

Research on Nanoscale Displacement Online Modeling and Control of PCA

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Abstract—This paper proposes the method of nanoscale micro-displacement modeling and control of the piezoelectric ceramic actuator (PCA) mounted on the end of a micro-nano robot. The robot works in the vacuum chamber of a Scanning Electron Microscope (SEM). We use the time-to-digital conversion (TDC) method to measure the displacement of the PCA. For the purpose of establishing the relationship of the applied voltage and the displacement of the PCA, we designed an online modeling and control system based on PC/104. Models with different order combinations are applied to fit the transfer function of the system and the least squares method is applied to identify the parameters of each model. In addition, the second-order transfer function model is used to approximate the open-loop transfer function model of piezoelectric ceramic by comparing the model fitting rate. Specially, some open-loop control experiments are performed to verify the accuracy of the model. Furthermore, a PID controller is proposed to achieve accurate position control for the PCA. In the end, simulation results demonstrate the feasibility and effectiveness of the closed-loop control system.

Keywords—piezoelectric ceramic actuators, online modeling, nano-positioning, scanning electron microscope, closed-loop control

I. INTRODUCTION

The past decades have witnessed the explosive development of nanoscience and nanotechnology [1]. Nanopositioning and nano-operation technology are widely seen as having huge potential to bring benefits to numerous areas of research and have been a fundamental research method of biology, chemistry, materials science, and physics [2]. Manipulation and interrogation at nanoscale with a Scanning Electron Microscope(SEM) necessitate positioning systems with nanoscale resolution [3]. The piezoelectric ceramic actuator (PCA) has become the core device of nanopositioning system by virtue of a number of attractive features: high resolution, accuracy, stability, and fast response, which has been widely applied in precision equipment such as SEM [4], nanopositioning system [5], Nanomanipulation instrument and micro-electromechanical system [6]. For example, it is necessary for nanopositioning that scanning the probe over a sample surface to control the interaction between the probe and sample. Additionally, SEM is the infrastructure of many cutting-edge scientific fields for high-precision imaging of the sample. The vast majority of researchers on nanopositioning use PCA to

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control the nanoscale movement of the scanning probe on the sample surface for keeping the probe at a nanoscale distance from the sample. The nanoscale micro-displacement sensing and modeling of its actuator have received great attention from worldwide researchers. However, there are still many problems that are not solved for nano-operation. One of the key requirements is the precise positioning method.

Over the past century, there has been a dramatic increase in high-precision machining and high-precision displacement measurement instruments are also emerging. Consequently, the measurement accuracy is continually increasing. Nevertheless, there are several particular limitations of the nanomanipulation under SEM, including space constraints, electromagnetic radiation, and difficulty in dissipation in the vacuum environment [7]. In the SEM vacuum chamber, the utilization of any laser-type sensors cause thermal emitting problems, whether laser generating device or the irradiation of laser itself will result in a thermal emitting. However, dissipation is a challenging task in the SEM vacuum chamber, which barely rely on nanomanipulation device pedestal conducting heat dissipation [8]. Measuring the displacement with a resistance strain gauge is to install it in the deformation part of the micro-motion device. This method was selected for its low cost and high stability. The Wheatstone bridge is applied in conventional resistance strain gauge measurement, suffering from the drawbacks of low accuracy and power consumption. In this paper, we employ TDC measurement method which has features of high precision and extremely low power consumption.

In the control techniques of piezoelectric ceramic, the most commonly means in previous research is the inversion-based method [9]. The main weakness of this method is that it is highly depended on the precision of the inverse model of the hysteresis [10] whereas the structure of the hysteresis causes some difficulties in constructing the inverse of the model as well as real-time application. Moreover, this method is generally utilized in feedforward control [11]. Due to the absence of a feedback mechanism, it is unable to remove the disturbances occurring from external sources. In addition, the calculation of the inverse model increases calculative complexity [12]. To overcome these imperfections, this paper proposes a direct modeling method without computing the inverse model of the hysteresis, which can effectively avoid the influence of the hysteresis inverse model on the positioning accuracy. In detail, we establish the online transfer function model between nanomanipulation system driving voltage and piezoelectric

ceramic deformation, and adopt the closed-loop control to suppress the external disturbance and the uncertainty of model.

