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A Novel Visual Servoing Feedback Control of Nonholonomic Wheeled Mobile Robots

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***Abstract*—** Currently, some dynamic tracking controllers have been proposed for nonholonomic mobile robots with the unknown visual parameters and has been proved to stabilize the closed loop systems in theory. However, there is lack of the relevant experiment verification except for several simulations. In this paper, we proposed a novel visual servoing feedback control strategy to make the nonholonomic mobile robot track the given reference trajectory. Firstly, we paste two red rectangles with different areas on the top of the robot as marks. The big area is used to describe the location of the robot, and the other is used to auxiliary calculate the orientation angle. The error between the desired marks' contour feature and the current one on the image plane is regarded as the objective of the tracking control of the robot. Secondly, the dynamic feedback tracking controller is used to calculate the robot velocities and the saturating process on them is necessary. Finally, the result of experiments have shown that the image error of the robot converged to the desired value.

***Keywords—nonholonomic mobile robot; trajectory tracking*;**

contour; Visual servoing feedback;

I. INTRODUCTION

The trajectory tracking control is an important problem of nonholonomic mobile robots, particularly, with the development of image processing techniques, the trajectory tracking control of nonholonomic mobile robot via visual servoing feedback has attracted much attention due to the inherent nonlinearity in robot dynamics and the usefulness in many applications. Over the past decade, visual servoing techniques have been applied in the field of mobile robots and many feedback control laws and modeling method s have been proposed in [2], [3], [4], and more recently in [5].

In [6], an adaptive controller that using the uncalibrated pinhole camera in the ceiling was designed to compensate for uncertain camera and mechanical parameters, but this adaptive law was proposed based on the estimators of the parameters in the different section of a parameter space. In [7] and [8], the adaptive controllers were designed respectively to compensate the unknown depth information and realize asymptotic stabilization and tracking of the robots by decomposing homographic matrix. However, because of the limitation of linear velocity and angular velocity of the practical robot, it was difficult to achieve that purpose. In addition, the homographic matrix decomposition is very complicated, and it is sometimes necessary for human intervention. In [9], the dynamic feedback tracking controller with the unknown visual parameters was designed and strictly proved stability of the whole closed loop system by Lyapunov method. Its calculation is indeed simple, but it lacks of the experimental verification.

A class of important problems about visual servoing feedback control is to track the moving object and extract object's information, such as the location and orientation. The algorithms which are used in moving target tracking consist of CAMShift, Optical flow, contour method, etc. CAMShift is a well-established and fundamental algorithm for kernel-based visual object tracking, in [10] [11]. This algorithm is often used by combining with other algorithm or image process techniques to track the moving targets. However, the process is very complicate, and tracking targets need have regular shapes. Optical flow method is a method that it uses the pixels in the image sequence change in the time domain and the correlation between adjacent frames to find on a frame with the corresponding relationship between the current frame, so as to calculate the movement of the object information between adjacent frames. In [12], this method is used to track moving targets. The effect is very well but the real-time performance is very bad. The contour method is used in [13], and this method is based on the target contours which can be extracted from the video. Its calculation costs low and it can be used to reduce the influence of light and surrounding environment during the tracking. In this paper, we will introduce a method that combine contours method and other image processing techniques to detect robot's position and orientation in the work place. We have implemented the

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proposed method in a (2, 0) mobile robot at the Robot Control Laboratory of University of Shanghai for Science and Technology. Experiments have been carried out to verify the performance of the proposed method.

The structure of this article is as follows: Section II gives an introduction of camera visual model and device description. Section III gives the introduction of controller design. Section IV gives a detailed introduction to the control strategy. In section V, the experiment has been carried out to verify the performance of the proposed method.

II. PREPARATORY WORK

2.1 Device description

In Fig.1, there is a pinhole camera fixed to the ceiling at the Robot Control Laboratory of University of Shanghai for Science and Technology, the type (2, 0) MT-R mobile robot produced by Shanghai ingenious Automation Technology Company is under the camera. We paste two red boards with rectangle but their areas are not equal on the middle of the robot as marks. The big one is used to describe robot's location, denoted by goal B. It is assumed that the center of goal B and the mass center point of robot are identical. The other is used to calculate the orientation angle of the robot, denoted by goal C.

