

# Development of Hydraulically-driven Soft Hand for Handling Heavy Vegetables and its Experimental Evaluation

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**Abstract**—In this study, we develop a hydraulically-driven soft robotic hand for handling heavy vegetables in a vegetable factory and report its experimental validations. The working population in agriculture is decreasing worldwide, creating a lot of demands for the robotic automation in harvest and transportation of agricultural produces. In particular, a vegetable factory deals with large and heavy vegetables, e.g., cabbages, with 2–3 kg weight and 20–30 cm diameter. A soft robot hand is suitable for handling a food or vegetable; however, most of existing soft robot hands cannot generate necessary output because they are usually actuated by the air-pressure. Therefore, we employ the hydraulic actuation for our soft hand to generate 1 or 2 MPa pressure. Using the developed soft hand, we report experimental validations including basic control performance evaluation and grasping experiments assuming a vegetable factory environment.

## I. INTRODUCTION

The decrease of the working population in agriculture is a worldwide problem, including Japan [1]. There are a lot of demands on the robotic automation in harvest and transformation of agricultural produces [2], [3], [4], [5], [6], [7], [8], [9], [10]. After harvesting, vegetables are transported to a vegetable or food-processing factory, cut into pieces and shipped out. Although each process is partially automated, manual tasks still remain especially picking a vegetable from a box container and carrying it. Fig. 1 shows an example of cabbages and container used in a factory. Such a manual task often forces a laborer to bear the burden because a factory usually deals with a number of vegetables. Moreover, the size and weight of each vegetable is larger and heavier than that for family use. For example, the weight and size of a cabbage processed in a factory are usually 2–3 kg weight and 20–30 cm diameter. It is important to automate the picking and carrying tasks of such heavy vegetables using a robot hand system. However, there are several challenges.

One of the requirements is that a robot hand should not damage the target vegetable. Another is that there are a lot of variations of size and weight even in a single vegetable type. A robot hand requires adaptability to such a variation. A soft robot hand made of flexible and continuously-deformable materials is a good solution for these requirements. Soft robotics is attracting much attentions and studied in a lot of applications including medical and food industry fields [11], [12], [13], [14]. Russo et al. [15] developed a link-mechanism hand that could sense contact forces between the hand and a fruit. Yamanaka et al. [16] developed a soft hand

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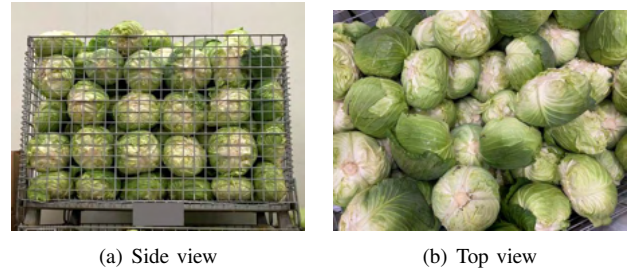


Fig. 1. Cabbages in a box at a vegetable factory

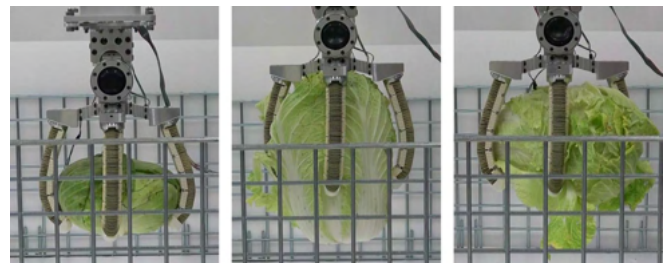


Fig. 2. Developed soft robotic hand grasping a 2 kg cabbage and 2.2 kg Chinese cabbage. In the case of Chinese cabbage, the adaptability to different directions is demonstrated.

