Kinematics Modeling and Trajectory Planning for NAO Robot Object Grasping based on Image Analysis

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***Abstract*—This paper presents a method of kinematics modeling and trajectory planning for NAO robot object grasping. In order to judge and grasp objects autonomously, this method combines the image analysis and kinematics knowledge. Firstly, the collected images by the NAO robot are processed through threshold segmentation and median filtering. According to the shape information of the object, the NAO robot determine automatically whether to adopt single-arm or double-arm grasping. Secondly, choosing the Denavit-Hartenberg (D-H) method, the kinematics model of the NAO robot's arm is built. By solving the forward and inverse solutions of kinematics, the joints variable angles of the NAO robot's arm are obtained. Then, the pose and position of each end-effector are calculated. Finally, the motion trajectory of the end-effector is planned by designing the trajectory planning in joint space. The experimental results show the effectiveness and intelligence of the method, which demonstrates that the proposed method has practical value for the research of NAO robot.**

***Keywords*—NAO robot; image analysis; object grasping; kinematics modeling; trajectory planning**

I. Introduction

With the development of science and technology, the research of robots has gotten great progresses. Different types of robots have different functions, and play important roles in various fields. Currently, the research of humanoid robots have become the focus in the field of robotics. Due to the integration of artificial intelligence, control and sensor technologies, the humanoid robots have higher intelligence. They can complete various human actions according to the demands of people.

In recent years, NAO robots have become one of the representatives in humanoid robots. NAO robot is a biped humanoid robot with 25 degrees of freedom in its whole body. The varieties of sensing equipments in its interior make it easier for us to operate NAO robots, and the reaction looks more sensitive compared with other robots. In addition, as a result of its open programming, NAO robot can use many libraries and complete numbers of difficult tasks. Thus, it is widely used in the field of humanoid robots research [1], [2].

Object recognition and grasping of humanoid robot is a relatively popular research direction. Therefore, many scholars have done some scientific research and achieved certain results. For example, BAI et al. researched the object recognition and location algorithm based on NAO robot [1]. TANG et al. presented an object location method of monocular visual based on NAO robot [3]. Although the above papers describe the algorithms of object recognition for the NAO robot in detail, they did not explain how to further realize object grasping. YUAN et al. studied the position-based visual servo grasping of NAO robots [4]. Wen et al. analyzed the kinematics model of NAO robot arm by using D-H method [5]. These papers ignore the judgment of the vision system, which causes NAO robot to lose its ability to judge autonomously, such as the decision of single-arm or double-arm operation. However, it is inevitable that some factors cause robots to fail to grasp in real life, consist of the hand grasping ability of the NAO robot, information of object and so on.

In view of above discussions, this paper presents an approach of kinematics modeling and trajectory planning for object grasping based on image analysis. Its purpose is to judge and grasp objects autonomously for NAO robot. Although much progress has made in developing methods for optimal object grasping, there has been comparatively less work on the kinematics modeling based on image analysis. Many previous methods have been aimed at kinematic modeling of robotic manipulators, while ours are based on NAO robot vision, and can grasp objects more autonomously. In order to identify the object and judge to grasp with correct way, we adopt the threshold segmentation and median filtering, which distinguishes the specific color features and regular shapes. By analysing the sizes of the objects in the image, NAO robot automatically determines whether to use single-arm to grasp. If the object is too large, NAO robot will choose double-arm to grasp autonomously. Furthermore, solving the forward and inverse solutions of NAO robot by kinematics analysis, the pose and position of each end-effector are calculated. According to the trajectory planning of the arm end-effecter, the simulation results show that the proposed method has practical value and reflects the intelligence of robot.

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The remainder of this paper is organized as follows, Section II describes object recognition and behavior judgment of NAO robot. In Section III, the kinematics model of NAO robot's arm is built. Section IV introduces the trajectory planning of NAO robot's arms to grasp objects. The experimental results verify the validity of proposed algorithms in Section V. Finally, some conclusions are presented in Section VI.

