

Research on Hand-eye Calibration Technology of Visual Service Robot Grasping Based on ROS

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Abstract: For the hand-eye calibration of the vision service robot, the traditional hand-eye calibration technology can't be realized which because the service robot is independently developed and there is no teaching device to feed back the pose information of the service robot in real time. In this paper, a hand-eye calibration method based on ROS (Robot Operating System) is proposed. In this method, ROS system is used to accurately control the arm of the service robot to rotate in different positions for many times. Meanwhile, the head camera of the service robot takes images of a fixed point in the scene. Then, the nonlinear equations were established according to the homography matrix of the two images and the position and pose information of the ROS system, and the accurate hand-eye relationship was optimized by the least square method. Finally, an experimental platform is built and the proposed hand-eye calibration method is verified. The experiment results show that the method is easy to operate, simple algorithm and correct result, which verifies the effectiveness of the algorithm and provides conditions for the realization of humanoid grasping of visual service robot.

Keywords: Service Robot, ROS, Least Square Method, Hand-eye Calibration

1 Introduction

At present, robot tracking control technology is a hot and challenging research topic in the field of robotics^[1]. This paper introduces the hand-eye coordination grasping and tracking control of vision, which is an innovative robot control technology researching problem. About 80 percent of the information that we get from our interactions with the outside world is through our eyes. Similarly, machine vision system, as an important part of the intelligent work of the whole service robot visual servo and information interaction with the external environment. The intelligent work of the service robot needs to obtain the three-dimensional coordinate information of the external environment

object through the vision sensor, and finally convert it to the robot base coordinate system. This is the primary task for the service robot to complete the humanoid grasping working, and the completion of hand-eye calibration is the primary task in this process. The visual sensor obtains three-dimensional coordinate information as the lowest level of the grasping system for the whole service robot, the accuracy of the three-dimensional coordinates is determined by the hand-eye calibration result, which directly determines the success or failure of the grasping work of the whole system. Hand-eye calibration determines the corresponding relationship between the camera coordinate system and the robot end-effector coordinate system. This relationship needs to be obtained through ex-

periments and calculations, which is called hand-eye calibration.

At present, the traditional camera calibration method is more, such as Tsai two-step^[2], direct linear transformation method^[3, 4] and the Zhang calibration^[5] and so on, these calibration methods have strong applicability, but by making high precision calibration targets, and then take the image to calculation internal and external parameters of camera, this method must have a calibration, but some environment cannot be placed calibration, this limits the application scope of this hand-eye calibration method. Therefore, under the constant exploration and research of researchers, the camera calibration technology is promoted to develop continuously. In 1992, Maybank proposed the self-calibration method^[6]. The emergence of self-calibration technology solves the problem of using targets for camera calibration, making calibration more flexible and simpler. In addition, active visual calibration is also a kind of self-calibration method, which obtains images by controlling the camera to do some specific movements so as to calibrate the internal parameters of the camera^[7]. The hand-eye calibration technology has also been developed, Literature^[8-10] proposes a self-calibration technology of structured light hand-eye system based on active vision, which requires four linearly independent translational motions and two rotation motions. In reference^[11, 12], calibration based on triorthogonal translational motion and orthonormal operation based on infinite plane homography matrix were also proposed. In literature^[13-16], a robot hand-eye relationship calibration method combining multiple calibration methods is proposed. The biggest advantage of this method is to complete the calibration of the camera and hand-eye relationship at one time. All the above calibration methods adopt different hand-eye calibration techniques according to the specific situation of the project.

No matter which hand-eye calibration technology, the robot teaching device needs to feed back the corresponding robot end pose information in a certain state in real time, which makes the service robot of this project unable to carry out hand-eye calibration with-

out teaching device. Therefore, a hand-eye calibration method for visual service robot grasping based on ROS system was proposed in this paper. ROS system is used to replace the teaching device to feed back the end pose information of the service robot in real time, and the least square method is used to solve the established hand-eye calibration relation equations, which simplifies the calibration process and improves the positioning accuracy. It provides effective location information for humanoid grasping and tracking control of service robot, which make the research of restaurant service robot technology is great significance.

