Control System of the Explosive Ordnance Disposal Robot Based on Active Eye-to-Hand Binocular Vision*

Lei Cai[1], Faliang Chang[1], Shaowen Li[3], and Xuexia Zhang[2]

[1] School of Control Science and Engineering, Shandong University, Jinan 250061, China
[2] College of Animal Science, Henan Institute of Science and Technology, Xinxiang 453003, China
[3] Troops 94569, PLA of China, Jinan 250023, China
caileil998@sohu.com

Abstract. Aiming at the disadvantages of manual operation and remote control of the EOD robot and to meet the demand of the technology and tactics, we propose a mobile robotic manipulation system equipped with an active eye-to-hand binocular vision sensor. The active vision system is able to observe arm gesture of a user by visually recognizing features on the arm and reconstructing the arm pose in Cartesian space. The target that is suspicious can thus be identified based on the arm pose. If confirmed, a vision based control law is able to drive the robot toward the target position and to fetch the target by the robotic arm. Experiments indicate that the proposed design of automatic control system is effective.

Keywords: explosive disposal robot, active eye-to-hand binocular vision, control system.

1 Introduction

The research of explosive ordnance disposal (EOD) robot is a hot spot in robot field currently, involving in knowledge in different fields, including mechanic design, the image processing, kinetic control, sensor technology, mechanics of communication etc. EOD robot is a robot that can replace man to reconnoiter, remove and deal with explosives or other dangerous articles in the dangerous environment directly; it can also attack terrorists effectively [1]. It is important to improve the power of antiterrorism and to safeguard the state development of politics and economy.

The EOD robots have been developed for many years in some countries, but for most of the current EOD robots, operator has to operate the buttons on the control panel in order to control and operate every freedom of motion of joints; it is very hard to operate [2]. A robot operating expert has to be familiar with the status of EOD and then judge which motions have to been taken in order to get the manipulator of the robot to a accurate position, a series of buttons have to be operated to realize the

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motions of the arm of the robot, the speed and the continuity lies on familiarity of the operator, which reduces the efficiency greatly [3].

In this paper, we focus on designing and implementing a mobile robot which can help users to retrieve household items. Aiming at the disadvantages of manual operation and remote control of the EOD robot and to meet the demand of the technology and tactics, we propose a mobile robotic manipulation system equipped with an active eye-to-hand binocular vision sensor. Experiments indicate that the proposed design of automatic control system is effective.

2 The Feature and Design of Active Eye-to-Hand Binocular Vision System

2.1 The Feature of Active Eye-to-Hand Binocular Vision System

Visual system works as eyes in an EOD robot; it captures real-time images and passes them to the console. With the images processing, EOD robot computes the position of the suspicious objects accurately, controls itself to be close to the objects and grasp it automatically. At the same time, the visual system lays a solid foundation for the research such as visual navigation and obstacle avoidance; it can also record the process of explosive handling, provide evidence for the police to crack criminal cases. Some features are as follows.

1. *Complexity:* To a general images processing system, cameras are fixed usually, and the distance between the object and cameras is fixed also. But, in EOD robot, cameras are fixed on the paw, because of the unceasing movement of the robot, the paw moves unceasingly too, but the position of cameras and the angle of observation are changing all the time, which gives some difficulties to the processing of images, some ordinary means can not be used [4].

2. *Real-time performance:* The result of images processing is the control information of EOD robot, and visual navigation is based on it [5]. So, the images processing system must be real-time, its speed of processing must be as quick as possible to meet the demand of the system.

2.2 Design of the Control System of EOD

The EOD robot control system is composed of multilayer structures; it comprises main control computer as control system layer, embedded PC/104 computer as motion control layer and DC motor servo control as low layer. We adopt PC, embedded PC/104 computer, ADT650 data acquisition card and 4-route DC motor servo control system in hardware control structure, while adopt Matlab RTW (Real-time Workshop) rapid control prototyping (RCP) method and apply PC target application environment to develop control system model for the EOD robot.

