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Adaptive Tracking Control for an Overhead Crane System ⋆

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Abstract: This paper proposes an adaptive control method for an underactuated overhead crane system. To improve the transferring efficiency and enhance the security of the crane system, the trolley is required to reach the desired position as fast as possible, while the swing of payload needs to be within an acceptable domain. To achieve these objectives, a novel two-step design strategy consisting of a trajectory planning stage and an adaptive tracking control design stage, is proposed to attack such an underactuated system as overhead crane. In the first step this paper proposes a new S curve as the desired trajectory for trolley tracking, and in the second step, it constructs an adaptive control law to make the trolley track the planned trajectory. As shown by Lyapunov Techniques, the proposed adaptive controller guarantees an asymptotical tracking result even in the presence of uncertainties including system parameters and various disturbances. Simulation results demonstrate that the new S trajectory and the tracking controller achieves a superior performance for the underactuated cranes.

1. INTRODUCTION

Due to great load capacity and high transferring efficiency, overhead crane systems have been widely used in building sites, product lines, ports, and so on. However, at present most of the crane systems in practice are manually operated by experienced workers. Obviously, this kind of manual operation presents such drawbacks as low efficiency and safety, long time training for operators, and so on. For this reason, some researchers have started to address the control problem of overhead crane systems. On one hand, the trolley is required to arrive at the desired position within a short time to increase transferring efficiency; while on the other hand, the payload swing should be suppressed within a given domain for safety concern. To make the problem even worse, overhead crane is an underactuated system. It is usually difficult, if not completely impossible, to reach the aforementioned two control objectives simultaneously.

Recently, the automatic control problem for an underactuated crane system has become a focus of the control community and many ambitious control laws have been proposed to improve the performance of an overhead crane. In Khalid (2004), Khalid *etc.* utilized an input shaping method, which is implemented in real time by convolving the human-generated signal with a chosen impulse sequence, to reduce the swing of overhead crane systems. The key of input shaping method is the requirement of *a priori* regarding the system's natural frequencies and damping ratios. Unfortunately, it often meets great difficulty when trying to obtain these system coefficients which vary with the changes of the payload or the rope length. In Fang (2001, 2003, 2001, 2005), Fang *etc.* proposed a series of energy-based controllers to regulate the trolley to a desired position while constrain the swing of payload at the same time. Noting that it is difficult to fulfill two objectives with a single control law, some researchers have recently brought up the fuzzy sliding-mode control strategies for an overhead crane system Chang (2004); Cho (2000); Wang (2004, 2006); Liu (2005). The basic idea of this design is to construct two fuzzy controllers with different objects. Usually, one controller aims to reduce the swing by slowing down the trolley when a large swing is detected, while the other intends to fasten the trolley to ensure high efficiency provided that the swing is within an acceptable range. The two controllers are switched between each other based on different situations. Though fuzzy sliding-mode control is able to reach a satisfactory performance for crane systems, it often involves a tedious and time-consuming work to collect proper fuzzy rules. Besides, it should be pointed out that, when transferring payloads, an overhead crane is unavoidably affected by various kinds of disturbance, such as the frictions between the trolley and the rail. Yet, most of the currently proposed controllers do not take these uncertainties of disturbance into account Fang (2001, 2003, 2001, 2005); Chang (2004); Cho (2000); Wang (2004, 2006); Liu (2005). For this reason, Aschemann and Ma *etc.* analyzed some major disturbances in the overhead crane systems and designed different controllers to reject these disturbances Aschemann (2000); Ma (2005). Yet these controllers require the prior knowledge of the system

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parameters including the mass of trolley and payload and the length of the rope. However, there is great difficulty in practice to accurately obtain these parameters, and some of the parameters, such as the rope length and the payload mass, vary for different transferring processes.

