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ROBOT MANIPULATOR USING A VISION-BASED HUMAN–MANIPULATOR INTERFACE

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ABSTRACT

It is much useful of the unstructured environment which the objects in it are unfamiliar to use human-robot interaction in remote teleoperation of robot manipulator. Traditionally, contacting mechanical devices under the interactive method can restrict the operator's motion. While camera-based tracking has the benefit of being non-contacting, previous vision-based approaches have used only few degrees of freedom for hand motion and have required hand motions that are unnatural for object manipulation tasks. Here we provide a non-contacting vision based method for robot teleoperation. By tracking by two cameras, we can get the three-dimensional position and orientation of the operator's hands during the manipulation of the robot. We also proposed the Kalman filter to eliminate the influence of the noise. As the experimental result, our method can let the operator perform manipulating more naturally and intuitively, which laid solid foundation for effective teleoperation of robot.
Keywords: *Robot-Manipulator Interface, Vision, Kalman Filter*

1. INTRODUCTION

As the rapid development of computer vision and artificial intelligence, more complicated tasks need to be carried out by fully autonomous robot. In those environment which is highly unstructured, the objects in it are unfamiliar and the motions of these tasks are unknown, there needs human intelligence to make decision and take control of the robot. As the bridge communicating the human intelligence and the actual motions of the remote robot, human-robot interface is the key technique of the whole teleoperation solution.

Joysticks and robot replicas as the most common used contacting mechanical devices, which take the role of interface between human and robot [1]. However, these devices require high precision motion control. That means that the operator needs to be experienced and well-trained in order to manipulate the robot effectively. Besides some devices which can track the operator's hand position and orientation in real time are also important to the robot teleoperation. This kind of devices includes electromagnetic tracking devices, inertial sensors and data gloves [2-3]. However, these devices are also contacting sensors and may hinder the natural human-limb motion.

Compared to the previously stated method, because of the non-contacting nature, the vision-based techniques which is non-invasive obviously has much advantages. So the interference to the operator's motions is massively reduced. There are many studies for vision-based human-limb tracking in human-machine interfaces [4-5], robotics and automation [6-11], virtual and augmented reality [12], surveillance [13], and biomechanics [14]. Among these interactive techniques, interface that combining hand gestures and speech recognition has allowed operator to give out commands more naturally and more intuitively. However, use his method, the motion of the manipulated robot is constituted by series of simple command, such as rotation, translating up and down, grabbing, etc. When the required complexity of robot motion is high, it is not easy to translate the actual motion into series of simple tasks. In paper [15], SIddharth Verma et al. present a markerless, camera-based human-limb tracking

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method. Using this method, contacting devices are not required, and the translation from actual motions to series of simple commands is not required as well.

What the operator needs to do is guiding the robot using naked limb. However, due to the high error in the calculated 3D positions of the index finger and thumb tip positions, the orientation control of the robot end-effector was not accurate enough. Based on this solution, Jonathan Kofman et al. [16] have made some effective improvement. They add markers onto operator's hand, leading a more accurate analysis of the human hand's orientation. They also adopted a semi-autonomous traded and shared control using robot-vision guidance, to achieve a more accurate positioning and orientation of the end-effector for object gripping tasks. However, the ratio between the operator's working space and the robot's working space is 1 to 1 by default, which means that in application when the robot need to move in large scale, the operator also need to move in large scale. Also, lack of the adjustment between coarse-control and fine-control has lead to inefficiency in manipulating the robot.

This paper presents a vision-based manipulation method, which has following advantages over the previously stated method:

Provides a natural and intuitive way to manipulate the remote robot;

Contacting devices that may hinder operator's motion are not required;

Utilizing virtual reality techniques, the whole teleoperation process is more accurate and safer;

The operator doesn't need to move as large scale as the remote robot.

