Adaptive Quantized Control of Offshore Underactuated Cranes with Uncertainty

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Abstract— **The anti-swing control of offshore cranes presents much more challenges. Most existing controllers for offshore cranes are designed based on linearized dynamics and require the accurate values of the plant parameters. In this paper, an adaptive sliding mode control scheme is investigated for a nonlinear underactuated crane system with unmodeled dynamics. The proposed control method can ensure asymptotic stability and does not need linearization of the complicated nonlinear dynamic equations during controller design and stability analysis. To reduce the communication burden in a network, a uniform quantizer is introduced in the input communication channel. A quantized adaptive sliding mode control scheme is further developed for the underactuated cranes to compensate for the effects of input quantization and uncertain parameters. The proposed controller together with the quantizer ensures the asymptotic stability of the closed-loop system in the sense of signal boundedness and zero stabilization error. Numerical simulations are conducted to illustrate the effectiveness of proposed schemes.**

I. INTRODUCTION

Cranes are used in various offshore industrial applications, e.g. load transportation, offshore drilling, and windmill farms, [1], [2], [3]. Since the number of available actuators or control inputs is less than the degree of freedom (DOF), cranes can be modeled as underactuated mechanical systems.The control task for cranes is to transport the load to the desired location precisely and quickly, while suppressing the payload swing simultaneously. It is desirable in industrial application, since it will increase transportation efficiency and ensure the safety of operations in various environments to avoid serious disasters.

Due to the theoretical and practical importance in the study of crane control systems, there has been a great deal of interest in the development of control schemes for offshore crane operations. Many control schemes have been proposed to control underactuated crane systems in the literature, such as PID control [4], model predictive control [5], neural network control [6], robust control in [7], energy-based nonlinear control [8], [9], [10], [11], [12], adaptive control in [13], [14], [15], [16], [17], sliding-mode control in [18], [19], [20], [21], [22], In [13] an adaptive control design method including path planning and tracking control was proposed for underactuated crane systems by combining theoretical analysis with empirical path planning methods. [14] studied adaptive control for flexible crane systems with the boundary output constraint. In [15], adaptive control of uncertain underactuated cranes was studied with a non-recursive control scheme. In [16], adaptive control for the cranes was investigated, where the updating law is designed to achieve accurate identifications of unknown parameters and exact compensation of the gravity-related lumped term. In [17], adaptive backstepping control was proposed for underactuated cranes with guaranteed transient performance. In [18], a robust sliding mode control was proposed for underactuated cranes with mismatched uncertainties. The sliding mode control for underactuated cranes with known parameters was proposed in [19], [20]. In [21], an anti-swing sliding mode control scheme for underactuated gantry cranes is proposed to keep the error variables staying on the surface. In [22], adaptive sliding mode control was designed for an offshore container crane with unknown disturbances.

Quantized control has attracted considerable attention in recent years, due to its theoretical and practical importance in practical engineering, where digital processors are widespread used and signals are required to be quantized and transmitted via a common network to reduce the communication burden. An important aspect is to use quantization schemes that yield sufficient precision, but require low communication rate for reducing the communication burden over the network. Control with input quantization has been studied in [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35].

From the above literature reviews, the position and anti-swing control of underactuated cranes have been extensively investigated and various control schemes have been proposed. However, how to apply a quantized control that the position error and the swing angle converge to the origin under parametric uncertainties remains unsolved. Most existing controllers for offshore cranes are designed based upon linearized dynamics and need the accurate values of the plant parameters. In this paper, an adaptive sliding mode control scheme is investigated for a nonlinear underactuated crane system with unmodeled dynamics. The parameters of the friction are not required to be known in the control design. The proposed control method can ensure asymptotic stability and does not need linearization of the complicated nonlinear dynamic equations during controller design and stability analysis. To reduce the communication burden in a network, a quantizer is introduced in the input communication channel. A quantized adaptive sliding mode control scheme is further developed for the underactuated cranes

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to compensate for the effects of input quantization and uncertain parameters. The proposed controller together with the quantizer ensures the stability of the closed-loop system in the sense of signal boundedness and stabilization error within an adjustable bound. Simulation results illustrate the effectiveness of the proposed schemes.