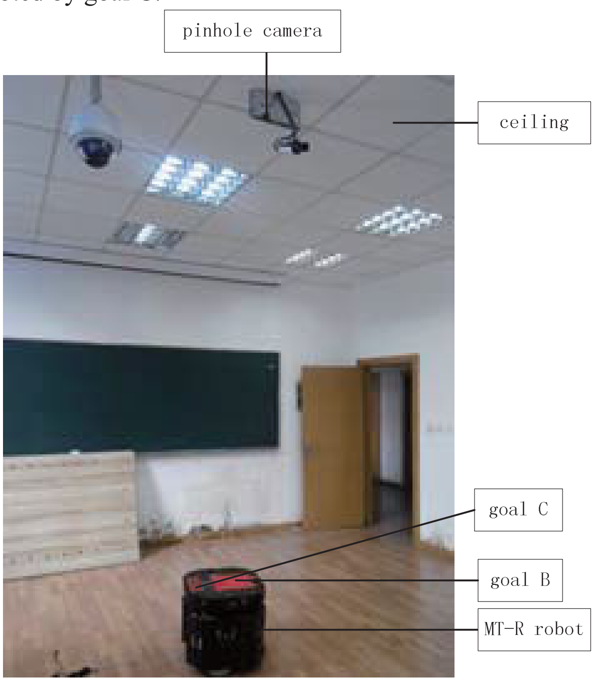

Fig. 1 Experimental set-up

2.2 Camera Visual Model

According to Fig.1, we set up a corresponding camera visual model in Fig.2, the two rear wheels of the robot are controlled independently by motors, and a front castor wheel prevents the robot from tipping over as it moves on a plane. Both wheels have the same radius denoted by r, and 2R is the distance between two wheels. Assume that the camera plane and the robot plane are parallel. There are three coordinate frames, namely the inertial frame $X-Y-Z$, the camera frame $X_1-Y_1-Z_1$ and the image frame $u-o_1-v$. Assume that the X_1-Y_1 plane of the camera frame is identical with the plane of the image coordinate plane. C is the crossing point between the optical axis of the camera and the $X-Y$ plane. Its coordinate relative to the $X-Y$ plane is (C_x, C_y) .The coordinate of the original point of the camera frame with respect to the image frame is denoted by (O_{c_1}, O_{c_2}), (x, y) is the coordinate of the mass center P of the robot with respective to the $X-Y$ plane. Suppose that (x_m, y_m) is the coordinate of (x, y) relative to the image frame. In this work the perspective camera model is used to obtain that [6]

$$\begin{bmatrix} x_m \\ y_m \end{bmatrix} = \begin{bmatrix} \alpha_1 & \\ & \alpha_2 \end{bmatrix} \begin{bmatrix} \cos\theta_0 & \sin\theta_0 \\ -\sin\theta_0 & \cos\theta_0 \end{bmatrix} \left(\begin{bmatrix} x \\ y \end{bmatrix} - \begin{bmatrix} c_x \\ c_y \end{bmatrix} \right) + \begin{bmatrix} O_{c_1} \\ O_{c_2} \end{bmatrix} \quad (1)$$

where, α_1 , α_2 are constants, which are dependent on the depth information, focal length, scalar factors along the u axis and the v axis respectively, θ_0 denotes the angle between u axis and X axis with a positive anticlockwise orientation.

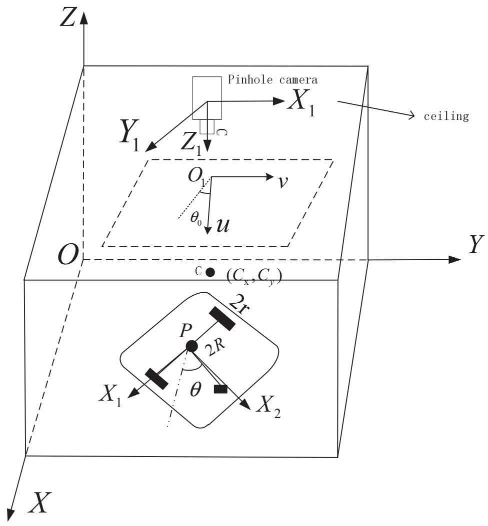

Fig. 2 Camera visual model

III. CONTROLLER DESIGN

The pose of the robot in the inertial coordinate frame $\{O, X, Y\}$ is defined as $q = (x, y, \theta)^T$, where (x, y) is the coordinate of position P , and θ is the orientation angle of robot between the robot frame $\{P, X_1, X_2\}$ and the inertial fame $\{O, X, Y\}$ with a positive anticlockwise direction.

