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FULL PAPER

Proposal of a shape adaptive gripper for robotic assembly tasks

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ABSTRACT
This paper proposes a novel robotic gripper used for assembly tasks that can adaptively grasp objects with different shapes. The proposed hand has a combined structure between two kinds of shape adaptive mechanisms where one is the granular jamming and the other is a multi-finger mechanism driven by a single wire. Due to the effect of the two shape adaptive mechanisms, the pose of a grasped object does not change during an assembly operation. The proposed hand has four fingers where two are the active ones and the other two are the passive ones. The pose of the grasped object can be uniquely determined since the passive fingers are used to orient an object placed on a table before the active fingers are closed to grasp it. Assembly experiments of some kinds of parts are shown to validate the effectiveness of our proposed gripper.

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KEYWORDS
Gripper; robotic assembly; granular jamming; underactuated hand

1. Introduction

Although industrial robots have been widely introduced to several production processes, it is still difficult for robots to perform the parts assembly. For robots to assemble a product, we usually need to prepare multiple grippers where each one of the grippers grasps one of the parts.[1] This is because the grippers have to be designed to grasp a part such that the pose of a grasped part can be strictly determined and does not change during the assembly process. We call such grippers as the *shape inadaptive grippers* in this research. However, since a product is usually composed of a lot of parts, a lot of shape inadaptive grippers are needed to complete a product. Since the flexibility of production is significantly reduced due to the existence of a lot of shape inadaptive grippers, robotic assembly is not widely introduced to production processes.

On the other hand, this research considers realizing the parts assembly by using a gripper which can potentially grasp multiple parts with different shapes. We call such grippers as the *shape adaptive grippers* in this research. While the underactuated hands have been proposed,[2,3] most of such hands cannot be used for assembly tasks since the pose of a grasped part cannot be uniquely determined. Here, Meier et al. [4] proposed a underactuated gripper moving in the 2D plane used for assembly tasks. On the other hand, this paper proposes a novel robotic gripper having the shape adaptivity in the 3D space. Our approach does not rely on the precise measurement on the pose of a grasped object.[5,6] By using our proposed shape adaptive gripper, the pose of a grasped part can be uniquely determined and does not change during the assembly task as mentioned above. The key idea to realize such preciseness and robustness is to combine two shape adaptive mechanisms where one is the granular jamming [7,8] and the other is a multiple finger mechanism driven by a single wire as shown in Figure 1.

The first feature of our proposed hand is to use the granular jamming for assembly tasks. Jamming gripper has a snug plastic bag attached to the palm where it encloses a granular material such as grained coffee. To pick up an object, jamming gripper presses its granular bag against the surface of an object and reduces the pressure of the granular bag. Jamming gripper can pick up objects with various shapes due to the jamming phenomenon where the granular bag is stiffened and molded to take on the shape of the object. So far, there has been no attempt to use the jamming gripper for industrial part's assembly. Consider a male–female parts assembly by using our proposed gripper. Our proposed hand will first grasps the male part and assembles it to the female part. Here, a granular bag attached to the palm is pressed against the surface of a male part and its pressure is reduced. Due to the jamming phenomenon, the male part will be firmly grasped during an assembly operation.

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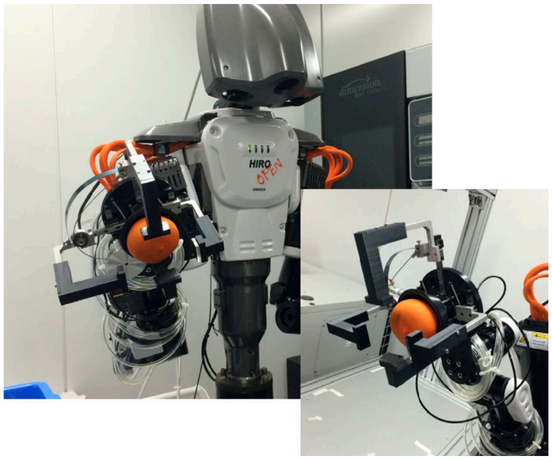


Figure 1. Universal hand for assembly tasks using granular jamming.

The second feature of our proposed hand is that the shape adaptivity is also realized by using a multi-finger mechanism driven by a single wire. The proposed hand has four fingers where two are the active ones and the other two are the passive ones. By the combination of passive/active fingers, we can realize the passive force closure [9] where active fingers press an object onto the surface of passive fingers. This mechanism can be well applied for assembly tasks due to the following two reasons. First, the pose of the grasped object can be uniquely determined since we can use the passive fingers to orient an object placed on a table. Here, there has been a number of works on orienting a polygonal part [10,11] and analysis on tolerance of object's initial position/orientation to orient an object,[12,13] our proposed method utilizes a physical simulation based method for checking the tolerance for an object's initial orientation. Secondly, the active fingers have the shape adaptivity. Due to its underactuation mechanism by using a wire and pulley, the active fingers can adapt to the shape of an object. After the passive fingers orient an object, the active fingers are closed and fit the shape of an object.

The rest of this paper is organized as follows; Section 2: It presents the shape inadaptive gripper; Section 3 shows the mechanism of the proposed shape adaptive gripper; Section 4 shows a physical simulation based method for uniquely determining the pose of an object, and lastly, Section 5 shows experimental results of the proposed hand.

2. Related works

There have been a number of works on mechanical design of robotic grippers as summarized in [2,14]. As for the robotic hands used for assembly tasks, the study has been mainly done on its mechanical impedance.[15,16]. For example, to perform the peg insertion for an object with simple shape such as cylinder and rectangular parallelepiped, RCC (Remote Center Compliance) hand was proposed.[15] Hanafusa et al. [16] studied the mechanical impedance of multi-fingered hand used for assembly tasks. However, little attention has been paied for its shape adaptivity during the assembly tasks.