that could grasp lightweight processed foods, employing a soft finger structure similar to the fiber-constrained finger developed by Suzumori et al. [17]. Ho et al. [18] developed a soft hand for non-spherical fruits such as banana. Most of existing soft hands are actuated by the air pressure [19], usually several hundred kPa. Therefore, a soft robot is a strongly application when grasping a lightweight food or fruit. There are attempts to develop a soft hand capable of a large output force. Su et al. [20] developed a pneumatic robotic hand and generated a large force using a link mechanism. Hagiwara et al. [21] developed a hydraulically-driven soft hand that is actuated by 1 MPa oil-pressure and can hold a 5 kg object. We consider that extending the hydraulically-driven soft hand is suitable for the vegetable grasping because it can achieve the flexible adaptability and high grasping force simultaneously.

In this study, we develop a hydraulically-driven soft robotic hand for handling heavy vegetables and report its experimental validations. Fig. 2 shows the developed soft hand grasping a 2 kg cabbage and 2.2 kg Chinese cabbage. A challenge is that a long and thin soft finger is required for picking up densely-aligned cabbages in a box, achieving a high payload forces. To make the previous soft finger [21]

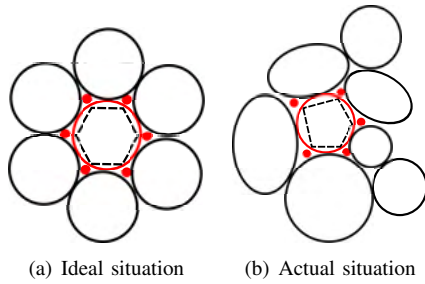


Fig. 3. Schematic illustration of cabbages in a container.

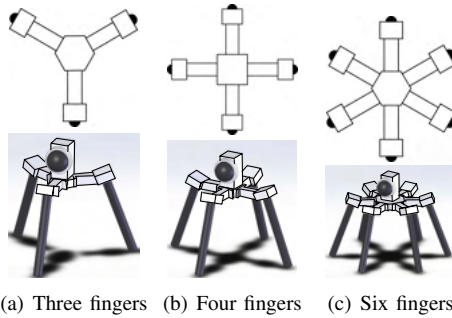


Fig. 4. Comparison of three-, four- and six-finger structure.

longer, we determine necessary reduction ratio parameter in the hydraulic pump, which can generate appropriate flow rate without degrading the control performance. We develop four-fingered soft hand and experimentally validate its capability. We show that the developed hand can stably grasp 10 kg dumbbells, and adaptively grasp 2 kg cabbage and 2.2 kg Chinese cabbage assuming a vegetable factory environment.

The rest of this paper is organized as follows. In Section II, we summarize the necessary specifications of a soft robotic hand, decide the basic design. In Section III, we present the structure of the developed hand driven by the hydraulic system and the soft finger. In Section IV, we report experimental validations including basic performance evaluation and grasping experiments assuming a vegetable factory environment. Finally, we summarize obtained results and conclude this paper.

## II. REQUIREMENTS AND ACTUATION PRINCIPLE OF SOFT HAND

### A. Requirement and Target Specifications Heavy Vegetable Handling

The target situation in this study is shown in Fig. 1, where cabbages are densely stored in a box container. The necessary specifications are summarized as follows:

1) *Finger Dimension*: In a preliminary survey at a vegetable factory, we measured the size and weight of cabbages and the size of gaps among cabbages in a container. The diameter and height of a cabbage are 220 mm and 150 mm on average, respectively. As shown in Fig. 1, cabbages are densely contained. A soft hand needs to insert fingers into small spaces among cabbages to grasp one tightly. From

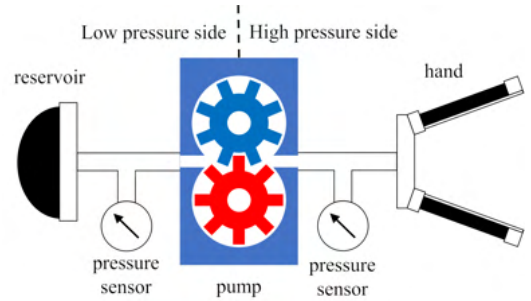


Fig. 5. Simple diagram of the robotic soft hand

these observations, we determine the finger diameter and the length as 30 mm and 180 mm, respectively.

