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Development of Robot Hand with Suction Mechanism for Robust and Dexterous Grasping

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Abstract— **In this study, we propose a robot hand referred to as iGRIPP 4 (Integrated Gripper for Power and Precision Grasp 4), which has suction mechanism at each fingertip. This robot hand can grasp various objects steadily and achieve dexterous manipulations with a simple mechanism. The iGRIPP 4 has three fingers and two servomotors which are designed to grasp objects in power grasp and precision grasp. The suction mechanism at the fingertips enhances grasp stability, and enables the hand to hold large objects. In addition, the combination of the grasp mechanism and the suction system make it possible to perform some dexterous manipulations. Examples of the manipulations include the picking up a thin object and the packaging an object in a bag. These manipulations generally require hands with many degrees of freedom and intricate control. In this paper, the mechanism of the iGRIPP 4 is presented, and the two dexterous manipulations that can be done with this robot hand are described.**

I. INTRODUCTION

In recent years, various non-anthropomorphic robot hands have been developed for robots not only in industrial fields but also in our everyday lives. Example of hands include: the BarrettHand [1], A Robotiq 3-Finger Adaptive Gripper [2], A Schunk Dexterous Hand [3], and A High-Speed Multifingered Hand [4]. To expand object manipulation capability of a non-anthropomorphic robot hands, some researchers added an additional mechanism to the robot hands. Nagata [5] proposed a parallel-jaw gripper which has a turntable at each fingertip. Tincani et al. [6] developed Velvet Fingers which has one degree of freedom active surfaces on the fingers. In this paper, we propose different approach to improve the ability of robot hands.

In order to improve dexterity of multi-fingered robot hands, we propose a concept: a combination of a grasp mechanism and vacuum pads. In this paper, we present a prototype of a robot hand which has both a grasp mechanism and vacuum pads. The combination of the grasp mechanism and vacuum pads allows the robot hand to grasp objects steadily. Furthermore, this robot hand is able to achieve some dexterous manipulations which are impossible for conventional robot hands. We call this robot hand as iGRIPP 4 (Integrated Gripper for Power and Precision Grasp) which is developed based on a robot hand iGRIPP 3 proposed by Chiba et al. [7]. The iGRIPP 4 has three fingers and two actuators and equips a vacuum pad at each fingertip (Fig. 1).

In previous studies, some end-effectors are developed which has both a grasp mechanism and a vacuum pad. A reconfigurable robotic gripper system (RGS) [8] has four arms in a crossbar configuration and a suction unit mounted on each of the arms for limp material handling. Monta et al. developed a parallel-jaw gripper which has vacuum pad among the jaws to perform fruit harvesting [9]. Liu et al. developed a similar gripper with multi-sensor and laser cutting device to cutting off the peduncle [10]. A gripper developed by Eftring is equipped on a wheelchair-mounted manipulator for people with physical disabilities [11]. This gripper has suction cups to turn the pages of a book. Although these end-effectors use the vacuum pads effectively, these grippers are designed to handle the particular object. Tomizawa et al. [12] have developed an end-effector with four soft suction cups for a Remote Shopping Robot. This end-effector is able to hold various shapes objects by changing the direction of the suction cups. Moreover, the end-effector can grasp an object by using the suction cups as a finger. However, the end-effector is not able to pinch relatively small objects because the shape of the suction cup is not designed as a fingertip. The iGRIPP 4 can achieve not only the holding of objects using suction cups but also power grasps and precision grasps by using the fingers as shown in Section II.

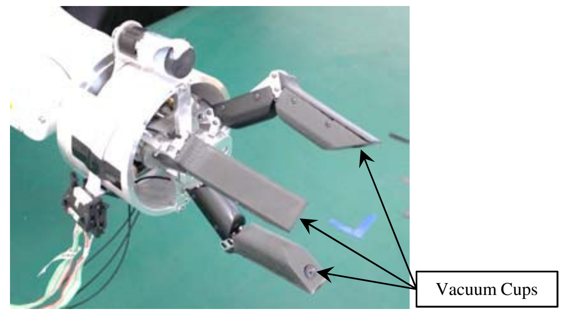

Fig. 1. Robot hand -iGRIPP 4-

The iGRIPP 4 is also designed to perform difficult tasks by combining the vacuum cups with the robot hand which has low degrees of freedom. In this paper, we present following two tasks:

- Pick up thin objects from a table surface.
- Open a bag and pack objects.

