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Adaptive Fuzzy Logic Based Inspection Robot for High Voltage Power Transmission Line*

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***Abstract*—This paper presents a bi-brachiate robot for the inspection tasks of the high voltage power transmission line (HVPTL). The robot adopts a turning around method to get across the component (obstacles for the robot) installed on the HVPTL, and the process of the obstacle negotiation is expressed in detail. A simplified two-link model of the robot during obstacle negotiating stage is given. The adaptive fuzzy system is employed to approximate the model's uncertain nonlinear functions, and the robot controller is given based on the approximation result. Simulation and field experiment results illustrate the validity of the proposed controller and effectiveness of the inspection robot.**

***Index Terms*—Inspection robot, Obstacle negotiation, Fuzzy system, Adaptive fuzzy control**

I. Introduction

The maintenance of the high voltage power transmission line is indispensable for power distribution systems. Nowadays, there are two kinds of way to carry out the inspection task: artificially field survey and helicopter inspection [1], but neither of them is effective. The development of mobile robot technology brings a new choice to this domain, and many researchers have done much work on the robot to inspect HVPTL since 1980s. Sawada et al.[2] developed an autonomous mobile robot which can move on the overhead ground wire (OGW) by a pair of driving wheels and a pair of supporting wheels. It can get across the obstacles, such as towers, by a special guide rail. Montambault and Pouliot [3] developed an inspection robot capable of clearing obstacles while operating on a live line. It can move along several axes, allowing it to adjust its shape in real time according to various line configurations and obstacles. The robot can run on the energized line for a long time and can be remotely operated from 5 km away. It has the ability of learning to clear obstacles by means of automated sequences. Wu et al. [4] designed an inspection robot with double-arms-symmetric suspension structure. It has two electro-magnetic sensors installed on each arm which can detect, identify, and localize obstacles. A motion planning strategy is applied to compute the non-collision path and the corresponding joint angles. Liang et al. [5] designed a tribrachiation mobile robot and a hierarchical control system with an embedded controller by which the robot can negotiate obstacles automatically. A recursive CCD method is used to solve the constrained inverse kinematics problem of the robot, and motion planning is done using hierarchical planning method by combining behavior reasoning and motion interpreting. Fu et al. [6] proposed a visual obstacle recognition algorithm based on the structure of the 220 KV power transmission line. The algorithm is composed by a straight line extraction algorithm and a circle or ellipse extraction algorithm utilizing the notion that the structure of all the obstacles in the line are circular or elliptic and that of the background objects are straight line.
In this paper, we propose a bi-brachiate inspection robot which can negotiate the obstacles in a way of turning around autonomously. Because the robot runs on the flexible HVPTL, it becomes a nonlinear, strongly coupling and under-actuated dynamic system during its obstacle negotiation [7]. The robot can be simplified to a two-link model while it is crossing the obstacles, which can be treated as a multi-input multi-output (MIMO) nonlinear system. The problem of controller designing for nonlinear systems have attracted lots of attention from the researchers, and many control methods have been proposed, such as feedback linearization method, passive control method, variable structure method, and intelligent control method [8, 9, 10, 11, 12, 13, 14, 17]. Among these methods, the fuzzy logic has found extensive applications for plants that are complex and ill-defined [15]. Many adaptive fuzzy controllers have been explored with the property of stable and even incorporated the expert knowledge systematically. In this paper, an adaptive fuzzy system is employed to approximate the robot model's uncertain nonlinear function, and then to design the robot controller with the approximation result based on the universal approximation theorem [16]. Simulation and field experiment results show the effectiveness of the proposed controller and the robot prototype.

II. Model Description

Generally, there are many components installed on the HVPTL, such as the vibration damper, the insulator strings

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and the space damper, as shown in Fig. 1. These devices are necessary to prevent the line from vibration and other damages. But they act as obstacles once utilizing robot technology to fulfill the inspection tasks.

