The basic performance of a miniature omnidirectional 6-legged inchworm robot from cm- to μ m-scale precise positioning

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In this paper, we describe the basic performance of a miniature omnidirectional inchworm robot driven by six piezoelectric actuators and a pair of Y-shaped electromagnets using the inchworm principle of motion. In several experiments, we determined the repeatability of positioning via translational motion in 8 directions within a several centimeter range. We also describe the theory of the feedforward plus feedback control method within 1 step motion and its experimental results with 50 nm measuring resolution. These results may be applied in the development of multi-functional precise processing in the biomedical and nanoscience fields.

Key words: omnidirectional, piezoelectric actuator, inchworm, feedforward plus feedback

1. INTRODUCTION

Recently, there has been rapid growth in the markets involved in compact portable devices. Currently, the smallest chip part is the 0201, which is sized 0.2 mm x 0.1 mm. To mount these tiny chip parts, several tools are required, including air nozzles for picking up and placing down the chip, dispensers for applying a solder paste and a UV cure adhesive, and electronic testing probes. In the biomedical science field, several field-specific tools are required, e.g., injection and holding pipettes to manipulate cells and DNA[1]. In the nanoscience field, atomic force microscopy is one of the most useful tools for visualizing, manipulating, and processing nano materials. Sometimes several AFM probes and electronic testing probes are required to determine how to assemble the nano materials and investigate the nanometer-scale physical phenomena under heterogeneous conditions[2]. To position these probes with nanometer-scale resolution, a combination of piezoelectric stages for fine positioning and linear stages for coarse positioning are usually used. However, it is difficult to conduct experiments that require multi-probes because the conventional linear stages are large, and multiple linear stages cannot be arranged on or around microscopes simultaneously. The use of miniature precise mobile robots has been reported to downsize multiaxial positioning devices[3-6]. In previous study in [5] and [6], we have reported that the basic performance of 4-legged omnidirectional inchworm mechanisms. However, we have also confirmed that their positioning repeatability becomes worse because of inclination of their U-shaped electromagnets when we attach only 140g of pay load on them[5]. Contributions of this paper are development of 6-legged mechanism to prevent the inclination of the electromagnets and to determine its basic performances from centimeter to micrometer positioning range. In

section 2, the design and motion sequence of a unique 6-legged 3-degrees-of-freedom (3DoF) inchworm mechanism is explained. In section 3, the basic performance of using translational motions for positioning the mobile robot in the cm-scale range is demonstrated. In section 4, positioning in the micrometer-scale range using feedforward (FF) plus feedback (FB) control with a single axis model is described. In addition, the feasibility of using this mechanism for flexible and multi-functional precise processing in the biomedical and nanoscience fields is discussed.

2. THE OMNIDIRECTIONAL MECHANISM

Fig. 1 shows the structure of the omnidirectional mobile mechanism. EM_1 and EM_2 are two Y-shaped electromagnets that are positioned so they do not attract each other. These Y-shaped electromagnets make a closed loop via the ferromagnetic surface to generate magnetic force. PZT_F , PZT_B , PZT_{L1} , PZT_{L2} , PZT_{R1} , and PZT_{R2} are the six piezoelectric actuators. We arranged EM_1 and EM_2 to cross each other and connect via the six piezoelectric actuators such that the mechanism can move accurately in any direction using the principles of inchworm motion. Photographs of the mechanism are

Fig. 1 Structure of the omnidirectional inchworm mechanism (top view)

shown in Fig. 2. The mechanism weighs 100 g and is 86 mm in length, 86 mm in width, and 11 mm in height. The mechanism has parallel leaf springs to maintain smooth contact of all the legs on the surface simultaneously. For the actuators, we selected

Fig. 2 Photograph of the omnidirectional mechanism

Fig. 3 Sequence of translational motion along the X axis

APA50XS “Moonie” piezoelectric actuators (Cedrat Inc.), which were connected in series[5]. Table I shows the typical performance of the piezoelectric actuator. Fig. 3 shows the motion sequence of the translational motions in the X -axis direction, where A_F , A_B , A_{R1} , A_{R2} , A_{L1} , and A_{L2} are the amplitudes of the input voltages to the corresponding actuators. We assumed that the displacements of the actuators were proportional to the input voltages. We defined 1-step motion as the movement of the mechanism from $t=T/4$ to $5T/4$. This mechanism moves in a manner similar to that of an inchworm while retaining the synchronization of the rectangular-shaped forces of the two electromagnets and the sine-wave-shaped displacements of the six piezoelectric actuators. By altering $A_F \sim A_{L2}$, the mechanism can move accurately with 3DoF[6]. As shown in Fig. 4, this allows the mechanism to move straight in any direction and rotate precisely around any point with less than a 10 nm resolution. Therefore, this small mechanism has the ability to move flexibly and widely on well-polished ferromagnetic surfaces.