The human hand tracking and positioning is carried out by stereo camera system. Kinematic algorithm is utilized to manipulate the virtual robot. The whole solutions contains following modules:

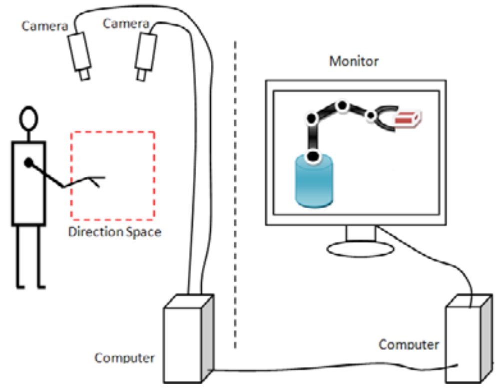

Figure 1. Non-Invasive Robot Teleoperation System

The operator's hand is captured by stereo-camera. Using the two yielded pictures of operator's hand, the 3D information of the hand is extracted and sent to virtual environment to perform preview of the manipulation.

Coordinate transformation system. Through mapping the coordinate of operator's console to the coordinate of the virtual robot's work space, the 3D information of the hand is transformed into the transformation matrix of the virtual robot relative to the virtual coordinate.

Robot manipulation system. Modeling using the D-H conversion, the system calculates the angle of every joint through performing reverse kinematic calculation and manipulating the virtual robot.

The remaining paper is organized as followed: Part II introduces the human hand tracking and positioning system. Part III introduces the coordinate transformation system. The adaptive multi-space transformation is given in part IV. The validation of the whole solution using 6 degree of robot is detailed in part V. The experiment analysis and the conclusion are detailed in part VI and VII.

2. HUMAN HAND TRACKING AND POSITIONING SYSTEM

In this system, two cameras deployed in different place of the working space are required. These two cameras can capture images of the same working space, but in different angles. The image processing system extracts the human hand from the images, and then extracts the markers which are plotted on the hand. Using the information of the markers in different images, the system can perform three dimensional reconstruction to obtain the three dimensional coordinates of the markers.

In robot teleoperation system, human-robot interface with high precision is required. The

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method presented in this paper suggests using human hand to manipulate the remote robot in a natural and intuitive way, therefore accurate extraction of the specific parts of the human hand is necessary. Common skin color segmentation method can't obtain precise result, so our solution utilizes a glove with marker points plotted on thumb tip, index finger tip, and the thenar space (the space between thumb and index finger). Operator need to wear this glove to perform the manipulation motion. Using this scheme, the accuracy of the marker tracking is greatly enhanced, even when the light condition of the working space is not good or there exists some noise signal. In order to guarantee the real time performance of the whole tracking process, instead of searching the whole image, the system uses Kalman filter to predict the target, and search the specific region based on the predict result.

In markers recognition, RGB color model is required. In 24 bit RGB color model, every color can be represented by red, green, and blue. Different combination yields different color. The glove using in our solution is yellow, and the marker is red. The tracking program needs to recognize the red point in the image to extract the human hand.

Assuming the value of the pixel *i* in the image is (R_i, G_i, B_i), the model to recognize the red pixel in the image is as follow:

$$\begin{cases} R_i > G_i + \delta_g \\ R_i > B_i + \delta_b \\ R_i > \delta \end{cases} \quad (1)$$

Where δ_g, δ_b, δ are the threshold values. These three inequations mean that the R value must larger than the value in the right of the inequation. The pixel which satisfies those three inequation is displayed as color red, may probably constitutes the marker point in the image.

After the marker points are extracting, the three dimensional coordinates of the markers need to be calculated. These coordinates are reconstructed using two-dimensional markers' positions extracting in two different images.

3. COORDINATE TRANSFORMATION SYSTEM

3.1. Positioning Model

In order to avoid large scale motion of the operator while performing manipulation, the working space of the operator need to confine in a relatively small space. Meanwhile the working space of the remote robot should not be confined. It means that the mapping from a relatively small space to an unconfined large space is necessary. The problem is direct mapping from small space to a large space will sacrifice precision. In order to solve this problem, a differential positioning method is adopted.

