A Fuzzy Adaptive PD Controller Based Microassembly System

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ABSTRACT

Proportional control based visual controller is the main method used in the visual serving, but small proportional gain results in the slowly response and large proportional gain will result in large overshoot or make the system instable. A PD visual controller for microassembly system is presented to acquire better dynamic response. The fuzzy logic is applied to tuning the controller gains which is a model free method. Thus, the difficulty in obtaining precise and detailed system model is avoided and we can get satisfactory performance which is robust to modeling error and external disturbances. Furthermore, image moments are selected as visual features to avoid image singularities and the Jacobian matrix is full rank and upper triangular, thus it has the maximal decoupled structure and simplified the controller. A series of simulations are performed on peg and hole assembly to investigate the feasibility and effectiveness of this method.

Keywords: Microassembly, visual servoing, fuzzy adaptive PD controller

1. INTRODUCTION

Today, as more microelectromechanical systems (MEMS) are commercially available, the cost and complexity of equipment, as well as the level of human skills required to assemble such devices has also increased. Therefore, automated assembly of MEMS has become a necessary technology in order to reduce manufacturing costs, and increase production volume [1]. Due to small size of these parts, the conventional MEMS fabrication technique can not meet these demands. Vision is a robotic sensor because it provides dense information about the task space while being a noncontact sensing modality, and thus machine vision technique has been utilized in microassembly[1][2], Especially the visual servoing technique has become a main research method [3].

Visually servoed assembly has been shown to effectively compensate for uncertainty in the calibration of camera-lens systems, manipulators, and workspaces. Our microassembly task is to insert a micro peg to a hole and the approach to visual servoing is an image-based one. The advantage of image-based visual servoing is that it eliminates the need to perform an explicit inverse perspective projection mapping [4]. For image-based systems the error is defined on the image plane, and the manipulator control input is typically defined either in joint coordinates or in task space coordinates. Therefore, it is necessary to relate changes in the image features to changes in the position of the object. The image Jacobian captures these relationships.

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The visual controller can derive the velocity control law based on the inverse Jacobian that will produce the desired change in the image [5]. The objective of the visual controller is to make the image error converge to zero and is the key issue in the high performance visual servoing system. Up to now simple proportional control law is used in most of the visual servoing system. However, small proportional gain results in slow response whereas large proportional gain will result in large overshoot or make the system even unstable. Therefore, it is difficult to acquire better dynamic response only with proportional control law. In this paper in order to avoid these problems we apply a PD visual controller to microassembly system. In the proposed controller the proportional part makes the system respond faster and the differential part can improve the dynamic performance.

Over the years, many techniques have been suggested for tuning of the PD parameters. Among them, the model-based tuning method appears to be very encouraging [6]. In real situations, however, highly precise and detailed modeling of the system is often difficult to achieve, because various uncertainties such as modeling error and external disturbances are involved in the system. Due to these difficulties, the PD controllers are rarely tuned optimally based on the system model and the engineers need to settle for a compromise performance. To this end a fuzzy adaptive PD visual controller is designed, based on the feature position error and the change of feature error, the PD parameters are tuned on line by fuzzy rules, thus we can get satisfactory performance which is robust to modeling error and external disturbances. The proposed controller is applied to the microassembly of micro peg and hole, and simulation is performed to investigate the feasibility and effectiveness of this method.

This paper is organized as follows: in Sec. 2, we introduce our microassembly system setup and task description. In Sec. 3, Fuzzy adaptive PD controller design using image moments as visual features is introduced. Sec.4 describes simulation results for the peg-in-hole task. Finally, Sec.5 provides a conclusion for the paper.

2. SYSTEM SETUP AND TASK DESCRIPTION

Fig. 1(a) shows the configuration of the proposed system, which is equipped with a zoom lens, an auto-focusing unit, a four-axis stage and a CCD camera. The micro peg is fixed on the microgripper, while the MEMS-fabricated structure with micro hole is laid on the four-axis micro motion stage. The four degrees of freedom motion with instantaneous visual information feedback makes it possible to achieve an accurate alignment between the peg and hole. The

Figure 1 Visual servoing system

motorized zoom lens has 0.5x to 2x magnification. An auto-focusing stage is powered by a stepping motor driver and controlled by a programmable multi-axis controller. The rotation stage and the Z stage are supplied by Physik Instrumente, which is controlled by a plug-in control board. The resolution for X and Y stages is 3 μ m, while the resolution of Z stages is 0.03 μ m. The resolution for the rotation stage is 32 μ rad.

