DESIGN AND RESEARCH OF MULTI AXIS MOTION CONTROL SYSTEM BASED ON PLC

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ABSTRACT: Robot plays a more and more important role in modern society, and its application is more and more extensive, especially medical robot that plays an important role in assisting doctors to perform surgeries. The future market of the robot will be very broad, and the medical robot is the focus in the medical device industry research. It can help doctors better carry out medical operations, and improve the efficiency and success rate of surgery. Therefore, the robot with higher accuracy and higher flexibility is concerned, and the control system and control algorithm as its core are the most important in the research. Based on this, this paper introduces the control algorithm and designs and tests the control system. Through the experiments, we verified the reliability of the system, the stability and accuracy of the movement process, and the feasibility of the motion control algorithm.

KEY WORDS: Control algorithm, control system, stability

1 INTRODUCTION

The manufacturing industry is the basic industry of the country, and it has always occupied the leading position of the world's industrialization process. It is the fundamental driving force of national modernization and industrialization. The level of the manufacturing industry directly reflects the country's comprehensive national strength and the level of productivity. It is an important indicator for reflecting the degree of a country's industrial shipments, which is directly related to the competitiveness of the country on the international market. As a result, the development of manufacturing technology has become one of the most important technical strategies in the world [1]. The early development of motion control technology mainly depends on the development of robot technology, numerical control technology and factory automation technology. The majority of them are general motion control system running independently. However, they usually only have single function, and the efficiency is not high. In consequence, the special motion control system is still very rare.

In China, the demand for motion control products is getting larger and larger, which makes the special motion controller has a good development prospect in our country. The design and manufacture of special and efficient processing equipment has become more and more important, and this control system is mainly used in special numerical control products and other mechanical automation equipment [2].

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PLC is an industrial control product that combines computer and automatic control technology. The core of PLC is the microprocessor, whose development is based on the logic control and hardware wiring. In the field of motion control, the realization of expected motion of PLC control target is mainly based on the integration of factors like displacement control, wheelbase control, acceleration and deceleration control and so on [3-4]. In general, PLC motion control module has the advantages of small size, high reliability, convenient maintenance and so on. Whereas, limited by the PLC working mode in early period, it makes the control motor cannot operate at high frequency and unable to realize the complex control relationship. Usually, it can only apply this kind of movement control modules on the occasions of the single axis motion and position control, which will be the main aspects needed to be broken through by PLC motion control technology [5-6].

2 TRAJECTORY PLANNING IN CARTESIAN SPACE

2.1 Linear trajectory planning

As shown in Figure 1, it is the space rectangular coordinate system. The points P_1 and P_2 are the starting point and the end point of the actuator end point in the space movement, and their coordinates are expressed as $[x_1, y_1, z_1]$ and $[x_2, y_2, z_2]$.

As shown in above figure, the distance between the points P_1 and P_2 can be expressed as:

$$d_{12} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{1}$$

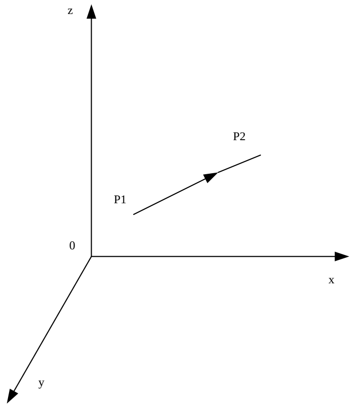

Figure 1. Spatial line

The method of space vector is used to represent the points and in the space rectangular coordinate system, and then they are represented as:

$P_1 = x_1 i + y_1 j + z_1 k$, $P_2 = x_2 i + y_2 j + z_2 k$.