In this paper, we propose a novel control method for an underactuated crane system. Specifically, a two-step strategy is proposed to attack such an underactuated system as overhead crane, to ensure that the trolley is pushed to a given position and the swing is always within acceptable range. In the first step, a path planning mechanism is employed based on the system dynamics and operators' experience, with the goal of selecting a suitable trajectory for the trolley along which the swing of payload will be constrained within an acceptable area. The second step is to construct a control law to guarantee that the trolley will track the planned trajectory. By decomposing the control of a crane into a two-stage design, this method exhibits some advantages including that it gets around the theoretical problem of attacking underactuated systems, and it enables the utilization of working experience when choosing proper trajectory for the trolley. Particularly, in this paper, a new S trajectory is proposed and an adaptive tracking controller is constructed to guarantee that the trolley will move along the selected trajectory. Specifically, an adaptive tracking controller is proposed for overhead crane systems to push the trolley along the desired trajectory, wherein an on-line estimation mechanism is introduced to address the uncertainties with system parameters and unknown disturbances. Due to this merit, the controller demonstrates great feasibility for utilization on an overhead crane in practice. The stability of the closed-loop system is proven by Lyapunov Stability Theory and Barbalat's Lemma. Simulation results are included to demonstrate the performance of the control method proposed in this paper.

The rest part of the paper is organized as follows: In section 2 the system model is introduced and some theoretical analysis is given. Section 3 describes the control design process for an overhead crane, including both trajectory planning and an adaptive tracking controller construction. Section 4 provides the stability analysis for the closed-loop system and simulation results are shown in section 5. Section 6 gives conclusions of the paper.

2. SYSTEM MODEL

Consider the 2D crane system described in Ma (2005):

$$M(q)\ddot{q} + V_m(q,\dot{q})\dot{q} + G(q) = u + F_d \tag{1}$$

where $q(t) = [\, x \ \theta \,]^T$ represents the system state vector. $M(q) \in \mathbb{R}^{2\times 2}$ is the system's inertia matrix. $V_m(q,\dot{q}) \in \mathbb{R}^{2\times 2}$ represents the Centripetal-Coriolis matrix, $G(q) \in \mathbb{R}^{2\times 1}$ denotes the gravity effects, $u(t) \in \mathbb{R}^{2\times 1}$ is the control input vector. The aforementioned variables are defined in detail as follows:

$$\begin{aligned} M(q) &= \begin{bmatrix} m_c + m_p & -m_p l \cos\theta \\ -m_p l \cos\theta & m_p l^2 \end{bmatrix}, \\ V_m(q,\dot{q}) &= \begin{bmatrix} 0 & m_p l \sin\theta\dot{\theta} \\ 0 & 0 \end{bmatrix}, \\ G(q) &= [\, 0 \ \ m_p g l \sin\theta \,]^T, \\ u(t) &= [\, F \ \ 0 \,]^T, \\ F_d(t) &= \begin{bmatrix} -F_r - 2k_{di}\dot{x} + k_{di} l \cos\theta\dot{\theta} \\ k_{di} l \cos\theta\dot{x} - k_{di} l^2\dot{\theta} \end{bmatrix}. \end{aligned}$$

where m_c, $m_p \in \mathbb{R}^+$ are trolley and payload mass respectively, and $l \in \mathbb{R}^+$ represents the length of rope. These three parameters are assumed constant but unknown in a transferring process. The system includes two degrees of freedom $x(t) \in \mathbb{R}^1$ and $\theta(t) \in \mathbb{R}^1$, which denote the trolley position and the swing angle (the angle between the rope and the vertical direction), respectively. $g \in \mathbb{R}^+$ is the gravity acceleration. $F(t) \in \mathbb{R}^1$ is the control input exerted on the trolley. $F_r + k_{di}\dot{x}$ denotes the friction acting on the trolley where $k_{di} \in \mathbb{R}^+$ stands for the unknown air friction coefficient, and $F_r(t) \in \mathbb{R}^1$ is the friction between the trolley and the rail, including both dynamical and static fraction. In the paper, the friction $F_r(t)$ is assumed of the following form Aschemann (2000):

$$F_r(t) = f_{r0}\tanh(\dot{x}/\epsilon) - k_r|\dot{x}|\dot{x} \tag{2}$$

where f_{r0}, $k_r \in \mathbb{R}^1$ are unknown friction-related parameters, $\epsilon \in \mathbb{R}^1$ is a static friction coefficient which can be obtained via an offline data analysis Aschemann (2000).

