Robotic Calibration-Free Hand-Eye Coordination Based on Auto Disturbances Rejection Controller[1)]

SU Jian-Bo QIU Wen-Bin
(Institute of Automation, Shanghai Jiaotong University, Shanghai 200030)
(E-mail: jbsu@sjtu.edu.cn)

Abstract A nonlinear mapping model between image and robot space for the robotic calibration-free hand-eye coordination problem is analyzed, and it is viewed as system unmodeled dynamics. Based on the principle of Auto Disturbances Rejection Controller for dynamical system with uncertainty, the robotic calibration-free hand-eye coordination controller is designed through compensating for the non-modeling dynamics and disturbance. This kind of controller, unlike other methods, is independent of specific tasks, and provides a unified approach for uncalibrated robotic visual servoing. Simulation and experiment results demonstrate the effectiveness of this method.

Key words Robot vision, hand-eye coordination, calibration-free, auto disturbances rejection controller

1 Introduction

The essence of the calibration-free approach to hand-eye coordination or visual servoing is to utilize the visual information fed from the camera to plan the robotic control so as to fulfil the prescribed task without any knowledge or with little knowledge of the eye-hand relationship and the camera model. Due to the great potential of the calibration-free eye-hand coordination technology, much research has been done in this area. The basic and the most investigated approach is based on the image Jacobian matrix[1,2]. Since a linear Jacobian matrix is used to approximately describe the nonlinear mapping between the position error in the image space and the robotic control, the Jacobian matrix is changing and needs on-line real-time estimation for the whole workspace as well as during the whole process of task fulfillment. Evidently, an on-line accurate estimation of the Jacobian matrix is the key to the effectiveness of this approach.

Currently, the following problems need to be solved for the estimation of the Jacobian matrix. 1) The estimation methods and procedures depend on the system configuration and the prescribed task, and it is difficult to give a general design theory[3]. 2) The estimation accuracy is related to the position of the manipulator in the workspace as well as the visual field, and no consistent tracking characteristics can be achieved. 3) The current estimation methods have problems such as estimation-lag, singularity, convergence and convergence speed. Especially, in dynamic circumstances, the aforementioned problems become more serious.

The artificial neural network (ANN) is proposed in [4,5] to approximate to the inverse Jacobian matrix to achieve satisfactory positioning with some success. However, the linearity of the Jacobian matrix has restricted the performance of the ANN. Thus, the research on the direct mapping of the nonlinear model from the visual observation error to the robotic control with the use of the ANN[6~8] is a breakthrough in the studies of the calibration-free robotic eye-hand coordination. Unfortunately, since the off-line training of the ANN needs as many training samples as possible from the whole robotic workspace,

1) Supported by National Natural Science Foundation of P. R. China(69875010)
Received March 20, 2001; in revised form May 20, 2002
收稿日期 2001-03-20; 收修改稿日期 2002-05-20

which has resulted in a large workload and a doubtful feasibility. This approach is restricted in practice.

The auto disturbances rejection controller (ADRC) is a nonlinear controller for a system with uncertainty. With estimation of the system's unmodeled dynamics and the external disturbance, and by using the extended state observer (ESO) output and the real-time compensation for the control input, the control for a system with an uncertainty is realized[9,10]. Therefore, in calibration-free robotic hand-eye coordination, if the image Jacobian matrix is regarded as the system's unmodeled dynamics, a controller for robotic eye-hand coordination can be designed based on the principle of the ADRC. On-line compensations for the varying Jacobian matrix with the use of an ESO are then supplied to the controller so that calibration-free robotic eye-hand coordination is achieved. This approach offers a task-free strategy for the estimation of the Jacobian matrix, and effectively solves the aforementioned problems.

This paper analyzes the nonlinear mapping between the image plane and the robotic workspace. The nonlinear mapping is then transformed to an appropriate model form for the ADRC. A controller design is presented for a single-eye robotic tracking. Simulation and experiment results demonstrate the effectiveness of this approach. As is seen, it successfully suppresses the effects of the model uncertainties and system disturbance, and therefore has a strong adaptability and robustness.

2 The visual mapping model

Under the single-eye global visual feedback, the task of the robotic eye-hand coordination is to design a robotic control that makes the target position and the hand position overlap each other in the image by using the error observed between them in the image. Suppose that the hand position is $W=(x_w, y_w, z_w)^{\mathrm{T}}$ in the robotic coordinate system and is $P=(p_x, p_y)^{\mathrm{T}}$ in the image observed by the camera. The target position in the image is $P^* =(p_x^*, p_y^*)^{\mathrm{T}}$, which is also the desired hand position in the image. The relation between the hand position in the image and that in the robotic coordinate system can be expressed as

$$P = g(W) \tag{1}$$

where $g(\cdot)$ is a function representing all the effects caused by the eye-hand relationship model, the robotic manipulator model and the camera model. Differentiation of the both sides of (1) leads to

$$\begin{cases} \dot{W} = U \\ \dot{P} = J(W) \cdot U \end{cases} \tag{2}$$

where $U=(u_x, u_y, u_z)^{\mathrm{T}}$ is the velocity vector in the robotic coordinate system, which is the system control input. $J(W)$ is the Jacobian matrix of $g(W)$. Eq. (2) describes the differential change of the hand position at a certain instant in the image caused by the differential hand motion in the robotic coordinate system. The essence of calibration-free is to estimate at any instant the current Jacobian matrix. Then based on its inverse matrix and the prescribed hand motion in the image, the calculation of the necessary hand motion in the robotic coordinate system is done.

