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Control concept to minimize the settling time for positioning of a 3-dof inchworm with piezoelectric elements

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Abstract

In this paper, a control concept for a 3-dof (degree-of-freedom) inchworm with piezoelectric elements (piezos) is described. The inchworm, which consists of piezos for thrusting and electromagnets for positioning, moves step by step synchronously with the switching of the piezos and the electromagnets. The inchworm repeats minute displacements caused by the piezos in the linear and rotational directions, and theoretically realizes an unlimited travel stroke. The direction and minute displacement of the inchworm are determined by the amplitude of the deformations of the individual piezos. The displacement of the inchworm is approximately proportional to the voltage applied to the piezo. To minimize the settling time for positioning of the inchworm, a feedback control loop is introduced and a controller is implemented. The xyθ position of the inchworm is measured with a USB camera. The controller calculates the number of step of the inchworm. At the beginning of the positioning when the inchworm is apart from the reference position, the large voltage is applied to the piezo. When the inchworm approaches the reference position, the controller calculates the number of step displacement. In the preliminary experiment, the positioning accuracy is approximately 30 μm.

settling time, precision positioning, inchworm, piezoelectric element

1. Introduction

A small-scale multi-axis positioning system is essential to ensure desktop manufacturing which enables savings in energy, space, and resources. We developed a three degree-of-freedom (dof) inchworm using piezoelectric actuators (piezos) and electromagnets, which obtains submicron accuracy along an unlimited travel stroke [1]. The 3-dof inchworm can move in arbitrary directions in three-dimensional space and manipulate small objects. The inchworm is used in a small scale manufacturing system, a multi-dof stage in a microscope, micro manipulation in a fertility study, and so on.

Precise position measurement plays an important role in positioning. Although some measuring devices using laser interferometry can measure the position with nanometer resolution [2], they are complicated devices. In addition, they measure one-dimensional displacement. Although we measured the position of the inchworm by optical displacement sensors, the measurement range of the sensors was smaller than the large travel stroke of the inchworm [1]. A camera vision system therefore was introduced to the position measurement of the inchworm [3]. The camera vision system can measure a position and orientation of the 3-dof inchworm in a three-dimensional space simultaneously, although the resolution of a camera vision system is inferior to that of high resolution sensors, such as an laser interferometer, a capacitance displacement meter, and an optical displacement meter.

In this paper, a control concept for a 3-dof inchworm is described. A feedback control loop is introduced to minimize the settling time for positioning of the inchworm. After the structure of the inchworm is described, a control concept of the inchworm is described. Then some experimental results show the feasibility of the proposed system.

2. Three-dof inchworm

A 3-dof inchworm consists of three stacked piezos and three electromagnets as shown in Figure 1. The piezo is 20 mm long, and it extends 17.4 μm at the applied voltage of 150 V_{DC}. The electromagnetic force of the electromagnet is approximately 5 N at 10 V_{DC}. Three piezos are connected in an equilateral triangle shape, and electromagnets are attached at the apexes of the triangle. This structure enables the inchworm to move in arbitrary directions in three-dimensional space. Dumbbell-shape hinges are used at the link between the electromagnet and piezo.

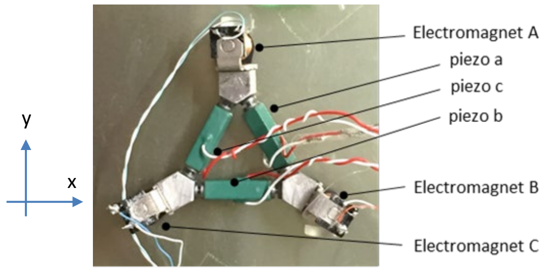


Figure 1. three-dof inchworm

One of the three electromagnets is not excited, and the others are excited. The non-excited electromagnet, which is a free electromagnet, sequentially moves by the deformation of the connected piezos. After one electromagnet moves, another electromagnet is free and moves.

