International Journal of Control and Automation
Vol. 9, No. 9 (2016), pp.265-274
http//dx.doi.org/10.14257/ijca.2016.9.9.26

Adaptive Control Scheme for Visual Servo Manipulator Based On the Dead Zone Mathematical Model

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Abstract

In this paper, a PD control algorithm based on fuzzy logic dead compensation has been proposed. The fuzzy logic dead zone compensator was used to compensate the dead zone which existed in the mechanical system, PD control scheme was used to control trajectory of the joints of robot, so that the stability and robustness can be improved. In order to verify the validity of the control algorithm, we realized the proposed adaptive control strategy in MATLAB. The simulation results has revealed that:comparing with the traditional PD control scheme, the proposed PD control algorithm based on fuzzy logic dead compensation can effectively compensate the dead zone which existed in the mechanical system, also the position tracking performance and precision of the manipulator has been enhanced.

Keywords*: PD control algorithm, Deadzone, Fuzzy logic deadzone mathematical model*

1. Introduction

As the rapid development of robotic visual measurement and control, research on the robot visual servo control has made new progress, Machine vision have been widely used in the industrial robot, military, aviation and space exploration and other fields[1-3]. Therefore, robot visual servo occupied an important position in the field of robot, accurate moving object detection algorithm and the control algorithm of robot was paid attention to by the researchers in the field of robot , robot visual servo is mainly composed of robot joints and the visual system.

Multi-joint robot is a kind of wide application of robots, the vast majority of industrial robot and intelligent mobile robot is a multi-joint robot, which have multiple joint robotic arm[4], as the control plant, Robot system is a very complicated nonlinear system with the features of multiple input multiple output with time-varying, strong coupling and nonlinear dynamics[5], dead zone feature is a typical nonlinear in the robotic control field.

How to overcome the impact on the robot control caused by the nonlinearity, especially the dead zone features, and improve the control precision of the robot, have always been the problem that the researchers have to face and solve. As to the question of dead zone, many researchers has paid unremitting efforts and obtained substantial progress about this problem. Such as Tao[6-7] has considered in the case of continuous and discrete, using adaptive invers to compensate a class of linear system . Cho, *etc*.[8] pointed on the known dead zone model of linear or nonlinear system, a new control scheme is proposed to improve its control precision. Hsu, *etc*.[9] has adopted the sliding mode control for the multi-input systems with nonlinear gap input structure to ensure the stability control. Liu, *etc*. [10] has studied the adaptive control on the kinematics equation and the gap of the flexible joint robot in his paper. Wu, *etc*.[11] have studied a robot indirect adaptive fuzzy control scheme under the premise that the square approximation error is integrable and the tracking error is convergence.

ISSN: 2005-4297 IJCA

In this paper , we aimed at the dead zone which has been existed in the manipulator of the machine vision system, a PD control algorithm based on fuzzy logic dead compensation has been proposed. the fuzzy logic dead zone compensator was used to compensate the dead zone in the mechanical system, PD control scheme was used to control trajectory of the joints of robot,so that the stability and robustness can be improved. In order to verify the validity of the control algorithm, we realized the proposed adaptive control strategy based on sub-block approximation algorithm in MATLAB.

2. Dead Zone Mathematical Model and Its Compensation Method

2.1. Dead Zone Mathematical Model

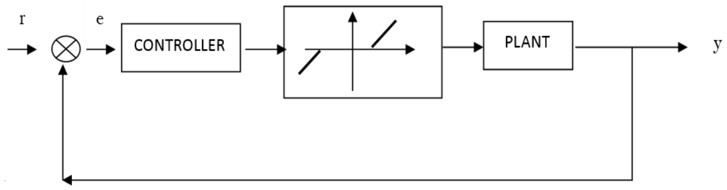

Figure 1. Actuator Control System with Dead Zone

Actuator control system with dead zone was shown in Figure 1 [12] . Dead zone is a kind of static nonlinear function, which is used to describe the system insensitivity to small signal .In the closed loop system, dead zone has a harmful effect on the dynamic and static performance for the system and the most common influence is to make the accuracy of the static output drop. In addition, in the dead zone system have no response, but it may cause limit cycles and unstable in the control system[13-14].