Our microassembly task is to insert the micro peg to the hole. For simplicity, the micro peg held by the griper is located on the optics axis and in the focus plan, which can be achieved by autofocus process. The distance between the peg and hole is estimated by the depth from focus technique that is described in [2]. We assumed that the tilting angle mismatch between the peg and hole is negligibly small, during the assembly process, the stage has a constant motion along Z axis, so in this paper we only research the accurate alignment between the peg and hole. With instantaneous visual information feedback, the stage will move the micro hole towards the peg and make an accurate alignment between them. This process can be achieved by three-axis micro motion stage that are two translation axes X and Y and one rotation axis Z. The coordinates system is shown in Fig.1(b), where $X^W - O^W - Y^W$ represents the world coordinates system and $X^C - O^C - Y^C$ represents the camera coordinates system and $u - v$ represents the image plane.

3. FUZZY ADAPTIVE PD CONTROLLER DESIGN

3.1 Image moments as visual features for visual servoing

The application of the image moments as visual features to image based visual servoing is interesting since they are generic, whatever the object shape complexity, they can be computed easily from a binary or a segmented image. They have intuitive meaning since the low order moments are directly related to the area, the centroid and the orientation of the object in the image. The most important objective of using moments in visual servoing is to try to determine features that can avoid the image singularities that may appear when conventional redundant image point features are used.

The analytical form of the interaction matrix or image Jacobian matrix related to any image moments was determined in [7]. Here we briefly recall the basic definition of image moments and give a general analytical form of their interaction matrix, and then visual features using image moments are selected to align the micro peg and hole.

We denote $R(t)$ the observed object in the image at time t which defined by a set of closed contours. The origin moments m_{ij} of order $i + j$ are defined by

$$m_{ij} = \iint_{R(t)} x^i y^j dx dy \quad (1)$$

The centered moments of order $i + j$ with respect to the centroid of the object are defined by

$$\mu_{ij} = \iint_{R(t)} (x - x_g)^i (y - y_g)^j dx dy \quad (2)$$

where x_g and y_g are the centroid of the object.

The interaction matrix or image Jacobian matrix describes the time variation of the moments with respect to the relative kinematic screw $V = (v, \omega)^T$, where $v = [v_x \ v_y \ v_z]^T$ and $\omega = [\omega_x \ \omega_y \ \omega_z]^T$ represent the translational and rotational velocity, respectively.

$$\dot{m}_{ij} = J_{m_{ij}} V, \quad \dot{\mu}_{ij} = J_{\mu_{ij}} V \quad (3)$$

where $\mathbf{J}_{m_y}$ is the image Jacobian matrix with respect to the origin moments and $\mathbf{J}_{\mu_y}$ the image Jacobian matrix

with respect to the centered moments. The details of the interaction matrix are explained in [7].

For peg and hole alignment task, three degrees of freedom stage including two translation motions and one rotation motion shown in Fig.1(a) with instantaneous visual information feedback makes it possible. Three moments based visual features are selected to provide visual information feedback. They are x_g and y_g which are the center of gravity of an object in the image, and the object orientation α . These three visual features are defined by origin and centered moments given as follows:

$$x_g = \frac{m_{10}}{m_{00}}, \quad y_g = \frac{m_{01}}{m_{00}}, \quad \alpha = \frac{1}{2} \arctan\left(\frac{2\mu_{11}}{\mu_{20} - \mu_{02}}\right) \quad (4)$$

In our configuration the object surface is parallel to the image plane. A simple form of image Jacobian $\mathbf{J}$ related to the three features is given by

$$\mathbf{J} = [\mathbf{J}_{x_g}, \mathbf{J}_{y_g}, \mathbf{J}_{\alpha}]^T = \begin{bmatrix} f/z_g & 0 & -y_g \\ 0 & f/z_g & x_g \\ 0 & 0 & 1 \end{bmatrix} \quad (5)$$

where z_g is the depth of the gravity center. The matrix presents partially decoupling properties, since it is upper triangular. So the image singularities problem is solved since the Jacobian matrix is full rank all the time.

3.2 PD controller design

Fig.2 shows the principle diagram of the image based visual servoing system, the objective of the visual servoing system is to move the object to the desired position where the object position is measured by the camera. The image Jacobian is used to relate the motion of the stage systems to the variation of feature in camera image with respect to time. This relation implies that if the rate of the feature vector motion is known, the motion of the stage can be specified with respect to camera coordinates. With the known relationship between the motion velocity and the image feature change, we can determine the stage velocity at any control instant that can lead to reaching a desired image feature vector.

For the case of the fixed camera system, we obtain the following relationship between the velocity of the stage motion and the feature change obtained in image coordinates.

$$\begin{bmatrix} \frac{dx_g}{dt} \\ \frac{dy_g}{dt} \\ \frac{d\alpha}{dt} \end{bmatrix} = \begin{bmatrix} f/z_g & 0 & -y_g \\ 0 & f/z_g & x_g \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix} \quad (6)$$

where $\mathbf{f} = [x_g, y_g, \alpha]^T$ is the visual features using image moments with respect to the image plane,

$\mathbf{u} = [v_x, v_y, \omega_z]^T$ is the velocity vector which is the defined as the control input.