Then the vector is used to represent the distance and direction of the points P_1 and P_2 :

$$P_{21} = P_2 - P_1 = (x_2 - x_1)i + (y_2 - y_1)j + (z_2 - z_1)k \quad (2)$$

Its unit direction vector can be expressed as:

$$n_{21} = \frac{P_{21}}{d_{12}} \quad (3)$$

It is assumed that the speed for the end point to move along the straight line in the space from P_1 and P_2 is v, and the total time used is T, then the position of the end point at the t moment can be expressed by a vector as $P_t = x_t i + y_t j + z_t k$, and then there are:

$$P_t = P_1 + n_{21} vt, \ t \in [0, T] \quad (4)$$

$[x_t, y_t, z_t]$ refers to the position of the robot end point in the space rectangular coordinate system at the moment of t.

2.2 Arc trajectory planning

When the three spatial points are not collinear, if it is necessary to go through these three points, and requiring smoothing motion path, then the commonly used method is to achieve through the method of circular arc trajectory planning. Because the end point of the robot is moving in space, in space circular arc, we can convert the space circular arc into the plane arc to solve the problems, made arc subdivision interpolation points, and finally, convert these interpolation points into values in space coordinates [7].

The coordinate of three spatial points are given, respectively: $P_1(x_1, y_1, z_1), P_2(x_2, y_2, z_2)$, and $P_3(x_3, y_3, z_3)$. We know that when the three spatial points are no collinear, we can determine a plane. As a result, first of all, we should determine whether the three spatial points are collinear.

The methods to judge whether three spatial points are collinear are shown as follows, namely:

Judge whether $\begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{bmatrix}$ is zero.

It is zero, it indicates that the three points are collinear, unable to determine the plane; if it is not zero, it suggests that the three points are not collinear, able to determine the unique plane. As a result, the plane where the three points located is:

$$\begin{bmatrix} x - x_1 & y - y_1 & z - z_1 \\ x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \\ x_3 - x_1 & y_3 - y_1 & z_3 - z_1 \end{bmatrix} = 0 \quad (5)$$

It is assumed that:

$$\det Azy = \begin{bmatrix} y_2 - y_1 & z_2 - z_1 \\ y_3 - y_1 & z_3 - z_1 \end{bmatrix} \quad (6)$$

$$\det Azx = \begin{bmatrix} x_2 - x_1 & z_2 - z_1 \\ x_3 - x_1 & z_3 - z_1 \end{bmatrix} \quad (7)$$

$$\det Axy = \begin{bmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_1 & y_3 - y_1 \end{bmatrix} \quad (8)$$

Then we can obtain:

$$(x - x_1)\det Azy - (y - y_1)\det Azx + (z - z_1)\det Axy = 0 \quad (9)$$

The plane equation passing through the middle point of P_1P_2 and vertical to $\overline{P_1P_2}$ is:

$$[x_2 - x_1 \quad y_2 - y_1 \quad z_2 - z_1] * \begin{bmatrix} x - \frac{x_1 + x_2}{2} \\ y - \frac{y_1 + y_2}{2} \\ z - \frac{z_1 + z_2}{2} \end{bmatrix} = 0 \quad (10)$$

After being simplified from (10), we can obtain:

$$\left(x - \frac{x_1 + x_2}{2}\right)(x_2 - x_1) + \left(y - \frac{y_1 + y_2}{2}\right)(y_2 - y_1) + \left(z - \frac{z_1 + z_2}{2}\right)(z_2 - z_1) = 0 \quad (11)$$

The plane equation passing through the middle point of P_2P_3 and vertical to $\overline{P_2P_3}$ is:

$$[x_3 - x_2 \quad y_3 - y_2 \quad z_3 - z_2] * \begin{bmatrix} x - \frac{x_3 + x_2}{2} \\ y - \frac{y_3 + y_2}{2} \\ z - \frac{z_3 + z_2}{2} \end{bmatrix} = 0 \tag{12}$$

After being simplified from (12), we can obtain:

$$\left(x - \frac{x_3 + x_2}{2}\right)(x_3 - x_2) + \left(y - \frac{y_3 + y_2}{2}\right)(y_3 - y_2) + \left(z - \frac{z_3 + z_2}{2}\right)(z_3 - z_2) = 0 \tag{13}$$

We obtain the center coordinate $P_c(x_c, y_c, z_c)$ from (11) and (13), then the radius R is:

$$R = \sqrt{(x_c - x_1)^2 + (y_c - y_1)^2 + (z_c - z_1)^2} \tag{14}$$

Finally, the transformation matrix of the base coordinate system and the plane coordinate system of the arc is obtained, so as to achieve the conversion between the plane and the space.

