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Research Article

An EtherCAT Based Delta Robot Synchronous Control Application

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ABSTRACT

The delta robot synchronous control based on the Ethernet Control Automation Technology (EtherCAT) protocol for painting application is proposed in this paper. Personal Computer (PC) is used as master and the delta robot motor drivers are used as slaves in this work. The Master sends command to slave base on the motion control profile CAN in Automation 402(CiA402). Subsequently, the program in C# perform the user's interface and EtherCAT communication. And the system is not only for easy use, but also for quickly high-precision. A complex painting application is proposed to show this system workable.

1. Introduction

In recent years, the problem of labor shortage is getting worse. Recent studies[1,2] proposed to reduce the labor costs, improve production efficiency, and stabilize production quality, the company has successively introduced automation technology or replace manpower with a robotic arm.

Jung and Lim[3] and Lin et al.[4] present that controlling each axis of the robotic arm needs to perform coordinate movement tasks at the same time, so accuracy and synchronization of control are important for the robotic arm. To achieve the multi-axis motors synchronous control, the system stability and data update times (cycle time) are also considered. In this paper, the industrial communication EtherCAT is selected as the communication protocol between the robotic arm and the PC, which has the advantages of processing on the fly and good synchronization[5,6,7,8,9].

Zhang et al.[10] and Lim et al.[11] proposed that using EtherCAT high speed communication to improve accuracy and to reach higher control frequency between the motor drivers and master. Cheng and Wang[12] used EtherCAT to communicate with multi-axis motors. The results show that EtherCAT solves the problem of transmitting large amounts of data in real-time and realizes high-precision synchronous control with high-efficiency algorithms. Wang et al.[13] compared EtherCAT and other common industrial protocols on multi-axis motor control. The result shows that EtherCAT control is accurate and synchronize.

2. Kinematics of the Delta Robot

The motion trajectory of the delta robot is based on a parallelogram as a track, moving on the X-axis, Y-axis, or Z-axis, and can rotate around the vertical axis of the platform center.

For the purpose of planning the trajectory in joint space, we use inverse kinematics to convert the current coordinates to the angle of each motor. To measure the following error in the cartesian space, we substitute the angle of each motor into the forward kinematics to get current coordinates. Fig.1 and Fig.2 are the kinematics analysis diagrams of the delta robot.

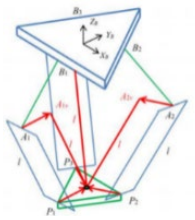

Fig.1 Delta robot FK diagram[15]

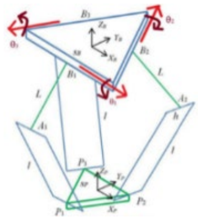

Fig.2 Delta robot IK diagram [15]

If the rotation angle of each axis motor (θ_1, θ_2, θ_3) is known, we can use vector loop equations proposed by recent studies[14,15] to derive the forward kinematics and calculate the coordinate vector ($A_{1v}{}'$, $A_{2v}{}'$, $A_{3v}{}'$). Finally, substitute the coordinate vectors into the sphere

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equations and quadratic formula to derive the final target coordinates P(*x, y, z*) of the end effector.

$$A_{1v'} = \begin{bmatrix} 0 \\ \frac{-\sqrt{3}}{3}s_P + \frac{-\sqrt{3}}{6}s_B - L\cos\theta_1 \\ -L\sin\theta_1 \end{bmatrix} \tag{1}$$

$$A_{2v'} = \begin{bmatrix} \frac{\sqrt{3}}{2}\left(\frac{\sqrt{3}}{6}s_B + L\cos\theta_2\right) - \frac{\sqrt{3}}{3}s_P\cos\frac{\pi}{6} \\ \frac{1}{2}\left(\frac{\sqrt{3}}{6}s_B + L\cos\theta_2\right) - \frac{\sqrt{3}}{3}s_P\sin\frac{\pi}{6} \\ -L\sin\theta_2 \end{bmatrix} \tag{2}$$

$$A_{3v'} = \begin{bmatrix} \frac{-\sqrt{3}}{2}\left(\frac{\sqrt{3}}{6}s_B + L\cos\theta_3\right) + \frac{\sqrt{3}}{3}s_P\cos\frac{\pi}{6} \\ \frac{1}{2}\left(\frac{\sqrt{3}}{6}s_B + L\cos\theta_3\right) - \frac{\sqrt{3}}{3}s_P\sin\frac{\pi}{6} \\ -L\sin\theta_3 \end{bmatrix} \tag{3}$$

If the final target coordinates P(x, y, z) is known, we can derive use vector loop equations proposed by recent studies [14,15] to calculate the rotation angle of each axis motor (θ_1, θ_2, θ_3) via the inverse kinematics. The relevant equation is such as Eq.(4)-Eq.(6).