Figure 2 shows one example of the control signals for y-displacement. While two of three electromagnets are excited and are On-state, they hold the position of the inchworm by the electromagnetic force. One of three electromagnets is not excited and is Off-state, and it moves by the deformation of the piezos. Three electromagnets sequentially moves by the deformation of connected piezos. While one electromagnet is in Off-state, the piezos connected to the electromagnet extend or contract and the electromagnet moves.

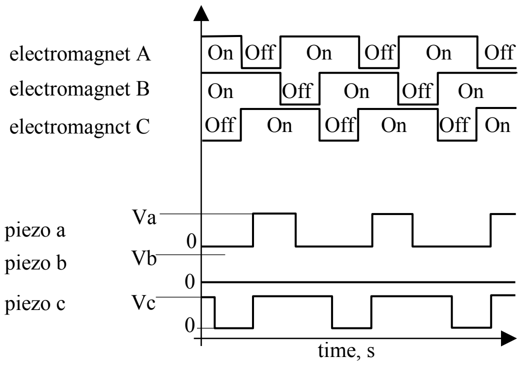


Figure 2. control signals for y-displacement

Figure 3 shows one example of the motion of the inchworm. Figure 3(1) indicates an initial condition. Three electromagnets are On-state and three piezos are in thier original length. When the inchworm moves in the y-direction, one control cycle consists of three motions. Off-state electromagnet shown by white circle sequentially moves by the extension and contraction of the piezos connected. In Figure 3(2), Off-state electromagnet A shown in white circle moves by the extension of piezo a and piezo c, while electromagnet B and electromagnet C are On-state and are not moved. Next, in Figure 3(3), Off-state electromagnet B shown in white circie moves by the contraction of piezo a. Then, in Figure 3(4), Off-state electromagnet C moves by the contraction of piezo c. By repeating the motion in Figure 3(2)- Figure 3(4), the inchworm moves in y-direction. The inchworm can move in arbitrary directions in three-dimensional space by changing the magnitude of extension and contraction of piezos.

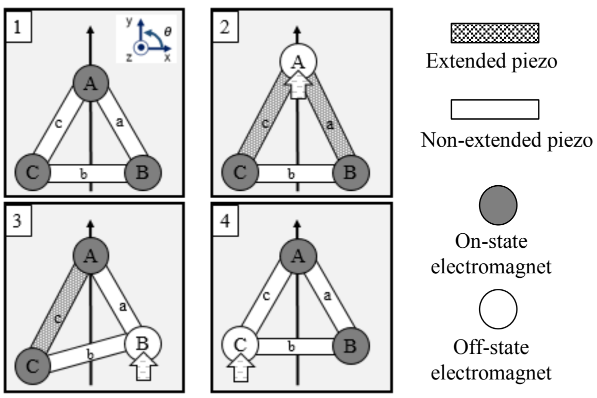


Figure 3. schematic motion of inchworm for y-displacement

A conventional piezo inchworm is essentially an incremental one-dimensional actuator similar with a stepper motor. The inchworm described in this paper, however, realizes 3-dof motion in a three-dimensional space. Since it does not use any guide elements, the electromagnets do not keep the inchworm's position. Therefore a 3-dof position measurement and feedback control are needed.

3. Position measurement and control of the inchworm

3.1. Position measurement with a USB camera

The position of the inchworm is measured with a USB camera [3]. It enables an xyθ position measurement of the inchworm, although there is not traceable sensor in the rotational displacement of the inchworm. Since the observed area of the camera is 60 mm x 45 mm and the effective pixels of the camera is 2048 x 1536, the resolution is 29.2 μm.