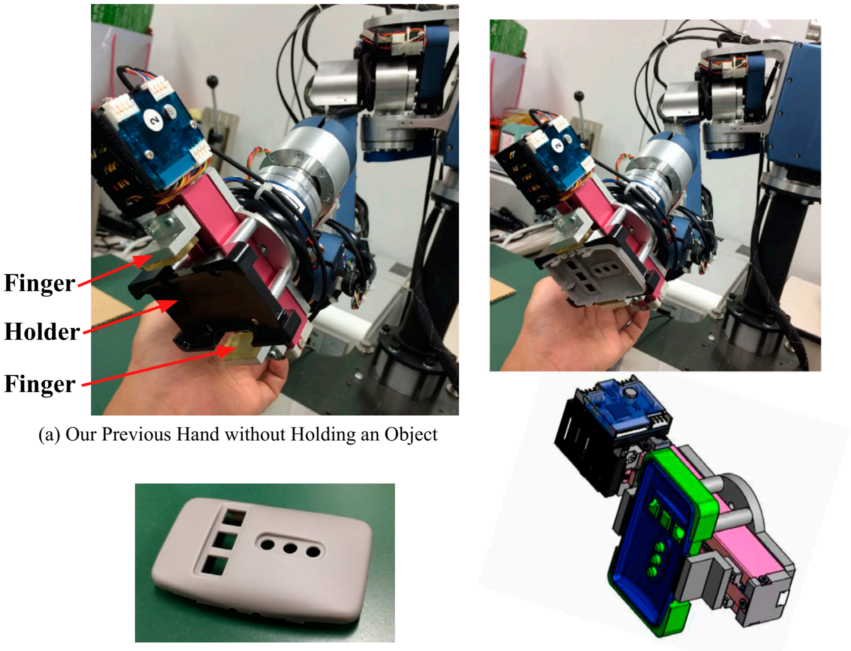
There have been a lot of works on underactuated hands in which the number of actuators is less than the number of DOF as summarized in [3]. Hirose et al. [17] first constructed a wire-driven underactuated hand called the Soft Gripper and showed its shape adaptivity. Laliberte et al. [18] proposed an underactuated finger link mechanism. Fukaya et al. [19] and Catalano et al. [20] also proposed wire-driven underactuated mechanism. Jamming Gripper can also be considered as a kind of underactuated gripper.[7,8] However, it is difficult for underactuated hands proposed so far to use for the part assembly.

Here, while Meier et al. [4] proposed a underactuated gripper moving in the 2D plane used for assembly tasks, this research proposes an underactuated hand moving in the 3D space used the assembly tasks.

This work consider checking the orientation of object where its pose

3. Shape inadaptive gripper

In this section, we present an example of shape inadaptive grippers, its limitations, and the motivations to build a shape adaptive hand. Although the gripper shown in Figure 2 was used to assemble a plastic part with snap joints,[21–23] its mechanism was not well explained in the previous papers. As shown in Figure 2(a), this hand has two fingers and a part holder between them. The holder is constructed by using a 3D printer to fit the shape of a part. In addition, the holder has two cutouts so that the fingers can enter in contact with an object. Since the pose of a grasped object is guided by the holder's shape as shown in Figure 2(c), it can be precisely determined and does not change during the assembly process even if an external force is applied to the object. Figure 3 shows an experimental result of parts assembly.[23] In this experiment, the male part with snap joints is grasped by the robot and is put into the female part. Although we can easily realize the parts assembly by using this hand, we have to newly construct a holder if the shape of a grasped object changes. On the other hand, our proposed gripper uses a granular material [7] along with four-finger shape adaptive mechanism. If the pressure of the granular bag is reduced, a granular material will become stiff and fit the shape of an object due to the jamming phenomenon. We can expect that the granular material can be used instead of the holder constructed by using a 3D printer.

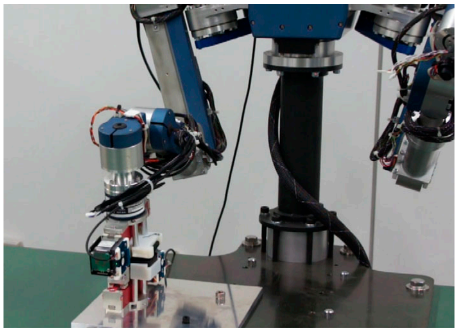


(a) Our Previous Hand without Holding an Object

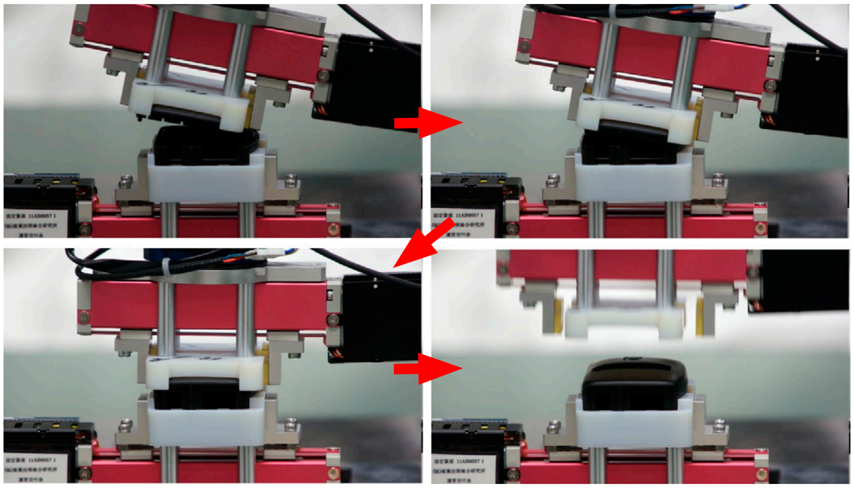
(b) Grasped Object

(c) Our Previous Hand Grasping an Object

Figure 2. Overview of our previous hand.