The path to be tracked in this study is given in the image coordinates. Assume that the geometric center point and the mass center point P of the robot are identical. The kinematics of the robot can be modeled by the following differential equations:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} v_1\alpha_1\cos(\theta-\theta_0) \\ v_1\alpha_2\sin(\theta-\theta_0) \\ \omega \end{bmatrix} \tag{2}$$

where v_1 is the forward velocity, ω is the angular velocity of the robot.

Differentiating (1) with respect to time and using (2), in the image frame, we obtain a camera object visual servoing kinematic model:

$$\begin{bmatrix} \dot{x}_m \\ \dot{y}_m \\ \dot{\theta}_m \end{bmatrix} = \begin{bmatrix} v_1\alpha_1\cos(\theta-\theta_0) \\ v_1\alpha_2\sin(\theta-\theta_0) \\ \omega \end{bmatrix} \tag{3}$$

In order to discuss the tracking problem of the system (3), we give a desired trajectory $q_r(t)=(x_r(t),y_r(t),\theta_r(t))^T$, generated by a reference robot whose equation of motion is:

$$\begin{bmatrix} \dot{x}_r \\ \dot{y}_r \\ \dot{\theta}_r \end{bmatrix} = \begin{bmatrix} v_r\alpha_1\cos(\theta_r-\theta_0) \\ v_r\alpha_2\sin(\theta_r-\theta_0) \\ \omega_r \end{bmatrix} \tag{4}$$

where (x_r, y_r) is the desired path of the mass center (x, y) in the image frame, θ_r is the desired direction, v_r and ω_r are the forward velocity and angular velocity of the reference mobile robot respectively. But in experiment, we acquire that information by using the coordinate of goal B and goal C.

In [9], the specific design process and strict proof of dynamic feedback controller have been given, so we only give the control law at here as follow:

$$\begin{cases} \dot{h} = -k_4h - e_1\cos(\theta-\theta_0) - e_2\sin(\theta-\theta_0) \\ v = \begin{pmatrix} v_1 \\ \omega \end{pmatrix} = \begin{cases} v_r + h \\ \omega_r - k_3e_3 + 2v_re_1\dfrac{\sin\frac{e_3}{2}}{e_3}\sin(\dfrac{\theta+\theta_r}{2}-\theta_0) - \\ 2v_re_1\dfrac{\sin\frac{e_3}{2}}{e_3}\cos(\dfrac{\theta+\theta_r}{2}-\theta_0) \end{cases} \end{cases} \tag{5}$$

where $h = v_1 - v_r$, $e_1 = x_m - x_r$, $e_2 = y_m - y_r$, $e_3 = \theta - \theta_r$.

But in actual experiment, the forward velocity and angular velocity calculated by controller sometimes are too large or too small and it does not meet actual speed values of the robot movement. Therefore, in this experiment, considering the actual situation, it had to do the saturation according to the speed of calculated values, and then adjusted robot's position.

IV. CONTROL STRATEGY

a) Extract the threshold value range of targets

In this experiment, a pinhole camera connected to an window7 PC is used to capture image at the rate of 10 fps, the PC connect with the mobile robot via serial port. In order to improve the stability of target tracking, we choose several places where the light intensity change is larger near the desired trajectory, then record marks' area and the pixel values of three-channel of marks' color. The data we collected is shown in table 1.

TABLE I. RANGE OF THRESHOLD

image coordinates	*Area of goal C*	*Area of goal B*	*R*	*G*	*B*
（298.5，74.5）	163.5	796.5	250	71	94
（386.1，93.7）	141	753.5	238	61	86
（420.4，148.3）	155.5	715	247	35	74
（421.4，215.7）	203	936.5	250	60	81
（411.3，281.4）	162.5	753	230	90	82
（299.9，27.3）	174	914.5	231	60	111
（202.2，266.9）	173	796.5	243	34	72
（180.8，193.1）	152	723	229	47	76
（181.5，152）	103	505	233	69	103
（187.9，121.1）	128	637.5	229	16	105
（219.2，92.5）	154	651.5	231	67	111

According to the data in table 1, in order to eliminate light and surrounding effects as much as possible, this article selects the scope of threshold of the three-channels and areas as follows: areas of target B and C are 500 ~ 1000 and 100 ~ 250, values of three-channels R, G, B are 228 ~ 255, 10 ~ 100, 60 ~ 120. Based on the range of R, G, B, we can do adaptive threshold process on pixel values.

b) Target extraction

According to the scope of threshold extracted from the above section, the following image processing is made:

Step 1: Traversal the image pixels' R, G, B values and determine whether the value of three-channels are all in the scope of threshold. If all in, then set that point pixels for full red (0,0,255). If not, set that point pixel for full black(0,0,0).

