

# Adaptive Fuzzy Sliding Mode Controller Design for Folding-Boom Aerial Platform Vehicle

Haidong Hu, En Li, Xiaoguang Zhao, Zize Liang and Wensheng Yu

**Abstract**—In this paper, an adaptive fuzzy sliding mode controller (AFSMC) is presented for the tracking control of work platform of folding-boom aerial platform vehicle. Chattering caused by the high speed switching control in sliding mode controller may degenerate the system performance and result in unpredictable instabilities. The proposed AFSMC could eliminate the chattering by substituting the discontinuous switching control with the continuous control obtained from adaptive fuzzy system. Since the adaptive control law is obtained from Lyapunov stability conditions, the stability and convergence of the overall system can be ensured. The simulation results demonstrate that the AFSMC is very effective in the case of system uncertainties. Not only is the vibration of the work platform suppressed, but also the tracking error of it is attenuated.

## I. INTRODUCTION

Aerial platform vehicle requires very high safety, because it is a kind of construction vehicle which needs hoist personnel to the appointed location in the aerial for installation or maintenance. Therefore, the steady movement and accurate positioning of the work platform should be ensured.

As vibration and trajectory deviation of the work platform could not be controlled effectively based on the rigid model of aerial platform vehicle which neglects the elastic deformation of long beam, the flexible nature should be considered in order to carry out the effective control. Therefore, the flexible multi-body dynamics equations of the arm system of folding-boom aerial platform vehicle have been established based on flexible multi-body dynamics theory and Lagrange's equation in the literature[1], which has been accepted by ICICIP2010.

The numerical solutions of the flexible model show that there exist vibration and small deviation of the trajectory of the work platform caused by the beam deflection. Therefore, the control objects are to eliminate the vibration in order to

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attain steady movement and make trajectory of the work platform follow the desired reference trajectory quickly.

Sliding mode control (SMC) is a control scheme to force the system state trajectories to reach the prescribed sliding mode surface and then remain on it by carrying out discontinuous control. SMC has been widely applied to robust control of nonlinear systems, such as trajectory tracking control of multi-link robots, for its robustness to parameter changes and external disturbances [2]. However, chattering caused by high-speed switching control degenerates the system performance and it may result in unpredictable instabilities. Therefore, several approaches have been proposed in order to reduce the chattering [3,4], among which the well known one is the application of saturation function [3] to the control input. In addition, various fuzzy systems have been applied to the construction of the control input in the literatures [4-8]. It is well known that fuzzy system can be used to approximate any nonlinear function over a compact set with arbitrary accuracy according to the universal approximation theorem [9]. As a result, an alternative way to solve the chattering problem is to substitute switching function with continuous control gain by applying the fuzzy system to the construction of the control input [10].

In this paper, an adaptive fuzzy sliding mode controller (AFSMC) for the tracking control of work platform of folding-boom aerial platform vehicle is proposed. The proposed controller combines the robustness of sliding mode controllers with the universal approximation capability of fuzzy logic systems. Meanwhile, an adaptive control law obtained from Lyapunov stability conditions is used to adjust the fuzzy control gain. Therefore, the stability and convergence of the overall system can be ensured by AFSMC. Simulation results have shown that the proposed control algorithm is very effective for suppressing the vibration and attenuating the tracking error of the work platform despite the system uncertainties.

This paper is organized as follows. Flexible multi-body dynamic model of folding-boom aerial platform vehicle is introduced and analyzed in Section II. In Section III, adaptive fuzzy sliding mode controller is designed to achieve the control objective. The simulation results for folding-boom aerial platform vehicle are illustrated in Section IV, and finally some concluding remarks are given in Section V.

## II. FLEXIBLE MULTI-BODY DYNAMIC MODEL OF FOLDING-BOOM AERIAL PLATFORM VEHICLE

The flexible multi-body dynamic model of the arm system of folding-boom aerial platform vehicle can be expressed as[1]

$$\begin{cases} G\ddot{\theta} + U\dot{\theta}^2 + H\ddot{q} + R = Q_\theta \\ M\ddot{q} + Nq + H^T\ddot{\theta} + V^T\dot{\theta}^2 = Q_q \end{cases} \quad (1)$$

In equations(1),  $\ddot{\theta} = [\ddot{\theta}_1 \ \ddot{\theta}_2]^T$ ,  $\dot{\theta}^2 = [\dot{\theta}_1^2 \ \dot{\theta}_2^2]^T$ , and  $\ddot{q} = [\ddot{q}_{11} \ \ddot{q}_{12} \ \ddot{q}_{21} \ \ddot{q}_{22}]^T$ .