After initializing the remote robot, the initial position of the end-effector (x^p, y^p, z^p)can be obtained using kinematic calculation. Next a virtual space called Working Space needs to be defined in the scopes of the filming region under two cameras. As depicted in Figure 2, operator's hand is only allowed to move in this working space, otherwise the motions of the operator will not be recognized. Inside the working space there is another virtual space called Direction Space. The interspace between working space and direction space is used to alter the robot's position.

If the hand of operator enter the interspace in X direction, then the position of the end-effector is ($x^{p+\sigma}, y^p, z^p$);

If the hand of operator enter the interspace in minus X direction, then the position of the end-effector is ($x^{p-\sigma}, y^p, z^p$);

If the hand of operator enter the interspace in Y direction, then the position of the end-effector is ($x^p, y^{p+\sigma}, z^p$);

If the hand of operator enter the interspace in minus Y direction, then the position of the end-effector is ($x^p, y^{p-\sigma}, z^p$);

If the hand of operator enter the interspace in Z direction, then the position of the end-effector is ($x^p, y^p, z^{p+\sigma}$);

If the hand of operator enter the interspace in minus Z direction, then the position of the end-effector is ($x^p, y^p, z^{p-\sigma}$);

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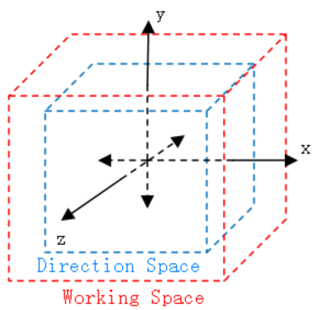

Figure 2. Positioning Model

Because σ is a adjustable parameter, the space manipulated by operator is in theory an infinite space. Coarse-control and fine-control can be obtained through adjust the value of σ.

3.2. Orientation Model

As depicted in figure 3, the orientation of the end-effector is in accordance with the orientation formed by thumb tip, index finger tip, and thenar space of the operator's hand.

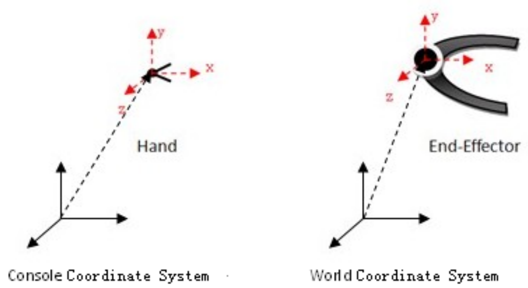

Figure 3. Orientation Model

It means that if only we can get the transformation matrix from the coordinate system of the console to the coordinate system of the operator's hand, the transformation matrix from the base coordinate system to the end-effector is also obtained. The derivation of the orientation matrix is detailed below:

Assuming the origin of the operator's hand coordinate system is identical to the one in console coordinate system, and the transformation matrix is a 3*3 matrix M. Let Point A in operator's hand coordinate system transfer to Point A' in console coordinate system, we have:

$$A' = MA \tag{2}$$

In the process of hand tracking and positioning, the unit vector $[x_1, x_2, x_3]$, $[y_1, y_2, y_3]$, $[z_1, z_2, z_3]$ in direction X, Y, Z can be measured by cameras yielding:

$$\begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} \tag{5}$$

Through (3), (4), (5), yielding:

$$\begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} = \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{bmatrix} \tag{6}$$

As stated before, the transformation matrix from console coordinate system to operator's hand coordinate system is identical to the one from base coordinate system to the end-effector coordinate system, and the translation relationship between end-effector and the base coordinate system is already yielding in positioning model, so the transformation matrix of orientation is:

$$M = \begin{bmatrix} x_1 & y_1 & z_1 & p_1 \\ x_2 & y_2 & z_2 & p_2 \\ x_3 & y_3 & z_3 & p_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

Noticing that the [p_1, p_2, p_3] is the translation matrix from base coordinate system to the end-effector.