Table I Performance of a pair of “APA50XS” actuators connected in series

Parameter	Quantity
Displacement (100 V)	$95.5 \pm 5 \mu\text{m}$
Generative Force (100 V)	18.0 N
Spring constant	115,000 N/m
Resolution (15-25deg C, < 50% rH)	1.52 nm
Height x Thickness x Length	12.9x6.4x9.2 mm
Weight	4 g

Fig. 4 Motion patterns of the omnidirectional robot

3. TRANSLATIONAL MOTION IN THE CM-RANGE

To generate translational motion, we applied a sinusoidal voltage to the piezoelectric actuators up to 100 V_{p-p}. The applied voltages to the actuators, $V_F \sim V_{L2}$, are determined as follows:

$$\begin{bmatrix} V_F \\ V_B \\ V_{R1} \\ V_{R2} \\ V_{L1} \\ V_{L2} \end{bmatrix} \equiv A \cdot \sin \omega t \begin{bmatrix} -\cos \phi \\ -\cos \phi \\ \frac{1}{2} \cos \phi - \frac{\sqrt{3}}{2} \sin \phi \\ \frac{1}{2} \cos \phi + \frac{\sqrt{3}}{2} \sin \phi \\ \frac{1}{2} \cos \phi + \frac{\sqrt{3}}{2} \sin \phi \\ \frac{1}{2} \cos \phi - \frac{\sqrt{3}}{2} \sin \phi \end{bmatrix} + V_0. \quad (1)$$

Here, the moving direction is defined as ϕ as shown in Figs. 3 and 4. We determined the offset voltage to be $V_0=50$ V, which is half of the maximum voltage of 100 V. A is defined as the coefficient for changing the step width of the inchworm motion. We defined $f (=1/T)$ as the frequency of the inchworm motion. Fig. 5 shows an experimental setup for motion in the cm-range. We attached 4 LEDs to the mechanism to measure its

Fig. 5 Experimental setup

Fig. 6 Distribution of end points of translational motions in 8 directions

position and posture by the image analyzer (Keyence CV5700). We generated input signals using a D/A board (LabVIEW PCI-6723), which were then amplified 32-fold by the amplifier. We assumed the displacements of the actuators are approximately proportional to their voltages. As shown in Fig. 3, the rectangular-shaped currents to EM_1 and EM_2 are defined as I_1 and I_2 , respectively. The amplitudes of I_1 and I_2 were determined to be $I_a=0.6$ A. Fig. 6 shows the experimental results for the end points of the geometric center after the mechanism moves with translational motion in any of the 8 directions from the origin with $A=50$ V, $f=100$ Hz, and 100 steps. The targeted angles for φ were $0, \pi/4, \pi/2, 3\pi/4, \pi, 5\pi/4, 3\pi/2$, and $7\pi/4$. The path lengths and end points were measured 20 times for each φ . The error bars in fig. 6 were calculated as $\pm 6\sigma$ in the x and y directions, where σ is the standard deviation. Normally, $\pm 3\sigma$ is sufficient for evaluating the repeatability of the positioning stages. In this study, we ensured that the average 3σ was $240 \mu\text{m}$ and the average CV was 1.5% for a path length of $5030 \mu\text{m}$, where CV is calculated as the ratio of σ to the average path length. In addition, we confirmed that the mechanism followed target directions accurately and had good positioning repeatability under open loop control, as shown in Fig. 6. We also confirmed that the mechanism still had 2.7% of the average CV with 140g of pay load under open loop control.