Figure 1 shows that nonlinear characteristics of the asymmetric dead zone can be represented as

$$\tau = D_u(u) = \begin{cases} u + d_-, & u < -d_- \\ 0, & -d_- \le u < d_+ \\ u - d_+, & d_+ \le u \end{cases} \tag{1}$$

Where u control input before entering the dead zone, τ is control input fterentering the dead zone, $d = [d_+ \; d_-]^T$ is the value of dead zone, $d_+ > 0,\, d_- > 0$.

Equation (1) can be changed as :

$$\tau = D_u(u) = u - sat_d(u) \tag{2}$$

$sat_d(u)$ is the saturation function of the asymmetric dead zone , represented as

$$sat_d(u) = \begin{cases} -d_- \;, & u < -d_- \\ u, & -d_- \le u < d_+ \\ d_+, & d_+ \le u \end{cases} \tag{3}$$

2.2. Dead Zone Fuzzy Compensator

According to the nonlinear characteristics of dead zone, dead zone compensation rules can be designed as follows:

$$\left.\begin{array}{l} IF\left(\omega \; is \;\; positive\right), THEN\left(u = \omega + \hat{d}_+\right) \\ IF\left(\omega \; is \; negative\right), THEN\left(u = \omega - \hat{d}_+\right) \end{array}\right\} \tag{4}$$

Where $\hat{d} = [\hat{d}_+ \ \hat{d}_-]^T$ is the estimate value of $d = [d_+ \ d_-]^T$.

Membership function is designed as:

$$\begin{cases} X_+(\omega) = \begin{cases} 0, & \omega < 0 \\ 1, & 0 \le \omega \end{cases} \\ X_-(\omega) = \begin{cases} 1, & \omega < 0 \\ 0, & 0 \le \omega \end{cases} \end{cases} \tag{5}$$

control input after fuzzy compensation is:

$$u = \omega + \omega_F \tag{6}$$

ω_F is obtained according to the following fuzzy rules

$$\left. \begin{array}{l} IF\left(\omega \in X_+(\omega)\right), THEN\left(\omega_F = \hat{d}_+\right) \\ IF\left(\omega \in X_-(\omega)\right), THEN\left(\omega_F = -\hat{d}_-\right) \end{array} \right\} \tag{7}$$

According to the fuzzy method, the output of the fuzzy system is

$$\omega_F = \frac{\hat{d}_+ X_+(\omega) - \hat{d}_- X_-(\omega)}{X_+(\omega) + X_-(\omega)} \tag{8}$$

Due to $X_+(\omega) + X_-(\omega) = 1$,so

$$\omega_F = \hat{d}^T X(\omega) \tag{9}$$

Where $\hat{d} = [\hat{d}_+ \ \hat{d}_-]^T$.

$$X(\omega) = \begin{bmatrix} X_+(\omega) \\ -X_-(\omega) \end{bmatrix} \tag{10}$$

According to the Figure 1,from equation (2) and equation (6),we can get:

$$\tau = D_u(u) = D_u(\omega + \omega_F) = \omega + \left[\omega_F - sat_d(\omega + \omega_F)\right] \tag{11}$$

Theorem 1: by using fuzzy compensation rule (7), the control input is

$$\tau = \omega - \tilde{d}^T X(\omega) + \tilde{d}^T \delta \tag{12}$$

Where The dead zone estimation error is $\tilde{d} = d - \hat{d}$,the unmatched item in the model need to meet $\|\delta\| \le 1$.

3. The Deadzone Fuzzy Compensator for Robotic Control System Design

3.1. System Description

The dynamic equations of the joints the manipulator is:

$$M(q)\ddot{q} + V_m(q,\dot{q})\dot{q} + F(q,\dot{q}) + G(q) + \tau_d = \tau \tag{13}$$

Where $q(t) \in R^n$ is the joint angular displacement, $M(q)$ is inertia matrix, $V_m(q,\dot{q})$ is Centrifugal force and coriolis forces, $G(q)$ is Gravity, $\tau \in R^n$ is Control moment, $F(q,\dot{q})$ is Friction torque, $\tau_d \in R^n$ is disturbance.