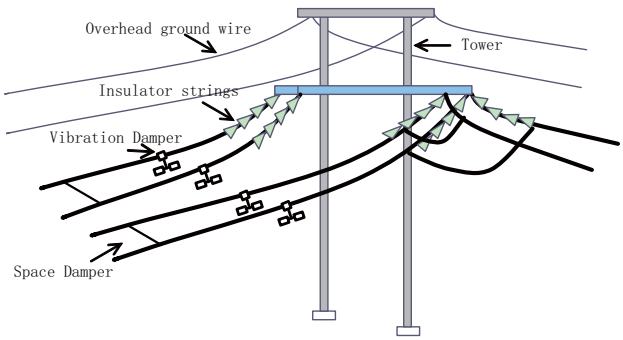


Fig. 1 Components installed on the HVPTL.

Based on these considerations, we design a bi-brachiate robot prototype which can inspect the line automatically, as shown in Fig. 2. The robot has two arms with a wheel and a claw at the top end of each arm. By the two wheels the robot can roll along the line when there are no obstacles in its detecting scope, and it can also grab the line by the claws to hold the robot body on the line. Each arm has a swing joint and a turning joint, which can drive the robot swing up/down and turn around to adjust its position and orientation to cross the obstacles. Besides, a counter-weight box is designed to adjust the center of the gravity of the robot to keep its stability and make it easier for the obstacle negotiation. When the robot encounters any type of obstacles, it takes a series of operations to get across the obstacle and continue the inspection work: 1) Close the claw of the forearm (the one closed to the obstacle) to grab the line. Move the counter-weight box to the front end of the slide rail. 2) Swing up the robot body to get the claw of the rear arm off the line by the swing joint of the forearm. 3) Turn the robot body around the forearm to get across the obstacle and swing down the robot to make the rear wheel hanging on the line by the turning joint and swing joint of the forearm. 4) Close the claw of the rear arm to grab the line. Now the robot has one arm across the obstacle and the other behind it. 5) Repeat procedure 1)∼3) to the rear arm, then the whole robot body will cross the obstacle.

It's critical to keep the robot stable and balance while it is crossing the obstacles with only one arm hanging on the line, because the whole robot body is loaded on one arm and all its weight is pressed on the contact point of the robot and the line, which will cause damages to the robot. During the obstacle negotiation process, the robot model can be simplified as a two-link manipulator, as shown in Fig 3.

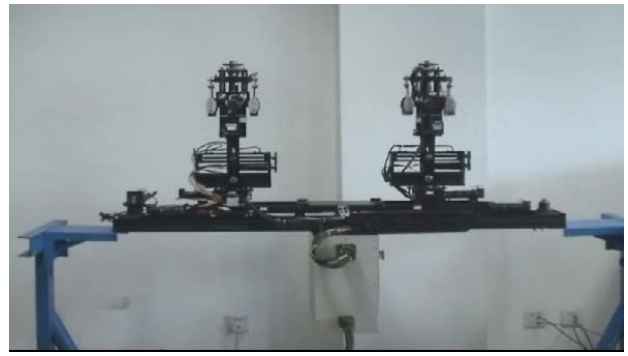


Fig. 2 Bi-brachiate inspection robot prototype.

The dynamic equations of the robot simplified model can be derived as:

$$\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{pmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{pmatrix} + \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \begin{pmatrix} \dot{q}_1 \\ \dot{q}_2 \end{pmatrix} + \begin{bmatrix} G_1 \\ G_2 \end{bmatrix} = \begin{pmatrix} \tau_1 \\ \tau_2 \end{pmatrix} \quad (1)$$