Define  $z = [\theta \ q]^T$  as generalized coordinates, where  $\theta = [\theta_1 \ \theta_2]^T$ , in which  $\theta_1$  and  $\theta_2$  are the angle of beam 1,2 with respect to the horizontal plane, respectively. And  $q = [q_{11} \ q_{12} \ q_{21} \ q_{22}]^T$ , in which  $q_{11}, q_{12}$  and  $q_{21}, q_{22}$  are the deflection variables associated with the two former model function of beam 1,2, respectively.

Then  $\dot{z} = [\dot{\theta} \ \dot{q}]^T$ ,  $\ddot{z} = [\ddot{\theta} \ \ddot{q}]^T$ . Therefore, Equations (1) can be written as:

$$D(z)\ddot{z} + C(z, \dot{z})\dot{z} + B(z) = u \quad (2)$$

$$\text{where } D(z) = \begin{bmatrix} G & H \\ H^T & M \end{bmatrix}, \quad C(z, \dot{z}) = \begin{bmatrix} U\dot{\theta} & X \\ V^T\dot{\theta} & 0 \end{bmatrix},$$

in which,

$$G = \begin{bmatrix} (\frac{1}{3}m_1 + m_2 + m)l_1^2 & (\frac{1}{2}m_2 + m)l_1l_2 \cos(\theta_1 - \theta_2) \\ (\frac{1}{2}m_2 + m)l_1l_2 \cos(\theta_1 - \theta_2) & (\frac{1}{3}m_2 + m)l_2^2 \end{bmatrix}$$

$$H = \begin{bmatrix} \frac{m_1l_1}{\pi} & -\frac{1}{2}\frac{m_1l_1}{\pi} & \frac{2m_2l_1}{\pi} \cos(\theta_1 - \theta_2) & 0 \\ 0 & 0 & \frac{m_2l_2}{\pi} & -\frac{1}{2}\frac{m_2l_2}{\pi} \end{bmatrix}$$

$$M = \begin{bmatrix} \frac{1}{2}m_1 & 0 & 0 & 0 \\ 0 & \frac{1}{2}m_1 & 0 & 0 \\ 0 & 0 & \frac{1}{2}m_2 & 0 \\ 0 & 0 & 0 & \frac{1}{2}m_2 \end{bmatrix}$$

$$U = \begin{bmatrix} 0 & (\frac{1}{2}m_2 + m)l_1l_2 \sin(\theta_1 - \theta_2) \\ -\frac{1}{2}(m_2 + m)l_1l_2 \sin(\theta_1 - \theta_2) & 0 \end{bmatrix}$$

$$V = \begin{bmatrix} 0 & 0 & \frac{-2m_2l_1 \sin(\theta_1 - \theta_2)}{\pi} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad \dot{\Theta} = \begin{bmatrix} \dot{\theta}_1 & 0 \\ 0 & \dot{\theta}_2 \end{bmatrix},$$

$$X = \begin{bmatrix} 0 & 0 & \frac{2}{\pi}m_2l_1 \sin(\theta_1 - \theta_2)(\dot{\theta}_1 + \dot{\theta}_2) & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

In addition,  $B(z)$  is given by

$$B(z) = \left[ \begin{array}{cccc} (\frac{1}{2}m_1 + m_2 + m)gl_1 \cos \theta_1 & (\frac{1}{2}m_2 + m)gl_2 \cos \theta_2 \\ \frac{EI_1\pi^4}{2l_1^3}q_{11} & \frac{8EI_1\pi^4}{l_1^3}q_{12} & \frac{EI_2\pi^4}{2l_2^3}q_{21} & \frac{8EI_2\pi^4}{l_2^3}q_{22} \end{array} \right]^T$$

where  $m_1, m_2$  and  $m$  are the mass of beam 1,2 and load, respectively;  $l_1, l_2$  are the length of beam 1,2;  $g$  is acceleration of gravity;  $E$  is the modulus of elasticity of the

beam material and  $I_1, I_2$  are the moment of inertia of the cross-section of beam 1,2.

