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A pick-and-place hand mechanism without any actuators and sensors

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Abstract— **This paper gives a novel pick-and-place hand mechanism without any actuators and sensors. Any payload does not effect to the internal mechanism at all. First we discuss the design guideline and a working principle. Second, we realize and apply the mechanism by combining a mechanical finite four states system and our previously developed passive closure gripper. Third, we analyze and clarify some properties of the hand. Furthermore, we confirm the validity of the developed hand by manipulation experiments.**

I. Introduction

This paper gives a pick-and-place hand without any actuators and sensors. In general, robotic hands are classified to 1) versatile type and 2) special type. The versatile type is dexterous like human hands [2]. There are many researches and developments of the versatile type, especially from the view points of control systems. On the other hand, in many important application fields, such as industry, rescue, demining and agriculture, not the versatile type but the special type is studied or already used. For example, recently, Davit et al. developed the hand for tasks in sub-sea [8]. Kaneko develped a hand for a high speed manipulator [5]. Kazerooni et al. developed sack grasping mechanism [6].

This paper is motivated by a special application research field, the field of agriculture. We start from the following rough classification of robotics from the viewpoint of economics:

- C1: *Private goods*
- C2: Short *annual running hours*

where economics terminology are expressed in *italic*. It is easy to find fields where either C1 or C2 is satisfied. For example, in the field of housekeeping, C1 is satisfied but C2 is not. On the other hands, in the field of rescue, C2 is satisfied but C1 is not. In the field of demining, neither C1 nor C2 is satisfied. However, in the field of agriculture, both of C1 and C2 are satisfied. That is, the existing agricultural machines (planters and harvesters etc.) are not *public goods* and the *annual running hours* is limited because of the seasonable reasons.

Then, based on the above rough classification, we show the relation between the field of agriculture and cost. First, C1 and C2 imply that the production is limited in the context of market principle, that is, the cost of the machine should be emphasized in the field of agriculture. Second, C2 also implies that the running cost is limited in comparison with the initial cost. Now, we can draw a short conclusion that the initial cost of the machine should be emphasized in the field of agriculture.

Setiawan proposed and developed an apple picking gripper with lower initial cost [11]. We focus on that the highest cost components are actuators and sensors. There are already many grippers which pick targets without actuators based on passive force/form closure principle [2]. However these grippers can not place the targets without actuators after picking.

In this paper, we realize a solution of this problem, that is, we give a novel robotic hand which does not require any actuators and sensors not only for picking but also for placing.

In Section II, we discuss the problem statement. In Section III, we discuss the design guideline and a working principle. In Section IV, we realize the hand mechanically while using our previous results. In Section V, we analyze and clarify some properties of the hand. Furthermore, in Section VI, we confirm the validity of the developed hand by manipulation experiments. In Section VII, we conclude this paper.

II. Problem Statement

In this section, we discuss the problem statement of the pick-and-place hand without any actuators and sensors.

Fig.1(a) shows the state transition diagram of the conventional pick-and-place. This is a finite two states system, where the input “1” means the varying torques and the input “0” means the fixed torques. Here we undistinguish and identify the pick-wise torques and the place-wise torques.

Apparently, it is impossible to realize this pick-and-place without actuators and sensors in general. Of course, there are already many grippers which pick targets without actuators based on passive force/form closure principle. However these grippers can not place the targets without actuators after picking. It is very hard to develop the pick-and-place hand without actuators and sensors in all situations.

Now we start from observation of actual pick-and-place motions of robots or humans. In many cases, not always, the actual pick-and-place has the following properties:

P1) If a hand exists, a manipulator also exists and is connected to the hand.

P2) The pick state (the place state) is transited to the place state (the pick state) just when the hand is on the ground, not in air.

Of course, there are some exceptional cases where P1 or P2 does not hold. For example, the hand in [5] picks the target in air after the hand is separated from the manipulator as an arrow flies. Not only P1 but also P2 do not hold in this case.