Although, conventional robot hands require many degrees of freedom and intricate control to perform these tasks, the iGRIPP 4 is able to perform the tasks with simple mechanism and control.

In the first half of this paper, the mechanism of the iGRIPP 4 is explained. In the second half of the paper, dexterous manipulations of objects by the iGRIPP 4 are described.

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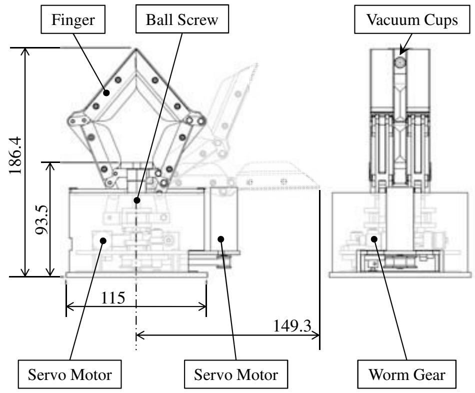


Fig. 2. Appearance and size of iGRIPP 4

(a) Grasping motion

(b) Turning motion

Fig. 3. Motion of iGRIPP 4

II. STRUCTURE OF ROBOT HAND

Developed robot hand named iGRIPP 4 has three fingers with two joints in each finger as illustrated in Fig. 2. These fingers have a vacuum pad at the fingertip. Two DC servo motors are installed inside. One motor curls the three fingers simultaneously (Fig. 3 (a)), and the other motor rotates the two fingers up to 180 degrees around the palm symmetrically (Fig. 3 (b)). Each finger employs a simple linkage system in order to grasp various objects. In addition, this mechanism also realizes a change of an arrangement of the vacuum pads leading to dexterous manipulation of objects.

A. Link Mechanism of Fingers

Fig. 4 shows the linkage system of the iGRIPP 4. A servomotor drives a ball screw in the heart of the robot hand. Bottom links of three fingers attached to a nut of the ball screw rotate links of the fingers. Therefore, three fingers curl and stretch synchronously.

Each finger employs four-bar linkage mechanism as shown in Fig. 4. Although there has been many researches of linkage for robot hands [13]-[16], we adopted the simplified mechanism because we mainly focus on the combination of robot hands and vacuum pads in this research. By this mechanism, the vacuum pad on the fingertip faces the opposite vacuum pad when the hand closes, and turns to outward when the hand opens. These configurations of vacuum pads make it possible to achieve dexterous manipulation of objects as shown in the latter part of this paper.

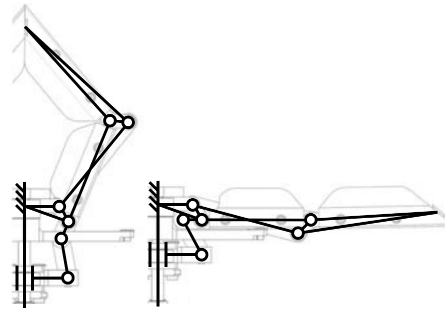


Fig. 4. Link mechanism

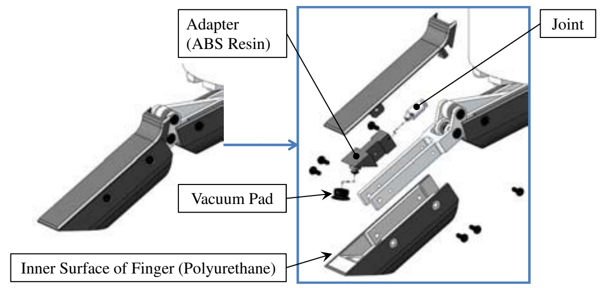


Fig. 5. Finger structure

The other servomotor drives a worm gear to spread two fingers. The worm gear drives the gear train, and the gears rotate two shafts connected with the links of two fingers. Hence, the two fingers spread around the palm symmetrically. Because the worm gear is not back-drivable, two fingers are able to keep the spread angle without any control from motor.

