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# Design and Performance Evaluation of a 3-DOF Mobile Microrobot for Micromanipulation

**Jungyul Park, Deok-Ho Kim, Byungkyu Kim***
*Microsystem Research Center, Korea Institute of Science and Technology,*
*39-1 Hawolgok-dong, Seongbuk-gu, Seoul 136-791, Korea*
**Taesung Kim**
*Department of Mechanical Engineering, University of Michigan G. G. Brown,*
*2350 Hayward, Ann Arbor MI 48109*
**Kyo-Il Lee**
*School of Mechanical and Aerospace Engineering, Seoul National University,*
*San 56-1, Shillim-dong, Kwanak-gu, Seoul 151-742, Korea*

In this paper, a compact 3-DOF mobile microrobot with sub-micron resolution is presented. It has many outstanding features: it is as small as a coin; its precision is of sub-micrometer resolution on the plane; it has an unlimited travel range; and it has simple and compact mechanisms and structures which can be realized at low cost. With the impact actuating mechanism, this system enable both fast coarse motion and highly precise fine motion with a pulse wave input voltage controlled. The 1-DOF impact actuating mechanism is modeled by taking into consideration the friction between the piezoelectric actuator and base. This modeling technique is extended to simulate the motion of the 3-DOF mobile robot. In addition, experiments are conducted to verify that the simulations accurately represent the real system. The modeling and simulation results will be used to design the model-based controller for the target system. The developed system can be used as a robotic positioning device in the micromanipulation system that determines the position of micro-sized components or particles in a small space, or assemble them in the meso-scale structure.

**Key Words:** Impact Actuating Mechanism, Piezoelectric, Modeling, Microrobot, Micromanipulation

## 1. Introduction

Recent advancements in micro/nano technology have created the need for appropriate devices for precise positioning of objects. These instruments are used to manipulate micro components or to measure nano-scale surface profiles with SPM (scanning probe microscope). Previous realizations of the platforms for micro positioning mainly involved parallel stages. This mechanism is very reliable and has a high resolution for positioning. Some drawbacks of such solutions are high space requirement, high cost and highly limited working space. To overcome these drawbacks, Higuchi's group (Higuchi et al., 1990: Yamagata et al., 1995: Mendes et al., 1996) presented the impact drive mechanism and platform which allow an unlimited travel range and yield a compact system. Later, many instruments using this mechanism (Juhas et al., 2000: Martel et al., 1999: Shim et al., 2001) have appeared.

In this paper, a compact 3-DOF ($x$, $y$ translation, $\theta_z$ rotation) mobile microrobot using the

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* Corresponding Author,
**E-mail**: bkim@kist.re.kr
**TEL**: +82-2-958-6730; **FAX**: +82-2-958-6910
Microsystem Research Center, Korea Institute of Science and Technology, 39-1 Hawolgok-dong, Seongbuk-gu, Seoul 136-791, Korea. (Manuscript **Received** September 27, 2002; **Revised** February 7, 2003)

impact actuating mechanism with sub-micron resolution is presented. The stacked piezoelectric actuator is used for impact actuation. The piezoelectric element can be controlled accurately from a few picometers to a few hundred micrometers, and can generate large force at high frequencies. Moreover, the piezoelectric element can be used as a sensor which has high sensibility, such as a force sensor and a pressure sensor (Nam et al., 2002). Therefore, much research has been made using piezoelectric actuators, such as active vibration control of a flexible cantilever beam (Oh et al., 1998), and piezoelectric smart structures for noise reduction (Lee et al., 1999). In this study, the stack piezoelectric actuator is used for its small size and large force with high frequency.

Therefore, the presented microrobot has many advantages with its small size, high precision, an unlimited travelling range, compact structures, and low cost. With the impact actuating mechanism, this system enable both fast coarse motion and highly precise fine motion with a pulse wave input voltage controlled. The developed system can be used as a robotic positioning device in micromanipulation systems that determines the position or assemble micro-sized components or particles in a small space.

The 1-DOF impact actuating mechanism in consideration of the stick-slip model between the microrobot and the base is simulated. This result is extended to a model for the 3-DOF mobile microrobot. Using these results, simulations are performed for the target system. In addition, experiments are carried out to verify usefulness of the simulations. The modeling and simulation results will be used to design the model-based controller for the target system.