After some mathematical analysis for the system dynamics, it can be shown that the inertia matrix $M(q)$ is symmetric, positive definite, and satisfies the following property:

$$m_1 \|\xi\|^2 \le \xi^T M \xi \le m_2 \|\xi\|^2 \qquad \forall \xi \in \mathbb{R}^2 \tag{3}$$

where m_1, $m_2 \in \mathbb{R}^+$ are positive constants. Besides, a skew symmetric relationship exists between the inertia matrix $M(q)$ and the Centripetal-Coriolis matrix $V_m(q,\dot{q})$ as follows:

$$\xi^T(\frac{1}{2}\dot{M} - V_m)\xi = 0 \qquad \forall \xi \in \mathbb{R}^2. \tag{4}$$

During the transferring process for payloads, for safety reason, the rope length should be kept invariable and the swing angle should be within a small range. Based on this observation, we make the following assumptions:

Assumption 1. The connection between the trolley and payload is a mass-less and rigid link.

Assumption 2. During the transferring process, the swing angle of payload always remains in the interval between $-\pi$ and π:

$$-\pi < \theta(t) < \pi.$$

Remark 1. This paper considers the control problem for a 2D overhead crane system, yet it should be pointed out that the proposed design method can also be applied to a higher dimension overhead crane by decoupling it into several 2D crane systems with similar structure Cho (2000); Liu (2005).

3. ADAPTIVE TRACKING CONTROLLER DESIGN

As stated previously, the overhead crane is an underactuated system. Subsequently, it is impossible to maximize the speed of trolley and minimize the payload swing at the same time. Therefore, it is required to make comprises between these two indexes to achieve an optimal performance for the overall system. To reach this target, a common method utilized in practice is to adjust the speed of the trolley based on the observations for payload swing. That is, when the swing is small, the trolley is sped up to increase working efficiency; on the contrary, the trolley is slowed down if the swing intends to overstep the acceptable domain. Yet this empirical practice often leads to such drawbacks including low efficiency and high possibility of operation failure. Based on this reason, we propose a two-step control strategy for an underactuated overhead crane by utilizing both theoretical analysis and operation experience. Specifically, the strategy includes two stages of path planning and adaptive tracking controller design, which will be introduced in detail in the following subsections.

3.1 Trajectory Design

According to operation experience, it is known that to achieve a superior performance, the desired trajectory should be a S curve or a series of shaped impulses. Selecting the initial position as zero, then the trolley is required to reach the desired position with positive constant coordinate. Usually, to obtain satisfactory transferring efficiency, the trolley should always move toward the desired position. Based on this fact, the following assumption about $x_d(t)$ is made:

Assumption 3. The desired trajectory $x_d(t) \in \mathbb{R}^1$ takes a limit of a positive constant $p_d \in \mathbb{R}^+$:

$$\lim_{t\to\infty} x_d(t) = p_d$$

where p_d denotes the desired position, and $x_d(t)$ has third time derivatives with $x_d(t), \dot{x}_d(t), \ddot{x}_d(t), x_d^{(3)}(t) \in \mathcal{L}_\infty$, and $\dot{x}_d(t) \geq 0$.

Although any trajectory satisfying Assumption 3 can be tracked using the controller constructed in the next subsection, different selections of trajectory will often lead to distinct performance. In this paper a new S trajectory is proposed for trolley tracking:

$$x_d(t) = \frac{p_d}{2} + \frac{p_d}{2\epsilon_2} \ln\left(\frac{e^{kt-\epsilon_1} + e^{-(kt-\epsilon_1)}}{e^{kt-\epsilon_1-\epsilon_2} + e^{-(kt-\epsilon_1-\epsilon_2)}}\right) \quad (5)$$

where p_d denotes the desired trolley position defined in Assumption 3, $k \in \mathbb{R}^+$ is a coefficient to adjust the rising rate of the trajectory (a larger k will lead to a faster moving of the trolley, and subsequently a bigger swing of payload), $\epsilon_1, \epsilon_2 \in \mathbb{R}^+$ are two control parameters introduced to optimize the swing performance of payload.