3. DESIGN OF CONTROL SYSTEM

3.1. Overall design

As the main parts of the hardware system are the host computer and the lower computer (LMC058), the design of the software can be divided into two parts: the host computer (IPC) and the lower computer. The lower computer refers to the core component of motion controller as the control system.

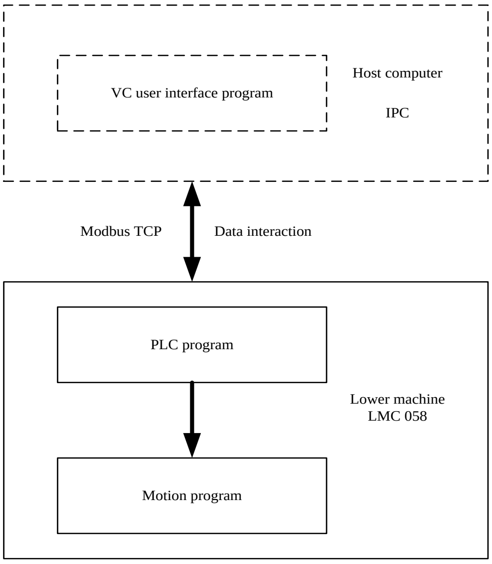

Figure 2. Software control system hierarchy

Its main tasks are: real-time detection of motion commands sent by the host computer and the completion of corresponding tasks in accordance with the different instruction information. At the same time, the controller real-time reads state information (such as position and velocity) of servo motor and uploads to the host computer to display to the operating users.

Therefore, the lower computer program is the focus of the entire software system, and this paper focuses on the design of the lower computer program to achieve the control requirements. The hierarchy of the entire software control system is shown in Figure 2.

3.2.Data exchange between the host and lower computer

The Ethernet bus mode is used between the host computer and the lower computer, namely between the controllers, which makes data interaction based on the Modbus TCP protocol. Modbus TCP network communication mode is shown in Figure 3.

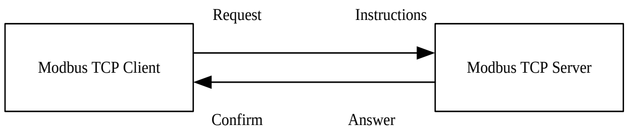

Figure 3.Modbus TCP network communication mode

TCP/IP protocol is the protocol model based on the Client/Server. In this paper, the host computer, as the client connection, is used as the server LMC058 motion controller.

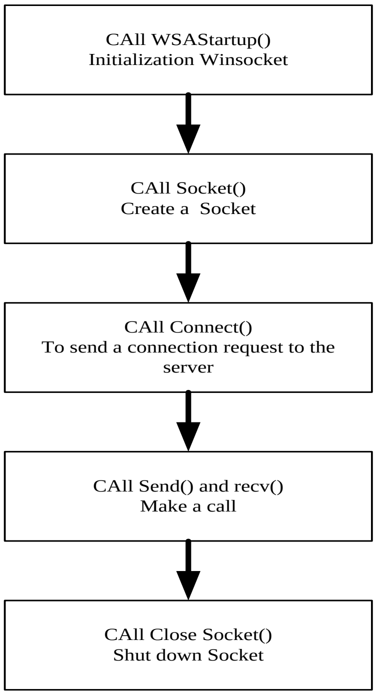

Figure 4. The flow chart of the client connecting with the server

Because the client is a user interface program written in VC, when the client connects to the server, it is possible to call the Windows API function to connect. The program flow chart of the client connecting with the server is shown in Figure 4.