Fingertips and inner links of the each finger are covered with a skin made of soft polyurethane. This structure increases the contact surface between the finger and an object. Thereby, a stable grasp can be achieved without self-adaptable linkage.

B. Suction Mechanism

Fig. 5 shows an internal structure of the fingertip of the iGRIPP 4.The diameter of the vacuum cup is 8 mm. The vacuum cup is attached to an adapter made of ABS resins on the fingertip. A urethane tube connects the adapter with a vacuum device placed outside of the robot hand. The inside diameter of the tube is 1 mm. The vacuum device is a vacuum ejector unit with a decompression of -78 kPa and a flow quantity of 8 l/min. The vacuum ejector unit includes an ejector, a pressure sensor, a solenoid valve and a release valve.

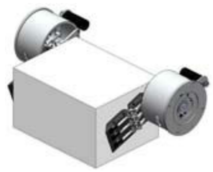
The holding force of the vacuum cup W [N] is proportional to the pressure inside the cup and the area of vacuum cup as follows:

$$W = \frac{AP}{10} \tag{1}$$

(a) Power grasp of cylinder

(b) Precision grasp of small object

(c) Precision grasp of small plate



(d) Grasp of large box using two hands

Fig. 6. Examples of object grasping by fingers and palm

(a) Hold of small box

(b) Hold of large plate

(c) Grasp of cuboid with two planes

(d) Grasp of cuboid with three planes

Fig. 7. Examples of object grasping by vacuums cups

where A is the area of the vacuum cup [cm^2], and P is the vacuum level [-kPa]. Therefore, the holding force of the vacuum cup of the iGRIPP 4 is theoretically 3.9 N. This is adequate holding force for a small object which is lighter than 0.4 kg. Additionally, the iGRIPP 4 is able to lift an object which is heavier than 0.4 kg by using the two or three vacuum cups on the fingers simultaneously.

Although the vacuum pads enable the iGRIPP 4 to achieve dexterous manipulation, they need an external vacuum apparatus. Thus the system of the iGRIPP 4 requires large space compared with conventional robot hands. We are planning to integrate a vacuum device into the iGRIPP 4 to overcome this weak point.

C. Grasping of Various Objects

The iGRIPP 4 is designed to achieve both power grasps and precision grasps (a classification by Napier [17]). Cylindrical objects can be held in a clamp formed by the three fingers (power grasp) as shown in Fig. 6 (a), and relatively small objects can be pinched between the two fingers and the opposing finger (precision grasp) as shown in Fig. 6 (b). The iGRIPP 4 can spread the two fingers to fit the object shape

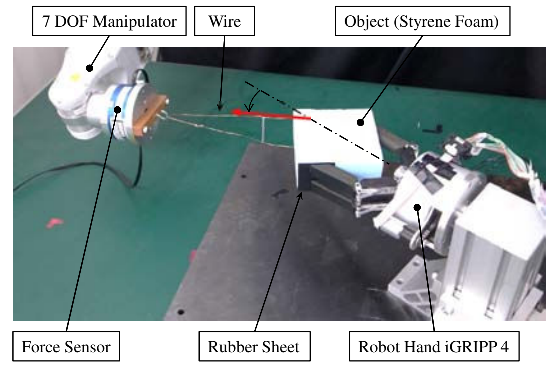


Fig. 8. Experimental system

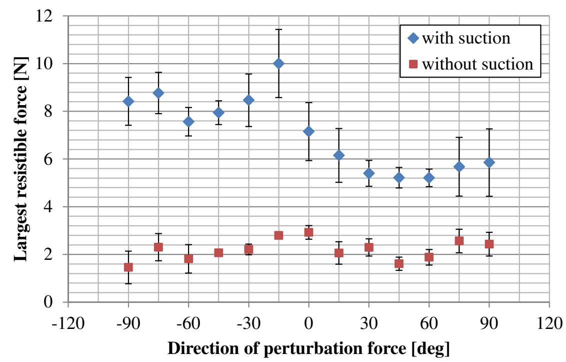


Fig. 9. Largest perturbation force that grasp can resist

in the precision grasp (Fig. 6 (c)). In addition, the iGRIPP 4 can level the fingers with the palm. Therefore, when a dual-arm robot is equipped with the iGRIPP 4, the robot can lift a large box by holding the box with fingers and palm of both hands, like human beings (Fig. 6 (d)).

