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Capillary force gripper with a polygonal nozzle for pick & place and rotation of 1mm objects

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In this paper, we describe newly proposed polygonal nozzle capillary force gripper with a rotation function. It enables fast water replenishment by the capillary phenomenon and fast droplet formation by diaphragm on/off control. Capillary force is one of the most dominant forces in micro-objects and is suitable for capturing and releasing micro-objects with heterogeneous and complex shapes because it acts on objects of any shape due to the flexible deformation of water. With the gripper developed in the previous research, it was impossible to control the object to arbitrary posture angle. In this study, we have developed the rotatable gripper by using polygonal nozzle and rotation stage. In experiments, we conducted pick-and-place of objects using the developed gripper and evaluated its position and angular accuracy from the target placement angle. We will continue to improve this gripper for practical use as a complex shaped fragile and soft materials in biomedical, soft matter, microorganism, microfossils, and MEMS fields.

NOMENCLATURE

R_1, R_2 = radius of curvatures of the meniscus
θ_1, θ_2 = contact angles
h = the distance between two planes
r_1, r_2 = capillary radii
γ = surface tension
Δp = Laplace pressure
F_L = Laplace pressure term of capillary force
F_T = surface tension term of capillary force
F_C = capillary force
θ_p = posture angle
dr = positioning error
$d\theta_p$ = angular error

1. Introduction

Recently, demand for micromanipulation has been increasing as electronic components become smaller and smaller. For example, micro-LEDs, which are expected to have high brightness and low power consumption, are less than 100µm in size, and 25 million of them constitute a 4K display [1]. Thus, micro-assembly technology plays a very important role.

Today, the dominant micromanipulation technology in the industrial field is air nozzle mounting using pneumatic pressure. However, while high-speed mounting is possible, it may damage the parts because it involves solid contact with the parts [2]. Therefore, we focused on a micromanipulation technology using the surface tension of water called capillary force. Since a liquid is interposed between the part and the tool, there is no risk of damaging the part, and it could be used for parts with complex shapes.

The grippers developed so far only support positioning of the object, and it is unable to control the posture angle [3]. For component mounting, it is also important to determine the posture angle of the component, and we have developed a gripper to control the posture angle of the object [5]. This paper describes an experiment to place an object at an arbitrary position and posture angle by newly attaching a "polygonal nozzle" and a "rotating stage" to the capillary force gripper.

2. Capillary force gripper with the polygonal nozzle

2.1 Composition of the mechanism

The structure of capillary force gripper was shown in Fig. 1. The gripper consists of a flow channel device, a tank, a valve, a shaft, and a nozzle. In this mechanism, by opening the valve, liquid is absorbed from the tank to the tip of the nozzle by ca pillary phenomenon, and by closing the valve and deforming the diaphragm, droplets are pushed outward from the nozzle.

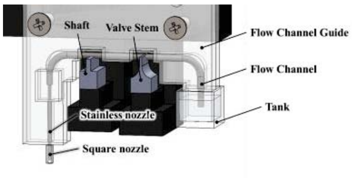


Fig. 1 Structure of Capillary Force Gripper

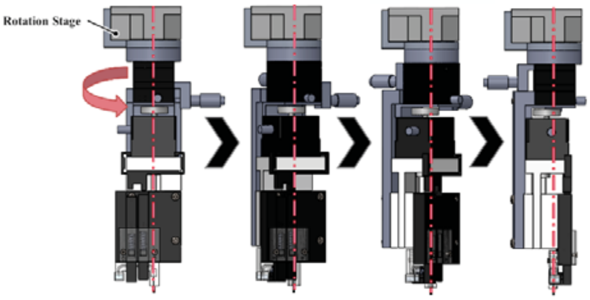


Fig. 2 The rotation mechanism of the gripper

In this study, our objective is to place an object at an arbitrary posture angle by using a mechanism attaching a rotation stage to the gripper shown in Fig. 1. Therefore, we used a polygonal nozzle matching the top surface of the object for the nozzle to compensate for the posture angle of the object before rotation. The polygonal nozzle was made from an acrylic plate using a cutting machine. Fig. 2 shows the mechanism with the rotation stage attached and the mechanism after rotation.

