End-effector with Wire Thrusting Mechanism for Bin Picking of Small Parts with Circular Holes

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***Abstract*— This paper describes an end-effector for picking small parts with circular holes, e.g. washers and spacers. There are many issues on the automation of bin picking of small metal parts. In such objects, even if a grasping target can be identified, it is a challenging task to pick it up stable. We propose a novel end-effector using wire thrusting mechanism which enables to grasp a part with holes by squeezing from inside of a hole. Then we built the proposed mechanism and performed experiments using actual 21 cylindrical metal parts. We confirmed that the gripping of the metal parts placed on a horizontal plane performed as designed. In addition, we also confirmed that the same degree of gripping was possible when the inclination was until 18 degrees from the horizontal state. Finally, we organized the points to be improved in the future.**

I. INTRODUCTION

In recent production sites, automation on production process is required to adapt "*small-rot multi-production.*" It is expected that various products can be produced on one production line by minimal equipment exchanges. The following flow is mentioned for the automation of *small-rot multi-production*. (1) Object recognition is performed with a vision sensor etc. to detect a grasping target from the state that parts are stacked randomly in a box. (2) A supplier robot picks up the object based on the recognition result and supplies it to an assembly robot. (3) The assembly robot embeds the object to the product. This is an ideal flow of automation. However, in practice, parts are often supplied by relying on parts feeders or human hands. With parts feeders, the equipment needs to be changed each time the target part changes, which takes time and money. On the other hand, sustainability of relying on manual operation will be in trouble because worker shortages are progressing.

The authors are interested in a function of feeding small parts, which is suitable to *small-rot multi-production*. In this study, we focus on picking up circular parts with holes such as washers and spacers. Assuming such parts are randomly stacked, we develop an end-effector to pick up one of them.

There are many issues on the automation of bin picking of small metal parts. As such objects have glossy surface, it is difficult for camera and laser scanner to obtain sensor data stably. Although the purpose of bin-picking is to pick one of the randomly stacked parts, target part selection including its pose estimation is a challenging issue for that reason. Moreover, even if a target part can be identified, it is also a challenging task to pick it up stably. If a grasping target is a relatively large metal object, a target part and remaining randomly stacked parts are not moved by a small external force. However, it is not always true for small parts because stacked state might be collapsed easily. This fact tells us that a stable grasping method is required for bin picking of small parts.

The contributions of this paper are as follows:

- We propose a novel end-effector to grasp small and light metal parts. Wire thrusting mechanism enables to grasp a part with holes by squeezing from inside of a hole.
- We built the proposed mechanism and performed experiments using actual 21 cylindrical metal parts such as washers. The experimental results almost agreed with the theoretical values. We also organized the points to be improved in the future.

This paper is structured as follows. Next section introduces related work, and Section III explains our problem settings and approach. Section IV explains the proposed end-effector in detail. Section V introduces proof experiments, and Section VI concludes this paper.

II. RELATED WORK

Many techniques for estimating the 3D pose of an object have been proposed to contribute to the construction of a flexible production line. Nakahara et al. [1] and Hayashi et al. [2] proposed pose estimation methods for randomly stacked objects. In these methods, depth information is first divided into some regions, and then 3D models are collated to each region. However, it is difficult for depth sensing to obtain data from glossy objects. Arai et al. [3] proposed a method to estimate 3D pose of a bolt with metallic luster using the phase shift method. They achieved a picking task using a general-purpose hand. However, when the positional relationship between the bolt and the workbench is poor or when some bolts overlap in the same direction, detection becomes difficult and the success rate of gripping decreases. Since washers and spacers used in this study are small and have a metallic luster, pose estimation from randomly stacked situation have a certain level of difficulties. On the other hand, since the geometric shape of a part is simple, the pose can be estimated relatively accurately by using a color image etc. as long as the outline is found. However, an estimation error is likely to occur for the inclination in the depth direction.