Moreover, the iGRIPP 4 is able to hold objects by using the vacuum pads on the fingertips. When the iGRIPP 4 holds objects by using the vacuum pads, the iGRIPP 4 can adjust the relative position between the vacuum pads to suit object size (Fig. 7 (a) (b)). In addition, the iGRIPP 4 can grasp objects robustly by sucking the objects. For example, the iGRIPP 4 can grasp a cuboid object with suction at the contact points (Fig. 7 (c) (d)).

D. Experiment to Quantify Stability of Grasp

In order to quantify the performance of the grasp with the suction mechanism, we measured the largest perturbation force that the grasp can resist. Fig. 8 shows the experimental setup. The iGRIPP 4 grasp an object made of styrene foam with two planes. Rubber sheets are pasted on the object to increase the coefficient of friction. A 7 degrees of freedom manipulator pulls a wire which is threaded through the object. A mounted force sensor measures the perturbation force during the pull motion.

Fig. 9 shows the experimental results. As shown in Fig. 9, the grasp with the suction mechanism acquire the strong resistible force compared with the grasp without the suction. The experimental results quantitatively show the validity of the grasp by the iGRIPP 4.

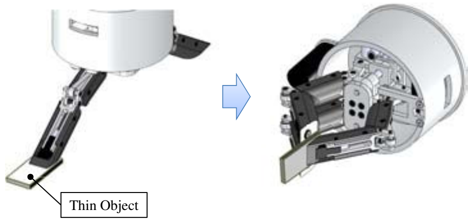


Fig. 10. Pick up thin objects from table by iGRIPP 4

III. DEXTROUS MANIPULATION 1

A. Pick Up Thin Objects from Table

The iGRIPP 4 can achieve dexterous tasks with the grasp mechanism and the vacuum cups like picking up a thin object initially placed on a flat surface. This is a typical task in daily life and it is desired that human support robots can execute such tasks. The dexterous tasks are achieved by the iGRIPP 4 as follows (Fig. 10) :

1) The iGRIPP 4 adheres to the object by the vacuum cups on the fingertip.
2) The iGRIPP 4 picks up the object from the table.
3) The iGRIPP 4 hold the object in precision grasp.

Some researchers conducted to achieve this task by using a robot hand. Kaneko et al. observed a human behavior for grasping column objects with different size initially placed on a table, and then pointed out that the human unconsciously changes the grasp strategy according to the size of objects [18]. They classify the grasp strategy, and verified it by experiments using a robot hand. Odhner et al. achieved the flip-and-pinch task for thin objects by an underactuated robot hand [19]. In these conventional researches, the robot hands imitate the human motion to pick up thin objects from a table.

One problem in conventional methods is that the orientation of the grasping object depends on the shape of the objects. Consequently, it is difficult to use the grasped object for next tasks; like the insertion of a key, a USB drive, etc. without an in-hand manipulation or a passing the grasped object from one hand to the other.

In contrast, the iGRIPP 4 can pick up the thin objects at an arbitrary orientation around the axis of the vacuum pad. Hence, the iGRIPP 4 can achieve next tasks using the grasped object without the need for the dexterous in-hand manipulation or the time-consuming manipulation to change the grip. Although a vacuum cup is able to pick up a thin object alone, the next tasks using the held object are difficult without precision grasp, because the holding force in a tangential direction, by the vacuum cup is limited.