If we define the error function as $\mathbf{e} = \mathbf{f}_d - \mathbf{f}_c$ and the change of the error as $\Delta \mathbf{e}$, where $\mathbf{f}_d$ is the desired feature vector and $\mathbf{f}_c$ is the current feature vector. The PD control law is given by

$$\mathbf{u}(k) = k_p \mathbf{J}^{-1} \mathbf{e}(k) + k_d \mathbf{J}^{-1} \frac{\Delta \mathbf{e}(k)}{T_s} \quad (7)$$

where k is the k th time step. T_s is the time interval, k_p and k_d are the control gains which will be tuned by the following algorithm.

Figure 2 Control diagram of the 3 DOF visual servoing system

3.3 Controller parameters tuning method using fuzzy logic

The parameter of the PD controller affects the control performance, so the optimization of the parameter is important to get the satisfactory dynamic performance. In real application, highly precise and detailed modeling of the system is often difficult to achieve, so the modeling error or uncertainty exists that will affect the control performance and limit the application of model free tuning method. During the past several years fuzzy logic has emerged as one of the most effective method to deal with the effects of these uncertainties. The combination of the conventional PD controller with fuzzy logic produces the fuzzy PD controller where the fuzzy logic is used to tune the PD gains online [8]. In this paper, a fuzzy adaptive PD visual controller is applied to visual servoing, based on the feature position error and the change of feature error, the PD parameters are tuned on line by fuzzy rules, and thus we can get satisfactory performance which is robust to modeling error and external disturbances.

As shown in Fig.2, the fuzzy adaptive PD visual controller comprises two parts, one is the conventional PD controller which is described by Eq.(7), and another part is the fuzzy section which has a supervisory role in tuning the gains of the PD controller during the system operation. The input vector to the fuzzy system is the error (e) and the change of error (Δe), and the output vector is the incremental values of the proportional and the derivative gains (Δk_p and Δk_d).

The fuzzy section of the PD controller comprises three blocks that are the fuzzifier, the fuzzy inference rules and defuzzifier block. The fuzzifier block fuzzifies the error and the change of error. In visual servoing the error and its change are in the image domain. Scaling and quantization constitute the fuzzification of the error and the change of error. The quantization of the error and the change of error require all the fuzzified values to remain within a certain range which is from Negative large (NL) to Positive large (PL). The fuzzy set "Error (e)" and fuzzy set "The change of error (ec)" have seven members that are {NL, NM, NS, ZO, PS, PM, PL}, respectively. The membership function is shown in Fig.3(a) Given the fuzzy rules, fuzzified error and change of error, a fuzzified output is produced using the compositional rule of inference. The fuzzy rules for tuning the controller gains are given in Table 1 and Table 2. The

fuzzified output is defuzzified by the defuzzification method and then Δk_p and Δk_d are obtained. There are many types of implication functions and defuzzification methods. The max-product implication function with the centre of gravity defuzzification method is used in this paper. The max-product implication function and the centre of gravity defuzzification method are shown by

Table 1 The fuzzy rules for Δk_p

Δk_p	ϵc	NL	NM	NS	ZO	PS	PM	PL
ϵ								
NL		PL	PL	PM	PM	PS	ZO	ZO
NM		PL	PL	PM	PS	PS	ZO	NS
NS		PM	PM	PM	PS	ZO	NS	NS
ZO		PM	PM	PS	ZO	NS	NM	NM
PS		PS	PS	ZO	NS	NS	NM	NM
PM		PS	ZO	NS	NM	NM	NM	NL
PL		ZO	ZO	NM	NM	NM	NL	NL

Table 2 The fuzzy rules for Δk_d

Δk_d	ϵc	NL	NM	NS	ZO	PS	PM	PL
ϵ								
NL		PS	NS	NL	NL	NL	NM	PS
NM		PS	NS	NL	NM	NM	NS	ZO
NS		ZO	NS	NM	NM	NS	NS	ZO
ZO		ZO	NS	NS	NS	NS	NS	ZO
PS		ZO	ZO	ZO	ZO	ZO	ZO	ZO
PM		PL	NS	PS	PS	PS	PS	PL
PL		PL	PM	PM	PM	PS	PS	PL

$$\mu_r(x, y) = \mu_A(x) \cdot \mu_B(y) \quad (8)$$

$$y_o = \frac{\sum_{r=1}^n \bar{y}^r \mu_r(\bar{y}^r)}{\sum_{r=1}^n \mu_r(\bar{y}^r)} \quad (9)$$

where a fuzzy subset A with elements x has a membership function $\mu_A(x)$ and a fuzzy subset B with elements y has a membership function $\mu_B(y)$, $\mu_r(x, y)$ is the resultant of the max-product implication function, y_o is the defuzzified output, $\bar{y}^r$ is the mean value of the membership function μ_r , r ($r=1, 2, \dots, n$) denote the r th fuzzy rule. The membership functions of the output variables are shown in Fig.3(b). Getting Δk_p and Δk_d , then the descaled output is added to the PD gains to readjust them by

$$k_p(i) = k_p(i-1) + C_p \cdot \Delta k_p(i) \quad (10)$$

$$k_d(i) = k_d(i-1) + C_d \cdot \Delta k_d(i) \quad (11)$$

where i is the time instant, C_p and C_d are the descaling coefficients for the proportional and derivative gains, respectively.