After dead zone, the control input is

$$\tau = D(u) = u - sat_D(u) \tag{14}$$

Manipulator has the following several characteristics:

characteristic 1 $M(q)$ is metric positive definite matrices, $m_2 I < M(q) < m_1 I, m_1$和$m_2$ is constant;

characteristic 2 $V_m(q,\dot{q})$ is bounded, and the upper bound is V_M;

characteristic 3 $\dot{M}\text{-}2V_m$ is skew symmetric;

characteristic 4 The unknown disturbances meet $\|\tau_d\| \le \tau_M$, τ_M is constant.

characteristic 5 the unknown dead-zone is bounded

$$\|D\| \le D_M \tag{15}$$

Assuming that dead zone width is constant, then

$$\dot{D} = 0 \tag{16}$$

Position tracking error is defined as:

$$e = q_d - q \tag{17}$$

To define the tracking error filtering function as:

$$r = \dot{e} + \Lambda e \tag{18}$$

Where Λ is positive definite matrix, then

$$\dot{q}_d + \Lambda e = \dot{q} + r$$

$$\begin{aligned} M\dot{r} &= M(\ddot{e} + \Lambda \dot{e}) = M(\ddot{q}_d - \ddot{q} + \Lambda \dot{e}) \\ &= M\ddot{q}_d - M\ddot{q} + M\Lambda\dot{e} = M\ddot{q}_d + V_m\dot{q} + F + G + \tau_d - \tau + M\Lambda\dot{e} \\ &= M(\ddot{q}_d + \Lambda\dot{e}) + V_m(\dot{q} + \Lambda\dot{e} - r) + F + G + \tau_d - \tau \\ &= -V_m r + f(x) + \tau_d - \tau \end{aligned} \tag{19}$$

The nonlinear function is

$$f(x) = M(\ddot{q}_d + \Lambda\dot{e}) + V_m(\dot{q} + \Lambda\dot{e} - r) + F(q,\dot{q}) + G(q) \tag{20}$$

3.2. Fuzzy Compensator for Dead Zone

Assuming there existed n control input in control system , $i = 1, 2, \cdots, n$,then

$$\tau_i = D(u_i) = u_i - sat_{d_i}(u_i) \tag{21}$$

Where $D = diag\{d_1, d_2, \cdots, d_n\}$, $d_i = [d_{i+} d_{i-}]^T$.

Re-write the equation (21) in vector form,

$$\tau = D(u) = u - sat_D(u) \tag{22}$$

Dead zones asymmetric saturation function is represented as

$$sat_D(u) \equiv [sat_{d_i}(u_i)] \tag{23}$$

The control input after fuzzy compensation is

$$u_i = \omega_i + \omega_{F_i} \tag{24}$$

Compensation term ω_{F_i} is determined by using the following fuzzy rules:

$$IF(\omega_i \in X_+(\omega_i)), THEN(\omega_{F_i} = \hat{d}_{i+})$$

$$IF(\omega_i \in X_-(\omega_i)), THEN(\omega_{F_i} = -\hat{d}_{i-})$$

Where $X_+(\bullet), X_-(\bullet)$ the membership degree of ω_i, $\hat{d}_i = [\hat{d}_{i+}\ \hat{d}_{i-}]^T$.

Take $\omega_F = [\omega_{F_1}\quad \omega_{F_2}\quad \cdots\quad \omega_{F_n}]$,then

$$\left.\begin{aligned} u &= \omega + \omega_F \\ u &= \omega + \hat{D}^T X(\omega) \end{aligned}\right\} \tag{25}$$

Where $\hat{D} = diag\left\{\hat{d}_1, \hat{d}_2, \cdots, \hat{d}_n\right\}$,

Then

$$X(\omega) = \begin{bmatrix} X_+(\omega_1) \\ -X_-(\omega_1) \\ X_+(\omega_2) \\ -X_-(\omega_2) \\ \vdots \\ X_+(\omega_n) \\ -X_-(\omega_n) \end{bmatrix} \tag{26}$$