(a) Overview of Assembly Experiment



(b) Zoomed View of Parts Assembly

Figure 3. Zoomed view of experiment.

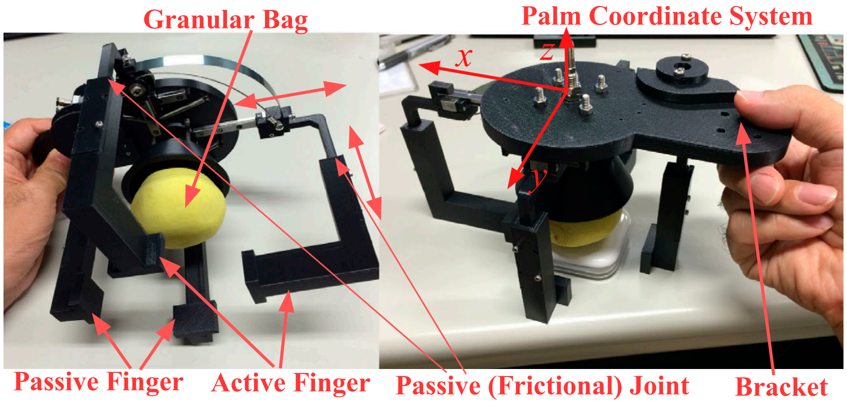


Figure 4. Overview of the proposed hand.

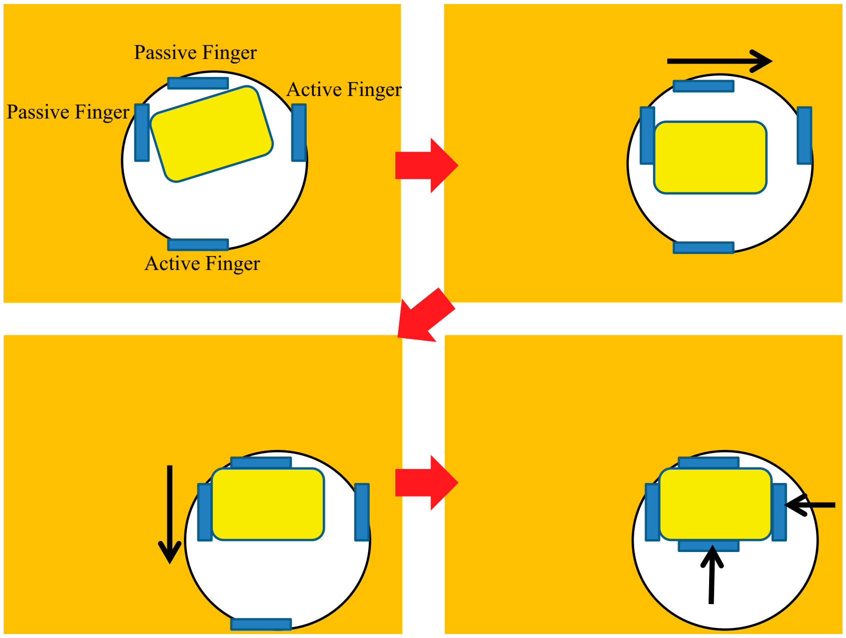


Figure 5. Horizontal motion of the proposed hand.

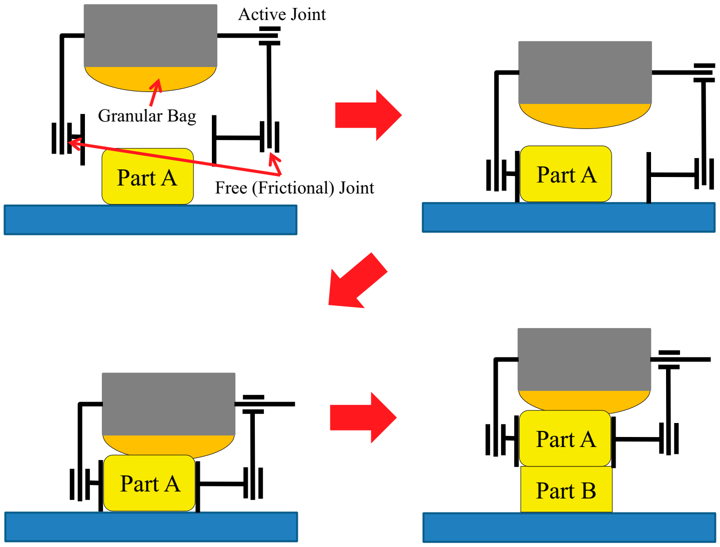


Figure 6. Vertical motion of the proposed hand.