2) *Number of Fingers*: We determined the number of fingers based on preliminary observations and experiments. Fig. 3 shows a schematic illustration of cabbages in a container. In an *ideal* situation where cabbages have the same diameter, as shown in Fig. 3(a), the six gap spaces among cabbages are arranged hexagonally, as indicated by the red line in the figure. Therefore, three- or six-finger would be candidates. However, we did not employ six-finger such as Fig. 4(c) because in general the less number of fingers is better for a robot hand. Furthermore, the number of spaces among cabbages is not always six, as shown in Fig. 3(b). When the number of space is five or less, it is difficult for a six-finger hand to insert the fingers.

Three-finger shown in Fig. 4(a) is a minimum number of fingers to grasp an object. In a preliminary experiment, however, a three-finger hand often failed to grasp a cabbages while a four-finger hand succeeded in many cases. In this study, we determine the number of fingers as four like Fig. 4(b). This setting is robust to the variety in the size and shape of a cabbage, as described in the following experiments. A problem of the four-finger hand is that the fingers should deform to be inserted to spaces among cabbages. To achieve this flexibility, we present a mechanical design of the finger structure in the next section.

### B. Structure of Hydraulic Actuation

When a thin and long finger generates a force at the finger tip to grasp a 2–3 kg cabbage, it is necessary to generate a large pressure by the actuation source. In this study, we employ the hydraulic actuation used in [21]. Fig. 5 shows the structure of the hydraulic system. Soft hand is connected to a hydraulic pump that supplies the oil flow from an oil-reservoir in the left side. There are two pressure sensors in the left and right sides of the pump, and the differential pressure generated by the pump actuates the fingers.

In this study, we use a gear pump developed by Komagata et al. [22], shown in Fig. 6. The size is  $47.2 \times 34 \times 32$  mm, the weight is 216 g. The gear pump can supply maximum 14 MPa with a small internal leakage. The theoretical discharge flow rate is  $1.32 \times 10^{-7} \text{ m}^3/\text{rad}$ .

The gear pump is driven by decelerating an electric motor with gears to obtain necessary flow rate. The previous soft

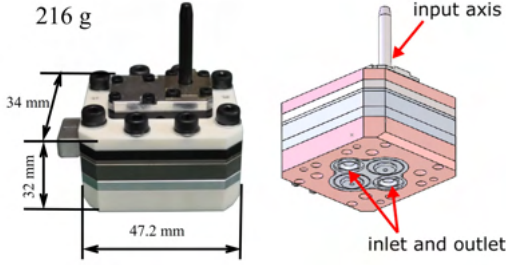


Fig. 6. Pump used in soft hand[22].

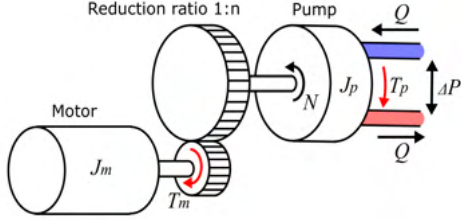


Fig. 7. Model for calculating torque need for motor to move pump.

hand [21] consists of two fingers, and the length of each finger was 80 mm. In this study, the number of fingers is four, and the length of each finger is 180 mm. Therefore, it is expected that more flow rate is necessary. In the following, we formulate the relationship between the flow rate and the reduction ratio. Fig. 7 illustrates the motor dynamics with the hydraulic pump. The motor dynamics is represented as follows:

