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Development of a Light Duty Arm with an Active-Fingertip Gripper for Handling Discoid Objects

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***Abstract*— This paper describes a development of a light duty arm with an active-fingertip gripper for handling discoid objects. The system is potentially capable of sharing the workspace with human workers, assuming the use in a cell manufacturing system. We propose a new 3-DOF gripper mechanism with two fingers which symmetrically move in parallel and each finger has a 2-DOF fingertip of a cylindrical shape. We also develop a lightweight arm with a weight compensation mechanism which is composed of a non-circular pulley and a spring to minimize required actuator torque. After verification of basic performance, the hand-arm system successfully performs a pick-and-place task for a discoid object from horizontal placement to vertical placement and vice versa. We demonstrate continuous 100 times pick-and-place operations without failure where its cycle time almost equals to a human worker.**

I. INTRODUCTION

A cell manufacturing system is being introduced for the production of a digital home electrical appliance. In a cell manufacturing system, small group of workers are responsible for the multi-process of the production such as tightening screws, assembling, appearance inspection and so on. Compared with a line manufacturing system, a cell manufacturing system can flexibly adapt the production adjustment and the high-mix low-volume production with a small investment for facilities. However the cell manufacturing system basically relies on the capability of human workers and it is labor-intensive method. Thus, there is a growing interest to apply the industrial robots for the cell manifucturing system.

Although several attempts have been made to replace all the process of the production by robots [1][2], it seems to be difficult to develop a competitively-priced general purpose robot which can perform all tasks of the human worker in the near future. Because the production processes require various dextrous manipulations and high level cognitive processes. Therefore it is more plausible for the present robots to help a human worker to increase worker's efficiency of the workability or to reduce the total numbers of human workers. Fig. 1 illustrates the conceptual image of the cooperation with a robot.

Fig. 1. Concept image of a light duty arm for a cellular manufacturing system

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As an example of the manifucturing process, we focus on a pick-and-place task of a discoid object shown in Fig. 2. In the processes of the production of the digital home electrical appliances, the parts are horizontally placed or vertically placed on the parts box in order to increase the workability of the human workers or to supply the parts for a special dedicated machine. The edge of the discoid, which is the black painted area in Fig. 2, indicates the only touchable area of the part to keep the quality of the discoid surface. So far, human workers are doing this task.

In the previous works, mechanical devices for handling a compact disk [3] or a silicon wafer [4] have been already proposed. However they use a center hole of the disk or a vacuum sucker for a pick-and-place task. To the best of our knowledge, there is no hand-arm system that accomplishes the above-mentioned task by only touching the outer edge of the discoid object.

In this paper, we propose a light duty arm with an active-fingertip gripper for handling discoid objects. The hand-arm system can perform a pick-and-place task from horizontal placement to vertical placement and vice versa, potentially capable of sharing with a human worker's workspace. We develop a prototype system and achieve the task with a sufficient repeatability.

A. *Target task description*

We set a target task as follows. These specifications are defined by a hearing with an actual manufacturer producing various digital electrical appliances.

- Maximum reach is 800mm and the size of the workspace is 550×450×150mm.
- The round-trip cycle time from the horizontal placement to the vertical placement and vice versa is 4sec.

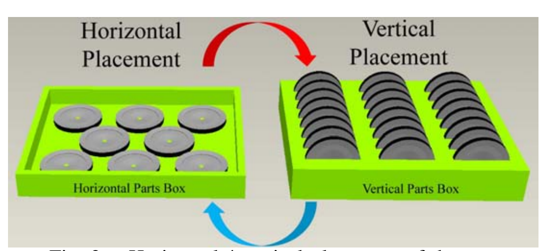

Fig. 2. Horizontal / vertical placement of the parts

- The diameter of a discoid object is 13-55mm where its maximum weight is 50g.
- The robot can share the human worker's workspace.
- The discoid parts are thickly placed and their minimum clearance is 10mm.