The captured images are processed by a computer (CPU: Intel Core i5-2400, clock: 3.10 GHz, 8 GB system memory). Two circular marks affixed to the electromagnets are found by using circular Hough transform of Matlab. The position of the inchworm is calculated after one step displacement is completed. As the central positions of the circles (x_1, y_1) and (x_2, y_2) are detected, the position (p_x, p_y) and orientation (p_θ) of the inchworm are calculated by

$$p_x = \frac{x_1 + x_2}{2}, p_y = \frac{y_1 + y_2}{2}, p_\theta = \tan^{-1}\frac{y_1 - y_2}{x_1 - x_2}. \qquad (1)$$

The resolution of the camera measurement system is 30 μm [3].

The processing time per one captured image is approximately 2 s. Therefore, the averaging calculation is not used in the experiment.

3.2. Control system

The block diagram of the position control is shown in Figure 4. The controller computes the number of cycles of the inchworm displacement in x-, y- and θ-direction. The number of cycles N_i $(i=x, y, \theta)$ are calculated by

$$N_x = \frac{r_x - p_x}{\Delta_x}, N_y = \frac{r_y - p_y}{\Delta_y}, N_\theta = \frac{r_\theta - p_\theta}{\Delta_\theta} \qquad (2)$$

where r_i, p_i, Δ_i denote the reference position, current position, and step displacement. The step displacement Δ_i is initially obtained by the preliminary experiment and is updated periodically in the positioning. Since the inchworm moves N_i steps, the averaging is realized and accidental error is eliminated. If the number of cycles N_i is negative, the inchworm moves in the reverse direction. The signal generator including an amplifier generates the signals applied to piezos and electromagnets.

In order to minimize the settling time of positioning, large piezo voltage is needed. The inchworm moves N_i steps in x-, y- and θ-direction. After the calculated steps are completed, the tuner changes the parameters Δ_i of the controller.

The proposed method calculates the number of step displacement in x-, y- and θ-direction. The next number of step displacement is determined after the calculated N_i steps in x-, y- and θ-direction are completed. The position of the inchworm is measured after one step displacement is completed, since the time used for image processing is approximately 2 s. The image processing time restricts the interval of the position measurement.

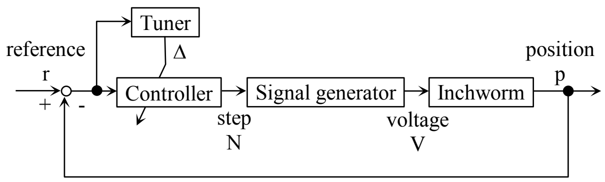


Figure 4. block diagram of the positioning system

4. Experimental

A preliminary experiment is conducted. The inchworm moves 300 μm in y-direction. The xyθ position is measured by a USB camera, and the y-position is compared to the position measured with a laser displacement sensor (Keyence, LK-G30A). The position obtained by the USB camera is used for feedback, since the control system will be applicable to a 3-dof positioning. The conventional sensors cannot measure the orientation of the inchworm, although this paper uses a laser sensor for evaluation. The position measured with the laser sensor is assumed to be a true value.

The step displacement Δ_y used in the controller is summarized in table 1. The number N_y of step is computed by equation (2). After one step is completed, the camera obtains the position of the inchworm. The laser sensor also measures the y-position of the inchworm continuously. After N_y step is completed, the next N_y is calculated and the inchworm moves. One step including position measurement costs 5 s.

Table 1 voltage, step displacement of inchworm, and number of steps

voltage to piezo, V	150	120	90
Δ_y, μm	17.00	14.53	8.85
N_y for 300 μm, steps	17	20	33

5. Results and discussion

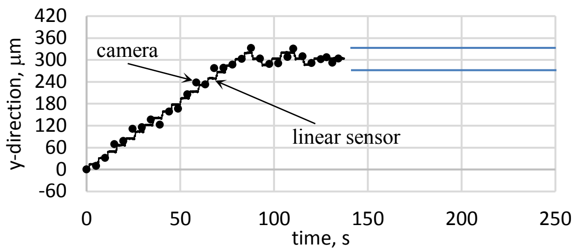
Figure 5 shows the experimental results. The step displacements are observed by the laser sensor. The results obtained by the camera are fluctuated, since the resolution of the camera is about 30 μm. In our previous work, the USB camera was used and the moving average calculation realized 5 μm resolution [3]. In this paper however the moving average calculation is not used since it costs calculation time.