Under the single-eye global visual feedback, U and P are 3-dimensional and 2- dimensional, respectively. Therefore, the Jacobian matrix defined in (2) can be expressed as

$$J(W) = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \end{bmatrix} \tag{3}$$

Then

$$\dot{P} = \begin{bmatrix} \dot{p}_x \\ \dot{p}_y \end{bmatrix} = J(W)U = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \end{bmatrix} \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} \tag{4}$$

That is

$$\begin{cases} \dot{p}_x = J_{11} \cdot u_x + J_{12} \cdot u_y + J_{13} \cdot u_z \\ \dot{p}_y = J_{21} \cdot u_x + J_{22} \cdot u_y + J_{23} \cdot u_z \end{cases} \tag{5}$$

3 Control scheme based on the ADRC

Since the essence of the Jacobian matrix approach is to design an on-line estimation method for the Jacobian matrix, lengthy try-and-error or iterations are used, where the former increases the cost of the system and works only for a static or slow-varying system, and the latter has time-delay, singularity and convergence problems. Their common drawback is that both of them are related to a specific task and lack a general design law.

The Auto Disturbances Rejection Controller (ADRC) is a kind of nonlinear controller for a set of uncertain systems. It generally composes of three parts: the tracking differentiator (TD), the extended state observer (ESO) and the law of nonlinear state error feedback (NLSEF). The TD is used to properly arrange the transient process of the system, while the ESO is used to observe the system output and estimate the system's unmodeled dynamics and the external disturbance. The NLSEF is a nonlinear control law that produces system control from the combinations of system errors of different orders. Through proper selections and adjustments of the functions and parameters in TD, ESO and NLSEF, the ADRC is able to control a set of uncertain systems of the form[6,7]:

$$x^{(n)} = f(x, \dot{x}, \ddot{x}, \cdots, x^{(n-1)}, w(t)) + b_0 u(t) \tag{6}$$

where $f(\cdot)$ is the unknown function, $w(t)$ is the system external disturbance, $u(t)$ is the system control signal, and b_0 is a known constant.

Let us now rewrite the visual mapping model in a form suitable to the ADRC. Suppose, in the robotic workspace, a reasonable estimate of $J(w)$ is

$$\hat{J}(W) = \begin{bmatrix} \hat{J}_{11} & \hat{J}_{12} & \hat{J}_{13} \\ \hat{J}_{21} & \hat{J}_{22} & \hat{J}_{23} \end{bmatrix} \tag{7}$$

System disturbances $\xi_1(t)$ and $\xi_2(t)$ are introduced due to the system model inaccuracy, the errors in image detection and the external disturbance, and then (5) is rewritten as

$$\begin{cases} \dot{p}_x = (J_{11} - \hat{J}_{11}) \cdot u_x + J_{12} \cdot u_y + J_{13} \cdot u_z + \xi_1(t) + \hat{J}_{11} \cdot u_x \\ \dot{p}_y = J_{21} \cdot u_x + (J_{22} - \hat{J}_{22}) \cdot u_y + J_{23} \cdot u_z + \xi_2(t) + \hat{J}_{22} \cdot u_y \end{cases} \tag{8}$$

Suppose

$$\begin{cases} a_x(t) = (J_{11} - \hat{J}_{11}) \cdot u_x + J_{12} \cdot u_y + J_{13} \cdot u_z + \xi_1(t) \\ a_y(t) = J_{21} \cdot u_x + (J_{22} - \hat{J}_{22}) \cdot u_y + J_{23} \cdot u_z + \xi_2(t) \end{cases} \tag{9}$$

(8) can be rewritten as

$$\begin{cases} \dot{p}_x = a_x(t) + \hat{J}_{11} \cdot u_x \\ \dot{p}_y = a_y(t) + \hat{J}_{22} \cdot u_y \end{cases} \tag{10}$$

Thus, the original system is decoupled into two first-order systems, where $a_x(t)$ and $a_y(t)$ are the total system disturbances (including the system's unmodeled dynamics and the external disturbance) in the x direction and the y direction, respectively.