2 Problem Analysis

The service robot system collects plate images through the 3D vision subsystem on the head, and performing image processing recognition, stereo matching and 3D reconstruction positioning. Then the 3D space position information of the plate in the robot base coordinate system is obtained through hand-eye coordinate transformation. Fitting tracking trajectory curve to give the desired trajectory. Then, inverse kinematics was used to solve the angle variation of each joint as the expected input. Finally, the controller outputs the control quantity to drive the joint motor to realize the end gripper tracking the desired trajectory to reach the target posture grasp, and complete the task of cleaning up the dinner plate, in which the solution of the hand-eye relationship is an indispensable process.

The hand-eye relationship configuration of visual robots mainly includes eye-in-hand and eye-to-hand two fixing installation modes, The eye on the hand is fixed at the end of the robot and moves with the end of the robot, so the posture relationship between the eye and the end of the hand is fixed and unchanged. In the eye-to-hand workspace, the eye and hand are independent, the eye is fixed at a certain position in the workspace, and the camera(eye) remains stationary, so the impact of vision accuracy which was caused by camera motion shaking is reduced. No matter which hand-eye installation form is adopted, hand-eye calibration must be carried out. Only through hand-eye calibration that can be connected the hand and eye.

Therefore, before the robot works, it is necessary to correspond the position and posture of the robot and the vision, and this process is hand-eye calibration.

Eye-to-hand installation is adopted in this paper. Eye-to-hand is beneficial to the experimental researching of the initial development process of the system, which is easy to independently verify the accuracy of the robot control part and binocular vision part, so as to facilitate the troubleshooting of errors in each part. If the fixed connection mode of eye on hand is not conducive to the debugging of the project development process, if the robot movement result doesn't reach the target point, it is difficult to explain whether there is a problem with the control technology or the inaccurate measurement of binocular vision system, and it is difficult to investigate the cause.

No matter which form of hand-eye relation is adopted, the final essence of the calibration process is to solve the transformation relationship between coordinate systems, as shown in Fig.1.

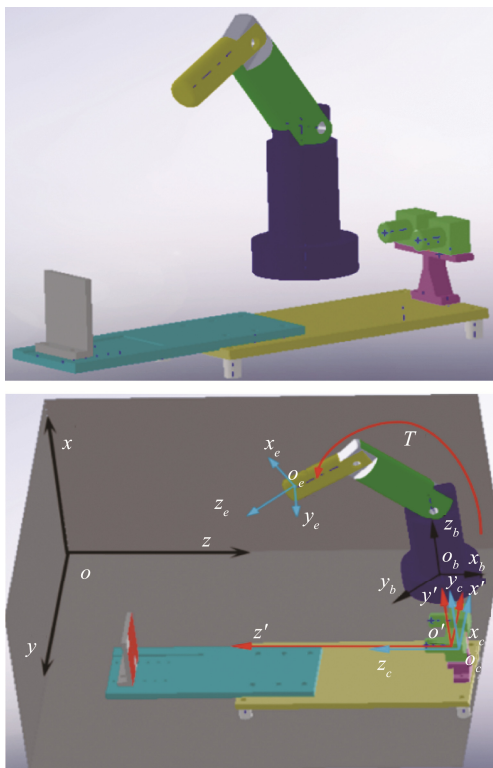


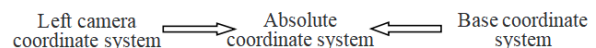
Fig.1 Eye-to-hand Coordination

According to the figure, the coordinate system

$o' - x'y'z'$ is set as the absolute coordinate system, which is the channel connecting the robot base coordinate system $o_b - x_b y_b z_b$ and the left camera coordinate system $o_c - x_c y_c z_c$. The transformation relationship R between the left camera coordinate system $o_c - x_c y_c z_c$ and the absolute coordinate system $o' - x'y'z'$ has been known in the previous working. The next task is to solve the transformation relationship R_{ob} between the robot's base coordinate system $o_b - x_b y_b z_b$ and the absolute coordinate system $o' - x'y'z'$. Controlling the end of the robot to detect each corner of the checkerboard, the robot homogeneous matrix T corresponding to each corner point is recorded, The T can be directly calculated according to the controller's teaching box obtained the corresponding angle of each joint and substituted it into the robot's forward kinematics model. So T is what we know. Therefore, coordinate values of each corner point under the robot base coordinate system can be obtained, as shown in Fig.2.