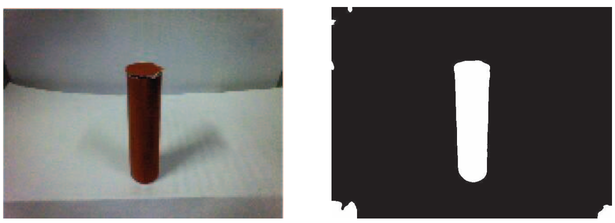
II. Object Recognition

In order to correctly judge and implement single-arm or double-arm operation, we need to obtain the objects information in the collected image. Through the observation and research of the the NAO robot's fingers, the grasping amplitude and the grasping space are chosen as the reference factors. By judging the width of the object, the NAO robot can decide to use single-arm or double-arm to grasp the object.

A. Image Preprocessing

In this paper, the objects we set are cylindrical sticks with red color. The stick is placed on the box with a height of 30 cm, and the distance between the tip of the robot and the bottom of the box is 10 cm. The distance between the stick and the front edge of the box is about 3 cm. Defining 2 cm in diameter as the standard of sticks, $X_0 = 2cm$. When the diameter X_i of the stick is less than or equal to X_0, NAO robot judges to implement single-arm grasping, or it will implement double-arm grasping.

The NAO robot obtains image with RGB color space, and its resolution is 640×480. RGB and HSV are different color spaces. In the RGB color space, the intensity of illumination has great influence on the object recognition, but the HSV color space has less influence compared with the former. Thus, it is more beneficial to choose HSV color space as the conversion format of the initial image. Combining the color-based threshold segmentation for the image and the median filtering technology, the noise interference in the image is removed and smooth binary image is obtained [6]. Fig.1(a) is the image collected by the NAO robot, and the processing result is shown as Fig.1(b).



(a) Collected image (b) Processed binary image

Fig. 1: Image processing

B. Image Analysis and Object Recognition

The basic unit of the image is the pixel, and we use pixel values to reflect the length or width in the image. We calculate the width of the stick in the binary image, and obtain the conversion relation between the pixel value in the image and the actual diameter of the stick. However, for the collected images, the width of the stick in the binary image will affected by the change of camera position and shooting angle during the collection prosess.

Assumption: Suppose that the objects are in the straight ahead of the NAO robot, and the camera position is stationary, thus, we can ignore the errors of shooting direction and angle. If and only if the objects are in the straight ahead of the NAO robot, it can capture their images.

Under the Assumption, this paper adopts fixed-point identification approach to eliminate the errors. keeping the relative position of NAO robot and stick unchanged, $W = \frac{X_0}{D_i}$, while W is the conversion factor on the basis of the known diameter X_0 and width of the pixel value ratio D_i. For the sticks of unknown diameter, we can calculate the actual diameter X_i of the stick by conversion factor W and the width of the pixel value D_i in the binary image. If the diameter $X_i \leq X_0$, the NAO robot will use single-arm to implement grasping; if the diameter $X_i > X_0$, the NAO robot will use double-arm to implement grasping.

The stick is presented as a rectangle in the binary image. Its two edges are parallel in the vertical direction, and perpendicular to the horizontal direction. By calculating the distance between the pixels on the left edge and right edge of the rectangle in the horizontal direction, the width D_i of the stick in the binary image can be obtained. In the processed binary image, the grayscale values of the rectangular edge are 1 and the grayscale values at other positions are 0 [7]. For the rectangle in binary image, a coordinate system is established in Fig.2.

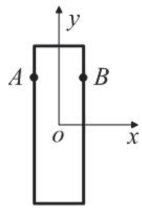


Fig. 2: Stick coordinate system

The coordinate of the point A on the left edge is defined as (x_1, y_1). On the right edge, the coordinate of the point B corresponded to the point A is (x_2, y_2). D_i is the distance between two coordinates [7]. The distance formula can be expressed as:

$$D_i = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{1}$$

Because of A and B in the same level, $y_2 = y_1$. So the distance formula can be reduced as:

$$D_i = \sqrt{(x_2 - x_1)^2} \tag{2}$$

Using this pixel value D_i and the conversion factor W, the actual diameter X_i of the stick is obtained.

$$X_i = D_i \times W \tag{3}$$

III. Robotic Kinematics Modeling

A. Structure and Model

In this paper, the NAO robot needs to implement single-arm or double-arm grasping operation. Since the left arm and right arm of NAO robot are symmetrical structure, the left arm is taken as an example for kinematics analysis. This method can be also extended to the kinematics analysis of double arms.