B. Experiment

We conducted experiments to demonstrate the effectiveness of the proposed method. Fig. 11 shows the experimental setup. A key and a USB thumb drive are handled by the proposed method (Fig. 12). We assume that a vision system could detect the position and orientation of the objects. In this experiment, we placed the target objects in a certain position and orientation manually. The iGRIPP 4 is attached to a 7 degrees of freedom manipulator. The manipulator and the table are fixed to a rectangular frame made of aluminum.

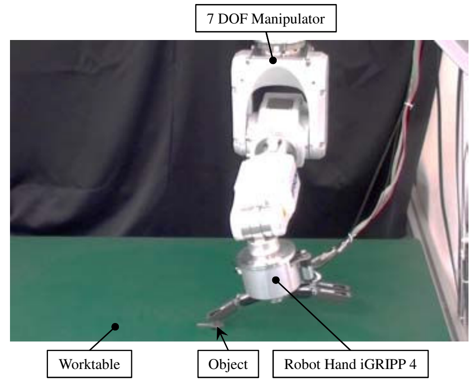
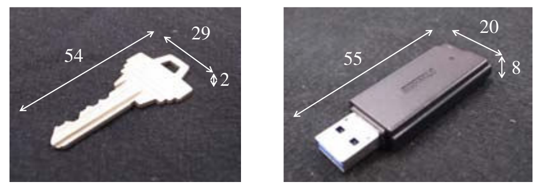


Fig. 11. Experimental system



(a) Key (9 [g]) (b) USB Thumb Drive (8 [g])

Fig. 12. Handling objects

First, one fingertip of the hand is moved to the top of the object. Next, the vacuum ejector starts suction, and then the robot hand picks up the object. Finally, the robot hand curls the fingers to grasp the object in precision grasp.

Fig. 13 and Fig. 14 shows the process of the object grasping. As shown in Fig. 13 and Fig. 14, the iGRIPP 4 was able to pick up the thin objects without using complex mechanism and control. However the iGRIPP 4 was not able to grasp the USB drive in a unique position because the fingertips facing each other are not parallel when the hand grasps the USB drive and the skin of the finger is not soft enough to adapt the shape of the object. The structure of the fingertip or the mechanism of the underactuated linkage of the iGRIPP 4 must be redesigned in order to grasp various objects in precision grasp robustly.

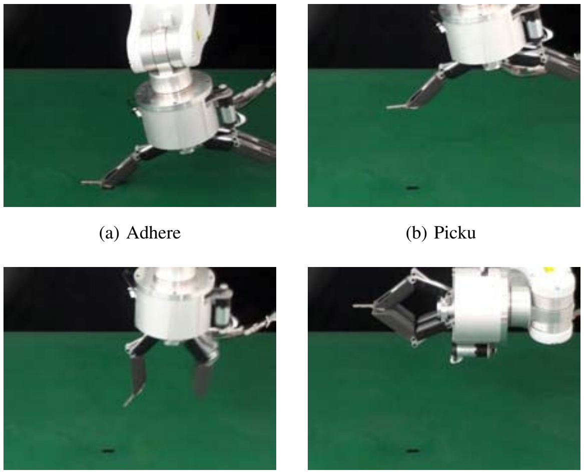
The position and orientation error of the grasped object is inevitable because of measurement errors in the position of the object and modeling errors in the robot hand and the object Therefore additional sensors such as force sensor are necessary to perform following tasks such as insertion of the grasped key or a USB drive. In our future work we will integrate vision system and force control to accomplish the tasks.

IV. DEXTROUS MANIPULATION 2

A. Open Bag and Pack Objects

The iGRIPP 4 can also achieve any dexterous task with the combination of the grasp mechanism and the vacuum cups like opening a bag and inserting an object in the bag. The dexterous task is achieved by the iGRIPP 4 attached to a dual-arm manipulator as follows (Fig. 15) :