So according to the coordinate system relations, similarly, the same calculation method is used to solve the transformation relationship between the left camera coordinate system $o_c - x_c y_c z_c$ and the absolute coordinate system $o' - x'y'z'$, The relation of homogeneous transformation matrix between base coordinate system $o_b - x_b y_b z_b$ and absolute coordinate system $o' - x'y'z'$ can be obtained, so the coordinate information of the object in the absolute coordinate system $o' - x'y'z'$ is transferred to the robot base coordinate system $o_b - x_b y_b z_b$. Finally, the target grabbing control operation can be performed in the robot base coordinate system $o_b - x_b y_b z_b$, namely, the following equation can be obtained:

$$\begin{bmatrix} a_1 & a_4 & a_7 & a \\ a_2 & a_5 & a_8 & b \\ a_3 & a_6 & a_9 & c \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} b_1 & b_4 & b_7 & d \\ b_2 & b_5 & b_8 & g \\ b_3 & b_6 & b_9 & h \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_b \\ y_b \\ z_b \\ 1 \end{bmatrix}$$



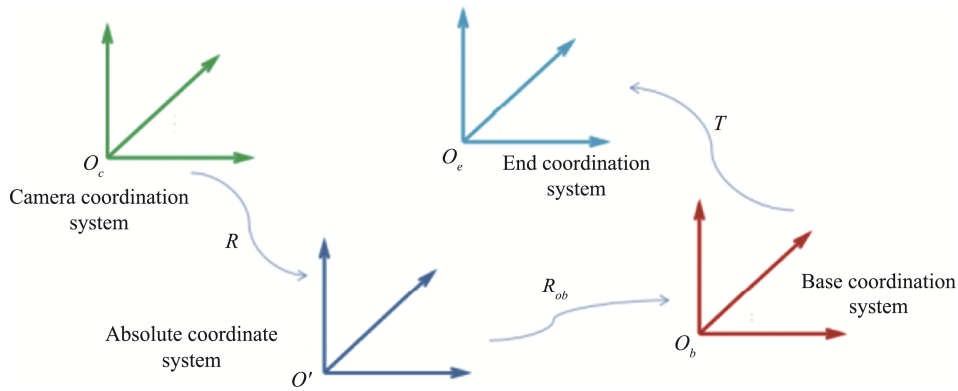


Fig.2 Transformation Relation of Coordination

According to the above analysis, aiming at the problems existing in the hand-eye calibration of the service robot grasping in this project, a hand-eye calibration technology based on the least square method was proposed in this paper.

3 Hand-eye Calibration Technology Based on Least Square Method

3.1 Principle of Hand-eye Calibration

A calibration method of hand-eye relationship based on least square method is proposed, that is not the same as traditional hand-eye calibration methods, because this project robot system under development, and is developed on the ROS system, There is no teaching function like industrial robot which is controlled by the control box to reach a specific position. However, the robot control of this project can only input the corresponding pose coordinate in the ROS system to make the robot run to the target pose. According to the functions of the robot in this project, the hand-eye calibration does not need checkerboard calibration board, which making the hand-eye calibration more flexible. First, in the ROS system, the target pose is randomly input within the robot's motion range to control the robot's motion target pose. At this time, the coordinate pose of the robot's end marking point is the pose information just entered in the ROS system. Then, a 3D camera is used to collect the image of the robot terminal target point, and the position and pose information of the target point in the 3D camera coordinate

system is read. In this way, the pose information of any space point in robot coordinate system and 3D camera coordinate system is obtained. According to the closed chain principle of robot and 3D camera, the relation between coordinate information in these two coordinate systems can be deduced, That's the equation between them that satisfies $AX = XB$. In this way, as many data points are used as possible, and then the least square method can be used to solve and calculate the hand-eye relationship matrix X , and finally achieve hand-eye calibration, as shown in Fig.3.

