A PNEUMATIC POSITIONING DEVICE COUPLED WITH PIEZOELECTRIC SELF-MOVING MECHANISM

Yung-Tien Liu, Chen-Hao Lee, and Rong-Fong Fung

ABSTRACT

This paper reports a new pneumatic positioning device coupled with a piezoelectric self-moving mechanism to overcome the main disadvantages of the inherent poor positioning accuracy obtained by traditional pneumatic cylinder. The new driving mechanism is to mount a piezoelectric Impact Drive Mechanism (IDM) to the controlled sliding table driven by the pneumatic cylinder. Based on the configuration, the first step of positioning process is to actuate the sliding table with rough position accuracy but with the benefits of high-speed and large-range due to the pneumatic cylinder. The second step is to drive the sliding table with high position accuracy by utilizing the impact force of IDM. The experimental results show that the controlled sliding table is successfully positioned in 0.236 s with rough accuracy of 10 µm and with the stroke of 100 mm by utilizing the pneumatic cylinder, and the final positioning accuracy of 10 nm with respect to the terminated position of the first-stage control is obtained in 1.479 s due to the actuations of IDM. It is shown that the pneumatic positioning device coupled with IDM has attractive practical applications in the field of precision industry.

KeyWords: Piezoelectric element, pneumatic cylinder, impact force, precision positioning, self-moving mechanism, IDM.

I. INTRODUCTION

Due to the advantages of high-speed ability and large travel range, the pneumatic control system has become one of the main technologies in the field of automation. However, because the air is compressible in nature and the nonlinear friction force always exists between the sliding surfaces of piston and the tube, it is very difficult to position a sliding table with positioning accuracy under micron-order by a pneumatic control system.

For improving the positioning performance of the pneumatic control system, many studies were reported. The most simple and basic method is to use two solenoid valves to improve the positioning accuracy of a pneumatic cylinder. The system could reach the positioning accuracy of 0.4 mm [1]. Without changing the mechanical structure, further studies were mainly focused on implementing the controllers by software with different strategies, e.g., the Pulse-width modulation (PWM) and Proportional-integral-differential (PID) controllers were integrated to actuate the simple ON/OFF solenoid valves with the positioning accuracy of 0.21 mm [2]; a fuzzy PWM controller was implemented to improve the positioning accuracy up to 0.1 mm [3]; using two-stage velocity and position feedback controllers could reach the positioning accuracy of 5 µm [4]; utilizing an on-line learning Neuro-fuzzy controller with tuning scaling factor could reach the positioning accuracy of 5 µm [5]. According to the above results, the most excellent positioning accuracy obtained by the pneumatic positioning system could reach only a few microns.

Concerning the pneumatic actuator that is applied in the high-precision industry, the authors had reported the combined piezo-pneumatic actuator [6] recently. This novel hybrid actuator featuring both large operational range and 10 nm-order positioning ability is successfully merchandised [7]. This device was aimed at providing an excellent adjusting tool for the assembly works of small and precision components such as the connectors of optic fiber. Its operation principle was based on the utilization of the long stroke of pneumatic cylinder for carrying
the piezoelectric actuating hammer to keep the contact with the target object to be positioned, and then the target object was actuated by the piezoelectric actuator via the form of intermittent contact force. In that design, because the pneumatic cylinder was not fixed to the sliding table and was used only for enormously enlarging the operational range of piezoelectric actuator, the benefit of high-speed characteristic of pneumatic cylinder for the actuation of target object was lost. Related to the new structure in which the pneumatic actuator was combined with the piezoelectric actuator, further studies were reported: a pneumatic servo position control system utilizing adaptive variable structure control (VSC) was proposed with the positioning accuracy of 10 µm [8]; an intelligent pneumatic-piezo hybrid positioning system utilizing self-organizing fuzzy sliding-mode control could reach the positioning accuracy of 0.1 µm [9].

To overcome the current limitation of the positioning accuracy due to traditional pneumatic system, a novel driving mechanism coupled with an effective control strategy is proposed in this paper. The main concept of the proposed mechanism is to mount a piezoelectric self-moving mechanism (Impact Drive Mechanism, IDM) [10] to the controlled sliding table driven by the pneumatic cylinder. Based on the configuration, the first stage of positioning process is to drive the table with rough positioning accuracy but with the benefits of high-speed and large-stroke abilities due to the pneumatic cylinder. The second stage is to drive the table with high-precision positioning accuracy by utilizing the impact force of IDM. Since IDM can overcome the non-linear stick-slip phenomenon of the frictional force existing on the sliding surfaces, the final ultra-precision positioning accuracy may reach as high as 10-nm order. Therefore, this new design will not only majorly improve the performance of IDM, in which its traveling speed is commonly several millimeters per second, but also bring the pneumatic actuator into the applications in the ultra-high positioning fields.