$$\theta_1 = 2\tan^{-1}\left(\frac{-z \pm \sqrt{4z^2 - 4F_1(F_1 - y - a)}}{F_1}\right) \tag{4}$$

$$\theta_2 = 2\tan^{-1}\left(\frac{2z \pm \sqrt{16z^2 - 4F_2(F_2 + 2\sqrt{3(x+b)} + y + c)}}{F_2}\right) \tag{5}$$

$$\theta_3 = 2\tan^{-1}\left(\frac{2z \pm \sqrt{16z^2 - 4F_3(F_3 - 2\sqrt{3(x-b)} - y - c)}}{F_3}\right) \tag{6}$$

where:

$$F_1 = (y + a) - \frac{1}{2L}(x^2 + y^2 + z^2 + a^2 + L^2 + 2ya - l^2) \tag{7}$$

$$F_2 = -\left(\sqrt{3(x+b)} + y + c\right) - \frac{1}{L}(x^2 + y^2 + z^2 + b^2 + c^2 + L^2 + 2(xb + yc) - l^2) \tag{8}$$

$$F_3 = \left(\sqrt{3(x-b)} - y - c\right) - \frac{1}{L}(x^2 + y^2 + z^2 + b^2 + c^2 + L^2 - 2(xb - yc) - l^2) \tag{9}$$

The parameters are defined as follows:

$$a = \frac{-\sqrt{3}}{6}s_P\,; \quad b = \frac{s_P}{2} - \frac{1}{4}s_B\,; \quad c = \frac{\sqrt{3}}{6}s_P - \frac{\sqrt{3}}{12}s_B\,;$$

name	meaning	value (mm)
s_B	base equilateral triangle side	865.9
s_P	platform equilateral triangle side	118.6
L	upper legs length	336.1
l	lower legs parallelogram length	1022.4

3. Path Planning

In order to complete the path planning of the image, first, upload the image from the user and convert the picture to a binary image. Then analyze and sort the coordinate pixels of the neighboring to connect them as paths. Finally, by setting the maximum moving distance of two points in cartesian space to get the velocity information.

During the drawing process, the trajectory planned by adjacent coordinate make the robot moves continuously and ensure the accuracy of the result. In this paper, greedy algorithm is used to solve the adjacent coordinate problem.

The greedy algorithm is a fast-iterative method to find successive regional optimal solutions. Each regional optimal solution must be proved the final problem obtain the overall optimal solution and can be reduced the problem range to get the overall optimal solution[16], the design steps are as follows:

(1) Store the path coordinate in the array, and then define the thresholds of adjacent points to complete the establishment of the problem model.

(2) Divide the problem into n.

(3) Define the purpose (Find the coordinates nearest to the target).

(4) Find the best solution to n small problems based on the greedy strategy.

(5) Combine the best solutions of n small problems to get the overall best solution.

4. System Architecture

The system architecture is showed in Fig.3 and the photo of actual configuration diagrams developed in this paper is presented in Fig.4. In the system we proposed, Windows operating system is used to be the computing platform to solve the most of the task in our experiment.

The Automation Device Specification(ADS) communication library provided by Beckhoff is used to exchange data between EtherCAT master software, TwinCAT, and the proposed user's human-machine interface based on Visual Studio C#, then the TwinCAT, will transmit the information with salvers, the three-axis's motor driver of delta-robot.

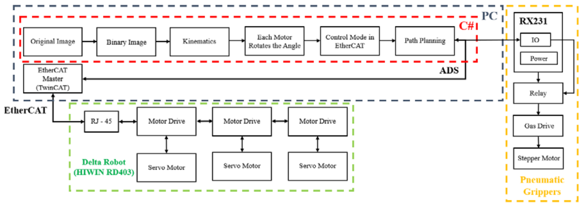


Fig.3 System architecture diagram

Fig.4 Actual configuration diagram

The CANopen over EtherCAT (CoE) is the standard communication protocol in EtherCAT system, and the CiA402 sub-protocol of the CANopen is proposed for motion controller. The proposed software system in this paper also follows the CiA402 protocol to control the robot.

For the purpose of control the robotic arm running according to the trajectory planned by their motion and control algorithm, the Cyclic Sync Position mode (CSP mode) and Cyclic Sync Velocity mode (CSV mode) in the CiA402 sub-protocol are more suitable for multi-axis synchronous control.

To accomplish the multi-axis synchronization control, we choose 4ms to be the communication cycle time of the CSP and CSV mode. The following will introduce the control methods based on these two control modes in this paper:

(1) Set CSP mode as the operation mode object of the driver, set the rotation distance of the motor to the Target Position object on the driver.

(2) Set CSP mode as the operation mode object of the driver, set the rotation distance of the motor to the Target Position object on the driver. Then following error will be calculated in real-time, and set to velocity offset object value to improve velocity references.

(3) Set CSV mode as the operation mode object of the driver, convert the rotation distance of the motor to speed, and set it to the Target Velocity object on the driver.

(4) Set CSV mode as the operation mode object of the driver, convert the rotation distance of the motor to speed, and set it to the Target Velocity object on the driver. Then following error will be calculated in real-time, and set it to the velocity offset object value to compensate error.

