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Adaptive sliding mode fuzzy control for a two-dimensional overhead crane

Diantong Liu [a,*], Jianqiang Yi [b], Dongbin Zhao [b], Wei Wang [b]

[a] Institute of Computer Science and Technology, Yantai University, Shandong Province 264005, China
[b] Key Laboratory of Complex Systems and Intelligence Science, Institute of Automation, Chinese Academy of Sciences, Beijing 100080, China

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Abstract

An adaptive sliding mode fuzzy control approach is proposed for a two-dimensional overhead crane. System linearization transforms the two-dimensional system to two independent systems: X-direction transport system and Y-direction transport system. Both the two systems are with the same dynamic model and include two subsystems: positioning subsystem and anti-swing subsystem. Combining SMC's robustness and FLC's independence of system model, a sliding mode fuzzy control approach is proposed for both X-direction transport and Y-direction transport. According to the influences on system dynamic performance, both the slope of sliding mode surface and the coordination between the two subsystems are automatically tuned by real time fuzzy inference respectively. The effectiveness of the proposed control approach is demonstrated by experiments with a two-dimensional prototype overhead crane.

Keywords: Overhead crane; Underactuated system; Sliding mode control; Fuzzy control; Adaptive tuning

* Corresponding author. Tel.: +86 535 6904991.
E-mail addresses: diantong.liu@163.com, diantong.liu@mail.ia.ac.cn (D. Liu).

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1. Introduction

Overhead crane works as a robot in many places such as workshops and harbors to transport all kinds of massive goods. It is desired for the overhead crane to transport the payloads to the required position as fast and as accurately as possible without collision with other equipments. Therefore, the payload swing angle should be kept as small as possible.

Many works have been done in controlling the overhead crane. Park et al. [1] and Singhose et al. [2] adopted input shaping control method. But the input shaping must be pre-calculated accurately according to the system model. These approaches lacked robustness to external disturbances and could not damp residual swing well. Moreover, zero initial condition must be satisfied. Lee [3] and Giua et al. [4] proposed feedback control methods. Besides needing accurate system model and onerous matrix computation, the above methods were greatly affected by system linearization and system parameters uncertainty. Moreno et al. [5] and Mendez et al. [6] used NN (neural network) to tune the parameters of state feedback control for improving the performance of overhead crane. The training of the network was done online for the same transport task, but the payloads of overhead crane usually are different for different transport task and the training of network must be done again.

Benhidjeb and Gissinger [7] compared fuzzy control with linear quadratic gaussian (LQG) Control of an overhead crane and their experiments indicated that the fuzzy controller could deal with different types of disturbances and be independent of system model. Lee and Cho [8] used fuzzy logic only in anti-swing control and applied position servo control for positioning and swing damping. Hua [9] only studied anti-swing control with fuzzy logic and did not take positioning control into consideration. Nalley and Trabia [10] adopted fuzzy logic to both positioning control and swing damping. However, because of the large number of fuzzy rules for the complex overhead crane system, it was difficult to set both rules and parameters of the controller only according to experiences.

Sliding mode control (SMC) [11] is a robust design methodology using a systematic scheme based on a sliding mode surface and Lyapunov stability theorem. The main advantage of SMC is that the system uncertainties and external disturbances can be handled under the invariance characteristics of system's sliding mode state with guaranteed system stability. Er et al. [12], Kakoub and Zribi [13] and Basher [14] used the variable structure control (VSC) with sliding modes to control the overhead crane. In [12] and [13], the VSC was used to the positioning control and the hoisting control, but another state feedback control scheme must be added for payload swing damping control. In [14], a reference model was defined to track, and the system model must be linearized. All the above VSC methods have difficulties in automatically coordinating positioning control and anti-swing control.

This paper presents a practical solution to analyze and control the overhead crane. Besides the payload swing, the trolley motions of two transport directions are considered. Now that SMC is capable of tackling non-linear system with parameter uncertainties and external disturbances, and fuzzy logic control is independent of system model, the crane system model is built to analyze system control characteristics without taking external disturbances (such as winds) and system parameters varying (such as different payload) into consideration. An adaptive sliding mode fuzzy control algorithm is designed for both X-direction transport and Y-direction transport of the overhead crane. Combining SMC's robustness and FLC's independence of system model, the proposed control law can guarantee a swing-free transport.

The remainder of this paper is organized as follows. In Section 2, the dynamic model of the two-dimensional overhead crane is built, the linearized model is derived and a conclusion is obtained that two-dimensional overhead crane can be divided into two independent transport systems. In Section 3, an adaptive fuzzy sliding mode control algorithm is proposed for both X-direction transport and Y-direction transport. In Section 4, the proposed algorithm is validated through experiments. Finally, in Section 5, conclusions are drawn.

2. Dynamic model of two-dimensional overhead crane

In this section, the system description of two-dimensional overhead crane will be given and its dynamic model will be built. Then the model will be transformed by linearization and state feedback to a system that is composed of two transport systems with the same structure. In this way, the analysis and implementation are simplified for system control.

