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A precision robot system with modular actuators and MEMS micro gripper for micro system assembly

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Abstract

A robotic system which consists of a precision manipulator and a micro gripper for a micro system assembly is presented. The developed P-R-R type 3 DOF robot is actuated by newly proposed modular revolute and prismatic actuators. As an end-effector of this manipulator, a micro gripper is designed and fabricated with MEMS technology, and the displacement of the jaw is up to 142.8 μm. A real gripping test is conducted to evaluate the robotic system.

Keywords: Precision robot system; Modular actuator; MEMS gripper; Micro system assembly

1. Introduction

A robotic system that can manipulate infinitesimal objects is an essential device for micro assembly systems and life science applications. Some robotics researchers have been interested in micro assembly systems which have sub-micrometer or nano meter accuracy for last decade [1, 2], and currently, some researches on cell manipulation have been reported, such as the patch & clamp, cell injection, and optical trapping [3]. A precision manipulator and micro gripper is an essential device for micro manipulation. As an actuator for precision robots, micro stepping motors, voice coil motors and piezoelectric actuator are used, and it is necessary to determine the required precision first, which depends on the size of object to manipulate. Commercial robotic systems which are actuated by stepping motors and have about 1 ㎛ resolution are announced by major manipulator manufacturer such as Sutter, RI and Narishige. For more precise robot systems, a piezoelectric actuator is widely used. A piezoelectric actuator is preferred to a conventional electro-magnetic actuator because it has good linear characteristics, fast response time, and compact size. But its displacement is too small to be used for a robotic system which has a large workspace, only a few hundred micrometers at most. So, various methods to extend its stroke have been introduced [4]. Some precision manipulators which are actuated by piezo actuator are produced by major vendors such as EXFO. The workspace, speed, and resolution are important features of precision robots.

The micro-gripper as an end-effector is a gripping and releasing apparatus to control the precise position, assemble micro parts. Micro grippers can be largely classified into four groups (thermal, electrostatic, pneumatic, piezo micro-gripper) according to the actuation mechanism [5].

In this paper, a 3DOF P-R-R type experimental precision manipulator which is actuated by piezoelectric actuators and has nanometer level resolution is devised. We propose a new prismatic and a revolute

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piezoelectric modular actuator which has a long stroke, and we built a 3DOF robot manipulator by combining the proposed actuators. Speed and resolution analysis of the devised manipulator was performed. And as an end-effector, a new silicon microgripper which is actuated by piezoelectric materials was fabricated with MEMS technology. Optimal shape of the micro gripper depends on the task and property of the object. Varying the mechanical design parameters, the displacement amplification effect of micro grippers is examined. And, finally, two real gripping tests are conducted to evaluate the performance of the experimental robotic system.

2. Design of prismatic and revolute actuator modules

To implement an experimental precision manipulator, a new prismatic and a revolute modular actuator is proposed.

2.1 Proposed prismatic actuator

The inchworm type actuator has strong force and good stiffness, but moves slowly at a speed of a few millimeters per second [6]. The basic operation principle of the inchworm actuator is described in [6]. The speed of an actuator determines the productivity, so the inchworm type actuators have been improved [7-10]. We adopt an inchworm style actuator as a prismatic actuator and propose an inchworm type actuator as shown in Fig. 1. To make the stage frame compact, the proposed actuator is integrated into the stage body.

The motion of an inchworm actuator consists of clamping motions and extension/contraction motions. Long stroke can be accomplished by repeating the clamping-extension sequence, and high resolution can be attained by the accurate displacement of extension/contraction motion. Motions of an inchworm actuator consist of a series of N discrete motions per each cycle, and then the average speed of inchworm actuator S is given as Eq. (1) [10].