Numerous existing systems depend on Micro Control Unit (MCU) control or industrial computer control. Systems based on MCU control possess the key advantages of reliability and simplicity. However, an unavoidable restriction is that it is difficult to achieve real-time control and complex control. Systems relied on industrial computer control have powerful data processing capabilities. It shall be noticed that the communication between the industrial computer and other hardwares is challenging. From above discussions, it is necessary to design an implementable system for the control of the PCA. This paper proposes an online modeling and control system based on PC/104. We make use of models with different order combinations to fit the transfer function of the system and the least squares method to identify the parameters of each model. By using the proposed system, experiments on the PCA are conducted where the piezoelectric ceramics positioning is considered as a second-order system. Additionally, a PID controller is adopted to eliminate undesirable properties such as oscillations and instability. Moreover, simulation results demonstrate the feasibility and effectiveness of the closed-loop control system.

The remainder of this paper is organized as follows. Section II introduced the configuration of the nanomanipulation system. The online modeling and control system based on PC/104 is described in Section III. In Section IV, the method of online modeling is presented and the experiments and simulation are given to verify the proposed method. Finally, this paper is concluded in Section V.

II. SENSING AND IDENTIFICATION SYSTEM

From Fig. 1, the designed sensing and identification system can be divided into two parts: inside SEM and outside SEM. The nanomanipulation system under SEM is composed of four manipulators with identical structure and symmetrical layout mounted on the base of the installation. Each manipulator consists of coarse and precise positioners. Three stick-slip-based piezo and linear positioners as a motion mechanism are perpendicular to each other, constituting the Cartesian motion mechanism of coarse positioners. In order to decrease dissipation in the SEM, the coarse positioners use the feedforward control aiming to move end effectors into the field of view of SEM. Precise positioners are consisted of three piezoelectric ceramic stacks, controlling the end of the nanomanipulation system to achieve nanoscale micro-displacement operation. The precise positioners are three flexure guided, preloaded piezo positioners with one strain gauge mounted on each pizeostack. The applied voltage results in the deformation of pizeostack. When the pizeostack expands or contracts, strain-induced resistance changes and the circuit will charge and discharge the standard capacitor connected with it. We use the time-to-digital convertor (TDC) method to measure the time of charge and discharge of the standard capacitor to calculate the amount of displacement of the piezoelectric ceramic, more details are shown in [13]. MCU is considered as a processor of this nanomanipulation system. Data processing and control algorithms are all carried out on the MCU. Data processing and control algorithms are all carried out by the MCU.

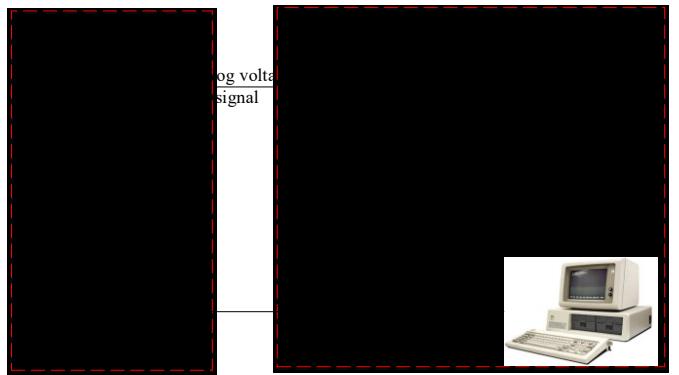


Fig.1. Hardware configuration of sensing and identification system

The weak real-time processing capacity of the MCU causes the system incapable of online system modeling and identification. Furthermore, the feature of limited computing ability of the MCU determines that it is difficult to execute complex modeling and system identification algorithms.