$u$  is control input vector and can be described as  $u = [u_1, u_2, u_3, u_4, u_5, u_6]^T = [Q_\theta^T, Q_q^T]^T = [Q_1, Q_2, Q_3, Q_4, Q_5, Q_6]^T$ , in which,  $Q_i$  ( $i = 1, 2 \dots 6$ ) is generalized force.

The following properties[3,11] are required for the design of AFSMC for folding-boom aerial platform vehicle.

Property 1: the matrix  $D(z)$  is symmetric and positive definite, and is bounded as  $d_m \leq \|D(z)\| \leq d_M, \forall z \in R^n$ , where  $d_m, d_M > 0$  are the minimum and maximum eigenvalues of  $D(z)$ , respectively.

Property 2: the matrix  $\dot{D}(z) - 2C(z, \dot{z})$  is skew symmetric, which suggests that  $x^T[\dot{D}(z) - 2C(z, \dot{z})]x = 0, \forall x \in R^n$ .

Property 3: The vector  $B(z)$  is bounded as  $B(z) \leq b_M$ , where  $b_M$  is a function of  $z$ .

For convenience, substitute  $D$ ,  $C$  and  $B$  for  $D(z)$ ,  $C(z, \dot{z})$  and  $B(z)$ , respectively.

In fact,  $D$ ,  $C$  and  $B$  cannot be exactly known, therefore there exist uncertainties in the dynamic model.

### III. DESIGN OF ADAPTIVE FUZZY SLIDING MODE CONTROLLER FOR FOLDING-BOOM AERIAL PLATFORM VEHICLE

#### A. Design of Sliding Mode Controller

The control objective is to drive the work platform to track the desired trajectory.

Therefore, the tracking error equation can be written as

$$e = z_d - z \quad (3)$$

where  $z_d$  denotes the desired reference trajectory vector. The sliding surface corresponding to the error state equation can be defined as:

$$s = \dot{e} + \lambda e,$$

where  $\lambda = \text{diag}[\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6]$ , in which  $\lambda_i$  is positive constant.

Define the reference state

$$\dot{z}_r = \dot{z} - s = \dot{z}_d - \lambda e, \quad \ddot{z}_r = \ddot{z} - \dot{s} = \ddot{z}_d - \lambda \dot{e}.$$

Then the control law  $u$  can be designed as follows:

$$u = \hat{u} - As - K \text{sgn } s \quad (4)$$

where  $\hat{u} = \hat{D}\ddot{z}_r + \hat{C}\dot{z}_r + \hat{B}$  in which  $\hat{D}, \hat{C}$ , and  $\hat{B}$  are the estimation of  $D, C$ , and  $B$ , respectively.

$A = \text{diag}[a_1, a_2, a_3, a_4, a_5, a_6]$  is a diagonal positive definite matrix in which  $a_i$  is positive constant.  $K \text{sgn } s$  is the switching control, in which  $K = \text{diag}[K_{11}, K_{22}, K_{33}, K_{44}, K_{55}, K_{66}]$  is positive definite diagonal gain matrix with the constant  $K_{ii} > 0$ . In addition,  $\text{sgn } s_i$  is discontinuous function and can be expressed as

$$sgns_i = \begin{cases} 1 & s_i > 0 \\ 0 & s_i = 0 \\ -1 & s_i < 0 \end{cases}$$

### B. Design of Adaptive Fuzzy Sliding Mode Controller

Since the chattering is induced by the discontinue control gain  $K \operatorname{sgn} s$ , the fuzzy gain  $k$  is used instead of the control gain  $K \operatorname{sgn} s$  to eliminate the chattering in this paper.