The S trajectory proposed in the paper leads to less payload oscillation than other curves, which could be illustrated in the subsequent Simulation Results. Besides, this trajectory can be adjusted easily by changing the parameters $k, \epsilon_1, \epsilon_2$ to satisfy different requirements.

3.2 Adaptive Tracking Controller Design

Recently, a series of energy-based control methods have been reported to address underactuated mechanism of pendubot Fantoni (2000) Lozano (2000). In the paper, we utilize this idea of energy analysis and define a non-negative function $E(t) \in \mathbb{R}^1$ as follows:

$$E(\bar{q}, \dot{\bar{q}}) = \frac{1}{2}\dot{\bar{q}}^T M(\bar{q})\dot{\bar{q}} + m_p g l(1 - \cos\theta) \quad (6)$$

where $\bar{q}(t) \in \mathbb{R}^2$ is defined as follows:

$$\bar{q}(t) = [\, r(t) \;\; \theta(t) \,]^T \quad (7)$$

with $r(t) \in \mathbb{R}^1$ representing the following defined tracking error:

$$r(t) = x(t) - x_d(t). \quad (8)$$

After taking the time derivative of (6), substituting (2) - (4) into the resulting expression, and then canceling common terms, we obtain the following expression:

$$\begin{aligned}\dot{E}(t) = &\dot{r}(F + g(t)) + l\cos\theta\dot{\theta}(k_{di}\dot{x}_d + m_p\ddot{x}_d)\\ &-k_{di}l^2\dot{\theta}^2\end{aligned} \quad (9)$$

where $g(t) \in \mathbb{R}^1$ represents the following nonlinear function containing unknown parameters:

$$\begin{aligned}g(t) = &-f_{r0}\tanh(\dot{x}/\epsilon) + k_r|\dot{x}|\dot{x} - 2k_{di}\dot{x} + 2k_{di}lcos\theta\dot{\theta}\\ &-(m_c + m_p)\ddot{x}_d.\end{aligned} \quad (10)$$

To accomplish the control goal, we have to attack the uncertainty within the nonlinear item $g(t)$. It is noted that although unknown parameters are involved in $g(t)$, they enter the dynamics of $g(t)$ only via a linear manner as follows:

$$g(t) = Y^T\omega \quad (11)$$

where $Y(t) \in \mathbb{R}^{5\times1}$ denotes the regress vector which can be measured online, and $\omega \in \mathbb{R}^{5\times1}$ is an unknown parameter vector. The detailed expressions for $Y(t)$ and ω are given as follows:

$$\begin{aligned}Y(t) &= [\, 2\cos\theta\dot{\theta} \;\; -\tanh(\dot{x}/\varepsilon) \;\; |\dot{x}|\dot{x} \;\; -2\dot{x} \;\; -\ddot{x}_d \,]^T,\\ \omega &= [\, k_{di}l \;\; f_{r0} \;\; k_r \;\; k_{di} \;\; m_c + m_p \,]^T.\end{aligned} \quad (12)$$

According to the structure of (9) and the subsequent stability analysis, we design an adaptive tracking controller as follows:

$$F(t) = -Y^T\hat{\omega} - k_p r - k_d\dot{r} \quad (13)$$

where k_p, $k_d \in \mathbb{R}^+$ are positive control gains, and $\hat{\omega}(t) \in \mathbb{R}^{5\times1}$ is the on-line estimation of ω, which is generated by the following update law:

$$\dot{\hat{\omega}}(t) = \Gamma Y\dot{r} \quad (14)$$

with $\Gamma \in \mathbb{R}^{5\times5}$ being a diagonal, positive definite, update gain matrix.