However, in many important application fields, such as industry, rescue, demining and agriculture, both P1 and P2 almost hold. In this paper, we do not discuss any cases where P1 or P2 does not hold. Our problem setting is that "*Find a pick-and-place hand mechanism (components and configuration) without any actuators and sensors under the assumptions of P1 and P2.* "

III. Design

A. Design Guideline

First of all, we focus and introduce passive force/form closure grippers, which pick targets without actuators. However, as discussed before, the passive force/form closure gripper can not place the targets without actuators. The passive force/form closure reduce the problem and our problem is replaced to "*Find a placing hand mechanism for passive force/form closure gripper without any actuators and sensors under the assumptions of P1 and P2.* "

Then, we discuss a design guideline of the reduced problem. First, by using P1, we can take the altitude of the hand as the input instead of the torques. The manipulator can always decide the altitude of the hand. Second, by using P2, we can introduce a new state "land", where the hand has reaction forces from the environment, such as the ground or the target. The reaction forces can deform the hand mechanism and transit the states from the pick state to the place state, or, from the place state to the pick state.

Fig.1(b) shows a new state transition diagram. This is a finite three states system, where the input "1" means the varying altitude and the input "0" means the fixed altitude. Here we undistinguish and identify taking-off wise and landing wise.

However, this system does not work. The causality does not hold as it is. A land state just after the pick state and another land state just after the place state are the same and can not be identified at all. This fact leads us to a conclusion that the hand should be a dynamical finite state system.

B. Working Principle

Fig.2 shows the state transition diagram of the pick-and-place without actuators and sensors. This is a cyclic finite four states system (c-FFSS) whose input is the same as that of Fig.1(b). There are two land states, the land1 state and the land2 state. The state equations are

$$\begin{cases} x_1(k+1) = x_1(k) \oplus u(k) \\ x_2(k+1) = x_2(k) \oplus x_1(k) \cdot u(k) \end{cases} \tag{1}$$

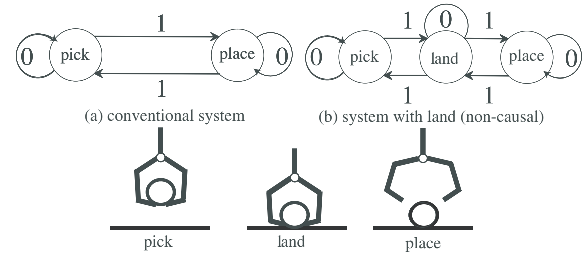

Fig. 1. State transition diagram (conventional and non-causal).

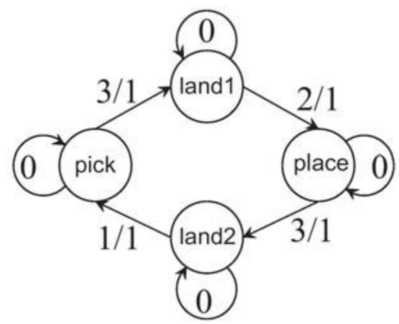

Fig. 2. State transition diagram (proposed).

where $(x_1, x_2)^T \in \mathrm{GF}(2)$ and $\oplus$ is adding operator and $\cdot$ is multiplicative operator in Galois field. The output equations are

$$\begin{cases} y_1(k) = (x_1(k) \oplus 1) \cdot x_1(k) \oplus 1 \\ y_2(k) = (x_1(k) \oplus 1) \cdot x_2(k) \oplus 1 \end{cases} \tag{2}$$

and the output can be expressed as follows:

$$y(k) = y_1(k)2^1 + y_2(k)2^0. \tag{3}$$

The output depends not only on the input but also on the states. If the input series are $\{..., 1, 1, 1, 1, ...\}$ then the output series are $\{..., 1, 3, 2, 3, ...\}$.

Now, we propose a kinematic solution of the reduced problem by combining the passive force/form closure gripper and the c-FFSS. Fig.3 shows an example of this combination.