4. MICROMETER-SCALE CONTROL

4.1 Single axis model

For micrometer-scale control in X axis, we calculated the optimal input signals to the 6 actuators for the minimum settling time and no slip conditions of the supporting electromagnet. In addition, we defined an equivalent single-axis dynamic model, as shown in Fig. 7. In this model, we defined x_1 as the x-axis position of EM_1 and x_2 as the x-axis position of EM_2 . Newton's equations of motion were applied to EM_1 and EM_2 as follows:

$$m_1 \ddot{x}_1 = 0 = 3c_s \dot{x}_2 + 3(k_s + k_L)x_2 - 3k_L f(t) + F_f. \quad (2)$$

$$m_2 \ddot{x}_2 = -3c_s \dot{x}_2 - 3(k_s + k_L)x_2 + 3k_L f(t). \quad (3)$$

Here, F_f is the frictional force, F_{ad} is the electromagnetic force between the ferromagnetic surfaces, and $f(t)$ is the enforced displacement of the piezoelectric actuator in the model. We neglected the frictional force of the free leg to simplify the problem. We determined the displacement of the 6 piezoelectric actuators as calculated by equation (4).

$$\begin{pmatrix} d_F & d_{L1} & d_{L2} & d_B & d_{R1} & d_{R2} \end{pmatrix} \equiv f(t) \begin{pmatrix} -1 & \frac{1}{2} & \frac{1}{2} & -1 & \frac{1}{2} & \frac{1}{2} \end{pmatrix}. \quad (4)$$

Fig. 7 Equivalent 1DoF dynamic model (side view)

4.2 FF control for minimum time trajectory

When EM_2 is positioned and stopped to specific target points, x_m , under the no slip condition of EM_1 , $f(t)$ can be calculated using equations (2), (3) and (4) as follows:

When $0 \leq t \leq \frac{t_m}{2}$,

$$f(t) = \frac{\mu F_N}{3k_L} \left(1 + \frac{3c_s}{m_2} t + \frac{3(k_s + k_L)}{2m_2} t^2 \right); \quad (5)$$

When $\frac{t_m}{2} \leq t \leq t_m$,

$$f(t) = \frac{\mu F_N}{3k_L} \left(-1 + \frac{3c_s}{m_2} (t_m - t) + 3(k_s + k_L) \left(-\frac{(t - t_m)^2}{2m_2} + \frac{t_m^2}{4m_2} \right) \right); \quad (6)$$

and when $t_m \leq t$,

$$f(t) = \frac{\mu F_N (k_s + k_L) t_m^2}{4m_2} = x_m. \quad (7)$$

Here, we define $F_N = m_2 g + F_{ad}$ as the perpendicular force of EM_2 , μ as the coefficient of static friction between the support leg and the surface, and t_m as the positioning time. This solution is bang-bang control with a combination of maximum and minimum accelerations. Fig. 8 shows the plot of the ideal displacement of $x_2(t)$ vs. time. Fig. 9 shows the plot of ideal enforced displacement of $f(t)$ vs. time. Fig. 10 shows the plot of the acceleration of $\ddot{x}_2(t)$. We used $f(t)$ of (5), (6), and (7) as the ideal input enforced displacements for FF control.

Fig. 8 Plot of an ideal x_2 vs. time Fig. 9 Plot of an ideal $f(t)$ vs. time Fig. 10 Plot of an ideal $\ddot{x}_2$ vs. time

4.3 Experimental setup

As shown in Figs. 11 and 12, we measured the displacement of the free leg with an optical linear encoder (MicroE Systems Inc., M3500), with a measuring resolution of $0.05\mu\text{m}$. The encoder was fixed to an inverse U-shaped jig fixed to a working table. In this setup, a glass scale was

Fig. 11 Experimental set

Fig. 12 Close up view of the mechanism with the encoder

placed on the free leg, and the support leg was fixed to the working table with clamp screws, so we measure relative position between the free leg and the support leg in X axis with 50 nm resolution. Input signals were generated with a D/A board (LabVIEW PCI-6723) and amplified 32-fold with an amplifier. We assumed that the displacements of the actuators are approximately proportional to their input voltages, which we defined as the proportional coefficient, C . Therefore, we can calculate the input voltage to the actuator, $V(t)$, as follows:

$$V(t) \equiv C \cdot f(t). \quad (8)$$

We determined the parameters as listed in table II, which were applied to equations (5), (6), (7), and (8) for calculating $V(t)$.

