

Anti-Swing Control of A New Container Crane With Fuzzy Uncertainties Compensation

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Abstract—A class of new container cranes with eight-link lifting mechanics which can reduce sway efficiently as a result of improved lifting structure have been put to use recently, and both modeling and swing control of such a crane system attracts a lot attention in the field of control technology development. In this paper, dynamics model of the new container crane is investigated, an anti-swing control scheme with fuzzy uncertainty compensation is proposed to ensure the positioning control as well as overall closed-loop system stability. None of the system parameters is required for the controller design in a priori. In the proposed control laws, the position error can be driven to a bounded area while the swing angle can also be rapidly damped so as to achieve minimal sway of the crane system. Stability analysis of the controller is also given. Finally, simulation results show the performance successfully.

Keywords—container crane; eight-link lifting; anti-swing control; fuzzy uncertainty compensation; positioning control

I. INTRODUCTION

Container crane systems are widely used throughout the world in thousands of harbors, warehouses, and etc. for loading and transporting heavy cargos. Crane systems are desired to be able to move to the required position as fast and as accurate as possible while placing the payload at the appropriate position, meanwhile, the payload swing angle should be kept as small as possible. However, these crane structures are highly flexible in nature, apart from their underactuated dynamics property in control, some external disturbances, such as wind, hit or motion of the crane support unit can cause the payload to oscillate, as a result, this oscillation may bring damage to surrounding equipment and the payload itself, also, swing of the payload or hook makes precision positioning time consuming and inefficient for transporting operation.

Generally, difficulties in using a container crane lies in three aspects: motion-induced oscillation, disturbance-induced oscillation, and positioning capability. Many works have been done to improve the structure of container cranes practically, e.g. enhance the stiffness of lifting-link mechanism, and develop swing-free equipments, as well as investigate new control methods for crane system.

Many solutions [1]-[14] have been extensively studied in recent years for the simultaneous control of payload swing and of crane trajectory tracking, and some of them have led to industrial applications. Generally speaking, the dynamic

equations of a crane are coupling, nonlinear and time-varying differential equations. The control schemes developed in the literature may be broadly grouped into three categories [11]: optimal control and linearized control [1], [4], and [5], command shaping control [6], [8], and nonlinear control [2], [9]. The implementation of these various control methods still presents several challenges. A common difficulty is the nonlinear behavior of drives and motors that actuate crane motion. Nonlinear behaviors such as friction, variables coupling of overhead crane system have been difficult to evaluate with traditional analysis techniques, and are, therefore, often neglected in controller design.

Resort to linearized theorem and optimal control approaches, many work has been done to design controller according to linearized crane model. A problem related to linearized control is its inability to be implemented in real-time, owing to the necessity of precomputation of system trajectories. Moreover, these linearized methods (such as time-optimal control etc.) cannot provide the sufficient accuracy of information about position error and load swing. Besides, the uncertain nonlinear factors such as the wind, the hit, and the friction of track will also reduce the performance of linearized crane control systems [12]. Command shaping is a reference signal modification technique that is implementable in real time [7]. Input shaping techniques have proven effective at significantly reducing motion-induced cable sway during crane motion. However, approaches on input shaping control which is naturally of open-loop control focused on the suppression of load swing but not solve the problem of position error during crane motion. Besides, the time period between the impulses of the input shaping method was also hard to obtain [11]. Nonlinear control is the most common strategy used in research efforts to mitigate positioning and cable sway errors, and some wonderful solutions for crane control have been derived by this means. However, these methods unavoidably need the prior knowledge of the crane dynamics which is actually hardly acquired, moreover, it is not easy for an engineer to design an industrial crane controller based on the mathematic model of the crane. For many years, the intelligent control (such as fuzzy-based methods and neural network-based methods) [13], [14] has been considered as a none-model based solution to nonlinear systems. It is well known that intelligent control derived from the desire of linguistic description or approximation of the whole nonlinearity for complex system, and it can be utilized to

formulate and imitate the human intelligence to construct control strategies, as well as approximate arbitrarily nonlinear dynamics.

In this paper, dynamics model of a new container crane system is investigated, then, an anti-swing tracking control law for this container crane system with fuzzy uncertainties compensation is presented to ensure the positioning control as well as overall closed-loop system stability. None of the crane dynamics parameters are needed for the controller design in a priori. In the developed control laws, the position error will be driven to zero while the sway angle being also rapidly damped so as to achieve minimal swing of the payload. Stability analysis of the proposed control law is given. Finally, simulation results show the performance successfully.

This paper is organized as follows. The modeling of the new container crane system and trajectory tracking problem is presented in Section II. The proposed adaptive anti-swing control law is illustrated in Section IV. In Section V, simulation results are given. This paper concludes with a summary in Section VI.

