A Novel Piezoelectric Micro-gripper's Control Based on Modified Smith Predictor

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Abstract—**We develop a micro-gripper that actuated by piezoelectric cantilever for the need of micro parts assembly. The displacement-voltage relationship model is given in this paper. For hysteresis of piezoelectric ceramic, a control scheme based on fuzzy adaptive PID with a Modified Smith Predicator for the control of micro-gripper is proposed. The results of micro-assembly prove that the model is efficiency and feasibility.**

Keywords-piezoelectric cantilever modeling; micro gripper; modified Smith predictor; fuzzy adaptive PID

I. INTRODUCTION

We must design the end-effecter for micro-surgery, IC assembly. Since the size of the object is generally micrometer or nanometer level, the design of the end-effecter has become an important research topic in the field of micro manipulation, with the requirement with a flexible attitude adjustment, positioning, capture, release and other operations. As the requirements of high-precision positioning for operational objects, the displacement control of end-effecter becomes an important prerequisite for automatic micro-assembly[1].

However, the Piezoelectric micro-gripper exists hysteresis and the control is non-linear. Japan Tanikawa , who proposed H_∞ controller to achieve the robustness control and the hysteresis compensation for two-finger micro hand, but it is difficult to obtain a fast system response. Paper [2] [3] [4]apply the typical Preisach model to compensate the impact of the piezoelectric hysteresis, but it has a litter effect; In the paper[5], it established a flexible hinge of the piezoelectric hysteresis model, the control model is simple and control is better, but closed-loop control is not achieved.

For the above problem, In this paper, we build the relationship model of displacement and voltage of piezoelectric-driven micro-gripper, and we propose the hybrid PID control algorithm based on Modified Smith Predicator feedforward compensation control for hysteresis[6]-[9]. The Micro-assembly has been proved effective control of the model structure, and have good reliability and validity..

II. THE STRUCTURE OF MICRO-GRIPPER

We employ the piezoelectric micro-gripper that uses the curved type piezoelectric bimorph cantilever as finger, two fingers with symmetrical structure. In order to achieve micro-power testing, the piezoelectric bimorph paste the strain gauge. From the analysis of materials mechanics, the cantilever root has the greatest moment when press an external force for the end of the cantilever. So we paste the strain gauges in the root of the bimorph cantilever to obtain the maximize strain signal. The micro-gripper is shown in Fig 1.

As a result of the two-finger symmetry structure, we can employ a single piezoelectric bimorph cantilever beam characteristics to study.

III. THE RELATIONSHIP MODELING BETWEEN DISPLACEMENT AND VOLTAGE OF MICRO-GRIPPER

The Piezoelectric bimorph cantilever beam is used two parallel piezoelectric ceramic to paste with the opposite polarization. The structure is shown in Fig.2. we ignores the thickness of the middle layer.

As the beam length is much greater than its width and the second stress tensor of cantilever is T2 = T3 = T4 = T5 = T6 = 0; the strain tensor is S1, S2, S3, S4, S5, S6 ≠ 0. So according to the first piezoelectric equation[7], we can obtain the strain of piezoelectric layer S1:

$$S_1 = s_{11}^E T_1 + s_{12}^E T_2 + s_{13}^E T_3 + ... + d_{31}E_3 = s_{11}^E T_1 + d_{31}E_3 \quad (1)$$

Where s_{ij}^E (i = 1,2,3, j = 1,2,3) is the elastic compliance coefficient in the constant electric field E; and d_{31} is the piezoelectric strain coefficient of piezoelectric body; and E_3 is the electric field. Then the piezoelectric layer T1 stress tensor is:

$$T_1 = (s_{11}^E)^{-1} S_1 \pm (s_{11}^E)^{-1} d_{31}E_3 = E_p S_1 \pm E_p d_{31}E_3 \quad (2)$$

Where E_p is the elastic modulus. In Fig.2, we set the origin coordinates of center cross-section of piezoelectric ceramics, y is the distance from the center, l is the width of beam cross-section, h is the thickness of each piezoelectric ceramic.

According to the moment balance equation of the material mechanics

$$M = \int_{h_{up}} T_1 l dy + \int_{h_{down}} T_1 l dy = 0 \qquad (3)$$

then

$$\int_{-h}^{0} (E_p y \rho + E_p d_{31} E_3) l y dy + \int_{0}^{h} (E_p y \rho - E_p d_{31} E_3) l y dy = 0 \quad (4)$$

where ρ is the type plane curvature when the cantilever is pure bending deformation.

We use the $E_3 = U/h$ into (4):

$$\rho = \frac{3 E_p d_{31} U}{2 E_p h^2} \qquad (5)$$

where U is the piezoelectric ceramic voltage.