2.1. System description

Fig. 1 shows the coordinate system of a two-dimensional overhead crane [15] and its payload. XYZ is the inertial coordinate system, M_X and M_Y respectively are the X-direction equivalent trolley mass and Y-direction equivalent trolley mass including the moment-of-inertia of the gear train and motors. θ is the swing angle of the payload in XYZ space and it has two components θ_X and θ_Y. θ_X and θ_Y are the swing angle projected on XZ plane and YZ plane respectively. Assume the dynamic model has the characteristic that the payload and the trolley are connected by a massless, rigid link.

2.2. System dynamics

According to Lagrangian equation:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = T_i \quad (i = 1, 2, 3, 4) \tag{1}$$

where, $L = K - U$, K is system kinetic energy, U is system potential energy, q_i is generalized coordinate (here is x, y, θ_X or θ_Y), and T_i is external force (here is f_X or f_Y)

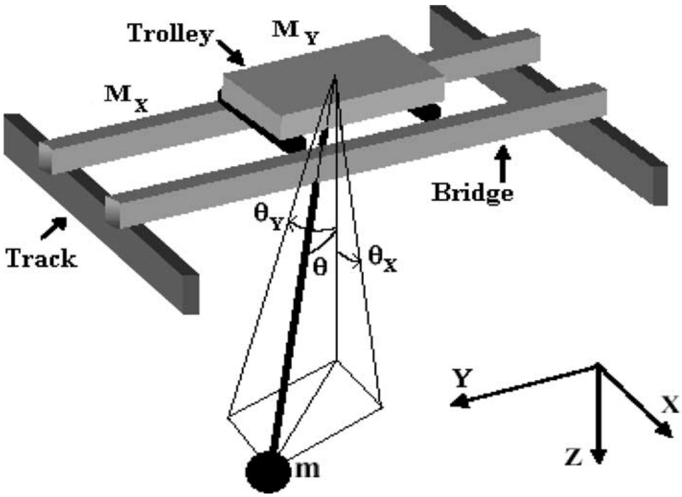

Fig. 1. Two-dimension overhead crane.

($T_3 = T_4 = 0$). The motion equations of the overhead crane system can be obtained with respect to the generalized coordinates x, y, θ_X and θ_Y.

$$(M_X + m)\ddot{x} + ml\ddot{\theta}_X \cos\theta_X \cos\theta_Y - ml\ddot{\theta}_Y \sin\theta_X \sin\theta_Y - ml\dot{\theta}_X^2 \sin\theta_X \cos\theta_Y \\ - ml\dot{\theta}_Y^2 \sin\theta_X \cos\theta_Y - 2ml\dot{\theta}_X\dot{\theta}_Y \cos\theta_X \sin\theta_Y = f_X - D_X\dot{x} \tag{2}$$

$$(M_Y + m)\ddot{y} + ml\ddot{\theta}_Y \cos\theta_Y - ml\dot{\theta}_Y^2 \sin\theta_Y = f_Y - D_Y\dot{y} \tag{3}$$

$$ml^2\ddot{\theta}_X \cos^2\theta_Y + ml\ddot{x}\cos\theta_X \cos\theta_Y + mgl\sin\theta_X \cos\theta_Y \\ - 2ml^2\dot{\theta}_X\dot{\theta}_Y \sin\theta_Y \cos\theta_Y = 0 \tag{4}$$

$$ml^2\ddot{\theta}_Y + \ddot{y}ml\cos\theta_Y + mgl\sin\theta_Y \cos\theta_X - ml\ddot{x}\sin\theta_X \sin\theta_Y \\ + ml^2\dot{\theta}_X^2 \cos\theta_Y \sin\theta_Y = 0 \tag{5}$$

where D_X and D_Y respectively denote the viscous damping coefficients of the crane in the X and Y directions, f_X and f_Y are the external forces on the overhead crane in the X and Y directions, respectively.

2.3. System model analysis

In industry, the maximum acceleration of the overhead crane is set smaller than the gravitational acceleration. For safety considerations, the rope length is usually kept constant when the overhead crane is in motion. For small swing around the vertical equilibrium, $\sin\theta_X \approx \theta_X$, $\sin\theta_Y \approx \theta_Y$, $\cos\theta_X \approx 1$ and $\cos\theta_Y \approx 1$. In addition,

$\sin\theta_X \sin\theta_Y \approx 0$, $\dot{\theta}_X^2 \approx 0$, $\dot{\theta}_Y^2 \approx 0$ and $\dot{\theta}_X\dot{\theta}_Y \approx 0$ also hold for small swing. The non-linear model can be simplified to the following linearized model:

$$\begin{aligned} &(M_X + m)\ddot{x} + ml\ddot{\theta}_X = f_X - D_X\dot{x} \\ &l\ddot{\theta}_X + \ddot{x} + g\theta_X = 0 \end{aligned} \tag{6}$$

$$\begin{aligned} &(M_Y + m)\ddot{y} + ml\ddot{\theta}_Y = f_Y - D_y\dot{y} \\ &l\ddot{\theta}_Y + \ddot{y} + g\theta_Y = 0 \end{aligned} \tag{7}$$