The left arm of the NAO robot consists of three joints, two connecting rods and three fingers. As shown in Fig.3, the shoulder has two degrees of freedom named "LShoiderRoll" and "LShoiderPitch", the elbow has two degrees of freedom named "LElbowRoll" and "LElbowrYaw", and the wrist has one degree of freedom named "LWristYaw".

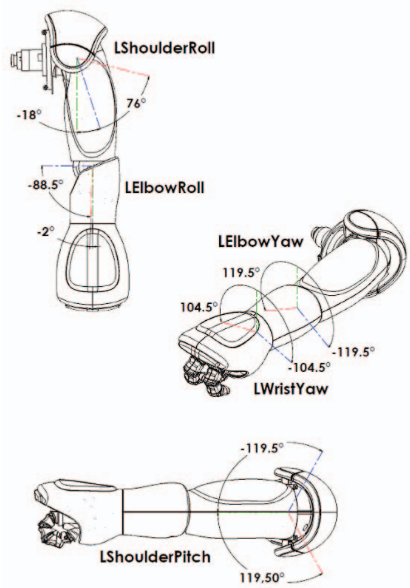


Fig. 3: The sketch map of joint motion angles

Because of the fingers have no relation to the joint movement of the robot's left arm, we ignore the degrees of freedom on the fingers part, and only construct model of one arm with five degrees of freedom. Fig.4 shows the joint motion angles of the NAO robot's left arm.

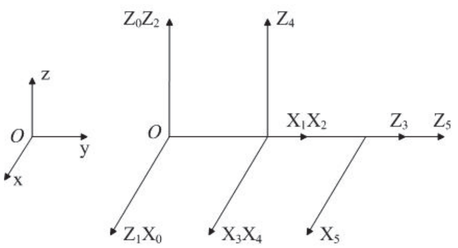


Fig. 4: The kinematic reference coordinate system of NAO robot's left arm

According to Denavit-Hartenberg (D-H) method [4], a kinematics model for the left arm of the NAO robot is built. Contrasting the coordinate system in Fig.4 and the fixed parameters of the NAO robot's left arm, the D-H parameter table is obtained and shown in Table I.

TABLE I: D-H parameters of the left arm

joint	θ_i/rad	d_i/mm	a_i/mm	α_i/rad
1	0	0	0	$\pi/2$
2	0	0	0	$-\pi/2$
3	0	105	0	$-\pi/2$
4	0	0	0	$\pi/2$
5	0	55.95	0	$-\pi/2$

In Table I, θ represents the rotation angle around the z axis, d represents the distance between two adjacent vertical lines on the z axis, a represents the length of each vertical line, and α represents the angle between two adjacent z axes [8]. According to the kinematics model, the structure model of the NAO robot's left arm can be obtained by using MATLAB Robotics Toolbox [8], [10]. That is shown in Fig.5.

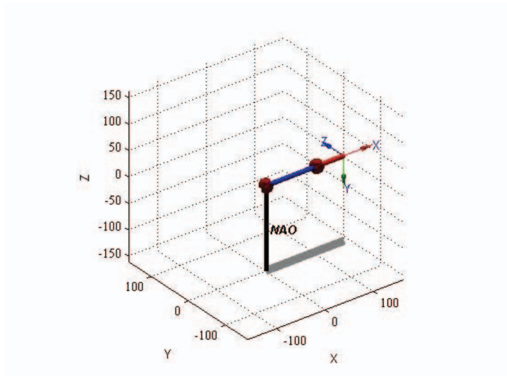


Fig. 5: The structure model of NAO robot's left arm

B. Forward Kinematics Solution

Forward kinematics solution means that the length of the connecting rods and the angle of each joint is known. According to the reference coordinate system, the pose of the robot end-effector relative to the reference coordinate system is obtained [8], [9]. The coordinate transformation matrix between the adjacent two joints is:

$$\begin{aligned} {}^{i-1}A_i = & Rot\left(Z_{i-1}, \theta_i\right) Trans\left(0, 0, d_i\right) \\ & Transa_i\left(a_i, 0, 0\right) Rot\left(X_i, \alpha_i\right) \end{aligned} \tag{4}$$

That is:

$${}^{i-1}A_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

In the above formulas, A is the coordinate transformation matrix, and i stands for the first i joint. Putting the D-H parameters in Table I into the transformation matrix formula, the transformation matrix between each of the two joints can be calculated. Multiply the matrices, the total transformation matrix between the first joint and the end-effector of the NAO robot is solved.

$${}^0A_5 = {}^0A_1{}^1A_2{}^2A_3{}^3A_4{}^4A_5 \tag{6}$$

C. Inverse Kinematics Solution

Inverse kinematics solution means that the desired pose of the robot end-effector on the reference coordinate system is known, then the joint motion parameters of the robot need to be found [9]. Defining the desired pose of the NAO robot's end-effector as:

$$ {}^{0}A_5 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7} $$

Let formula(6) and formula(7) equal, the five joints variable angles of NAO robot's left arm are obtained.

$$ \begin{cases} \theta_1 = \arctan \frac{p_y + 0.05595 o_y}{p_x + 0.05595 o_x} \\ \theta_2 = \arctan \frac{-c_1(p_x + 0.05595 o_x) - s_1(p_y + 0.05595 o_y)}{p_z + 0.05595 o_z} \\ \theta_3 = \arctan \frac{c_1 o_y - s_1 o_x}{s_2 o_z + c_1 c_2 o_x + c_2 s_1 o_y} \\ \theta_4 = \arctan \frac{c_1 o_y - s_1 o_x}{s_2 s_3 o_z - c_1 s_2 s_3 o_x - s_1 s_2 s_3 o_y} \\ \theta_5 = \arctan \frac{c_1 s_2 a_x + s_1 s_2 a_y - c_2 a_z}{c_2 n_z - c_1 s_2 n_x - s_1 s_2 n_y} \end{cases} \tag{8} $$

IV. TRAJECTORY PLANNING

There are two methods of trajectory planning of NAO robot's arms, they are the trajectory planning in joint space and in Cartesian space [11]. The purpose of these two methods is displaying the desired trajectory of the arm joints in the located coordinate system, which is based on the requirements and indexs of the task. The trajectory planning in Cartesian space can show the trajectory of robot's arm end-effector intuitively and clearly. However, this method needs to use the inverse kinematics algorithm, and demands to find the joint angle of each pose in the movement process. The calculation process is more complex, and it is easy to enter into the singularity point of the robot. By contrast, trajectory planning in joint space can not display the movement condition of the robot's arm end-effector intuitively, it has less calculations, and does not produce singularity point. It is conducive to observe the changes of the displacement, speed and acceleration for each joint. In this paper, the joints setting and movement planning of NAO robot's arms are relatively simple, so it would be convenient for us to choose the trajectory planning in joint space.

For the operation of the trajectory planning in joint space, the joint variable angle of the starting point and the ending point need to be obtained with the inverse kinematics solution firstly. $Q(t)$ is a smooth function that is defined to describe the trajectory [12]. The smooth function $Q(t)$ uses a quintic polynomial function and sets up six constraint conditions. For the constraint conditions, $Q_n(t)$ is considered as the smooth function of a joint n, Q_α regards as the starting joint angle of $Q_n(t)$ at the initiative time $t_0 = 0$, and Q_β regards as the ending joint angle of $Q_n(t)$ at the terminal time t_f. $Q_n(t_0) = Q_\alpha$, $Q_n(t_f) = Q_\beta$. Then the angular velocity and the angular acceleration are expressed as $\dot{Q}_n(t_0) = \dot{Q}_\alpha$, $\dot{Q}_n(t_f) = \dot{Q}_\beta$, $\ddot{Q}_n(t_0) = \ddot{Q}_\alpha$, $\ddot{Q}_n(t_f) = \ddot{Q}_\beta$ at the initiative time and the terminal time.