Therefore, an approach that absorbs pose errors by hardware is desirable. There are several approaches that is possible to achieve it. Brown et al. [4] manufactured a hand using the jamming transition. The advantage is that the hand can grip an object regardless of the pose of the object. On the

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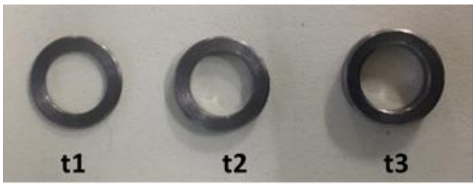

Fig. 1 Examples of ring metal parts

TABLE I
A LIST OF METAL PARTS
(THE VALUE IN ORANGE CELL SHOWS WEIGHTS[g])

		thickness[mm]		
outer diameter [mm]	inner diameter [mm]	1	2	3
10	5.5	0.43	0.86	1.29
10	6	0.39	0.79	1.18
11	7	0.44	0.89	1.33
12	8	0.49	0.99	1.48
14	10	0.59	1.18	1.78
15	11	0.64	1.28	1.92
16	12	0.69	1.38	2.07

other hand, there is a risk of picking multiple objects, which is not suitable for bin picking. The device proposed by Fukusaki et al. [5] enables to handle fragile and small objects dexterously, but it is not suitable for metal parts because of using a magnetic field. The hand proposed by Shimaji et al. [6] imitated a human finger and was able to pick up a thin stick object. The three fingers hand proposed by Baba et al. [7] reproduced a human nail and enabled to pick up thin objects like a coin or a card. Robot hands that imitate human hands are highly versatile. However, because such finger tends to be large size, there is a risk of collapsing randomly stacked state at bin-picking of small and light objects. A gripping device proposed by Matsui et al. [8] was made of an elastic material, and it enables to grip a flat object. This device is required to be combined with a specific supply device.

As described above, various methods for bin picking have been proposed. However, no suitable method for picking up only one small ring-shaped metal part has been found. In this study, we develop an end-effector to cope with such objects.

III. PROBLEM SETTINGS AND APPROACH

A. *Target objects and situations*

Gripping targets in this study are listed in TABLE I. These are ring-shaped metal parts made of *SS400*. There are seven types of radius: 5.5, 6, 7, 8, 10, 11, 12mm, respectively. There are three types of thickness: 1, 2, 3mm, respectively. That is, the total number of combinations is 21. The proposed end-effector will be made to cope with all of them.

The final goal of our study is the bin-picking of above-mentioned parts. In this study, we cope with situations that one metal part is placed on and focus on the development of end-effector to pick up it. However, for applying to bin-picking task in the future, each metal part can be placed with a certain amount of inclination. That is, we design the end-effector to make it possible to pick up a metal part on such a situation.

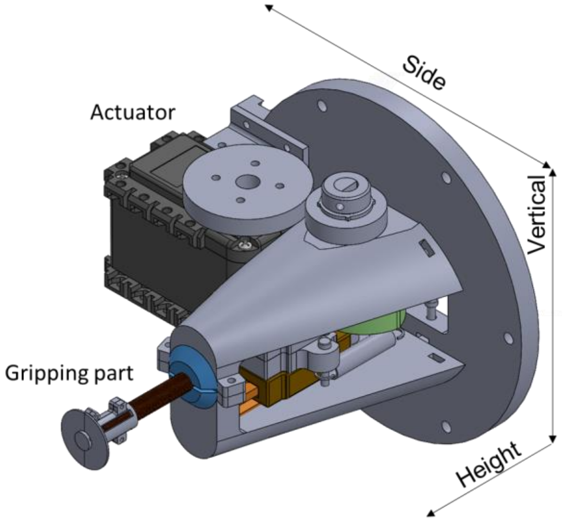

Fig.2 Appearance of Robot Hand

B. *The concept of end-effector*

When thin ring metal parts are stacked at random, almost of them have certain level of inclination even though they might not have large angle. As another trend, if the parts are small and light, the stacked condition is easily collapsed when end-effectors touch surrounding parts while picking.

From these facts, one feasible approach is to a grasp an object by squeezing from inner circular part. Moreover, it is expected to have flexible mechanism that adapts to the inner circular parts even if the part is inclined. We must configure such a device in a small size.