II. PROBLEM FORMULATION

A. Container Crane Dynamics

The schematic drawing in figure 1 presents a structure of a new container crane system with eight-link lifting mechanism which has been put in use recent years.

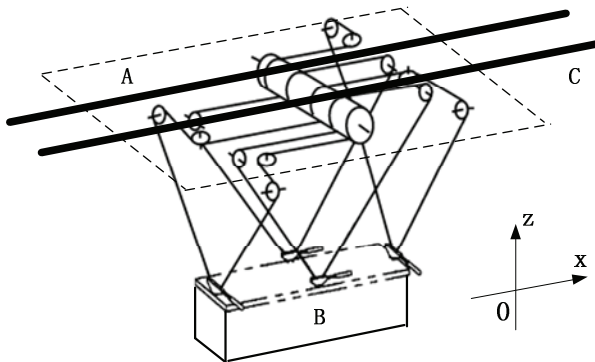


Figure 1. a new container crane system with eight-link lifting mechanism.

A – trolley system B – payload C – track

To facilitate modeling the new container crane system, it is assumed that the crane system possesses the following characteristics:

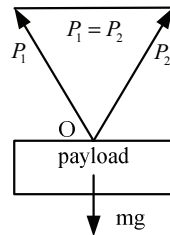


Figure 2. inverted-triangle and payload with $P_1 = P_2$.

- The payload mass B and crane trolley A are assumed to be connected by eight massless, rigid links
- The payload mass B is assumed to be concentrated at a point and the value of this payload mass and the overall trolley mass are known exactly.
- The pulley wheels in A and hinged joints, where the payload links connect to crane trolley are assumed to be frictionless.

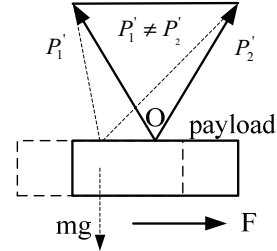


Figure 3. inverted-triangle link and payload with $P_1 \neq P_2$.

- The control input to the system is the mechanical force applied directly to the trolley.

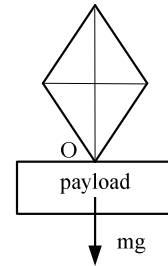


Figure 4. equivalent parallelogram mechanism for an inverted-triangle link system.

- To simplify the analysis, only trolley moving along x-axis direction will be considered.

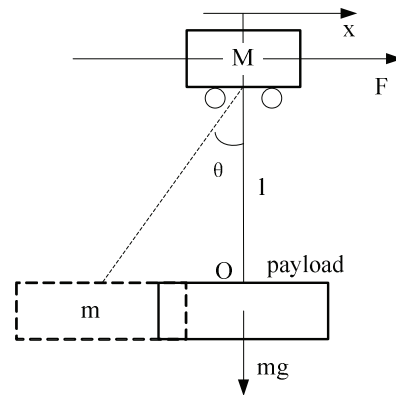


Figure 5. swing of the payload in x-z plane.

In figure 1, when the trolley moves at a constant speed, the inverted-triangle link mechanism endures a balanced force $P_1 = P_2$ as shown in figure 2, and the payload moves accompanying with crane trolley at the same velocity. When the trolley starts up or brakes down, an inertial force coming from payload drives the inverted-triangle link frame

distorted, then $P'_1 < P'_2$ as shown in figure 3, while the projection force F of P'_1 and P'_2 on x-axis given by the distorted inverted-triangle system tries to reject this distortion and draw back the payload mass to its 'origin' O , as a result, swing of payload along x-axis shrinks. Furthermore, when the inverted-triangle link frame is forced to distort due to starting up or braking down, the link system is therefore equivalently stretched along x-axis. This effect of interplay force given by link system can be described using a parallelogram mechanism as shown in figure 4 [15]. The complex force F of the parallelogram system eventually has the payload move along horizontal direction rather than arc of a pendulum as shown in figure 5. Then, this kind of linear motion of payload under effect of parallelogram mechanism can be modeled as a spring oscillator system, the new container crane finally can be present as figure 6, where M , m are mass of the trolley and payload respectively, x position of the trolley, l the equivalent length of link, θ payload angle with respect to the vertical.

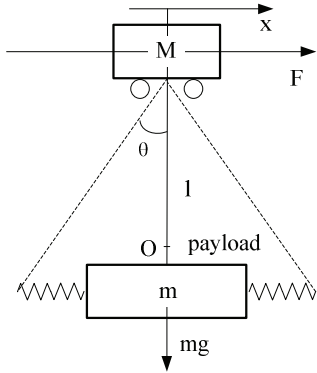


Figure 6. equivalent model for the container crane system

The purpose of this paper is to control the motion of the container crane in figure 6 to achieve the desired position of its payload along a given trajectory.