$$\begin{aligned}
M_{11} &= (m_1 + m_2 + \frac{1}{3}m_3)l_3^2 \cos^2 q_2 + (\frac{1}{3}m_1 + \frac{2}{3}m_2 + m_3)l_2^2 \\
&\quad + \frac{1}{3}(m_1 + m_2)(l_1^2 - l_1 l_2) \\
M_{12} &= \frac{1}{2}((m_1 + m_2)l_1 - (m_1 + m_2 + m_3)l_2)l_3 \sin q_2 \\
M_{21} &= M_{12} \\
M_{22} &= \frac{1}{3}l_3^2 \sin^2 q_2 + (m_1 + m_2)l_3^2 \\
C_{11} &= -2(m_1 + m_2 + \frac{1}{3}m_3)l_3^2 \dot{q}_2 \cos q_2 \sin q_2 \\
C_{12} &= \frac{1}{2}((m_1 + m_2)l_1 - (m_1 + m_2 + m_3))l_3 \dot{q}_2 \cos q_2 \\
C_{21} &= (\frac{1}{4}(m_1 + m_2)l_1 \dot{q}_2 - \frac{1}{4}(m_1 + m_2 + m_3)l_2 \dot{q}_2 \\
&\quad + (m_1 + m_2 + \frac{1}{3}m_3)l_3 \dot{q}_1 \sin q_2)l_3 \cos q_2 \\
C_{22} &= (-\frac{1}{4}(m_1 + m_2)l_1 \dot{q}_1 + \frac{1}{3}m_3 l_3 \dot{q}_2 \sin q_2 \\
&\quad + \frac{1}{4}(m_1 + m_2 + m_3)l_2 \dot{q}_1)l_3 \cos q_2 \\
G_1 &= (\frac{1}{2}(m_1 + m_2)l_1 + (\frac{3}{2}m_1 + \frac{5}{2}m_2 + m_3)l_2)g \sin q_1 \\
&\quad + (m_1 + m_2 + \frac{1}{2}m_3)g l_3 \cos q_1 \cos q_2 \\
G_2 &= -(m_1 + m_2 + \frac{1}{2}m_3)g l_3 \sin q_1 \sin q_2
\end{aligned}$$

Where m_1 denotes the mass between the claw and swing joint of one arm, m_2 denotes the mass between the swing joint and the turning joint of the arm, m_3 denotes the mass of the sliding rail of the robot, and l_1, l_2, l_3 are their length respectively. g is the acceleration of the gravity. q_1 denotes

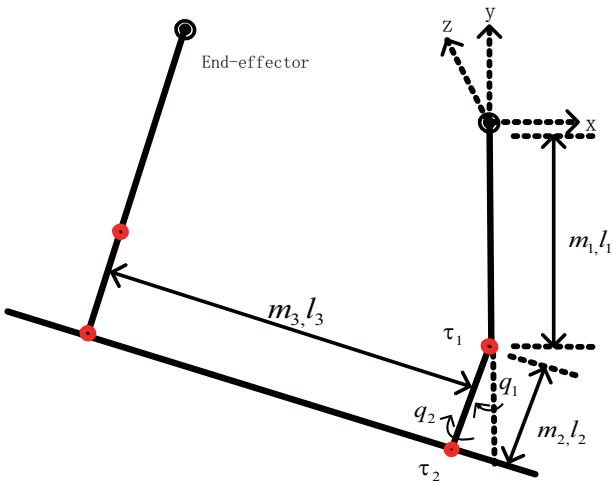


Fig. 3 Two-link model of bi-brachiate inspection robot.

the angle of the swing joint which can swing the robot up and down. q_2 denotes the angle of turning joint which can turn the robot around the arm. τ_1 and τ_2 are the input force of the swing joint and the turning joint.
Rewrite (1) to the standard form of MIMO nonlinear systems as:

$$\ddot{q} = F(x) + G(x)\tau \tag{2}$$

where

$$\begin{aligned} q &= [q_1,\ q_2]^T \\ x &= [q_1,\ \dot{q}_1,\ q_2,\ \dot{q}_2]^T \\ \tau &= [\tau_1,\ \tau_2]^T \\ F(x) &= \begin{bmatrix} f_1(x) \\ f_2(x) \end{bmatrix} \\ &= \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}^{-1} \left(- \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} - \begin{bmatrix} G_1 \\ G_2 \end{bmatrix} \right) \\ G(x) &= \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}^{-1} \end{aligned}$$

III. Adaptive Fuzzy Controller

The simplified model of the robot can be regarded as a multi-input multi-output(MIMO) nonlinear dynamic system. The properties of the system, such as nonlinear, unstable and under actuated, have drawn a lot of researchers' attention, and many excellent methods have been explored. Among all these methods, the adaptive fuzzy logic method has some advantages like approximating continuous functions over a compact set to an arbitrary degree of accuracy, if enough number of rules have been considered. The unique property of fuzzy logic system is that it can make use of linguistic information in a systematic way.