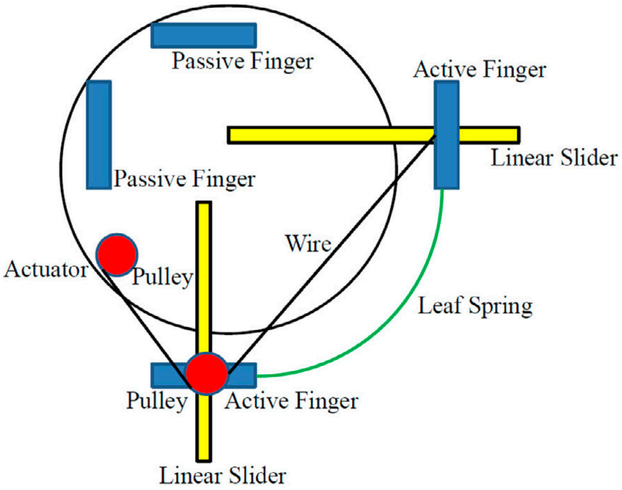


Figure 7. Activation mechanism of the proposed hand.

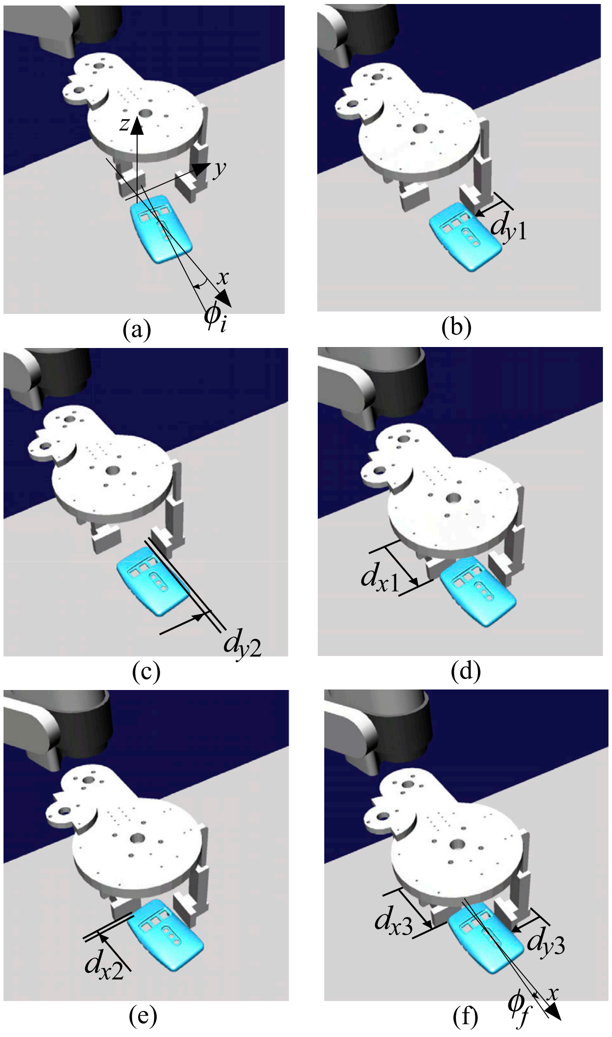


Figure 8. Finger motion in dynamics simulation.

4. Shape adaptive gripper

This section explains the shape adaptive gripper proposed in this research. This gripper has a combined structure between two kinds of shape adaptive mechanisms. Figures 4, 5 and 6 show the snapshot of our proposed shape adaptive gripper, its horizontal and vertical motion, respectively. When grasping a part placed on the horizontal table, the granular material and the multi-finger mechanism have the shape adaptivity in the vertical and the horizontal directions, respectively.

We consider the coordinate system fixed to the palm (Figure 4). As shown in Figure 5, the assembly strategy starts by moving the palm along a planar surface such that the two passive fingers simultaneously contact an object. By re-positioning the object against the corner of the passive fingers, we are able to compute its pose. Here, the horizontal motion of the gripper is explained more detail in the next section. After the palm moves in the horizontal direction, the active fingers are closed to press an object onto the surface of the passive fingers. Since each finger has a free translational joint as shown in Figure 6, the granular bag can be pressed against the object such that the granular bag is molded with the shape of the object.

Finally, the object is picked up and is assembled. The proposed hand has the following features:

Granular Material: The proposed hand's granular material is formed by placing grained coffee within a tight-and-elastic rubber balloon. The rubber balloon is attached on the anterior part of the gripper palm. In this way, when the gripper presses vertically downwards on an object, the granular bag is also pressed against the object. The elastic bag including the grained coffee becomes stiff and conforms to the shape of the object.

Active Fingers: The propose hand has four fingers: two are passively actuated, two are actively actuated, enabling the passive force closure [9]. Its actuation mechanism within the $x - y$ plane with respect to the palm coordinate system is shown in Figure 7. Each active finger has one translational joint moving in the $x - y$ plane and one translational free joint moving in the z direction. The proposed hand has the shape adaptive mechanism where two active fingers are actuated by only one actuator enabling the hand to fit the shape of a grasped object. As shown in the figure, this shape adaptive mechanism is realized by using a wire and pulley system. Also, a leaf spring is attached between two active fingers such that the active fingers can be opened by using the return force of the spring.