Step 2: Finding the target contours. Determine whether the area of contour is in the scope threshold of target B or C, if in, keep it, if all not in, remove the outline.

The processed image is shown in figure 3, the large area is target B, and the small area is target C.

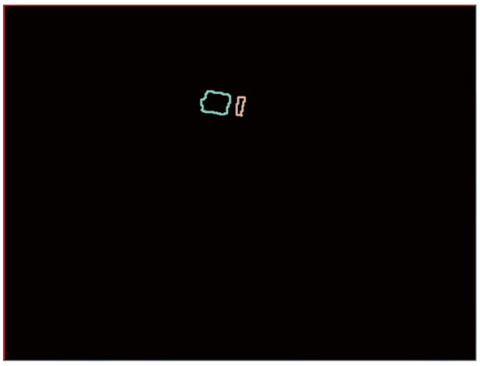

Fig. 3 processed image

c) Extracting the desired trajectory's information

We define the desired trajectory as a circle with its center coordinate (300,190), and radius 100 in image frame. In this paper, the description of desired trajectory is not changed according to time. But according to the coordinate of target B, we use a variable *i* to describe the quadrant which the robot is located in. From the first quadrant to the fourth, three, two, and then return to the first quadrant. The value of *i* is 0, 1, 2, 3, 0, respectively, and robot's orientation is calculated as follows:

$$\theta = 90 * i + \begin{cases} a\tan(\frac{y_{m1} - y_m}{x_{m1} - x_m}) * 180 / \pi & x_{m1} \neq x_m \\ 90 & x_{m1} = x_m \end{cases} \quad (6)$$

where θ is in the scope of 0~360.

No matter whether the robot is moving at the right of y axis or at the left of y axis, the equation of calculating central angle of rotation is the same, and they are all calculated as follows:

$$\beta = \begin{cases} a\tan\left(\frac{y - y_m}{x_m - x}\right) & x_m \neq x \\ 90 & x_m = x \end{cases} \quad (7)$$

According to fig.4, we can acquire desired orientation:

$$\theta_r = 90 * \mathrm{i} + \begin{cases} a\tan(\frac{x_m - 300}{190 - y_m}) * 180 / \pi & y_m \neq 190 \\ 90 & y_m = 190 \end{cases} \quad (8)$$

And the location coordinates are:

$$\begin{aligned} x_r &= 300 + 100 * \cos(\beta) \\ \mathrm{y}_r &= 90 + 100 * (1 - \sin(\beta)) \end{aligned} \quad (9)$$

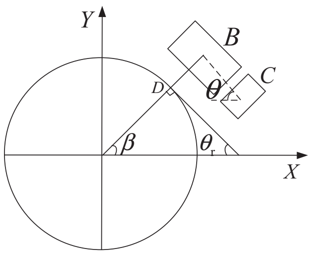

Fig. 4 calculate orientation angle

d) Control strategy

Step 1. System initialization. Judge whether there is a frame input. If yes, then enter next step, else, continue initialization.

Step 2. Capture a frame image and process it on Microsoft Visual Studio 2010, extract target contours and calculate the orientation of the mobile robot.

Step 3. Calculate robot's desired position and orientation on the basis of the coordinate of target B and target C.

Step 4. According to (3), we can calculate error information e_1, e_2, e_3 between actual trajectory and desired trajectory.

Step 5. Judging whether the scope of e_3 is in $(0,5)$. If yes, then continue step 6, if not, the robot will adjust its orientation at current position, and return to step 2.

Step 6. Judging whether the scope of e_1, e_2 are all in the range of $(0,4)$. If they all exceed that scope, then continue step 7, else, continue step 8.