## 2. 3-Dimensional Microrobotic Manipulation System

Figure 1 shows the schematic of a sensor-based microrobotic manipulation system (Kim et al., 2002). It comprises a self-sensing AFM cantilever and a 3-DOF mobile microrobot under a confocal laser scanning microscope (model: ZEISS LSM5 PASCAL) (Sheppard, 1997). In order to observe the microscopic physical environment, a microrobotic manipulation system is equipped with different kinds of sensors, such as a visual sensor and a piezoresistive force sensor. The confocal laser scanning microscope as a visual sensor has a lateral resolution of about 200 nm and a vertical resolution of about 100 nm. In addition, the self-sensing AFM cantilever can sense gripping force with sub-nanonewton resolution by measuring changes in stress-induced electrical resistance. The developed mobile microrobot on a well-polished base is used as a subsystem which provides 3-DOF motion with sub-micron resolution in a small working space under the confocal laser scanning microscope.

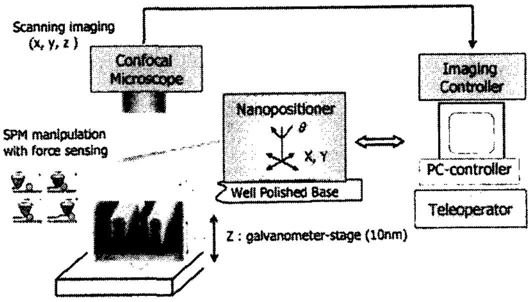


**Fig. 1** Schematics of a microrobotic manipulation system consisting of a 3-DOF mobile microrobot, a piezoresistive AFM cantilever, and a confocal laser scanning microscope

As shown in Figure 1, the 3-DOF mobile microrobot is integrated with a piezoresistive AFM-cantilever ("AFM-based nanomanipulator" for short) which can move in the $x$, $y$, and $\theta_z$ directions by using the compact and simplified impact actuating mechanism. It comprises one square shaped main body and four inertia parts integrated with multilayer piezoelectric actuators (model: AE505D08 from Tokin). The structure is symmetric and has three contact points at the bottom of the main body for reliable performance in translation and rotation. It has no limitation in the travel range with sub-micron resolution. Its moving and rotating velocity and direction are easily controlled with a saw-tooth wave input generated. When it is needed to translate in the $x$-direction, the 2nd piezoelectric actuator must be extended and the 4th contracted rapidly. If