Two ADRC are designed for the control in the x direction and the y direction, respectively. The tracking control in the x direction is taken as the example to demonstrate the design of the ADRC. From (10), we obtain the system equation:

$$\begin{cases} \dot{x}_w = u_x \\ \dot{p}_x = a_x(t) + \hat{J}_{11} u_x \\ y_1 = p_x \end{cases} \tag{11}$$

where p_x is the system state variable, y_1 is the system output, and u_x is the control input. When $p_x^*(t)$ is the system input, design the ADRC as follows:

$$\begin{cases} \dot{z}_{1\_x} = -r_x fal(z_{1\_x} - p_x^*, \alpha_{0\_x}, \delta_{0\_x}) \\ \varepsilon_{0\_x} = z_{2\_x} - p_x \\ \dot{z}_{2\_x} = z_{3\_x} - b_{1\_x} fal(\varepsilon_{0\_x}, \alpha_{1\_x}, \delta_{1\_x}) + \hat{J}_{11} u_x \\ \dot{z}_{3\_x} = -b_{2\_x} fal(\varepsilon_{0\_x}, \alpha_{2\_x}, \delta_{2\_x}) \\ \varepsilon_{1\_x} = z_{1\_x} - z_{2\_x} \\ u_{0\_x} = k_{0\_x} fal(\varepsilon_{1\_x}, \alpha_x, \delta_x) \\ u_x = u_{0\_x} - z_{3\_x}/\hat{J}_{11} \end{cases} \tag{12}$$

where

$$fal(\varepsilon, \alpha, \delta) = \begin{cases} |\varepsilon|^{\alpha} \mathrm{sign}(\varepsilon), & |\varepsilon| > \delta \\ \varepsilon/\delta^{1-\alpha}, & |\varepsilon| \leqslant \delta \end{cases} \tag{13}$$

Similarly, the controller in the y direction can be designed. The overall system control diagram is given in Fig. 1, where b_0 is corresponding to $\hat{J}_{11}$ and $\hat{J}_{22}$ in the x direction and y direction, respectively.

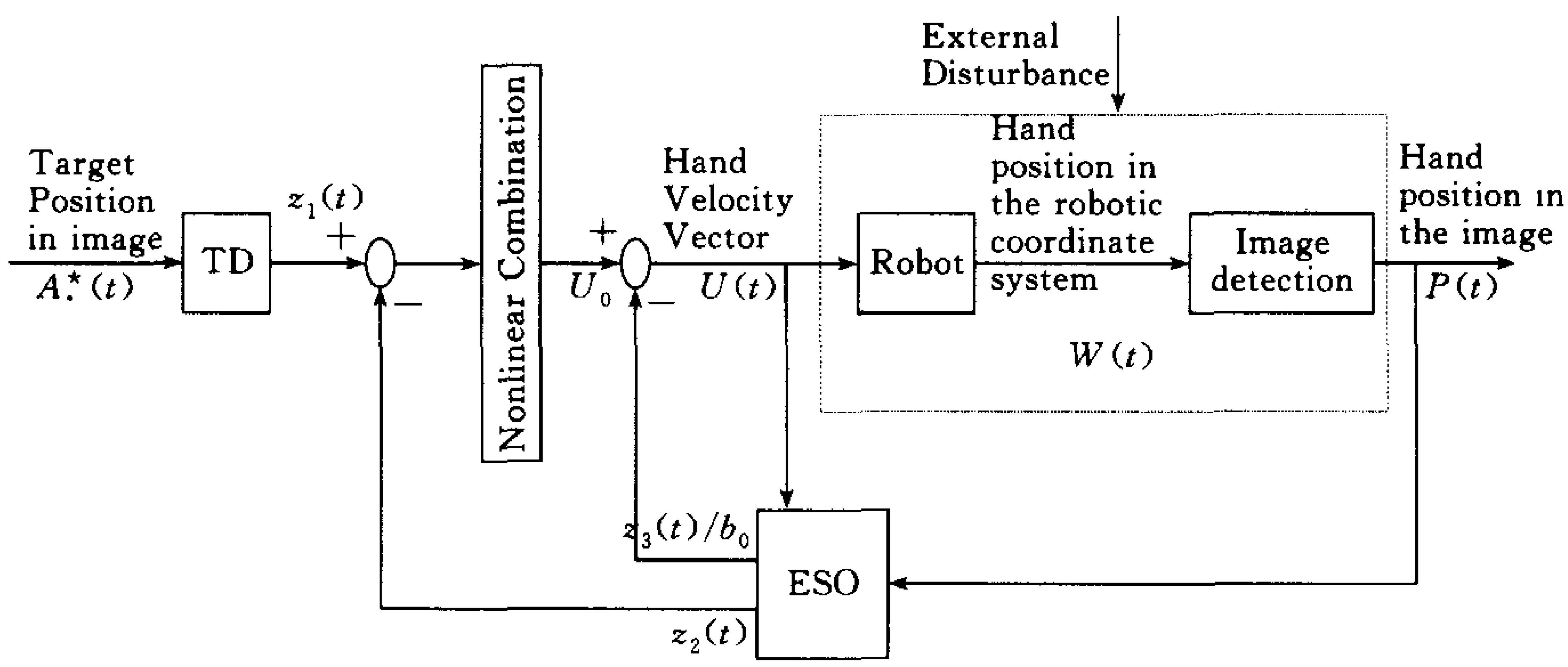

Fig. 1 The ADRC—based structure of calibration—free robotic hand—eye coordination

