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 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 easy use, but also quickly high-precision. A complex painting application is proposed to show this system workable.

Keywords: delta robot, kinematics, path planning, EtherCAT

1. Introduction

In recent years, the problem of labor shortage is getting worse. [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.

[3][4] knows that controlling each axis of the robotic arm needs to perform coordinate movement tasks at the same time, so accuracy and synchronization are important for control the robotic arm. Using Ethernet to realize synchronous control of each axis is low-stability and take lots of time for the response and cyclic task. Therefore, in order to achieve the precise synchronous control of each axis, this system uses the industrial communication EtherCAT as the communication protocol between the robotic arm and the PC, which has the advantages of processing on the fly and good synchronization[5]-[9].

[10][11] proposed that using EtherCAT high speed communication to improve accuracy and to reach higher control frequency between the motor drivers and master. [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. [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.

If the rotation angle of each axis motor ($\theta_1, \theta_2, \theta_3$) is known, we can use vector loop equations proposed by [14][15] to calculate the coordinate vector ($A_{1v'}, A_{2v'}, A_{3v'}$) via the forward kinematics. Finally, the above coordinate vectors are substituted into the sphere equations and quadratic formula to derive the final target coordinates P(*x, y, z*) of the end effector.

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

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

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

If the final target coordinates P(x, y, z) is known, we can use vector loop equations proposed by [14][15] to calculate the rotation angle of each axis motor ($\boldsymbol{\theta_1}$, $\boldsymbol{\theta_2}$, $\boldsymbol{\theta_3}$) via the inverse kinematics. The relevant equation is such as Eq.(1)-Eq.(3).

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

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

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

where:

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

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

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

The parameters are defined as follows:

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

name	meaning	value (mm)
s_B	base equilateral triangle side	865.9388
s_P	platform equilateral triangle side	118.5589
L	upper legs length	336.1
l	lower legs parallelogram length	1022.4

To plan the trajectory in the joint space, we translate the current coordinates to each axis angle from the inverse kinematics, to calculate the following error in the cartesian space, the current axis was translated to coordinates by inverse kinematics. Fig.1 and Fig.2 are the kinematics analysis diagrams of the delta robot.

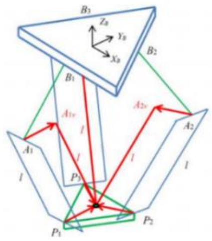


Fig.1 Delta robot FK diagram [15]

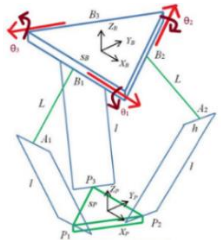


Fig.2 Delta robot IK diagram [15]

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. At last, we can solve the point to point velocity by planning maximum movement distance between each coordinate point in the cartesian space.

The path planned by adjacent coordinate make the robot moves continuously during the drawing process and accurately shows the image. After test, we use the greedy algorithm to find the adjacent coordinate.

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

Fig.3 and Fig.4 show the system architecture and actual configuration diagrams developed in this paper. In order to complete the communication of the hardware, image processing, path planning, calculation of the forward and inverse kinematics, and the delta robot control algorithm, the Windows operating system as the computing platform used in this paper.

The Automation Device Specification(ADS) communication protocol from Beckhoff is used to exchange data between TwinCAT, the EtherCAT master station, and the user's human-machine interface based on Visual Studio C#.

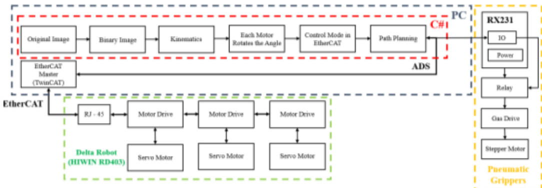


Fig.3 System architecture diagram

Fig.4 Actual configuration diagram

To complete the motor control of each axis of the robotic arm, the system uses the CiA402 sub-protocol based on the CANopen over EtherCAT (CoE) protocol that conforms to the EtherCAT application layer.

In addition, the user could plan the robotic arm's trajectory by their motion and control algorithm, so 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 complete the purpose of multi-axis synchronization control, the system chooses CSP and CSV modes with 4ms as the communication cycle time. The following will introduce the control methods based on these two control modes in this paper:

(1) Use CSP mode, set the command of motor rotation angle distance to the Target Position object on the driver.

(2) Use CSP mode, set the command of motor rotation angle distance to the Target Position object on the driver, as well as calculate the following error in real-time, and set to velocity offset object value to improve velocity references.

(3) Use CSV mode, convert the command of motor rotation angle distance to speed, and set it to the Target Velocity object on the driver.

(4) Use CSV mode, convert the command motor rotation angle distance to speed, and set it to the Target Velocity object on the driver as well as calculate the following error in real-time, and set it to the velocity offset object value to compensate error.