II. Problem Formulation

A. Underactuated Crane Model

An offshore crane system suffering from ship motions in Figure 1 is complicated. In this paper, the main focus is to control the payload position and suppress the swing angles as fast as possible. A 2-D underactautued crane system with a payload suspended is considered, as illustrated in Figure 2 in [13]. The crane dynamics with constant rope length is described as follows:

$$(M+m_p)\ddot{x}+m_pl\ddot{\theta}\cos\theta-m_pl\dot{\theta}^2\sin\theta=u+F_r \tag{1}$$

$$m_pl^2\ddot{\theta}+m_pl\cos\theta\ddot{x}+m_pgl\sin\theta=0 \tag{2}$$

where $x(t)$ and $\theta(t)$ represent the position of the cart and the swing angle of the rope, respectively. $u(t)$ is the control input. M denotes the weight of the crane system, m_p denotes the weight of the load, l denotes the length of the rope, and g is the gravitational constant, $g=9.8m/s^2$. F_r denotes the friction force which is approximately modeled as

$$F_r=f_1\tanh(\dot{x}/\xi)-f_2|\dot{x}|\dot{x}=\beta^T\psi(\dot{x}) \tag{3}$$

where

$$\psi(\dot{x})=[\tanh(\dot{x}/\xi),\quad -|\dot{x}|\dot{x}]^T \tag{4}$$

$$\beta=[f_1,\quad f_2]^T \tag{5}$$

where f_1 and f_2 are the friction parameters, ξ is a constant, $\psi(x,\xi)$ is a nonlinear function and β is an unknown parameter vector.
The following assumption is assumed.

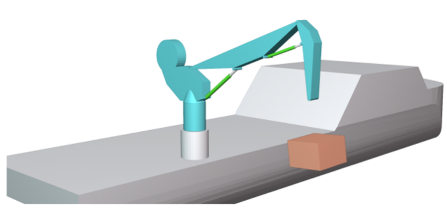

Fig. 1. Illustration of an offshore crane

Assumption 1: The swing angle satisfies $\theta(t) \in (-\pi/2,\pi/2)$.

Remark 1: The length of the rope l is a constant and available for control design. It is commonly required in [9], [21]. The friction parameters are not required to be known.

Remark 2: Note that the payload is always beneath the trolley during the overall transferring process, such that the swing angle $\theta(t)$ satisfies $\theta(t)\in(-\pi/2,\pi/2)$ in [5], [9], [16], [21].

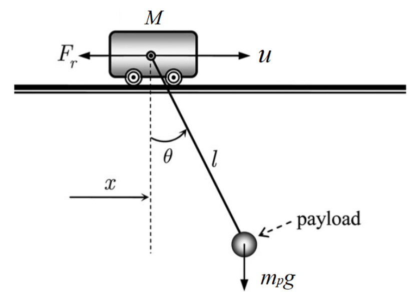

Fig. 2. Illustration of an underactuated crane [13]

In this paper, the control objective is to drive the crane from its initial position $x(0)=0$ to reach the target position x_d and suppress the pendulum swing angles at the same time, such as $x(t)\to x_d$ and $\theta(t)\to 0$ as $t\to\infty$.

III. Energy-based adaptive control

To facility the control design and stability analysis, the matrix representation of system (1)-(2) is written as

$$\boldsymbol{q}=[x,\ \theta]^T \tag{6}$$

$$M(q)\ddot{\boldsymbol{q}}=\begin{bmatrix} m_pl\dot{\theta}^2\sin(\theta)\\ -m_pgl\sin(\theta)\end{bmatrix}+\begin{bmatrix} u+\beta^T\psi\\ 0\end{bmatrix} \tag{7}$$

where the matrix $M(q)$ is defined as

$$M(q)=\begin{bmatrix} M+m_p & m_pl\cos(\theta)\\ m_pl\cos(\theta) & m_pl^2\end{bmatrix}. \tag{8}$$

It is clear that $M(q)=M(q)^T$ is positive, definite, and bounded. First, we analyze the energy storage function of pendulum crane, which can be written as follows:

$$E=\frac{1}{2}\dot{q}^TM(q)\dot{q}+m_pgl(1-\cos(\theta)) \tag{9}$$

Differentiating $E(t)$ gives that

$$\dot{E}=\dot{q}^TM(q)\ddot{q}+\frac{1}{2}\dot{q}^T\dot{M}(q)\dot{q}+m_pgl\sin(\theta)\dot{\theta} \tag{10}$$