The processing flow of control system is as follows: after obtains the 3D coordinates of the object with binocular vision system, sends the 3D coordinates to the control system in the console, and then sends them to the PC/104 motion control layer by data transmitter-receiver, computes the motion angle of every joint, corresponding pulse count, rotating angle of the motors and the object position, finally, the control system drives the paw to grasp the object.

3 Key Technologies of Active Eye-to-Hand Binocular Vision System

The active binocular vision system is capable of identifying the target by observing the gesture of a user. Specifically, image preprocessing, target and head tracking, and reconstruction of the arm direction are employed as follows.

3.1 Image Preprocessing

The image preprocessing of the proposed vision system consists of two parts, color filtering with connected component labeling and edge detection [6]. Combining with connected component labeling, color filtering can be used to detect the target in the image plane under different lighting conditions according to the color difference between the target and the background. In order to locate the precise target position, edge detection has been further used by

$$g(x, y) = \sum_{i=-a}^{a} \sum_{j=-b}^{b} w(i, j) f(x+i, y+j) \tag{1}$$

where $g(x, y)$ is the edge image, $w(i, j)$ is an $m \times n$ soble mask, $f(x, y)$ is the input image, $a = (m-1)/2$, and $b = (n-1)/2$.

3.2 Target and Head Tracking

Because the target is defined as a green mug, a rectangle template has been created for template matching. Therefore, the target can be detected by finding the smallest d in Eq. (2).

$$d = \sum_{i=-1}^{m} \sum_{j=-1}^{n} T_r(i, j) - f(x, y) \tag{2}$$

where $T_r(i, j)$ is the rectangle template. m and n are the template size.

During the target detection process, the size of the target may be changing due to the movement of the robot. Therefore, the template is also scaled into different sizes for effective matching result.

Similarly, the head detection also uses image preprocessing to filter out the skin color and the edge image. Then, the head can be detected in image space by using ellipse template to find the smallest differences between the template and the real image. The detection system flowchart is shown in Fig. 1.

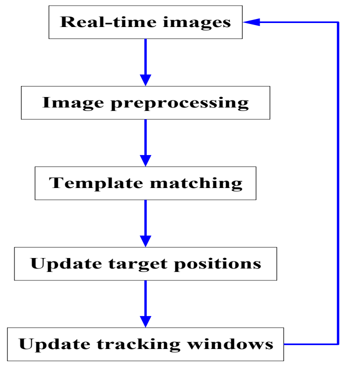

Fig. 1. Flowchart for target and head detection

3.3 Reconstruction of Arm Direction

In this paper, two feature centers of the blue and red segments on the arm of the user are used for identifying the arm pose. Since the position of these features in image space can be detected, the position of the features in Cartesian space, rR (red segment) and rB (blue segment), can thus be calculated by using Eqs. (3) and (4) based on calibrated camera model.

$$A(\theta)r = B(\theta) \tag{3}$$

$$r = \left[A^T(\theta)A(\theta)\right]^{-1} A^T B(\theta) \tag{4}$$

where

$$A(\theta) = \begin{bmatrix} u_1 k_1^T - f_1 i_1^T \\ v_1 k_1^T - f_1 i_1^T \\ u_2 k_2^T - f_2 i_2^T \\ v_2 k_2^T - f_2 i_2^T \end{bmatrix}, B(\theta) = \begin{bmatrix} \left(u_1 k_1^T - f_1 i_1^T\right) c_1 \\ \left(v_1 k_1^T - f_1 i_1^T\right) c_1 \\ \left(u_2 k_2^T - f_2 i_2^T\right) c_2 \\ \left(v_2 k_2^T - f_2 i_2^T\right) c_2 \end{bmatrix},$$

θ denote camera extrinsic parameter vector, c_i is the coordinate of the optical center with respect to the base frame, f_i denotes the focal length, $[u_i, v_i]^T$ denotes the feature's image coordinate, and i_i, j_i and k_i are the columns of the rotation matrix of camera $i, j = 1, 2$.