$$(nJ_m + J_p)\dot{\omega} = nT_m - T_p \quad (1)$$

where  $J_m$  [ $\text{kg} \cdot \text{m}^2$ ] is the moment of inertia of the motor drive shaft,  $J_p$  [ $\text{kg} \cdot \text{m}^2$ ] is the moment of inertia of the pump,  $n$  is the reduction ratio,  $T_m$  [ $\text{N} \cdot \text{m}$ ] is the motor torque, and  $T_p$  [ $\text{N} \cdot \text{m}$ ] is the torque that the pump receives from the oil. The angular acceleration  $\dot{\omega}$  [ $\text{s}^{-2}$ ] of the pump drive shaft is calculated as

$$\dot{\omega} = \frac{T_m - \frac{1}{n}T_p}{J_m + \frac{1}{n}J_p} \quad (2)$$

In this equation,  $T_p$  [ $\text{N} \cdot \text{m}$ ] is given as follows:

$$T_p = \frac{q\Delta P}{2\pi} \quad (3)$$

where  $q$  [ $\text{m}^3/\text{rev}$ ] is the displacement per pump one revolution, and  $\Delta P$  [ $\text{Pa}$ ] is the differential pressure.

From Eq. (2), increasing the reduction ratio  $n$  increases the angular acceleration of the drive shaft of the pump  $\dot{\omega}$ . Under the condition that the speed of the motor is not saturated, the rotation speed of the pump  $N$  [ $\text{rpm}$ ] also increases. Therefore,  $N$  is expressed in the following equation.

$$N = \frac{q\Delta 1}{2\pi} \int \dot{\omega} dt, N < 2\pi \frac{V}{nk_t} \quad (4)$$

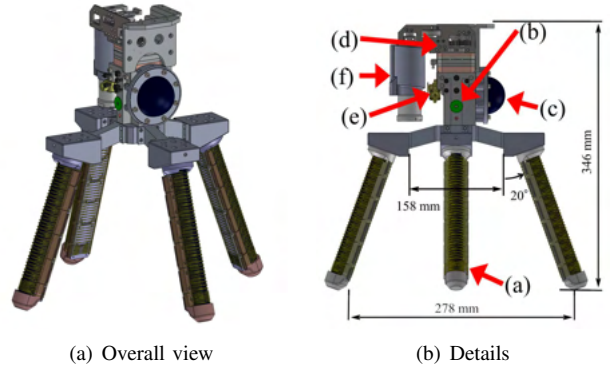


Fig. 8. Four-fingered soft hand.

where  $V$  [ $\text{V}$ ] is the voltage value supplied to the motor and  $k_t$  [ $\text{Nm/A}$ ] is the torque constant of the motor.

Furthermore, since the pump flow rate  $Q$  [ $\text{m}^3/\text{min}$ ] is expressed by the Eq. (5), increasing  $n$  also increases the pump flow rate  $Q$ .

$$Q = qN \quad (5)$$

In this study, we set the reduction ratio to 1 : 6.

### III. DESIGN OF SOFT HAND

#### A. Structure of Soft Hand

Fig. 8 shows the design of the soft hand. The dimension is 278 mm width and 346 mm height, which was designed assuming average 220 mm diameter and 150 mm height cabbage. The soft hand consists of (a) soft fingers, (b) pressure sensors, (c) reservoir storing oil, (d) hydraulic pump, (e) electric motor driving the pump and (f) oil supply port. This is a *self-contained* hand equipped with the hydraulic pump and reservoir while most soft hand utilize an external pneumatic pump as the power source. The basic structure is similar to our previous soft hand [21], except for the detailed structure of the soft finger. The total weight is approximately 2.8 kg, including the hydraulic pump and the electric motor.

#### B. Structure of Soft Finger

We employ a fiber-constrained soft actuator to make a long and thin finger. Fig. 9 shows the structure of the fiber-constrained finger. The main part is a tube structure made of nitrile butadiene rubber (NBR), which is an oil-resistant material. The NBR tube is constrained by Kepler thread, forming a double helix, as shown in Fig. 9(b). This structure constrains the deformation preventing the expansion of the tube in the radial direction. Then, an elastic outer-shell plate is attached to one side of the tube, as indicated by the light gray part in Fig. 9(c). This plat can bend but cannot extend while the NBR tube can extend by supplying the pressure inside. This difference generates a bending motion shown in Fig. 9(d).