As a result, the new control law can be obtained as

$$u = \hat{D}\ddot{z}_r + \hat{C}\dot{z}_r + \hat{B} - As - k \quad (5)$$

Then, substituting (5) into (2) leads to

$$\dot{s} = -(C + A)s + \Delta f - k, \quad (6)$$

where  $k = [k_1, k_2, k_3, k_4, k_5, k_6]^T$ .  $\Delta f$  is defined as the lumped uncertainties and is given by  $\Delta f = \Delta D\ddot{z}_r + \Delta C\dot{z}_r + \Delta B$ , in which  $\Delta D$ ,  $\Delta C$  and  $\Delta B$  are the uncertainties of  $D$ ,  $C$  and  $B$  respectively and can be expressed as  $\Delta D = \hat{D} - D$ ,  $\Delta C = \hat{C} - C$ ,  $\Delta B = \hat{B} - B$ . In addition, assume that  $\Delta f_i$  is bounded, i.e.,  $|\Delta f_i| < \beta_i$ ,  $\beta_i > 0$ , where  $\beta_i$  is the boundary of  $\Delta f_i$ .

The control gain  $k_i$  is fuzzified by the fuzzy system with  $s_i$  as the input.

The fuzzy IF-Then rules can be written as:

IF  $s_i$  is  $A^m$  THEN  $k_i$  is  $B^m$ , where  $A^m$  and  $B^m$  are fuzzy sets.

In the rules, both  $s_i$  and  $k_i$  are selected to have the same kind of membership functions:  $NB$ ,  $NS$ ,  $ZE$ ,  $PS$ ,  $PB$ , which represent negative big, negative small, zero, positive small, and positive big, respectively. These membership functions are chosen to be Gaussian functions and defined as

$\mu_A(x_i) = \exp[-\frac{(x_i - \alpha_i)^2}{\sigma_i^2}]$ , where  $A$  denotes one of the fuzzy sets  $NB, \dots, PB$ ,  $x_i$  represents  $s_i$  or  $k_i$  and  $\alpha_i$  and  $\sigma_i$  are the center and width of the membership functions.

Therefore, the rule base can be described as follows:

- IF  $s_i$  is  $NB$  THEN  $k_i$  is  $NB$
- IF  $s_i$  is  $NS$  THEN  $k_i$  is  $NS$
- IF  $s_i$  is  $ZE$  THEN  $k_i$  is  $ZE$
- IF  $s_i$  is  $PS$  THEN  $k_i$  is  $PS$
- IF  $s_i$  is  $PB$  THEN  $k_i$  is  $PB$

By using the singleton fuzzification, product inference and center average defuzzification, the output value of the fuzzy system is given by

$$k_i = \frac{\sum_{m=1}^M \theta_{k_i}^m \mu_{A^m}(s_i)}{\sum_{m=1}^M \mu_{A^m}(s_i)} = \theta_{k_i}^T \xi_{k_i}(s_i), \quad (7)$$

where  $M$  is the amount of the fuzzy rules, here  $M = 5$ .  $\theta_{k_i} = [\theta_{k_i}^1, \dots, \theta_{k_i}^m, \dots, \theta_{k_i}^M]^T$  is the adjustable parameter

vector,  $\xi_{k_i}(s_i) = [\xi_{k_i}^1(s_i), \dots, \xi_{k_i}^m(s_i), \dots, \xi_{k_i}^M(s_i)]^T$  is the vector of the fuzzy basis functions  $\xi_{k_i}^m(s_i) = \frac{\mu_{A^m}(s_i)}{\sum_{m=1}^M \mu_{A^m}(s_i)}$ .

Since the fuzzy gain  $k$  is used to approximate the system uncertainty  $\Delta f$ , chattering caused by the discontinue control gain  $K \operatorname{sgn} s$  can be reduced. Further, in order to minimize the approximation errors between  $\Delta f$  and  $k$ , an adaptive control law is employed.

Assume that  $\theta_{k_{id}}$  is the ideal parameter vector so that  $k_i = \theta_{k_{id}}^T \xi_{k_i}(s_i)$  is the optimal compensation for  $\Delta f_i$ . Then based on the Wang's theorem[10], there exists  $\varepsilon_i > 0$  such that

$$|\Delta f_i - \theta_{k_{id}}^T \xi_{k_i}(s_i)| \leq \varepsilon_i, \quad (8)$$

where  $\varepsilon_i$  can be as small as possible.