In the following description, an adaptive fuzzy logic controller will be designed based on the method described in [15]. Although the robot's dynamic equation is derived, both the two nonlinear functions of $F(x)$ and $G(x)$ are not obtained accurately due to the simplification and the disturbance. So we design a fuzzy system containing a well-defined adaptive fuzzy controller using adaptive control law to approximate the nonlinear functions, and then give the robot controller based on the approximation result of the adaptive fuzzy system.

A. Fuzzy System

The fuzzy system used in this paper is a mapping from $U \subseteq R^n$ to R, where $U = U_1 \times \cdots \times U_n, U_i \subset R, i = 1, 2, \cdots, n$. The input vector is $x = [x_1, \cdots, x_n]^T \in U \subset R^n$ and the output variable $y \subset R$. Then the lth rule of the fuzzy system can be described as a set of if-then rules in the following form:

$$R^l:\ \text{if } x_1 \text{ is } F_1^l \text{ and } \cdots \text{ and } x_n \text{ is } F_n^l,\ \text{then } y^l \text{ is } C^l \tag{3}$$

where $F_i^l, l = 1, \cdots, M$ denotes the fuzzy set defined on the universe of discourse of the ith input, and C^l is a fuzzy set defined on R.
By utilizing the singleton fuzzifier, product inference engine, and center-average defuzzifier, the output of the fuzzy system can be shown as:

$$y(x) = \frac{\sum_{l=1}^{M} \bar{y}^l \left(\prod_{i=1}^{n} \mu_{F_i^l}(x_i) \right)}{\sum_{l=1}^{M} \left(\prod_{i=1}^{n} \mu_{F_i^l}(x_i) \right)} \tag{4}$$

where $\bar{y}_l$ is the point at which the membership function μ_c^l achieves its maximum value, and $\mu_c^l(\bar{y}^l) = 1$.
Equation(4) can be rewritten as follows:

$$y(x) = \xi^T(x)\theta \tag{5}$$

where $\theta = [y^1, \cdots, y^M]^T$ is a vector of all the parameters, and $\xi(x) = [\xi_1(x), \cdots, \xi_M(x)]$ is a set of fuzzy basis functions defined as

$$\xi_l(x) = \frac{\prod_{i=1}^{n} \mu_{F_i^l}(x_i)}{\sum_{l=1}^{M} \left(\prod_{i=1}^{n} \mu_{F_i^l}(x_i) \right)} \tag{6}$$

By using the fuzzy system described above, the approximation of the nonlinear function $f_i(x)$ and $g_{ij}(x)$, as well as the adaptive fuzzy laws of the functions can be derived.

B. Design of System Controller

The purpose to design the system controller is to insurance the output of the system keeping up with the desired trajectory, and all the variables of the system bounded. Assume the desired trajectory as $q_d = [q_{d1}(t), q_{d2}(t)]^T$, and define the tracking error as

$$e(t) = q_d(t) - q(t) \tag{7}$$

where $e(t) = [e_1(t), e_2(t)]^T$ denotes the tracking errors of q_1 and q_2, and $q(t) = [q_1(t), q_2(t)]^T$ denotes the actual trajectory. The filtered tracking errors are defined as:

$$\begin{aligned} s_1(t) &= \dot{e}_1(t) + \lambda_1 e_1(t) \\ s_2(t) &= \dot{e}_2(t) + \lambda_2 e_2(t) \end{aligned} \tag{8}$$

Let $v_1 = \ddot{q}_{d1} + \lambda_1 \dot{e}_1$ and $v_2 = \ddot{q}_{d2} + \lambda_2 \dot{e}_2$, and denote $s(t) = [s_1(t), s_2(t)]^T$ and $v(t) = [v_1(t), v_2(t)]^T$, then we can get the following nonlinear control law as long as the nonlinear function $f_i(x)$ and $g_{ij}(x)$ are exactly known:

$$u = G^{-1}(-F(x) + v + K_0 s) \tag{9}$$

where $K_0 = diag[k_{01}, \cdots, k_{0p}]$ with $k_{0i} > 0$ for $i = 1, 2$.