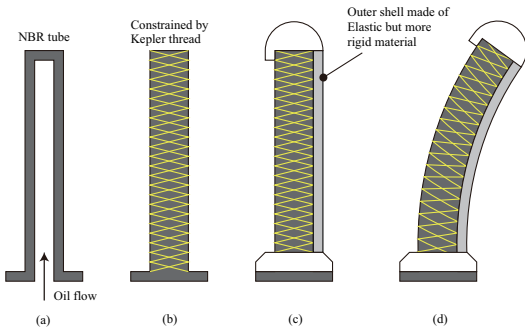


Fig. 9. Structure and bending mechanism of fiber-constrained soft finger.

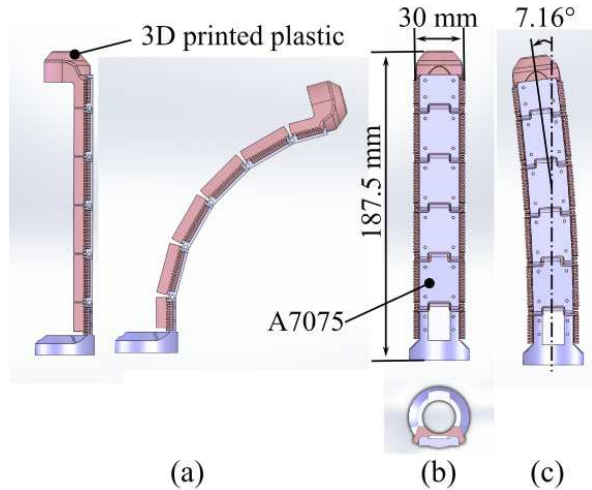


Fig. 10. Structure of outer shell of the finger.

### C. Design of Finger Outer Shell

In our previous study [21], the outer-shell was made of a rubber-like material. In this study, we design six outer shells connected by hinges to bear a high actuation force. Fig. 10 shows the structure of the outer shell, where the silver and red parts are made of A7075 and 3D printed plastic, respectively. Plastic parts have a cylindrical groove that fit a tube out line. The outer shell constrains the length of one side of the tube when the inside of the NBR tube is pressurized, this constraint generates a bending motion shown in Fig. 10(b).

Note that we design a hinge with a backlash on purpose, so that the finger can bend in the direction shown in Fig. 10(c). This deformation contributes to the adaptive grasping, allowing the insertion of the fingers into spaces among cabbages as discussed in Section II-A.2.

Fig. 11 shows a soft finger that we developed. Shore A hardness of NBR used as the tube is 70. The dimension of the tube is as follows: 184 mm length, 18 mm outer diameter, and 10 mm inner diameter. A disadvantage of the oil pressure is that the leakage of the oil would damage a vegetable. The tube has the base flange with 4 mm thickness and 36 mm diameter. This flange is sandwiched by the base of the outer shell and the connecting part, which suppresses the oil leakage. The control method of an actuator bending

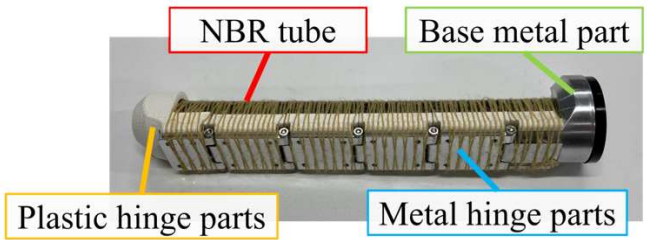


Fig. 11. Soft finger made of NBR.