Following, define the estimation error to be  $\tilde{\theta}_{k_i} = \theta_{k_i} - \theta_{k_{id}}$ . Thus, (7) can be rewritten as  $k_i = \tilde{\theta}_{k_i}^T \xi_{k_i}(s_i) + \theta_{k_{id}}^T \xi_{k_i}(s_i)$ . The design objective is to calculate the adjustable parameters  $\theta_{k_i}$  such that  $\tilde{\theta}_{k_i}$  is minimized, which can be attained when parameters are closed to the optimal values  $\theta_{k_{id}}$ .

Here, the adaptive control law is chosen as

$$\dot{\tilde{\theta}}_{k_i} = s_i \xi_{k_i}(s_i) \quad (9)$$

### C. Analysis of Stability

Consider the following Lyapunov function candidate

$$V = \frac{1}{2} s^T Ds + \frac{1}{2} \sum_{i=1}^n (\tilde{\theta}_{k_i}^T \tilde{\theta}_{k_i}) \quad (10)$$

The derivative of (10) with respect to time can be described as

$$\begin{aligned} \dot{V} &= \frac{1}{2} [\dot{s}^T Ds + s^T \dot{D}s + s^T D\dot{s}] + \frac{1}{2} \sum_{i=1}^n (\dot{\tilde{\theta}}_{k_i}^T \tilde{\theta}_{k_i} + \tilde{\theta}_{k_i}^T \dot{\tilde{\theta}}_{k_i}) \\ &= \frac{1}{2} [2s^T D\dot{s} + s^T \dot{D}s] + \frac{1}{2} \sum_{i=1}^n 2\tilde{\theta}_{k_i}^T \dot{\tilde{\theta}}_{k_i} \end{aligned}$$

Since  $\dot{D}(z) - 2C(z)$  is a skew symmetric matrix, and  $s^T \dot{D}(z)s = s^T (2C(z))s$ .

Thus,

$$\dot{V} = s^T [D\dot{s} + Cs] + \sum_{i=1}^n \tilde{\theta}_{k_i}^T \dot{\tilde{\theta}}_{k_i} \quad (11)$$

Substituting (6) into (11) leads to

$$\begin{aligned} \dot{V} &= s^T [-(C + A)s + \Delta f - k + Cs] + \sum_{i=1}^n \tilde{\theta}_{k_i}^T \dot{\tilde{\theta}}_{k_i} \\ &= -s^T As + \sum_{i=1}^n (s_i[\Delta f_i - k_i]) + \sum_{i=1}^n \tilde{\theta}_{k_i}^T \dot{\tilde{\theta}}_{k_i} \end{aligned}$$

Since  $k_i = \tilde{\theta}_{k_i}^T \xi_{k_i}(s_i) + \theta_{k_{id}}^T \xi_{k_i}(s_i)$ , then

$$\dot{V} = -s^T As + \sum_{i=1}^n s_i[\Delta f_i - \theta_{k_{id}}^T \xi_{k_i}(s_i)] + \sum_{i=1}^n \tilde{\theta}_{k_i}^T [-s_i \xi_{k_i}(s_i) + \dot{\tilde{\theta}}_{k_i}] \quad (12)$$

Putting (9) into (12), the derivative of Lyapunov function becomes

$$\dot{V} = -s^T As + \sum_{i=1}^n s_i [\Delta f_i - \theta_{k_{id}}^T \xi_{k_i}(s_i)]$$

In (8),  $\varepsilon_i$  can be chosen as small as possible such that

$$|\Delta f_i - \theta_{k_{id}}^T \xi_{k_i}(s_i)| \leq \varepsilon_i \leq \eta_i |s_i| \quad (13)$$

where  $0 < \eta_i < 1$ .