listing the quintic polynomial:

$$ Q_n(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 \tag{9} $$

Then

$$ \begin{cases} \dot{Q}_n(t) = a_1 + 2a_2 t + 3a_3 t^2 + 4a_4 t^3 + 5a_5 t^4 \\ \ddot{Q}_n(t) = 2a_2 + 6a_3 t + 12a_4 t^2 + 20a_5 t^3 \end{cases} \tag{10} $$

Taking the constraint conditions into the equations above, the following coefficients can be obtained:

$$ \begin{cases} a_0 = Q_\alpha \\ a_1 = \dot{Q}_\alpha \\ a_2 = \frac{1}{2}\ddot{Q}_\alpha \\ a_3 = \frac{20Q_\beta - 20Q_\alpha - \left(12\dot{Q}_\alpha + 8\dot{Q}_\beta\right)t_f + \left(\ddot{Q}_\beta - 3\ddot{Q}_\alpha\right)t_f^2}{2t_f^3} \\ a_4 = \frac{30Q_\alpha - 30Q_\beta + \left(16\dot{Q}_\alpha + 14\dot{Q}_\beta\right)t_f + \left(3\ddot{Q}_\alpha - 2\ddot{Q}_\beta\right)t_f^2}{2t_f^4} \\ a_5 = \frac{12Q_\beta - 12Q_\alpha - \left(6\dot{Q}_\alpha + 6\dot{Q}_\beta\right)t_f + \left(\ddot{Q}_\beta - \ddot{Q}_\alpha\right)t_f^2}{2t_f^5} \end{cases} \tag{11} $$

Then the quintic polynomial can be gotten. Further more, the angle, angular velocity and angular acceleration of the NAO robot's arm joints from the starting point to the ending point can be acquired, thus the motion trajectory of the NAO robot's arm end-effector is further obtained.

V. EXPERIMENTAL RESULTS AND SIMULATION

A. Experimental Results of Object Recognition

In order to show the results of object recognition, we have three sticks with different diameters to test the experiment, each stick for 150 groups of experiments, and conducted a total of 450 groups of experiments. While keeping the relative position of the NAO robot and the stick unchanged, the experiments are established. The NAO robot identifies the stick diameter and judges the grasping mode, the success times and success rates in the 450 experiments are counted out. The results are shown in Table II.

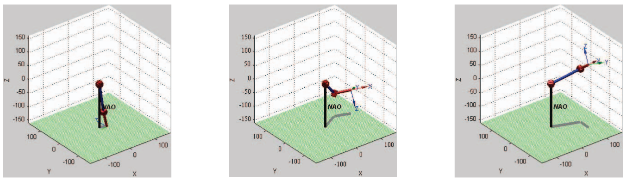
TABLE II: Success rate statistics of object recognition

Stick diameter	Success times	Success rate
$X > 2cm$	141	94%
$X = 2cm$	138	92%
$X < 2cm$	132	88%

From Table II, the experiment has a high success rate. For several sets of data that can not be successfully identified, environmental factors play a major role. The main reason that leads to the error of object recognition is the influences of illumination changes in the experimental environment. It can be seen that, the success rate is the highest when $X > 2cm$, and the success rate decreased when $X \leq 2cm$. In conclusion, the stick diameter becomes smaller, the success rate will decline. The reason is that the smaller the object to be identified, the greater the environmental impact of the image. The experimental results show that the method of object recognition in this paper has higher success rate and can improve the autonomous judgment ability of NAO robot.