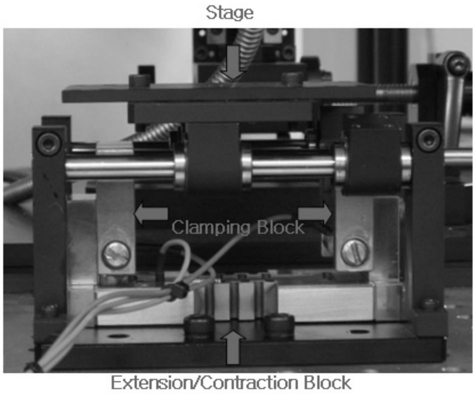

Fig. 1. Proposed inchworm type actuator.

$$S = \frac{\sum_{i}^{N} d_i}{\sum_{j}^{N} t_j} \tag{1}$$

d_i : travel of i-th motion (zero for clamping motion)
t_j : time required to complete j-th motion

To estimate S, we need to approximate t_j. Each piezo actuator of the inchworm actuator is modeled with two models, electrical and mechanical. Electrical response time t_e is given as Eq. (2) [11].

$$t_e = C\frac{V}{I} \tag{2}$$

I : current, C : capacitance of piezo actuator,
V : voltage input

Mechanically, each piezo actuator can be modeled with 2nd order mass-spring-damper system. Mechanical response time t_m is approximated to the rising time as Eq. (3).

$$t_m \approx \frac{1.8}{\omega_n} \tag{3}$$

ω_n : natural frequency

Then, t_j is given as Eq. (4)

$$t_j \geq \max(t_e, t_m) \tag{4}$$

So, design rules to increase the speed of the actuator are as follows.

1) Increase the travel length through one cycle.
2) Decrease the time required to complete each motion.
3) Decrease the number of steps to be required to complete one cycle

Maximum speed and resolution of proposed inchworm actuator is 6.5 mm/s and 10nm, respectively, as shown in Fig. 2 and Fig. 3.

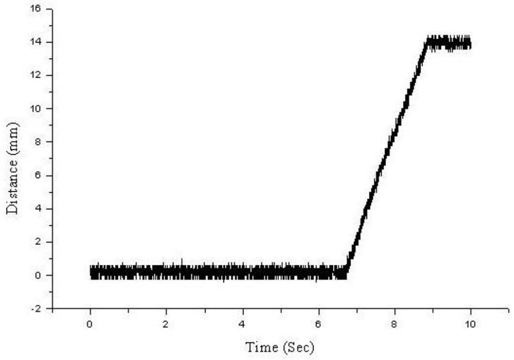

Fig. 2. Speed of prismatic actuator (6.5 mm/s, Δd = 14.2 mm, Δt = 2.2)

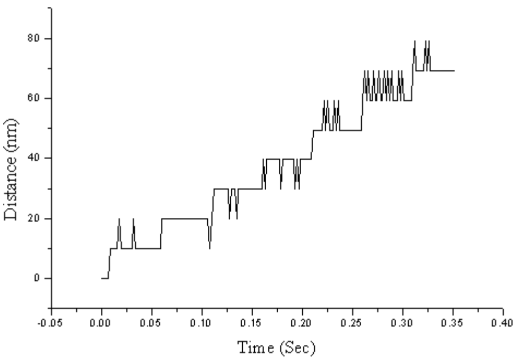

Fig. 3. Resolution of prismatic actuator

Table 1. Comparison between proposed actuator and commercial inchworm actuator (Exfo, IW-800).

Resolution	
Developed inchworm	10 nm
Commercial inchworm	N/A
Maximum Speed	
Developed actuator	6.5 mm/s
Commercial actuator	1.5 mm/s
Stroke	
Developed actuator	26 mm
Commercial actuator	50 mm

2.2 Design of a revolute actuator

A newrevolute actuator which is actuated by piezo electric actuator is proposed in this paper. The basic principle is the inertial driving method [4], but we adopt an actuation ring to transfer the displacement of the piezo actuator to the rotation of a moving disk.