This paper is organized as follows: In section 2, the operation principle of the IDM is introduced. This is followed by section 3, where the experimental setup is described. The control system and the experimental results are explained in sections 4 and 5, respectively. In addition, the discussion concerning the problems due to the configured positioning device is given in section 6. Finally, this paper is summarized in section 7.

II. OPERATION PRINCIPLE

2.1 Operation principle of IDM

Figure 1 shows the configuration of the pneumatic positioning device coupled with IDM. The IDM consists of a sliding table \( M \), a piezoelectric actuator, and an inertial body \( m \). The sliding table is supported by two guided rods. One side of the sliding table is fixed to the piezoelectric element and the other side is attached to cylinder rod. The inertial body is attached to the right end of piezoelectric element, but it does not touch the sliding surface. Figure 2 shows the operation principle of IDM. The precise motion is carried out through the following steps:

1. At the beginning, the piezoelectric actuator is contracted.
2. A rapid extension of the piezoelectric actuator is made, and an impulsive reactive force is generated to move the sliding table toward the left against the holding friction.
3. After the rapid extension, the piezoelectric actuator is contracted slowly by a constant acceleration so that the reactive force will not exceed the static friction that holds the sliding table. Therefore, the sliding table can be kept at the previously actuated position.
4. At the end of slow contraction stage, the motion of the piezoelectric actuator is suddenly stopped. This will cause another movement toward the left.

Repeating these steps, the sliding table proceeds with step-like movements. The size of the step can be varied from several nanometers up to several micrometers. The motion toward the right can be made by re-
versing the extensions and contractions of the above steps.

Figure 3 shows the voltage waveforms applied to the piezoelectric actuator, where $\Delta V$ is the amplitude of the voltage waveform. No.1 corresponds to the rapid extension, No.2 is used for the slow contraction and stop, and No.3 is the combination of No.1 and No.2. The combined waveform can move the sliding table by larger step-motion than others.

2.2 Characteristics of pneumatic cylinder coupled with IDM

The characteristics of the proposed mechanism are described as follows:

(1) The advantages of high-speed and large operational range can be obtained based on the structure, and therefore the mechanism meets the requirements in automation industry.

(2) Due to the utilization of rapid deformation of the piezoelectric actuator, the non-linear characteristics of hysteresis and drift in the piezoelectric actuator do not need to be considered. This will simplify the controller.

(3) When the final high-precision positioning is obtained, the voltage applied to the piezoelectric actuator is terminated. This can simplify the controller of the piezoelectric actuating system.

(4) The sliding table can be positioned with a high-precision positioning accuracy up to 10-nm order.

III. EXPERIMENTAL SETUP

3.1 Positioning device

Figure 4 shows the schematic experimental setup for examining the performance of the positioning device utilizing the pneumatic cylinder and the piezoelectric self-moving mechanism, which consists of a sliding table $M$ with $20 \times 20 \times 70 \text{ mm}^3$ dimension, a piezoelectric element ($10 \times 10 \times 20 \text{ mm}^3$, Tokin), and an inertial body $m$ with $20 \times 20 \times 10 \text{ mm}^3$ dimension. The pneumatic cylinder ($\phi 10 \times 250 \text{ mm}$) is fixed on the base by a fixed wall and a support. The piston rod is connected to the sliding table, which is the target object to be positioned. The IDM is mounted on the sliding table on the opposite side. Two parallel cylindrical guide rods are used for guiding and supporting the sliding table. Therefore, the sliding table can be actuated to move with one degree-of-freedom (DOF). A linear scale (Mitutoyo: AT-11T) with the measuring range of 250 mm and the resolution of 10 $\mu$m is mounted beside the sliding table. The movable connecting part of the linear scale is directly connected to the sliding table. A target plate for the proximity sensor is set on the sliding table for defining the reference origin. For avoiding the disturbance from circumference, the experimental setup is fixed on the air table. Figure 5 is the photograph of the positioning device.