According the theorem 1,the control input after dead zone is

$$\tau = \omega - \tilde{D}^T X(\omega) + \tilde{D}^T \delta \tag{27}$$

Where $\tilde{D} = D - \hat{D} = diag\left\{\tilde{d}_1, \tilde{d}_2, \cdots, \tilde{d}_n\right\}$.

$$\|\delta\| \le \sqrt{n} \tag{28}$$

Take $A = \left[a_{ij}\right], B \in R^{m\times n}$,Define F norm as

$$\|A\|_F^2 = tr\left(A^T A\right) = \sum_{i,j} a_{ij}^2 \tag{29}$$

3.3. The Design of the Control Law

ideal control law without the dead zone compensation is designed as

$$\omega = \hat{f}(x) + K_v r - v \tag{30}$$

Where $\hat{f}(x)$ is estimated value of $f(x)$,is robust item, $K_v > 0$.

Control law with the dead zone compensation is designed as

$$u = \omega + \hat{D}^T X(\omega) \tag{31}$$

Put (30) into (27),

$$\tau = \hat{f}(x) + K_v r - v - \tilde{D}^T X(\omega) + \tilde{D}^T \delta$$

Then

$$\begin{aligned} M\dot{r} &= -V_m r + f(x) + \tau_d - \tau \\ &\quad -\left(\hat{f}(x) + K_v r - v - \tilde{D}^T X(\omega) + \tilde{D}^T \delta\right) \\ &= -V_m r - K_v r + \tilde{D}^T X(\omega) - \tilde{D}^T \delta + \left(\tilde{f} + \tau_d + v\right) \end{aligned} \tag{32}$$

Where $\tilde{f} = f(x) - \hat{f}(x)$,

Assuming that $\tilde{f}$ is bounded,then

$$\left\|\tilde{f}\right\| \le f_M(x) \tag{33}$$

Theorem 2 when the control law is (30), deadzone compensator is (31), the membership function is (26),we realize the adaptive compensation for the dead-zone, so the robust is :

$$v(t) = -\left(f_M(x) + \tau_M\right)\frac{r}{\|r\|} \tag{34}$$

Adaptive adjustment algorithm for the width of dead zone is

$$\dot{\hat{D}} = \Gamma X(w) r^T - \kappa\Gamma\hat{D}\|r\| \tag{35}$$

Where $\kappa > 0$, $\Gamma > 0$.

So we can get $r(t)$ and $\hat{D}$ are bounded,can make the tracking error $r(t)$ arbitrarily small by increasing the PD gain K_v .

PROOF:

Define the Lyapunov function as :

$$L = \frac{1}{2} r(t) M r + \frac{1}{2} tr\left(\tilde{D}^T \Gamma^{-1} \tilde{D}\right) \tag{36}$$

Considering the robot has the characteristic of skew symmetric:

$$\begin{aligned}
\dot{L} &= \frac{1}{2} r^T \dot{M} r + r^T M \dot{r} + \frac{1}{2} tr\left(\tilde{D}^T \Gamma^{-1} \dot{\tilde{D}}\right) \\
&= \frac{1}{2} r^T \dot{M} r + r^T\left(-V_m r - K_v r - v + \tilde{D}^T X(\omega) - \tilde{D}^T \delta\right) \\
&+ \left(\tilde{f} + \tau_d + v\right) + tr\left(\tilde{D}^T \Gamma^{-1} \dot{\tilde{D}}\right) \\
&= \frac{1}{2} r^T \left(\dot{M} - 2V_m\right) r - r^T K_v r + r^T\left(\dot{f} + \tau_d + v\right) \\
&+ r^T\left(\tilde{D}^T X(\omega) - \tilde{D}^T \delta\right) + tr\left(\tilde{D}^T \Gamma^{-1} \dot{\tilde{D}}\right)
\end{aligned}$$

Due to

$$r^T\left(\tilde{D}^T X(\omega) - \tilde{D}^T \delta\right) = r^T \tilde{D}^T\left(X(\omega) - \delta\right) = tr\left(\tilde{D}^T\left(X(\omega) - \delta\right) r^T\right)$$