From (8), we have

$$\dot{M}(q)=-m_pl\sin(\theta)\dot{\theta}\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}. \tag{11}$$

Then substituting (7) and (11) into the resulting equation (10), the derivative of $E(t)$ is given as

$$\begin{aligned}\dot{E}&=\dot{q}^T\begin{bmatrix} m_pl\dot{\theta}^2\sin(\theta)+u+\beta^T\psi\\ -m_pgl\sin(\theta)\end{bmatrix}\\ &\quad-\frac{1}{2}m_pl\sin(\theta)\dot{\theta}\dot{q}^T\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}\dot{q}+m_pgl\sin(\theta)\dot{\theta} \qquad (12)\\ &=\dot{x}[u(t)+\beta^T\psi] \qquad (13)\end{aligned}$$

which indicates that the pendulum crane system, with $u(t)+\beta^T\psi$ as the input and $\dot{x}(t)$ as the output, is passive.
To achieve the control objective, the following Lyapunov

control function is constructed:

$$V = E + \frac{k_1}{2}e^2 + \frac{1}{2}\tilde{\beta}^T\Gamma^{-1}\tilde{\beta} \tag{14}$$

where $e(t) = x(t) - x_d$ is the tracking error of the position, k_1 is a positive constant, $\hat{\beta}$ is an estimate of β, $\tilde{\beta} = \beta - \hat{\beta}$, $\Gamma \in$ is a positive definite matrix. Then the time-derivative of V is

$$\begin{aligned}\dot{V} &= \dot{E} + \dot{x}k_1 e - \tilde{\beta}^T\Gamma^{-1}\dot{\hat{\beta}} \\ &= \dot{x}[u(t) + k_1 e + \beta^T\psi] - \tilde{\beta}^T\Gamma^{-1}\dot{\hat{\beta}} \end{aligned} \tag{15}$$

The adaptive control law and parameter estimator are designed as

$$u(t) = -k_1 e - k_2\dot{x} - \hat{\beta}^T\psi \tag{16}$$

$$\dot{\hat{\beta}}(t) = \Gamma\psi\dot{x} \tag{17}$$

where k_2 is a positive constant. Thus

$$\begin{aligned}\dot{V} &= \dot{x}\left(-k_1 e - k_2\dot{x} - \hat{\beta}^T\psi + k_1 e + \beta^T\psi\right)) - \tilde{\beta}^T\Gamma^{-1}\dot{\hat{\beta}} \\ &= -k_2\dot{x}^2 - \tilde{\beta}^T\Gamma^{-1}(\dot{\hat{\beta}} - \Gamma\psi\dot{x}) \\ &= -k_2\dot{x}^2 \leq 0. \end{aligned} \tag{18}$$

It directly implies that

$$V(t) \leq V(0). \tag{19}$$

We then have the following stability and performance results based on the developed control scheme.

Theorem 1: Considering the closed-loop adaptive system consisting of the system (1)-(2), the adaptive controller (16), and the parameter updating law (17). All signals in the closed-loop system are ensured to be bounded. Furthermore, asymptotic tracking of position is achieved, i.e. $x(t) - x_d \to 0$, $\theta(t) \to 0$, $\dot{x}(t) \to 0$, $\dot{\theta}(t) \to 0$ as $t \to \infty$.

Proof: By applying the LaSalle-Yoshizawa theorem to (18), V is uniformly ultimate bounded. The matrix $M(q)$ is positive definite and bounded. This further implies that $\dot{e} = \dot{x}$, $\dot{\theta}$, e, $\tilde{\beta}$ are bounded and $\dot{e} = \dot{x}$ is asymptotically stable, such as $\lim_{t\to\infty}\dot{x} = 0$. x is also bounded since $e = x - x_d$ and x_d are bounded. From (16), it follows that the control input u is bounded. Equation (18) shows that $\dot{V}$ is bounded, such as $\dot{V} \in \mathcal{L}_\infty$. Again from (10), it shows that $\ddot{\theta} \in \mathcal{L}_\infty$. Hence, Barbalat's lemma is employed to show that $\lim_{t\to\infty}\dot{\theta} = 0$. Based on the fact that $\theta(t)$ and $\sin(\theta(t))$ have the same sign for $\forall\ \theta \in (-\frac{\pi}{2},\ +\frac{\pi}{2})$. Equation (1) can be written as

$$\frac{d}{dt^2}\Big[\ (M + m_p)x + m_p l\sin\theta\Big] = u + F_r \tag{20}$$

Then the asymptotically stable $e,\ \dot{x},\ \theta,\ \dot{\theta},\ u\ \to 0$ as $t \to \infty$.