3.2 Control system

Figure 6 shows the configured control system for the positioning device. The control system for the pneumatic cylinder includes one personal computer (PC), a compressed air supplying system (including pump, air filter, piping), a 2 $\times$ 5 directional valve for supplying the compressed air to the proportional valve (FESTO: MPyE-5-1/8-HF-010 B) which is the main device for precisely controlling the motion of the pneumatic cylinder, a proximity sensor, a linear scale used for detecting the rough positioning accuracy of the sliding table, a 12-bit digital-to-analog (D/A) converter used for transferring the command to the proportional valve, a 16-bit analog-to-digital (A/D) converter used for data acquisition of the gap sensor, and the Digital Input/Output (DIO) ports for decoding the linear scale.
One the other hand, the control system for the piezoelectric actuator is different from that for the pneumatic cylinder in that a high-speed voltage amplifier (nF: HSA-4014) is used for actuating the piezoelectric actuator and a capacitive gap sensor (ADE-5300-177) with the measuring range of 25 µm and with the resolution of 5 nm is used for precisely detecting the sliding table. The control system for the piezoelectric actuator will be carried out when the sliding table meets the required rough positioning accuracy obtained by the pneumatic cylinder.

**IV. CONTROL STRATEGIES**

Figure 7 shows the flow chart of the control algorithm for the positioning device utilizing the pneumatic cylinder and the piezoelectric actuator. The system can be classified into two main modes: one is for rough positioning accuracy of the sliding table actuated by the pneumatic cylinder, and the other is for precise and final positioning accuracy obtained by the piezoelectric actuator. As shown in the block diagram, when the sliding table reaches the target position within 10 µm precision range, the control mode for the piezoelectric actuator is subsequently carried out. The control procedure will be iterated until the position error is within 10 nm range. According to the flow chart of control strategies, the block diagram of the whole control system is decoupled into two sequential control loops as shown in Fig. 8. The dotted lines shown in Fig. 8(b) indicate that the piezoelectric control system operates in terms of several open-loop control practices due to the pulse-like actuators for the PZT actuator. The control algorithm is implemented by LabVIEW (Laboratory Virtual Instrument Engineering Workbench) package which is a Windows supported graphical programming language. The control models and control strategies are described in the following sections.

4.1 Controller design for the pneumatic cylinder

For simplicity, the linear mathematical model of the pneumatic control system is derived based on the method of system identification [11]. A Pseudo Random Binary Sequence (PRBS) signal with the amplitude mar-
gin of ±0.6 V and the exciting period of 2.54 s is applied to the proportional valve. At the same time, the displacement of the sliding table is recorded by the linear scale with the sampling rate of 20 ms. According to 1000 sets of data obtained by the measured displacements and their corresponding PRBS input signals, the 2nd order transfer function $G(s)$ in s-domain is derived as follows,

$$G(s) = \frac{57.82s + 4938}{s^2 + 125.23s + 1.347}, \quad (1)$$

and the corresponding transfer function $G(z^{-1})$ in z-domain is

$$G(z^{-1}) = \frac{b_1z^{-1}}{1 + a_1z^{-1} + a_2z^{-2}} = \frac{2.567z^{-1}}{1 - 1.684z^{-1} + 0.6833z^{-2}}. \quad (2)$$

Based on Eq. (2), the linear mathematical model for the pneumatic close-loop control system having the proportional gain $K_p$ and integral gain $K_i$ can be described by state space model as follows:

$$X(k+1) = AX(k) + Bu(k)$$
$$Y(k) = CX(k) \quad (3)$$

where

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ a_2 & (a_1 - a_2 + K_p b_1) & (1 - a_1 - (K_i + K_p)b_1) \end{bmatrix},$$
$$B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, C = [0 \ K_p b_1 \ (K_i + K_p)b_1].$$

Applying the Jury stability test [12] in which the characteristic equation of the discrete-time system can be expressed as a function of $z$, the suitable range of $K_p$ is determined as follows:

$$0 < K_p < \frac{1}{b_1(1 - a_1 + a_2) - \frac{K_i}{2}}, \quad (0 < K_p < 1.312), \quad (4)$$

If $K_i > 0$, the control system is stable theoretically. And, for obtaining the steady error within 0.01 mm, the theoretical value of $K_i$ is 100$T_s$, where $T_s$ is the sampling period.

### 4.2 Control algorithm for the pneumatic cylinder

The control process for the long-range positioning table actuated by the pneumatic cylinder starts at the reference origin with sensing made by the proximity linear scale sensor. The final target position of the sliding table is set to 100 mm from the reference origin. Referring to Fig. 8(a), when the command of the final target position is given, the controller will calculate the error ($e_t$) between the detected position and the target position (100 mm), and then it sends a calculated driving voltage ($v_1$) to the proportional valve for eliminating the position error. When the sliding table reaches the target position within the error range for 10 $\mu$m (or within the position ranging from 99.99 mm to 100.01 mm), the control process for the pneumatic cylinder is terminated. At this state, the control process is ready for the actuation by the piezoelectric actuator.