The workspace and the cycle time are defined by an ordinary human worker's ability. We set 500g load capacity of the arm including the mass of the end-effector. To share the human worker's workspace, the maximum power of the joint actuator should be less than 80W [5]. Additionally, the total weight of the robot should be as small as possible to increase safety for the human worker. Reducing weight also contributes to increase the ease of changing the installation place which is beneficial to the cell manufacturing.

II. Development of an active-fingertip gripper

A. Proposal of a two-fingered gripper with the cylindrical fingertips

It is not energy efficient if the robot changes the posture of the discoid object by rotating wrist joint which also rotates a whole gripper mechanism. Because the weight of the discoid object is very light and the total weight of the gripper is much heavier than the target object. Thus, it is desirable to rotate only the fingertips and the discoid object while other gripping mechanisms with the heavy weight such as the actuators and the structural frames remain stationary. A three-jaw chuck is usually used to grasp a cylindrical part. However it is impossible to pick up the parts from the vertical placement parts box shown in Fig. 2 right. Moreover, if the discoid objects are deeply inserted in the vertical parts box, a general two-fingered gripper can not grasp the discoid object.

Therefore we propose a new 3-DOF two-fingered gripper with the cylindrical fingertips (Fig. 3) [6]. The proposed gripper has two fingers which symmetrically moves in the horizontal direction for a grasping motion. The finger has a yaw joint to rotate the cylindrical fingertip around the cylinder axis and also has a pitch joint to change the direction of the cylinder axis. The posture change of the discoid object from the horizontal placement to the vertical placement is performed by rotating the pitch joint (Fig. 3 right). Moreover rotation of the both cylindrical fingertips in the outward direction while keeping their pitch angles at 90deg performs to pick up the discoid object from the vertical parts box shown in Fig.5. Additionally slow rotation of the both cylindrical fingertips in the inward direction also achieves a gentle placement in the vertical parts box which is beneficial for handling a fragile part.

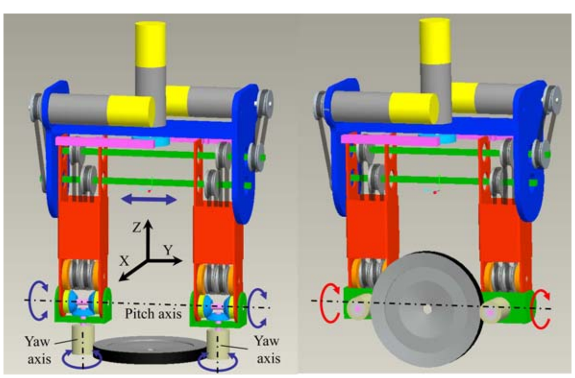

Fig. 3. Basic functions of the proposed gripper

Although humans do not have a rotational DOF along to the finger longitudinal axis, we believe that a human's hand is not necessarily the best configuration to perform the specific task. Our approach is similar to the reference [7] which solves the object manipulation in a very simple way using the cylindrical rotational fingers.

Fig. 4 illustrates the detailed design of the gripper. All actuators which has relatively heavy weight are mounted on the base frame not to move around the joint axis. The actuator torques rotate the two driving shafts passing through the fingers. The pitch and yaw rotations are performed by the differential mechanism using bevel gears. The rotations of the shafts are transmitted via timing belts to the differential mechanisms. Driving the two shafts in the same direction produces the fingertip pitch rotation, while the opposite direction produces the fingertip yaw rotation. By sharing the same driving shafts for left-and-right fingertips driving, the rotations of the driving shafts are equally supplied to the left-and-right fingers. Therefore the amplitudes of the angular velocities of the left-and-right fingertips in the pitch / yaw direction are mechanically the same. This mechanism guarantee a symmetric movement without requiring the accurate velocity control of the actuators. Moreover we can use small output actuators because the differential mechanism can be a coupled driving system [8]. The two driving shafts are also used as the horizontal guide shafts for opening and closing the fingers for a grasping motion. Thus the finger mechanism should be free to move along to the driving shaft, which is possible by using a ball spline. For the symmetric opening and closing motion of the fingers, there are several possible mechanisms. For example, Fig. 4 bottom uses a rack and pinion mechanism and Fig. 6 uses a timing belt.