C. Design of Adaptive Fuzzy Law

As mentioned before, the system nonlinear functions $f_i(x)$ and $g_{ij}(x)$ are not known exactly $a\ prior$, we define a fuzzy system to approximate the two nonlinear functions as follows:

$$\begin{aligned} \hat{f}_i(x, \theta_{f_i}) &= \xi_{f_i}^T \theta_{f_i} \ \ , i = 1, 2 \\ \hat{g}_{ij}(x, \theta_{g_{ij}}) &= \xi_{g_{ij}}^T \theta_{g_{ij}} \ \ , i = 1, 2 \end{aligned} \tag{10}$$

where ξ_{f_i} and $\xi_{g_{ij}}$ are the fuzzy basis function and their parameters are fixed, and θ_{f_i} and $\theta_{g_{ij}}$ are the adaptive adjustable vectors and their adaptive control law are given as follows:

$$\begin{aligned} \dot{\theta}_{f_i} &= -\eta_{f_i}(x) s_i \\ \dot{\theta}_{g_{ij}} &= -\eta_{g_{ij}}(x) s_i u_j \end{aligned} \tag{11}$$

Now,we can denote the approximated $F(x)$ and $G(x)$ as:

$$\begin{aligned} \hat{F}(x) &= [\hat{f}_1(x), \hat{f}_2(x)]^T \\ \hat{G}(x) &= \begin{bmatrix} \hat{g}_{11}(x) & \hat{g}_{12}(x) \\ \hat{g}_{21}(x) & \hat{g}_{22}(x) \end{bmatrix} \end{aligned} \tag{12}$$

Substituting (12) to (9), we can get the adaptive fuzzy control law as follows:

$$u = \hat{G}^{-1}(x, \theta_g)(-\hat{F}(x, \theta_f) + v + K_0 s) \tag{13}$$

Since the approximated function $\hat{G}(x, \theta_g)$ is not guaranteed to be nonsingular, the regularized inverse of $\hat{G}^{-1}(x, \theta_g)$ is used to make sure that the controller is always well-defined, which is shown as:

$$\hat{G}^T(x, \theta_g)[\varepsilon_0 I_2 + \hat{G}(x, \theta_g \hat{G}^T(x, \theta_g))]^{-1} \tag{14}$$

Substituting (14) to (13), the final adaptive fuzzy controller is given as:

$$\begin{aligned} u =& \hat{G}^T(x, \theta_g)[\varepsilon_0 I_2 + \hat{G}(x, \theta_g \hat{G}^T(x, \theta_g))]^{-1}(-\hat{F}(x, \theta_f) \\ &+ v + K_0 s) \end{aligned} \tag{15}$$

D. Stability Analysis

We can get the conclusion that $e_i(t) \to 0$ asymptotically if $s_i(t) \to 0$ for $i = 1,\ 2$ from (8), so the control objective turns to design a robot controller to make the $s_i(t) \to 0$, instead of $e_i(t) \to 0$ for $i = 1, 2$. The time derivatives of the filter error $s(t)$ can be written as:

$$\dot{s} = v - F(x) - G(x)u \tag{16}$$

where v is defined as in (9).
Substitute (16) into (9) to get:

$$\dot{s}(t) = -K_0 s(t) \tag{17}$$

Resolve the differential equation above and obtain the result as follows:

$$s_i(t) = s_i(0) e^{-K_{0i} t},\ i = 1, 2 \tag{18}$$

which implies that $s_i(t) \to 0$ when $t \to 0$, so we can make sure that $e_i(t) \to 0$ and $\dot{e}_i(t) \to 0$ when $t \to 0$. Fuzzy systems like (5) can approximate continuous functions up to an arbitrary degree of accuracy over a compact set, if there are enough number of fuzzy rules. So the approximation error is limited. Finally, we can see that the designed control input (15) ensures the boundedness of all the variables in the closed-loop system and guarantees the output tracking a desired trajectory.

IV. Results

In this section, the simulation results of the simplified model and the field experiment results are described.