Table II Parameters

Symbol	Parameter	Quantity (Average $\pm \sigma$)
m_2	Mass of electromagnetic leg	0.045 [kg]
k_s	Spring constant of the actuators in shear deformation	Negligibly small
k_L	Spring constant of the actuators in compression deformation	115000 [N/m]
c_s	Damping constant of the actuators in shear deformation	$5.5 \pm 0.93\text{ [Ns/m]}$
C	Proportional coefficient	$-1.02\text{ [V/}\mu\text{m]}$
μ	Coefficient of static friction	0.14
F_{ad}	Electromagnetic force	14.1 [N]

4.4 Experiments of FF plus FB control

As shown in Fig. 7, there are many springs in the mechanism because we use the mechanical amplifier to the actuators as shown in Fig. 2. Those springs easily generate non-negligible vibrations. If we use only proportional-integral-derivative (PID) control without FF control, it is difficult to remove an overshoot and a vibration under sub- μm scale. The overshoot and the vibration are harmful for delicate precise processing because tiny samples might be easily collapsed. FF control is good for decreasing the overshoot and the residual vibration and also good for decreasing settling time. However, it is impossible to eliminate the vibration completely especially under sub- μm scale only by FF control because there are numerous non-linear effects such as a thermal drift and a hysteresis of the actuators. PID control is good for surely reducing the residual vibration and the non-linear effects after FF control. These are the reason why we selected the FF plus PID control. In Fig. 13, we show the block diagram of PID control for FB control of the free leg. First, we moved the free leg by the FF control, and if the positioning error was within 2%, we changed the control to PID control to remove the residual vibration and the non-linear effects, as shown in Fig. 14. We set the target positions to $5\mu\text{m}$, $10\mu\text{m}$, $15\mu\text{m}$, $20\mu\text{m}$, $25\mu\text{m}$, and $30\mu\text{m}$. We also conducted experiments with only FF control to show how long the residual vibration influences the precise positioning. We repeated the experiments 10 times at each target position. As shown in Fig. 15, we found that the settling time

could be decreased down to 0.05 s, which is one-sixth the time required under pure FF control. The residual vibration remained at least 250 ms after the positioning error became within 2% by FF control. As shown in Fig. 16, we were also able to decrease the positioning error down to 0.05 μm . Therefore, we found that the mechanism has less than 50 nm positioning resolution. In Fig. 14, the FB cycle is approximately 0.015 s, and the natural cycle of the mechanism is approximately 0.0025 s. The FB cycle should be less than the natural cycle to make the integral and derivative control more effective however the FB cycle becomes larger than the natural cycle on this experimental set up. The main factor that determines the FB cycle is the calculation time of the LabVIEW software and communication speed

Fig. 13 Block diagram of PID control

Fig. 14 Plot of $x_2(t)$ vs. time by FF and PID control

Fig. 15 Plot of settling time vs. target position

Fig. 16 Plot of positioning error vs. target position

between the software and the DA-board of PCI-6723. We plan to minimize the FB cycle by using a FPGA board. However, we have confirmed FF plus PID control is feasible for controlling the mechanism in μm scale positioning with the encoder of 50 nm measuring resolution.

5. CONCLUSIONS AND FUTURE WORKS

In this paper, we described the basic performance of a miniature omnidirectional 6-legged inchworm robot. In addition, we described a feedforward (FF) plus feedback (FB) control method to obtain 0.05 μm positioning resolution with μm -scale on a single axis. In experiments, we were able to move the robot with translational motions in 8 directions under open loop control in cm scale range. We also ensured that the mechanism had good positioning repeatability, i.e., the 3σ of the final position was 240 μm and the average CV was 1.5 % for a path length of 5030 μm under open loop control. In FF and PID control experiments, the settling time could be decreased to 0.05 s when the target position was up to 30 μm with a positioning resolution of 50 nm. In future work, we plan to minimize the FB cycle by using a FPGA board. We also plan to develop the device to obtain 3DoF simultaneous FF plus FB control with less than 50 nm resolution. In addition, we plan to develop the chip mounting and cell-processing organized by the robot to allow flexible and multifunctional precise processing for use in nanoscience, biomedical, and chip/MEMS mounting technologies.

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