Furthermore, multiplying  $s_i$  on both sides of (13) gives

$$s_i |\Delta f_i - \theta_{k_{id}}^T \xi_{k_i}(s_i)| \leq \eta_i |s_i|^2 = \eta_i s_i^2$$

Hence,

$$\begin{aligned} \dot{V} &\leq -s^T As + \sum_{i=1}^n \eta_i s_i^2 \\ &= \sum_{i=1}^n (-a_i + \eta_i) s_i^2 \\ &= -s^T (A - \eta) s \end{aligned} \quad (14)$$

where  $\eta = \text{diag}[\eta_1, \eta_2, \eta_3, \eta_4, \eta_5, \eta_6]$ . Choosing  $a_i > \eta_i$  can make  $(A - \eta)$  is positive definite. Thus,  $\dot{V} \leq 0$ , which shows the stability in the Lyapunov sense.

In (14),  $\dot{V} = 0$  only when  $s = 0$ . As a result, the overall system is asymptotically stable. That is to say,  $\lim_{t \rightarrow \infty} s = \lim_{t \rightarrow \infty} (\dot{s} + \lambda e) = 0$ , which implies  $\lim_{t \rightarrow \infty} z = z_d$  and  $\lim_{t \rightarrow \infty} \dot{z} = \dot{z}_d$ . Therefore, the control object can be attained with the proposed adaptive fuzzy sliding mode controller.

#### IV. Simulation Results

The parameters and the initial conditions of the dynamic equation (2) are chosen as follows:

$m_1 = 650\text{kg}$ ,  $m_2 = 550\text{kg}$ ,  $m = 150\text{kg}$ ,  $l_1 = 7.5\text{m}$ ,  $l_2 = 8.5\text{m}$ ,  $g = 9.8\text{m/s}^2$ ,  $EI_1 = 6 \times 10^8 \text{N}\cdot\text{m}^2$ ,  $EI_2 = 5 \times 10^8 \text{N}\cdot\text{m}^2$ , the initial angles are  $\theta_1 = 2\pi/3\text{rad}$  and  $\theta_2 = 0.52\text{rad}$ , the initial angular velocities  $\dot{\theta}_1$  and  $\dot{\theta}_2$  are zero.

With the parameters selected above, the dynamic equation (2) meets the three properties mentioned in section II. Therefore, the design of AFSMC can follow the steps given in section III.

The controller parameters are set as  $\lambda = 100\text{diag}[1, 1, 1, 1, 1, 1]$ ,  $A = 50000\text{diag}[1, 1, 1, 1, 1, 1]$ .

Gaussian membership functions are selected as follows:

$$\mu_{NB}(x_i) = \exp[-(\frac{x_i + \pi/6}{\pi/24})^2],$$

$$\mu_{NS}(x) = \exp[-(\frac{x_i + \pi/12}{\pi/24})^2],$$

$$\mu_{ZE}(x) = \exp[-(\frac{x_i}{\pi/24})^2],$$

$$\mu_{PS}(x) = \exp[-(\frac{x_i - \pi/12}{\pi/24})^2],$$

$$\mu_{PB}(x) = \exp[-(\frac{x_i - \pi/6}{\pi/24})^2]$$

In order to demonstrate the robustness of the proposed AFSMC to large system uncertainties, the estimations of  $D$ ,

$C$  and  $B$  are chosen to be  $0.9D$ ,  $0.8C$  and  $0.7B$ , respectively.

The desired reference trajectory vector is given by

$$z_d = [2\pi/3 \quad \pi t/180 \quad 0 \quad 0 \quad 0 \quad 0]^T,$$

$$\text{then } \dot{z}_d = [0 \quad \pi/180 \quad 0 \quad 0 \quad 0 \quad 0]^T,$$

$$\ddot{z}_d = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T.$$

The AFSMC is realized using the MATLAB-Simulink environment.

The numerical simulation results of the proposed AFSMC are depicted in Fig.1~Fig.8.