Passive Fingers: The proposed hand has two passive fingers where its motion in the $x - y$ plane relative to the palm coordinate system is fixed. Each passive finger has one translational free joint moving in the z direction. After the horizontal motion of the palm,

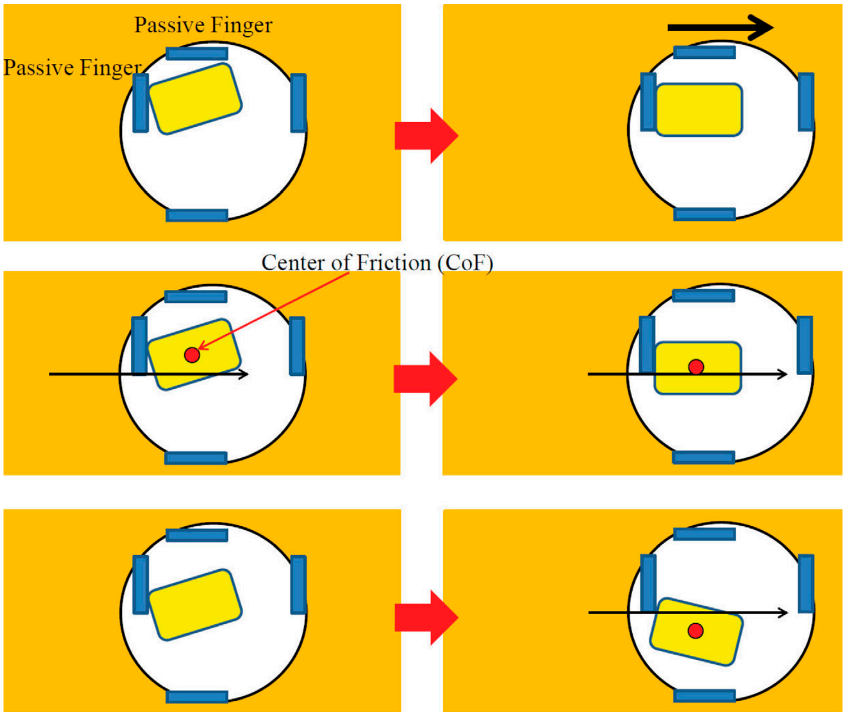


Figure 9. Dependency of final object orientation on object position: final orientation is determined depending on the relative position between object's CoF and edge of a passive finger.

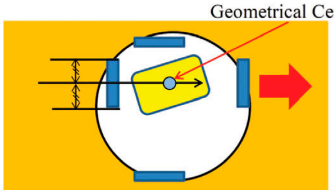


Figure 10. Initial position of object assumed in the physical simulation.

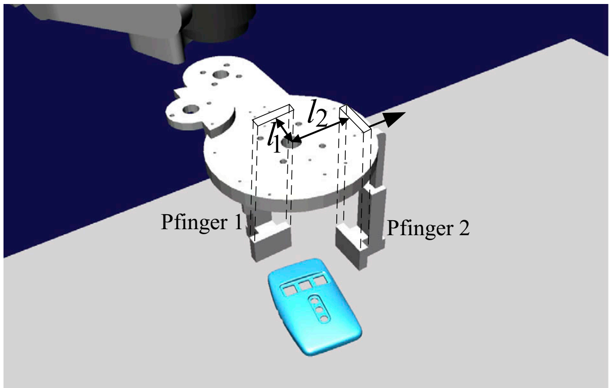


Figure 11. Definition of Pfinger offset.

two passive fingers simultaneously contact an object. For part's assembly to succeed, the pose of an object simultaneously contacting two passive fingers should be uniquely determined (hand motion details are presented in the next section). Also, while the horizontal motion of the passive fingers relative to the palm coordinate system is fixed, its positions are adjustable as will be discussed in the next section.

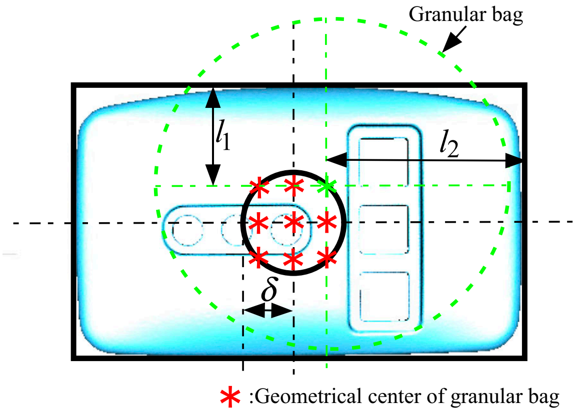
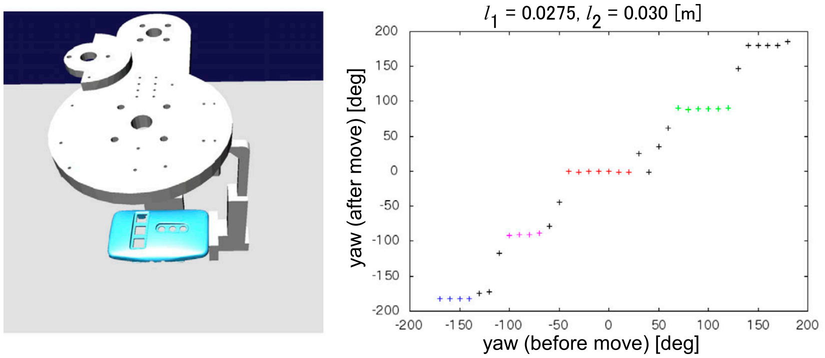
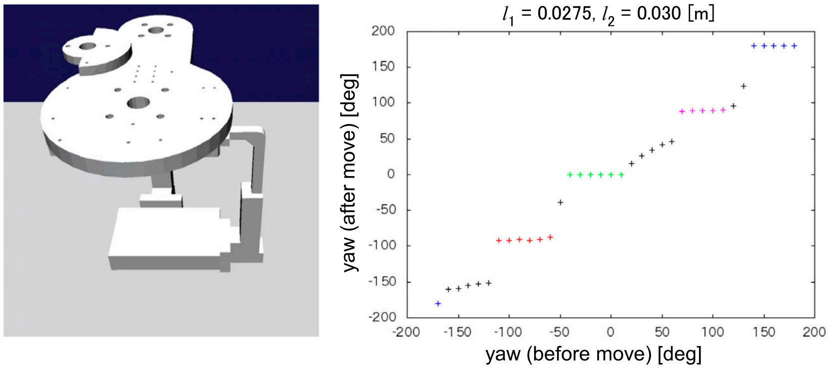


Figure 12. Candidates of Pfinger position.