2.2 Approximation of the capillary force

In this section, we estimate the capillary forces by assuming that the cross-sectional curve of the meniscus cut in the plane containing the axis of symmetry is part of a circular arc [4]. A schematic diagram is shown in Fig. 3.

The radius of curvature of the meniscus R_1 can be expressed using the distance between two planes h and the contact angles θ_1 and θ_2 as follow:

$$R_1 = \frac{h}{\cos\theta_1 + \cos\theta_2} \tag{1}$$

By r_2, we obtain R_2 from a similar arc approximation, which can be expressed as follow:

$$R_2 = r_2 - R_1(1 - \sin\theta_2) \tag{2}$$

Here, from Laplace's equation, the Laplace pressure acting on the surface of the liquid bridge can be expressed as follow:

$$\Delta p = \gamma\left(\frac{1}{R_2} - \frac{1}{R_1}\right) \tag{3}$$

γ is the surface tension, andr_1 is given as follows:

$$r_1 = r_2 + R_1(\sin\theta_2 - \sin\theta_1) \tag{4}$$

Thus, the suction force acting on the flat plane (top surface of the cube) by the Laplace pressure F_L is expressed as follows:

$$F_L = \pi r_1^2 \Delta p. \tag{5}$$

The pulling force acting on the flat plane owing to the surface tension is given as follows:

$$F_T = 2\pi r_1 \gamma\, sin\,\theta_1 \tag{6}$$

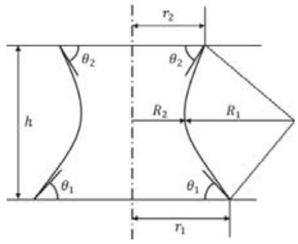


Fig. 3 Capillary bridge between two parallel planes.

From (5) and (6), the required capillary force F_C which is the sum of F_L and F_T, is given as follows:

$$F_C = F_L + F_T = \pi\gamma r_1\left[r_1\left(\frac{1}{R_2} - \frac{1}{R_1}\right) + 2\sin\theta_1\right] \tag{7}$$

3. Experiments

3.1 Experimental Procedure

The flow of the automatic pick-and-place process conducted in this study is described below [3].

1) Place the object at an arbitrary position on the place surface and measure the xy coordinates with a CCD camera.
2) Move the XY stage so that the place position is directly below the gripper.
3) The Z stage is moved to lower the gripper to apply droplets to the place surface.
4) Move the XY stage so that the objects are positioned directly under the gripper.
5) The Z stage is moved to raise the gripper and pick up the objects.
6) Move the XY stage so that the place position is directly below the gripper.
7) Move the rotation stage to rotate the object to an arbitrary posture angle.
8) The Z stage is moved to lower the gripper to place the objects.
9) Move the XY stage so that the objects are within the field of view of the CCD camera and measure the xy coordinates with the CCD camera.

3.2 Experimental Conditions

Table 1 shows the objects used in the experiments and Table 2 shows the experimental conditions.

Table 1 Details of micro-objects

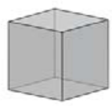
CAD	
Size	Length: 1 [mm] Hight: 1 [mm]
Material	Acrylic
Contact angle	70.0 ± 1.95[deg]

Table 2 the experimental conditions

Placement angle θ_p[deg]	Number of samples
0	16
15	12
30	20
45	16
60	12

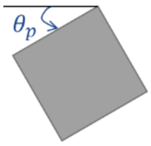


Fig. 4 Definition of θ_p

θ_p in Table 2 represents the attitude angle of the placement targ et and is defined as shown in Figure 4.

3.3 Experimental Results

First, the success rates for pickup and place are shown in Table 3 for each condition.