3.3 Kinematics program

(1) Interpolation stage

After the trajectory planning, the trajectory obtained is a segment of straight line or arc. For linear or circular motion, it can be divided into accelerated motion segment, uniform motion segment and deceleration motion segment. What is input is the starting point position, the end position, the starting point velocity, the terminal velocity, the starting point attitude and the end point attitude of the motion segment. What is output being the position and attitude of the interpolation points. It is necessary to interpolate the motion segment into an integer interpolation segment in the interpolation phase, and make it accurate in displacement.

The input starting point speed v_s, end point velocity v_e and displacement s are divided by the radius r of arc. Then we can obtain the arc starting point angular velocity $w_s = v_s / r$, end point angular velocity $w_e = v_e / r$, and angular displacement $\theta = s / r$, similar to a line.

According to the size of and , we can judge it as uniform motion or acceleration and deceleration motion, and plan the interpolation point according to the center angle.

According to the input starting point velocity and the end point velocity and direction, we can determine whether it is line segments or arcs segment. In addition, from the initial velocity and the end point velocity, we determine whether it is uniform acceleration segment, uniform deceleration segment or uniform segment. When the angle of the two velocity directions is less than 1 degree, it is considered as a linear motion. When the difference between the two velocities is less than 0.0001m/s, it is regarded that the two speeds are equal, doing uniform linear motion. When the end velocity is greater for 0.0001m/s than the initial velocity, it does uniform acceleration motion; when the end velocity is less 0.0001m/s than that of the initial velocity, it does uniform deceleration motion. Linear interpolation is used as an example, introduced as follows.

As the starting points and end points are known, we can obtain the distance s, the acceleration a, and movement time between the initial point and the end point, as follows:

$$s = |p_2 - p_1|, a = \frac{v_2^2 - v_1^2}{2s}, t_{toal} = \frac{2s}{v_1 + v_2} \tag{15}$$

In consequence, the interpolation segment is taken an integer $N = [t_{toal} / 0.008]$. [x] represents the largest integer no more than x, and after taking integer, the motion time is $t_{total} = 0.008N$. After taking integer, the displacement s' and the displacement error Δs compensated for per interpolation segment are shown as follows:

$$s' = v_1 t_{total} + \frac{1}{2} a t_{total}^2 \tag{16}$$

$$\Delta s = \frac{s - s'}{N} \tag{17}$$

Therefore, in an acceleration segment, a uniform velocity segment or a deceleration straight line segment, the displacement of the interpolation point is as follows:

$$s_i = v_1(i \times T) + \frac{1}{2} a (i \times T)^2 + i \times \Delta s \tag{18}$$

(2) Inverse solution phase

The inverse solution is to design based on the kinematics inverse analysis. The process of positive and negative solution is vividly expressed in Figure 5.

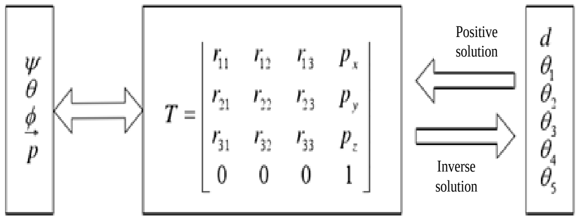

Figure 5. The process of positive and negative solution

The process of inverse solution function is to obtain the angle that each joint needs to rotate based on the two points position and attitude of the input. The main steps are as follows:

(1) The pose matrix is solved by point position and attitude;
(2) The 8 groups of inverse solutions are obtained by the pose matrix;
(3) Choose the best inverse solution in the 8 groups of inverse solutions;
(4) Determine whether the best inverse solution is correct;
(5) Solve the angle that the joint needs to move;
(6) Determine whether the displacement of the joint is reachable;
(7) Obtain the return value.

The optimal inverse solution selects the method based on the energy optimization. That is to say, for the joint with large quality, we set large weighted coefficient, and for the joint with small quality, we set small weighted coefficient. At last, we select the group inverse solution makes the Y value smallest as the optimal inverse solution.