Due to the major drawbacks of the nanomanipulation system, the outside SEM is necessary for a piezoelectric ceramic movement sensing and identification. The design of the outside SEM can be divided into five parts: PC/104, MCU, driving system, IIC bus, RS485. To ensure high-speed and real-time delivery of the voltage command from PC/104 to the MCU, it is reasonable to employ RS485 protocol in communication of between MCU and PC/104. In order to guarantee the reliable transmission of the sensing information from nanomanipulation system to PC/104, the IIC communication protocol is used between the nanomanipulation system and PC/104. The MCU is used to transmit the instructions of PC/104 and execute some simple data processing, such as filtering. Furthermore, complex data processing, identification algorithms and control algorithms are carried out on the PC/104. The new established system performs a remarkable feature of sufficiently high computational speed. Therefore, it has a number of attractive advantages: online calculating and modeling, implement of complex algorithms, file storage, and graphical display etc.

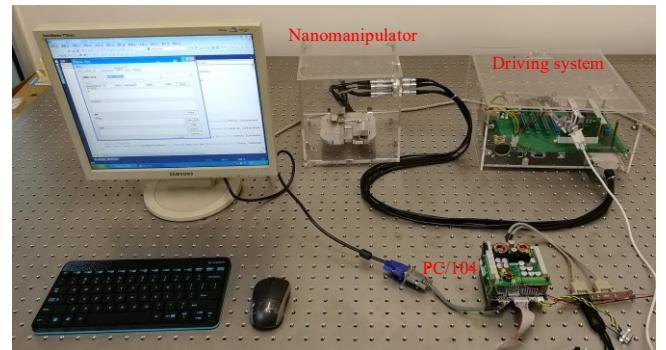


Fig.2. Experiment setup of the nanoscale manipulation

When the PC/104 sends a motion instruction, the driving signal is delivered to the MCU via the 485 bus. The MCU converts the digital signal into an analog signal. The driving system magnifies the analog signal to generate the desired voltage, and applies to the piezoelectric stacks to control the movement of manipulator. When the control voltage is applied

to the PCA, it will produce a nanoscale motion. The resistance strain gauge measures the nanoscale displacement through the TDC method and transmits the data to PC/104 through the IIC bus for further processing. The hardware structure is exceedingly essential for completing the data acquisition. Experiment setup is shown in Fig.2.

The software architecture of the data acquisition system can be divided into three parts: system initialization, system steady-state response, system dynamic response. The procedure of Piezoelectric ceramic position initialization process can be described as the following steps. Apply a zero voltage to the PCA and read the sampling data of the piezoelectric ceramic sensing and identification system every 50ms for 100 times. Finally, calculate the average value as the initial position of the PCA. In the process of system steady-state response, an incremental voltage from zero voltage (the voltage value starts at 0 to the maximum value 150v in increment of 2.3mv) is forced to PCA and the steady-state displacement output of the PCA is automatically recorded in piezoelectric ceramic sensing and identification system to further data process. The description of system dynamic response process is listed as follow. Employ a step input signal to the PCA and read the sampling data of the piezoelectric ceramic sensing and identification system every 10ms until the output of the system achieving steady-state. Ultimately, establish the transfer function model of the nanomanipulation system.

III. MODELING AND CONTROL OF THE PCA

PCAs are controlled by piezoelectric ceramic motors, and the performance of piezoelectric ceramic motors directly determines the positioning accuracy of the PCA. Piezo-actuated stages themselves suffer from the inherent drawbacks produced by the inherent nonlinearities, such as creep and hysteresis, making modeling and control of such systems challenging [14,15]. Moreover, the hysteresis characteristic is relevant to frequency, so the output of the PCA is affected by the frequency of input voltage signal [16]. To address these challenges, this paper proposes an online modeling and control of the PCA. Online modeling allows us to adjust the model parameters in time and improves the accuracy of modeling. In addition, this method offers an effective way of controlling in real-time and possesses attractive features of universality and adaptability.