To derive dynamic equation of the above crane system, the total energy associated with the crane system needs to be computed using the Lagrangian approach. The kinetic energy of the above crane can be divided into two parts:

$K = K_{trolley} + K_{payload}$, where $K_{trolley} = \frac{1}{2} M \dot{x}^2$ denotes trolley kinetic energy and $K_{payload} = \frac{1}{2} m (\dot{x} + l \dot{\theta} \cos \theta)^2$ is payload kinetic energy. Finally, we have

$$K = \frac{1}{2} (M + m) \dot{x}^2 + m l \sec^2 \theta \cdot \dot{\theta} \cdot \dot{x} + \frac{1}{2} m l^2 \sec^4 \theta \cdot \dot{\theta}^2 \quad (1)$$

The potential energy of the payload shifting from its origin can be express using spring oscillator system, i.e.

$$P = -\frac{1}{2} k_s (l \theta)^2 = -\frac{1}{2} k_s l^2 \theta^2 \quad (2)$$

where k_s is an equivalent spring coefficient which relates to the structure of reverted-triangle system and its links.

The Lagrange equations of motion are formed as

$$\begin{aligned} \frac{d}{dt} \left[\frac{\partial L}{\partial \dot{x}} \right] - \frac{\partial L}{\partial x} &= u \\ \frac{d}{dt} \left[\frac{\partial L}{\partial \dot{\theta}} \right] - \frac{\partial L}{\partial \theta} &= 0 \end{aligned} \quad (3)$$

where u represents control force acting on the trolley.

After calculation about above equations, the dynamics of the new container crane depicted in figure 6 may be expressed in the Lagrange form as

$$M(q) \ddot{q} + C(q, \dot{q}) \dot{q} + G(q) + \tau_d = U \quad (4)$$

where $q(t) = [x(t), \theta(t)]^T$ is position and swing angle variable vector, $M(q)$ is the inertia matrix, $C(q, \dot{q})$ is the coriolis/centripetal matrix, $G(q)$ is the gravity vector, τ_d denotes bounded unknown disturbance (including e.g. unstructured unmodeled dynamics), and $U = [u(t), 0]^T$ is the control input torque. For the 2D container crane shown in Figure 6, we have the followings,

$$\begin{aligned} M(q) &= \begin{bmatrix} M_{pp} & M_{p\theta} \\ M_{p\theta} & M_{\theta\theta} \end{bmatrix}, \quad C(q, \dot{q}) = \begin{bmatrix} C_{pp} & C_{p\theta} \\ C_{p\theta} & C_{\theta\theta} \end{bmatrix}, \\ G(q) &= \begin{bmatrix} G_p \\ G_\theta \end{bmatrix}, \quad \tau_d = \begin{bmatrix} \tau_p \\ \tau_\theta \end{bmatrix}, \quad U = \begin{bmatrix} u \\ 0 \end{bmatrix} \end{aligned} \quad (5)$$

The following properties are easily be demonstrated for the container crane [16]:

Property 1: $M(q)$ is a positive definite symmetric matrix bounded by $\alpha_1 I \leq M(q) \leq \alpha_2 I$ with $\alpha_{1,2}$ positive constant.

Property 2: $C(q, \dot{q})$ is bounded by $c_b(q) \|\dot{q}\|$ with $c_b(q) \in R$.

Property 3: The matrix $\dot{M} - 2C$ is skew-symmetric.

B. Trajectory Tracking Problem

Given a desired trajectory within a compact set, i.e. $q_d(t) \in R^{2 \times 1}$, the tracking error is $e(t) = q_d(t) - q(t)$ and the filtered tracking error may be defined as

$$s(t) = [s_x(t), s_\theta(t)]^T = \dot{e}(t) - \lambda e(t) \quad (6)$$

where $\lambda = \lambda^T > 0$ is a design parameter matrix, usually selected diagonal. A controller will be designed to keep the filtered tracking error $s(t)$ bounded.

Since the linear time-invariant system (6) is exponentially stable from the input $s(t)$ to output $e(t)$, the boundedness of the $s(t)$ implies the boundedness of the output tracking error $e(t)$. In fact, these ultimate bounds can be related as

$$\|e\|_2 \leq \frac{\|s\|_2}{\sigma_{\min}(\lambda)}, \quad \left\| \frac{e}{\lambda} \right\|_2 \leq \|s\|_2 \quad (7)$$

where $\sigma_{\min}(\lambda)$ is the minimum singular value of λ .