4 Simulations and experiments

4.1 Simulations

In our simulations, the camera focal length $f=6$mm, the camera image plane quantization resolution are $N_x=4.9/582$mm/pixel and $N_y=3.7/512$mm/pixel. Define the center of the image plane as the origin of the coordinate system. The rotational angles of the camera pose with respect to the robotic base coordinates are $\psi=80°$, $\theta=-70°$ and $\varphi=-160°$ and the translational movement vector is $T=[40, 10, 1500]^{\mathrm{T}}$mm.

The initial positions of the hand and the target are at the origin and at the coordinates (0, 150) in the image plane, respectively. The target is making a circular movement, which is unknown to the robotic controller.

$$\begin{cases} p_x^*(t) = 150\sin(t/5) \\ p_y^*(t) = 150\cos(t/5) \end{cases} \tag{14}$$

Suppose that the external disturbance in both the x and y directions are normal distributed random noise with a maximum magnitude of ± 5 pixels and a zero average. Same ADRCs with same control parameters are used in both the x and y directions. The parameters selected are shown in Table 1. The system response is given in Fig. 2.

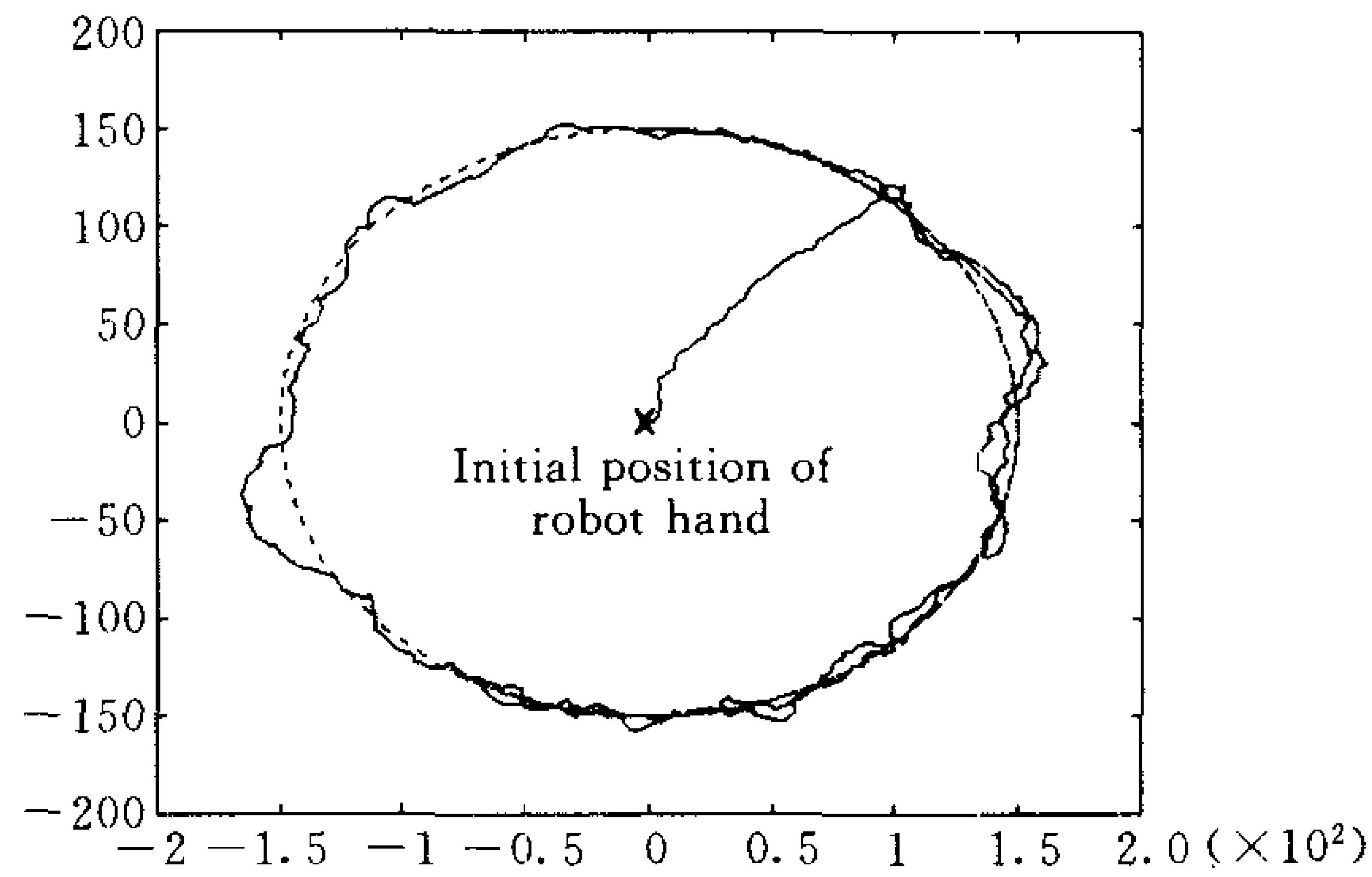

Fig. 2 The tracking trajectory of the hand in the image plane with the ADRC to track a planar moving object