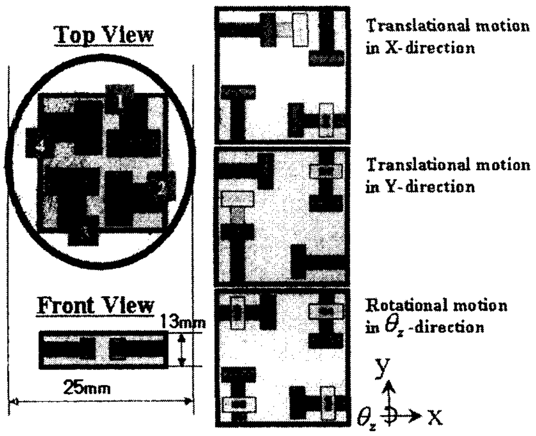


**Fig. 2** Schematics of a 3-DOF mobile micro robot: mechanical design and operating principle

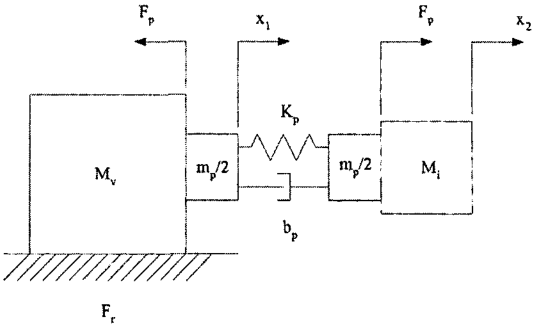


**Fig. 3** Schematics of the 1-DOF impact actuating mechanism in motion

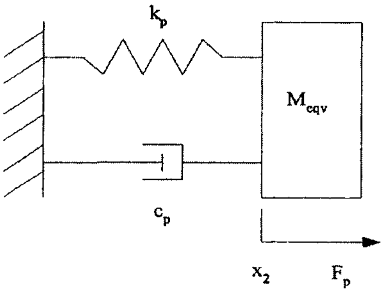


**Fig. 4** Schematics of the 1-DOF impact actuating mechanism when stuck

the opposite direction is desired, the behaviors of the 2nd and 4th piezoelectric actuators are required in the reverse direction. The similar method is used to move in the y-direction and $\theta_z$ rotation. Two piezoelectric actuators are used for translation and four piezoelectric actuators are required for rotation (see Figure 2).

## 3. Analytic Models

### 3.1 Modeling of 1-DOF impact actuating mechanism

For estimation of the operating conditions and performance, modeling of the target system is essential. First, the 1-DOF impact actuating mechanism is presented using a switching model including the stick-slip model. We assume that a piezoelectric actuator behaves like a mass-spring-damper system (Michael et al., 1997: Adriaens, et al., 2000). In the previous work, the modeling of a piezoelectric actuator was focused on the behavior in which one end of the actuator is fixed and the other is free. In this article, we separate the slip model in which the inertia part and the main body move simultaneously, and the stick model in which the inertia part moves but the main body is stuck as the criterion of an equilibrium point between the friction force and the piezoelectric force. Figures 3 and 4 show a diagram for the 1-DOF impact actuating mechanism when it moves or is stuck. This modeling is described in Eqs. (1) ~ (2). In the slip model, it is assumed that the mass of a piezoelectric actuator is divided into identical parts. In the stick model, because it is similar to the model employed by Adriaens et al. (2000), the mass of the piezoelectric actuator is added to the inertia mass.

Slip model

$$\begin{aligned}(M_v+1/2m_p)\ddot{x}_1&=b_p(\dot{x}_2-\dot{x}_1)+k_p(x_2-x_1)-F_r-F_p\\(M_i+1/2m_p)\ddot{x}_2&=b_p(\dot{x}_1-\dot{x}_2)+k_p(x_1-x_2)+F_p\end{aligned}\qquad(1)$$

subject to

$$\mu_s(M_v+m_p+M_i)g\leq|b_p(\dot{x}_2-\dot{x}_1)+k_p(x_2-x_1)-F_p|$$

In Eq. (1), $F_r=Sgn(\dot{x}_1)\mu_k(M_v+m_p+M_i)g$ is the friction force, $F_p$ is the piezoelectric force produced by voltage in PZT, $M_v$ is the mass of the main body, $M_i$ is the mass of the inertia part, $m_p$ is the mass of the piezoelectric actuator, $b_p$ is the damping coefficient of the piezoelectric actuator, and $k_p$ is the spring constant of the piezoelectric actuator.

Stick model

$$M_{eqv}\ddot{x}_2 = b_p(-\dot{x}_2) + k_p(-x_2) + F_p \tag{2}$$

subject to

$$\mu_s(M_v + m_p + M_i)g > |b_p(\dot{x}_2 - \dot{x}_1) + k_p(x_2 - x_1) + F_p|$$

In Eq. (2), $M_{eqv} = M_i + \frac{4m_p}{\pi^2}$ is the equivalent mass of inertia part and PZT.

### 3.2 Modeling of the 3-DOF mobile microrobot

Figure 5 shows a schematic diagram for the 3-DOF mobile microrobot. The modeling technique in the previous chapter can be easily extended to the modeling of the 3-DOF mobile microrobot. Since modeling of translation in the x-direction and in the y-direction is conducted in the same way, modeling of translation only in the x-direction is described in this article. Rotation of the main body is considered as the sum of torques induced from the acceleration of four inertia parts and the friction force.