B. Grasping Experiment Simulation

When the NAO robot judges single-arm to grasp the stick, the total time of NAO robot complete the specified action is set up within 5s, the time interval is 0.1s. The initial angle of five joints are 0, and the ending angles are $\theta_1 = \frac{\pi}{6}$, $\theta_2 = \frac{\pi}{6}$, $\theta_3 = -\frac{\pi}{4}$, $\theta_4 = -\frac{\pi}{3}$, $\theta_5 = -\frac{\pi}{6}$. In order to observe the movement pattern of NAO robot's arm more intuitively, the motion of the NAO robot's left arm from the initiative time t_0 to the terminal time t_f are simulated. The motion condition is shown in Fig.6.



(a) (b) (c)

Fig. 6: Simulated motion of robot's left arm

Fig.6(a) to Fig.6(c) show the range of motion of NAO robot's left arm clearly. It can be seen that each joint of the NAO robot's left arm is coordinated during the movement, and the posture of joints change constantly. The above figures are conducive to understand the motion attitude of NAO robot's left arm.

According to the set angles of the joints, the angle, angular velocity and angular acceleration of each joint for the NAO robot's left arm from the initiative time t_0 to the terminal time t_f period [13] are simulated.

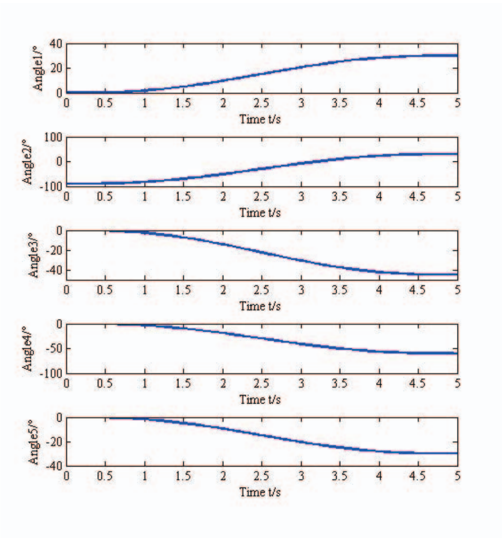


Fig. 7: The angle of each joint changes with time

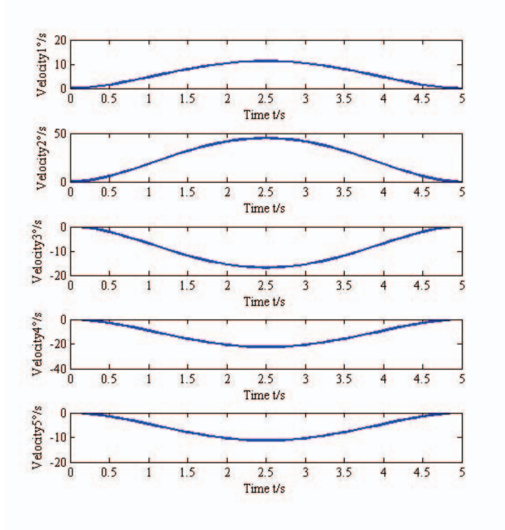


Fig. 8: The angular velocity of each joint changes with time

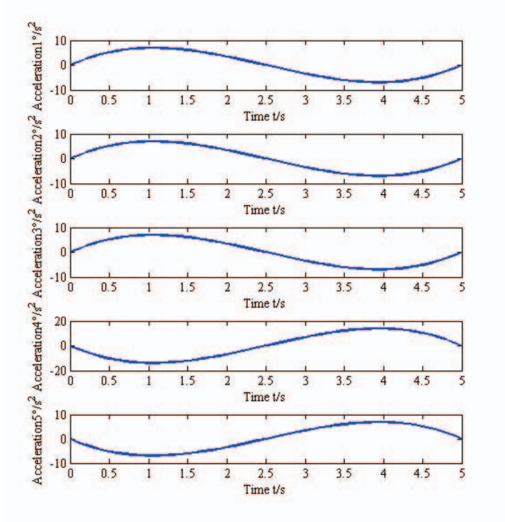


Fig. 9: The angular acceleration of each joint changes with time

Fig.7 to Fig.9 show the curves of the parameters of the five joints. The minus sign represents the change direction of angle, angular velocity and angular acceleration. 'Angle1' to 'Angle5' mean the motion angle of five joints during the course of movement, 'Velocity1' to 'Velocity5' mean the angular velocity of five joints in the movement process, and 'Acceleration1' to 'Acceleration1' mean the angular acceleration of five joints.