Differentiate $s(t)$ and using (6), the crane dynamics (4) may be written in terms of the filtered tracking error as

$$M\dot{s} = -Cs + f + \tau_d - U \quad (8)$$

where the nonlinear function $f(X)$ is

$$f(X) = [f_x, f_\theta]^T = M(q)(\ddot{q}_d + \lambda \dot{e}) + C(q, \dot{q})(\dot{q}_d + \lambda e) + G(q) \quad (9)$$

The generalized input vector $X \in R^{N \times 2}$ may be selected as $X = \begin{bmatrix} q^T, \dot{q}^T, q_d^T, \dot{q}_d^T \end{bmatrix}^T$.

Let's define a computed-torque like input in terms of a feedback linearization estimate plus PD control law as

$$U_0 = \hat{f} + K_v s \quad (10)$$

where $\hat{f}(X)$ is any estimate of $f(X)$ and $K_v = K_v^T > 0$ is a gain matrix. The closed-loop error system then becomes

$$M\dot{s} = -(K_v + C)s + \tilde{f} + \tau_d \quad (11)$$

where the functioned estimate error is $\tilde{f} = f - \hat{f}$.

Therefore, (11) is an error system wherein the filtered tracking error $s(t)$ is driven by the functional error $e(t)$ and the disturbances. Define a lumped system uncertainty $\zeta = \tilde{f} + \tau_d$, then (11) can be rewritten as

$$M\dot{s} = -(K_v + C)s + \zeta \quad (12)$$

Lemma 1: The system (12) with input ζ and output $s(t)$ is BIBS stable.

Proof: Let the Lyapunov function be

$$L = \frac{1}{2} s^T M s \quad (13)$$

Differentiation L along (12) obtains

$$\dot{L} = -s^T K_v s + \frac{1}{2} s^T \left(\dot{M} - 2C \right) s + s^T \zeta \quad (14)$$

Using property 3 results in

$$\dot{L} = -s^T K_v s + s^T \zeta \leq -\|s\|^T (K_{v\min} \|s\| - \|\zeta\|) \quad (15)$$

Let $\zeta \in L_\infty$ be bounded by b_ζ . Then $\dot{L}$ is decreasing when

$$\|s\| > b_\zeta / K_{v\min} \quad (16)$$

As inside the bounded region defined by (16) about the origin, $s(t)$ is bounded, and outside of it, $s(t)$ is a non-increasing function, i.e. there exist some constant $\gamma_1, \gamma_2 > 0$ such that $\|s(t)\| < \gamma_1 b_\zeta + \gamma_2$, thus, $s(t) \in L_\infty$.

This shows that bounded input results in bounded states. $\square$

III. ADAPTIVE ANTI-SWING CONTROLLER DESIGN

A. Fuzzy Uncertain Compensator

In this paper, a fuzzy uncertainty observer (FUO) $\hat{f}(X)$ is applied to estimate the nonlinear dynamics $f(X)$, moreover, a parameter adaptive law is also provided so that the estimate is guaranteed to monitor and represent well the whole uncertain dynamics existing in the container crane, as well as the asymptotic stability is preserved.

The basic configuration of a fuzzy system consists of fuzzifier, fuzzy rule base, fuzzy inference engine, and defuzzifier. The fuzzy inference engine maps from input vector $X = (x_1, x_2, \dots, x_n)^T \in R^n$ to an output variable $Y \in R$ for single output case, which is based on the fuzzy IF-THEN rules. The i th IF-THEN rule of k fuzzy rules defining fuzzy implication can be written as

Ruleⁱ: If x_1 is A_1^i and $\dots$ and x_n is A_n^i ,
then y is y^i

where A_j^i and y^i denote a fuzzy variable for premise part and a singleton for consequent part respectively. Then, the output of the fuzzy system with center average defuzzifier, product inference engine and singleton fuzzifier can be obtained as

$$y(x) = \frac{\sum_{i=1}^k y^i \left(\prod_{j=1}^n \mu_{A_j^i}(x_j) \right)}{\sum_{i=1}^k \left(\prod_{j=1}^n \mu_{A_j^i}(x_j) \right)} = \hat{\phi}^T \xi(x) \quad (17)$$

with $\xi^T = (\xi^1, \xi^2, \dots, \xi^k)$, where ξ^i is fuzzy basis function, expressed as

$$\xi^i = \frac{\prod_{j=1}^n \mu_{A_j^i}(x_j)}{\sum_{i=1}^k \left(\prod_{j=1}^n \mu_{A_j^i}(x_j) \right)} \quad (18)$$

and $\hat{\phi}^T = (y^1, y^2, \dots, y^k)$ is an adjustable parameter vector, $\mu_{A_j^i}(\cdot)$ is the membership function of fuzzy variable A_j^i .

In this paper, the universal approximation capability of above fuzzy system will be implemented as a fuzzy uncertain observer (FUO) [18].