The speed can be judged as follows:

In the calculation of the optimal inverse solution, we first of all determine whether the rotation angle of within 8mm in the interpolation period can be reached in each solution, namely velocity reachable and acceleration reachable. It is assumed that 6 maximum rotation angles in each inverse solution is θ, and the velocity that the motor through reducer can achieve is b rpm, then:

$$\theta < \frac{8 \times 360 \times b}{60 \times 1000} \tag{19}$$

In addition, assuming that the maximum acceleration can be provided by the motor is $a_{\max}$, then the maximum acceleration required by rotating θ degrees within 8mm is $a_{req} = 2\theta / 0.008^2$, and then it needs to meet $a_{req} < a_{\max}$, namely:

$$\theta < \frac{0.008 \times 0.008 \times a_{\max}}{2} \tag{20}$$

The number of pulses per rotation of the motor corresponds to is c, and then the angle a pulse corresponds to is 360/c, which is the minimum precision value. The flow chart of speed reachable judgment is shown in Figure 6.

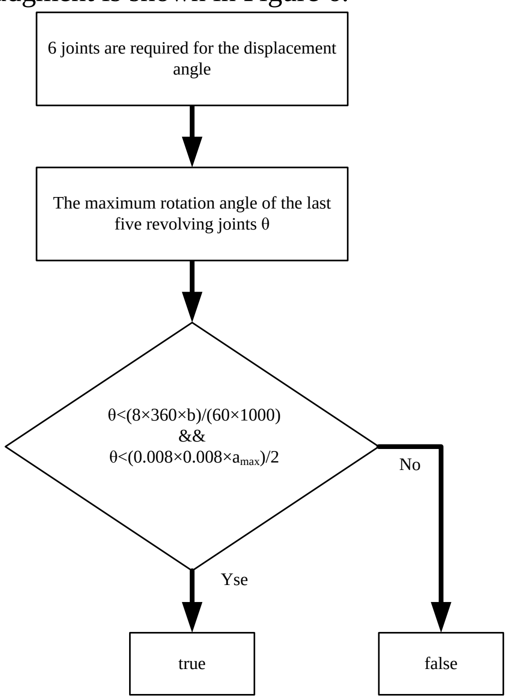

Figure 6. The flow chart of speed reachable judgment

3.4 Multi axis linkage program

Multi axis synchronous motion control is the core part of robot control. When the end point of the robot expects to perform a trajectory in space, such as linear movement, the movement of each joint of the robot is nonlinear, then a better choice is to use the electronic cam control. The electronic cam is similar to the mechanical cam, which can be described as the nonlinear motion between the shaft and the spindle. Here, we choose a virtual time axis as the main shaft, while taking 6 axes, to achieve a master and multi slaves, so as to realize the synchronization control of the 6 axes. When the slave shaft is coupled with the main shaft, the control of the slave shaft can be accomplished by controlling the motion of the main shaft.

In this paper, we use a virtual axis as the main shaft to ensure that the calculation is simple and easy to be controlled. The motion relationship between master-slave shaft is described by establishing the cam table. The cam table is the table with two columns of data, the first column is the position of the main shaft, and the second column the position of the slave axis corresponding to the main shaft. As a result, in the realization of 6 axes synchronous motion, it is necessary to establish 6 corresponding electronic cam tables to describe the relationship between the shaft and the spindle. Once the cam table is generated, the track of each slave axis will be generated, and then in the main shaft movement, the slave shaft will move according to the trajectory generated.

The overall flow chart of the synchronous control of the electronic cam is shown in Figure 7.