From Fig.7 the changes of joint angles over time according to the quintic polynomial are shown. It can be seen that the angles are monotonically increasing. This shows that the joint angles of the NAO robot's left arm are coordinated to increase until reaching the designated position during the course of movement. In Fig.8, through the derivation calculation of each motion angle, the curves of the angular velocity of each joint with time are obtained. The angular velocities show the trend of increase first and then decrease. Then, the derivatives of the angular velocity of the motion angles are calculated and the change curves are obtained in Fig.9. Generally speaking, the changes of angular velocity and angular acceleration can be obtained by the changes of angle. The above three figures show the parameters of each joint when the NAO robot's left arm moves, and provide datas for the trajectory planning. It can be seen that if the NAO robot wants to grasp the object, each joint of the arm needs to be coordinated.

According to the trajectory planning in joint space, the motion trajectory curve of the NAO robot's left arm end-effector is drawn. It is shown in Fig.10.

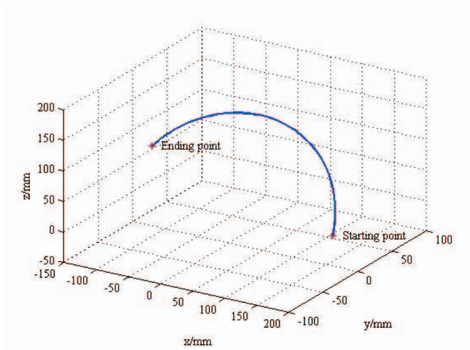


Fig. 10: The motion trajectory of the end-effector of NAO robot's left arm

When the NAO robot judges double-arm to grasp the stick, the motion trajectory of the robot's arms end-effector is shown in Fig.11.

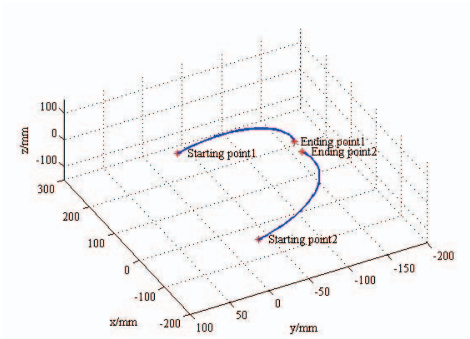


Fig. 11: The motion trajectory of end-effector of NAO robot's double arms

From the starting point to the ending point in Fig.10 and Fig.11, the end-effectors present smooth curves in the three-dimensional coordinate system. Thus the motion trajectory of the NAO robot's arm end-effector is clearly presented during motion. Of course, the simulation results will be somewhat different from those in the actual environment, but It can be seen that this method has practical value for NAO robot's actual operation.

VI. Conclusion

In this paper, in order to judge and grasp objects autonomously, a method combining image analysis and robot kinematics is proposed to implement kinematic modeling and trajectory planning for NAO robot's arms. It improves the intelligence and autonomy of objects grasping. Through the processed images of NAO robot, the shape information of the sticks are obtained, and useful information is extracted by analyzing images. According to the diameter of the stick in the binary image, NAO robot judges to grasp the stick with single-arm or double-arm. Combining the Denavit-Hartenberg (D-H) method, the kinematics model of the NAO robot's left arm is built, and the kinematics equations to solve forward and inverse solutions of kinematics are listed. By choosing the trajectory planning in joint space, the trajectory planning of the NAO robot's arms end-effector are drawn. The experiment of object recognition proves this method has a high success rate, and it can improve the autonomous judgment ability of NAO robot. Experiments simulate the motion environment of NAO robot's arms, and the results show that this method has practical value for the research of NAO robot, and has effectiveness for the object grasping in practical application.

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