Can see from the disturbing degree equation: $\ddot{y}(x) = \rho$, the relationship model between y and voltage U is:

$$y = \frac{3 E_p d_{31} U}{4 E_p h^2} l_{pze}^2 \qquad (6)$$

Where l_{pze} is the length of the cantilever free-end.

IV. HYSTERESIS MODELING AND MODIFIED SMITH PREDICTOR

As the complexity of piezoelectric ceramic structure and working mechanism, the external electric field strength and the piezoelectric ceramic displacement, strain have been the creep, hysteresis and non-linear and other undesirable characteristics, as shown in Fig. 3.

The crystal polarization effect causes generally hysteresis. However, the hysteresis is a negative factor for high precision positioning control. Therefore, we design Fuzzy PID closed loop control algorithm based on the smith predictor.

A. The Principle Diagram of Smith Predictor

Fig.4 shows the principle of. The control system consists of controller $G_c(S)$, predictor $G_m(S)(1-e^{-rs})$, control object $G_o(S)e^{-rs}$.

Under condition of predictor model matching object model, namely, $G_o(S) = G_m(S)$, The transfer function of control system can be represented as (7).

$$\Phi(s) = \frac{G_c(S) G_o(s) e^{-\tau s}}{1 + G_c(S) G_o(s)} \qquad (7)$$

It can be seen from (7) that delay link e^{-rs} is not located in close loop control link, meaning that hysteresis delay can

not affect the stability of control system. Delay link e^{-rs} defers only time r for control system and the control performance is same as the object model with transfer function $G_o(S)$. Therefore, Smith predictor eliminates the hysteresis delay and improves the performance.

B. Fuzzy Adaptive PID Control with a Modified Smith Predictor

Generally, the structure of position based micro-gripper can be constructed as Fig.5. Firstly, Control system obtains object position r(s) and end-effector position c(s) using image processing. Secondly, employs the trajectory planning as feedback to predict the next movement for manipulator. In real task, although robotic current position can be obtained from joint feedback, we need that estimate relative position of object and end-effector for calibration error, position estimation error and system error. So, we present a control scheme based on fuzzy adaptive PID with a modified smith predicator to offset hysteresis[10]-[12].

The structure with modified smith predictor is shown in Fig.6. We give that the transfer function of micro-gripper is Gr and the transfer function of PID controller is G with Kp,Ki,Kd from fuzzy deduction. $G_m(S)(1-e^{-rs})$ is the transfer function of smith predictor. D is the transfer function of disturbance. M is a new added the transfer function of disturbance rejection. It can be seen from Fig.4 that control system is a standard smith predictor when M is lacked in system structure.

The response of control system can be written as (8) when meets $G_m(S) = G_r(S)$:

$$C(S) = T_1(S) R(S) + T_2(S) D(S) \qquad (8)$$

where

$$T_1(S) = \frac{G_m G e^{-rs}}{1 + G_m G} \qquad (9)$$

$$T_2(S) = \frac{[1 + G_m G - G_m G e^{-rs}] G_m e^{-rs}}{(1 + G_m G)(1 + M G_m e^{-rs})} \qquad (10)$$

According to (9), Characteristic equation has not delay link, then PID controller can be decided only by system itself. In addition, the response of disturbance can be also controlled only by the new-added controller M. It has been shown[10] that the smith predictor gives a steady state error under disturbances for open loop unstable process. Clearly, the new-added controller M can improve the system performance of disturbance rejection. Next, the control process based new structure will be given.

In the micro-operations, the piezoelectric bimorph cantilever can be modeled by mass - spring - damper system. The system can be characterized as follows:

$$m\ddot{x} + c\dot{x} + kx + F_{hy} = F \qquad (11)$$

Where m is the mass of the bimorph cantilever beam, c is damper, the k is the stiffness; F , F_{hy} is the self-generated force of piezoelectric bimorph and the produced force during the process of hysteresis respectively; x is the displacement of cantilever deflection.

Therefore, we can use the improved smith predictor to build the produced force during the process of hysteresis:

$$\frac{dq}{dt} = Aq\frac{dx}{dt} + Bu\frac{dx}{dt} \qquad (12)$$

$$F_{hy} = Cq \qquad (13)$$

$$A = \begin{bmatrix} 0 & 1 \\ -(\frac{2\pi}{T})^2 - (\frac{2}{T}\ln(\frac{P_{n-1}}{P_n}))^2 & -sgn(dx/dt)\frac{2}{T}\ln(\frac{P_{n-1}}{P_n}) \end{bmatrix} \qquad (14)$$

$$B = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \qquad (15)$$

$$C = [G((\frac{2\pi}{T})^2 + (\frac{2}{T}\ln(\frac{P_{n-1}}{P_n}))^2) \quad sgn(dx)S] \qquad (16)$$

Where u is the input voltage, T is the second-order damped response oscillations period, P_n is the amplitude of deviation from second order oscillation steady-state response , G is the DC voltage gain, S is the initial slope.