The crane is normally driven by servomotors and the servomotors have three control modes: position control, speed control and torque control. In practice, the viscous damping and the masses of trolleys and payload usually are unknown or always change. It is difficult to design a controller without those parameters' exact values in position control mode or in torque control mode. Therefore, the speed control mode is used through the following state feedback transform:

$$\begin{aligned} &u_X = (M_X + m)^{-1}(f_X - D_X\dot{x} - ml\ddot{\theta}_X) \\ &u_Y = (M_Y + m)^{-1}(f_Y - D_Y\dot{y} - ml\ddot{\theta}_Y) \end{aligned} \tag{8}$$

then the system model can be described as

$$\begin{aligned} &\ddot{x} = u_X \\ &l\ddot{\theta}_X + u_X + g\theta_X = 0 \end{aligned} \tag{9}$$

$$\begin{aligned} &\ddot{y} = u_Y \\ &l\ddot{\theta}_Y + u_Y + g\theta_Y = 0 \end{aligned} \tag{10}$$

It can be seen that the transformed system model is independent of the viscous damping and the masses of trolleys and payload, and the system inputs become the accelerations of the two-direction transport. The system control inputs u_X and u_Y can be directly calculated through the transformed model and some control algorithm that is also independent of the viscous damping and the masses of trolleys and payload. For a given acceleration, servomotors in speed control mode can automatically determine the output torque according to the actual system, so it is not necessary to calculate the external control forces f_X and f_Y through the state feedback transform (8). That is to say, as long as the servomotors installed in the trolley are driven with an acceleration that is obtained through some control algorithm, the control tasks can be easily implemented in practice.

From (6) and (7) or (9) and (10), it can be seen: the linearized dynamic model consists of the X-direction transport dynamics and Y-direction transport dynamics. The X-direction dynamics and Y-direction dynamics are decoupled and with the same structure. Therefore, the same control algorithm can be designed for both the X- and Y-direction transport systems.

3. Control design

In this section, an adaptive slide mode fuzzy controller will be designed for the two-dimensional overhead crane. Assume the desired state is generalized coordinates origin. Since the two-dimensional overhead crane can be decoupled into two independent transport systems, a control algorithm will be designed for both of them. Only the X-direction transport system is considered below.

3.1. Sliding mode fuzzy control (SMFC)

Consider a second-order system of the form as follows:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= f(X) + b(X)u \end{aligned} \tag{11}$$

where, $X = (x_1, x_2)$ is state variable vector, $f(X)$ and $b(X)$ are continuous linear or nonlinear functions, u is the control input. The sliding mode function is defined as

$$s = x_2 + \lambda_1 x_1 \tag{12}$$

To make the system state approach the sliding mode surface, we can take the control input such that the control input on the two sides of the sliding mode surface are opposite in sign and its magnitude is proportional to the distance between the state vector and the sliding mode surface [16]. Therefore, the following sliding mode fuzzy control is designed to obtain the control input:

R_i: IF s IS F_i THEN u IS U_i

where F_i is the linguistic value of s in the ith-fuzzy rule, and U_i is the linguistic value of u in the ith-fuzzy rule. The fuzzification of the sliding mode function is illustrated in Fig. 2.

3.2. Adaptive sliding mode fuzzy control (ASMFC)

The X-direction transport systems can be represented as:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= f_1(X) + b_1(X)u \\ \dot{x}_3 &= x_4 \\ \dot{x}_4 &= f_2(X) + b_2(X)u \end{aligned} \tag{13}$$

where, $X = (x_1, x_2, x_3, x_4)$ is the state variable vector that represents crane position, velocity, payload swing angle and angle velocity, $f_1(X)$, $f_2(X)$, $b_1(X)$ and $b_2(X)$ are continuous nonlinear or linear functions, u is the control input.

From (13), the X-direction transport system has two coupled subsystems: positioning subsystem and anti-swing subsystem. In order to decouple the system, two sliding mode functions are defined for the two subsystems:

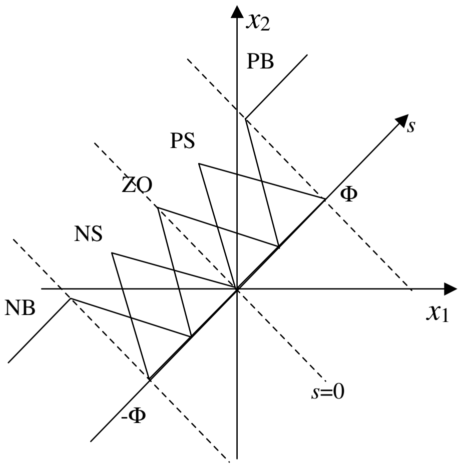

Fig. 2. Fuzzification of sliding mode function in sliding mode fuzzy control.

$$s_1 = x_2 + \lambda_1 x_1 \tag{14}$$

$$s_2 = x_4 + \lambda_2 x_3 \tag{15}$$

where λ_1 and λ_2 are positive real numbers.

System performance is very sensitive to the slope λ_1 (or λ_2) of the sliding mode function: when the value of λ_1 (or λ_2) becomes larger, the rise-time will become smaller, but at the same time, both overshoot and settling-time will become larger, and vice versa. If the slopes are fixed, the control system may perform differently for different control situations. Such a control system is difficult to cover all the control situations in good performance. To solve the problem, it is desirable to design a control law to adjust the slope λ_1 (or λ_2) of the sliding mode function in real time.