IV. Adaptive Sliding Mode Control

To facility the sliding mode control design and stability analysis, the system (7) is further transformed to the following model.

$$\ddot{x} = \phi_1(\theta,\dot{\theta}) + b_1(\theta)(u + \beta^T\psi) \tag{21}$$

$$\ddot{\theta} = \phi_2(\theta,\dot{\theta}) + b_2(\theta)(u + \beta^T\psi) \tag{22}$$

where $\phi_i(\theta,\dot{\theta})$ and $b_i(\theta)$ are defined as

$$\phi_1 = \frac{m_p l\dot{\theta}^2\sin(\theta) + m_p g\sin(\theta)\cos(\theta)}{M + m_p\sin^2(\theta)} \tag{23}$$

$$b_1 = \frac{1}{M + m_p\sin^2(\theta)} \tag{24}$$

$$\phi_2 = -\frac{(M + m_p)g\sin(\theta) + m_p l\dot{\theta}^2\sin(\theta)\cos(\theta)}{(M + m_p\sin^2(\theta))l} \tag{25}$$

$$b_2 = -\frac{\cos(\theta)}{(M + m_p\sin^2(\theta))l} \tag{26}$$

Clearly, system (21)-(22) is an underactuated system.
We firstly design the sliding surfaces of the trolley and payload subsystems as

$$s_1 = c_1(x - x_d) + \dot{x} \tag{27}$$

$$s_2 = c_2\theta + \dot{\theta} \tag{28}$$

where c_1, c_2 are predefined positive constants. Then the second layer sliding surface is designed as

$$S = \lambda s_1 + s_2 = \lambda c_1(x - x_d) + \lambda\dot{x} + c_2\theta + \dot{\theta} \tag{29}$$

where λ is a constant. The derivative of S yields

$$\begin{aligned}\dot{S} &= \lambda c_1\dot{x} + \lambda\ddot{x} + c_2\dot{\theta} + \ddot{\theta} \\ &= \lambda c_1\dot{x} + \lambda\phi_1 + c_2\dot{\theta} + \phi_2 + (\lambda b_1 + b_2)(u + \beta^T\psi) \end{aligned} \tag{30}$$

Define the Lyapunov function as

$$V = \frac{1}{2}S^2 + \frac{1}{2}\tilde{\beta}^T\Gamma^{-1}\tilde{\beta} \tag{31}$$

The control law and the parameter update law are designed as

$$\begin{aligned}u(t) = &\frac{-k_1 S - k_2 sign(S)}{\lambda b_1 + b_2} - \hat{\beta}^T\psi \\ &- \frac{c_1\lambda\dot{x} + \lambda\phi_1 + c_2\dot{\theta} + \phi_2}{\lambda b_1 + b_2} \end{aligned} \tag{32}$$

$$\dot{\hat{\beta}}(t) = \Gamma\psi S \tag{33}$$

Then the derivative of V

$$\begin{aligned}\dot{V} &= S[-k_1 S - k_2 sign(S) + \tilde{\beta}^T\psi] - \tilde{\beta}^T\Gamma^{-1}\dot{\hat{\beta}} \\ &= -k_1 S^2 - k_2|S| - \tilde{\beta}^T\Gamma^{-1}(\dot{\hat{\beta}} - \Gamma\psi S) \\ &= -k_1 S^2 - k_2|S| \end{aligned} \tag{34}$$

Equation (31) and (34) imply that S is uniformly bounded and monotonically decreasing, and that it also converges asymptotically to zero as $t \to \infty$. It further implies that the first layer sliding variables s_1 and s_2 are asymptotically stable, as shown in [18]. The stability and performance results are summarized in the following theorem.