A. The Step Response Of System

The discrete sampling data of the system are obtained by applying the step input signal to the nanomanipulation system, then the step response curve is plotted as shown in Fig.3. Displacement output curve of the piezoelectric ceramic actuator shows that the output of the piezoelectric ceramic changes rapidly to a certain position when a step input signal is applied to the system. Then the output begins to jitter and we call this phenomenon as the crawling effect of the piezoelectric ceramic actuator. The magnified crawling effect is plotted separately as shown in Fig.4.

B. System Identification And Results Comparision

In this paper, we use the heuristic method to establish the transfer function model between the driving voltage of

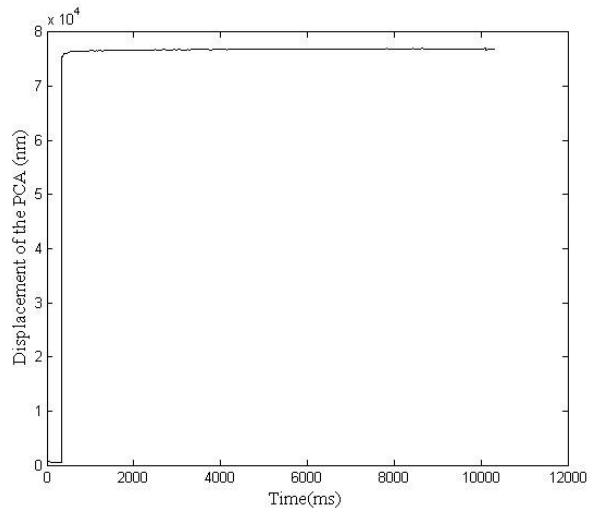


Fig.3. Displacement output curve of the PCA

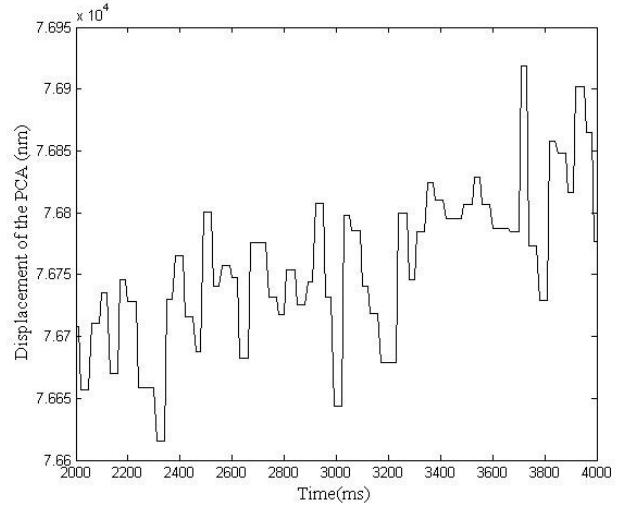


Fig.4. The crawling effect of the PCA

nanomanipulation system and the deformation of piezoelectric ceramic. In order to avoid the complicated mathematical processing, the least squares method is used to identify each model. TABLE I lists poles number, zeros number, delay, expression of system transfer function, and fitting rate of models with different orders. Although the first-order system model possesses the features of simple-structure and easy-to-implement, the fitting rate is 84.39%, much lower than the second-order and third-order models. Therefore, the first-order system model has not been adopted. The third-order system model with three poles and one zero and a delay has the highest fitting rate of 93.4%. The fitting rate of second-order system model is as high as 90.35%, a little lower than the third-order models. However, it is much easier to implement than the third-order system models. By considering the complexity and the fitting rate of each system model, we choose the second-order system model with two poles and one zero whose fitting rate is 90.35% and transfer function expression is shown in (1).