(5) Set CSV mode as the operation mode object of the driver, convert the rotation distance of the motor to speed, and set it to the Target Velocity object on the driver. Finally, the following error which calculated in real-time, will be compensated by proportional-derivative controller (PD controller) shown in Fig.5.

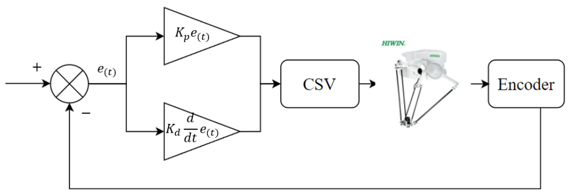


Fig.5 PD controller system block diagram

5. System Testing Result

To discuss the method proposed in this paper, we compared the accuracy with different maximum movement distances (such as: 0.1mm, 0.01mm, and 0.005mm) with each method.

The root-mean-square error (RMSE) can be a simple standard to make comparison of the data in different numerical range. The equation is as Eq.(10) and the correlation results are shown in Tab.1 to Tab.2.

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}(\hat{y}_t - y_t)^2}{n}} \quad (10)$$

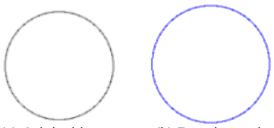
Tab.1 Different control methods and motor moving distance in the specified path of the RMSE

Control Method / Maximum moving distance of motor(mm)	CSP mode	CSP mode, compensate error to Velocity Offset	CSV mode	CSV mode, compensate error to Velocity Offset	CSV mode with PD controller to compensate error
0.005	8.554E-02	8.872E-02	9.424E-02	3.952E-02	4.009E-02
0.01	1.601E-01	1.656E-01	1.882E-01	7.410E-02	7.502E-02
0.1	1.673E+00	1.705E+00	1.731E+00	7.162E-01	5.077E-01

Tab.2 Different control methods and motor moving distance in the specified path of the final coordinate error

Control Method / Maximum moving distance of motor(mm)	CSP mode	CSP mode, compensate error to Velocity Offset	CSV mode	CSV mode, compensate error to Velocity Offset	CSV mode with PD controller to compensate error
0.005	8.689E-02	8.689E-02	9.540E-02	3.880E-02	4.089E-02
0.01	1.587E-01	1.620E-01	1.912E-01	7.260E-02	7.693E-02
0.1	1.770E+00	1.770E+00	1.867E+00	7.116E-01	5.261E-01

The more distance we move means the more angle that motor rotate, will cause bigger moving error. To discuss the relationship between moving distance and error, there are three moving distance commands are tested, they are 0.005, 0.01 and 0.1 mm. It can be concluded from Tab.1 and Tab.2. The better choice between two kinds of CSP method is the simple CSP control. On the other hand, CSV mode with PD control is the better one in CSV control.



(a) Original image (b) Drawing path

Fig.6 The command drawing path

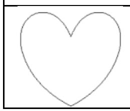
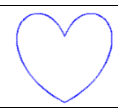
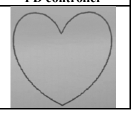
Fig.7 The drawing result in the CSP mode

Fig.8 The drawing result in the CSV mode with PD controller

Tab.3 The RMSE of five control method with a maximum movement distance of 0.1mm

	CSP mode	CSV mode with PD controller
RMSE(mm)	9.1214E-01	**4.3303E-01**

Tab.4 The drawing result in the CSP mode and CSV mode with PD controller to compensate error

Original image	Drawing path	CSP mode	CSV mode with PD controller
			

To ensure the accuracy of the painting, it is necessary to compensate the error. In this paper, we choose CSV mode with PD controller to be our control method. Error distance will be computed in real-time, and convert it to velocity. Then the PD controller is used to speed up or slow down to complete compensation. We take Fig.6 as the example. 0.1mm is used as the maximum moving distance to compare the two results of simple CSP mode and CSV mode with PD control. Fig.7 and Fig.8 are the drawing results. Tab.3 shows the RMSE of two control mode. According the result of RMSE, it is easy to find that the CSV mode with PD controller is a better choice. These two methods with the maximum moving distance 0.1mm are also used to draw other figures, and the results are shown in Tab.4.

6. Conclusion

The proposed image processing methods convert the image to a binary image, analyze and sort the coordinate pixels of the neighboring to connect them as path. The experimental results show that the analyzed image command coordinate points are enough to present the original image information.

Using CSP mode or CSV mode as the control method, it is necessary to adjust the proportional coefficient and derivative coefficient of the motor drivers to prove the accuracy. After adjustment in the actual proposed system, the motion error was not reduced due to incorrect adjustment methods or mechanical problems. In order to perfect remake human paintings, the CSV mode with PD control is used. This method calculates the following error distance in real-time. The following error distance is defined as the distance between the command and actual position of the end effector in motion control. Convert the following error distance to velocity, then the PD controller is used to improve the velocity to complete compensation.

Experiments have confirmed that the error in the CSV mode with PD control is less than 0.5mm which is the smallest error compared with other methods. Moreover, this control method compensates error in real-time and precisely control the delta robot to completely remake paintings.

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