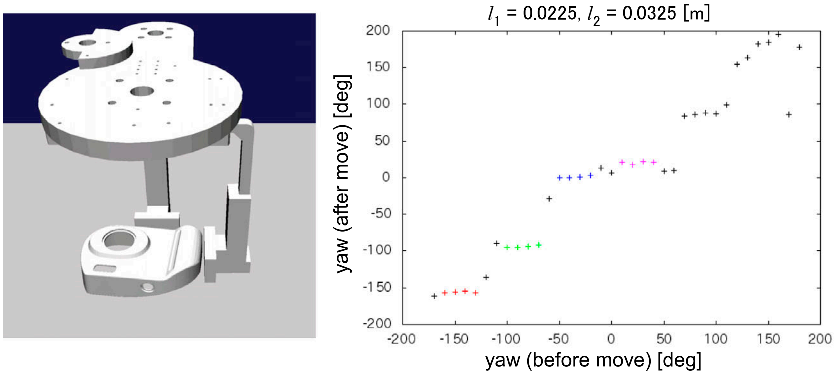
Passive Joints: Each finger has a free (frictional) joint in the z direction of the coordinate system fixed to the palm. Due to these passive joints, the palm can move vertically even after the fingers contact an object. This enables the granular bag to contact an object of various shapes. Furthermore, due to both friction from the passive joints and granular jamming from the granular bag, the hand will not drop the grasped object after picking it up.



(a) Optimal position of passive fingers for Part 1 and plot of ϕ_i–ϕ_f



(b) Optimal position of passive fingers for rectangular parallelepiped and plot of ϕ_i–ϕ_f



(c) Optimal position of passive fingers for Part 3 and plot of ϕ_i–ϕ_f

Figure 13. Optimum Pfinger position and constant region of final object orientation.

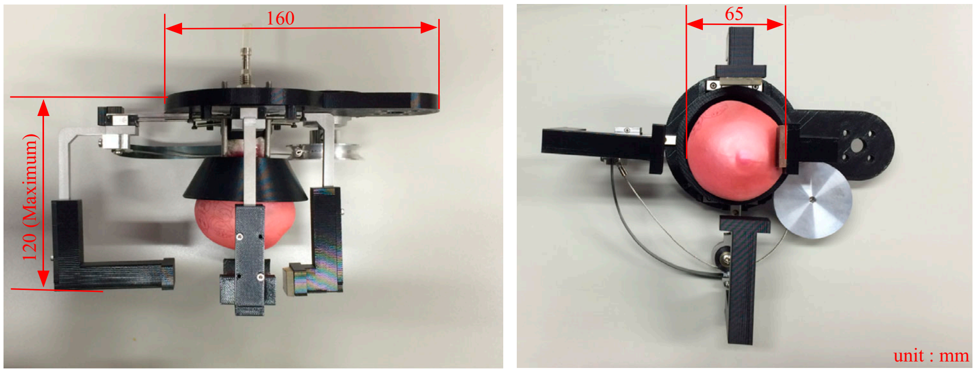
5. Grasping motion determination

In our proposed method, the passive fingers are used to orient an object. For the assembly task to be successful, the horizontal motion of the palm should result in the pose of an object uniquely determined with two passive fingers simultaneously contacting an object. We impose these assumptions:

- (**A1**) Rough information on an object's pose is given before the palm moves horizontally.
- (**A2**) Horizontal motion of the palm is quasi-static where the effect of dynamics can be neglected.
- (**A3**) Friction coefficient is uniform within the contact area between an object and table.

This section describes a method for checking the error tolerance of the object's initial orientation through physical simulation on computer. This section also shows that the tolerance changes depending on the position of the passive fingers relative to the palm. In the following, we will explain the horizontal motion of the palm and a method for adjusting the position of the passive fingers relative to the palm by using physical simulation.

Figure 8 shows the horizontal motion of the hand introduced in this research. The palm first moves to push an object in the y−direction by a distance d_{y1} and moves back from an object by a distance d_{y2}. Then, the palm moves to push an object in the x−direction by a distance d_{x1} and moves back from an object by a distance d_{x2}.



(a) Side view (a) Bottom view

Figure 14. Size of developed hand.

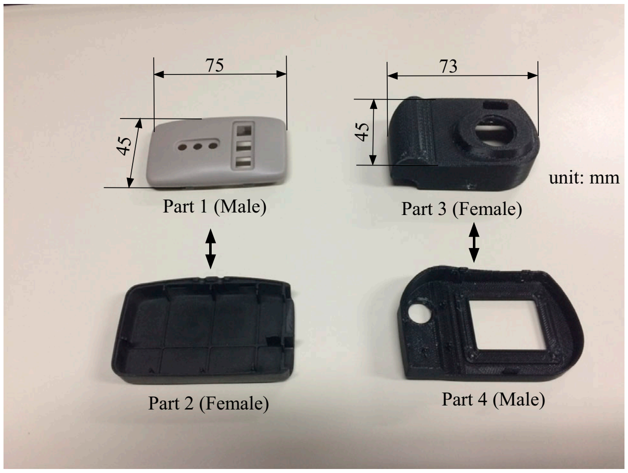


Figure 15. Objects used in experiment.