Equations of motions for translation and rotation are derived as follows:

Modeling of translation

$$\begin{aligned}(M_{mv} + 3m_p + 2M_{mi})\ddot{x} &= b_p(\dot{x}_1 - \dot{x}) + k_p(x_1 - x)\\ &\quad + b_p(\dot{x}_2 - \dot{x}) + k_p(x_2 - x)\\ &\quad - (F_{p1} + F_{p2}) - F_r \qquad (3)\\ (M_{mi} + 1/2m_p)\ddot{x}_1 &= b_p(\dot{x} - \dot{x}_1) + k_p(x - x_1) + F_{p1}\\ (M_{mi} + 1/2m_p)\ddot{x}_2 &= b_p(\dot{x} - \dot{x}_2) + k_p(x - x_2) + F_{p2}\end{aligned}$$

Modeling of rotation

$$\begin{aligned}I_{mv}\ddot{\theta} &= M_{meqv}(\ddot{x}_1 - \ddot{x}_2 + \ddot{y}_1 - \ddot{y}_2)\,l - F_r a\\ M_{meqv}\ddot{x}_1 &= b_p(-\dot{x}_1) + k_p(-x_1) + F_{p1}\\ M_{meqv}\ddot{x}_2 &= b_p(-\dot{x}_2) + k_p(-x_2) + F_{p2} \qquad (4)\\ M_{meqv}\ddot{y}_1 &= b_p(-\dot{y}_1) + k_p(-y_1) + F_{p3}\\ M_{meqv}\ddot{y}_2 &= b_p(-y_2) + k_p(-y_2) + F_{p4}\end{aligned}$$

In Eqs. (3) ~ (4), $I_{mv}$ is the equivalent rotational inertia of the main body, $M_{mv}$ is the mass of the main body in the microrobot, $M_{mi}$ is the mass of the inertia part in the microrobot, $M_{meqv}$ is the equivalent mass of the inertia part and PZT in the microrobot.

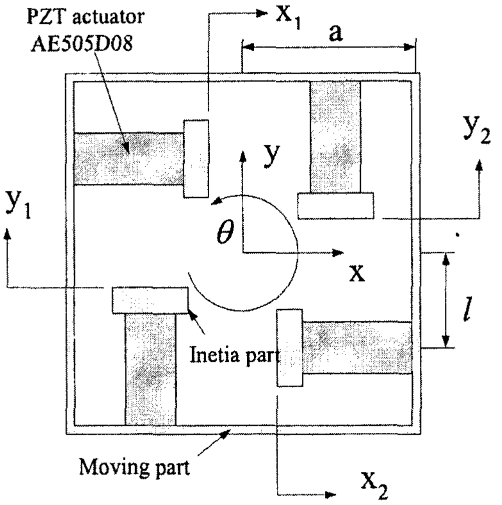


**Fig. 5** Schematics of the 3-DOF mobile microrobot

Based on the above equations, various simulations were performed using MATLAB/SIMULINK to design the control strategy and shapes of the input signal. These simulations can be used to evaluate the effect of the parameters such as the ratio of masses between the main body and the inertia part, and the friction coefficient between the target system and the base.

Figure 6 shows the simulation results regarding the effect of ratio of masses between the main body and the inertia part in the 1-DOF impact actuating mechanism. The assumption for simulation is that a force of 800 N force is generated from the multilayer piezoelectric actuator. As a result, the main body should be made as heavy as possible and the inertia part as light as possible for more accurate positioning of the target system. Thus, we select SUS304 for the inertia part and aluminum for the main body. Figure 7 shows the experimental results about variation of step size according to the ratio of masses between the main body and the inertia part in the 1-DOF impact actuating mechanism. The data points are determined as the mean value of repetition of identical simple saw-tooth wave forms. The variation of step size in the experiments is similar to that of simulation. A small value of the mass ratio leads to the small step size of the main body. Using this small step size, the microrobot can be controlled accurately.