Table 1. The ADRC parameters used in the simulation

TD			ESO						NLSEF			Est. of b_0	
α_0	δ_0	r	α_1	δ_1	b_1	α_2	δ_2	b_2	α	δ	k_0	$\hat{J}_{11}$	$\hat{J}_{22}$
0.5	0.1	10	0.1	1	10	0.1	2	60	0.1	10	30	0.9	0.9

It is seen from Fig. 2 that the hand can catch up and track the target quickly. Fig. 2 also shows that the tracking in the x direction presents a rather large error systematically, which occurs when the direction of the movement of the x component is changing.

4.2 Experiments

In our experiments, the robotic hand is to reach the target in the workspace, which is now a plane. When the error between the position of the hand image and that of the target image is within a certain range, the task is done. The camera is fixed above the plane where the robotic manipulator works so that it can observe both the manipulator and the target. Same order and structure of ADRCs are used in both the x and y directions. In order to overcome the larger tracking error in the x direction, the parameters for each of the directions in the ADRC are selected differently and empirically as shown in Table 2 and Table 3, respectively. Fig. 3 and Fig. 4 show the example of the system response and the control input in the x direction, respectively.

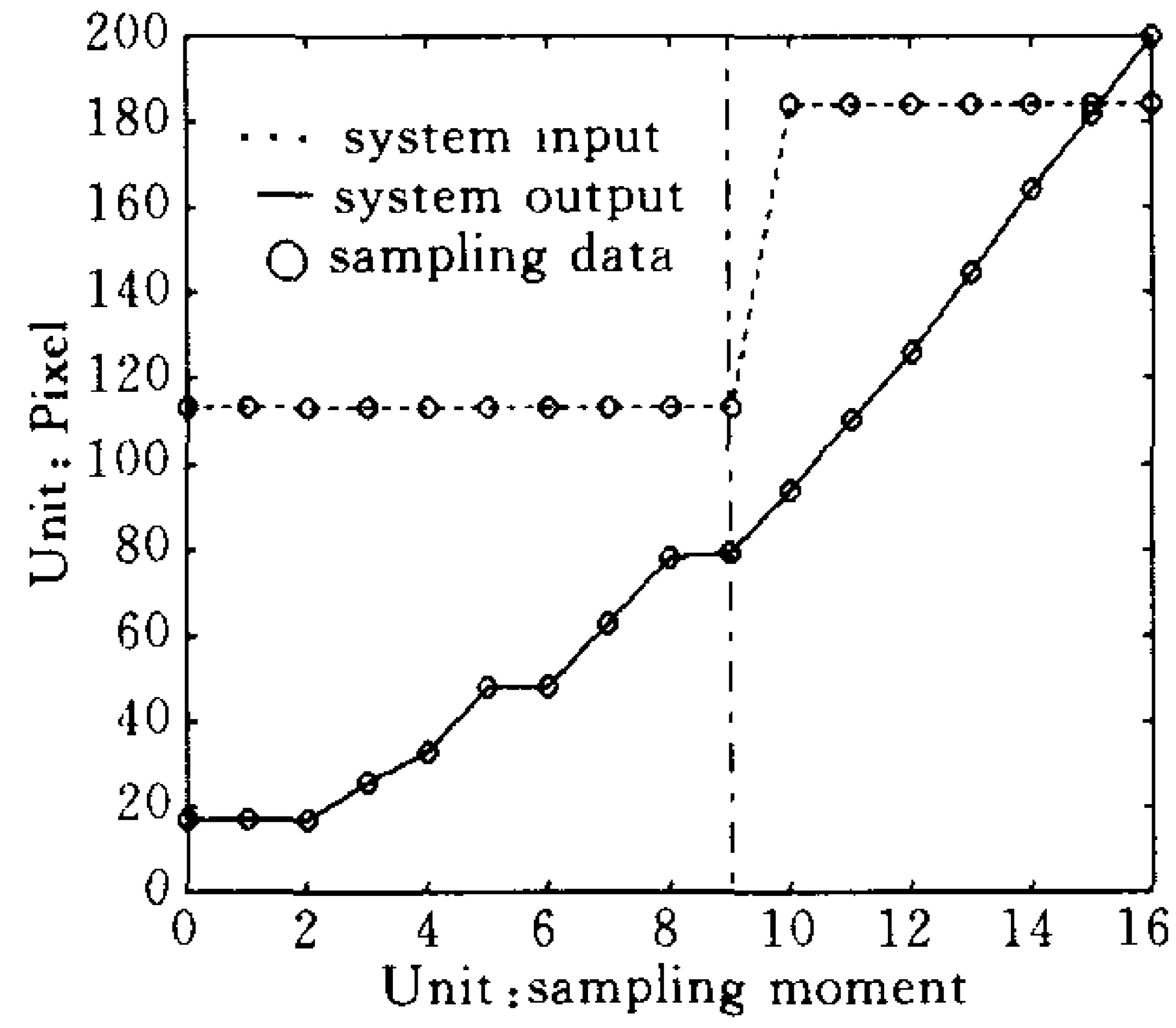

Fig. 3 System response in the x direction

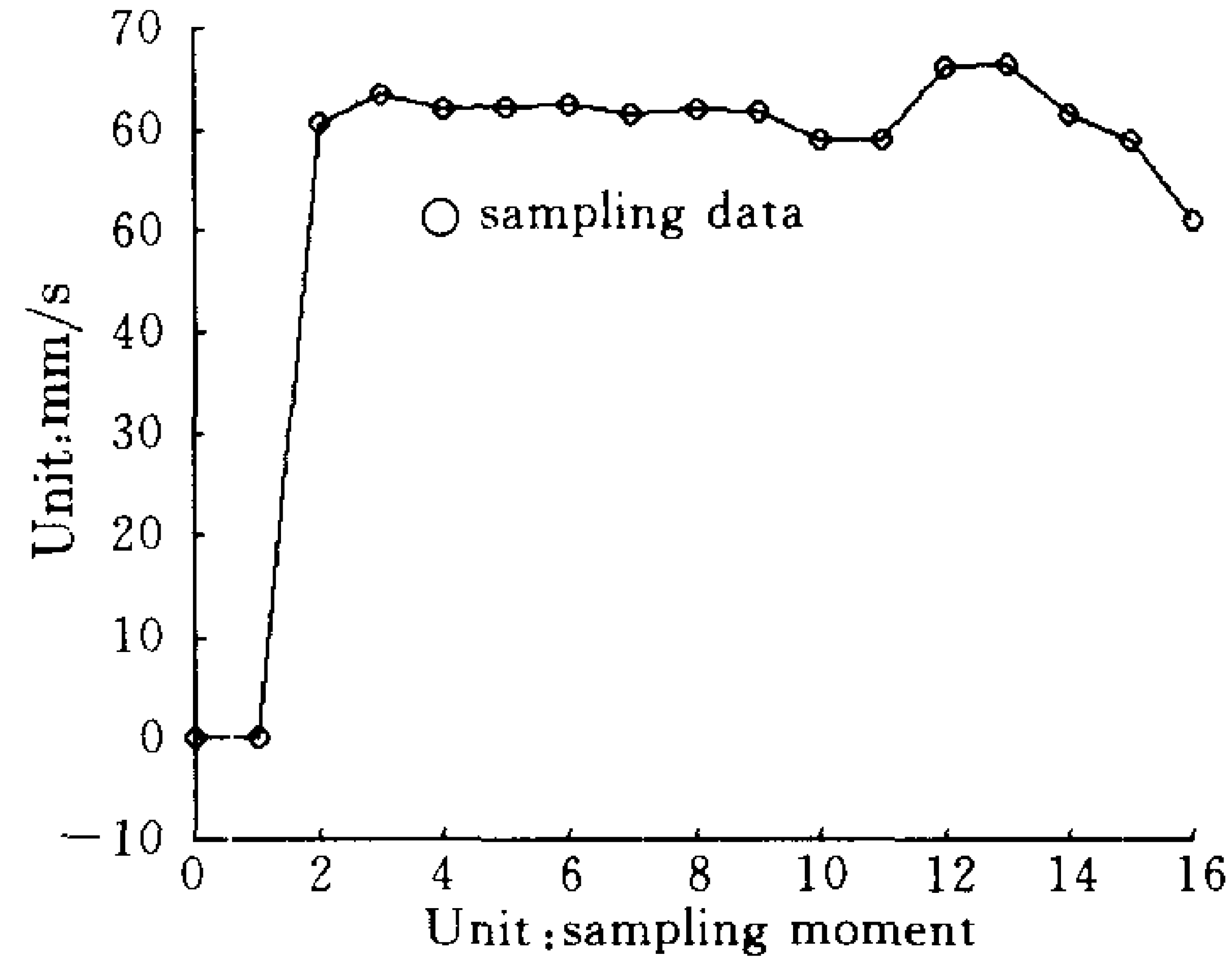

Fig. 4 System control in the x direction (the velocity of the gripper)

Table 2 The ADRC parameters for x direction used in the experiment

TD			ESO						NLSEF			
α_0	δ_0	r	α_1	δ_1	b_1	α_2	δ_2	b_2	α	δ	k_0	$\hat{J}_{11}$
0.5	15	130	0.1	8	80	0.1	8	100	0.1	10	400	0.4