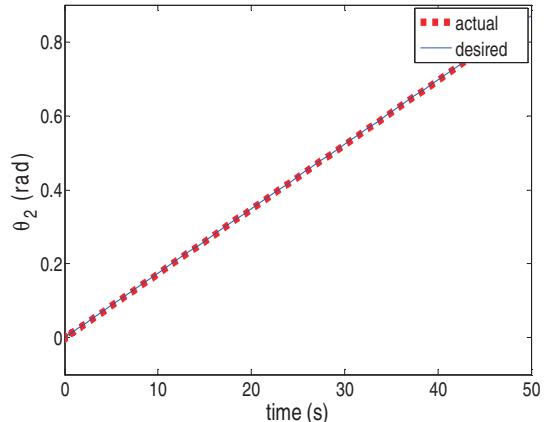


Fig.1 The tracking of  $\theta_2$

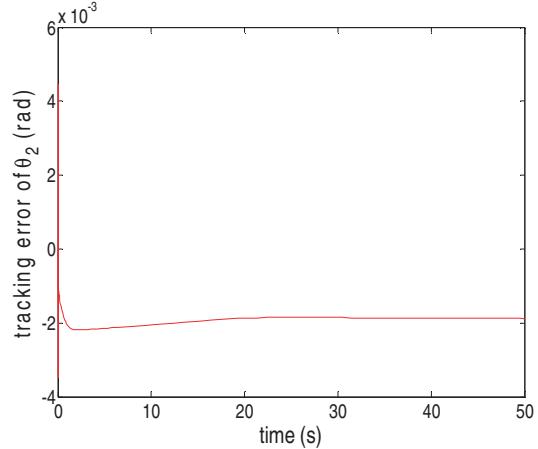


Fig.2 The tracking error of  $\theta_2$

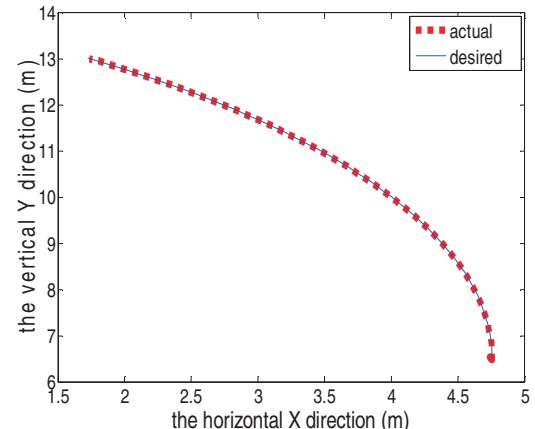


Fig.3 The trajectory tracking of the work platform

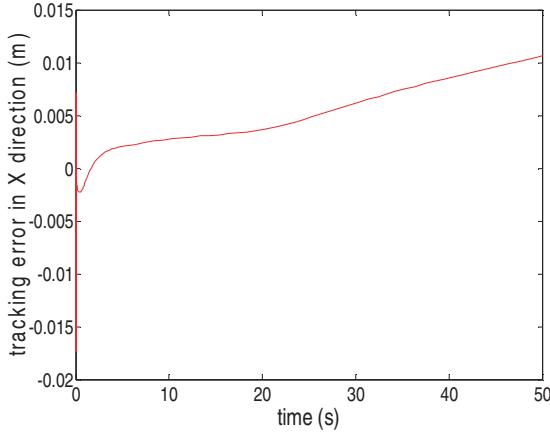


Fig.4 The trajectory tracking error of the work platform in the horizontal X direction