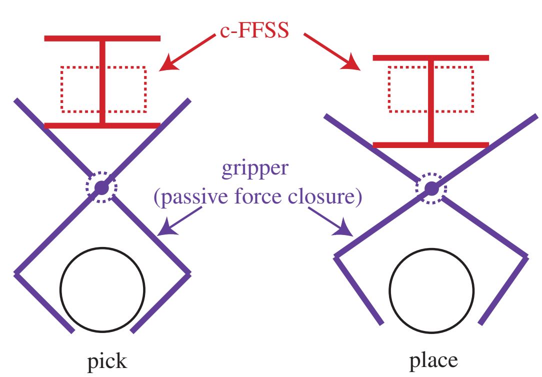

Fig. 3. Working principle (solid: moving parts, dash:fixed parts).

Fig. 4. Appearance of the previous hand (No.2).

The solid lines are links and move while picking and placing. The dashed lines are connected to the manipulator and fixed. The below (blue) part is a passive force/form closure gripper and the above (red) part is a c-FFSS. The input is the altitude of the fixed parts. The output is the displacement of the c-FFSS which decides the finger displacement. The states are transited by the reaction forces at two land states.

The remaining problem is how to realize the c-FFSS and to combine with the passive force/form closure gripper in actual mechanical world.

IV. Realization and Application

In this section, as a case study of the remaining problem, we realize a c-FFSS and apply to a waterman gripper, which is one of the applications and developed in our previous works.

A. Application to Watermelon Grippers

There are many developed hands for agricultural robots [7], [1], [3]. As discussed above, Setiawan developed the low-cost agricultural gripper [11].

We developed watermelon grippers. In one of the previous studies, Iida developed a watermelon gripper (No.1) [4]. This gripper is based on a passive force closure principle and does not require actuators for picking. It accomplishes picking within a 40-mm allowable positional error. However, this gripper can not place the targets without a hydraulic actuator after picking.

In this next work [9], [10], we re-designed the hand (No.2) from the viewpoint of initial cost. We design a wire mechanism to realize placing using less power, that is, we replace the hydraulic actuator to a small DC motor by using P2. First, the wires suspend the fingers and the gravity keeps the finger closed. Second, after the hand contacts with the platform by the vertical motion of the manipulator, the wire tension can be zero because of the reaction forces. Third, a light and small DC motor reels the wires using low power and keeps the fingers open. Finally, the hand can rise without re-contacting watermelons.

However, still, this re-designed gripper can not place the targets without the actuator after picking.

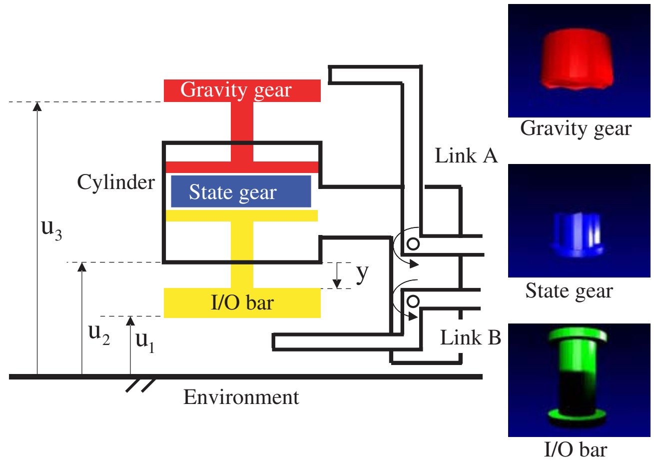

Fig. 5. Configuration of c-FFSS.

Fig. 6. Gravity gear (left) and state gear (right).