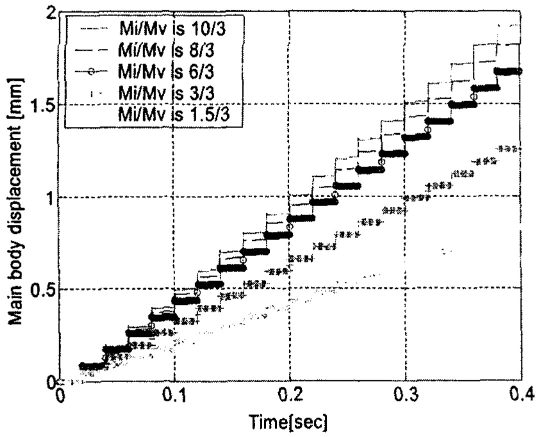


**Fig. 6** Variation of displacement according to the ratio of masses

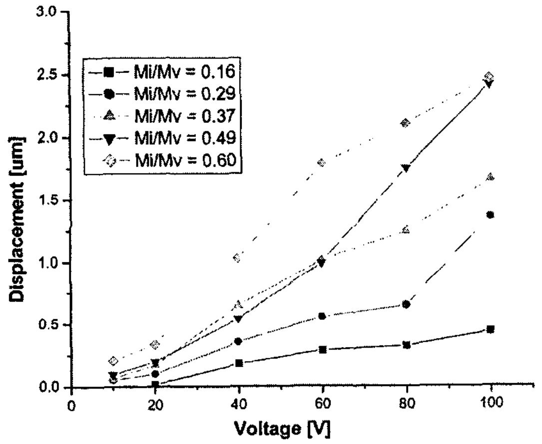
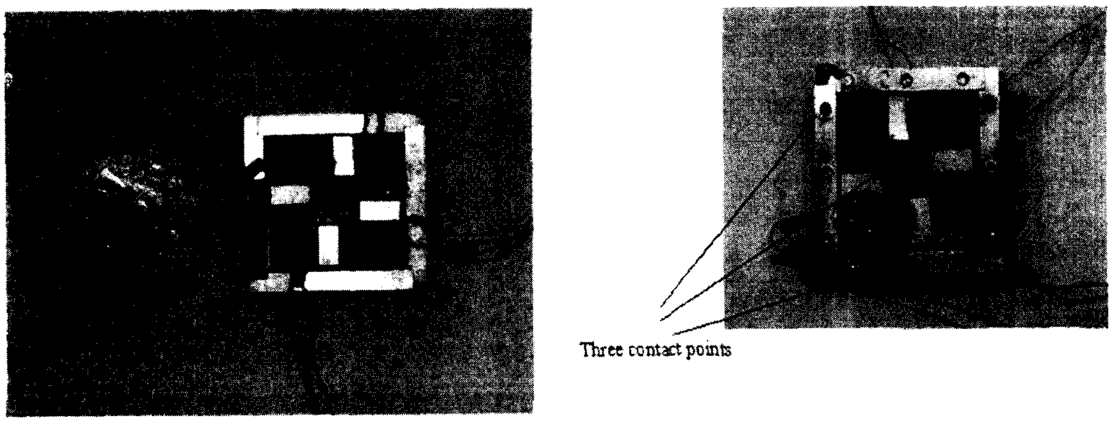


**Fig. 7** Experimental results about variation of displacement according to the ratio of masses

## 4. Fabrication and Experimental Setup of 3-DOF Mobile Microrobot

Figure 8 shows a photograph of the fabricated 3-DOF mobile microrobot. The dimension of the 3-DOF mobile microrobot is 26.5×26.5×7 mm. The main body is composed of four SUS304 metals and its dimension is 26.5×7×3 mm. The inertia part is made of aluminum and its size is 6×6×3 mm. There are three contact points which correspond to the vertices of an equilateral triangle at the bottom of the main body for preserving the stability of the system. Three contact points are required for stable control of a microrobot. If four or more contact points exist, at least one of them is redundant in movement. In previous work, such as Fahlusch and Fatikow (2001), and Martel et al. (1999), three legs are used for the microrobot. To guarantee uniform friction force, the well-polished base is made of Cr-plated S45C.

*Figure 9 shows the experimental setup for the* 3-DOF mobile microrobot. The control program was implemented using the C++ Builder. A 12-bit digital analog (DA) converter was used to supply pulses to the four piezoelectric actuators. The displacement and velocity are monitored by a laser vibrometer from Polytec and data is acquired through a 12-bit analog digital (AD) converter to the main computer.