A. Simulation Results

The system parameters are given as: $m_1 = 10kg$, $m_2 = 2.5kg$, $m_3 = 20kg$, $l_1 = 0.4m$, $l_2 = 0.1m$, $l_3 = 0.8m$, $\lambda_1 = 30$, $\lambda_2 = 30$, $K_0 = 15I_2$, $\varepsilon_0 = 0.1$, $\eta_{f_i} = 0.5$, $\eta_{g_{ij}} = 0.5$, for $i, j = 1, 2$. The desired trajectory of the robot's end effector taking the obstacle negotiation procedure is given as follows:

$$q_{d1}(t) = \begin{cases} \pi t/180 & t \le 10 \\ \pi/18 - \pi(t-10)/540 & 10 < t \le 40 \\ 0 & t > 40 \end{cases}$$

$$q_{d2}(t) = \begin{cases} 0 & t \le 10 \\ \pi(t-10)/30 & 10 < t \le 40 \\ \pi & t > 40 \end{cases}$$

This desired trajectory is designed based on the process of the obstacle negotiation when the forearm of the robot has grabbed the line and the rear arm is about to get across the obstacle. The end-effector of the robot first swings up from the line, then turns about $180°$ around the forearm and swings down to the line at the same time. The 3D vision of the desired trajectory is shown in Fig. 4, where the red circle shows the start point of the end-effector.

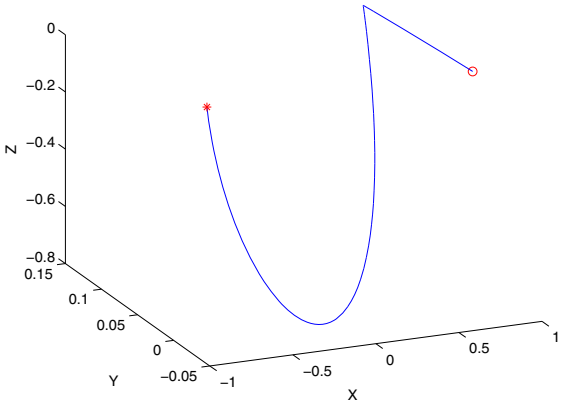


Fig. 4 Desired trajectory of the robot's end-effector.

The membership functions are defined as:

$$\mu_{F_i^1}(x_i) = \exp\left(-\frac{1}{2}\left(\frac{x_i + 0.25}{10}\right)^2\right)$$
$$\mu_{F_i^2}(x_i) = \exp\left(-\frac{1}{2}\left(\frac{x_i}{10}\right)^2\right)$$
$$\mu_{F_i^3}(x_i) = \exp\left(-\frac{1}{2}\left(\frac{x_i - 0.25}{10}\right)^2\right), \ i = \ 1, \ 2, \ 3, \ 4$$

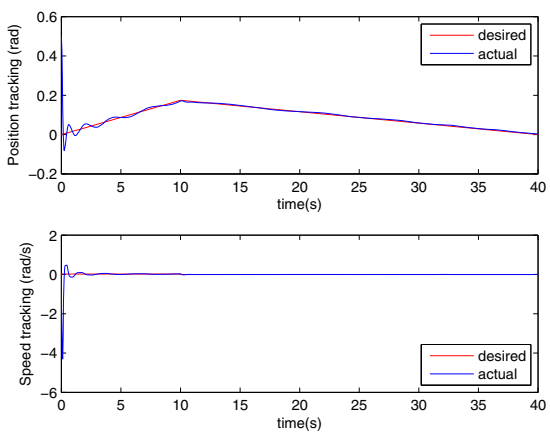


Fig. 5 Position and speed tracking of q_1.

The position and speed tracking results of q_1 and q_2 are shown in Fig. 5 and Fig. 6, while the position and speed tracking error of q_1 and q_2 are shown in Fig. 7. As shown in Fig. 5 and 6, the actual trajectories of q_1 and q_2 almost overlap their desired trajectories, as well as the speed tracking. The overshoots of the trajectory tracking indicates that the obstacle negotiation process is not ideal, which can be decreased by adjusting the system parameters. As we can see in Fig. 6, there is a step at about 10s caused by the sudden change of the speed of q_2. So further study can be made on the parameter adjusting to smooth the curves and stabilize the control performance. The tracking errors shown in Fig. 7 are limited, which demonstrates the tracking capability of the proposed controller and its effectiveness for the tracking control of uncertain nonlinear systems.