Then

$$\begin{aligned}
& r^T\left(\tilde{D}^T X(\omega) - \tilde{D}^T \delta\right) + tr\left(\tilde{D}^T \Gamma^{-1} \dot{\tilde{D}}\right) \\
&= tr\left(\tilde{D}^T\left(X(\omega) - \delta\right) r^T\right) + tr\left(\tilde{D}^T \Gamma^{-1} \dot{\tilde{D}}\right) \\
&= tr\left(\tilde{D}^T X(\omega) r^T - \delta r^T + \Gamma^{-1} \dot{\tilde{D}}\right)
\end{aligned}$$

Also due to $\tilde{D} = D - \hat{D}$, $\dot{\tilde{D}} = -\dot{\hat{D}}$,then

$$\begin{aligned}
\dot{L} &= -r^T K_v r + r^T\left(\tilde{f} + \tau_d + v\right) + tr\left(\tilde{D}^T X(\omega) r^T - \delta r^T - \Gamma^{-1} \dot{\hat{D}}\right) \\
&= -r^T K_v r + r^T\left(\tilde{f} + \tau_d + v\right) \\
&\quad + tr\left(\tilde{D}^T X(\omega) r^T - \delta r^T - \Gamma^{-1}\left(\Gamma X(\omega) r^T - \kappa\Gamma\hat{D}\|r\|\right)\right)
\end{aligned} \tag{37}$$

Then

$$\begin{aligned}
\dot{L} &= -r^T K_v r + r^T\left(\tilde{f} + \tau_d + v\right) + tr\tilde{D}^T\left(-\delta r^T + \kappa\left(D - \tilde{D}\right)\|r\|\right) \\
&= -r^T K_v r + r^T\left(\tilde{f} + \tau_d - \left(f_M(x) + \tau_M\right)\frac{r}{\|r\|}\right) + tr\tilde{D}^T\left(-\delta r^T + \kappa\left(D - \tilde{D}\right)\|r\|\right)
\end{aligned}$$

$$
\begin{aligned}
&= -r^T K_v r + r^T \left(\tilde{f} + \tau_d - \left(f_M(x) + \tau_M \right) \frac{r}{\|r\|} \right) \\
&\quad + tr\tilde{D}^T \left(-\delta r^T + \kappa \left(D - \tilde{D} \right) \|r\| \right) \\
&\le -K_m \|r\|^2 + \sqrt{n} \|\tilde{D}\| \|r\| + \kappa D_M \|\tilde{D}\| \|r\| - \kappa \|\tilde{D}\|^2 \|r\|
\end{aligned} \tag{38}
$$

In the equation (38) , $\|\delta\| \le \sqrt{n}$, $K_m = \sigma_{\min}(K_v)$,then

$$\dot{L} \le -\|r\| \left[K_m \|r\| - c_0 \|\tilde{D}\| + \kappa \|\tilde{D}\|^2 \right] \tag{39}$$

Where $c_0 \equiv \left(\sqrt{n} + \kappa D_M \right)$.

In order to make $\dot{L} \le 0$,so the following will be guaranteed

$$K_m \|r\| - c_0 \|\tilde{D}\| + \kappa \|\tilde{D}\|^2 > 0$$

The following situation should be considered:

Case one: $K_m \|r\| - c_0 \|\tilde{D}\| + \kappa \|\tilde{D}\|^2 > 0$,then

$$
\begin{aligned}
K_m \|r\| - c_0 \|\tilde{D}\| + \kappa \|\tilde{D}\|^2 &= K_m \|r\| - c_0 \|\tilde{D}\| + \kappa \|\tilde{D}\|^2 + \frac{c_0^2}{4\kappa} - \frac{c_0^2}{4\kappa} \\
&= K_m \|r\| - \frac{c_0^2}{4\kappa} + \kappa \left(\|\tilde{D}\| - \frac{c_0}{2\kappa} \right)^2 > 0
\end{aligned}
$$

The error convergence results is

$$\|r\| > \frac{c_0^2}{4K_m\kappa} \equiv b_r \tag{40}$$

From the equation(40), $r(t)$ is bounded.

Due to $K_m = \sigma_{\min}(K_v)$,so we can make the tracking error $r(t)$ arbitrarily small by increasing the PD gain K_v.

