disturbances. In this case, a sinusoidal with amplitude of 2 degree is added into the inputs. The system responses are little oscillation but it is insignificant.
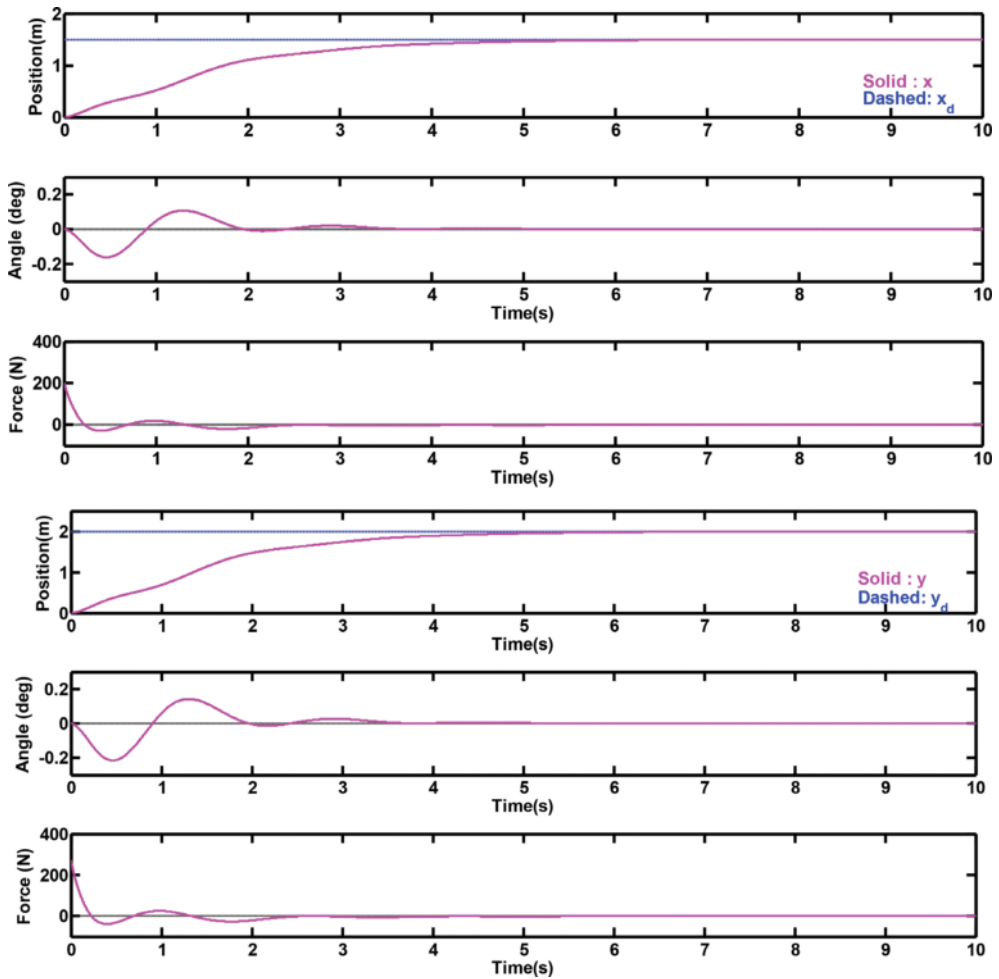
Figure 3. Simulation result of the robust adaptive controller for the case of 150% variation system parameters.

