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Positioning of a 3-DOF inchworm stage with optical navigation

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Abstract
The positioning of a 3-DOF inchworm stage with optical navigation is described. Since the stage does not use any guide nor preload, a closed loop feedback position control system is employed to retain an accurate position of the stage. The stage consists of piezoelectric actuators (piezos) for thrusting and electromagnets for positioning. A non-excited electromagnet is moved by the deformation of piezos, and the excited electromagnets retains their positions. However, there are some disturbances. A weak electromagnetic force prevents the stage from retaining an accurate positon. A friction force reduces the displacement of a non-excited electromagnet. Therefore, the orientation of the stage is measured with light source and optical detector, and the deformation of the piezos are controlled. The position error is reduced from 5.9 μm to 2.6 μm by the feedback.

positioning, inchworm, piezoelectric actuator, feedback control

1. Introduction

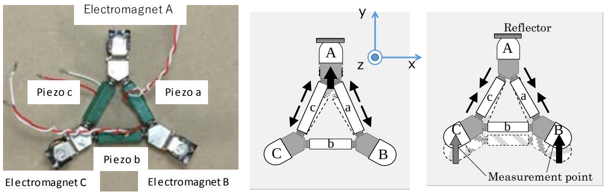
A high precision positioning stage with a long stroke is required in a precise motion system. The stage usually has one degree of freedom (DOF) in linear or rotational direction. We previously presented a multi DOF stage using piezoelectric actuators (piezos) [1, 2]. The goal of the project is to realize a large travel and multi DOF precision stage without guide mechanisms, although conventional multi DOF stages consist of one-dimensional stages. The developed stage utilized the principle of an inchworm, and can realize unlimited travel.

The developed stage consists of piezos for thrusting and electromagnets for positioning [1, 2]. Three stacked-type piezos are connected in a triangle form, and the stage realizes 3-DOF motion on a surface. Three electromagnets generate electromagnetic force while a voltage is applied to the coil. The electromagnets connect and disconnect the stage and a surface. The non-excited electromagnet moves sequentially by the deformation of the piezos.

In this paper, a 3-DOF inchworm stage with optical orientation feedback control system is described. The orientation of the stage is measured. A position control strategy is introduced to the 3-DOF inchworm stage. Since the stage does not use any guide nor preload, a closed loop feedback control system is employed to retain the position of the stage. Some experimental results are shown.

2. Three DOF inchworm stage and control

Figure 1 shows a 3-DOF inchworm stage we developed [1]. Commercially available stacked-type piezos a, b, c (NEC-tokin, AD0505D16) and electromagnets A, B, C (4000 turns, 800 mH and 300 Ω) are used. The displacement of the piezo (20 mm long) at maximum drive voltage, 150 V_{DC}, is 17.4 μm. The electromagnetic force is about 5 N when 10 V_{DC} is applied. Three metal parts bond the piezos in 60 degrees. The size of the stage depends on the dimensions of the piezos and electromagnets. Three electromagnets can connect and disconnect the stage and a surface.



(a) (b) (c)

Figure 1. 3-DOF inchworm; (a) photo, (b) displacement of electromagnet A, and (c) displacement of electromagnets B and C

2.1. Operating principle of the stage

The detail of the operating principle of the inchworm stage is described in the 2016 euspen conference [1]. The stage repeats the following two intervals, and moves in y-directions shown in figure 1. (1) As shown in figure 1(b), non-excited electromagnet A is moved by the deformation of piezo a and piezo c, while electromagnet B and electromagnet C are excited. (2) As shown in figure 1(c), non-excited electromagnet B and electromagnet C are moved by the deformation of piezo a and piezo c, while electromagnet A is excited. The displacements in x- and in rotational direction are obtained with similar control signals. One control cycle used in this paper is 1 s.

2.2. Orientation measurement using PSD

The orientation of the inchworm stage is measured with a laser and a position sensitive detector (PSD), as shown in figure 2. The orientation is measured with an optical beam deflection method. A laser beam is irradiated on a reflector fixed on electromagnet A shown in figure 2. The reflected beam is irradiated on the PSD surface. The PSD outputs the irradiated laser beam position (x_{PSD}) on its active surface. A positive output of the PSD is defined as a positive rotational displacement of the inchworm stage. The distance L between the reflector and the PSD is 70 mm. The orientation θ of the stage is approximated as

$$\theta = {}^{kV_{PSD}}\!/_{(2L)} = {}^{x_{PSD}}\!/_{(2L)} \qquad (1)$$

where k is the sensitivity of the PSD output which is experimentally obtained as 1.67 V/mm, and V_{PSD} denotes an output voltage of the PSD.

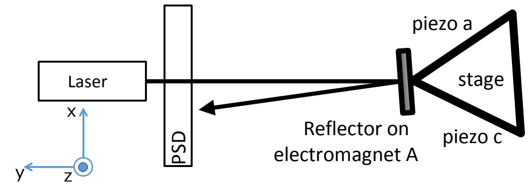


Figure 2. Orientation measurement of an inchworm

2.3. Orientation control of the stage

Figure 3 shows a control flowchart which defines a control voltage applied to piezos. While the inchworm stage moves in the y-direction, the voltages applied to piezo a (V_a) and piezo c (V_c) are equal. However, a friction disturbs the motion of the stage. The stage changes its orientation (θ) which is calculated by the PSD output (x_{psd}). If the orientation is positive, the voltage applied to piezo a (V_a) is reduced. In this paper, the constant voltage (V_{const}) applied to piezos is 150 V_{DC}. The small voltage (V_{small}) is 100 V_{DC} or 130 V_{DC}. Although these two piezos deform simultaneously, the different voltages (V_a, V_c) are applied according to the flowchart. The voltages are determined at every control cycle, 1 s.