In the control process with the pneumatic cylinder, if the overshoot of the sliding table is too large, the sliding table will collide with the capacitive gap sensor, which is set just near the target position by a distance of only 0.1 mm. For avoiding the collision, the control process for the pneumatic cylinder is divided into three ranges as shown in Fig. 9. When the controlled sliding table is located in the range I, from 0 to 30 mm, a higher constant voltage ($v_{1(I)}$) is applied to the proportional valve for actuating the pneumatic cylinder with a higher accelerating speed. In the middle range II, from 30 to 60 mm, the pneumatic cylinder is actuated with a lower accelerating speed compared to that for range I by a smaller constant voltage ($v_{1(II)}$). When the sliding table enters the position range III, from 60 to 100 mm, a proportional-integral compensator (PI controller) is used to control the proportional valve with varying voltage ($v_{1(PI)}$).

### 4.3 Controller design for the piezoelectric actuator

Figure 10 depicts the simplified IDM model based on the assumptions that a very short time period $\Delta t$ of impulsive force $F_p$ is applied to the piezoelectric actuator, and the forces caused by air pressure acting on both sides of the piston are at equilibrium. In this model, $M$ is the total mass of piston, rod, and sliding table together, $m$ is the inertial body, and $F_t$ is the total friction force exerted onto the sliding surfaces of piston, bush, and guide rods.
The heuristic qualitative control model is therefore derived based on the instantaneous expansion of piezoelectric element [6]. According to the conservation law of momentum, the following equations are valid.

\[ M \cdot V_M = m \cdot V_m, \]  
\[ (5) \]

where \( V_M \) and \( V_m \) are the instantaneous velocities of \( M \) and \( m \), respectively. If we assume that there is no energy loss during the instantaneous expansion of the piezoelectric actuator, the strain energy \( E_s \) generated by applying a voltage \( V \) to the piezoelectric element may be expressed as the sum of kinetic energies \( E_M \) and \( E_m \) respectively corresponding to \( M \) and \( m \) as follows:

\[ E_s = E_M + E_m \]  
\[ (6) \]

In Eq. (6), only \( E_M \) is valid for the actuation of the sliding table and it will be consumed by the frictional energy. Hence, the predicted displacement \( X \) excited by one single actuation can be derived as follows:

\[ X = \frac{m}{m+M} \cdot \frac{E_s}{F_i} \quad (F_i > 0) \]  
\[ (7) \]

Equation (7) can be summarized as a simple formulation describing the relation between the predicted displacement \( X \) and the control parameter of the applied voltage \( V \), i.e.,

\[ X = n \cdot c \cdot f(\Delta V) \]  
\[ (8) \]

where,

\[ c = \frac{m}{m+M} \cdot \frac{1}{F_r}, \]
\[ f(\Delta V) = \frac{1}{2} k_e (\xi_e (\Delta V))^2, \]

\[ (9) \]

\( n \) is an adaptation coefficient with an initial value of 1, and \( \xi_e \) is the excited static displacement of the piezoelectric actuator caused by the applied voltage \( V \). The coefficient \( n \) will be updated based on the measured historical values of displacement \( X \) and the historical values of the product of \( c \) and \( f(\Delta V) \).

4.4 Control algorithm for the piezoelectric actuator

According to the inverse function of Eq. (8), a voltage command \( (v_2) \) is determined and then applied to the amplifier. The amplified voltage \( (\Delta V) \) is therefore supplied to the piezoelectric actuator for the actuation of the sliding table. This control process is iterated until the positioning error falls within 10 nm range, the resolution of the measuring system.

V. EXPERIMENTAL RESULTS

Since the positioning device is composed of the pneumatic cylinder and the piezoelectric actuator, both their motion behaviors are examined individually. Finally, the effectiveness of the coupled system is also verified experimentally.

5.1 Position control by the pneumatic cylinder

As mentioned in section 4.1, for avoiding the collision between the sliding table and the capacitive gap sensor, a special technique with three different control modes is considered. In this experiment, for examining the performance obtained by the pneumatic cylinder only, the position control is carried out based on the PI-controller without installation of the gap sensor. Figure 11 shows the measured motion behavior of the sliding table actuated by the pneumatic cylinder. It can be seen that the sliding table reaches the target position 100 mm in 0.115 s with the positioning error of 10 \( \mu m \) for \( K_p = 1 \) and \( K_i = 1 \). Based on the result, the effectiveness of the control system for the pneumatic cylinder is confirmed. The maximum overshoot of the sliding table is recorded as 6.55 mm. It is predictable that the sliding table will collide with the gap sensor if it is initially installed.