4. KALMAN FILTER FOR ESTIMATION POINTS

In the position estimating process, we use KF to estimate the state P of the position from a set of noise measurement. In this estimation, six measurements are available: three velocity components in the hand frame and three position components in the hand frame. Let the direction cosine matrix M_{H2S} from the hand frame to the world frame is

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$$M_{H2S}=\begin{bmatrix} m_{X_x} & m_{Y_x} & m_{Z_x} \\ m_{X_y} & m_{Y_y} & m_{Z_y} \\ m_{X_z} & m_{Y_z} & m_{Z_z} \end{bmatrix} \quad (8)$$

The acceleration of the hand in the shoulder frame can be expressed as [30]

$$\begin{aligned} V_x &= m_{X_x} \cdot A_x + m_{Y_x} \cdot A_y + m_{Z_x} \cdot A_z \\ V_y &= m_{X_y} \cdot A_x + m_{Y_y} \cdot A_y + m_{Z_y} \cdot A_z \\ V_z &= m_{X_z} \cdot A_x + m_{Y_z} \cdot A_y + m_{Z_z} \cdot A_z \end{aligned} \quad (9)$$

Where (A_x, A_y, A_z) are the velocity of hand measurement components in each axis in the hand frame. The velocity components (V_x, V_y, V_z) in each axis in the hand frame can be defined as

$$\begin{aligned} V_x &= \dot{p}_x \\ V_y &= \dot{p}_y \\ V_z &= \dot{p}_z \end{aligned} \quad (10)$$

From (9) and (10), the state $x_k^{'}$ of the position KF is expressed as

$$x_k^{'}=[p_{x,k}, V_{x,k}, A_{x,k}, p_{y,k}, V_{y,k}, A_{y,k}, p_{z,k}, V_{z,k}, A_{z,k}] \quad (11)$$

The subscript k represents the state at time k. According to (9) and (10), the state-transition matrix $A_k^{'}$ is defined as

$$A_k^{'}=\begin{bmatrix} 1 & t & m_{X_x}\Delta t^2/2 & 0 & 0 & m_{Y_x}\Delta t^2/2 & 0 & 0 & m_{Z_x}\Delta t^2/2 \\ 0 & 1 & m_{X_x}\Delta t & 0 & 0 & m_{Y_x}\Delta t & 0 & 0 & m_{Z_x}\Delta t \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & m_{X_y}\Delta t^2/2 & 1 & t & m_{Y_y}\Delta t^2/2 & 0 & 0 & m_{Z_y}\Delta t^2/2 \\ 0 & 0 & m_{X_y}\Delta t & 0 & 1 & m_{Y_y}\Delta t & 0 & 0 & m_{Z_y}\Delta t \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & m_{X_z}\Delta t^2/2 & 0 & t & m_{Y_z}\Delta t^2/2 & 1 & t & m_{Z_z}\Delta t^2/2 \\ 0 & 0 & m_{X_z}\Delta t & 0 & 0 & m_{Y_z}\Delta t & 0 & 1 & m_{Z_z}\Delta t \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (12)$$

Since there is no control inputs, the system input matrix is

$$B^{'} \cdot u_{k-1}^{'}=0 \quad (13)$$

We use accelerations to estimated the position states, so the process noise vector is

$$w_k^{'}=[0, 0, w_x^{'}, 0, 0, w_y^{'}, 0, 0, w_z]^T \quad (14)$$

Where $(w_x^{'}, w_y^{'}, w_z)$ are the process noise of the hand velocity.

Since the cameras are calibrated and initialized, the observation matrix $H^{'}$ for the position estimation is

$$H^{'}=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (15)$$

So the nine states are observable.

The determined position $P_k(p_{x,k}, p_{y,k}, p_{z,k})$ at time k is the optimal value of the position of the human hand.

5. ROBOT MANIPULATION SYSTEM

The experiment is carried out using Granda six degree-of-freedom modular virtual robot. The task is to grab the target object placing in the virtual robot's working space, and place the object to the destination.

There is two working mode for the virtual robot. The First one is calculating the angle of every joints using reverse kinematic according to the position of the end-effector. When all the joints finish executing the requested angle, the end-effector of the virtual robot reaches the destination. This mode is suited for the situation that no obstacle is presented in the virtual robot's working space. While the second mode is the situation that obstacle is presented in the virtual robot's working space. In this mode virtual robot must move along a safe path, which leads to that the operator must assure that the virtual robot will not make collision against the obstacles.