(a) Top view of microrobot (b) Bottom view of microrobot

**Fig. 8** Photograph of the 3-DOF mobile microrobot

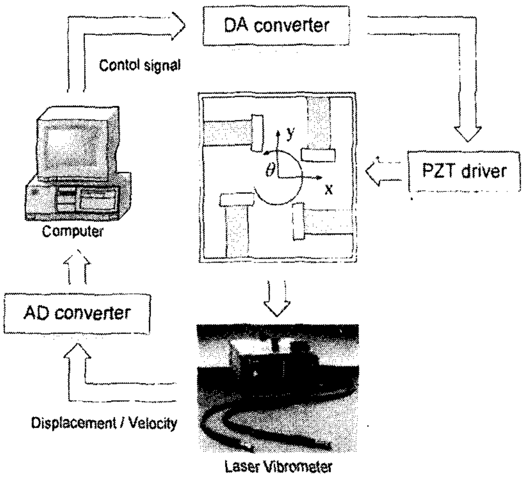


**Fig. 9** Experimental setup for the 3-DOF mobile microrobot

## 5. Experimental Work on the 3-DOF Mobile Microrobot

To examine the performance of the device, a simple saw-tooth wave is applied to the piezoelectric actuator. The driving frequency is 500 Hz, and the voltage amplitude is 20 V for fine motion and 80 V for coarse motion. As shown in Figure 10, the speed of the device is almost constant (has a constant slope) when the frequency and amplitude of the input signal are fixed. Figure 11 shows that the device provides translational motion with around 0.1 $\mu$m resolution, when 50 V is applied. 50 V is the smallest input size that can distinguish the smallest displacement signal from the raw data. Below this voltage, we can not determine smallest resolution because of noise in signal. Through these results, the presented device can be effectively used for micromanipulation systems.

Figure 12 shows the comparison of simulations with experiments. The experimental result shows the translational motion in the x-direction when the saw-tooth input voltage, whose amplitude is 80V and frequency is 1 Hz, is applied. The simulation conditions are the same as those of the experiments. As indicated in Figure 11, the model derived in this study is feasible and the simulation is very useful in estimating the behavior of the target system.

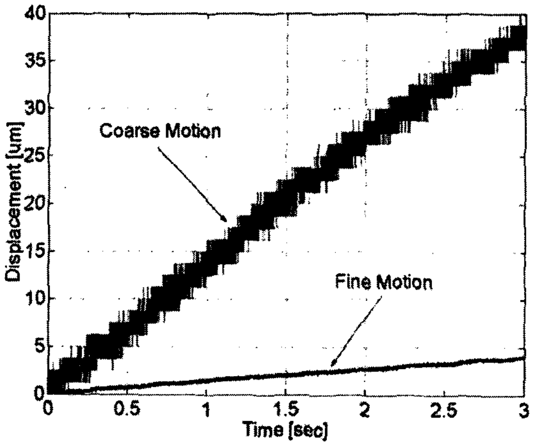


**Fig. 10** Comparison of coarse translational motion with fine translational motion

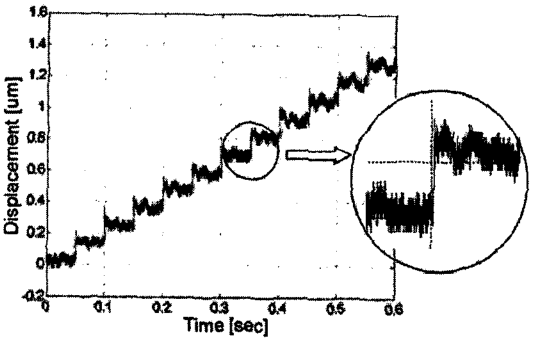


**Fig. 11** Experimental result showing the resolution in translational motion below the sub-micron level when 50 V is applied

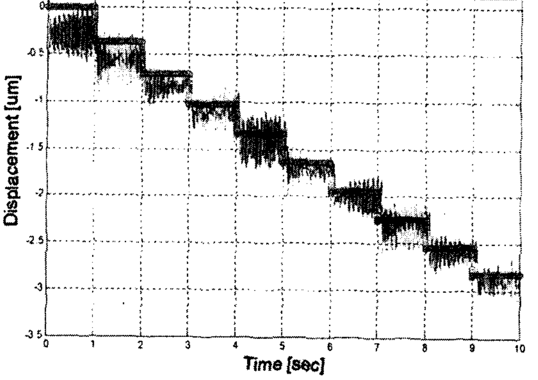


**Fig. 12** Comparison of simulation with experiment results

Using the modeling and simulation, not only can we predict behavior of the system, but also we can calculate the sensitivity of the system parameters and design the model-based controller for the target system.