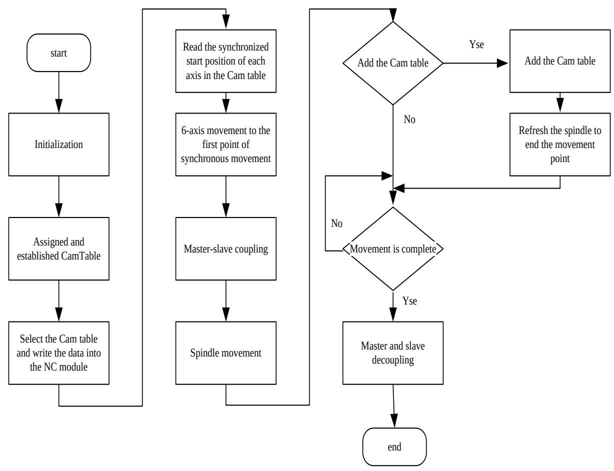

Figure 7. Multi axis program flow chart

The realization of six axes synchronous motion function is comparatively complex, and the electronic cam function block used is various and complicated in logic. The main process of electronic cam includes initialization, Cam table assignment, Cam table section, master-slave shaft coupling, spindle motion, master-slave shaft decoupling and so on. Each part of the process needs to use one or more function blocks to achieve, and we should pay attention to the logical relationship between each part.

4 TEST RESULTS

Six axis synchronous motion is the most important part of the control system, but also the difficulty of the control system. Only when 6 axes synchronous motion process is smooth and stable can it meet the requirements. The 6 axis synchronous motion is the foundation for the movement of the straight line, arc movement, curve and so on movements.

In the test, we first of all let the end point of the robot in space to move only along the X axis, so as to observe the changes of the Y axis and the Z axis value, as well as along the Y axis to move, so as to observe the changes of X axis and Z axis. Because of the single direction of the Z axis movement, only 1 axis moving up and down, we do not do this test.

When moving along the X axis, the motion starting point is $P_1 = [400 \quad 300 \quad 900]^T$, and the end point is $P_2 = [900 \quad 300 \quad 900]^T$, to ensure only moving in X direction. When moving along the Y axis, the motion starting point is $P_1 = [600 \quad -300 \quad 900]^T$, and the end point is $P_2 = [900 \quad 300 \quad 900]^T$, to ensure that the changes are only in the Y direction.

As shown in Figure 8, it is the space position diagram moving along X axis and Y axis, respectively. From the figure, we can see that, when moving only along a shaft direction, the other two positions basically remained unchanged, the error controlled in the range of 1mm, which can meet the design requirements of the control system. In addition, from the figure, we can find that the end point of the trajectory is smooth, consistent with the planned S type trajectory, and the acceleration and deceleration processes are relatively flat.

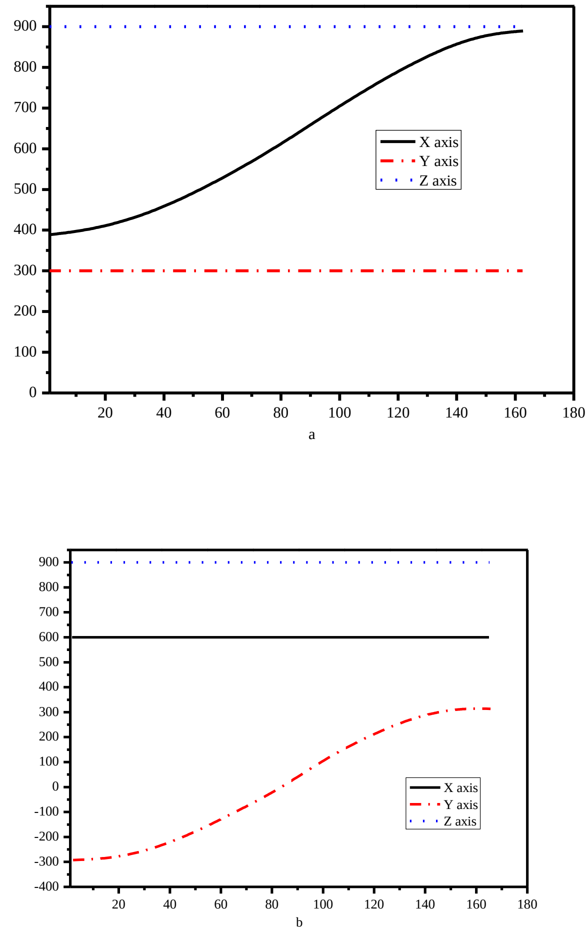

Figure 8. The movement trajectory along the X axis (a), and Y axis (b)

In addition to the above movements along the single axis, we also test the space straight line motion. When the linear motion is measured, the motion interpolation period is T=8ms, the starting position is , end point is , starting velocity is , end point velocity is , and the maximum velocity is .