TABLE I.
RESULTS DF SYSTEM IDENTIFICATION

Order	Poles number	Zeros number	Delay	Expression	Fiting rate
1	1	0	No	$G(s) = \frac{0.0499}{s + 0.0373}$	84.39%
2	2	0	No	$G(s) = \frac{0.005}{s^2 + 0.0805s + 0.0037}$	88%
2	2	1	No	$G(s) = \frac{-0.024s + 5.7117 \times 10^{-4}}{s^2 + 0.0277s + 4.3183 \times 10^{-4}}$	90.35%
3	3	0	No	$G(s) = \frac{7.4284 \times 10^{-4}}{s^3 + 0.01119s^2 + 0.0138s + 5.546 \times 10^{-4}}$	89.95%
3	3	0	Yes	$G(s) = \frac{8.3876 \times 10^{-4}}{s^3 + 0.1161s^2 + 0.0149s + 6.2622 \times 10^{-4}} e^{-0.01s}$	90%
3	3	1	No	$G(s) = \frac{-0.0158s + 0.0019}{s^3 + 0.1532s^2 + 0.0262s + 0.0014}$	92.33%
3	3	1	Yes	$G(s) = \frac{-0.0175s + 0.0021}{s^3 + 0.1602s^2 + 0.0286s + 0.0016} e^{-0.01s}$	92.39%
3	3	2	No	$G(s) = \frac{1.833s^2 - 0.0421s + 0.0108}{s^3 + 0.3959s^2 + 0.0961s + 0.0081}$	93.4%
3	3	2	Yes	$G(s) = \frac{1.4544s^2 - 0.079s + 0.0113}{s^3 + 0.3965s^2 + 0.0976s + 0.0084} e^{-0.01s}$	89.95%

$$G(s) = \frac{-0.024s + 5.7117 \times 10^{-4}}{s^2 + 0.0277s + 4.3183 \times 10^{-4}} \quad (1)$$

IV. EXPERIMENTS VERIFICATION

A. Experiment of Model Verification

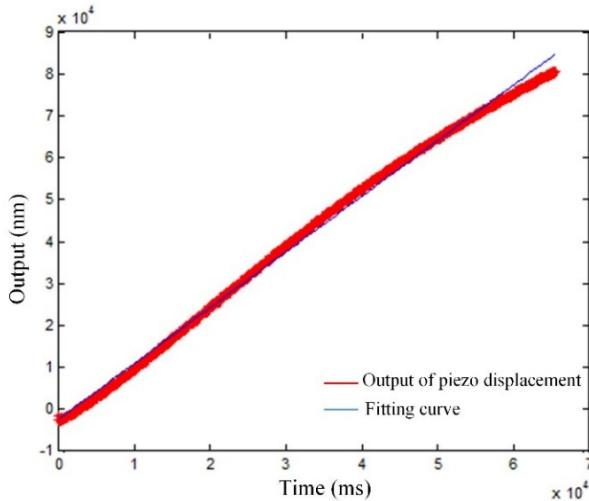


Fig.5. Comparation of output of the PCA displacement and fitting result

The red curve in Fig.5 representing the steady-state input-output relationship of the system fitted by a polynomial model gets the expression in (2), and fitting result is shown as blue curve. The result of this experiment shows that the relationship of input and output approximates to be linear in steady-state.

$$y = 1.3u - 2634.6 \quad (2)$$

B. The Open-loop Control Experiment Of System

Calculate the corresponding input according to the given steady-state output value and the system transfer function model and apply this input into nanomanipulation then get a real-output. It has verified model established in Section III is valid.