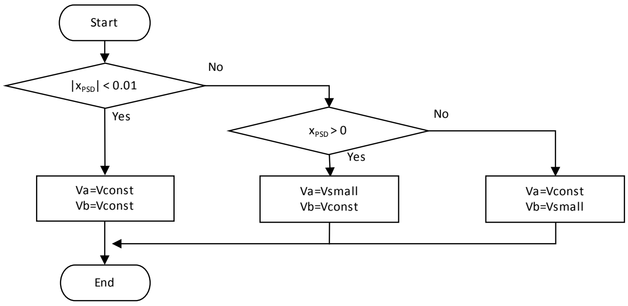


Figure 3. Orientation control method

3. Experimental results

Experimental results are evaluated by a PSD output (x_{PSD}). Figure 4 shows an experimental result obtained without optical navigation. The PSD output and the positions of electromagnet B and C in y-direction are plotted. The voltage applied to piezo a and piezo c is a rectangular waveform (0 V or 150 V). While the stage moves about 440 μm during 20 steps, 20 s, the PSD output fluctuates between -0.03 mm and 0.04 mm which causes unintended positioning error.

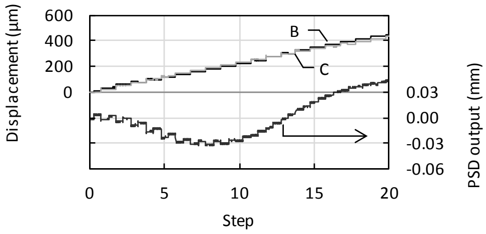
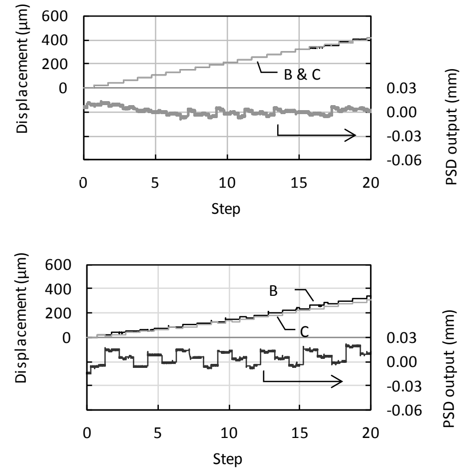


Figure 4. Displacement and PSD output without navigation

Figure 5 shows experimental results obtained with optical feedback. The voltages applied to piezo a and c are changed. In figure 5(a), the voltage applied to a piezo is 0/150 V or 0/130V according to the PSD output. When the PSD output is positive, the small voltage (V_{small}=130 V) is applied to piezo a. By the use of optical feedback, the PSD output is smaller than 0.01 mm and the stage retains its orientation. The difference between the point B and point C is caused by misalignment of a measurement system.

In figure 5(b), the applied voltage is 0/150 V or 0/100 V. In this case, the PSD output shows step displacement. This result is caused by the rectangle signal applied to the piezos. The orientation error obtained by using optical navigation is smaller than 0.02 mm, although the PSD output without optical navigation is larger than 0.04 mm. The optimal small voltage V_{smal}l will be discussed in future.



(b)

Figure 5. Displacement and PSD output with optical navigation. (a) V_{small} is 130 V and (b) V_{small} is 100 V.

Figure 6 shows a magnified result of feedback control in figure 5(b). The equal step voltage 150 V is applied to both piezo a and piezo c (V_a=V_c=150 V) at 0.6 s. After the first step displacement, the difference of the positions of electromagnet B and C is 5.9 μm at 1 s. Then, the voltage applied to the piezo c (V_c=100 V) is determined according to the flowchart as shown in figure 3. After the second step displacement at 1.6 s, the difference is reduced to 2.6 μm at 2 s. This shows that the changes of the voltage applied to piezos reduces the orientation error of the stage.

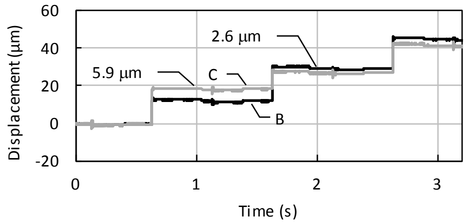


Figure 6. Close-up of y-displacement measurement

4. Summary

The positioning of a 3-DOF inchworm stage with optical navigation was discussed. From the experimental results obtained by the y-displacement, the orientation error in the linear displacement is reduced by the use of feedback control. Since the inchworm stage can move not only on a flat surface but also a rusty surface, the optical navigation using a position sensitive detector is suitable for positioning of the 3-DOF inchworm stage. In future, a 3-DOF positioning is realized by measuring the positions of three electromagnets. This work was financially supported by the Japan Society for the Promotion of Science, Grant-in-Aid for Scientific Research (C), No. 26420212.

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