IV. END-EFFECTOR WITH WIRE THRUSTING MECHANISM

A. Overview *of the end-effector*

Figure 2 shows an appearance of the proposed end-effector. The base size is 100mm by 110.5mm and the height is 95mm. The end-effector mainly consists of three parts: the gripping part where holds one metal part, the actuation part where drives the grasping part, and the connector part where plays a role of connecting the actuation part and manipulator. Depending on the relationship between thickness and radius of metal parts, the gripping part selects two-pattern grasps by thrusting thin wire from the tip of the end-effector. The thrusting mechanism is driven by a servo motor. To translate evolutional power of motor to wire thrusting motion, cam-mechanism is assembled to the motor. If the radius of ring parts is given in advance, the amount of thrusting can be strictly calculated. For getting the thrusted wire back again into the end-effector, a spring is used. It enables to release the grasped part.

B. *Gripping mechanism*

Thrusting mechanism: A gripping method we apply is a squeezing grip. Three thin wires with 0.5mm diameter made by polystyrene are thrusted from the tip of end-effector

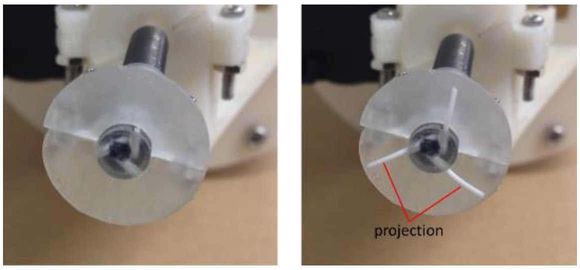

Fig.3 Extrusion of protrusions
(Left: before extrusion, Right after injection)

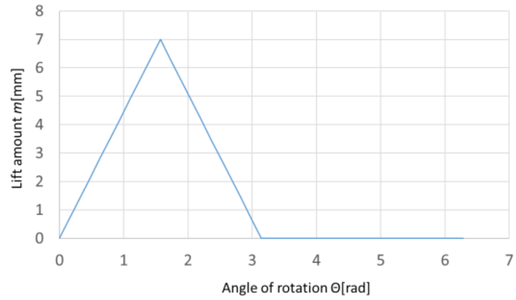

Fig.5 Relationship between rotation angle and lift amount
(Angular range:$0 \leq \theta_{cam} \leq \pi/2$)

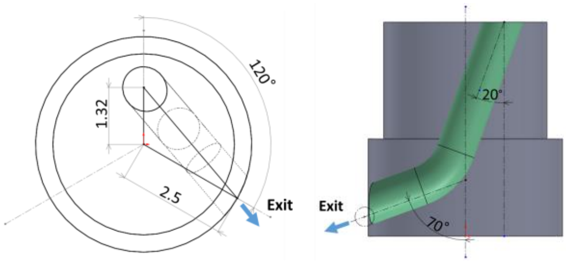

Fig.4 Extrusion route (Left: bottom view, Right: side view)

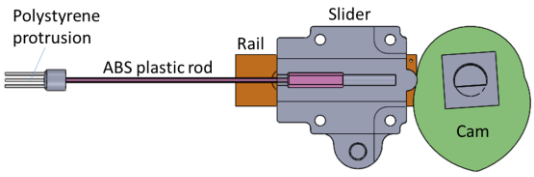

Fig.6 Relative relationship between cam and slider

simultaneously, the wires directed to outside is pressed onto the inner side of a target metal part. As shown in Fig. 3, this enables to squeeze the part by three points and enables to make force closure state.

The tip of end-effector is cylindrical shape whose diameter is smaller than the inner diameter of metal parts. It has three holes where a wire path through. One attention point here is to prevent plastic deformation of the wires. For this reason, the thrusted wires from the holes are slightly inclined from horizontal direction. Moreover, entrance part of the holes is shifted about 1.3mm from the center core of the cylinder, and the direction of the exit path of the holes are rotated with 120 degrees. See the left panel of Fig.4 for understanding them more. These ideas enable to make a path with a gradual curve. Practically, as shown in the right panel of Fig.4, a wire is inserted with 20 degrees inclination from vertical axis and is output with 70 degrees inclination. These angles were determined from our trials that investigate the balance between preventing large curvature path and preserving large amount of thrusting.

Extrusion mechanism: To structure the end-effector in small size, cam-slider mechanism is adopted for the part that adjusts the amount of wire thrusting. An actuator is a servo motor AX-18A manufactured by Dynamixel Inc. Moving force is conveyed to the cam by gears with 32 teeth (motor side) and 20 teeth (cam side).