Theorem 2: Considering the closed-loop adaptive system consisting of the underactuated crane system (1)-(2), the adaptive sliding mode controller (32) with (29), the parameter updating law (33). All signals in the closed-loop system are ensured to be bounded. Furthermore, asymptotic stability is achieved, such as $x(t) - x_d \to 0$, $\theta(t) \to 0$, $\dot{x}(t) \to 0$, $\dot{\theta}(t) \to 0$ as $t \to \infty$.

V. Adaptive Quantized Control

We consider a control system with input quantization as shown in Figure 3, such that the input u is quantized at the encoder side to be sent over the network. The network is assumed noiseless, so that the quantized input $q(u)$ is recovered and sent to the crane plant.
The same model (21)-(22) with input quantization is given as follows:

$$\ddot{x} = \phi_1(\theta, \dot{\theta}) + b_1(\theta)(q(u) + \beta^T \psi) \tag{35}$$

$$\ddot{\theta} = \phi_2(\theta, \dot{\theta}) + b_2(\theta)(q(u) + \beta^T \psi) \tag{36}$$

where $q(u)$ is the quantized input.

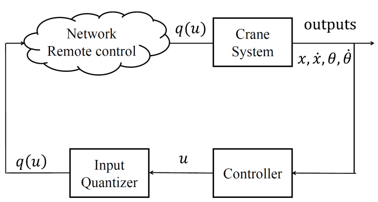

Fig. 3. Crane control with input quantization over a network

A. Uniform quantizer

A uniform quantizer is considered in the paper, which is modeled as

$$q(u) = \begin{cases} u_i sgn(u), & u_i - \frac{l}{2} < |u| \le u_i + \frac{l}{2} \\ 0, & |u| \le u_0 \end{cases}, \tag{37}$$

where $u_0 > 0$ and $u_1 = u_0 + \frac{l}{2}$, $u_i = u_{i-1} + l$ with $i = 2, \ldots,$ and l is the length of the quantization interval. $q(u)$ is in the set $U = \{0, \ \pm u_i\}$. The map of the uniform quantizer (37) is shown in Figure 4. The quantizer $q(u)$ has

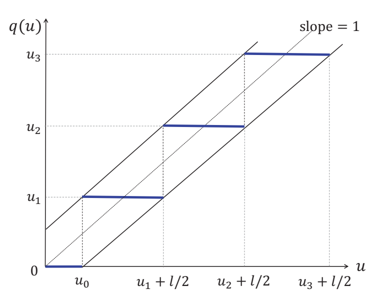

Fig. 4. The map of uniform quantizer $q(u)$

the following property.

$$|q(u) - u| \quad \le \quad \delta, \tag{38}$$

where $\delta > 0$ is quantization bound.
In order to propose a suitable control scheme, we decompose the quantizer into the following form.

$$q(u) = u + d(t) \tag{39}$$

where $d(t) = q(u(t)) - u(t)$. Clearly the property (38) is satisfied with $|q(u) - u| \le \delta = \max\{u_0, \ l\}$.

B. Adaptive Quantized Control

The control law and the parameter update law are designed as

$$\begin{aligned} u(t) = & \frac{-k_1 S - k_2 sign(S)}{\lambda b_1 + b_2} - \hat{\beta}^T \psi \\ & - \frac{c_1 \lambda \dot{x} + \lambda \phi_1 + c_2 \dot{\theta} + \phi_2}{\lambda b_1 + b_2} \end{aligned} \tag{40}$$

$$S = \lambda c_1 (x - x_d) + \lambda \dot{x} + c_2 \theta + \dot{\theta} \tag{41}$$

$$\dot{\hat{\beta}}(t) = \text{Proj}\{\Gamma \psi S\} \tag{42}$$

where Proj$\{\cdot\}$ is the projection operator given in [36].

Remark 3: The projection operator $\text{Proj}\{\cdot\}$ in (42) ensures that the estimate and estimation error are nonzero and within known bound, that is $\|\hat{\beta}\| \le k_\beta$ and $\|\tilde{\beta}\| \le k_\beta$, and has the property $-\tilde{\beta}^\top \Gamma^{-1} \text{Proj}(\psi \text{S}) \le -\tilde{\beta}^\top \Gamma^{-1} \psi \text{S}$, which are helpful to guarantee the closed-loop stability.
The stability and performance results are summarized in the following theorem.