In mechanical systems, the value of λ_1 (or λ_2) is typically limited by three factors: the frequency of the lowest unmodelled structural mode, the largest unmodelled time delay, and the sampling rate. According to the mechanical system limitation, the slope of the sliding mode function is given for the lth subsystem ($l = 1$ or 2) by

$$\lambda_l = \lambda_l^{\mathrm{b}} + B_l \Delta\lambda_l \tag{16}$$

where, λ_l^{b} is the basic value of λ_l, B_l is the tuning scope of λ_l, and $\Delta\lambda_l$ is the tuning variable. The value of $\Delta\lambda_l$ can be obtained according to the following fuzzy rules:

$$R_i:\ \text{IF } |x_{2l-1}| \text{ IS } A_l^{\mathrm{i}} \text{ THEN } \Delta\lambda_l \text{ IS } \Delta\lambda_l^{\mathrm{i}} \tag{17}$$

where, R_i is the ith rule among m rules, A_l^{i} is a fuzzy set of input variable $|x_{2l-1}|$, and λ_l^{i} is a fuzzy set of output variable λ_l. Furthermore, the absolute value of the trolley position is selected as the input variable for the positioning subsystem, while the absolute value of the swing angle is as the input variable for the anti-swing subsystem. The output singleton fuzzy sets and the center-of-gravity defuzzification method are used:

$$\Delta\lambda_l = \left(\sum_{i=1}^{m} \mu_{A_l^i}(|x_{2l-1}|) \times \Delta\lambda_l^i\right) \Bigg/ \sum_{i=1}^{m} \mu_{A_l^i}(|x_{2l-1}|) \tag{18}$$

$\mu_{A_l^i}(|x_{2l-1}|)$ is the firing degree of the ith rule. According to (16) and (18), each slope will change dynamically between λ_l^b and $\lambda_l^b + B_l$.

Therefore, when the absolute value of the trolley position x_1 or swing angle x_3 is larger, the above fuzzy system will generate a larger value. As a result, the slope of the corresponding sliding mode function (s_1 or s_2) will get larger so as to make the system state approach quickly its sliding mode surface and equilibrium point. Further, the convergence speed in the sliding mode surface is also higher if a larger λ_1 (or λ_2) is used.

Based on the two sliding mode functions, a composite sliding mode function can be further defined as

$$s = s_1 + \lambda s_2 = x_2 + \lambda_1 x_1 + \lambda(x_4 + \lambda_2 x_3) \tag{19}$$

where λ is a real number. Tuning the coefficient λ can adjust the influences of the positioning subsystem and the anti-swing subsystem in the sliding mode function. When λ becomes smaller, the positioning subsystem is strengthened; and when λ becomes larger, the anti-swing subsystem is strengthened. Here, we set the sliding mode function slope as

$$\lambda = \lambda^b + B\Delta\lambda \tag{20}$$

where, λ^b is the basic value of λ, B is the tuning scope of λ, and $\Delta\lambda$ is the tuning variable. λ changes between λ^b and $\lambda^b + B$. Because $|s_2|$ should not be too large for safety and we should pay more attention to the anti-swing subsystem, here we adopt s_2 as the input variable and establish the following fuzzy rules in order to calculate the value of $\Delta\lambda$

$$R_j: \text{ IF } |s_2| \text{ IS } F_2^j \text{ THEN } \Delta\lambda \text{ IS } \Delta\lambda_j \tag{21}$$

where, R_j is the jth rule among n rules, F_2^j is a fuzzy set of the input variable $|s_2|$, and $\Delta\lambda_j$ is a fuzzy set of output variable $\Delta\lambda$. The output singleton fuzzy sets and the center-of-gravity defuzzification method are used

$$\Delta\lambda = \left(\sum_{j=1}^{n} \mu_{F_2^j}(|s_2|) \times \Delta\lambda^j\right) \Bigg/ \sum_{j=1}^{n} \mu_{F_2^j}(|s_2|) \tag{22}$$

where $\mu_{F_2^j}(|s_2|)$ is the firing degree of the jth rule. Therefore, if the anti-swing subsystem state is far from its sliding mode surface $s_2 = 0$, a larger value of λ is obtained. In this case, the anti-swing subsystem will occupy the main part in the composite sliding mode function (19), and the corresponding control action will force the anti-swing subsystem state to get small. However, if the anti-swing subsystem state is small, the slope λ will also become small. As a result, in the composite sliding mode function (19), the positioning subsystem will take the priority over the anti-swing subsystem so that the trolley is controlled to its destination.

For the X-direction transport system of the overhead crane, the composite sliding mode function s works as the input to the sliding mode fuzzy control. To determine the final control action, therefore, we design following fuzzy rules:

$$R_k:\ \text{IF } s \text{ IS } F_k \text{ THEN } u_f \text{ IS } U^k \tag{23}$$

where, R_k is the kth rule among p rules, F^k is a fuzzy set of the input variable s, and U^k is a fuzzy set of the output variable u_{f}. The output singleton fuzzy sets and the center-of-gravity defuzzification are used:

$$u_{\mathrm{f}} = \left(\sum_{k=1}^{p} \mu_{F^k}(s) \times U^k\right) \Bigg/ \sum_{k=1}^{p} \mu_{F^k}(s) \tag{24}$$

where $\mu_{F^k}(s)$ is the firing degree of the jth rule and u_{f} is the output of the adaptive sliding mode fuzzy controller.