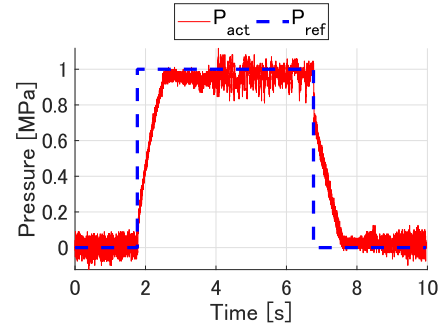


Fig. 12. Step response for soft hand.

by thread wrapping was reported [23]. However, we expect a uniformly bending to a soft finger, and set the interval of thread evenly.

## IV. EXPERIMENTAL VALIDATIONS OF DEVELOPED SOFT HAND

### A. Measurement of Time Constant in Pressure Control

To quantitatively evaluate the operating speed of the developed soft hand, we measured a step response applying the pressure control of the pump and calculated the time constant. The target value of the pressure control was set as 1.0 MPa. Fig. 12 shows the result of the step response, where the blue and red lines indicate the reference and measured pressure values, respectively. The time constant is calculated as 0.4 s assuming a first-order lag system.

In the case of our previous soft hand with two fingers [21], the time constant was 0.7 s. As discussed in Section II-B, we set the reduction ratio as 1 : 6 while the previous one was 1 : 3.5. Therefore, the reduction ratio is increased by 1.71 (= 6/3.5) times while the time constant was increased by 1.75 (= 0.7/0.4) times. From this result, the flow rate of the oil to generate the finger deformation is not significantly affected by the length or number of fingers, rather by the reduction ratio. We consider that a sufficient response speed is obtained for an efficient grasping of vegetables.

### B. Maximum Payload Test

We conducted the maximum payload test of the developed soft hand. Fig. 13 shows the experimental apparatus. The developed soft hand is mounted on an electrical lift moving the hand in the vertical direction. Fig. 14 and accompanied

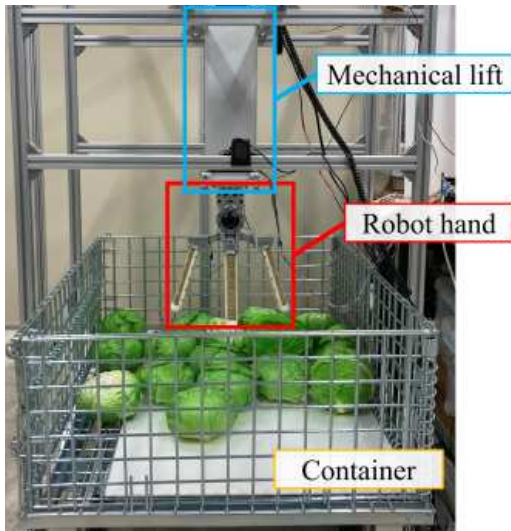


Fig. 13. Experimental apparatus for grasping of vegetables.

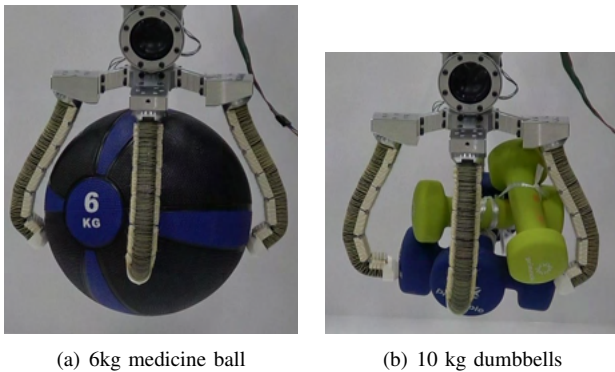


Fig. 14. Heavy object payload operations.

video show the experimental scenes. Fig. 14(a) is a medicine ball with a total weight of 10 kg, Fig. 14(b) is dumbbells with a total weight of 10 kg. The reference pressure was set as a step input with 2.0 MPa for 10 s. We started the pressure control after the soft hand approached to the object. It was shown that the developed soft hand could stably grasp the heavy object. The hand has a enough high output force for grasp heavy vegetables.