Table 3 The ADRC parameters for y direction used in the experiment

TD			ESO						NLSEF			
α_0	δ_0	r	α_1	δ_1	b_1	α_2	δ_2	b_2	α	δ	k_0	$\hat{J}_{22}$
0.5	10	100	0.1	8	150	0.1	8	200	0.1	8	320	0.6

Fig. 5 demonstrates the motion trajectory of the hand in the image. During the 0～9 sampling periods, the target is always still at (113, 108). The initial position of the hand is at (17, 4). At the 9^{th} sampling instant, the hand is at (71, 79), which is close to the target, and the target is moved to a new position (184, 212) (in this neighborhood, there is another target position seen, which is the instant target position taken by the camera during the motion). Then the hand keeps on moving toward the new target position. At the 16^{th} sampling instant, the hand moves to (200, 207). The position difference between the hand and the target is now smaller than the prescribed threshold. The system then believes that the hand has arrived at the target position and the motion stops. In the whole process, both the control inputs and the hand tracking movements are smooth, which confirms the effectiveness of the parameter selections.

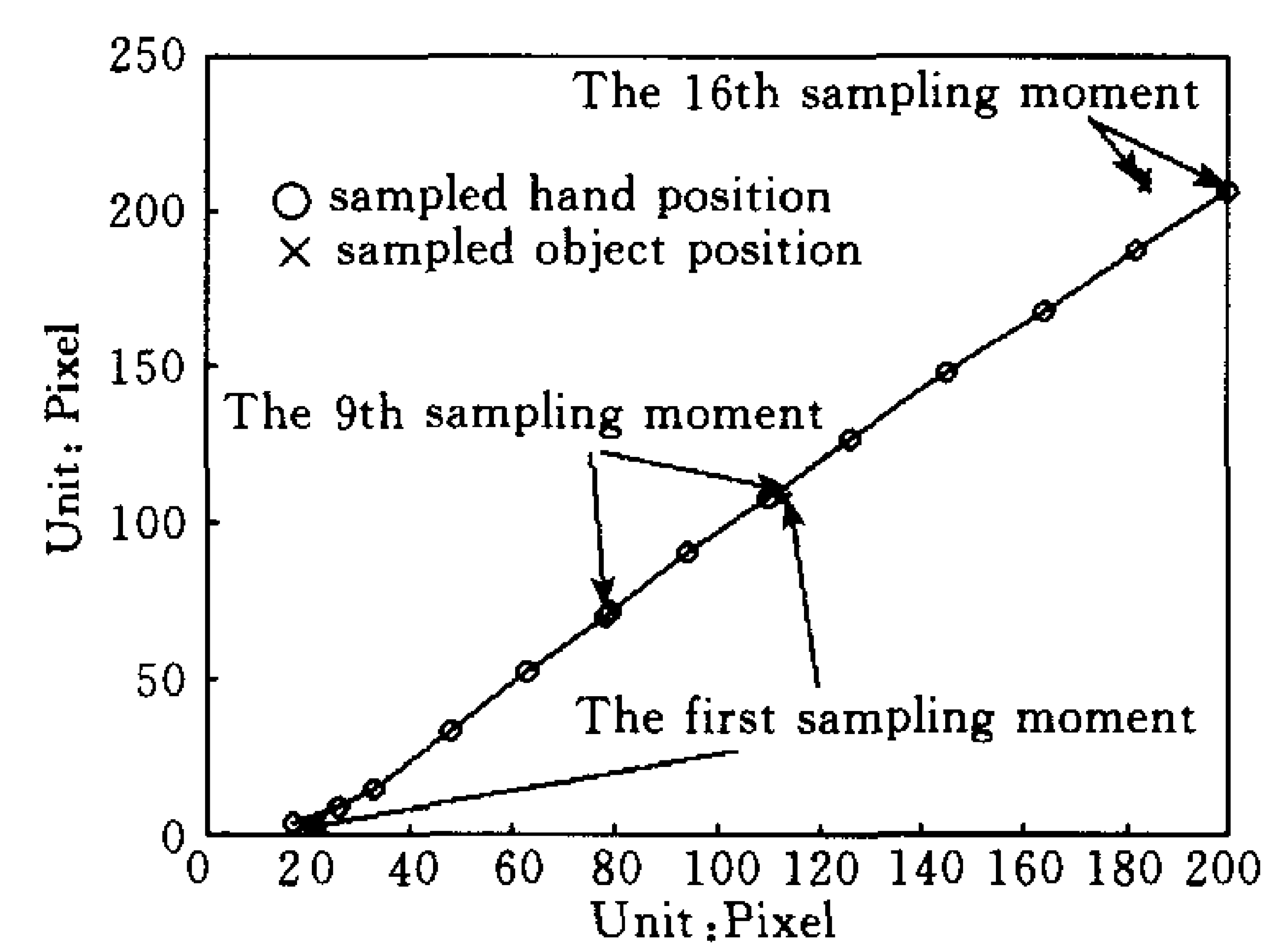

Fig. 5 The tracking trajectory of the hand in the image plane

5 Conclusion

A new approach based on the principle of the ADRC is proposed for calibration-free robotic eye-hand coordination without any knowledge of eye-hand relationship and camera parameters. This approach is different from the conventional control strategy for calibration-free robotic eye-hand coordination, and it is based on the Jacobian matrix in the sense that the estimation of Jacobian matrix is independent of specific tasks and system configuration, thus has a general meaning. A typical case is analyzed in this article. The design procedure of the ADRC for calibration-free robotic eye-hand coordination is presented. Simulations and experiments demonstrate that this approach suppresses the effects of the external disturbance, and therefore has a strong adaptability and robustness.

The future work lies in the studies of the further application of the ADRC theory in the calibration-free robotic eye-hand coordination control, especially the application of the ADRC in the case that the robotic model itself is unknown.

References

1 Hager G D, Chang W C, Morse A S. Robot feedback control based on stereo vision: Towards calibration-free hand/eye coordination. In: Proceedings of 1994 IEEE International Conference on Robotics and Automation. San Diego, California, USA: IEEE Computer Society Press, 1994. 2850～2856

2 Yoshimi B H, Allen P K. Alignment using an uncalibrated camera system. *IEEE Transactions on Robotics and Automation*, 1995, **11**(4):516～521