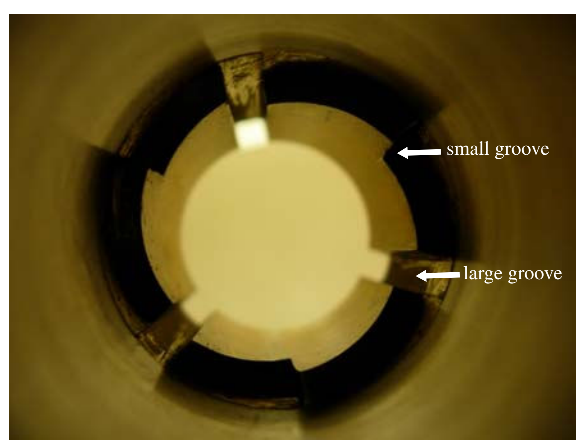

Fig. 7. Cylinder inside

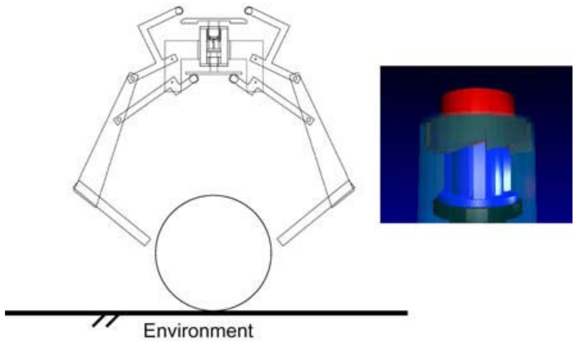

Fig. 8. Place state.

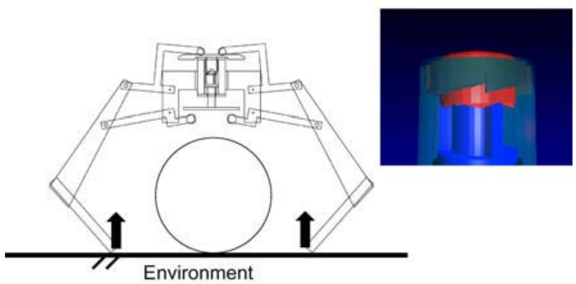

Fig. 9. Land 2 state.

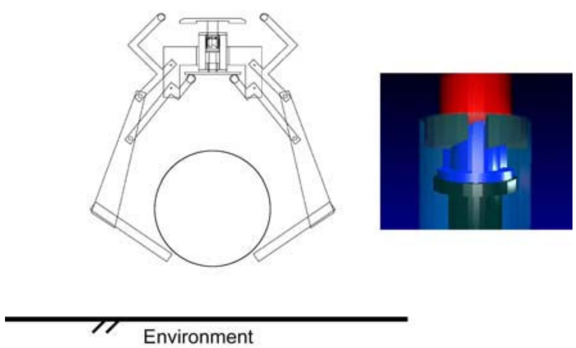

Fig. 10. Pick state.

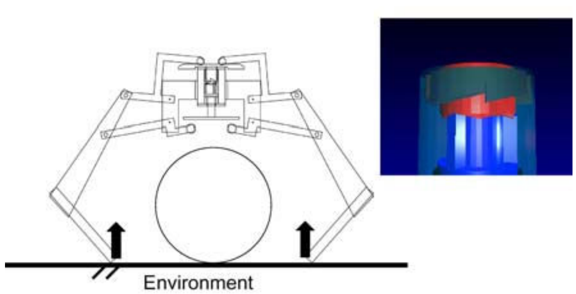

Fig. 11. Land 1 state.

B. Working Principle

Fig.5 shows a configuration of a mechanical c-FFSS. This c-FFSS consists of two gears (the gravity gear and the state gear), I/O bar and one cylinder. The gravity gear and I/O bar move vertically only and the state gear moves the vertically and rotationally. There are three input ports, that is, the altitude of the gravity gear, the state gear and I/O bar. The reaction forces are generated by the input and is converted to I/O bar. The output is the displacement of I/O bar.

Fig.6 shows an appearance of two gears, the gravity gear and the state gear. Fig.7 shows an appearance of the cylinder inside, where there are the gears (cylinder gears). In order to avoid the unprefarable backlash and indeterministic cases between the state gears and others, the each groove (and the corresponding teeth) number is selected as three.