Theorem 1. *For X-direction transport system (9) of the two-dimensional overhead crane, consider the proposed adaptive fuzzy sliding mode controller (24) with the sliding mode function (14), (15) and (19). If the parameter adaptation algorithms (16)–(18) and (20)–(22) are applied and the parameter λ is a negative real number, then the closed loop system is asymptotically stable.*

Proof. According to the theory of sliding mode control, the stability of the closed loop system consists of the stability in the sliding mode surface and the accessibility of sliding mode surface.

(a) The stability in the sliding mode surface.

Both the sliding mode surfaces $s_1 = 0$ and $s_2 = 0$ are stable because λ_1 and λ_2 are positive real numbers. The stability in the composite sliding mode surface is decided by the coupling factor λ in Eq. (19) and the definitions of the swing angle and the control input u. Assume a positive angle and a positive u are along the positive X-direction. When the position sliding mode function $s_1 > 0$, a negative control input is required such that the sliding function s_1 approaches the sliding mode surface $s_1 = 0$. However, when the anti-swing sliding mode function $s_2 > 0$, a positive driving force is required such that the sliding function s_2 approaches the sliding mode surface $s_2 = 0$. Therefore, the roles of the two sliding mode functions in control are contradictive, and the coupling factor λ should be negative for the stability in sliding mode surface.

(b) The accessibility of sliding mode surface.

Choose the Lyapunov function candidate

$$V = s^2/2 \tag{25}$$

The time derivative of the composite sliding mode function (19) is

$$\dot{s} = \dot{s}_1 + \lambda\dot{s}_2 + \dot{\lambda}s_2 = \dot{x}_2 + \lambda_1\dot{x}_1 + \dot{\lambda}_1x_1 + \lambda(\dot{x}_4 + \lambda_2\dot{x}_3 + \dot{\lambda}_2x_3) + \dot{\lambda}s_2 \tag{26}$$

Substituting Eqs. (13), (16), (18), (20) and (22) into Eq. (26)

$$\begin{aligned}\dot{s} &= f_1(X) + \lambda_1 x_2 + B_1 \frac{\mathrm{d}(\Delta\lambda_1)}{\mathrm{d}x_1}\dot{x}_1 x_1 + \lambda\left(f_2(X) + \lambda_2 x_4 + B_2 \frac{\mathrm{d}(\Delta\lambda_2)}{\mathrm{d}x_3}\dot{x}_3 x_3\right) \\ &\quad + B\frac{\mathrm{d}(\Delta\lambda)}{\mathrm{d}s_2}s_2\dot{s}_2 + (b_1(X) + \lambda b_2(X))u \\ &= f_1(X) + \lambda_1 x_2 + B_1 \frac{\mathrm{d}(\Delta\lambda_1)}{\mathrm{d}x_1}x_1 x_2 \\ &\quad + \left(\lambda + B\frac{\mathrm{d}(\Delta\lambda)}{\mathrm{d}s_2}s_2\right)\left(f_2(X) + \lambda_2 x_4 + B_2\frac{\mathrm{d}(\Delta\lambda_2)}{\mathrm{d}x_3}x_3 x_4\right) \\ &\quad + \left(b_1(X) + \lambda b_2(X) + B\frac{\mathrm{d}(\Delta\lambda)}{\mathrm{d}s_2}s_2 b_2(x)\right)u\end{aligned}$$

It is easy to obtain the time derivative of the Lyapunov function candidate

$$\dot{V} = s\dot{s} = M(X)s + N(X)su \tag{27}$$

where

$$\begin{aligned}M(X) &= f_1(X) + \lambda_1 x_2 + B_1\frac{\mathrm{d}(\Delta\lambda_1)}{\mathrm{d}x_1}x_1 x_2 \\ &\quad + \left(\lambda + B\frac{\mathrm{d}(\Delta\lambda)}{\mathrm{d}s_2}s_2\right)\left(f_2(X) + \lambda_2 x_4 + B_2\frac{\mathrm{d}(\Delta\lambda_2)}{\mathrm{d}x_3}x_3 x_4\right)\end{aligned}$$

$$N(X) = b_1(X) + \lambda b_2(X) + B\frac{\mathrm{d}(\Delta\lambda)}{\mathrm{d}s_2}s_2 b_2(x)$$

Form Eq. (9), we can see: $b_1(X)$ is positive, and $b_2(X)$ is negative. The design of the fuzzy inference (17), (18) and (21), (22) can guaranty $\frac{\mathrm{d}(\Delta\lambda_1)}{\mathrm{d}x_1}$, $\frac{\mathrm{d}(\Delta\lambda_2)}{\mathrm{d}x_3}$ and $\frac{\mathrm{d}(\Delta\lambda)}{\mathrm{d}s_2}$ are bounded, so $M(X)$ is bounded. According to the design principle of fuzzy inference (21), (22), B should be negative, $\frac{\mathrm{d}(\Delta\lambda)}{\mathrm{d}s_2}$ should be nonnegative as $s_2 > 0$ and $\frac{\mathrm{d}(\Delta\lambda)}{\mathrm{d}s_2}$ should be nonpositive as $s_2 < 0$, i.e. $\frac{\mathrm{d}(\Delta\lambda)}{\mathrm{d}s_2}s_2$ is nonnegative. We can see the term $N(X)$ in Eq. (27) is always positive. Therefore, it can be realized through the design of the fuzzy inference (23), (24) that increasing the control input u will result in decreasing $s\dot{s}$ as the sliding mode function s is negative, and decreasing the control input u will result in decreasing $s\dot{s}$ as the sliding mode function s is positive. Therefore, the sliding mode surface $s = 0$ can be accessible. □

Remark 1. According to the system dynamic model that the X-direction transport system and Y-direction transport system are decoupled and with the same linearized model, the control algorithm is also applicable to Y-direction transport system.