3 Su J B, Xi Y G. Image tracking for a 3-D moving object based on uncalibrated global visual feedback. *High Technology Letters*, 2000, **10**(7):85～87 (in Chinese)

4 Hashimoto H, Kubota T, Sato M, Hurashima F. Visual control of robotic manipulator based on neural networks. *IEEE Transactions on Industrial Electronics*, 1992, **39**(6):490～496

5 Stanley K, Wu Q M J, Jerbi A, Gruver W A. Neural network-based vision guided robotics. In: Proceedings of 1999 IEEE International Conference on Robotics and Automation. Detroit, Michigan, USA: Omnipress, 1999. 281～286

6 Pan Q L, Su J B, Xi Y G. Uncalibrated 3D robotic visual tracking based on stereo vision. *Robot*, 2000, **22**(4):293～299(in Chinese)

7 Pan Q L, Su J B, Xi Y G. Uncalibrated 2D robotic visual tracking based on artificial neural network. *Acta Automatica Sinica*, 2001, **27**(2):194～199(in Chinese)

8 Pan Q L, Su J B, Xi Y G. Eye-in-hand 3D robotic visual tracking without calibration. *Acta Automatica Sinica*, 2002, **18**(3):371～377(in Chinese)

9 Han J Q. The extended state observer of a class of uncertain systems. *Control and Decision*, 1995, **10**(1):85～88 (in Chinese)

10 Han J Q. The auto disturbances rejection controller and its applications. *Control and Decision*, 1998, **13**(1):19～23 (in Chinese)

11 Sutanto H, Sharma R, Varma V. Image based autodocking without calibration. In: Proceedings of IEEE International Conference on Robotics and Automation, Albuquerque, New Mexico, USA: Omnipress, 1997. 974～979

12 Hsu L, Aquino P L S. Adaptive visual tracking with uncertain manipulator dynamics and uncalibrated camera. In: Proceedings of the 38th Conference on Decision & Control, Phoenix, Arizona, USA: Omnipress, 1999. 1248～1253

SU Jian-Bo Received his Ph. D. degree from Southeast University, Nanjing, P. R. China in 1995. From 1995 to 1997, he was a postdoctoral research fellow in the Institute of Automation, Chinese Academy of Sciences, Beijing, P. R. China. Now he is a professor and the director of the Department of Automation, Shanghai Jiaotong University, Shanghai, P. R. China. His research interests include sensor-based robotics, multi-robot coordination, multi-sensor data fusion, etc.

QIU Wen-Bin Received his master degree from the Department of Automation, Shanghai Jiaotong University in 2001. His research interests are robotic hand-eye coordination, image processing, etc.

基于自抗扰控制器的机器人无标定手眼协调

苏剑波　　邱文彬

（上海交通大学自动化研究所　上海　200030）

（E-mail: Jbsu@sjtu.edu.cn）

摘　要　研究机器人无标定手眼协调问题.分析了图像空间到机器人操作空间之间的非线性映射关系,并把非线性的映射关系看成是系统的未建模动态.基于自抗扰控制器思想,通过对系统未建模动态和外扰的补偿,完成了不依赖于任务的无标定手眼协调控制器的设计,实现了广泛意义的机器人无标定手眼协调控制.仿真和实验结果表明了该方法的有效性.

关键词　机器人视觉,手眼协调,无标定,自抗扰控制器

中图分类号　TP24