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Design of Fuzzy Cross Coupling Controller for Cartesian Robot

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***Abstract*- In the three-axis Cartesian robot system driven by direct current motor, factors such as mechanical inertia, load disturbance and complex contour error model would affect the pose accuracy of the end effector. Aiming at the problem, a fuzzy cross coupling controller is designed. First, the contour error model of three axis robots and the dc motor model are established; then the coupling compensation algorithm is derived and three-axis cross coupling controller is designed. And tracking error and contour error are both reduced by the antedisplacement of compensation of contour error; in the end, the performance of the cross coupling controller is verified by simulation. It turns out that the designed fuzzy cross coupling controller has high accuracy and strong robustness.**

Keywords*- *cartesian robot; fuzzy cross coupling controller; tracking error; contour error

I. INTRODUCTION

Nowadays, industrial robot technology is becoming more and more widely applied in manufacturing industry[1].As one style of the industrial robots, cartesian coordinate robots have the characteristics of large stroke, high load capacity, high dynamic performance and strong expansion ability. They can be easily assembled with paws of various types and sizes, so that they are capable of any automation tasks such as welding, assembling, spray painting, palletizing, detection, printing, etc.

The three-axis motion control of Cartesian coordinate robots is important, for the control will directly affect the pose accuracy of the end effector. Currently, domestic and foreign scholars on the research of the motion control of the Cartesian coordinate robot have been focusing on the single axis tracking control, and the main means include friction compensation, feedforward control and disturbance compensation, etc[2]. However, those methods are limited in improving three-axis synchronization, trajectory tracking and contour error control. The external disturbance of the system and parameter perturbation can seriously affect the accuracy of three-axis synchronization, trajectory tracking and contour error control.

To solve this problem, this paper designs a fuzzy cross coupling controller. First, the contour error model of three axis robots and the dc motor model are established. Then, the coupling compensation algorithm is derived and three-axis cross coupling controller is designed. And tracking error and contour error are both reduced by the antedisplacement of compensation of contour error. In the end, the position loop controller based on fuzzy PID are designed in single axis. The simulation results show that the designed fuzzy cross coupling controller has high accuracy and strong robustness.

II. THE CONTOUR ERROR MODEL OF CARTESIAN ROBOT

A. The Contour Error Model of Cartesian Coordinate Robot

As shown in fig 1[3], assuming at time t_0, in three-dimensional system of coordinate, P is the actual spot of end effector, and its coordinate is (a, b, c). $F(t)$ is a desired trajectory, R is desired position, R's coordinate is (x_1, y_1, z_1), $\overrightarrow{PR}$ is the tracking error vector of Cartesian coordinate robot, and it is marked as $\vec{e}$. Its projections on X, Y, Z axis are respectively e_x, e_y and e_z, which are the tracking error of each axis; R''s coordinate is (x_0, y_0, z_0), straight line RR' is $F(t)$'s tangent line at R; We draw a line perpendicular to line RR' from point P, and the foot point is Q, and its coordinate is (x, y, z). Then $\overrightarrow{PQ}$ is the contour error vector of the robot, marked as $\vec{\varepsilon}$.

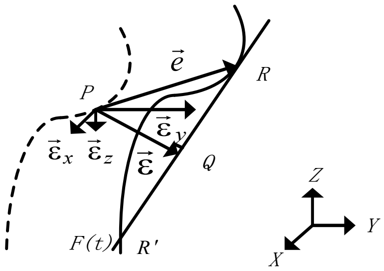

FIGURE I. MODEL OF REAL-TIME CONTOUR ERROR FOR ANY TRAJECTORY

The expressions of tracking error vectors $\vec{e}$ and $\overrightarrow{RR'}$ are:

$$\vec{e}=\overrightarrow{PR}=\begin{bmatrix} e_x \\ e_y \\ e_z \end{bmatrix}=\begin{bmatrix} x_1-a \\ y_1-b \\ z_1-c \end{bmatrix} \tag{1}$$

$$\overrightarrow{RR'}=\begin{bmatrix} \Delta R_x \\ \Delta R_y \\ \Delta R_z \end{bmatrix}=\begin{bmatrix} x_1-x_0 \\ y_1-y_0 \\ z_1-z_0 \end{bmatrix} \tag{2}$$

Equation of straight line RR' can be obtained by R, Q, R':

$$\frac{x-x_1}{x_1-x_0}=\frac{y-y_1}{y_1-y_0}=\frac{z-z_1}{z_1-z_0}=t_0 \tag{3}$$