The shape of the cam is as follows: basial diameter is 5mm, and the distance from the center of the circle is 12mm at $\pi/2$ rad position. That is, it can draw a curvature trajectory which the amount of lifting becomes 7mm (See Fig.5).

$$m = 7 \cdot \frac{2}{\pi}\theta_{cam} \qquad \left(0 \leq \theta_{can} \leq \frac{\pi}{2}\right). \qquad (1)$$

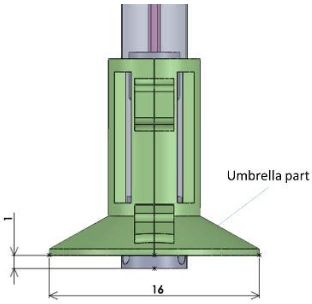

Fig.7 Umbrella part position relation

The movement of the cam is conveyed to a slider part. The part consists of polystyrene cylinder and ABS plastic rod. They are arranged on the same straight line as the center of the cam (See Fig.6).

Error absorption mechanism: Because target objects in this paper are thin metal parts, it is difficult for object detection methods to accurately estimate situations whether some parts are duplicated or not. This causes a failure that the end-effector picks up two or more parts simultaneously. To reject such case, as shown in Fig.7, an umbrella-shaped part is attached directly above the wire thrusting port. This part directory touches to the planar surface of metal parts. After that, little positioning error is automatically disabled among thrusting wires.

Another possible problem on pose estimation is orientation error. To cope with that, a solid coiling spring is adopted to the path of wires as shown in Fig. 8. Due to this flexible part, when the tip of the end-effector is pressed against a target metal part, the inclination of the tip is adjusted to the surface of the part. This enables to pick up the target part even if high-precision detection is not possible.

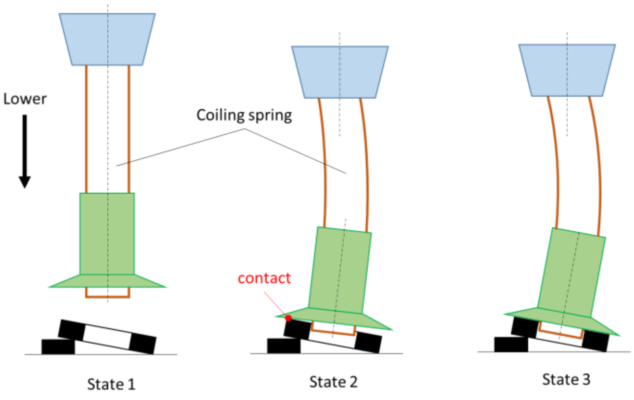

Fig.8 Error absorption procedure

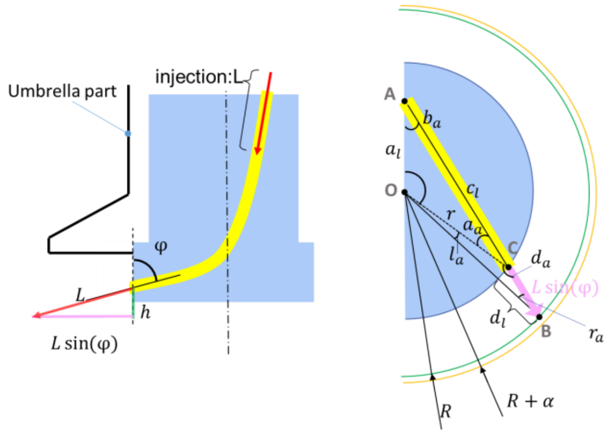

Fig.9 Geometrical relationships on extrusion path
(left: Front view , right: bottom view)

The flexible part houses the ABS plastic rod and connects to the umbrella part at the end of the end effector. The solid coiling springs is 5mm diameter, which is made of piano wire with 0.45mm diameter. The spring is straight cylindrical when unloaded and bends flexibly when a lateral load is applied.

Based on the two mechanisms for error absorption, the procedure of picking is as follows:

- Lower the end-effector vertically toward the target part,
- Contact a part of the umbrella-shaped cover to the part,
- The cover rotates around the contact point and fits to the surface of the part.