This design permits the gripper to be sufficiently lightweight and compact, which can manipulate a discoid object with the small energy consumption.

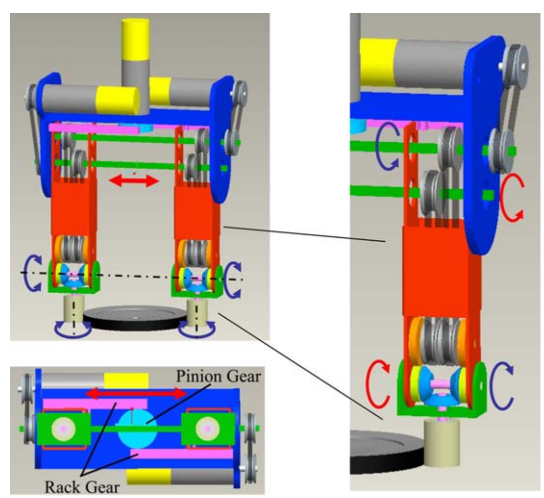

Fig. 4. Coupled drive mechanism using bevel gears

B. Passive compliance for the grasping

In the case of picking up a discoid parts from the vertical parts box, the distance between fingers must be adjusted by synchronizing the fingertip rotations and the relative height of the discoid object shown in Fig. 5. However the measurement of the relative height of the discoid object and the synchronized grasping control seem to be difficult because the grasping movement largely depends on the unknown frictional force between the fingertips and the discoid object.

Thus we propose to introduce a passive compliance property in the opening direction shown in Fig. 6. This compliance passively adjusted the finger distance depending on the width of the discoid object and the fingers generate sufficient grasping forces supplied by the springs. Additionally, this mechanism provides the gripper with a function of the grasping force control by commanding the relative position of the fingers where the position control loop can be very stable.

C. Fingertip mechanism

Fig. 7 shows the detailed design of the fingertips. It is desirable for the fingertips to be as thin as possible because the discoid parts in the vertical placement (Fig.2 left) are thickly placed whose minimum clearance is 10mm. However it is difficult to develop the fingers smaller than 10mm width using commercially available mechanical parts. Therefore we make a thin cylindrical fingertip only and introduce an offset between the axis of cylinder rotation and that of the bevel gear of the differential mechanism. The diameter of the cylindrical fingertip is 6mm, composed of a $\phi 3mm$ stainless shaft and a silicone tube. Additionally, we install subsidiary passive roller attached to the end of the supporting link which also passively rotates around the cylinder axis with torsional compliance. By introducing subsidiary rollers, the discoid object handling becomes 4 points contact. As a result, the gripper can perform a stable grasping which is especially effective in the case of a large discoid object.

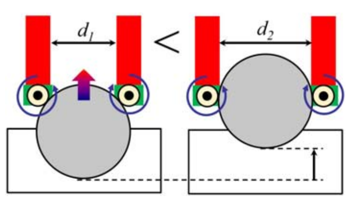

Fig. 5. Finger distance depending on the relative height of the discoid object

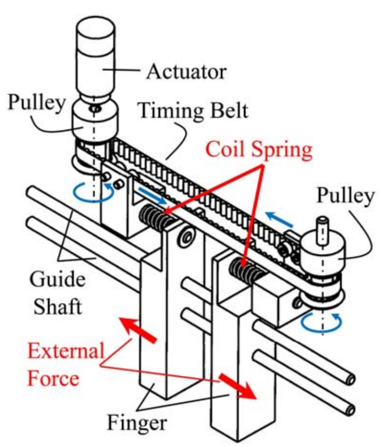

Fig. 6. Passive compliance mechanism against the outward external force

D. Development of the gripper prototypes

We set the design specifications for the pitch / yaw rotation and opening and closing velocity as $4.4, 5.8 rad/s$ and $120 mm/sec$, respectively. We selected a DC coreless motor of 1.5W (Maxon Japan Co.,Ltd: RE10).