Theorem 3: Considering the closed-loop adaptive system consisting of the underactuated crane system (1)-(2) with a uniform input quantizer (37), the adaptive sliding mode controller (40) with the surface (41), the parameter updating law (42). All signals in the closed-loop system are ensured to be bounded. Furthermore, asymptotic stability is achieved, such as $x(t) - x_d \to 0$, $\theta(t) \to 0$, $\dot{x}(t) \to 0$, $\dot{\theta}(t) \to 0$ as $t \to \infty$.

Proof: Define a Lyapunov function as

$$V = \frac{1}{2} S^2 + \frac{1}{2} \tilde{\beta}^T \Gamma^{-1} \tilde{\beta} \tag{43}$$

Then the derivative of V is derived as

$$\dot{V} = -k_1 S^2 - k_2 |S| + (\lambda b_1 + b_2) S d(t) \tag{44}$$

$$- \tilde{\beta}^T \Gamma^{-1} (\dot{\hat{\beta}} - \Gamma \psi S)$$

$$= -k_1 S^2 - k_2 |S| + (\lambda b_1 + b_2) S d(t) \tag{45}$$

$$- \tilde{\beta}^T \Gamma^{-1} (\text{Proj}\{\Gamma \psi S\} - \Gamma \psi S)$$

$$\le -k_1 S^2 - k_2 |S| + |(\lambda b_1 + b_2) \delta| |S| \tag{46}$$

$$\le -k_1 S^2 - \bar{k}_2 |S| \tag{47}$$

where the control parameter k_2 satisfies

$$k_2 > |(\lambda b_1 + b_2) \delta| \tag{48}$$

where $\bar{k}_2 = k_2 - |(\lambda b_1 + b_2) \delta| > 0$. It shows that all signals are bounded since the parameter estimates $\hat{\beta}$ are bounded with the projection. The proof of asymptotic stability is same as the proof in Theorem 2. ■

Remark 4: The control parameter k_2 and the quantization parameter δ are chosen to satisfy (48).

VI. Simulation

In this section, a numerical simulation in Matlab is shown to illustrate the effectiveness of the proposed schemes. The physical parameters for the crane system are given as $M = 5kg$, $m_p = 0.1kg$, $l = 0.5m$, $g = 9.8m/s^2$. The friction parameters are $f_1 = 0.5, f_2 = 0.005, \xi = 0.1$. The reference signal is set as $x_d = 1$ m.
The control gains are designed as follow. For the energy-based adaptive control: $k_1 = 4$, $k_2 = 8$, $\Gamma = \text{diag}\{1.6,\ 0.1\}$. For the adaptive sliding mode control: $c_1 = 0.75$, $c_2 = 10$, $\lambda = -4$, $k_1 = 8$, $k_2 = 0.05$, $\Gamma = \text{diag}\{1.6,\ 0.1\}$. The initial value of the states are $x(0) = 0$ and $\theta(0) = 0$. The initial estimated friction parameters are $\hat{\beta}(0) = 0$.

A. *Without quantization*

Two proposed control schemes, energy based adaptive control (EAC) and adaptive sliding mode control (ASMC), are compared to show their effectiveness and superiority. Figure 5 and Figure 7 and show the position x, swing angle θ and control input $u(t)$ using EAC and ASMC methods proposed in the paper respectively. Figure 8 and Figure6 show the velocity $\dot{x}$ and swing velocity $\dot{\theta}$ using EAC and ASMC respectively. As shown in the simulations, both methods are able to drive the cart from the initial position to reach the target position x_d in 6 seconds for ASMC and 10 seconds for EAC. ASMC method is able to suppress the swing angle in 6 seconds. The EAC dose not suppress the angle in 20 seconds and will suppress it in about 200 seconds. The results with ASMC method show that tracking of position is achieved and the velocity of cart, the swing angular and its velocity converge to zero, in accordance with the findings of Theorem 2. Therefore in terms of position stabilization and anti-swing control, the adaptive sliding mode control scheme outperforms the energy based adaptive control scheme.