Fig.8 shows this procedure.

C. *Calculation for determining the length of wire*

In this subsection we introduce how to calculate the relationship between motor rotation and the amount of wire thrusting. For gripping a metal part, it is insufficient only to contact a tip of wire to the inner circle of the part. That is, the amount of wire thrusting is calculated based on the distance to contact plus the amount to generate the force that sufficiently pushes the part.

Let R be a radius of a virtual circle which corresponds to inner radius of target metal parts. See green curve depicted in Fig. 9. Then let $R+\alpha$ be a slightly large radius depicted by orange curve. The amount of wire thrusting L is calculated from $R+\alpha$. Parameters $a_l, c_{l,} a_l, a_{a,} b_a c_{a,} r, \varphi$ shown in this figure are known at the design stage. First, calculate $\overline{\mathrm{OB}}$ based on a geometrical relationship, then calculate unknown length on a triangle OBC as follows:

$$d_l = (\mathrm{R}+\alpha) - \mathrm{r},$$

$$d_a = \pi - a_a.$$

Then calculate two values using sine theorem:

$$r_a = \sin^{-1}\left\{\frac{\mathrm{r}}{\mathrm{R}+\alpha}(\sin d_a)\right\},$$

$$l_a = \pi - (d_a - r_a).$$

Finally, the amount of wire thrusting is calculated by sine theorem:

$$L = \frac{\sin l_a}{\sin d_a}(\mathrm{R}+\alpha)\frac{1}{\sin\varphi}.$$

Because L is equal to m shown in Eq. (1), the following formula holds,

$$\theta_{cam} = \frac{\pi}{14}L.$$

The cam is coaxial with a 40-tooth gear, and a 62-tooth gear is attached to the motor shaft. Therefore, the required amount of rotation θ_{motor} is

$$\theta_{motor} = \frac{40}{62}\frac{\pi}{14}L,$$

$$\theta_{motor} = \frac{5}{112}\frac{\sin l_a}{\sin d_a}(\mathrm{R}+\alpha)\frac{\pi}{\sin\varphi}.$$

The experiments described in the next section, α was set to 1mm.

V. Proof Experiments

A. *Two gripping patterns and the selection criterion*

As already mentioned, when the gripping part is brought close to a metal part from vertically above, wires are thrusted at an angle of 70 degrees with respect to the horizontal plane. Therefore, depending on the radius and thickness of the metal part, there are possible two patterns where the inner peripheral side is squeezed and where the wire is hooked on the bottom of the part.

Fig. 10 shows three gripping cases according to the shape of the part. The leftmost panel is the squeezing grip and the remaining two are the hooking grip. Let radius and thickness be R_1, t_1, respectively. Hooking grip is selected at the cases of $\mathrm{R}_1 < \mathrm{R}_2$ and $\mathrm{t}_1 = \mathrm{t}_2$, or $\mathrm{R}_1 = \mathrm{R}_3$ and $\mathrm{t}_1 > \mathrm{t}_3$. Since the position of the wire tip is proportional to the distance from the center of the cylinder part, this relationship can be represented by the blue line in Fig. 11. The horizontal axis shows the radius of a target metal part, and the vertical axis shows the vertical distance, which is h in the Fig. 9, from the injection port to the tip of wires when α is added to the radius. Based