This c-FFSS is applied to the watermelon gripper (No.3) by re-design of the finger links (Link B). There exists additional link (Link A), which is discussed later. Table I summarizes the comparison of the watermelon grippers with respect to the number of actuators and sensors.

Fig.8, 9, 10, 11 show the each state of the realized hand. Now, we describe the working principle as follows:

• the place state: The gravity makes the fingers close and makes I/O bar goes up via Link B. The state gear and the gravity gear also go up at the same time. The state gear fits to the cylinder gear at the small groove after rotating and rising. When the state gear stops, I/O bar also stops. The displacement of I/O bar is small and the fingers keep open.

• the land2 state: The reaction forces open the fingers and make I/O bar start the free fall. The state gear and the gravity gear also fall at the same time. When the state gear falls at a certain distance (the depth of small groove of the cylinder gear), the state gear can rotate freely. Because the falling gravity gear can not rotate by the key, the state gear must rotate and fit to the gravity gear. When I/O bar stops at the bottom of the cylinder, the state gear and the gravity gear also stop.

• the pick state: The gravity of the target and the fingers make the fingers close and makes I/O bar go up via Link B. The state gear also goes up at the same time. The state gear fits to the cylinder gear at the large groove after rotating and rising. Even after the state gear stops rotating, the state gear keeps going up. The displacement of I/O bar is large and the fingers keep close. I/O bar goes up until hit to the cylinder (i.e. $y = 0$ in Fig.5), that is, any stress of any gears do not depend on the target payload at all.

• the land1 state: The reaction force open the fingers and makes I/O bar starts the free fall. The state gear and the gravity gear also fall at the same time. When the state gear falls at a certain distance (the depth of large groove of the cylinder gear), the state gear can rotate freely. Because the falling gravity gear can not rotate by the key, the state gear must rotate and fit to the gravity gear. When I/O bar stops at the bottom of the cylinder box, the state gear and the gravity gear also stop.

V. Analysis

A. Additional Advantages

The realized c-FFSS reduce all actuators and sensors. However, the c-FFSS has additional advantages.

• Durability (the stress)
In the cases of u_1 and u_2, any stress (normal stress, tangent stress) of any gears (gravity gear, state gear, cylinder gear) do not depend on the target payload at all. This is an important keypoint of this paper and achieves high durability, since the cylinder is much more rigid than the gears inside of the cylinder. In the case of u_3, we can also have this advantage only by a slight design modification (omitted here).

• Reliability (the number of components)
The number of the c-FFSS components is only four and small. This achieves high reliability. The realized c-FFSS is not unique and the c-FFSS can be realized in different ways. However, it is hard to develop the c-FFSS with less component while keeping the durability, although we can not proof that the realized c-FFSS is the minimal realization.

• Design freedom
There is no spring components. In almost all design cases, we does not design spring components, but select them from trade catalogs. This fact implies a serious design limitation and makes design procedure more iterative. There are some cases where the best spring specification, size and force, does not exist in the catalogs. In this sense, the realized c-FFSS has high design freedom.

B. Friction

For the proposed hand, the most serious issue is friction, which is not discussed yet. The design parameters should satisfy not only trivial geometrical conditions but also a certain friction condition between the gears.