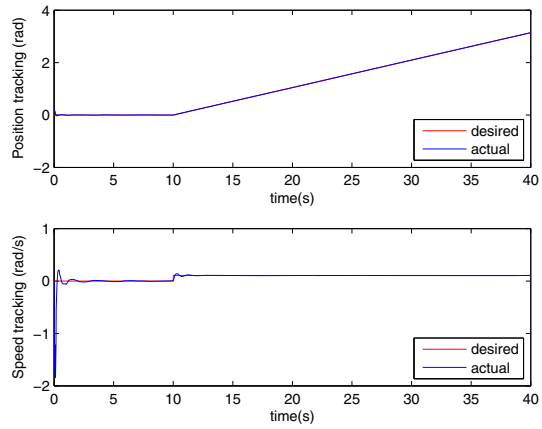


Fig. 6 Position and speed tracking of q_2.

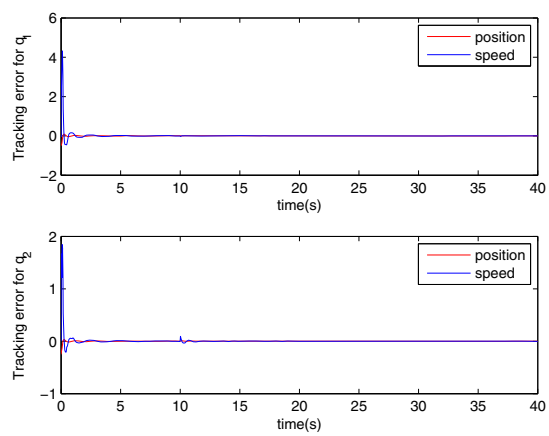
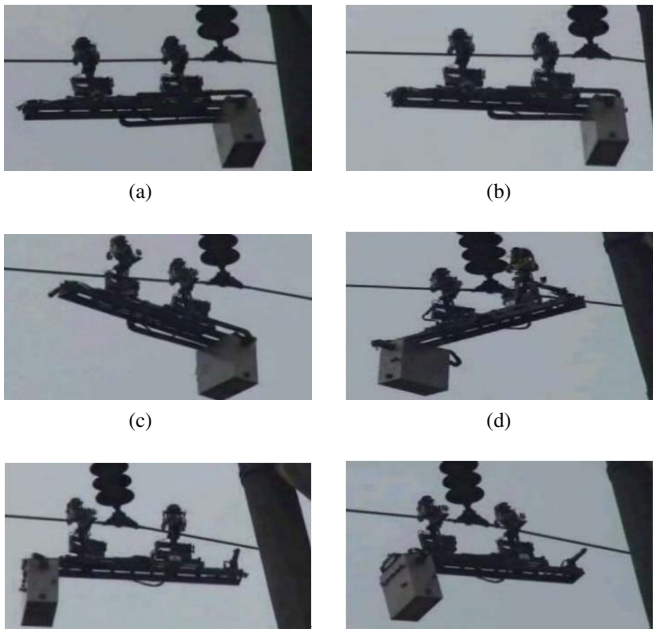


Fig. 7 Position and speed tracking error of q_1 and q_2.

B. Field Experiment Results

The proposed system controller is applied to the robot prototype and a series of field experiments have been taken. Fig. 8 shows the process of insulator strings negotiation in

the field of the power transmission. The experiment results have shown the timeliness and effectiveness of the controller.



(a) (b) (c) (d) (e) (f)

Fig. 8 Field experiment: insulator strings negotiation.

V. Conclusion

In this paper, we design an bi-brachiate inspection robot for high voltage power transmission line which can get across the obstacles installed on the line automatically. When taking obstacle negotiation procedure, the robot adopts a turning around method with one arm hanging on the line and the other turning the robot body around it. Due to the uncertainty of the robot modeling and environment disturbance, an adaptive fuzzy system is used to approximate the robot uncertain nonlinear functions. The robot controller is derived based on the adaptive fuzzy systems and its stability is guaranteed by analysis. Simulation results have confirmed the success of the proposed robot controller with acceptable tracking errors and operation stability, and the field experiments show the timeliness and effectiveness of the robot prototype and the proposed controller.

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