4. SIMULATION OF VISUAL SERVOING

Based on the motor-stage system in section 2, we simulate the system to evaluate the performance of the controller. The structures of these three axes are similar and so we use the same transfer function to represent these axes. The simulation diagram is shown in the block diagram as shown in Fig.2. The following transfer function is used to describe the motor-stage system in simulation.

Figure 3 Membership function of input and output

$$G(s) = \frac{127.4 s^2 - 2.817 \cdot 10^4 s + 1.193 \cdot 10^7}{s^3 + 1501 s^2 + 2.0218 \cdot 10^5 s + 1.176 \cdot 10^7} \quad (12)$$

We use four corners coordinates to constitute the object image and then the moments can be computed from the four corners. In simulation, the coordinate transformation from the world coordinates system to the image plane is shown as

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = M_2 M_1 \begin{bmatrix} X^w \\ Y^w \\ 1 \end{bmatrix} \quad (13)$$

$$\text{where } M_1 = \begin{bmatrix} \cos \Delta \theta^w & -\sin \Delta \theta^w & \Delta x^w \\ \sin \Delta \theta^w & \cos \Delta \theta^w & \Delta y^w \\ 0 & 0 & 1 \end{bmatrix}, \quad \begin{cases} \Delta \theta^w = \theta^w(k) - \theta^w(k-1) \\ \Delta x^w = x^w(k) - x^w(k-1), \\ \Delta y^w = y^w(k) - y^w(k-1) \end{cases}, \quad M_2 = \begin{bmatrix} m & 0 & u_0 \\ 0 & m & v_0 \\ 0 & 0 & 1 \end{bmatrix},$$

In the above equations M_1 expresses the transformation from the world coordinates system to the camera plane coordinates system, and M_2 is the projection matrix which gives the relationship between the image and the pixel coordinates in the homogeneous coordinates space, m is a fixed scale factor that related to the camera parameters, (u_0, v_0) are the center of the pixel coordinates system.

The adaptive fuzzy PD controller is applied to the microassembly systems. Given the initial gains of PD controller $k_p = 10$ and $k_d = 0.5$, the fuzzy logic is applied to adjust the controller gains online which is explained in Sec.3. The simulation results are shown in Fig.4(a)~(d). Fig.5 and Fig.6 show the tuning process of gains k_p and k_d . The gains are adjusted using fuzzy inference according to the error and the change of error, where we do not need the system model or accuracy model. To show that the fuzzy adaptive controller is robust to modeling error and external disturbances, another simulation is performed where the disturbance is added to the system during operation and the results are shown in Fig.7(a)~(d). Fig.8 and Fig.9 show the tuning process of gains k_p and k_d while the disturbance exists. According to simulation results, it is shown that the fuzzy adaptive PD controller provides satisfactory performance no matter the

modeling error and external disturbances exists or not. Furthermore, image moments are selected as visual features instead of point coordinates which are mostly used in visual servoing. These independent visual features can avoid image singularities that might cause control instabilities, where the Jacobian matrix is full rank and upper triangular, thus it has the maximal decoupled structure and simplified the controller.

Figure 4 Simulation results based on fuzzy adaptive PD controller

Figure 5 Tuning process of gain k_p

Figure 6 Tuning process of gain k_d

(a) Image-plane feature motion

(b) Control input

(c) Image moments error

(d) Stage motion of the three axes

Figure 7 Simulation results based on fuzzy adaptive PD controller with disturbance

Figure 8 Tuning process of gain k_p with disturbance

Figure 9 Tuning process of gain k_d with disturbance

5. CONCLUSIONS

Instead of proportional control based visual controller, a PD visual controller for microassembly system is presented in this paper to acquire better dynamic response. The fuzzy logic is applied to tuning the controller gains which is a model free method. Thus, the difficulty in obtaining precise and detailed system model is avoided. Based on the feature position error and the change of feature error, the control gains are tuned on line by fuzzy rules, therefore we can get satisfactory performance which is robust to modeling error and external disturbances. Furthermore, image moments are selected as visual features to avoid image singularities and then the Jacobian matrix is full rank and upper triangular, thus it has the maximal decoupled structure and simplified the controller.

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