From the pick state to the land1 state and from the place state to the land2 state, unpreferable friction can be overcame by the reaction forces on the finger tips because the reaction forces are controlled freely by the manipulator. The worst situation is that the state transits from the pick state to the land1 state since I/O bar tries the state gear to go up against the gravity, the friction from the the gravity gear f_s^g and that from the cylinder gear f_s^c. The state gear moves vertically and rotationally while the gravity gear moves vertically only with I/O bar because the rotation of the gravity gear is constrained by the key to the cylinder. In this case, the state gear should satisfy the following condition:

$$F \geq \frac{m_g g(\mu_s^c \mu_s^g \sin\bar{\theta} - \mu_s^c \cos\bar{\theta} + \mu_s^g \cos\bar{\theta} + \sin\bar{\theta})}{(\sin\theta_c - \mu_s^c \cos\theta_c)(\cos\theta_g - \mu_s^g \sin\theta_g)} + g(m_o + m_s) \equiv F_c \qquad (4)$$

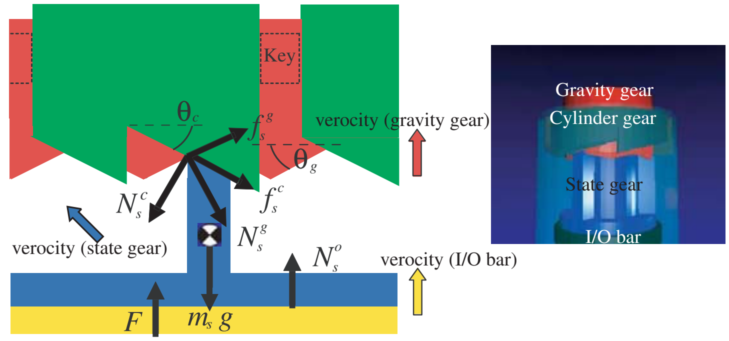

Fig. 12. Statics from the land1 state to the place state.

where F: the force from I/O bar, g: gravity acceleration, sub/surscript g: the gravity gear, c: the cylinder gear, s: the state gear, m_i: mass of i, μ_j^i: friction coefficient from i to j, $\bar{\theta} \equiv \theta_c + \theta_g$ (Fig.12) .

This condition is equivalent to that of the case from the place state to the land2 state.

C. Input Ports

This hand has three input ports: the altitude of the gravity gear u_1, the altitude of the cylinder u_2 and the altitude of I/O bar u_3. Some important properties are different among the ports as shown in Table II.

• Durability
In the cases of u_1 and u_2, as discussed before, any stress of any gears do not depend on the target payload at all. In the case of u_3, since the gravity gear should suspend both the hand and the target, the stress of the gravity gear is very large, as it is.

• Reliability
In the cases of u_1 and u_3, Link A is needed to make the relative displacement between I/O bar/the gravity gear and the cylinder. Until Link A contacts with the gravity gear at the land states, I/O bar or the gravity gear can move with the cylinder at the same time and can not have a relative displacement to the cylinder.

In the case of u_2, Link A is not needed since the cylinder altitude is controlled directly.

• Friction
In the case of u_1, F is nothing but the total weight. In the cases of u_2 and u_3, F is given by the gravity momentum of the fingers only. However, the input u_3 means that the gravity gear is always supported and can be neglected from Fig.12. This fact implies that F_c is smaller than that in the cases of u_1 and u_2.

TABLE I
Comparison of the Watermelon Grippers

	picking actuator	placing actuator	sensor
No.1	0	1 (large) + 1 (small)	4
No.2	0	1 (small)	0
No.3	0	0	0

TABLE II
Comparison of the Input Ports

	Payload stress	Link A	F	F_c
u_1	small	need	large	large
u_2	small	no need	small	large
u_3	large	need	small	small

Fig. 13. Appearance of the proposed hand (No.3).

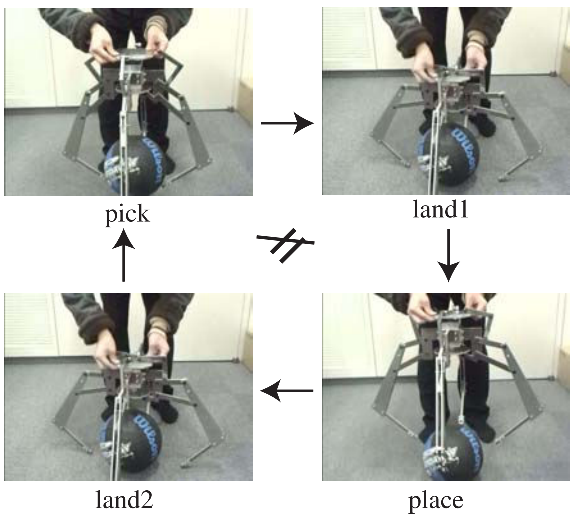

Fig. 14. Pick-and-place (manual).