We developed two prototypes shown in Fig. 8. The first prototype aimed at a verification of the basic mechanism and a clarification of the mechanical problems. The main structural parts were made of duralumin (A2017) and the opening / closing mechanism was composed of the two slide-screws and two resin nuts.

Based on the result of the first prototype, the second prototype aimed at saving the weight, achieving compactness, reducing backlash of the driving system, reducing the total number of the parts and maximization of the joint workspace. The main structural parts of the second prototype were made of magnesium (AZ31) and the opening / closing mechanism was composed of a ball screw with two bi-directional nuts. In order to reduce the mechanical play, we carefully revised the specification of the tolerance for manufacturing. The second prototype successfully reduced the total weight of the mechanism from $334g$ to $185g$, which is a weight saving of 45%.

III. Development of a light duty arm

In order to increase safety of the robot for a human worker, one of the most fundamental solution is to minimize the output power of the robot, which is also preferable in terms of energy efficiency. To reduce the required power for the

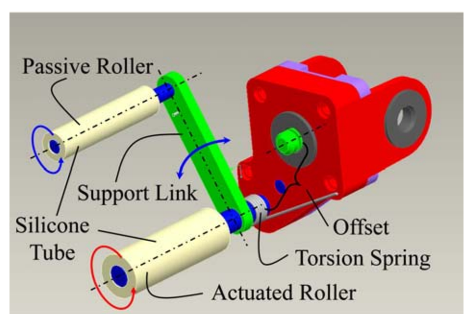

Fig. 7. Fingertip with an offset and a support passive roller

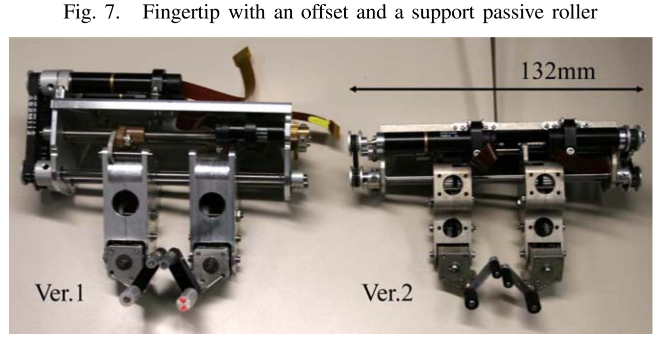

Fig. 8. Prototype models of the hand mechanism

operation, we choose lightweight materials and a mechanical configuration where the heavy actuators can be mounted on the base link. Moreover a weight compensation mechanism with a non-circular pulley and a spring is introduced to compensate a large gravity torque due to the long link length.

A. Mechanical design of the arm

We adopt a parallel 4-bar linkage mechanism to decrease the moment of inertia of the arm. Three actuators are installed in J_0, J_1 and J_2 to construct a 3-DOF cylindrical polar coordinate system shown in Fig. 9. We used CFRP pipes of $1mm$ thickness to reduce the total weight of the arm. The length of the links were chosen considering the stiffness of the 4-bar linkage structure and its maximum reach avoiding a singular posture. The required actuator power and needed reduction ratio were estimated by using a dynamics simulator to achieve the specification described in Section II. We selected a DC coreless motor of 20W (Maxon Japan Co.,Ltd: RE25) and a harmonic drive with the reduction ratio of 100. The play at the end of the arm due to the backlash in the joint is estimated about 0.068mm. In this paper, we focus on a pick-and-place task and it is preferable to keep the hand mechanism always vertical. Thus a parallel link mechanism was installed on the wrist pitch joint. Table 1 shows the specifications of the prototype model. The developed arm is extremely light weight compared with a commercially available industrial robot with the same arm length such as the reference [9] ($35kg$).