To construct a FUO for estimating $\hat{f}(X)$ in (9), we have the following assumption:

Assumption 1: Let the input vector X for the fuzzy logic system (17) belong to a compact set M_X , the optimal parameter vector ϕ of (17) is defined as

$$\phi^* = \arg \min_{\phi \in M_\phi} \left(\sup_{X \in M_X} \left| f(X) - \hat{f}(X | \hat{\phi}) \right| \right) \quad (19)$$

which exists in a convex region $M_\phi = \{\phi \mid \|\phi\| \leq m_\phi\}$, where m_ϕ is a design parameter. Then, the fuzzy logic system (17), which is a zero-order TS fuzzy system, is employed as a FUO for the estimate of the uncertain f as follows:

$$\hat{f} \triangleq \hat{\phi}^T \xi(X) \quad (20)$$

Remark 1: to avoid algebraic loop in the implementation of FUO [18], $X = \begin{bmatrix} q^T, \dot{q}^T, q_d^T, \dot{q}_d^T, \ddot{q}_d^T \end{bmatrix}^T$ is used instead of control input U . Since the control input is a function of the state q and reference trajectory q_d , Then, the following observation dynamics is applied [18],

$$\dot{\mu}_i = -\sigma_i \mu_i + p_i(i, \dot{i}, \hat{\phi}) \quad (21)$$

where $p(i, \dot{i}, \hat{\phi}) \triangleq \hat{f}(X \mid \hat{\phi}) + F + GU + \sigma_i \dot{i}$, $\sigma_i > 0$ is an observer design parameter, and an observer error variable is defined as $\zeta_i = \dot{i} - \mu_i$, moreover, observation error dynamics can be obtained as

$$\dot{\zeta}_i = -\sigma_i \zeta_i + f(X) - \hat{f}(X \mid \hat{\phi}) \quad (22)$$

By assumption 1 and the universal approximation capability of the FUO in (20), the nonlinear dynamics $f(X)$ can be described as

$$f(X) = \hat{f}(X \mid \phi^*) + \varepsilon(X) \quad (23)$$

where $\varepsilon(X)$ denotes an uncertain estimation error satisfying $|\varepsilon(X)| \leq \bar{\varepsilon}$, and its upper bound $\bar{\varepsilon}$ can be arbitrarily shrunk by increasing the number of the fuzzy rules.

Then (22) becomes

$$\dot{\zeta}_i = -\sigma_i \zeta_i + \hat{f}(X \mid \hat{\phi}^*) - \hat{f}(X \mid \hat{\phi}) + \varepsilon(X) \quad (24)$$

Remark 2: if the bounded and adjustable parameter vector $\hat{\phi}$ is updated by adaptive law

$$\dot{\hat{\phi}} = \rho \zeta \xi(X) \quad (25)$$

where $\rho > 0$ is an observer design parameter, then the uncertainty observation error is uniformly ultimately bounded within a region of which size can be kept arbitrarily small (see Theorem 1 in [18]). Therefore, if the observation error ζ converges to zero, $\hat{f}(X)$ converges to the close neighborhood of the actual nonlinear $f(X)$.

B. Controller Design

A FUO is employed as uncertainty compensator for the container crane dynamics in above section. The nonlinear crane function $f(X)$ in (9) can be uniformly approximated by the FUO in (23) for some optimal parameter ϕ^* , where the estimate error $\varepsilon(X)$ is bounded

by a known $\bar{\varepsilon}$ constant. Note that $\bar{\varepsilon}$ becomes smaller as the number of the fuzzy rules increases.

Assumption 2: The desired trajectory is bounded, i.e.

$$\|q_d^T, \dot{q}_d^T, \ddot{q}_d^T\| \leq Q_d \text{ with } Q_d \text{ known constant.}$$

Assumption 3: The unknown disturbance τ_d in (4) is bounded, i.e. $\|\tau_d\| \leq b_{\tau_d}$ with b_{τ_d} known.

Assumption 4: The fuzzy logic input X is bounded above by $\|X\| \leq c_1 + c_2 \|s\|$ with c_1, c_2 known computable constants.

Define now a control input torque as

$$U_c = U_0 - V = \hat{f} + K_v s - V \quad (26)$$

with an addition $V(t)$ to enhance robustness of the system is given as

$$V = K_z \left(\|\hat{\phi}\| + m_\phi \right) s \quad (27)$$

where m_ϕ is a design parameter which satisfies $\|\phi\| \leq m_\phi$, and $K_z = K_z^T > 0$ a design parameter. Observer that $V(t)$ vanishes when $s(t) \rightarrow 0$.