Then (11) can be written as second-order damped oscillation system:

$$\begin{cases} \dot{x} = Rx + Su + WF_{hy} \\ y = Qx \end{cases} \qquad (17)$$

C. Parameter Identification and PID Closed Loop Control

Assume that the system is less damping system,

$$\xi = 0.04 \quad A = \begin{bmatrix} 0 & 1 \\ -0.02 & -0.052 \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$
$$C = [4.02 \quad 0.011]$$

Therefore, we can determine the system parameters of (17).

We design a two DOF controller based fuzzy adaptive PID control law for micro-gripper.

The fuzzy adaptive PID controller applies error e and error change ec as its input. Then, we build a fuzzy rule table based

practice experiences, which gives the counterpart relationship between Kp,Ki,Kd and error e , error change ec. So, we can revise online control system parameters. (18) shows the revised computation formula.

$$\begin{aligned} K_p &= K_p^* + \{e_i, ec_i\}_p \\ K_i &= K_i^* + \{e_i, ec_i\}_i \qquad (18) \\ K_d &= K_d^* + \{e_i, ec_i\}_d \end{aligned}$$

Then, the control output can be represented as (19).

$$u(t) = \hat{J}_v^{-1}(t) \cdot u'(t) = \hat{J}_v^{-1}(t) \cdot [K_P\tilde{\xi}(t) + \beta K_I \sum_{j=0}^{t} \tilde{\xi}(j)T + K_D \frac{\tilde{\xi}(t) - \tilde{\xi}(t-1)}{T}] \qquad (19)$$

Where $u(t)$ is the control output of controller in task space and $\hat{J}_v(t)$ is jacobian matrix.

V. EXPERIMENT

Now, we use the piezoelectric bimorph cantilever as the experimental object. Young's modulus is $E = 7 \times 10^{10} \, \text{N/m}$, the beam size is $40 \times 2 \times 0.2 \, \text{mm}^3$

We can obtain the relationship of micro-gripper displacement and voltage according to the ideal model: $y = 2V$

Piezoelectric bimorph drive power increments from 0V to 75V, while measures the displacement of the free end of piezoelectric bimorph. When reach the maximum voltage and then decrements gradually voltage. After repeated measurements, we can draw the curve as shown in Fig.7. It can be seen from Fig.7 that in theory-driven displacement and driving voltage is linear, but it is a big delay when the voltage increments process and the voltage decrements process.

Joining the feedforward Fuzzy PID closed loop controller based the modified smith predictor; the system linearity is improved significantly, and compensates the hysteresis characteristics of the piezoelectric actuator. Then, we test the tracking experiments based the proposed method. Fig.8 shows the tracking results of fuzzy PID controller. Fig.9 shows the tracking error using feedforward fuzzy PID closed loop controller based modified smith predictor. We can seen from the Fig.8 that the feedforward fuzzy PID closed loop controller based modified smith predictor is better, inhibited significantly the hysteresis effect of piezoelectric cantilever beam.

VI. CONCLUSION

We developed a micro-gripper based on piezoelectric, and established the relationship model of displacement and voltage of micro-gripper. For piezoelectric ceramic hysteresis, we proposed the hybrid PID control algorithm based on modified smith predictor feedforward compensation control. Then, we test the tracking experiments. The results show that modified smith predictor feedforward and fuzzy PID closed-loop tracking controller is better, inhibited significantly

the impact of the hysteresis effect of the piezoelectric cantilever and achieve control requirements.

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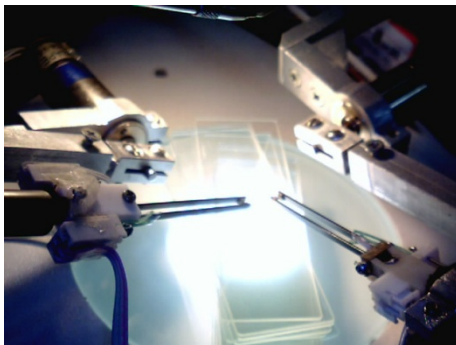