Finally, the palm moves to push an object in both $x-$ and $y-$directions by a distances of d_{x3} and d_{y3}, respectively. Let ϕ_i be the orientation of an object about the vertical axis before the horizontal motion of the hand, and let ϕ_f be the orientation after such motion.

We set the object at multiple initial orientations for physical simulation. Then, we consider iteratively running the physical simulation for all initial angles of the object. At each iteration, the hand moves as shown in Figure 8. After each iteration, we plot (ϕ_i, ϕ_f). Lastly, after finishing the iteration of physical simulation, we calculate the region on the ϕ_i axis of the $\phi_i - \phi_f$ plot where ϕ_f is nearly constant. If the initial orientation of an object is included in the constant region, the final orientation will converge to the same one. For the assembly task to succeed, we need the information on ϕ_f. Hence, if the constant region is large, we can easily estimate ϕ_f with rough information on ϕ_i. On the other hand, if the constant region is small, we need ϕ_i to be precisely known.

This research just considers dependency on object's initial orientation ϕ_i to the final orientation ϕ_f although the final orientation may also depend on object's initial position. This is because we can easily visualize the tolerance in the initial orientation. In Figure 9, the gripper tries to orient an object from three different initial positions. The object's final orientation of the bottom case is different from the upper two cases. As shown in figure, this difference is introduced due to difference on the relative position between object's center of friction (CoF) and the edge of a passive finger.[24,25] Hence, we can expect that the dependency on object's initial position to the final orientation will be reduced if we use the passive finger with large contact area. In our physical simulation, we set the initial position of an object such that the horiontal line perpendicular to the surface of the passive finger firstly contacting an object passes through the geometrical center of both object and the passive finger as shown in Figure 10.

Then we explain how to adjust the position of the passive fingers relative to the palm. As shown in Figure 11, two passive fingers are denoted as the Pfingers 1 and 2. We assume that the positions of the Pfingers 1 and 2 in the x and y directions, respectively are adjustable. As shown in Figure 12, let us consider the shape of the granular bag and an object projected onto the horizontal plane. We consider the circle with radius δ centered at the geometrical center of the object's 2D bounding box. We set the center of the granular bag at multiple positions within this circle. This is because, when the center of the granular bag contacts near the geometrical center of object's 2D bounding box, we can intuitively expect the granular jamming working effectively. Depending on the position of the granular bag, the position of the passive fingers are determined as shown as l_1 and l_2 in Figure 12. We iterate the above set of physical simulations for all positions of the Pfingers 1 and 2. Finally, we adapt the positions of Pfingers 1 and 2 such that the region in the ϕ_i axis of the $\phi_i - \phi_f$ plot with constant ϕ_f is the largest.

Figure 13 shows the result of calculation for three kinds of parts where the optimal position of the passive fingers is shown in the left and where the plot of $\phi_i - \phi_f$

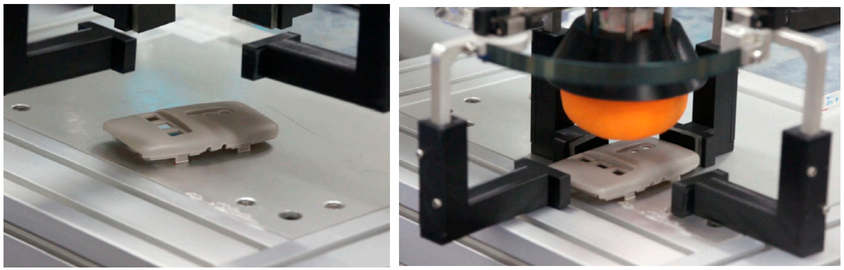

(a) Approach 1
(b) Approach 2
(c) Orient
(d) Grasp
(e) Transfer
(f) Assemble
(g) Release 1
(h) Release 2

Figure 16. Snapshot of assembly experiment of Parts 1 and 2.

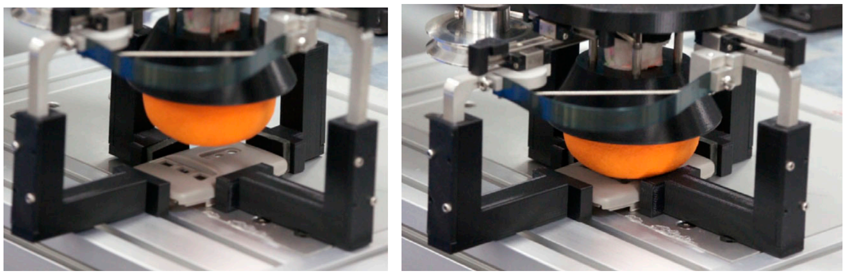
is shown in the right. As an engine of physical simulation, we used Choreonoid.[26] Here, $d_{x1}$and d_{y1} should be large enough such that the object's final orientation converges to a single value. On the other hand, d_{x2} and d_{y2} can be small since d_{x2} and d_{y2} are used to avoid an object slipping on the surface of a passive finger. d_{x3} and d_{y3} should be same as or larger than d_{x2} and d_{y2}, respectively, for an object to enter in contact with two passive fingers. We set $d_{y1} = d_{x1} = 0.04$ m, $d_{y2} = d_{x2} = d_{y3} = d_{x3} = 0.005$ and $\delta = 0.005$ m for all the objects. For the plot of $\phi_i - \phi_f$, the colored dots are included in a region where ϕ_f is nearly constant. As shown in figure, if an object is a rectangular parallelepiped or can be well approximated by a rectangular parallelepiped, we have a large region with constant ϕ_f.