(5) Use CSV mode, convert the command of motor rotation angle distance to speed, and set it to the Target Velocity object on the driver, as well as calculate the following error in real-time. Compensate the error according to the proportional-derivative controller (PD controller) shown in Fig.5.

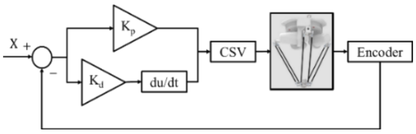


Fig.5 PD controller system block diagram

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 $\sqrt{\frac{\sum_{t=1}^{n}(\hat{y}_t - y_t)^2}{n}}$ and the correlation results are shown in Fig.6 to Fig.8 and Tab.1 to Tab.2.

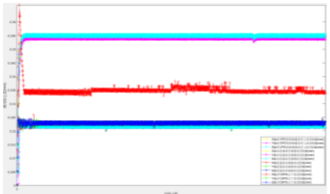


Fig.6 Movement error diagram of five control method with a maximum movement distance of 0.005mm

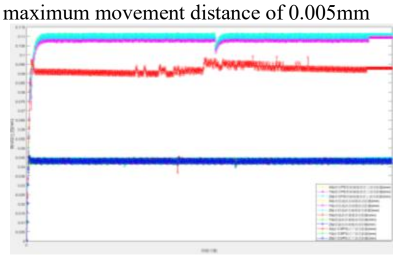


Fig.7 Movement error diagram of five control method with a maximum movement distance of 0.01mm

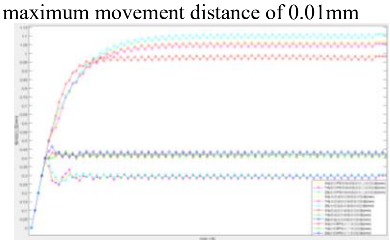


Fig.8 Movement error diagram of five control method with a maximum movement distance of 0.1mm

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.

To completely reproduce the human painting, it is necessary to compensate the errors instantly when drawing the path. In this case, we choose CSV mode with PD control to be our control method. It will compute the error distance in real-time, next convert the error distance to velocity, then use the PD controller to speed up or slow down to complete compensation. We take Fig. 9 as the example. Use 0.1mm as the maximum moving distance to compare simple CSP mode with CSV mode with PD controller. Fig.10 and Fig.11 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.

(a) Original image (b) Drawing path

Fig.9 The command drawing path

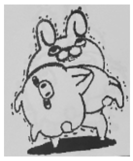


Fig.10 The drawing result in the CSP mode

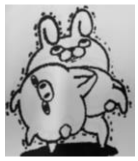


Fig.11 The drawing result in the CSV mode with PD controller

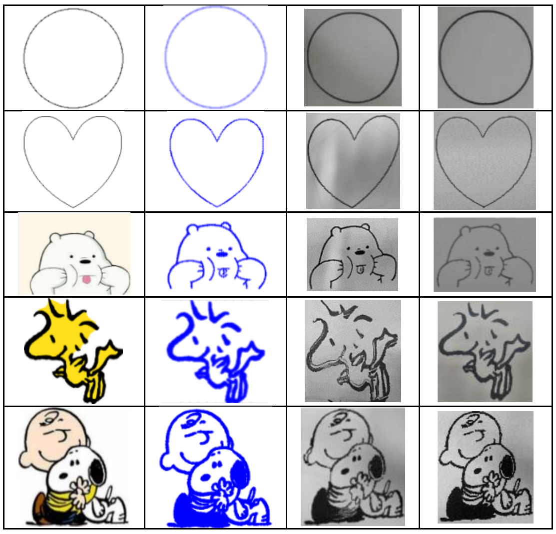
Tab.3 The RMSE of five control method with a maximum movement distance of 0.1mm

	CSP mode	CSV mode with PD controller to compensate error
RMSE(mm)	9.1214E-01	4.3303E-01

We also use these two control methods with the maximum moving distance 0.1mm to draw other figures. The results are shown in Tab.4.

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 compensate error



6. Conclusion

For the image processing, it converts the image to a binary image, analyze and sort the coordinate pixels of the neighboring to connect them as path. After the test, the analyzed image command coordinate points are enough to present the original image information.

For the robotic arm control, if you want to use CSP mode and CSV mode, you need to adjust the proportional coefficient and derivative coefficient of the motor drivers to reduce the error. After the actual adjustment, the error was not reduced due to incorrect adjustment methods or mechanical problems. In order to fully reproduce human paintings, we used in the CSV mode with PD control. This method can via calculating the following error distance of the end effector in real-time, convert the following error distance to velocity, and use the PD controller to improve the velocity to complete compensation.

Experiments have confirmed that in the CSV mode with PD control, the error is less than 0.5mm which is the smallest error in these control methods. What's more, this control method compensates error in real-time, that can precisely control the delta robot to complete the path planning and fully reproduce human paintings.

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