4. STABILITY ANALYSIS

Theorem 1. The controller given in (13) ensures that the position/velocity of the trolley tracks the desired trajectory/velocity asymptotically fast, and the swing angle/velocity is regulated to zero in the sense that:

$$\lim_{t\to\infty} (\, x(t) \;\; \dot{x}(t) \;\; \theta(t) \;\; \dot{\theta}(t) \,) = (\, x_d(t) \;\; \dot{x}_d(t) \;\; 0 \;\; 0 \,).$$

Proof: To prove Theorem 1, we first define a non-negative function denoted by $V(t) \in \mathbb{R}^1$ as follows:

$$V(t) = E + \frac{1}{2}k_p r^2 + \frac{1}{2}\tilde{\omega}^T \Gamma^{-1}\tilde{\omega} \tag{15}$$

where $\tilde{\omega}(t) \in \mathbb{R}^{5\times 1}$ denotes the parameter estimation error:

$$\tilde{\omega}(t) = \omega - \hat{\omega}(t).$$

After taking the time derivative of (15) and then substituting the formulas of (9) - (14) into it, we obtain the following expression of $\dot{V}(t)$:

$$\dot{V}(t) = -k_d\dot{r}^2 - k_{di}l^2\dot{\theta}^2 + l\cos\theta\dot{\theta}(k_{di}\dot{x}_d + m_p\ddot{x}_d). \tag{16}$$

After noting the following fact:

$$l\cos\theta\dot{\theta}(k_{di}\dot{x}_d + m_p\ddot{x}_d) \le \frac{1}{4}k_{di}l^2\dot{\theta}^2 + \frac{(k_{di}\dot{x}_d + m_p\ddot{x}_d)^2}{k_{di}},$$

an upper bound of $\dot{V}(t)$ can be obtained as:

$$\dot{V}(t) \le -k_d\dot{r}^2 - \frac{3}{4}k_{di}l^2\dot{\theta}^2 + \frac{(k_{di}\dot{x}_d + m_p\ddot{x}_d)^2}{k_{di}}. \tag{17}$$

Integrating both sides of (17) yields:

$$\begin{aligned} V(t) \le{}& V(0) + \int_0^t \frac{(k_{di}\dot{x}_d + m_p\ddot{x}_d)^2}{k_{di}}dt \\ & -k_d\int_0^t \dot{r}^2 dt - \frac{3}{4}k_{di}l^2\int_0^t \dot{\theta}^2 dt. \end{aligned} \tag{18}$$

According to Assumption 3, it can be proven that $(k_{di}\dot{x}_d + m_p\ddot{x}_d) \in \mathcal{L}_2$, hence:

$$\int_0^t \frac{(k_{di}\dot{x}_d + m_p\ddot{x}_d)^2}{4k_{di}}dt \in \mathcal{L}_\infty. \tag{19}$$

Therefore, equation (18) can then be utilized to show that $V(t) \in \mathcal{L}_\infty$. Based on this fact, the following conclusion can be obtained by utilizing (15), (6) and the property of (3):

$$\dot{r}(t), \dot{\theta}(t), r(t), \tilde{\omega}(t) \in \mathcal{L}_\infty. \tag{20}$$

According to the definition of $\tilde{\omega}(t)$, equations (1), (12), (13) and (20), it is easy to see that:

$$\hat{\omega}(t), Y(t), F(t), \ddot{x}(t), \ddot{\theta}(t), \ddot{r}(t) \in \mathcal{L}_\infty. \tag{21}$$

On the other hand, after making some mathematical arrangement, (18) can be rewritten in the following manner:

$$\begin{aligned} k_d\int_0^t \dot{r}^2 dt + \frac{3}{4}k_{di}l^2\int_0^t \dot{\theta}^2 dt \le{}& \int_0^t \frac{(k_{di}\dot{x}_d + m_p\ddot{x}_d)^2}{k_{di}}dt \\ & +V(0) - V(t). \end{aligned} \tag{22}$$