Remark 2. From Theorem 1, the position control and the anti-swing control are contradictive. In the proposed control algorithm, the composite sliding mode function (19) works as the antecedent, in which the first and second terms respectively determine the position control and the anti-swing control role in the overall system control. Therefore, the percentage of the anti-swing control role in the overall system control can be obtained by $|\lambda s_2|/(|s_1| + |\lambda s_2|)$. The basic and maximum anti-swing control percentages are usually set according to actual requirement such as the maximum of swing angle. As long as the percentages are known, the parameters λ^{b} and B can be obtained through the basic and maximum percentages.

Remark 3. The proposed control design is independent of the linearized system model, i.e. the control algorithm is designed for nonlinear overhead crane system. The linearized model derived in Section 2 is used to explain the two-dimensional overhead crane consisting of two approximately independent transport systems. Moreover, the control mode can be changed through the state transform.

Remark 4. When the initial payload angles are zeros, both X-direction transport and Y-direction transport will arrive at the goal at the same time with the same adaptive sliding mode fuzzy controller.

Remark 5. Now that the servomotors adopt speed control mode while the output of the controller is acceleration, actual input of the servomotors is:

$$u = \int_{t_0}^{t_{\mathrm{c}}} u_{\mathrm{f}} \, \mathrm{d}t \tag{28}$$

where t_0 and t_{c} are initial time and current time separately.

The control scheme is illustrated in Fig. 3, where x_{1r} and x_{3r} respectively are the desired position and swing angle. Only in the anti-swing subsystem of the X-direction transport system, the slope of the sliding mode function is automatically adjusted by fuzzy inference system, which is called as adjustor 1. The coordination between the positioning subsystem and anti-swing subsystem are automatically realized by another fuzzy inference system, which is called as adjustor 2.

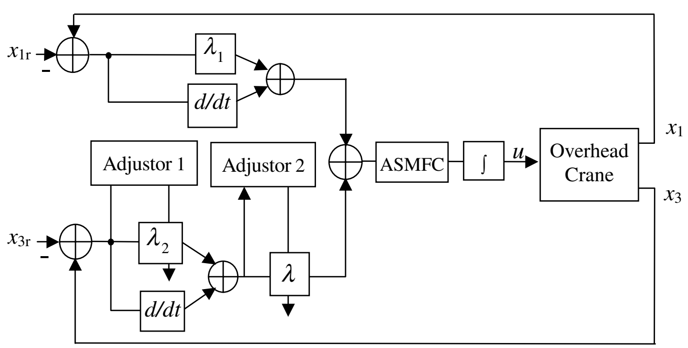

Fig. 3. Control scheme.

4. Experiment studies

A two-dimensional prototype overhead crane is built, which is illustrated in Fig. 4. The prototype consists of two sets of components that include mechanical system, data sampling system, and control system. For the mechanical system, the trolleys are driven by AC servomotors to move along the track for X-direction and along the bridge for Y-direction. The payload is connected to a cable that is attached to the underside of the trolley, where two precise angle sensors are installed to measure the swing angles of X-direction and Y-direction. In order to avoid affecting each other, the two angle sensors are improved to a compact size as Fig. 5 from [17,18], which can detect a big range of swing angles. The data sampling system includes the two angle sensors and two position sensors installed in the servomotors. The control algorithm is implemented on a Programmable Multi-Axis Controller (PMAC) manufactured by Delta Tau Data Systems Inc.,

Fig. 4. Two-dimension prototype overhead crane.

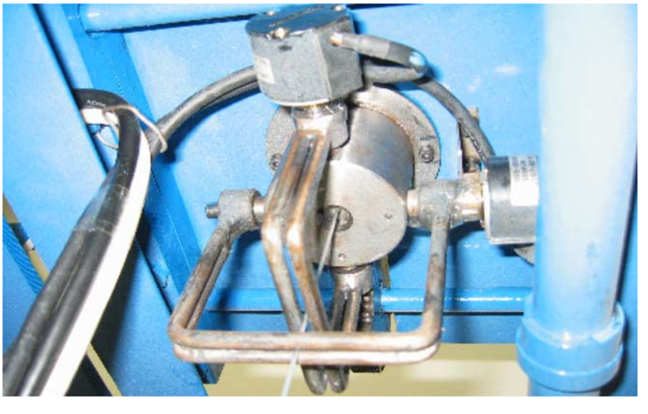

Fig. 5. The scheme of the angle sensors.

and the PMAC is inserted in a Pentium III 800 MHz PC running under the Windows operating system. Some hardware limitations should be concerned in the overhead crane system. The input voltage of the servomotors is limited between −10 and +10 (V). The rated power of each motor is 400 W. An allowable cart's displacement is from 0 m to 1.4 m in *X*-direction and from 0 m to 0.6 m in *Y*-direction.