Case two: $\kappa \|\tilde{D}\|^2 > c_0 \|\tilde{D}\|$,The dead zone estimated value convergence results is

$$\|\tilde{D}\| > \frac{c_0}{\kappa} \equiv b_{\tilde{D}} \tag{41}$$

4. Numerical Simulation

We has implemented the proposed algorithm in the joint manipulator in the Matlab simulation platform to verify the proposed algorithm's validity, we choose a two-link planar manipulator, as shown in the Figure 2, for simulation[15].

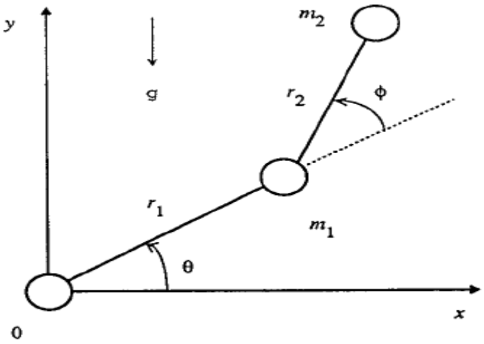

Figure 2. Two-Link Robot Manipulator Model

The dynamic equation as follows:

$$\begin{bmatrix} D_{11}(\phi) & D_{12}(\phi) \\ D_{12}(\phi) & D_{22}(\phi) \end{bmatrix} \begin{bmatrix} \ddot{\theta} \\ \ddot{\phi} \end{bmatrix} + \begin{bmatrix} -F_{12}(\phi)\dot{\phi} & -F_{12}(\phi)(\dot{\phi}+\dot{\theta}) \\ F_{12}(\phi)\dot{\theta} & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta} \\ \dot{\phi} \end{bmatrix} + \begin{bmatrix} g_1(\theta+\phi)g \\ g_2(\theta+\phi)g \end{bmatrix} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (42)$$

In the dynamic equation

$$D_{11}(\phi) = (m_1+m_2)r_1^2 + m_2 r_2^2 + 2m_2 r_1 r_2 \cos(\phi)\frac{n!}{r!(n-r)!},$$

$$D_{12}(\phi) = m_2 r_2^2 + m_2 r_1 r_2 \cos(\phi),\ D_{22}(\phi) = m_2 r_2^2,$$

$$F_{12}(\phi) = m_2 r_1 r_2 \sin(\phi),\ g_1(\theta+\phi) = (m_1+m_2)r_1 \cos(\phi) + m_2 r_2 \cos(\phi+\theta),$$

$$g_2(\theta+\phi) = m_2 r_2 \cos(\phi+\theta),$$

The parameters of the dynamic equation for simulation are expressed as:

$$m_1 = m_2 = 0.5kg, r_1 = 1m, r_2 = 0.8m$$

In the process of simulation, PD control and the proposed one have been realized in the MATLAB simulation platform so that we can get the advantage of the proposed one, simulation results were shown from Figure 3 to Figure 6.