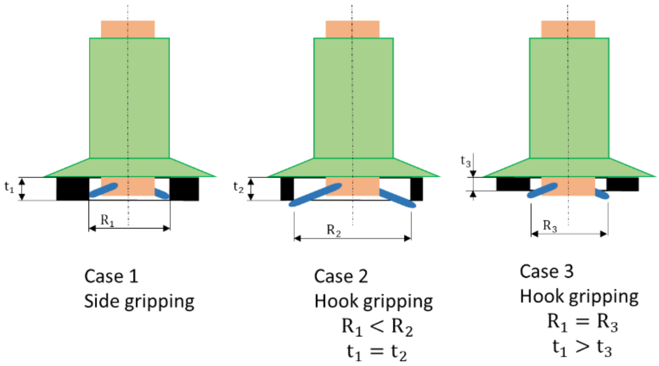

Fig.10 Gripping patterns

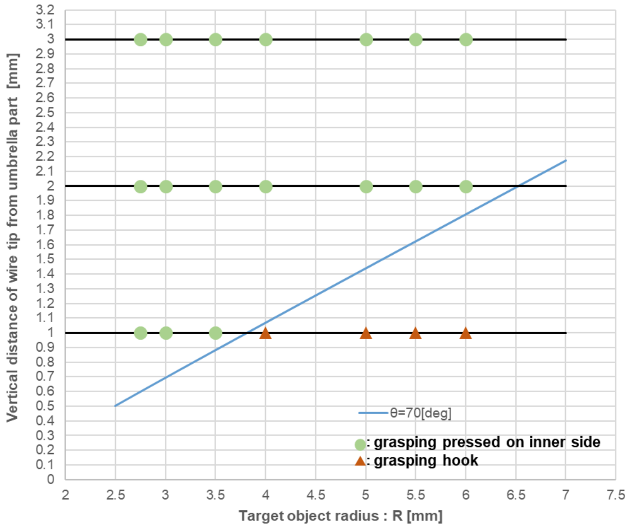

Fig.11 The relationship between the radius of inner circle and vertical distance. Blue line shows a theoretical line of gripping type. Green circles and red triangles show gripping type: squeezing grip or hooking grip, respectively.

on this graph, it is possible to select the squeezing or the hooking.

For example, if the inner diameter of a metal part is 5mm, first refer to the place of 5mm on the horizontal axis. Looking at it vertically upward, then the height when crossing the blue line is 1.13mm. Therefore, if the thickness of the part is less than 1.13mm, hooking grip is selected. If it is larger, squeezing grip is selected. Since the thickness of target parts in this paper is either 1, 2 or 3mm, a gripping method is directly selected: squeezing when 1mm and hooking otherwise.

B. Gripping metal parts placed horizontally

The end-effector described in the previous section was manufactured. Using it, experiments were conducted against 21 types of metal parts introduced in Section III. It was verified whether these parts were divided into squeezing grip and hooking grip along theoretical values. In an experiment, a metal part was placed on a horizontal table. The end-effector was moved from vertical upward direction, then wires was thrusted off just after contacting with the part and confirmed whether it could be picked up. The end-effector was attached to the tip of a serial link manipulator, Manipulator-H manufactured by ROBOTIS Inc. MoveIt! was used to generate manipulator motions. Figure 12 shows an example of the experiments. A washer with 8mm inner circular diameter and 2mm thickness was picked up by the proposed end-effector.

Figure 12 shows the results. Here, the green circle indicates squeezing grip and the red triangle indicates hooking grip. This result shows that the designed wire thrusting mechanism functioned as expected. In addition, parts whose radius and thickness positions above the blue theoretical line were picked up dexterously, even if multiple metal parts are stacked. This is because other parts below the target part are not touched by the wires.

C. Gripping metal parts placed on an inclined plane

A metal part was placed on an inclined plane, and the angle that the end-effector could pick it up was clarified by experiments. Figure 13 shows the instrument used. There was a rotatable plate at the top, and a recess with a diameter 0.3mm larger than the outer diameter of the part was added at the center. After the plate was rotated around the central axis, gripping was tried.