Substituting the control (26) into (8) results in

$$M \dot{s} = -(K_v + C)s - V + \begin{bmatrix} f_p - \hat{f}_p \\ f_\theta - \hat{f}_\theta \end{bmatrix} + \tau_d \quad (28)$$

Let $f = [f_p, f_\theta]^T$, and $s = [s_p, s_\theta]^T$, the functional approximation error $\tilde{f}$ is

$$\tilde{f} = f - \hat{f} = \hat{f}(X \mid \hat{\phi}^*) - \hat{f}(X \mid \hat{\phi}) + \varepsilon(X) \quad (29)$$

Then, substitute (29) into (28) yields the final form of the closed-loop error system dynamics as

$$M \dot{s} = -(K_v + C)s + \begin{bmatrix} \hat{f}_x(x \mid \hat{\phi}_x^*) - \hat{f}_x(x \mid \hat{\phi}_x) + \varepsilon(x) \\ \hat{f}_\theta(\theta \mid \hat{\phi}_\theta^*) - \hat{f}_\theta(\theta \mid \hat{\phi}_\theta) + \varepsilon(\theta) \end{bmatrix} - V + \tau_d \quad (30)$$

Rewriting (30), we have closed-loop error dynamics as

$$M \dot{e} + (\lambda M + K_v + C)e + (K_v + C)\lambda e = \tilde{f} + \tau_d - V \quad (31)$$

Moreover, by define $E = (e, \dot{e}, \zeta)^T$ and using (24) and (31), the augmented closed-loop trajectory tracking error dynamics becomes

$$\dot{E} = \Pi E + \Gamma \phi^T \xi(X) + \Gamma_1 V + \Gamma \tau_d \quad (32)$$

with $\Pi = \begin{bmatrix} A & B^T \\ B & D \end{bmatrix}$ is a stable matrix, $\Gamma = \begin{bmatrix} H \\ I \end{bmatrix}$, $\Gamma_1 = -\begin{bmatrix} H \\ O \end{bmatrix}$, where $A = \begin{bmatrix} O & I \\ -k_1 & -k_2 \end{bmatrix}$, $D = \begin{bmatrix} -\sigma_x & 0 \\ 0 & -\sigma_\theta \end{bmatrix}$, $H = \begin{bmatrix} O \\ I \end{bmatrix}$, and $B \in R^{2 \times 4}$, $I \in R^{2 \times 2}$, $O \in R^{2 \times 2}$ denote identity and null matrices, respectively, k_1 , k_2 are known matrices relate to M , C , K_v , and λ .

Remark 3: there exists a positive definite matrix P such that

$$\Pi^T P + P \Pi = -R \quad (33)$$

for an arbitrary positive definite matrix R [20].

Theorem: Consider the 2D container crane with uncertainties in (4), let assumption 1~4 hold, the control input torque (26) with $K_z > c_2$ is given as (26) and (28), the filtered trajectory tracking error dynamics $s(t)$ is asymptotically stable, and FUO estimate is uniformly ultimately bounded with the specific bounds. Moreover, the tracking error may be kept arbitrarily small by increasing the gain K_v .

Proof: Let the Lyapunov function candidate be

$$L = \frac{1}{2} E^T P E + \frac{1}{2} \tilde{\phi}^T \tilde{\phi} \quad (34)$$

which is a positive definite function since assumption 4 holds.

Differentiate (34) with respect to time along the solution of the error dynamics (31) yields,

$$\begin{aligned} \dot{L} &= E^T P \Pi E + E^T P \Gamma \phi^T \xi + E^T P \Gamma \tau_d + E^T P \Gamma_1 V + \tilde{\phi}^T \dot{\tilde{\phi}} \\ &= E^T P \Pi E + E^T P \Gamma \tau_d + E^T P \Gamma_1 V + \tilde{\phi}^T \left(E^T P \Gamma \xi + \dot{\tilde{\phi}} \right) \end{aligned} \quad (35)$$

By choosing fuzzy rule tuning methods as

$$\dot{\tilde{\phi}} = -E^T P \Gamma \xi, \quad (\dot{\hat{\phi}} = -E^T P \Gamma \xi) \quad (36)$$

and using $\Lambda = \Gamma \xi + \Gamma_0 V$, then we have

$$\dot{L} \leq -\frac{1}{2} E^T Q E + E^T P \Lambda \quad (37)$$

By completing the square, after adding and subtracting $\frac{\alpha}{4} E^T P E + \frac{1}{\alpha} \Lambda^T P \Lambda$, (37) becomes

$$\begin{aligned} \dot{L} &\leq -\frac{1}{2} E^T Q E + \frac{\alpha}{4} E^T P E + \frac{1}{\alpha} \Lambda^T P \Lambda \\ &\leq -\frac{1}{4} \lambda_{\min}(Q) \|E\|^2 + \frac{\lambda_{\max}(P)^2}{\lambda_{\min}(Q)} \|\Lambda\|^2 \end{aligned}$$