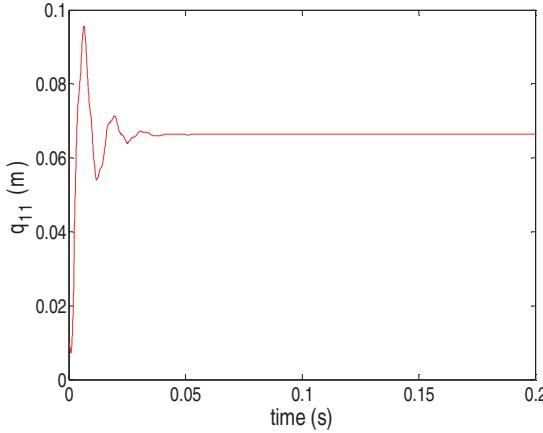


Fig.5 Deflection variable  $q_{11}$  varying with time

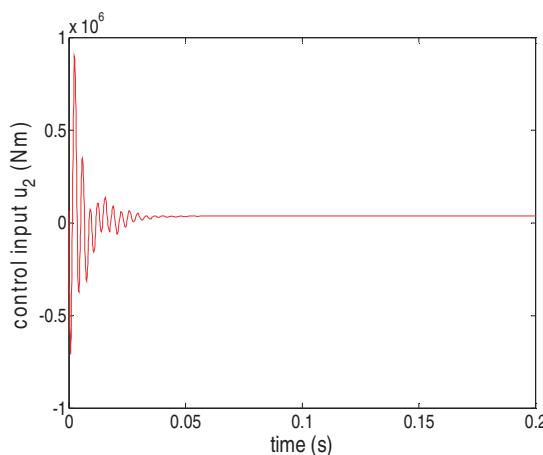


Fig.6 The regulation of the control input  $u_2$

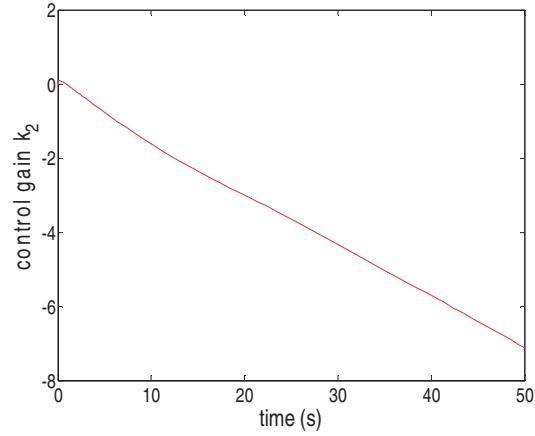


Fig.7 The adaptive adjustment of control gain  $k_2$

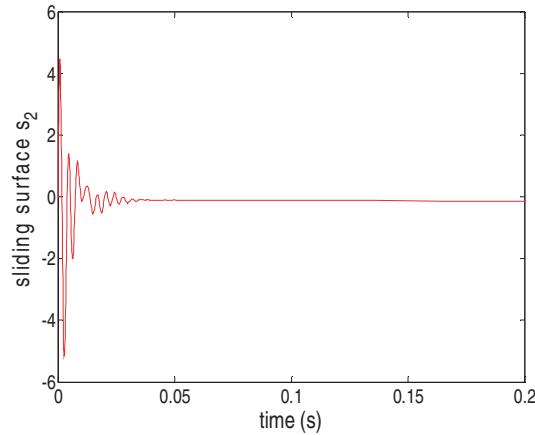


Fig.8 The time response of sliding surface  $s_2$

It is evident from Fig.1~Fig.8 that the performance of the AFSMC is good for both the trajectory tracking and vibration suppression of the work platform of folding-boom aerial platform vehicle in spite of the system uncertainties.

As is shown in Fig.1, the actual trajectory of  $\theta_2$ , as well as the actual trajectory of work platform shown in Fig.3, is able to follow the desired trajectory very closely by using the proposed AFSMC.

Fig. 2 and Fig. 4 demonstrate that the tracking errors are very small, which reflects that the tracking performance is good.

Fig. 5 shows that the vibration is suppressed very quickly. The deflection variable  $q_{11}$  converges to a small steady state value with a transient. Therefore, the work platform can keep the steady movement following the desired trajectory.

The control input  $u_2$ , which is used for regulating the trajectory of work platform, is shown in Fig. 6.

Fig. 7 shows the adaptive adjustment of control gain  $k_2$ .

As the system errors will converge to zero when the system states are on the sliding surface, the objective in an AFSMC is to force the states to the sliding surface.

It can be seen from Fig. 8 that adaptive sliding mode controller approaches its objective after an initial adaptation period, which reflects the existence of tiny errors.

## V. CONCLUSION

An AFSMC is proposed for the trajectory tracking control of the work platform of folding-boom aerial platform vehicle. In order to overcome the chattering caused by the high speed switching control in SMC, fuzzy logic control system with the universal approximation capability is used to substitute for the switching control. At the same time, an adaptive control law is utilized to on-line adjust the fuzzy control gain. As a result, chattering is eliminated with the proposed controller. Since the adaptive control law is derived from Lyapunov stability conditions, the stability of the overall system can be guaranteed. Simulation results have shown that AFSMC is a very effective control scheme for suppressing the vibration and attenuating the tracking error of the work platform in the case of system uncertainties.

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