In DH representation, A_i presents the homogeneous coordinate transformation matrix from coordinate *i*-1 to *i* :

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$$A_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & l_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & l_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & r_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (16)$$

For a robot having six joints, the homogeneous coordinate transformation matrix from base coordinate system to end-effector's coordinate system is defined as:

$$T_6 = A_1A_2 \ldots A_6 = \begin{bmatrix} n_6^0 & s_6^0 & a_6^0 & p_6^0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (17)$$

In which n_6^0 is the row vector of the end-effector, s_6^0 is the pitch vector, a_6^0 is the yaw vector, and p_6^0 is the position vector.

Using (7), (17), yielding:

$$T_6 = M \quad (18)$$

Through (18) the angle of six joints can be obtained: $(\theta_1, \theta_2, \ldots, \theta_6)$.

6. EXPERIMENTS

To verify the proposed method, a series of five tests were carried out to copy the human hand motion in the human-robot-manipulator interfaces for robot teleoperation. The tests were designed to compare between our method and the method [11] in the accuracy of controlling the robot movements in real time to perform object manipulation tasks, as well as the ability of the manipulator to copy human hand-arm motion. To be difference from method[11], which is direct position and orientation control, our method use velocity control. During each test, an operator moved their arm in the working volume to perform a pick-and-place object-manipulation task (Figure 5). The task was picking up an object and placing the object on a target with the object and target edges aligned, as shown in figure 6. Since controlling robot to pick and place the object needs to close and open the claws, we used the motion of left arm to give the order. When the distance of two blue points was so small, it meant closing the claws. Instead, when the distance of two blue points was so large, it meant opening the claws. The object was a rigid plastic block, 180 mm in height, 90 mm in wide and 50 mm in thick. The target was a 180 mm×90 mm square paper. The 2D error $E_{pos,2D}$ in translation was the distance between the center of the target and that of the object. The 2D error $E_{ori,2D}$ in rotation was the angle θ between the edge of the target and that of the object (figure 4).

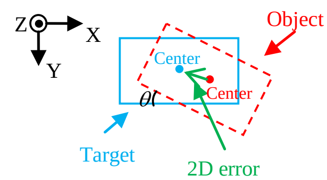

Figure 4. Definition Of Errors

Figure 5. The Environment Of The Experiment

A GOOGOL GRB3016 robot model was used in our experiments. Table 1 lists the nominal robot link parameters of the robot.

Table 1. The Nominal Link Parameters In DH Model For The GOOGOL GRB3016 Robot

Joint \ DH	a (mm)	α (rad)	d (mm)	θ (rad)
1	150	$-\pi/2$	250	0
2	570	$-\pi$	0	$-\pi/2$
3	150	$\pi/2$	0	0
4	0	$-\pi/2$	650	0
5	0	$-\pi/2$	0	$-\pi/2$
6	0	0	-200	0

In experiment, we compared our method and method [11] in accuracy and operating time. Fig 6 shows the errors for 5 tests with two methods. In our method, the absolute 2D errors for 5 tests ranged from 0.74 mm to 4.83 mm in X translation, 1.69 mm to 6.57 mm in Y translation and 0.65 deg to 1.47 deg in Z rotation, with the mean absolute errors (MEs) of 3.25 mm, 3.98 mm and 1.17 deg. In method [11], the 2D absolute errors for 5 tests ranged from 4.79 mm to 6.48 mm in X translation, 3.79 mm to 6.63 mm in Y translation and 1.97 deg

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to 2.55 deg in Z rotation, with the mean errors (MEs) of 5.79 mm, 5.46 mm and 2.34 deg. Comparing with method [11], the total translation errors of our method drop 2.56 mm, as well as the Z rotation errors drop 1.16 deg. The translation errors of our method are slight smaller than that of method [11], but the rotation errors of our method are less than half of that of method [11]. In our method, we used AMT to measure the orientation of the human hand, so the rotation errors are smaller in out method. But due to the perceptive limitations and the motor limitations, the human operator is hard to carry out the high precision operation. In experiment 2, we used AMT to assist the operator to perform a high precision manipulation (peg-into-hole).