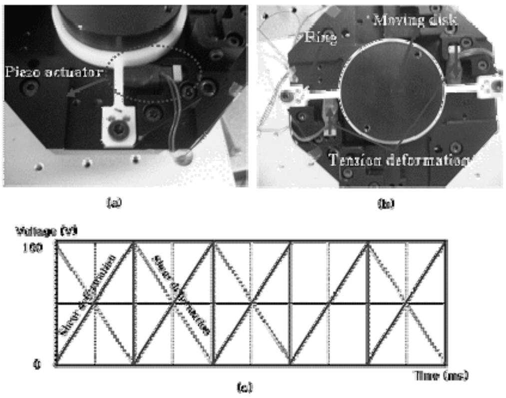

Fig. 4. Proposed revolute actuator and control input.

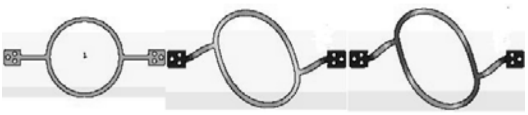

Fig. 5. Deformation process of actuation ring.

Table 2. Resolution and speed of continuous and step motion.

Motion type	Resolution	Maximum speed
Continuous motion	160 μradian	0.0353rad/s (at 220Hz)
Step motion	4 μradian	-

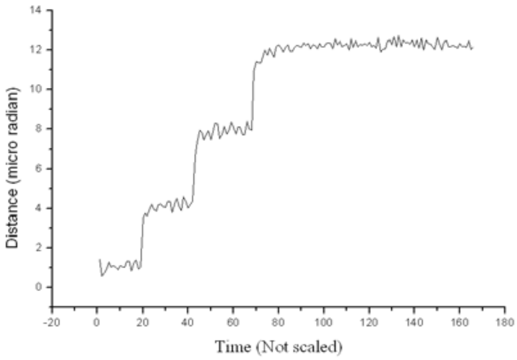

Fig. 6. Resolution of the proposed revolute actuator with step command.

As shown in Fig. 4, proposed revolute actuator consists of two piezo actuators, moving disk, and actuation ring. Displacement of the piezo actuator, which is connected to the arm of an actuation ring, brings deformation of the actuation ring, and deformation makes the moving disk rotate. The control input wave form is depicted in Fig. 4(c). The control input, which is drawn with a solid line, rotates the moving disk clockwise in this case, and the control input of the dashed line rotates it counterclockwise. Fig. 5

shows the deformation of the actuator ring as the piezo actuator is extended.

Two kinds of motion are possible, continuous and step motion. A pulse train of the saw wave puts the moving disk in continuous motion and one pulse of the wave in step motion.

3. Micro gripper

3.1 Design of micro-grippers

The basic design is inspired from the micro-gripper proposed by Carrozza et al. [12], but fabrication processes are wholly different from that of Carrozza. We process it with MEMS technology. Fig. 7 shows a schematic of the silicon micro-gripper actuated by piezo actuator. The actuation part is attached to the piezo actuator, and by extension and contraction of piezo actuator which extends to 10.2 µm at applied voltage of 120 V, micro-gripper jaws can close and open, respectively. With this actuation mechanism, the micro-gripper can generate a large gripping range for a small actuating displacement [5].

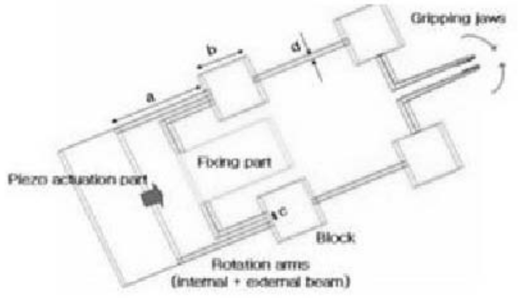

Fig. 7. The schematic of micro-gripper and design parameters.

Table 3. Design parameters of piezoelectric gripper.

Type No.	Beam length (a)	Block Size (b)	Gap between beams (c)	Beam Width (d)
1	4000 µm	2000 µm	200 µm	100 µm
2	4000 µm	2000 µm	200 µm	200 µm
3	4000 µm	2000 µm	200 µm	400 µm
4	4000 µm	2000 µm	200 µm	800 µm
5	4000 µm	2000 µm	400 µm	200 µm
6	4000 µm	2000 µm	600 µm	200 µm
7	4000 µm	2000 µm	800 µm	200 µm
8	4000 µm	2000 µm	1600 µm	200 µm

3.2 Fabrication processes

Experimentally, we made eight kinds of micro-grippers of varying design parameters [5].