Step 7. Dynamic feedback controller is used to calculate robot's forward velocity and angular velocity. If the angular velocity calculated is higher than 0.035, then set the value of velocity of 0.035. On the contrary, if angular velocity is lower than 0.01, set the velocity value of 0.01.

Step 8. Robot moves at the speed of value we have processed in step 7. Return to step 2, and repeat the same process.

The specific control process are shown in the below figure.

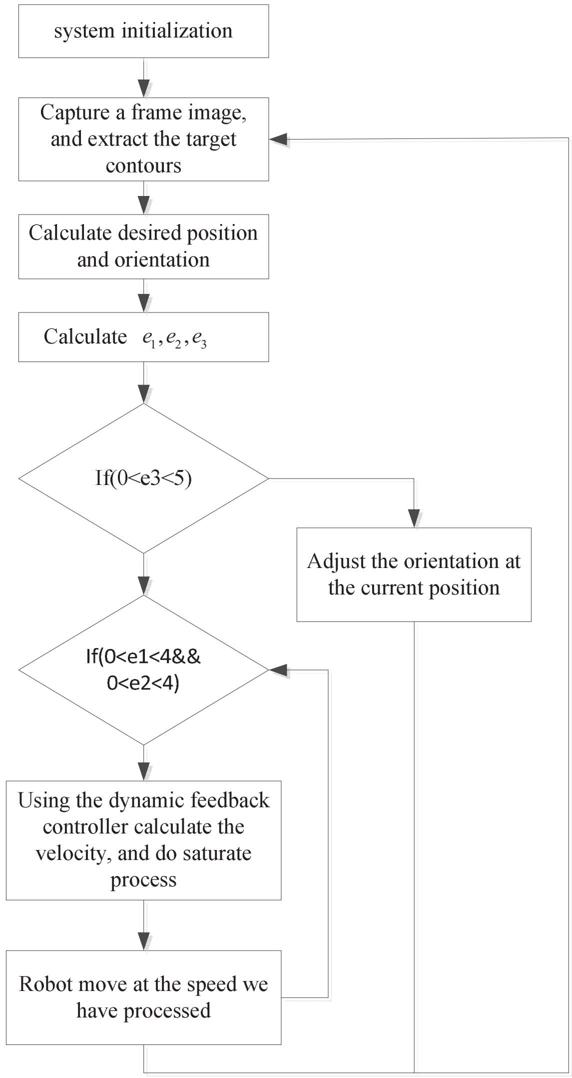

Fig. 5 control process

V. EXPERIMENTAL RESULTS AND ANALYSIS

In this experiment, the initial kinematic errors are $e_1 = 28.75$, $e_2 = 35.18$, $e_3 = 2.67$, the parameters in controller are chosen as $K_{d1} = K_{d2} = 20$, $K_3 = K_4 = 2$, $d_B = 2$, $\delta(t) = \frac{1}{(1+t)^3}$, $\alpha = 1$, $\theta_0 = 0$, $\Gamma = diag\{1,1\}$, $v_r = 0.1m/s$, $\omega_r = 0.02rad/s$, the diameter of two standard wheels is 0.2m, the distance between two motorized standard wheels is 0.4m, and the constant torque is 25.5mNm/A.

In Fig. 5 and Fig. 6, we can see the error curve of the robot's position, the unit of abscissa axis is frame, and the unit of vertical axis is pixel. After 700 frames, robot's position gradually coincided with desired trajectory, but the orientation is not synchronous with the position.