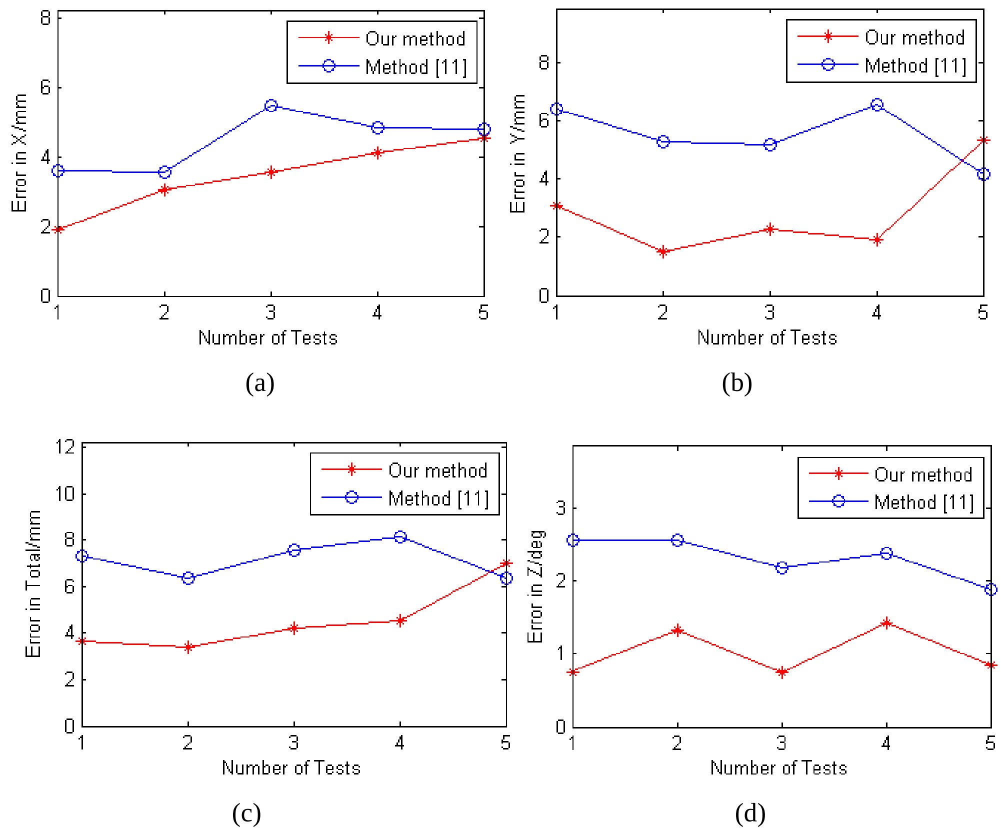

Figure 6. The Comparing Result Of The Experiment

Since the method [11] needs to execute big movements to control the robot manipulator, the operating time of method [11] is longer than that of our method. The mean time of method [11] is 163.8 s, which is more than that of our method (130.6 s)

Table 2. Comparison Of Operation Time

Tests	1	2	3	4	5
Our method	123s	135s	127s	121s	147s
Method [11]	176s	148s	156s	165s	174s

7. CONCLUSION

This paper presents a vision-based manipulation method for robot teleoperation. Through tracking and positioning the operator's hand, the three-dimensional coordinates of the hand are acquired. Utilizing these coordinates, the position and orientation matrix of the end-effector can be achieved to calculate the angle of every joints of the virtual robot using reverse kinematics. The virtual robot is able to grab the object in a way that the operator manipulates the robot naturally and intuitively. Future work may include adding multi-angles reality augmentation and two-dimensional collision detection, in order that the operator can

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manipulate the virtual robot in unstructured environment in a more accurate and safer way.

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