The proposed silicon micro-gripper is fabricated by a simple surface, bulk MEMS technology. Fig. 8 shows fabrication processes and fabrication result of eight types of micro-grippers.

Firstly, the 500 µm - thickness silicon bare wafer is cleaned. After cleaning, HMDS, AZ 4620 positive PR is coated about 7 µm – thickness in 3000 rpm. Flatting of the coated PR surface, soft baking and UV exposure process are carried out. After exposure, PEB (Post Exposure Baking) is done at 110℃ hot plate for 3 mins and AZ 4620 PR develop process is performed by dipping the exposure wafer in AZ 400 developer solution. The next process is 4-points (up, down, right, left) PR bonding by using AZ 1512 positive PR to make a lower supporting structure which is needed to penetrate the 500 µm-thickness silicon bare wafer. After a bonding process, a silicon DRIE process is performed to penetrate the upper silicon wafer with 110:1 etching ratio for the silicon: AZ 4620 PR. The last process is to remove AZ 4620 PR used as the etching mask and LASER dicing process follows to

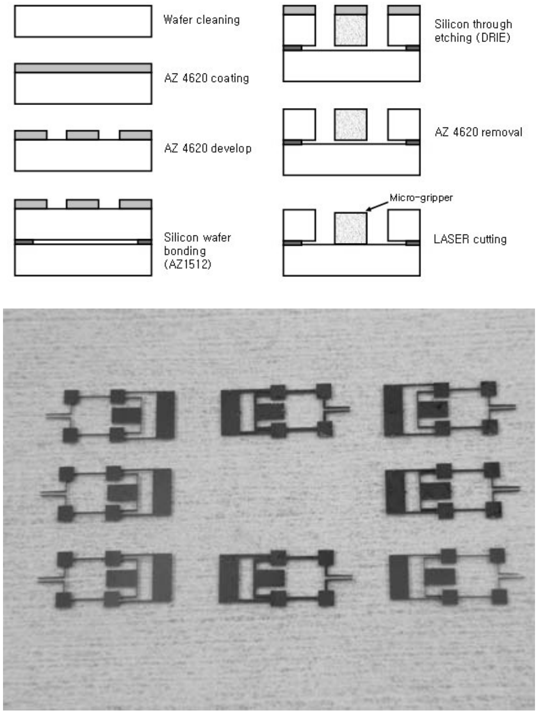

Fig. 8. Fabrication processes and fabricated micro-grippers.

cut edge fixing corners which hold the micro-gripper from scattering in four directions. Finally, individual micro-grippers are separated.

3.3 Measurement of micro gripper

Jaw displacement of eight type grippers versus applied voltage is graphed in Fig. 9, and it is linear with respect to applied voltage. Jaw displacements are measured with a laser vibrometer.

In Fig. 9, the type-5 micro-gripper (4000 μm beam length, 400 μm gap, 200 μm beam width) has the largest gripping displacement, which is 142.8 μm at an applied voltage of 120 V, and it shows about 14 times amplified results in comparison to the piezo actuator displacement.

3.4 Miniature type micro gripper

A miniature type micro gripper is fabricated by the same process. The miniature type is half the size of type 5, but the jaw is 3 times longer than type 5. A fabricated miniature type micro gripper is shown in Fig. 10.