VI. Experiment

In order to confirm the validity of the developed hand, we execute the pick-and-place experiments.

A. Experimental Methods

Fig.13 shows an appearance the developed hand. First, as a pilot experiment, the hand is moved manually. Fig.14 shows the appearances of each state. Note that the land1 state and the land2 state are the same with respect to the appearance. This is the case of u_3 and the cases of u_1 and u_2 are omitted here.

Second, motivated by the pilot study, the hand is moved automatically by the existing 1-d.o.f. robotic manipulator. Fig.15 shows an experimental setup. The hand is mounted on the manipulator via two pulleys and a wire. This is a challenging situation because the arbitrary reaction force is not realized any more.

The initial state is the place state in all input port cases and the manipulator generates pick-and-place motions twice in repeat while the platform height is changed once. More

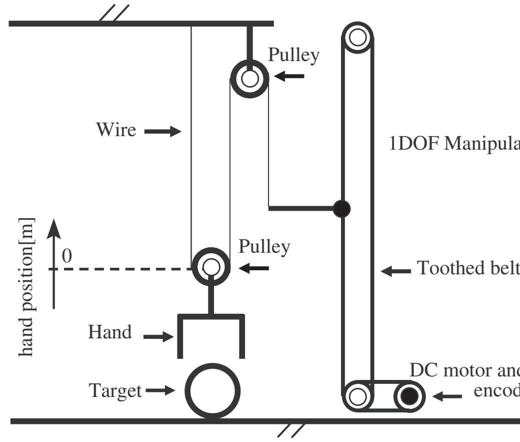

Fig. 15. Experimental setup.

precisely, the manipulator is controlled as follows:

$$\begin{cases} v = -K_p(u_i - u_d) - K_d\dot{u}_i & t \in I_1 \equiv [10k, 10k+5) \\ v = r & t \in I_2 \equiv [10k+5, 10(k+1)] \end{cases} \tag{5}$$

where v is the contol input, $K_p = 11.2270, K_d = 7.2864, r = 2.9$, and $k, i = 1, 2, 3$. The torque constant is 42.25 N/V. The height of platform is 0.45 m and 0.55 m and the target is a bowling ball and its mass is 5.0 kg.

B. Experimental Results and Discussion

Fig.16 shows the joint displacement in the case of u_1. First, the steady-state error in I_1 were 0, 0.05, 0, 0.05 m in order, periodically. This difference corresponds to the target existence, picking and placing. Second, the steady-state error in I_2 were -0.45, -0.45, -0.55, -0.55 m in order. This difference implies the platform height changes. These results correspond to the fact that the ball was picked and placed actually for the different platform.

Fig.17 and Fig.18 also show the joint displacement in the cases of u_2 and u_3, respectively. In both cases, the pick-and-place was realized successfully.

In all, the developed hand realizes the pick-and-place successfully without any actuators, sensors, springs and the payload stress.

Assume to design the world largest pick-and-place hand. In such a case, the design limitation will be nothing but actuators for the huge hand. Apart from the initial cost problem, our results are fundamental in robotics.

VII. Conclusion

This paper gave a novel pick-and-place hand without any actuators and sensors. Any payload does not effect to the internal mechanism at all. First we discussed the design guideline and a working principle. Second, we realized and applied to the hand by combining a mechanical finite four states system and our previously developed hand. Third, we analyzed and clarified some properties of the hand. Furthermore, we confirmed the validity of the developed hand by manipulation experiments. Future works are applications to other passive closure grippers, except watermelon grippers.