Based on the previous facts of $(k_{di}\dot{x}_d + m_p\ddot{x}_d) \in \mathcal{L}_2$ and $V(t) \in \mathcal{L}_\infty$, (22) can then be employed to conclude that:

$$\dot{r}(t), \dot{\theta}(t) \in \mathcal{L}_2. \tag{23}$$

Based on the previous facts of $\dot{r}(t), \dot{\theta}(t) \in \mathcal{L}_2 \cap \mathcal{L}_\infty$ and $\ddot{r}(t), \ddot{\theta}(t) \in \mathcal{L}_\infty$, Barbalat's Lemma Khalil (2002) can then be directly utilized to show that:

$$\lim_{t\to\infty} \dot{r}(t) = 0, \lim_{t\to\infty} \dot{\theta}(t) = 0. \tag{24}$$

According to Assumption 3, we know that (see Appendix for detail):

$$\lim_{t\to\infty} \dot{x}_d(t) = 0, \lim_{t\to\infty} \ddot{x}_d(t) = 0,$$

hence, it is easy to see by (8) and (12) that:

$$\lim_{t\to\infty} \dot{x}(t) = 0, \lim_{t\to\infty} Y(t) = 0. \tag{25}$$

After substituting (2) and (13) into (1), and then making some mathematical manipulation, we can obtain the following equation about $\ddot{x}(t)$:

$$\ddot{x}(t) = f_{aux1}(t) + f_{aux2}(t) \tag{26}$$

where $f_{aux1}(t)$, $f_{aux2}(t) \in \mathbb{R}^1$ denote the following auxiliary functions:

$$\begin{aligned} f_{aux1}(t) ={}& (-m_p l\sin\theta\dot{\theta}^2 + k_{di}\cos^2\theta\dot{x} - k_{di}l\cos\theta\dot{\theta} \\ & -k_d\dot{r} - f_{r0}\tanh(\dot{x}/\epsilon) + k_r|\dot{x}|\dot{x} - 2k_{di}\dot{x} \\ & +k_{di}l\cos\theta\dot{\theta} - Y^T\hat{\omega})/(m_c + m_p\sin^2\theta), \\ f_{aux2}(t) ={}& (-m_p g\sin\theta\cos\theta - k_p r)/(m_c + m_p\sin^2\theta). \end{aligned} \tag{27}$$

It can be concluded that:

$$\lim_{t\to\infty} f_{aux1}(t) = 0, \dot{f}_{aux2}(t) \in \mathcal{L}_\infty$$

by utilizing (20), (24) and (25). Therefore, the Extended Barbalat's Lemma Khalil (2002) can be directly employed on equation (26) to show that:

$$\lim_{t\to\infty} \ddot{x}(t) = 0. \tag{28}$$

On the other hand, after some calculation for (1), the expression of $\ddot{\theta}(t)$ can be obtained as follows:

$$\ddot{\theta}(t) = \frac{1}{l}\cos\theta\ddot{x} - \frac{g}{l}\sin\theta + \frac{k_{di}}{m_p l}\cos\theta\dot{x} - \frac{k_{di}}{m_p}\dot{\theta}. \tag{29}$$

We can then go through a similar analysis on $\ddot{\theta}(t)$ to show that:

$$\lim_{t\to\infty} \ddot{\theta}(t) = 0, \lim_{t\to\infty} \sin\theta(t) = 0. \tag{30}$$

Assumption 2 can then be employed to show that:

$$\lim_{t\to\infty} \theta(t) = 0.$$

Substitute (24), (25), (28) and (30) into the system dynamics of (1) yields:

$$\lim_{t\to\infty} F(t) = 0.$$

Based on this fact, it is straightforward to see from (13), (24) and (25) that:

$$\lim_{t\to\infty} r(t) = 0. \tag{31}$$

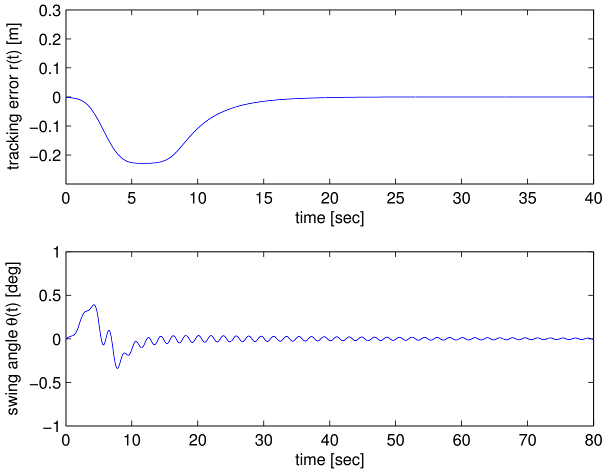

Fig. 1. Control performance

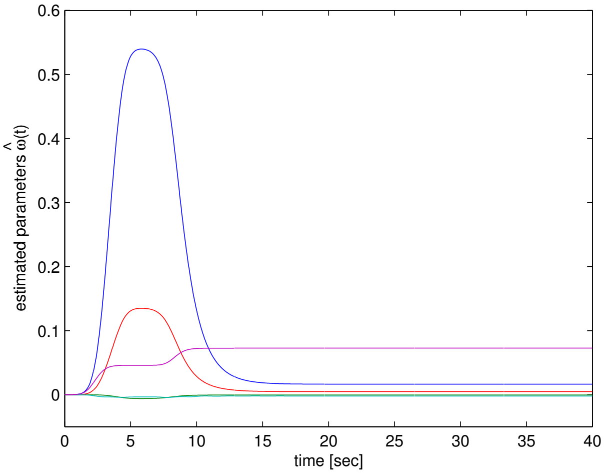

Fig. 2. Parameters estimation performance

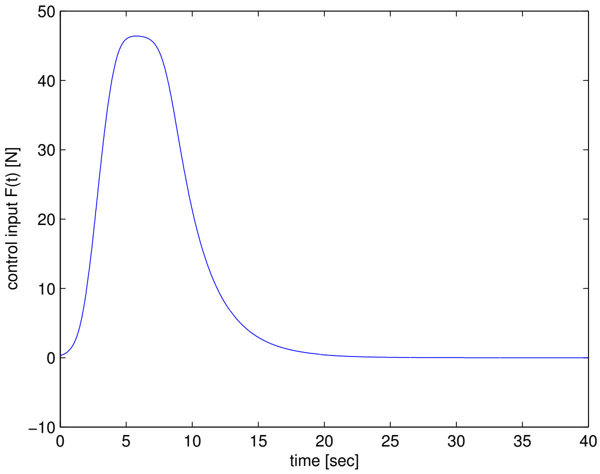

Fig. 3. Control input

5. SIMULATION RESULTS

To illustrate the controller performance, we simulate the constructed adaptive tracking controller of (13) in a crane testbed with the following parameters Fang (2001):

$$m_c = 3.5,\ m_p = 0.5,\ l = 0.9,\ g = 9.8.$$

And the friction parameters are chosen as follows:

$$f_{r0} = 50,\ k_r = -0.05,\ k_{di} = 0.02,\ \epsilon = 0.1.$$

The desired location of the trolley is selected as $p_d = 1$, and an S curve defined in (5) with the following parameters is selected as the desired trajectory:

$$k = 1,\ \epsilon_1 = 3,\ \epsilon_2 = 6.$$

The initial state of the system is chosen as:

$$x(0) = 0,\ \dot{x}(0) = 0,\ \theta(0) = 0,\ \dot{\theta}(0) = 0.$$

The control law is tuned until a best performance is achieved, which yields the following control gains:

$$k_p = 200,\ k_d = 10,\ \Gamma = 5I_5$$

where I_5 is a fifth-order identity matrix. Fig. 1 plots the tracking error of the trolley and the swing angle of payload, while the parameter estimation results are presented in Fig. 2, and control input is depicted in Fig. 3.