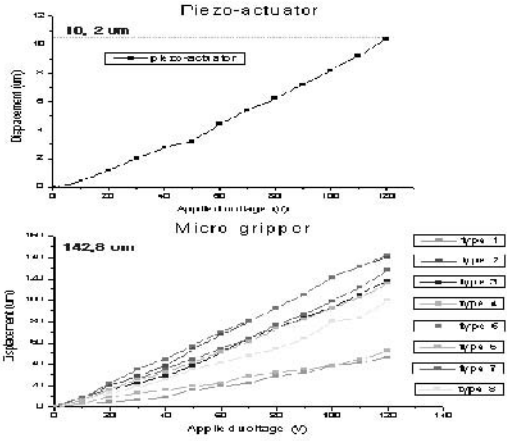

Fig. 9. Measured displacement of micro gripper jaw.

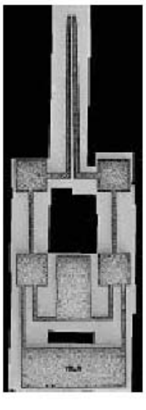

Fig. 10. Miniature type micro gripper.

4. Experimental manipulator

An experimental P-R-R type micro manipulator, which is a combination of one prismatic actuator and two revolute actuators proposed in previous section, is constructed as shown in Fig. 11. A micro gripper is connected to a revolute joint, the third axis, by gripper holder. The total length of the arm including the micro gripper is 116.79 mm, and the height is 157 mm. The stroke of the proposed prismatic and revolute actuator is 28 mm and ± 30 degrees, respectively. Theoretical resolution is 0.5 μm (x,y axis), 0.01 μm (z axis), and maximum speed of the end-effector is 5 mm/s which are obtained by multiplying the Jacobian matrix.

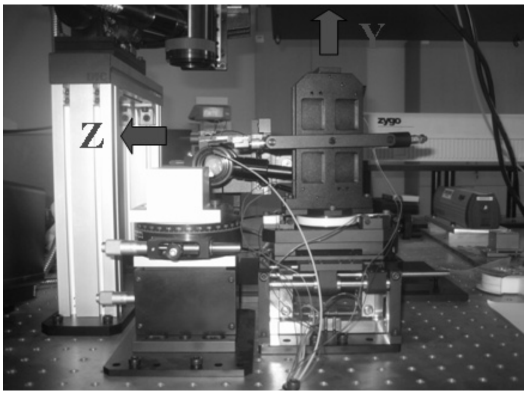

Fig. 11. Developed experimental manipulator.

Fig. 12. Picking and placing a rectangular part.

5. Experiments

The first experiment is to pick-and-place a small rectangular part, of which the size is about 100 μm. Fig. 12 shows the gripping test and it shows the micro gripper pick up a micro part. The main screen in Fig. 12 displays the top view, and the small screen of the upper left of the main screen displays a side view.

The second experiment is to pick-and-place a small pin, of which the size is 1.2 mm long and 100-200 μm thick. Fig. 13 shows the gripping procedure, approaching to the object, gripping and lifting the object.

(a) Approaching

(b) Gripping

(c) Lifting an object

Fig. 13. Picking and placing a pin.

6. Conclusion

A precision manipulator and micro gripper for micro assembly system and life science applications were developed in this paper. The developed precision manipulator is a 3-DOF P-R-R type manipulator that is actuated by one inchworm type linear actuator and two ring actuation revolute actuators. The size of the robot is about 157 mm x 52 mm x 45 mm, and the length of the arm is 116.79 mm including the micro gripper. A small-sized robot is preferable for micro assembly and life science applications because the workspace is very restrictive. For the devised precision robot, a new ring actuation revolute actuator and an inchworm type actuator which is integrated into the stage were proposed. The ring actuation revolute actuator has 4 μradian revolute resolution and the inchworm prismatic actuator has 10 nm resolution. As an end- effector, a piezoelectric micro gripper was designed and fabricated by using MEMS technology. At an applied voltage of 120 V, the piezo micro-gripper generated about 142.8 μm maximum gripping displacement.

We conducted two real gripping experiments to evaluate the robotic system. In real a gripping test of a 100 μm micro part, it was easy to handle the gripping object with gripping and releasing motion. And in an experiment with a micro pin, we could pick and place the object, watching the video scope. We think that the new manipulator and gripper will be appropriate for micro system assembly tasks and life science applications.

Acknowledgment

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