5.2 One single actuation by the IDM

For examining the motion behavior of the sliding table actuated by the IDM, one single driving voltage waveform is applied to the piezoelectric actuator under
Fig. 12. The forward and backward motion behaviors obtained by one single actuation for the IDM.

the condition that the chambers of pneumatic cylinder is open to the atmosphere. Figure 12(a) and (b) shows the recorded forward and reverse movements of the sliding table, respectively.

Referring to Fig. 12(a), when the applied voltage waveform increases rapidly from 0 to 10 V in 10 µs, the sliding table can move up to the distance of 5 nm. In the following state of slow contraction of the piezoelectric actuator, the sliding table remains still at the actuated position of 5 nm. At the instant when the applied voltage waveform is returned to 0 V, the sliding table is actuated again and reaches the final position of 10 nm. Therefore, though there is only one single voltage waveform being applied to the piezoelectric actuator, the sliding table performs twice step-motions. This phenomenon coincides with the operation principle described in section 2.1. For the reverse movements shown in Fig. 12(b), the motion behavior is similar to the forward movements except the motion direction reverses and the piezoelectric actuator is initially expanded. According to these experimental results, it is confirmed that the sliding table actuated by the IDM features the ability of 10-nm order step-motion.

5.3 Continuous actuations by the IDM

The continuous motion behavior of the sliding table is also examined by actuating the IDM continuously. Figure 13 shows the recorded displacements of the sliding table actuated by both forward and backward voltage waveforms with the same amplitude of 10 V. It can be seen that the sliding table can perform step-like motions due to every actuation, and the final position of 50 nm is obtained after five time actuations. Because the time scale is too large, the phenomenon in which the sliding table performs twice step-motions by one single actuation as shown in Fig. 12 is unable to be observed. Referring to every step-motion, it can be seen that the displacement is getting smaller and smaller. This can be interpreted that the friction force is varied during the actuating process. Though with the phenomenon of varied displacement, it can still be reasonably confirmed that the sliding table features the self-moving ability by the actuation of IDM.

5.4 Position control by the coupled actuators

The experimental results mentioned above are focused on the individual positioning performances obtained by the pneumatic cylinder or the IDM. In fact, the positioning device featuring the advantages of high-precision, high-speed, and large travel-range by coupling two actuators together is the main topic of this paper. Figure 14 shows the recorded displacement of the sliding table and the controlled commands for the proportional valve ($v_1$) and the piezoelectric actuator ($\Delta V$) with respect to time axis. According to the control algorithm mentioned in section 4, the control processes are divided into two sequential stages.

In the first stage of experiment, the sliding table actuated by the pneumatic cylinder moves from the ref-
VI. DISCUSSION

In this paper, the use of two types of sensor with different resolutions (10 μm, 10 nm) and measuring ranges (250 mm, 25 μm) would result in problems where the absolute position of the sliding table is difficult to be defined precisely by the capacitive sensor which has a higher resolution of 10 nm, and also the more complicated control strategies concerned with control stability should be configured. Though these problems can be effectively solved by using one single sensor having both large measuring range and ultra-high resolution, such as the expensive laser interferometer or very high-speed linear encoder, for demonstrating the fundamental performances of the proposed device, the authors purposely decouple the hybrid control algorithm into two sequential SISO systems, the control algorithm for each control loop is derived separately as mentioned in section 4. As for the pneumatic control system, it is a minimum phase system because there is no zero on the right half of the s-plane according to the transfer function expressed by Eq.(1). On the other hand, the piezoelectric control system can be regarded as a special control system formed by several open-loop control practices since the PZT actuator is intermittently actuated by the pulse-like waveform as shown in Fig. 3 and the control loop is with a relatively longer sampling time interval of 147.9 ms as shown in the experimental result of Fig. 14. Since the experimental works are carried out based on the configuration of the sequential control coupled with open-loop control strategies, the control performance concerning robustness is not considered in this paper.

VII. CONCLUSION

The paper proposed a new pneumatic positioning device coupled with a piezoelectric self-moving mechanism (Impact Drive Mechanism, IDM). An experimental setup was configured, the fundamental experiments were carried out, and the control algorithm was implemented for examining the performance of the positioning device. Main results were obtained as follows:

(1) The sliding table actuated by the IDM was confirmed to have the forward and backward moving abilities with 10-nm order step-motion.

(2) The sliding table was successfully positioned by the pneumatic cylinder with the stroke of 100 mm and with the positioning accuracy of 10 μm, and the final target position with the positioning accuracy up to 10 μm was obtained by the IDM.

It is shown that the proposed positioning device featuring the performance of high-precision, high-speed, and large operational range has attractive practical applications in the field of precision industry.

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