The expression of vector $\overrightarrow{PQ}$ is:

$$\overrightarrow{PQ} = \begin{bmatrix} x-a \\ y-b \\ z-c \end{bmatrix} = \begin{bmatrix} x_1 + (x_1 - x_0)t_0 - a \\ y_1 + (y_1 - y_0)t_0 - b \\ z_1 + (z_1 - z_0)t_0 - c \end{bmatrix} = \begin{bmatrix} e_x + \Delta R_x t_0 \\ e_y + \Delta R_y t_0 \\ e_z + \Delta R_z t_0 \end{bmatrix} \tag{4}$$

The inner product of vector $\overrightarrow{PQ}$ and vector $\overrightarrow{RR'}$ is zero:

$$\overrightarrow{PQ} \cdot \overrightarrow{RR'} = 0 \tag{5}$$

Formula (2) and formula (4) are substituted into formula (5):

$$t_0 = -\frac{e_x \Delta R_x + e_y \Delta R_y + e_z \Delta R_z}{\Delta R_x^2 + \Delta R_y^2 + \Delta R_z^2} \tag{6}$$

If we substitute the parameter t_0 obtained from formula (6) back to formula (3), we can get the coordinate of the point Q:

$$Q = \begin{bmatrix} x_1 - \Delta R_x \dfrac{e_x \Delta R_x + e_y \Delta R_y + e_z \Delta R_z}{\Delta R_x^2 + \Delta R_y^2 + \Delta R_z^2} \\ y_1 - \Delta R_y \dfrac{e_x \Delta R_x + e_y \Delta R_y + e_z \Delta R_z}{\Delta R_x^2 + \Delta R_y^2 + \Delta R_z^2} \\ z_1 - \Delta R_z \dfrac{e_x \Delta R_x + e_y \Delta R_y + e_z \Delta R_z}{\Delta R_x^2 + \Delta R_y^2 + \Delta R_z^2} \end{bmatrix}^T \tag{7}$$

Then the expression of contour error vector $\vec{\varepsilon}$ is:

$$\vec{\varepsilon} = \overrightarrow{PQ} = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{bmatrix} = \begin{bmatrix} e_x - \Delta R_x \dfrac{e_x \Delta R_x + e_y \Delta R_y + e_z \Delta R_z}{\Delta R_x^2 + \Delta R_y^2 + \Delta R_z^2} \\ e_y - \Delta R_y \dfrac{e_x \Delta R_x + e_y \Delta R_y + e_z \Delta R_z}{\Delta R_x^2 + \Delta R_y^2 + \Delta R_z^2} \\ e_z - \Delta R_z \dfrac{e_x \Delta R_x + e_y \Delta R_y + e_z \Delta R_z}{\Delta R_x^2 + \Delta R_y^2 + \Delta R_z^2} \end{bmatrix} \tag{8}$$

B. Compensation of Contour Error of Cartesian Robot

In addition to correcting the component e_x, e_y and e_z of the tracking error vector $\vec{e}$ in each axis, we also need to compensate contour error component ε_x, ε_y and ε_z, and of each axis. The system compensation vector C can be expressed as:

$$\vec{C} = \begin{bmatrix} C_x \\ C_y \\ C_z \end{bmatrix} = \begin{bmatrix} e_x + \lambda \varepsilon_x \\ e_y + \lambda \varepsilon_y \\ e_z + \lambda \varepsilon_z \end{bmatrix} \tag{9}$$

In this expression, λ is the cross coupling gain, which could affect the speed of the correction of contour error.

III. DYNAMIC STRUCTURAL MODELING OF DC MOTOR

In this paper, DC motor as the controlled object, we need to establish its dynamic mathematical model. The armature circuit equation of DC motor is[4]:

$$U_a = RI_d + E + L\frac{dI_d}{dt} \tag{10}$$

In the equation, U_a is armature voltage, I_d is armature current, and E is induced electromotive force. When viscous friction and elastic torque is neglected, we can get the equation of motion on the motor shaft:

$$T_e - T_L = \frac{GD^2}{375}\frac{dn}{dt} \tag{11}$$

In the equation, T_e is electromagnetic torque, T_L is load torque, and GD^2 is the flywheel moment of electric traction system reduced onto motor shaft. The induction electromotive force equation and the electromagnetic torque equation under the rated excitation are as follows:

$$E = C_e n \tag{12}$$

$$T_e = C_m I_d \tag{13}$$

C_e is electromotive constant, and C_m is torque coefficient. We substitute formula (12) and formula (13) to formula (10) and formula (11), and then we get:

$$U_a - E = R(I_d + T_l \frac{dI_d}{dt}) \tag{14}$$

$$I_d - I_{dL} = \frac{T_m}{R}\frac{dE}{dt} \tag{15}$$

Here, $T_L = L/R$, which is armature circuit electromagnetic time constant, and $I_{dL} = T_L/C_m$, which is load current, and $T_m = GD^2R/(375C_eC_m)$, is electromechanical time constant. Under zero initial condition, the transfer function between voltage and current is obtained on the basis of Laplace transform of both sides of formula (15):

$$\frac{I_d(s)}{U_a(s) - E(s)} = \frac{1/R}{T_l s + 1} \tag{16}$$

The transfer function between voltage and current is obtained on the basis of Laplace transform of both sides of formula (16):

$$\frac{E(s)}{I_d(s) - I_{dl}(s)} = \frac{R}{T_m s} \tag{17}$$

The dynamic structure diagram of dc motor under rated excitation is obtained, as shown in Fig 2.

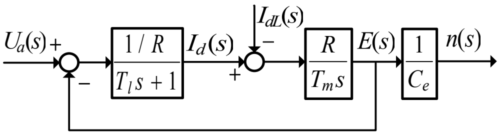

FIGURE II. DYNAMIC BLOCK DIAGRAM OF THE DC MOTOR

IV. DESIGN OF THREE-AXIS CROSS COUPLING CONTROLLER BASED ON FUZZY PID

A. Double Closed Loop Design of Single Axis Direct Current Speed Regulating System

As shown in fig 3, in the current and speed double closed loop DC speed control system, the cascade connection of the current regulator (ACR) and the speed regulator (ASR) forms the current negative feedback inner loop and the speed negative feedback outer loop[5].

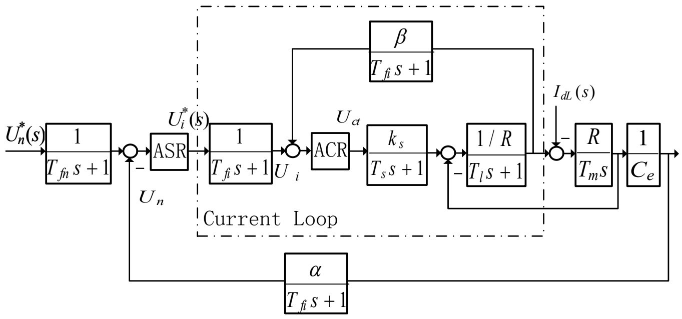

FIGURE III. BLOCK DIAGRAM OF THE DOUBLE-LOOP DC SPEED-REGULATING SYSTEM

The role of the current loop is to limit the current, and we correct it as a typical type I system. The overshoot and dynamic prompt drop of revolving speed can be measured by anti disturbance index, which works well as a type II system. We adopt PI regulator as the speed regulator. The dynamic structral diagram of the speed loop system adjusted to the type II system is shown in Fig 4.

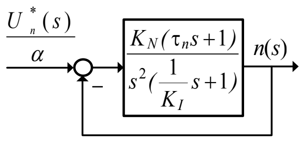

FIGURE IV. THE TYPICAL TYPE Ⅱ BLOCK DIAGRAM OF CORRECTED SPEED LOOP

Here, $K_I=K_iK_s\beta/(\tau_iR)$, is the open loop gain of electric current loop, $K_N=K_n\alpha R/(C_eT_m)$, is the gain of speed loop.

B. The Design of Closed Loop Based on the Single Axis Position of Fuzzy PID

Since the response of the position loop is slower than that of the speed loop, the speed loop's order can be reduced, that is to say, it will be simplified into a series of inertia and integral links. In this way, the dynamic structure of the position loop is obtained as shown in Fig 5.

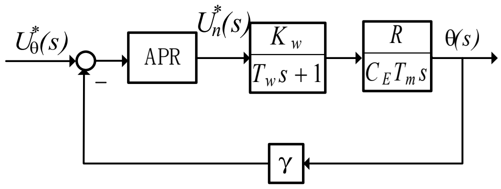

FIGURE V. POSITION LOOP DYNAMIC BLOCK DIAGRAM

The design requirement of the position loop is to make the output position accurately reproduce the input position signal. Thus, the system is corrected to I system. The position regulator adopts a fuzzy PID controller[6].

The input quantity of fuzzy controller is e and ec, and the output quantity is ΔKp, ΔKi and ΔKd . The position tracking error and velocity of the single axis are input as e and ec, and seven fuzzy subsets are selected, and their corresponding language value is NB, NM, NS, Z, ,PS, PM and PB. The quantification factor kec=ke=0.01, scale factor k1=0.5, k2=k3=0.1. The definition of fuzzy membership function of input and output is shown in Fig 6.