## 6. Conclusions

In this paper, we propese a 3-DOF mobile microrobot for applications in micromanipulation. The device is as small as a coin, can move in the $x$, $y$, and $\theta_z$ direction on the plane with sub-micrometer resolution. It can travel an unlimited range, and is simple and compact. Therefore, it can be realized at low cost. By using the impact actuating mechanism, this system is capable of both fast coarse motion and highly precise fine motion by controlling a pulse wave of the input voltage.

To estimate the operating conditions and performance, modeling of the target system is derived. Based on the model, simulations are performed using MATLAB/SIMULINK to design the control strategy and shapes of the input signal. Experiments are conducted to check the system performance of positioning. The minimum step size, which can be controlled, is around 0.1 $\mu$m in translation and can easily be controlled by changing the amplitude of the voltage. Simulations are verified through the experiments and faithfully represent the real system.

The 3-DOF mobile robot provides the guidelines for design of a microrobot system, which is used in a small space, and when long travel length with sub-micro resolution is required. The presented 3-DOF mobile microrobot may effectively be used in micromanipulation systems.

## Acknowledgment

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## References

Adriaens, H., et al., 2000, "Modeling Piezoelectric Actuators," *IEEE/ASME Transactions on Mechatronics*, Vol. 5, No. 4, pp. 331~341.

Fahlbusch, S. and Fatikow, S., 2001, "Implementaton of Self-Sensing SPM Cantilevers for Nano-Force Measurement in Microrobotics," Ultramicroscopy, Vol. 86, pp. 181~190.

Higuchi, T., et al., 1990, "Precise Positioning Mechanism Utilizing rapid Deformations of Piezoelectric Elements," *Micro Electro Mechanical Systems, Proceedings, An Investigation of Micro Structures, Sensors, Actuators, Machines and Robots. IEEE*, pp. 222~226.

Juhas, L., et al., 2000, "Development of Platform for Micro-Positioning Actuated by Piezo-Legs," *Proceedings of the 2000 IEEE International Conference on Robotics & Automation*, San Francisco, CA, pp. 3647~3653.

Kim, D. H., et al., 2002, "Implementation of Self-Sensing MEMS Cantilevers for Nanomanipulation," Proc. the 4th Korean MEMS conference, pp. 120~125.

Lee, J. K., et al., 1999, "Piezoelectric Smart Structures for Noise Reduction in a Cabin," *KSME International Journal*, Vol. 13, No. 6, pp. 451~458.

Martel, S., et al., 1999, "NanoWalker : A Fully Autonomous Highly Integrated Miniature Robot for Nano-Scale Measuremtents," Proceedings of the European Optical Society (EOS) and SPIE International Symposium on Enviosense, Microsystems Metrology and Inspection, Vol. 3825, Munich, Germany 12 pages.

Mendes, J., et al., 1996, "Printed Board Positioning System Using Impact Drive Mechanism," SICE, Tottori, pp 1123~1128.

Michael, G. and Nikola, C., 1997, "Modeling Piezoelectric Stack Actuators for Control of Micromanipulation," *IEEE Control Systems Magazine*, Vol. 17, No. 3. pp. 69~79.

Nam, Y. S. and Sasaki, M., 2002, "Strain Rate Self-Sensing for a Cantilevered Piezoelectric Beam," *KSME International Journal*, Vol. 16, No. 3, pp. 310~319.

Oh, J. E., et al., 2000, "Active Vibration Control of Flexible Cantilever Beam Using Piezo Actuator and Filtered-X LMS Algorithm," *KSME International Journal*, Vol. 12, No. 4, pp. 665~671.

Sheppard, C. J. R., 1997, Confocal Laser Scanning Microscopy, Springer.

Shim, J. Y. and Gweon, D. G., 2001, "Piezo-Driven Metrological Multiaxis Nanopositoner," *Review of Science Instruments*, Vol. 72, No. 11, pp. 4183~4187.

Yamagata, Y. and Higuchi, T., 1995, "A Micropositioning Device for Precision Automatic Assembly Using Impact Force of Piezoelectric Elements," *IEEE International Conference on Robotics and Automation*, Nagoya, Aichi, Japan, pp. 666~671.