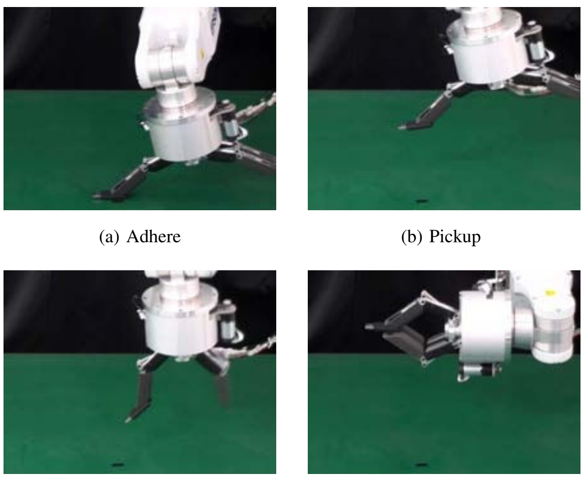
1) One iGRIPP 4 grasps the mouth of the bag in precision grasp.



(a) Adhere (b) Picku

(c) Grasp (middle) (d) Grasp

Fig. 13. Picking and grasping of key



(a) Adhere (b) Pickup

(c) Grasp (middle) (d) Grasp

Fig. 14. Picking and grasping of USB thumb drive

2) This iGRIPP 4 adheres to the bag at the contact points.
3) The iGRIPP 4 then opens the bag by spreading the fingers.
4) The other iGRIPP 4 grasps the object and inserts it to the bag.

Conventional robot hands are not able to achieve this dexterous task. It is difficult to package the object with the robot hands, because the deformation of the bag has to be controlled. In general, packaging of objects is conducted by a single-purpose machine or labors.

The iGRIPP 4 can open the bag and package the object by adhering to the bag. The vacuum pad on the fingertips fixes around the mouth of the bag. This approach greatly simplifies the dexterous manipulation. Actually, this method is adopted by some packaging machines.

B. Experiment

To demonstrate the effectiveness of the proposed method, we conducted experiments. Fig. 16 shows the experimental setup. A paper and a name card are inserted to an envelope and a plastic case respectively. The iGRIPP 4 are attached to a dual-arm manipulator. The dual-arm manipulator is fixed to a rectangular aluminium frame.

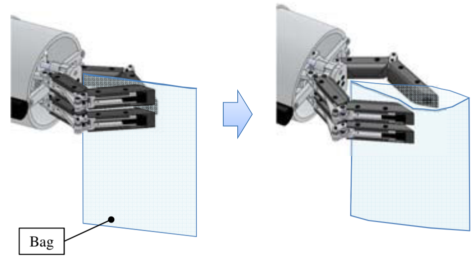


Fig. 15. Open bag by iGRIPP 4

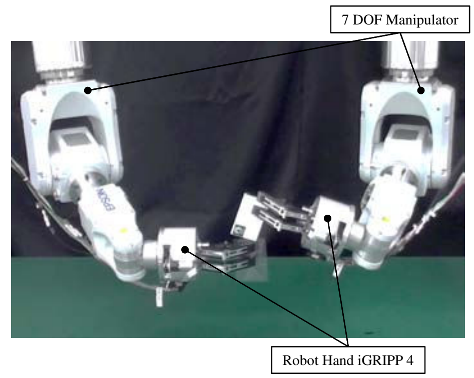


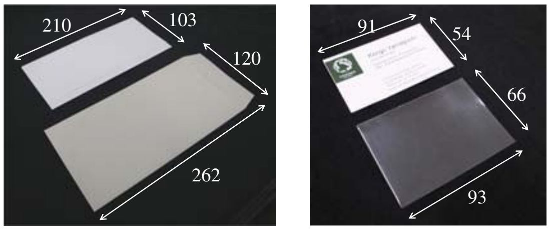
Fig. 16. Experimental system

First, one iGRIPP 4 pinches the mouth of the bag, and the other iGRIPP 4 grasp the object. In this experiment, we set the target objects in previously arranged position and direction manually. Note that the picking up of these thin objects can be achieved without additional equipment such as parts feeders by using the above-mentioned method. Second, the vacuum ejector starts to suck the bag. Third, the iGRIPP 4 spreads the fingers with a constant torque to open the mouth of the bag. Finally, the other iGRIPP 4 inserts the grasping object in the bag. The manipulator imitated a human motion for the insertion of the object; initially a corner of the object is inserted, and then the object is thrust in the bag.