### C. Basic Grasping Experiment

We demonstrated that the developed soft hand can grasp a commercial cabbage and Chinese cabbage at the apparatus shown in Fig. 13. Fig. 2 and accompanied video show the experimental scenes of grasping a 2 kg cabbage and 2.2 kg Chinese cabbage. The reference pressure was set as a step input with 1.0 MPa for 10 s. We started the pressure control after the soft hand approached to the cabbage or Chinese cabbage. It was shown that the developed soft hand could grasp the cabbage and Chinese cabbage. Especially in the case of the Chinese cabbages, the soft hand adaptively grasped it when the layout was changed.

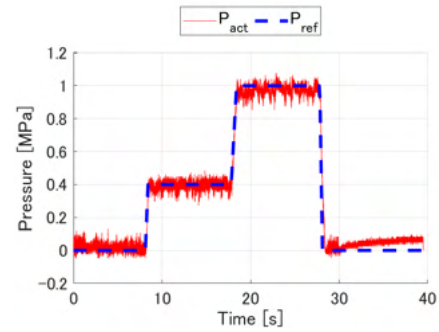


Fig. 15. Pressure control in the grasping experiments.

TABLE I  
SUCCESS RATE OF GRASPING A CABBAGE IN A CONTAINER

	No. of trials	No. of success	Success rate
Strategy 1)	11	7	63.6 %
Strategy 2)	16	15	93.8 %
Total	27	22	81.5 %

### D. Grasping Experiment of Cabbage in A Container

Assuming a realistic environment, we tested experiments for grasping a cabbage with 1.4 kg from a container with densely contained cabbages. We tested the following two strategies:

- 1) Aligned the center of the hand to that of a target cabbage.
- 2) Aligned three fingers of the hand to three spaces around a target cabbage

We determined these alignments manually. In both cases, we set the control procedure as follows:

- Set the reference pressure as 0.3 MPa for the first 10 s, and insert the fingers.
- Set the reference pressure as 1.0 MPa for the next 10 s, grasping an object.

To insert, the hand must narrow itself at the first step because of the diameter of the target cabbage is smaller than the hand. Fig. 15 shows the graph of the pressure control, where the blue and red lines indicate the reference and measured pressure values, respectively. Figs. 16 and 17 shows the experimental scenes with Strategies 1) and 2), respectively.

We tested 11 trials for Strategy 1) and 16 trials for Strategy 2). Table I summarized the success rate of the experiments. The success rate of Strategy 2) achieved 93.8 %. We observed that a target cabbage was damaged by fingers in the failure cases by Strategy 1) but less damaged in the successful cases in Strategy 2).

## V. CONCLUSION

In this paper, we developed a soft robotic hand that can grasp heavy vegetables, actuated by a self-contained hydraulic pump. We evaluated reported the experimental results of the basic performance evaluation and the validation



(a) Narrowing



(b) Inserting



(c) Grasping

Fig. 16. Cabbage grasping operation of the robotic hand in the case of align the center point of the hand and a cabbage.

of adaptive grasping of vegetables. The obtained results are summarized as follows.

- 1) The time constant of the pressure control was 0.4 s, which implied that the hand had sufficient response speed even though the number and the length of the fingers were increased compared to our previous hand.
- 2) The experiments showed that the developed hand could stably hold a 10 kg object.
- 3) The experiments showed that the developed hand could hold a 2 kg cabbage and 2.2 kg Chinese cabbage. Moreover, we demonstrated that the developed hand could pick up 1.4 kg cabbage in a container.

One of the future works is the striving to decrease the outer oil leakage. By a flexible cover, we aim to minimize the oil pollution of vegetables and increase the gripping force. Also, we are planning to attach the developed hand to a robotic manipulator and apply to the handling task of vegetables in a factory.



(a) Narrowing



(b) Inserting



(c) Grasping

Fig. 17. Cabbage grasping operation of the robotic hand in the case of align the center point of the hand and a cabbage.

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