The results measured by the laser sensor indicates that the large piezo voltage realizes the large step displacement. Therefore, at the beginning of the positioning, the large piezo voltage and small number of step displacement minimizes the settling time. The difference between the sensor and the camera is caused by the initial position measurement error.

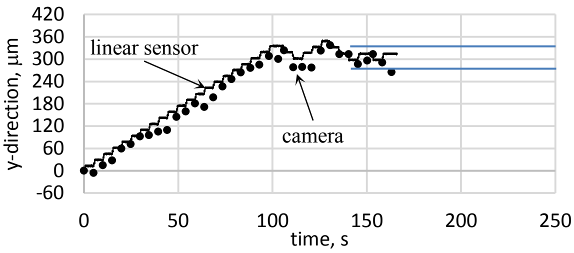
Since the number of step displacement is calculated first, the inchworm passes the final position and the overshoot occurs. These results imply that the step displacements Δ_y shown in table 1 are smaller than those of experimental results. After the inchworm completes the N_y steps and passes the final position, the next N_y is calculated by equation (2). The overshoot is associated with settling time.

Figure 5(a) shows that the inchworm reaches the reference position, 300 μm, in 130 s by the use of piezo voltage of 150 V. The resolution is about 30 μm. The position of the inchworm fluctuates by the piezo voltage of 120 V and 90 V. A poor measurement resolution and uncertainty of the step displacement Δ_y cause the fluctuation. In Figure 5(c) at 210 s, the position measured by the camera is 270 μm, while that measured by the laser sensor is 315 μm. This causes the inchworm moves in the wrong direction. In addition, the step displacement Δ_y for 90 V is smaller than that for 120 V and 150 V, and the larger number N_y induces a large positioning error. Therefore, the resolution of the measurement system needs to be improved.

In this paper, we used an inexpensive USB camera and a commonly used personal computer. The resolution of the position measurement therefore was approximately 30 μm. High resolution cameras, for example, 24 megapixel camera (6016 x 4000) or 8k camera (8192x4320), improve the resolution of the measurement. High performance computers, for example, a high end CPU: Intel Core i9, 32 GB system memory, and graphic processing unit, shorten the image processing time, which enable the moving average calculation of the captured images. The experiment was conducted in a room where lighting conditions were not controlled. Improvement of the components of the position measurement system and experimental conditions develops the performence of the position measurement and the positioning of the 3-dof inchworm. To minimize the positioning time, first, a large voltage is applied to piezo for the predetermined control cycle. Then the number of control cycle in x-, y-, and θ-direction is calculated and the voltage applied to piezo is changed. These developments will realize the submicron resolution of positioning [3].



a)



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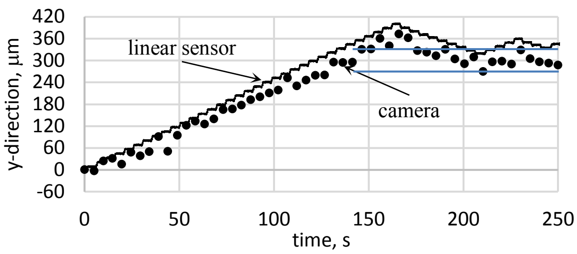

c)

Figure 5. experimental results obtained by piezo voltage of a) 150 V, b) 120 V, and c) 90 V

6. Summary

This paper described the position control strategy of a 3-dof inchworm. A feedback position control was introduced, and the number of step displacement of the inchworm was used. The experimental results showed the resolution was about 30 μm which corresponded to the resolution of the measurement system.

In future work, the parameters in the controller is tuned experimentally. A high performance computer and a high resolution camera are used in a feedback loop, and they will improve the resolution of the proposed system. The position and orientation of the inchworm are controlled by the proposed feedback loop.

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