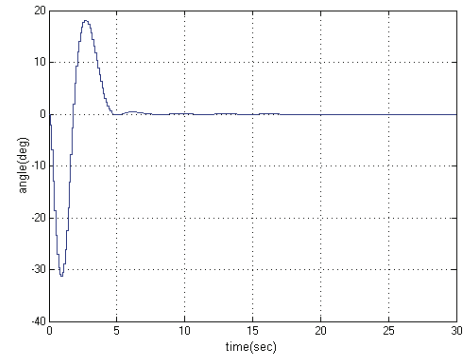
$$\leq -\frac{1}{4} \lambda_{\min}(Q) \|E\|^2 + \frac{\lambda_{\max}(P)^2}{\lambda_{\min}(Q)} (2 \|\tau_d\|^2 + \|V\|^2) \quad (38)$$

where $\alpha = \lambda_{\min}(Q) / \lambda_{\max}(P)^2$, $\lambda_{\max}(\cdot)$ and $\lambda_{\min}(\cdot)$ denote maximum and minimum eigenvalues respectively.

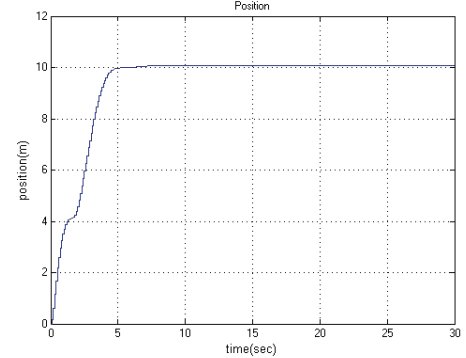
Thus, $\dot{L}$ is negative outside a compact set and the augmented error E is uniformly ultimately bounded. Moreover, using Barbalat's Lemma [19], $\|E(t)\| \rightarrow 0$ as $t \rightarrow \infty$.

IV. SIMULATION RESULTS

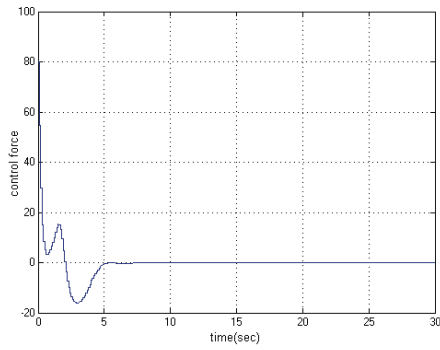
The proposed controller performance is tested under two different payload conditions, first set is selected to mimic a light weight application condition where $M = 10kg$, $m = 5kg$, $l = 1m$ and $k_s = 50$, then, change the crane payload with $M = 10kg$, $m = 50kg$, and $l = 1m$ to simulate a heavy load application, and test the performance of the proposed controller without incorporating any additional information about the system. Normal parameters employed in simulation are given as gain $K_v = [12, 5]^T$, and $\lambda = (1.2, 1.2)^T$. For the premise parts of the FUO in (20), seven Gaussian functions and two sigmoid functions are used as in [18]. Both simulation results are compared with performance of PID controller for container crane, given in [21], where parameters of PID controller are (20, 0.1, 40).



(a) swing angle of the payload

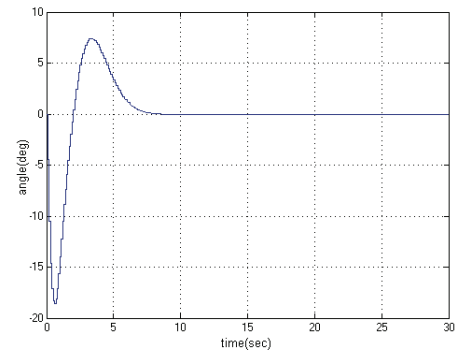


(b) position of the trolley

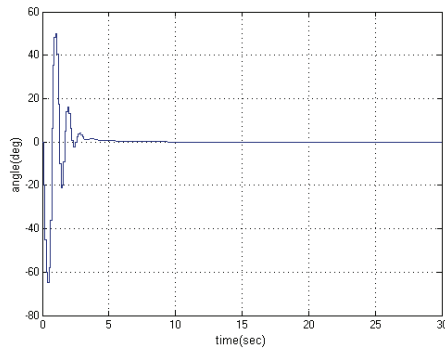


(c) control input U_c

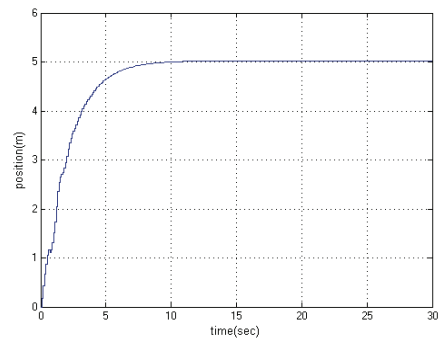
Figure 7. performance of proposed controller with light payload