Due to the structures of the angle sensors as Fig. 5, each angle sensor has a small insensitive area from −0.2° to + 0.2° in measuring the swing angles of *X*-direction or *Y*-direction. Because of the effect of the measuring installation's weight, the angle insensitive area appears only when the swing angle approaches zero. In the following experiments, a line segment between a positive angle and a negative angle of the angle insensitive area is added in the actual angle curve when the sign of measured angle turns from negative to positive or from positive to negative.

To confirm the effectiveness of the proposed control algorithm, some experiments have been performed with the prototype overhead crane. In the control algorithm, the adaptive tuning of the slope of the sliding mode function is only used in the anti-swing subsystem. The parameters of the controller are as follows: $\lambda_1 = 0.5$, $\lambda_2^{\mathrm{b}} = 2.28$, $B_2 = 3$, $\lambda^{\mathrm{b}} = -0.1$, $B = -0.46$. The tunings of λ and λ_2 adopt the same fuzzy rules table given in Table 1 and the same membership functions illustrated in Fig. 6. The sliding mode fuzzy rules are provided in Table 2 and the membership function is in Fig. 2 ($\Phi = 1$).

Two experiments have been performed with the two-dimensional prototype overhead crane, the payload transport experiment and the fast damping swing experiment. Figs. 7 and 8 show the experimental results of transport from position (−1.2, −0.6) to desired position (0, 0) with zero initial angles. Fig. 9 is the time response of the sliding mode functions. Fig. 10 shows the *X*-direction transport when the initial angles are not zero. The *Y*-axis for velocity is 0.2 m/s each grid in Figs. 7 and 10 and 0.1 m/s each grid in Fig. 8. From the experiment results, it is clear that

Table 1
Rules table for tuning λ and λ_2

$\lvert e_3\rvert$ or $\lvert s_2\rvert$	S	M	L
$\Delta\lambda_2$ or $\Delta\lambda$	0	0.5	1

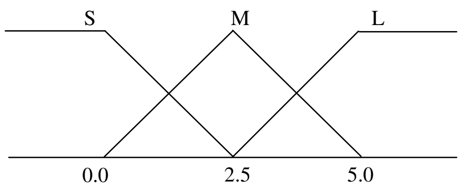

Fig. 6. Membership function of adjustors antecedent variable.

Table 2
Rules table of sliding mode fuzzy controller

s	NB	NS	ZO	PS	PB
u_f	2.5	1.25	0	−1.25	−2.5

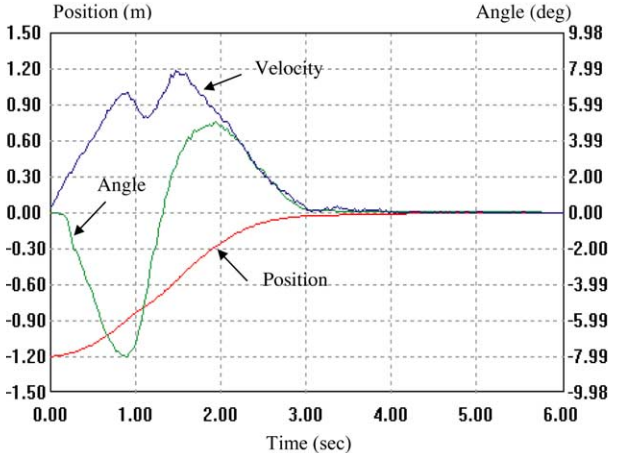

Fig. 7. Time responses of X-direction transport.

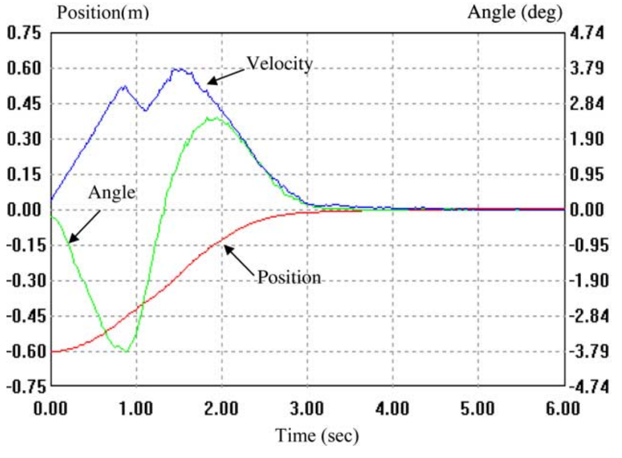

Fig. 8. Time responses of Y-direction transport.

the proposed control law can make the X-direction transport and Y-direction transport arrive at goal at the same time when initial angles are zero. Whether the initial angles are zero or not zero, the control law can accurately transport the payload

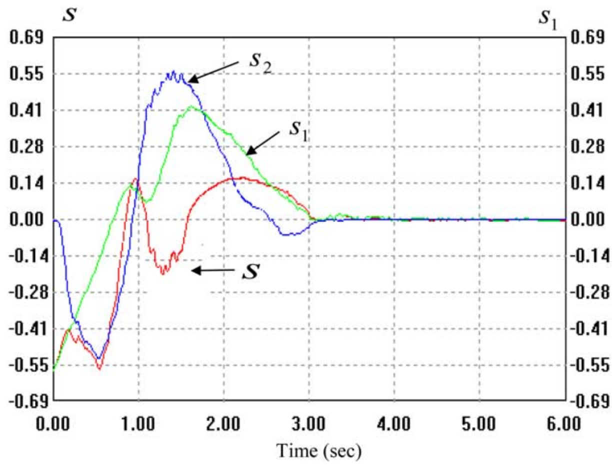

Fig. 9. Time response of sliding mode function.