6. Experiment

We show experimental results of the proposed hand where its overview is shown in Figure 1 where we attached the proposed hand to the tip of the 6 DOF right arm of the HIRO dual-arm robot. To drive the active fingers, the wire is connected to a pully driven by an air actuator. We used a 5 ports solenoid valve (SMC SY5120-5LZ-C6: 0.15-0.7 MPa) to drive the air actuator. To reduce the pressure of the granular bag, we used the air ejector (Tokuyama Seiki TVR-2-S10HS). The jamming gripper is constructed by installing grained coffee into a toy balloon. The size of developed hand is shown in Figure 14. The stroke of the active and the passive fingers are set as 50 and 30 mm, respectively.

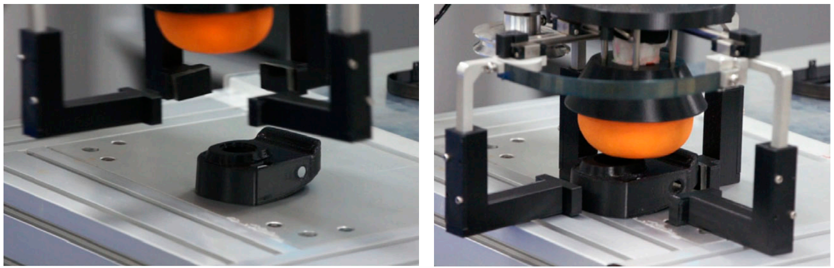


(a) Approach (b) Orient

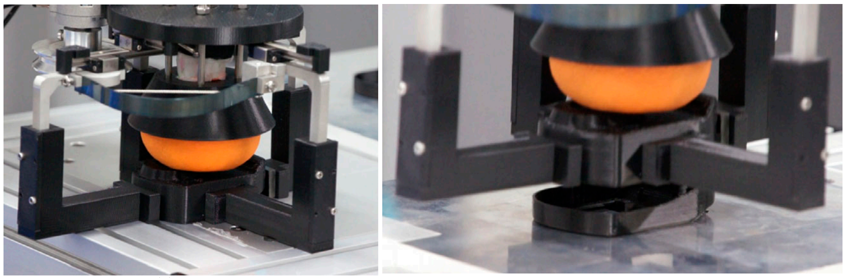


(c) Grasp 1 (d) Grasp 2

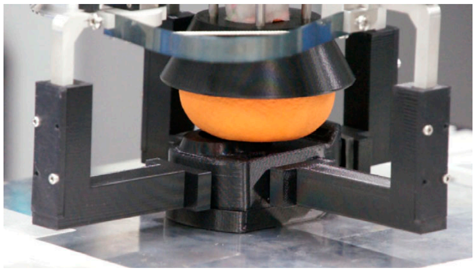
Figure 17. Snapshot of experiment from different initial orientation of object.



(a) Approach (b) Orient



(c) Grasp (d) To Assemble



(e) Assemble

Figure 18. Assembly experiment of Parts 3 and 4.

Figure 15 shows the objects used in experiments. The proposed hand grasps the parts 1 and 3 and assemble them to the parts 2 and 4, respectively. Here, in the experiment of shape inadaptive gripper shown in Section 3, the gripper grasps the part 1 and assemble it to the part 3. If the gripper does not fit the shape of the part 1, it becomes difficult to assemble the part 1 to the part 2 since the gripper cannot exert enough grasping force onto the part 1. In experiment, we roughly placed an object on a table such that the fingers do not collide with an object while the gripper approaches to an object.

Figure 16 shows the result of experiment where the proposed hand first orients the part 1 placed in table, then grasp and transfer it, and finally assemble it to the part 2 which is fixed to table. In the experiment, it took 7 s to orient the part 1 and about 10 s to lift it up and assemble it to the part 2.

The assembly was successful since the granular bag played the similar role to the holder used in the shape inadaptive hand. Figure 17 also shows the result of experiment where the part 1 is assembled to the part 2. Here, although the initial posture of the part 1 is different from that of the experiment shown in Figure 16, it is included in the same region with constant ϕ_f of $\phi_i - \phi_f$ plot. Also, the motion of the robot and the position of the passive fingers used in both experiments are same. In spite of the difference of the initial posture of the part 1, the assembly was successful in both experiments.

Figure 18 shows the result of experiment where the proposed hand assembles the part 3 to the part 4. Here, since that parts 3 and 4 are produced roughly by using a 3D printer, we judged the assembly succeeded if all the snap joints attached to the male part (part 4) are inserted into the female part (part 3). As shown in figure, even if the assembled part has a different shape, the assembly was successfull by using the same hand.

7. Conclusions

In this paper, we proposed a universal robotic gripper for assembly tasks. Since the pose of a grasped object cannot be uniquely determined just by using a jamming gripper, we proposed a novel mechanism where granular jamming is used combined with a multiple finger mechanism. We showed that, due to the jamming phenomenon, the granular bag of the proposed hand can be used instead of the parts holder of our previous hand used for assembly tasks. We also show a method for orienting an object by using the passive fingers based on physical simulation. Furthermore, the active fingers have underactuation mechanism and can adapt to the shape of an object. Experimental results on assembly of two kind of parts are shown.

For future research, we will extend our proposed hand such that it can assemble more general class of objects with more complicated assembly strategy.

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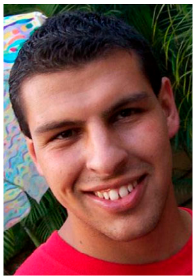

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