In **Table 1**, θ_{max}, φ_{max}, θ_{ss}, and φ_{ss} are maximum and steady state values of θ and φ, respectively. From the above results is can be seen that the proposed controller gives a good performance under various conditions of working. It has the ability to adapt with the uncertainties of the system such as the variation of the trolley mass, load mass, and cable length. Moreover, this controller is also robust to the external disturbance.
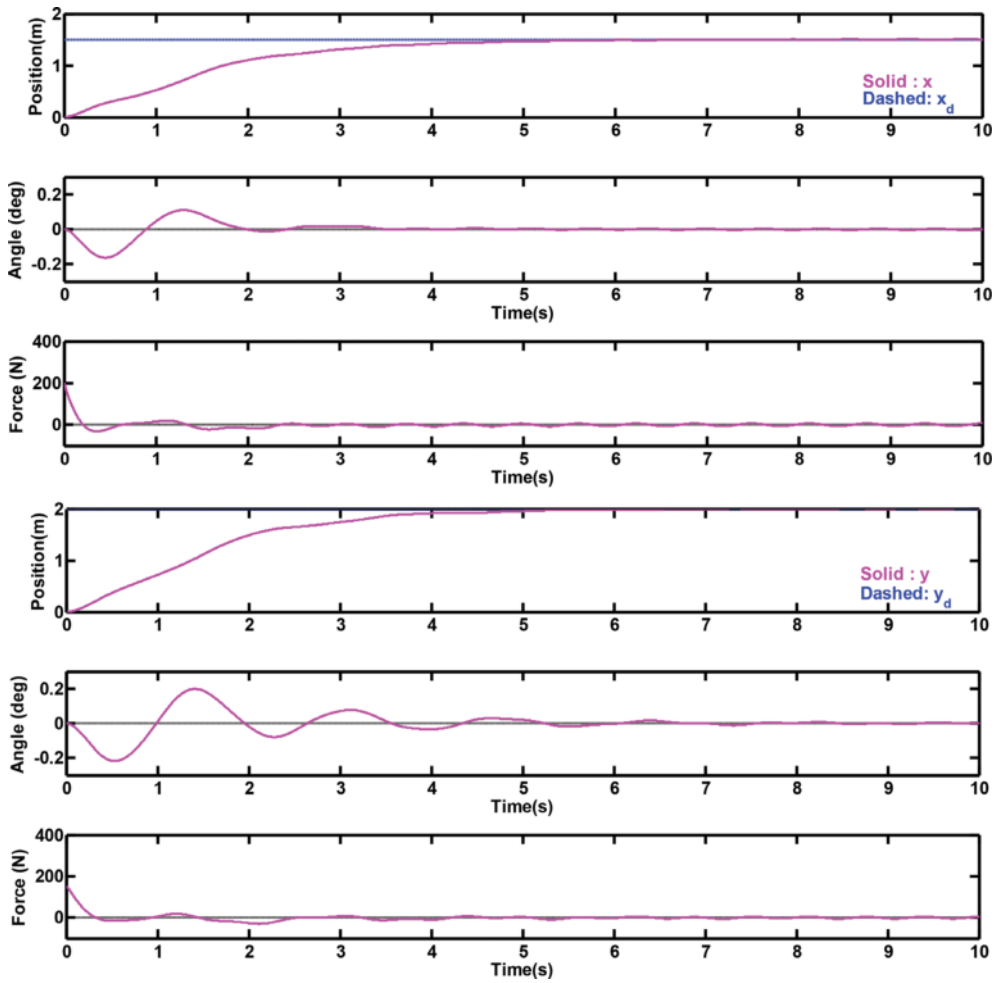
Figure 4. Simulation result of the robust adaptive controller for the case of existing external disturbances.

	θ_{max} (deg)	θ_{ss} (deg)	φ_{max} (deg)	φ_{ss} (deg)	x-axis settling time (sec)	y-axis settling time (sec)
Case 1	0.2	0	0.3	0	3	4
Case 2	0.2	0	0.25	0	5	5
Case 3	0.2	0	0.25	0	4	5

Table 1. Summarize the results for all cases.

4. Conclusion

In this chapter an adaptive robust controller which can adapt with the system uncertainties and robust to the external disturbances is establishes based on Euler–Lagrange model of the overhead crane system. Using this controller, the error dynamic of the system is show in the form of state space model. By using Lyapunov theory, it is shown that the overall system is input-to-state stable. The proposed robust adaptive controller is verified through the Matlab/Simulink toolbox under the three conditions, i.e., nominal system parameters, variation system parameters, and external disturbances. The simulation results indicate that the presented scheme gives the good performances for the overhead crane system (fast response, small swing angle in the transient time and no swing angle in the steady state, no position error) even that the system is uncertainties and existing the external disturbances.

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