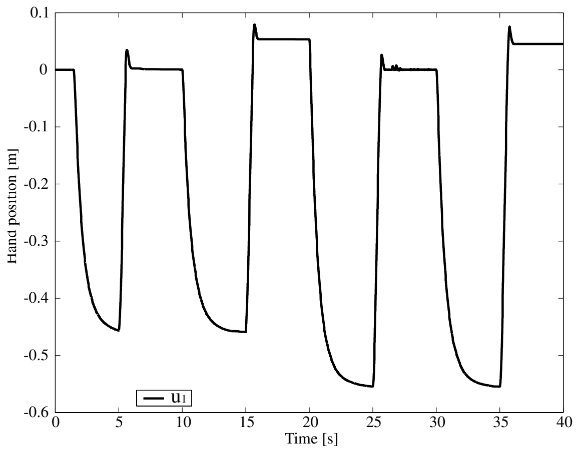

Fig. 16. Experimental result (u_1).

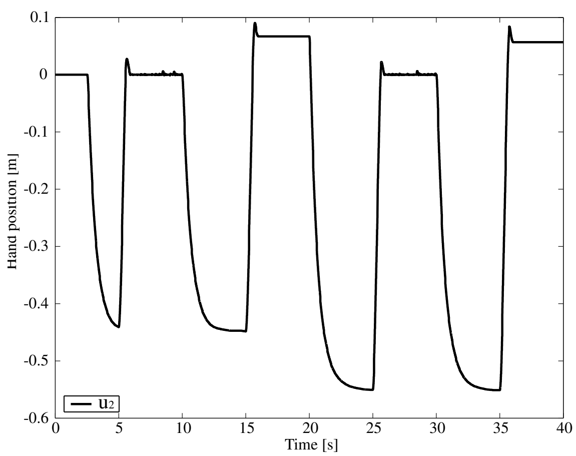

Fig. 17. Experimental result (u_2).

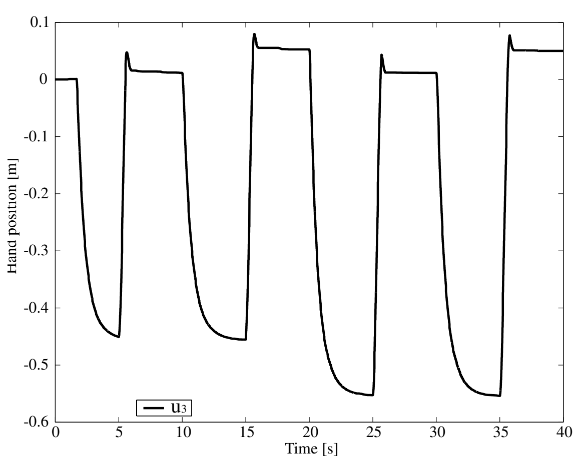

Fig. 18. Experimental result (u_3).

The advantages are summarized as follows, 1) No actuators 2) No sensors 3) No springs 4) No payload stress.

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APPENDIX

An appearance of the first watermelon gripper (No.1) is shown in Fig.19 for a comparison. This hand can pick the target without actuators but can not place it without a hydraulic actuator.

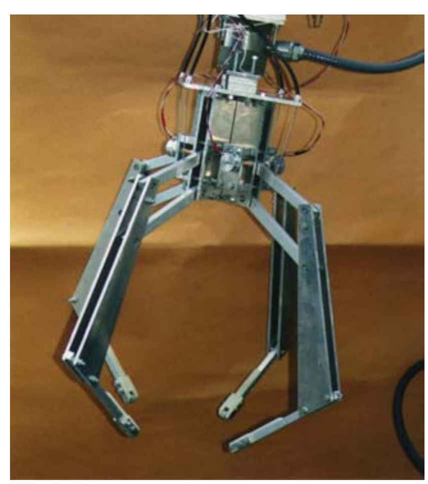

Fig. 19. Appearance of the previous hand (No.1).