It can be seen that the tracking error of the trolley position reaches zero after 20 seconds and the swing angle goes to zero asymptotically fast. In the transferring process, the swing angle is less than 0.4 degree, which implies that the swing distance of payload in horizontal direction is less than 0.9 [m]$\times$ sin(0.4 [deg]) = 0.0063 [m].

To demonstrate that the new S trajectory (5) proposed in this paper leads to a better performance, the adaptive controller (13) is used to tracking the following trajectories separately:

$$x_{d1}(t) = p_d(1 - e^{-0.5t}) \tag{32}$$

$$x_{d2}(t) = p_d \frac{\tanh 0.3(t-1) + 1}{2} \tag{33}$$

where p_d denotes the desired trolley position defined in Assumption 3. Fig. 4 and Fig. 5 are the tracking performances for the two trajectories defined in (32) and (33). From these two figures, it is easy to see that although the transfer efficiencies of the trolley are identical, the anti-swing performance of tracking (32) or (33) is not as good as that of tracking the trajectory (5) proposed in this paper.

6. CONCLUSION

In this paper, an energy-based adaptive tracking control strategy is proposed for an underactuated crane system which ensures trajectory tracking of the trolley as well as the regulation for the swing of payload. Specifically, two steps are involved in the design to achieve a superior performance: firstly, this paper proposes a new S trajectory for trolley tracking; secondly, it constructs an adaptive controller to ensure that the trolley tracks a properly selected trajectory to reduce payload swing. As proven by Lyapunov techniques, the proposed adaptive control law guarantees an asymptotical tracking result even in the presence of uncertainties involved with system parameters and various disturbances. Simulation results are provided to show that the proposed control law not only achieves excellent steady-state tracking result, but also exhibits

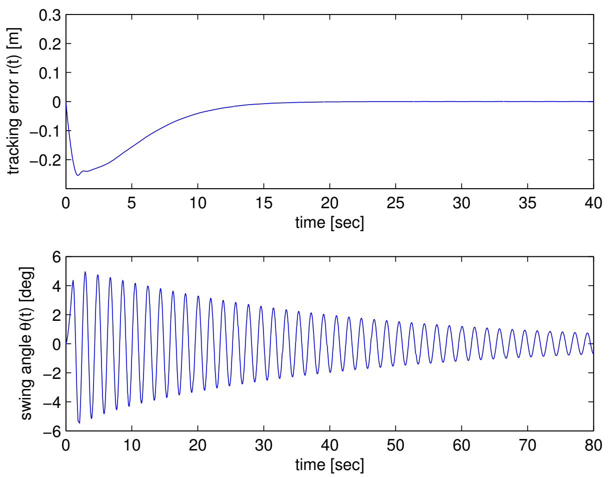

Fig. 4. Performance of tracking trajectory defined in (32)

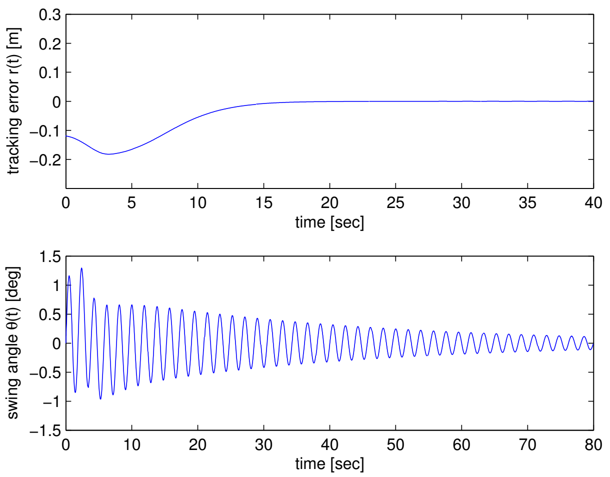

Fig. 5. Performance of tracking trajectory defined in (33)

superior transient performance for the swing of payload. Future work will attack the path planning problem for the crane system based on a rigorous theoretical analysis. Besides, future work will also target to extend the proposed design process to a class of general underactuated systems.

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