Fig. 18 and Fig. 19 shows the process of the object handling. As shown in Fig. 18 and Fig. 19, the iGRIPP 4 was able to open the bag and insert the object to the bag with simple mechanism and control. However the insertion task failed sometimes. This is due to a position error of initial setting. The initial error of the objects leads to unexpected contact between the bag and the insert object because the position and orientation of the objects were not detected with sensors. We will implement a vision system for the reliable accomplishment of the task in our future work.

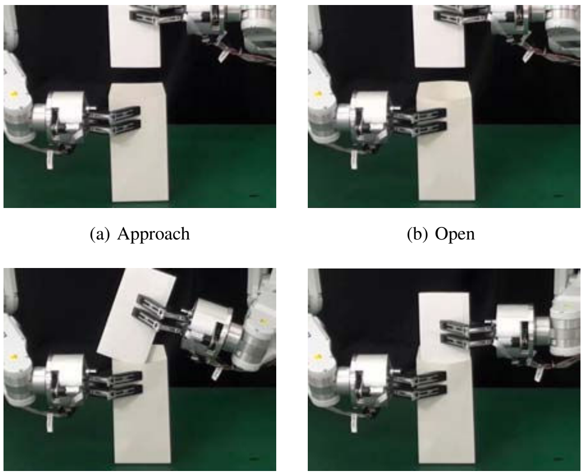
V. CONCLUSIONS

In this paper, we propose the low degrees of freedom robot hand called iGRIPP 4, which has a vacuum pad at each fingertip. The combination of the grasp mechanism and vacuum pads allows the iGRIPP 4 to grasp objects steadily. Furthermore, this robot hand is able to achieve some dexterous manipulations which are impossible for conventional robot hands. In this paper, following two dexterous



(a) Envelope and paper (b) Case and name card

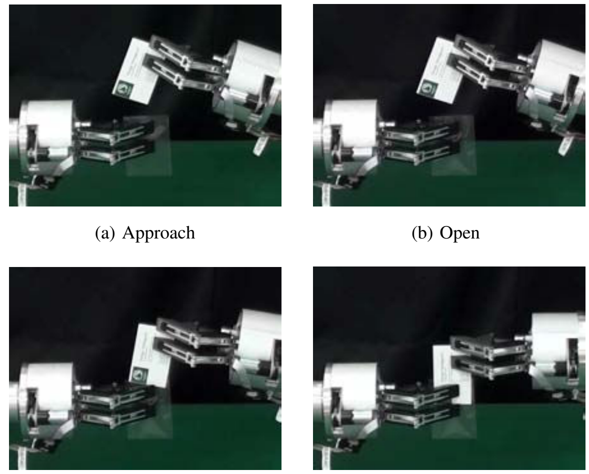
Fig. 17. Handling objects



(a) Approach (b) Open

(c) Insert (middle) (d) Insert

Fig. 18. Packaging of paper



(a) Approach (b) Open

(c) Insert (middle) (d) Insert

Fig. 19. Packaging of name card

manipulations by the iGRIPP 4 are described; the picking up a thin object from a table and the packaging of an object. Although these tasks are difficult for the conventional robot hands, the iGRIPP 4 achieves these tasks with simple mechanism and control.

The vacuum cups of the iGRIPP 4 increase the capability of the low degrees of freedom robot hand. It means that an anthropomorphic robot hand that has vacuum pads could perform more dexterous manipulation. We will develop many degrees of freedom robot hand with suction mechanism in future research. Future work includes the redesign of the iGRIPP 4. The structure of the fingertip should be improved for more adaptive grasp. In addition, an implementation of tactile sensors and force sensors are necessary to achieve more dexterous manipulations. We will also implement a vacuum device into the robot hand to increase its usability. Ongoing research is a theoretical grasp analysis of the robot hand with suction mechanism to evaluate the validity of the robot hand with vacuum pads and discover more effective manipulation with this hand.

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