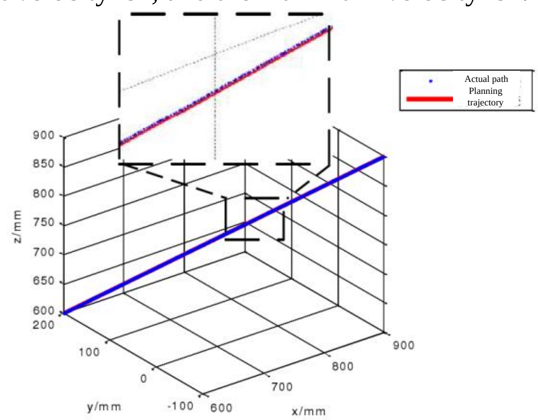

Figure 9. Spatial linear movement trajectory diagram

The change values of each axis are 300mm. Let the robot moves along a cube diagonal straight line in space. The results are shown in Figure 9, andwe can find that the movement trajectory of the robot in the end point is consistent with the straight line trajectory required actually. Similarly, in the test of arc movement, the interpolation cycle is T=8ms, the starting point position is , middle point position is , terminal position is , starting point velocity is , end point velocity is , and the maximum velocity is . Let the robot to draw a semicircle trajectory in space, and the diameter is 200mm. The results are shown in Figure 10, and we can find that the trajectory of the end point of the robot is consistent with the circular arc trajectory required actually.

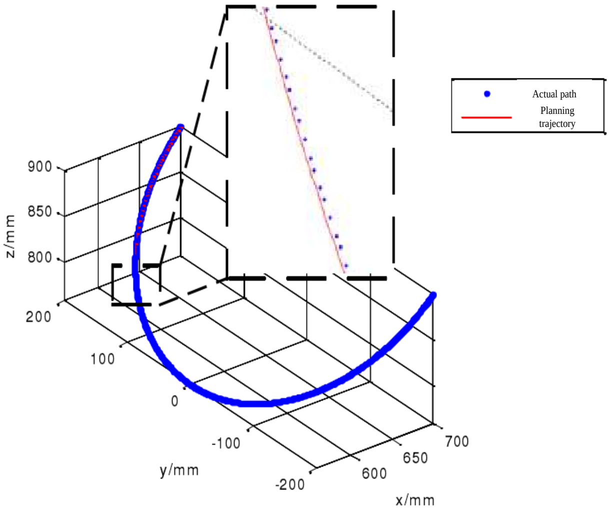

Figure 10. Space circular arc trajectory

In the statistical calculations of the linear and circular test data, the maximum error of trajectory is 1.04mm in the linear motion, and the average error is 0.51mm. The maximum error of trajectory in the circular motion is 0.95mm, and the average error is 0.33mm.

5 CONCLUSION

This paper, based on the analysis of the actual motion demand of medical robot, designs the motion control system, and ultimately achieves the control requirements. In addition, it completes the multi axis motion and motions are more accurate. The error is controlled within 1mm, reached the control requirements. The PLC control part finished back to zero, stop, error reset, servo power on and outage, motor brake, zero correction and so on functions. In addition, we completed the design of 6 axes synchronous motion control scheme based on the electronic cam. The experiments proved that, the electronic cam had high synchronization accuracy, and the error was very small. At present, the control system also has some parts needed to be enhanced and improved. For instance, the trajectory planning algorithm needs more research and practical testing, so as to ensure that the robot is more stably, more smoothly, and more accurately reaching the target point. The performance of the control system needs more tests, so as to ensure the reliability, stability and security of the system.

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