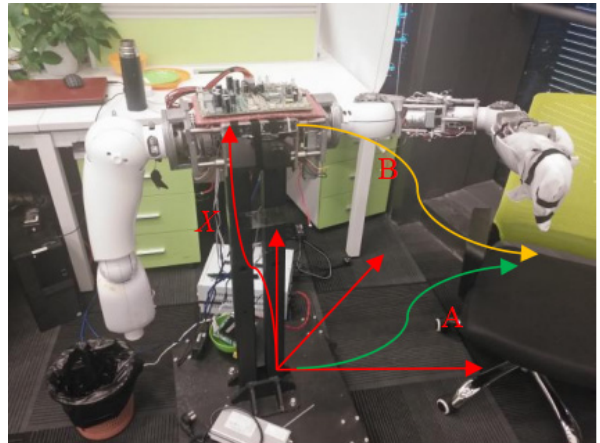


Fig.3 Chart of Hand-eye Calibration Geometry

3.2 Hand-eye Calibration Process Method

The robot communicates with the ROS system and runs the system. The process of hand-eye calibration method is discussed below.

(1) Rotation Matrix R of Hand-eye Relation Calibration

Let point p be the fixed point in 3D space, that is the single fixed point of this calibration, its coordinates in the world coordinate system, robot terminal coordinate system and camera coordinate system are respectively is X_w , X_E and X_c . After the robot moves flat b_m from its initial position, the camera coordinate system and the terminal coordinate system are shifted to obtain the new coordinate system, and the image of the single fixed point p is taken.

$$X_E = RX_C + t \quad (1)$$

$$X_{E1} = RX_{C1} + t \quad (2)$$

And then flat to get:

$$X_{E1} - X_E = b_1 \quad (3)$$

Substitute the above equation into Equations (1) and (2) to obtain:

$$R(X_{C1} - X_C) = b_1 \quad (4)$$

Substitute the relationship between space points and pixel coordinate points in the pixel coordinate system into the above equation:

$$R(z_1 M^{-1} m_1 - z_0 M^{-1} m_0) = b_1 \quad (5)$$

Simplify getting

$$z_1 m_1 - z_0 m_0 = MR^{-1} b_1 \quad (6)$$

Which b_1 can be read directly from the robot controller, m_0 and m_1 are the pixels which is spatial points p in the figure before and after robot translation in image coordinate system, that is $m_0 = (u'_0 \ v'_0 \ 1)^T$ and $m_1 = (u_1 \ v_1 \ 1)^T$. to set $A_0 = [A_1 \ A_2 \ A_3]^T = MR^{-1}$, so getting that

$$\begin{cases} z_1 u_1 - z_0 u'_0 = A_1 b_1 \\ z_1 v_1 - z_0 v'_0 = A_2 b_1 \\ z_1 - z_0 = A_3 b_1 \end{cases} \quad (7)$$

Simplify and eliminate z_1 get that

$$\begin{cases} z_0 (u_1 - u'_0) = A_1 b_1 - u_1 A_3 b_1 \\ z_0 (v_1 - v'_0) = A_2 b_1 - v_1 A_3 b_1 \end{cases} \quad (8)$$