Table 3 Success rate of pick-up and place-down

θ_p[deg]	Pick-up	Place-down	Pick & Place
0	94% (15/16)	87% (13/15)	81% (13/16)
15	83% (10/12)	100% (10/10)	83% (10/12)
30	95 % (19/20)	89% (17/19)	85% (17/20)
45	100% (16/16)	94% (15/16)	94% (15/16)
60	75% (9/12)	100% (9/9)	75 % (9/12)
Total	91% (69/76)	92% (64/69)	84% (64/76)

In all conditions, the success rate of pick-and-place failed to reach 100%. The reasons for this are that the amount of gripper descent was kept constant and that electrostatic forces were generated on the placement surface. In the former case, the size of the droplet formed at the nozzle varied from trial to trial, and if the droplet was smaller than a certain size, it did not contact the object and could not pick up or place the object. We consider that this problem could be solved by detecting the distance between the object and the droplet from the images and feeding it back to the control system. In the latter case, it is necessary to set up an experimental environment where electrostatic forces do not occur.

Second, the positioning and angular errors are shown in Table 4.

Table 4 Comparison of the positioning errors dr and the angular errors $d\theta_p$

θ_p[deg]	Positioning errors dr		Angular errors after arrangement $d\theta_p$	
	Average [μm]	Standard deviation [μm]	Average [deg]	Standard deviation [deg]
0	182.2	109.1	-5.5	7.3
15	66.7	46.3	1.0	10.9
30	100.6	46.0	-2.1	4.2
45	160.5	81.9	-1.1	9.1
60	121.7	71.1	1.7	14.8

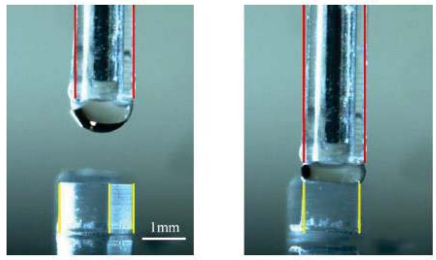
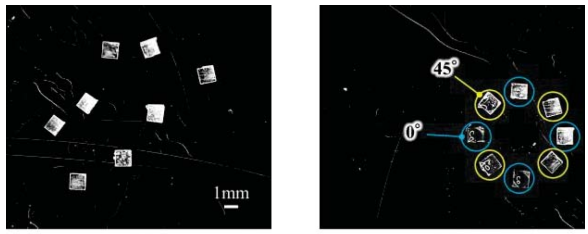


Fig. 5 Automatic correction of posture angles by shape matching effect



(a) **(b)**

Fig. 6 Arrangement of the cube-shaped samples under condition $\theta_p = 0, 45$[deg]: (a) Initially; (b) After the arrangement of the pick & place operations

The positioning errors exceeded 10 percent of the object's edge length except for the 15-degree case. There are two possible reasons for this large positioning error. The first is that the droplet size was so large that the object moved as the droplet evaporated after placement was completed. The second reason is that the gripper was set to a constant descent amount for a placement droplet of an inconsistent size, which caused the object to fall to the ground when the area of the object in contact with the droplet was small during placement.

The angular error shows a large variation from the standard error. This is due to the size of the placement droplet as well as the positioning error. After pick-up, the posture angle of the object was corrected according to the nozzle posture by using a polygonal nozzle as shown in Figure 5, and the object could be moved to an arbitrary posture angle by rotating the entire gripper with the rotation stage. However, after the placement was completed, the object rotated as the placement droplet evaporated, causing a large angular error.

To improve both positioning error and angular error, it should be considered to study the optimum droplet size for placement and the amount of the object to be pressed into the droplet for placement. For this purpose, it is necessary to introduce nozzle sharpening and control of gripper descent based on visual feedback.

Finally, Figure 6 shows the appearance of the object before and after the experiment.

4. Conclusion

In this study, we developed a rotatable polygonal nozzle type capillary force gripper with a rotating stage. This gripper was used to pick and place 1 mm cubes, and its positioning and angular errors were evaluated. The polygonal nozzle was fabricated by a cutting machine from an acrylic plate. Although we confirmed that posture angle of the object was corrected by using the polygonal nozzle, large positioning and angular errors occurred depending on the size of the placed droplet due to a thick nozzle (1 mm square) and lack of reproducibility in the size of the droplet to be formed. Future prospects include increasing the number of cameras installed in the experimental facility to enable real-time feedback control; sharpening the nozzle and incorporating feedback control to ensure reproducibility of droplet size; and increasing the number of object types to accommodate complex shapes to demonstrate the versality of the mechanism.

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