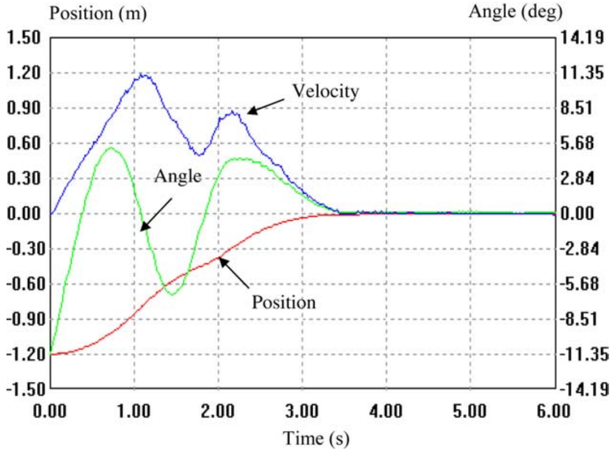

Fig. 10. Time responses with initial angle.

while damping the swing angle, especially at goal. Moreover, when s_2 is far from zero, the anti-swing control occupies the absolute main part in the system control because of a large λ. The position control occupies the main part in the system control as s_2 is about zero.

Figs. 11 and 12 show the fast damping swing experiment results and the control is added from the 6th second in order to compare the system performance between before and after the proposed control algorithm is added. Fig. 11 is the phase plane of X-direction angle (Y-axis) and Y-direction angle (X-axis) and Fig. 12 is their corresponding time responses. It can be seen: before the proposed control algorithm is added, the swing of the payload is almost undamped. But after the proposed

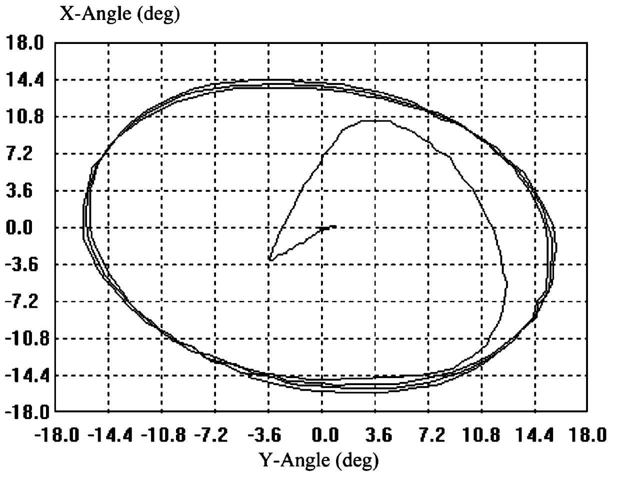

Fig. 11. Phase plane in damping swing.

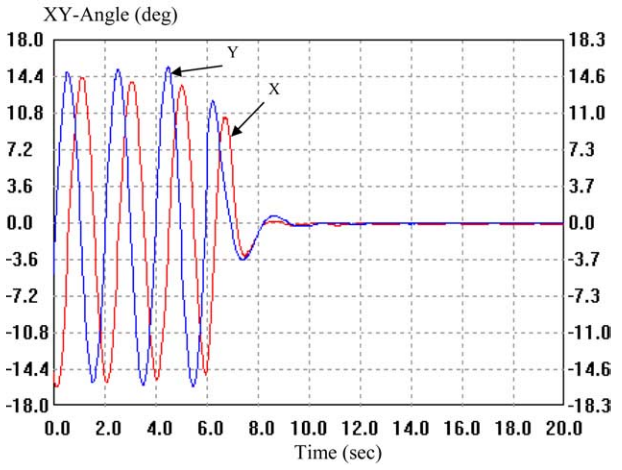

Fig. 12. Time response of *Y*-direction angle damping.

control algorithm is added, it only takes about 4 s to damp the payload swing angle from about 14° to 0°. That is to say, the proposed control law can damp swing angle in short time while keeping the position.

5. Conclusion

In this paper, a two-dimensional overhead crane is transformed to two independent systems that are with the same dynamic model in order to simplify the system analysis. An adaptive sliding mode fuzzy control approach has been designed for both X-direction transport and Y-direction transport, in which both the slope of sliding mode surface and the coordination between the two subsystems are automatically tuned by real time fuzzy inference respectively. The system stability is analyzed via the SMC concept and its effectiveness has been demonstrated by experiments on a two-dimensional prototype overhead crane. The experiments have shown the proposed control law guarantees both accurate positioning control and prompt damping of payload swing. Moreover, the experiments also show the system stability and performance can be guaranteed in spite of large initial swing angle.

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