Thus, when the robot is controlled to do translation movement j times, the equations of j groups the above equation can be obtained, which can be written as:

$$AX = B$$

Among that

$$A = \begin{bmatrix} b_1^T & 0_{1 \times 3} & -u_1 b_1^T \\ 0_{1 \times 3} & b_1^T & -v_1 b_1^T \\ \vdots & \vdots & \vdots \\ b_j^T & 0_{1 \times 3} & -u_j b_j^T \\ 0_{1 \times 3} & b_j^T & -v_j b_j^T \end{bmatrix}, \quad B = \begin{bmatrix} z_0 (u_1 - u'_0) \\ z_0 (v_1 - v'_0) \\ \vdots \\ z_0 (u_j - u'_0) \\ z_0 (v_j - v'_0) \end{bmatrix},$$

$$X = [X_1 \ X_2 \ X_3]^T \quad (9)$$

The least square method is used to solve the above equation, to set $z_0=1$, which can solve for X that is one scale factor away from A_0 . In order to find the true value z_0 , R is the unit orthogonal matrix, that is $R^T=R^{-1}$, so $A_0=MR^{-1}$ will be written in the following matrix form:

$$A_0 = \begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix} = \begin{bmatrix} \alpha_x & \lambda & u_0 \\ 0 & \alpha_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_1 \\ r_2 \\ r_3 \end{bmatrix} = z_0 \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} \quad (10)$$

$z_0 X_3 = r_3$ is given by the above formula, so there is

$$z_0 = |r_3| / |X_3| = \frac{1}{|X_3|}. \text{ Expanding the above Equation (10)}$$

to get

$$\begin{cases} A_1 = \alpha_u r_1 + \lambda r_2 + u_0 r_3 \\ A_2 = \alpha_v r_2 + v_0 r_3 \\ A_3 = r_3 \end{cases} \quad (11)$$

According to r_1 , r_2 and r_3 are the unit orthogonal matrix, to use r_1 , r_2 and r_3 to do the dot product or cross product to the left and right of the above formula to solve the camera parameters M_1 and the rotation part R of the hand-eye relationship matrix. $r_3 = A_3$, $v_0 = A_2 r_3^T$, $u_0 = A_1 r_3^T$, $\alpha_v = |A_2 \times r_3|$, $r_1 = A_2 \times r_3 / |A_2 \times r_3|$, $r_2 = r_3 \times r_1$, $\alpha_u = A_1 r_1^T$, $\lambda = A_1 r_2^T$.

(2) Calibration of Translation Vector t of Hand-eye Relationship

To control the robot to rotate more than twice and take the image of a single fixed point p . After each rotation, the position and pose matrix relationship between the world coordinate system and the terminal coordinate system is as follows:

$$T_{6i} = \begin{bmatrix} R_{HW}^i & t_{HW}^i \\ 0 & 1 \end{bmatrix}$$

All parameters of the above formula can be read directly from the robot controller. Since the single fixed point p is fixed in the world coordinate system, the coordinate relationship between the point p in the world coordinate system and its image coordinate system after each movement can be obtained, as following

$$\begin{cases} X_W = z_1 R_{HW}^1 R M^{-1} m_1 + R_{HW}^1 t + t_{HW}^1 \\ X_W = z_2 R_{HW}^2 R M^{-1} m_2 + R_{HW}^2 t + t_{HW}^2 \\ X_W = z_3 R_{HW}^3 R M^{-1} m_3 + R_{HW}^3 t + t_{HW}^3 \\ \vdots \\ X_W = z_i R_{HW}^i R M^{-1} m_i + R_{HW}^i t + t_{HW}^i \end{cases} \quad (12)$$

Since that do twice exercises, subtract the above equation in pairs to get:

$$\begin{cases} z_1 A_1 - z_2 A_2 + B_1 t = C_1 \\ z_1 A_1 - z_3 A_3 + B_3 t = C_3 \end{cases} \quad (13)$$

among $A_1 = R_{HW}^1 R M^{-1} m_1$, $B_1 = R_{HW}^1 - R_{HW}^2$, $C_{1i} = t_{HW}^2 - t_{HW}^1$, A_2 and B_2 formation in matrix form in a similar way as following

$$\begin{bmatrix} A_1 & A_2 & 0_{3 \times 3} & B_1 \\ A_1 & 0_{3 \times 3} & A_3 & B_3 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ t \end{bmatrix} = \begin{bmatrix} C_1 \\ C_3 \end{bmatrix} \quad (14)$$

According to the least square method^[17], the translation vector t of hand eye relationship and the depth information z_i of single fixed point of each pose were obtained.