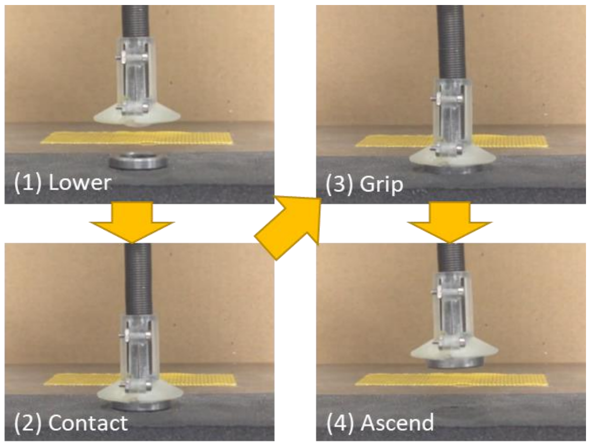

Fig.12 An example of picking a washer

TABLE II shows the results. Here, the experiment was performed with the inclination angle increased every 5 degrees. A white circle means that squeezing grip was possible, and a filled circle means hooking grip was possible. When gripping was not possible, x was marked. Up to 15 degrees, the result was the same as when a metal part was placed on horizontal plane because the posture error was absorbed by the flexible mechanism. On the other hand, when the inclination was 20 degrees, three types of parts could not be gripped. At 25 degrees, only some parts with a thickness of 1 mm could be gripped. Additionally, experiments were performed at 16, 17, 18, and 19 degrees in order to verify the angular region that could hold all 21 parts. Gripping was possible up to an inclination of 18 degrees.

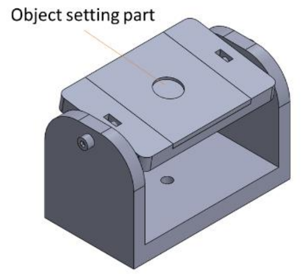

Fig.13 Tilting device

TABLE III
POSSIBLE/IMPOSSIBLE GRIP FROM INCLINED PLANE

Tilt angle = 5, 10, 15[deg]

		thickness[mm]		
		1	2	3
Inner diameter [mm]	5.5	○	○	○
	6	○	○	○
	7	○	○	○
	8	○	○	○
	10	●	○	○
	11	●	○	○
	12	●	○	○

Tilt angle = 20[deg]

		thickness[mm]		
		1	2	3
Inner diameter [mm]	5.5	○	○	○
	6	○	○	○
	7	○	○	○
	8	○	○	○
	10	●	○	○
	11	●	○	×
	12	●	×	×

Tilt angle = 25[deg]

		thickness[mm]		
		1	2	3
Inner diameter [mm]	5.5	×	×	×
	6	×	×	×
	7	×	×	×
	8	○	×	×
	10	●	×	×
	11	●	×	×
	12	●	×	×

The reason why gripping was failed at a certain tilt or more is that there is a bias in the contact between the wire and the part. Figure 14 illustrates this phenomenon. The red point is the place where the end-effector is touched first, and this point will leave at the end when lifting the part. As a result, the wire that was in contact with the side surface slips. In the experiment of gripping a 1mm thickness part at 25 degrees inclination, it was observed that gripping was succeeded only when the inner diameter was large. The reason is the softness of the polystyrene protrusions. The larger the radius, the larger the thrusting amount, so the wire will bend. This serves to absorb the bias of squeezing grip. In other words, in the case of parts with a small inner diameter, the amount of wire thrusting is small, and the above function cannot be expected. Therefore, it is probable that slip occurred during lifting.

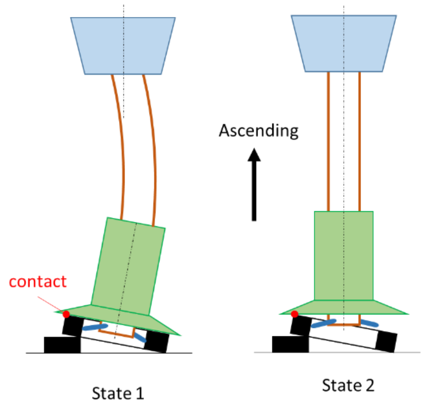

Fig.14 Transition of the injection part in ascending the hand

VI. CONCLUSIONS

In this paper, we proposed a gripping mechanism for small metal parts with circular holes. Even if there is a slight deviation in the posture relationship between the metal part and the end-effector, a wire thrusting mechanism and a spring-based mechanism are incorporated to absorb the error during the gripping process. We confirmed that the gripping of the metal parts placed on the horizontal plane performed as designed. In addition, we also confirmed that the same degree of gripping was possible when the inclination was until 18 degrees from the horizontal state.

One of the future works is to improve the proposed mechanism. It is necessary to find a design and a mechanism that can absorb the posture error even when there is a larger inclination. It is also important to construct a system that uses a vision sensor to perform 3D recognition. Onda et al. [9] has built a system that accurately picks up circular shape objects. The end-effector developed in this study can be picked if a circle can be detected. By referring to these studies, we can detect the glossy small washer and spacer and systematize the flow until bin-picking

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