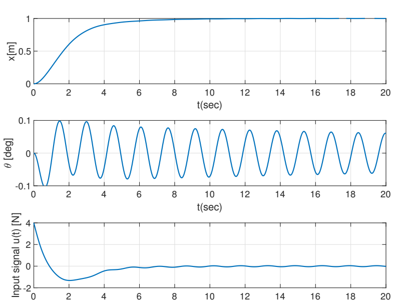

Fig. 5. Energy-based control: position x, payload swing θ, and control $u(t)$

B. *With quantization*

The system is then tested with a uniform quantized input and with the proposed adaptive control method in section V. The quantization level is chosen as $l = 1$ and $u_0 = \frac{l}{2}$. Figures 9 shows the position x, swing angle θ and control input $u(t)$. Figure 10 shows the velocity of the cart $\dot{x}$, and swing velocity $\dot{\theta}$ using the quantized adaptive sliding mode control method. The results show that tracking is achieved

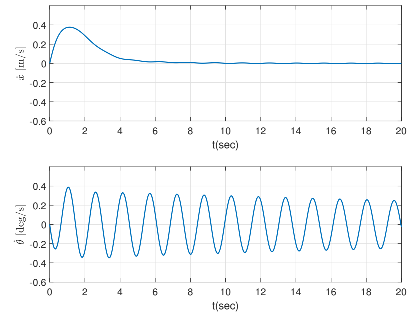

Fig. 6. Energy-based control: velocity $\dot{x}$, payload swing speed $\dot{\theta}$

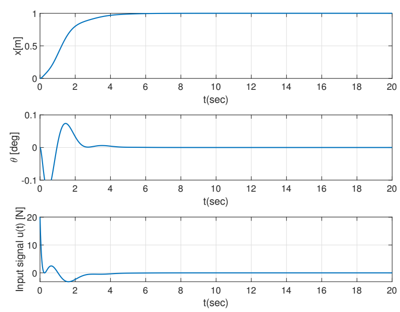

Fig. 7. ASMC: position x, payload swing θ, and control $u(t)$

and that all signals are uniformly bounded, in accordance with the findings of Theorem 3.

VII. CONCLUSIONS

The paper proposes a nonlinear adaptive sliding mode control scheme for underactuated offshore cranes with uncertainties. The proposed control method can ensure asymptotic stability and does not need linearization of the complicated nonlinear dynamic equations during controller design and stability analysis. To reduce the communication burden in the remote control of cranes, a uniform quantizer is introduced in the input channel. The proposed quantized adaptive control scheme ensures the closed-loop asymptotic stability. Simulation results illustrate the effectiveness of proposed schemes.

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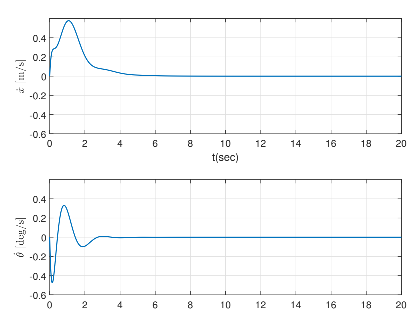

Fig. 8. ASMC: velocity $\dot{x}$, payload swing speed $\dot{\theta}$

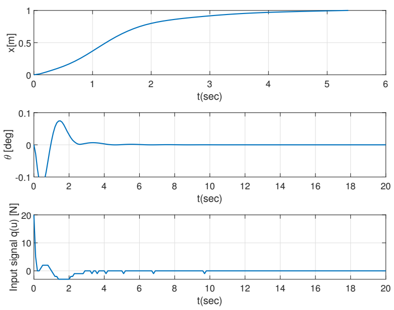

Fig. 9. Quantized ASMC: position x, payload swing θ, and control $u(t)$

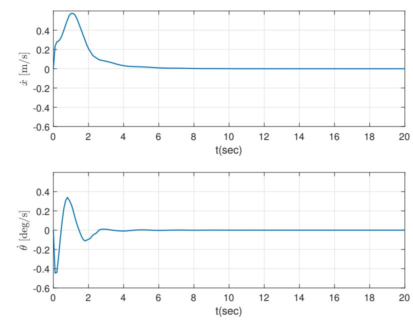

Fig. 10. Quantized ASMC: velocity $\dot{x}$, payload swing speed $\dot{\theta}$

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