4 Hand-eye Calibration Test

According to the equation form $AX=XB$ hand-eye calibration method, in order to verify the effectiveness of this hand-eye calibration technology, a hand-eye calibration experimental platform was built. The hand-eye calibration test equipment includes frame,

robot system, binocular vision system (3D camera) and computer system. The 3D camera and the robot arm are fixed on the rack, and the relative pose between them can be directly measured with the measurement tool, which provides reference for the verification of the subsequent hand-eye calibration experiment results, as shown in Fig.4. The ROS Kinect version operating control interface is shown in Fig.5, the position information of the end of the arm can be obtained in real time on the interface. After the target is adjusted on the experimental table, the robot's arm is controlled by ROS system to move in different positions for more than eight times, and coordinate pose information corresponding to each pose information in 3D camera coordinate system and target image are collected respectively, as shown in Fig.6. Then, the equations were established for the eye calibration model based on these pose information, and the hand-eye relationship was finally calculated by using the algorithm of this paper, as shown in Table 1.

According to the above hand-eye calibration position and pose information matrix results, it can be seen from the macro perspective that the end pose of 3D camera and robot are basically the same, and the pose distance between them is roughly correct.

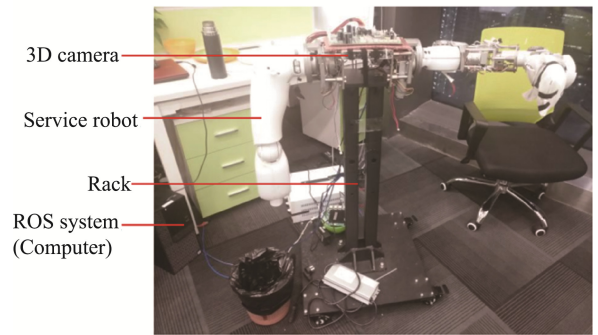


Fig.4 Experiment Platform of Hand-eye Calibration

Table 1 Hand-eye Calibration Parameter

R_i	t
$R_i = \begin{bmatrix} 0.992347 & 0.019736 & 0.1026737 \\ -0.014653 & 1.001284 & -0.009712 \\ -0.107483 & 0.009836 & 0.9953982 \end{bmatrix}$	$t = [100.57, 120.68, 100.78]^T$