With the positions of the two features r_R and r_B in Cartesian space, the target searching region in image space can be determined based on the projection of the two features in binocular image space using Eq. (5).

$$G(r)=\begin{bmatrix}u_1\\v_1\\u_2\\v_2\end{bmatrix}=\begin{bmatrix}f_1\dfrac{i_1^T(r-c_1)}{k_1^T(r-c_1)}\\f_1\dfrac{j_1^T(r-c_1)}{k_1^T(r-c_1)}\\f_2\dfrac{i_2^T(r-c_2)}{k_2^T(r-c_2)}\\f_2\dfrac{j_2^T(r-c_2)}{k_2^T(r-c_2)}\end{bmatrix} \tag{5}$$

Since the arm and the target may not both appear in the binocular images, the target searching region determined based on the arm pose must be updated according to the initially detected arm pose and the motion of the active cameras and the mobile robot it self. The system can thus effectively locate the target within the searching region to reduce redundant computation. The procedure to determine target searching region is illustrated in Fig. 2.

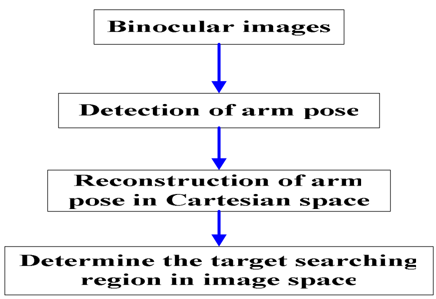

Fig. 2. Procedure to determine target searching region

4 Experiments and Results Analysis

We test the EOD robot with the mode of horizontal grasp which is run automatically, that is to say, the crossing angle between the small arm the robot and the horizontal is zero. When several test points on the X, Y and Z directions are chosen, we can get the trend of the error on the three directions. The best grasp space can be got in the meantime.

4.1 X-Axis Direction

On the X direction, we place some objects before the EOD robot from near to far every 10 cm. Table 1 and fig.3 show that the far the manipulator is on the X direction, the more the error is, therefore, we reach the conclusion that it is better to get near to the object in the course of grasping. On the other hand, because of the field of vision, the value of X can not be too small; otherwise, the robot may not grasp the object or beyond its vision.

Table 1. Experiment data of auto grasp in X-axis

Test No.	Actual coordinates of object(cm)		Final coordinates of paw(cm)		Error of location(cm)		
	X	Y	X	Y	DX	DY	DZ
1	58.2	23.1	55.3	24.6	-0.5	-3.1	1.5
2	65.3	24.1	68.7	23.8	-1.4	-3.4	1.2
3	74.5	19.8	76.8	21.8	-1.9	-2.1	2.1
4	87.3	19.7	86.4	20.6	-2.5	-1.2	1.4
5	92.2	21	97.8	22	-2.6	-1.9	0.9
6	105.3	18.9	112	20	-3.4	-0.3	0.9

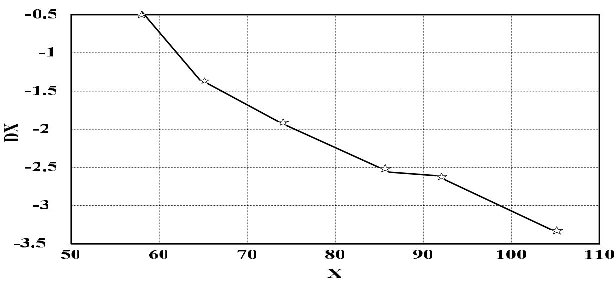

Fig. 3. Error analysis chart in X-axis

4.2 Y-Axis Direction

On the Y direction, we place some objects before the EOD robot from low to high and select 7 test points. Table 2 and fig.4 show that it has the least error when the value of Y is between -10cm and 30cm, the lower or the higher the test point is, the more the error is.