The open-loop transfer function of the system obtained by system identification is shown in (3) and the relationship of output and input is shown in (4). we can obtain (5), (6) and (7) according to the final value theorem (FVT).

$$G(s) = \frac{Y(s)}{U(s)} = \frac{-0.024s + 5.7117 \times 10^{-4}}{s^2 + 0.0277s + 4.3183 \times 10^{-4}} \quad (3)$$

$$Y(s) = \frac{-0.024s + 5.7117 \times 10^{-4}}{s^2 + 0.0277s + 4.3183 \times 10^{-4}} U(s) \quad (4)$$

$$= \frac{-0.024s + 5.7117 \times 10^{-4}}{s^2 + 0.0277s + 4.3183 \times 10^{-4}} \times \frac{U_0}{s}$$

$$\lim_{t \rightarrow \infty} y(t) - y_0 = \lim_{s \rightarrow 0} s Y(s) \quad (5)$$

$$= \lim_{s \rightarrow 0} s \times \frac{-0.024s + 5.7117 \times 10^{-4}}{s^2 + 0.0277s + 4.3183 \times 10^{-4}} \times \frac{U_0}{s} \quad (5)$$

$$= 1.32267 U_0 \quad (5)$$

$$\lim_{t \rightarrow \infty} y(t) = 1.32267 U_0 - y_0 = 1.332267 U_0 - 2634.6 \quad (6)$$

$$U_0 = \frac{\lim_{t \rightarrow \infty} y(t) + 2634.6}{1.332267} \quad (7)$$

Verifying the model with two specific output values, when $y_1(t)=57220$, the input calculated from the formula (7) is $u_1=15322$. when $y_2(t)=57220$, the input calculated from the formula(7) is $u_2(t)=44927$. Apply the input u_1 and u_2 to the system, and read the real-output of the system measured by sensors, then calculate the average value of output shown as (8) and (9). This experiment confirmed that the output of the model approaches to the real-output of the system.

$$\dot{y}_1(t) = 57220 \quad (8)$$

$$\dot{y}_2(t) = 58618 \quad (9)$$

C. Simulation of Closed-loop PID Control

In this paper, based on the open-loop transfer function model of the system, PID control method is applied to design the nano-controller. Moreover, the parameters of the controller are: $k_p = 0.25$, $k_i = 0.005$, $k_d = 1$. In this feedback scheme, the nonlinearities including hysteresis and creep of the piezoelectric ceramic actuator are treated as uncertainties. The PID controller

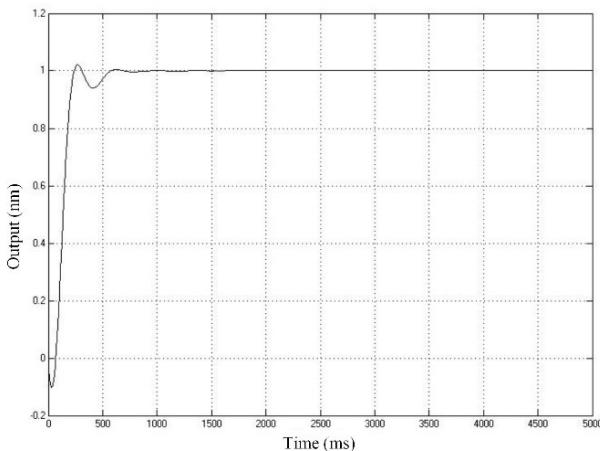


Fig.6. Simulation of PID control

will force the output to track desired input based on the tracking error between the input and output. With the feedback scheme, the performance of the system can be improved in the presence of unexpected disturbances. Fig.6 shows the result of the PID control. Overall, the result strengthens the idea that the PID controller can effectively control the piezoelectric ceramic system to verify the effectiveness of the controller further and lay a foundation for the future closed-loop control experiment.

V. CONCLUSION

In this paper, a PC/104 based movement modeling and control method of piezoelectric ceramic actuator has been proposed. The design and implementation of the system hardware configuration were detailed. The main advantage of this system is the simplicity of the structure and the system is easy to use. In addition, the methods dealing with online modeling, parameter identification, and control of the PCA were presented. Specifically, the proposed methods avoid complex calculations to attain the system model. The simulation results illustrated the effectiveness of the feedback control strategy.

In future work, we will study the control effect when the proposed controller is applied in the actual system. The modeling and compensation of inherent nonlinearities of the PCA will also be studied to achieve accurate positioning.

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