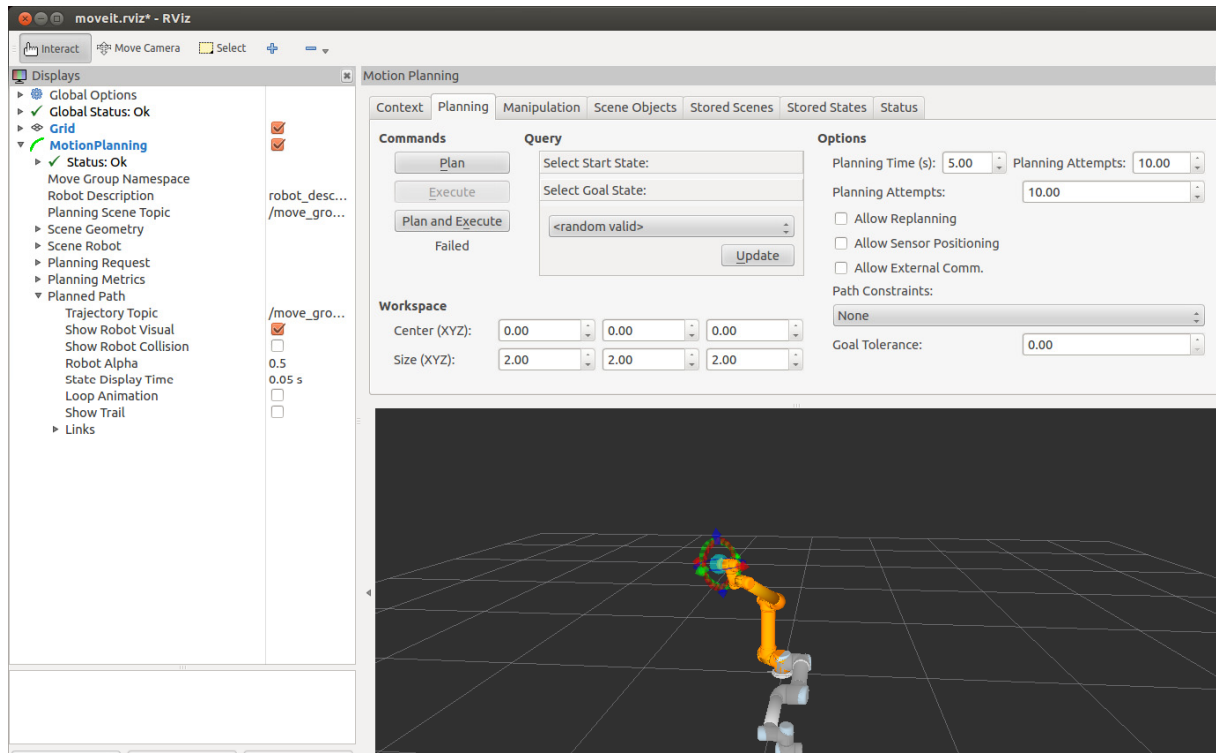


Fig.5 ROS System Control Interface

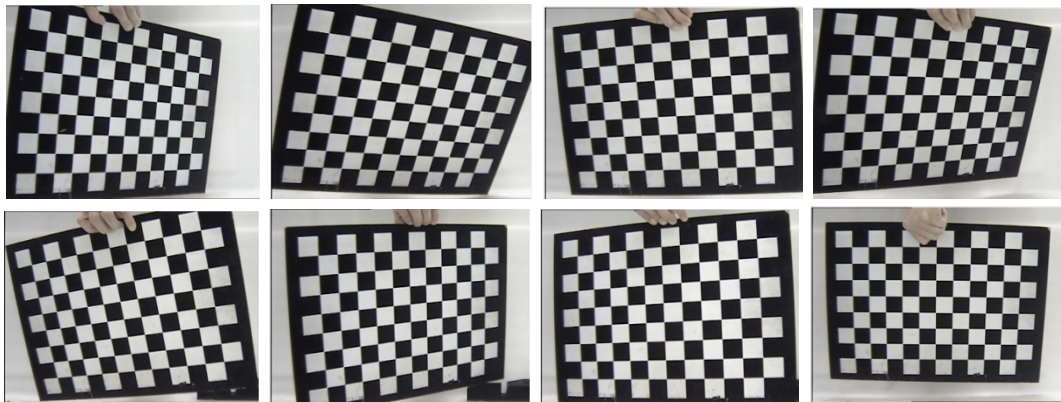


Fig.6 Image of Hand-eye Relationship

5 Conclusion

This paper focuses on the research of hand-eye calibration technology for service robot visual grasping. Since the service robot in this project is independently developed, there is no teaching device to feed back the pose information of the service robot in real time, so the traditional hand-eye calibration technology can't be applied. In this paper, a hand-eye calibration method based on ROS (robot operating system) is proposed. To

set the trajectory points of the service robot through ROS system, then the equations are established based on the hand-eye relation equation and solved by the least square method. Therefore, a more accurate homogeneous matrix of hand-eye relation is obtained by calibration. Finally, a hand-eye calibration experiment was carried out on an experimental platform. The experimental results show that the proposed algorithm can accurately calculate the pose relation matrix between the hand and the eye, which effectively verifies

the feasibility of the proposed method, and provides a foundation for the realization of the grasping control technology of the service robot in the next step.

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