4.3 Z-Axis Direction

On the Z direction (Z direction means that the arm move from left to right or in reverse order), we place some objects right in front of the EOD robot on the line parallel with Z direction every 20 cm and select 7 test points. Table 3 and fig.5 show that the error changes from big to small when move the object from left to right or in reverse order, and after passing the middle position when it is right in front of the robot, the error changes from small to big. Therefore, we arrive at a conclusion that, in the course of grasping, there is the least error when the manipulator is just in front of the robot, otherwise, the error increases.

Table 2. Experiment data of auto grasp in X-axis

Test No.	Actual coordinates of object(cm)		Final coordinates of paw(cm)		Error of location(cm)		
	X	Y	X	Y	DX	DY	DZ
1	58.2	23.1	55.3	24.6	-0.5	-3.1	1.5
2	65.3	24.1	68.7	23.8	-1.4	-3.4	1.2
3	74.5	19.8	76.8	21.8	-1.9	-2.1	2.1
4	87.3	19.7	86.4	20.6	-2.5	-1.2	1.4
5	92.2	21	97.8	22	-2.6	-1.9	0.9
6	105.3	18.9	112	20	-3.4	-0.3	0.9

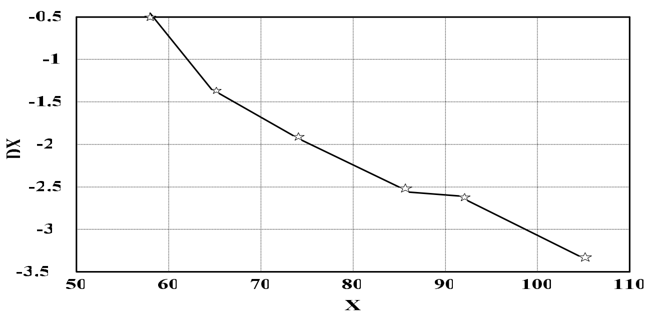

Fig. 4. Error analysis chart in X-axis

Table 3. Error analysis chart in Z-axis

Test No.	Actual coordinates of object(cm)		Final coordinates of paw(cm)		Error of location(cm)		
	X	Y	X	Y	DX	DY	DZ
1(-60)	102.6	20.9	106.4	21.2	-4	-1.6	2.4
2(-40)	92.8	20.8	94.6	23.5	-2	-2.4	2.1
3(-20)	86.7	21	88.2	25.7	-1.5	-4.7	1.7
4(0)	85.1	22.4	85.6	25.8	-0.5	-3.5	1
5(20)	86.5	21.3	87.5	24.1	-1.2	-3	0.5
6(40)	95.2	20.8	98.3	23.3	-3	-2.6	0.9
7(60)	106.3	21.2	110	23	-4	-1.7	1.6

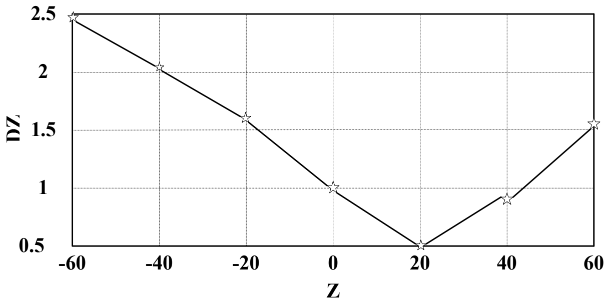

Fig. 5. Error analysis chart in Z-axis

5 Conclusion

Aimed at the disadvantages of manual operation and remote control of the EOD robot, a control system design of a EOD robot based on the binocular vision location is pretended. Apply binocular vision location to EOD robot, the location precision is high and the error is less the 5mm, there is nothing to intervene in the course of grasp. The control system adopts real-time system based on PC target; the method has the advantages such as it is rapid to develop and easy to debug, and it is a strong tool in the development and test of a control system. The successfully and automatically grasp experiments indicates the control system is valid.

In addition, the motion of the manipulator is a control of point to point; our next work is to research the problem such as the track planning of the manipulator and the path planning of robot, so as to solve the problem of speed plan control of the manipulator and obstacle avoiding.

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