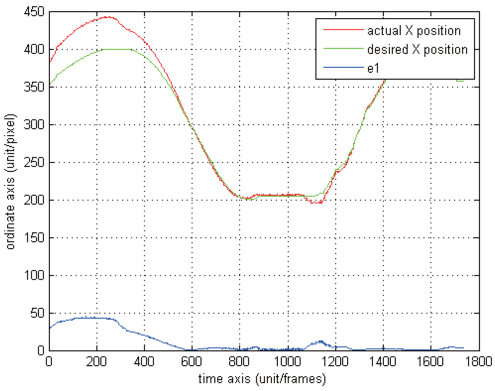

Fig. 5 x position error cureve

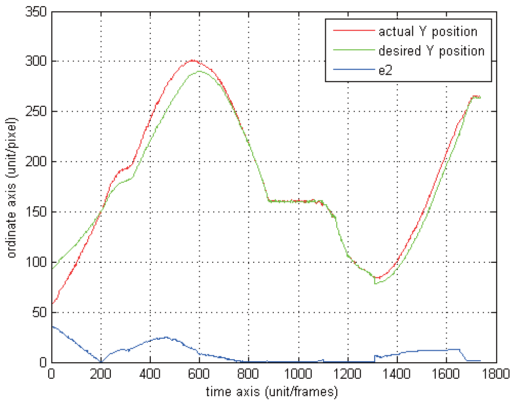

Fig. 6 y position error curve

In Fig. 7, there is a peak at about 200-300 frames because the robot was moving from the first quadrant to the second quadrant, and the robot need adjust its orientation at that time. From 1250 frames to 1350 frames, the reason that the angle error changes too big is that at that time, the robot was moving at third quadrant that the light intensity was too strong and the areas of markers detected in the image were too small or sometime they were not detected in image, as the calculate of orientation were based on markers' location, so the big error changes appeared. When the robot across that area, the orientation gradually coincided with desired orientations.

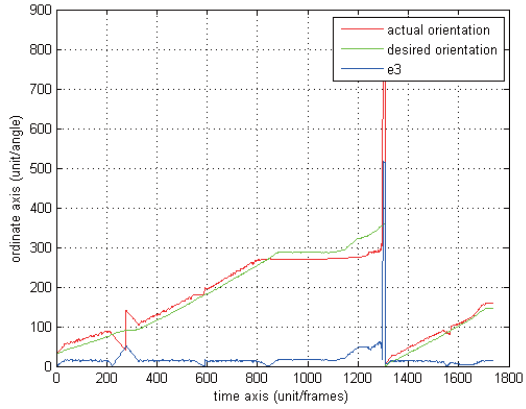

Fig. 7 orientation angle error curve

Fig. 8 reflects the changes of the angular velocity calculated from the dynamic feedback controller, and the robot we used in this experiment can only been controlled by the angular velocity without the forward velocity. When the angular velocity was greater than 0.03, set angular velocity of a value of 0.03. When it was less than 0.01, set angular velocity of a value of 0.01.

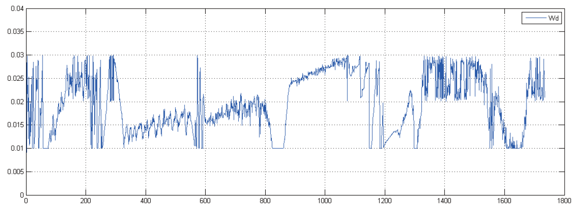

Fig. 8 angular velocity curve

Fig 9 really reflects the effect of the robot trajectory tracking. In this diagram, the error position of robot was less than 5 pixels, and the orientation angle error was less than 5 degrees. Hence the robot was regarded as the achievement of tracking the given reference trajectory gradually.

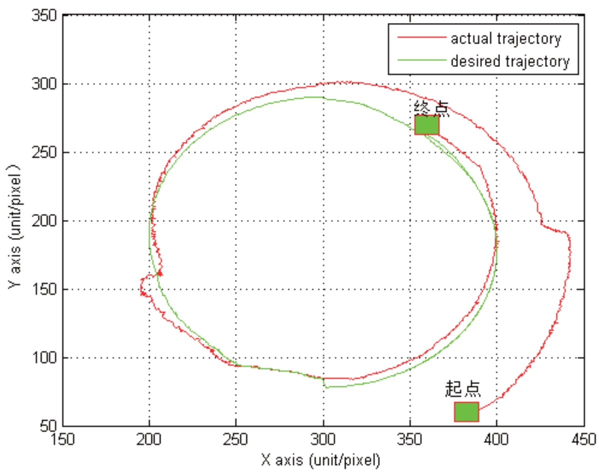

Fig. 9 track trajectory

VI. CONCLUSION

This paper proposed a novel visual servoing feedback control strategy so that the controlled wheeled mobile robot is gradually tracking reference trajectory. In this article, we adopt contour method and other image process techniques to track moving target, and use the position of the robot on the image frame to describe the desired trajectory. On the basis of the forward velocity and the angle velocity of the robot, which were calculated by dynamic feedback tracking controller, we added the saturated process with the angular velocity in case of too high or too low velocity. Experimental results demonstrated the effectiveness of the proposed control strategy. In the future, the algorithm of tracking the moving object and output saturation control need to be improved to get rid of the markers.

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