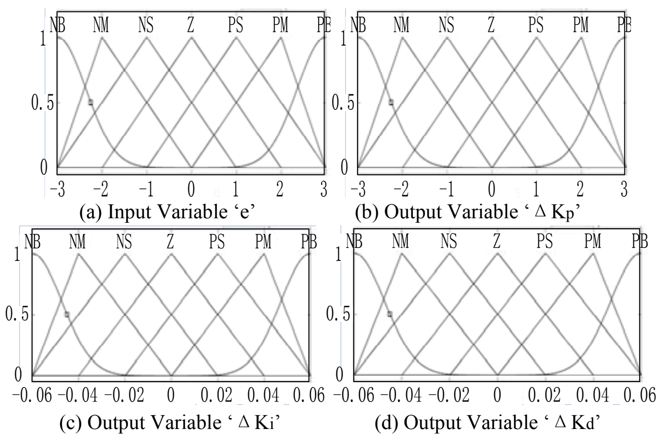

FIGURE VI. FUZZY MEMBERSHIP FUNCTION OF INPUT AND OUTPUTS

The fuzzy control rule, the core of the fuzzy controller, is equivalent to corrector device. According to the actual experience or repeated data processing, it can be summed up that in the cases of different errors and error rates the self-tuning requirements of Kp, Ki, Kd are as follows:

When |e(t)| is bigger, we should enhance proportional action, increase Kp, quicken the response of system; Ki should be decreased in order to control overshoot. When |e(t)| is medium, Kp should be decreased to make Kp smaller; Ki and Kd should be moderate to ensure the speed of response. When |e(t)| is smaller, to obtain small steady state error, the sum should be bigger. When |ec(t)| is smaller, Kd should be medium; when |e(t)|is bigger, Kd should be bigger.

C. The Design of Three-axis Cross Coupling Controller Based on Fuzzy PID

From the contour error estimation algorithm used above, it is known the contour error e is only related to command position R and the actual position P, therefore, the designed cross coupling controller is in the loop section of the control system, and its structure is shown in Fig 7.

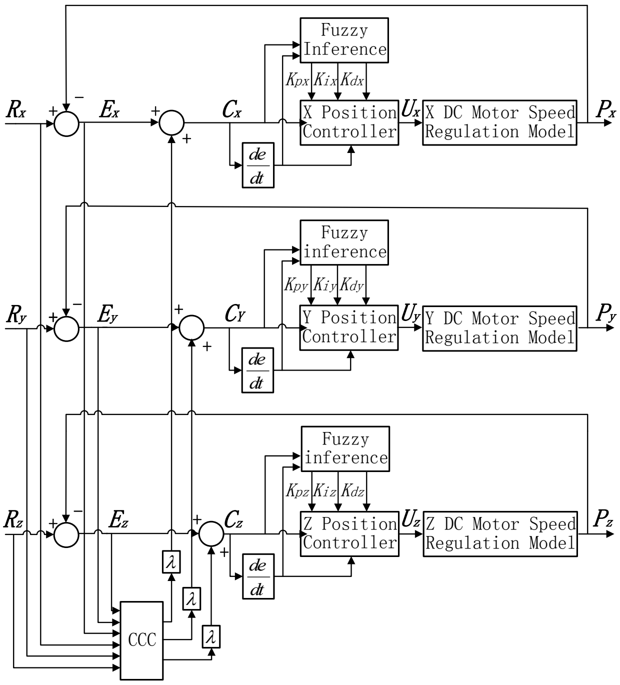

FIGURE VII. STRUCTURE BLOCK DIAGRAM OF FCCC SYSTEM FOR CARTESIAN ROBOT

Compared with the traditional cross coupling structure, the design of the three-axis cross coupling controller in this study has been completed contour error compensation before the position loop controller. According to the geometric relation of the contour error compensation in Fig 1, when the gain value Kp is adjusted, there will be effect in the contour error compensation C. It is equal to adjusting the amount of C rather than the direction. At this point, C's direction is up to the factor λ, so the adjustment of Kp and the adjustment of λ are independent on their own.

V. SIMULATION AND ANALYSIS

Three DC motors are used as the driving parts of the robot, and the parameters of the motor are shown in Tab 1.