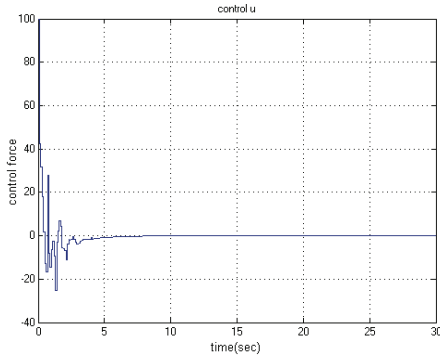
(a) swing angle of the payload



(a) swing angle of the payload

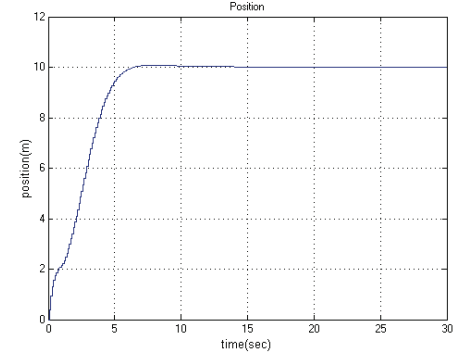


(b) position of the trolley

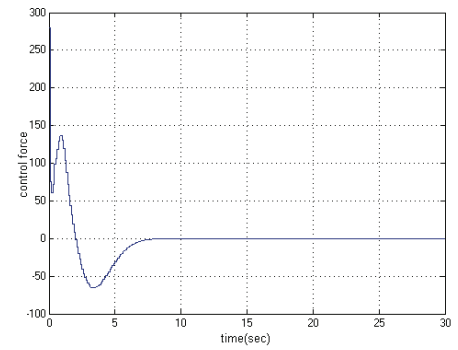


(c) control force

Figure 8. performance of PID controller with light payload

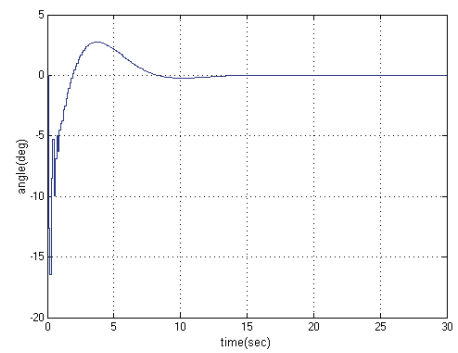


(b) position of the trolley

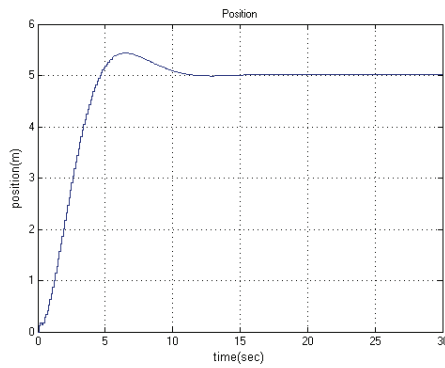


(c) control input U_c

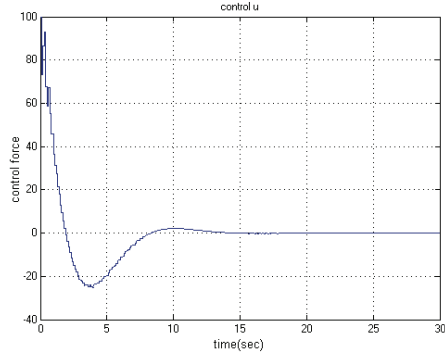
Figure 9. performance of proposed controller with heavy payload



(a) swing angle of the payload



(b) position of the trolley



(c) control force

Figure 10 performance of PID controller with heavy payload

From figure 7 to figure 10, it is shown that the proposed controller guarantees robust performance against payload variations and system parameters changing, and shows good transient response performance compared with PID controller.

V. CONCLUSION

Dynamics model of a new container crane system is investigated. A FUO based controller law is proposed for the container crane with underactuated dynamics problem. Multi-loop controller comprising an inner loop consisting of fuzzy uncertain observer with online adaptive update law and robustness terms making the whole system to remain bounded, hence keeping the internal signals in a compact region. Controller design does not rely on any prior knowledge of crane nonlinear system dynamics. The developed controller has been applied to two different crane applications for simulation study, and the simulation results have shown performance of the controller successfully.

VI. ACKNOWLEDGMENT

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