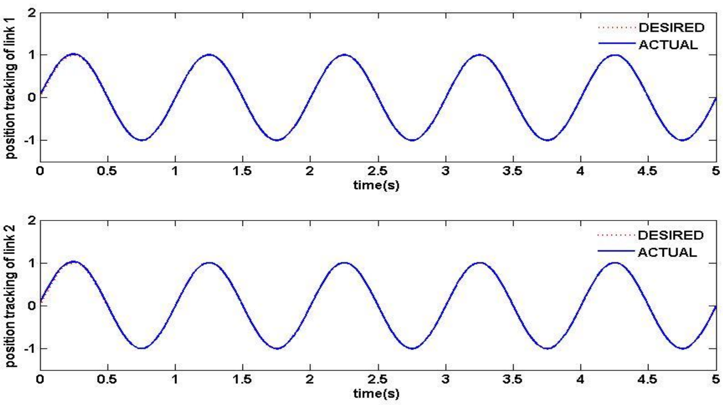

Figure 3. Position Tracking with Fuzzy Logic Deadzone Compensation

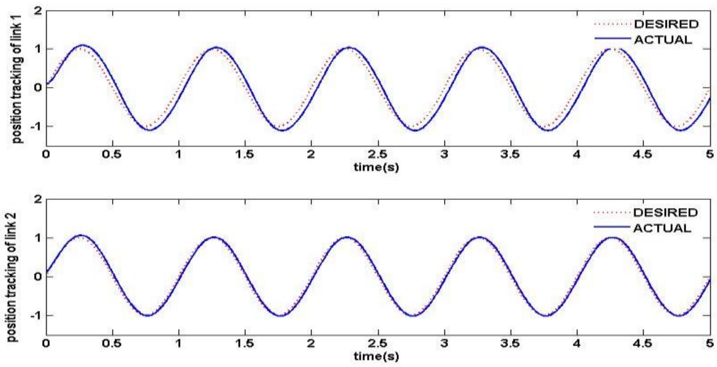

Figure 4. Position Tracking without Fuzzy Logic Deadzone Compensation

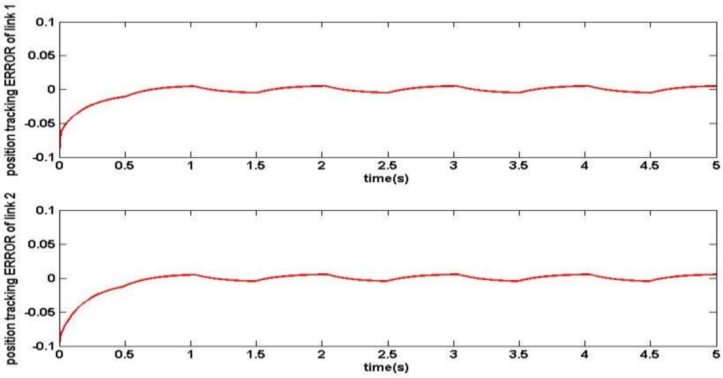

Figure 5. Position Tracking Error With Fuzzy Logic Deadzone Compensation

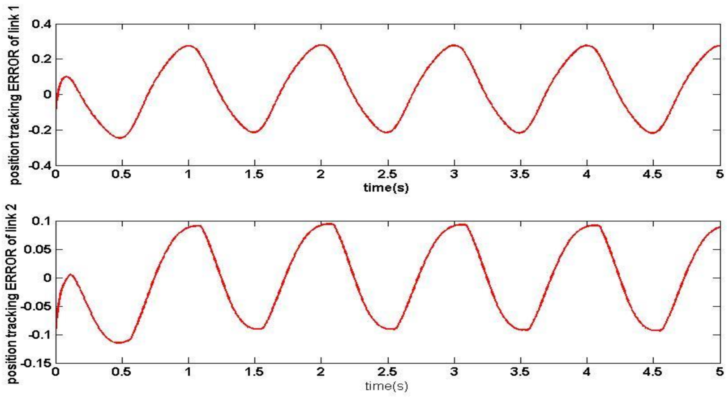

Figure 6. Position Tracking Error without Fuzzy Logic Deadzone Compensation

Figure 3 expressed the position tracking of the adaptive control scheme based on the fuzzy dead zone compensation, the Figure 4 illustrated the position tracking performance by using PD control scheme. Figure 5 and 6 revealed the position tracking error by using the adaptive control scheme based on the fuzzy dead zone compensation and traditional PD, respectively.

From the simulation results we can obtain that the proposed adaptive control scheme based on the fuzzy dead zone compensation has good performance on position tracking, dead zone compensation comparing with the traditional PD control scheme.

5. Conclusions

Pointing on the dead zone which has been existed in the manipulator of the machine vision system would affect the effect of visual servo system, a PD control algorithm based on fuzzy logic dead compensation has been proposed.

(1)The fuzzy logic dead zone compensator was designed to compensate the dead zone, PD control scheme was used to control trajectory of the joints of robot, so that the stability and robustness can be improved.

(2)We has implemented the proposed algorithm in the joint manipulator in the Matlab simulation platform to verify the proposed algorithm's validity.

(3)From the simulation results we can obtain that the proposed adaptive control scheme based on the fuzzy dead zone compensation has good performance on position tracking, dead zone compensation , comparing with the traditional PD control scheme.

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