TABLE I. PARAMETERS OF THE DC MOTOR

Rated Torque	Rated Speed	Rated Voltage	Rated Current	Armature Resistance	Armature Inductance	Moment of Inertia	Electro-mechanical Time
Nm	Rpm	V	A	Ω	mH	Ncm2	ms
0.1	2000	24	1.3	3.7	1.4	164	4.7

Firstly, the cross coupling controller with proportional control is simulated and analyzed. Input the desired trajectory as a spatial spiral line, that means cosine signal with 100mm tracking peak value of drive X axis motor and 2πrad/s frequency, sinusoidal signal with same value of drive Y axis motor, and ramp signal with 1 tracking gradient of drive Z axis motor. At 1s, 100N disturbance is enforced suddenly to single axis. Under this circumstance, the desired trajectory and the actual output trajectory of the end effector of the Cartesian robot are shown in Fig 8. Fig 9 is the position tracking error curve of the three axes. It can be seen from two figures that the output trajectory coincides with the desired trajectory, the tracking error is less than 1mm, and the three axes have good robustness and tracking accuracy.

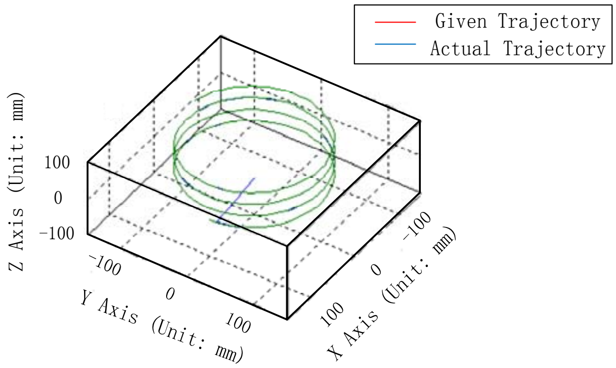

FIGURE VIII. GIVEN AND ACTUAL OUTPUT TRAJECTORIES OF CCC

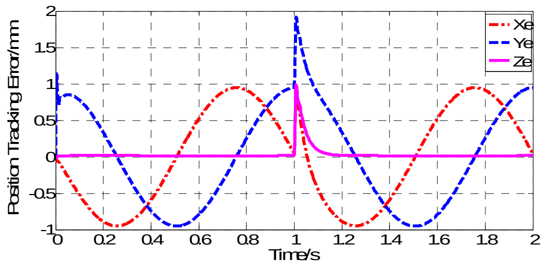

FIGURE IX. POSITION TRACKING ERROR CURVES OF CCC

Fig 10 is the tracking error curve of the three axes using fuzzy control on the position loop. It can be seen that the accuracy of the three axis of FCCC can reach about 0.08mm. Compared with the conventional CCC, the FCCC can recover the balance more quickly after the sudden disturbance. Figure 11 is the contour error curve with the fuzzy control on the position loop when the system is perturbed and the parameters change. It can be seen that the contour error accuracy can reach 0.03mm. In addition, current and speed of three DC motors also have good tracking performance. The simulation results show that the fuzzy cross coupling controller is robust and fast, and at the same time the contour error accuracy is also improved.

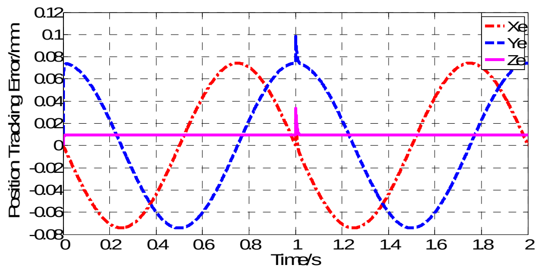

FIGURE X. POSITION TRACKING ERROR CURVES OF FCCC

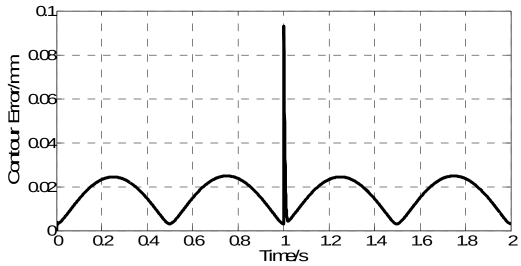

FIGURE XI. CONTOUR ERROR OF FCCC

VI. CONCLUSION

Aiming at the common industrial Cartesian coordinate robot, this paper establishes the contour error model of arbitrary track and the direct current motor model, derives the coupling compensation algorithm and designs three-axis cross coupling controller. The tracking error and contour error are both reduced by the antedisplacement of compensation of contour error. The simulation results show that the designed controller has high accuracy and strong robustness.

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