Figure 1. The piezoelectric micro-gripper
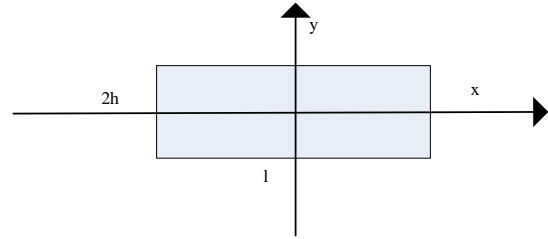

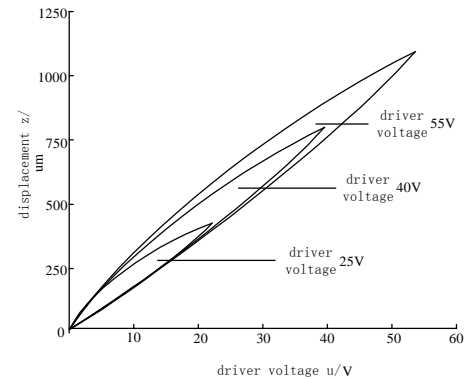Figure 2. The beam cross-section

Figure 3. The hysteresis loop under different peak voltage
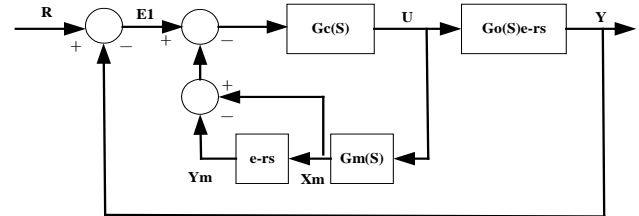

Figure 4. The principle diagram of smith predictor
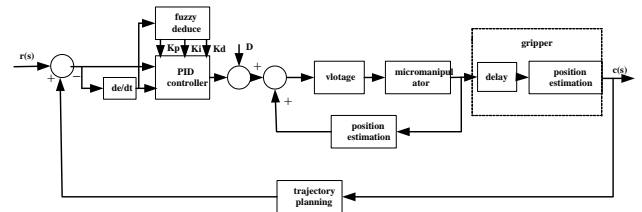

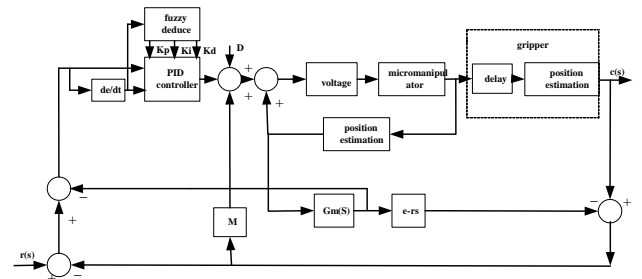Figure 5. The structure of position

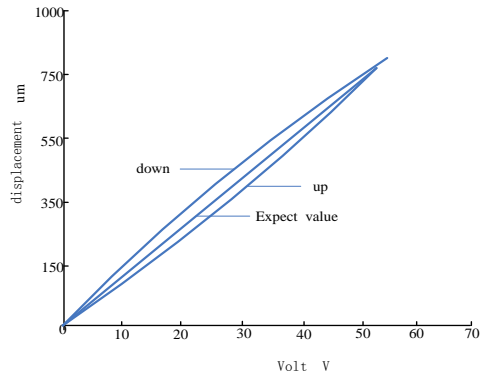Figure 6. The structure with modified smith predictor

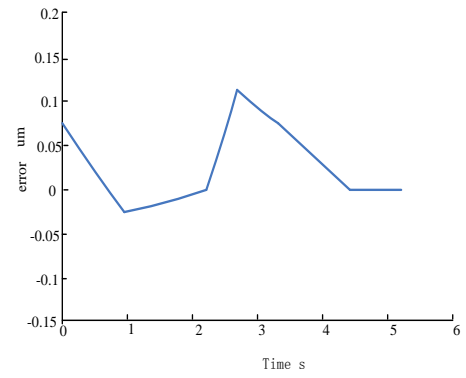Figure 7.   The voltage - displacement curve

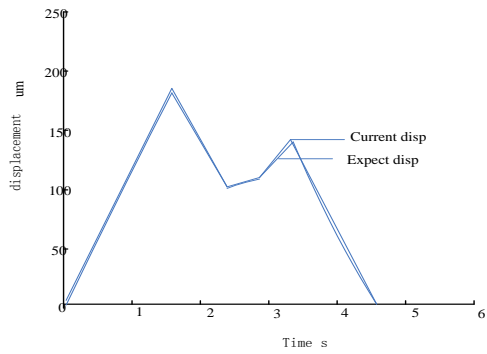Figure 9.   The modified smith predictor of fuzzy PID tracking error

Figure 8.   The Fuzzy PID controller, the tracking results