B. Weight compensation mechanism with a non-circular pulley and a spring

In this section, we discuss the basic principle of the weight compensation mechanism (WCM) using a non-circular pulley and a spring. More detailed discussion can be found in [10]. Let us consider a WCM for an 1-DOF pendulum system (Fig.10). The arm link with the non-circular pulley and the end-mass freely rotates to the base link. One extremity of the spring is connected to the base link and the other extremity is connected to the flexible part without elongation such as a wire or a belt. The extremity of the flexible part is fixed to the pulley. Therefore arm link rotation winds the flexible part and the stretched spring generates the compensation torque whose magnitude equals to the spring force multiplied by the diameter of the non-circular pulley.

If we can design pulley radius $r(\theta)$ satisfying the following identity of θ, the system becomes totally balanced system with zero gravity.

$$F_s \cdot r(\theta) = Mgl\sin\theta, \tag{1}$$

TABLE I

SPECIFICATIONS OF THE LIGHT DUTY ARM

Arm Length mm	500(Link 1)+500(Link 2')	
Maximum Reach mm	R=985	
Range of Motion deg	J_0: $\theta_0 = \pm 90$	
	J_1: θ_1 = 0, 90 (where $\theta_1 - \theta_2 > 20$)	
	J_2: θ_2 = -90, 0 (where $\theta_1 - \theta_2 < 160$)	
Actuator	Maxon RE25 (20W) * 3	
Payload kg	0.5	
Total Weight kg	4.5	

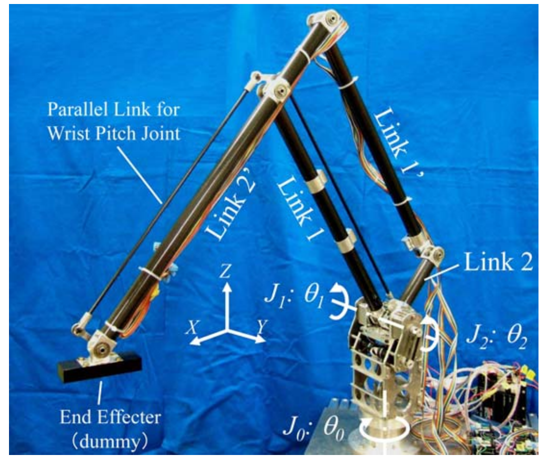

Fig. 9. Prototype model of a light duty arm

where F_s is spring force and M, g, l are the weight of the end mass, gravity acceleration and link length, respectively.

This mechanism is composed of only three parts (non-circular pulley, flexible part and spring) and very simple structure. And additional moment of inertia can be minimized with the high stiffness spring and small diameter non-circular pulley.

C. Detailed design of the WCM

The weight compensation torques for each joint are calculated by mass property data and the transposed Jacobian matrices of the link model [10]. The gravity torque for each joint can be come down to a virtual 1-DOF pendulum system. Here, we assume the link length of $0.5m$ for the simulated equivalent pendulum. The gravity torque τ_1 for J_1 is equivalent to an inverted pendulum with the end mass of $0.858kg$. Similarly, τ_2 for J_2 is equivalent to an ordinary

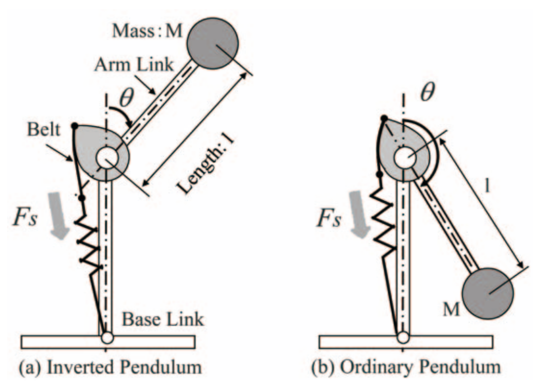

Fig. 10. Basic principle of the weight compensation mechanism with a non-circular pulley and a spring

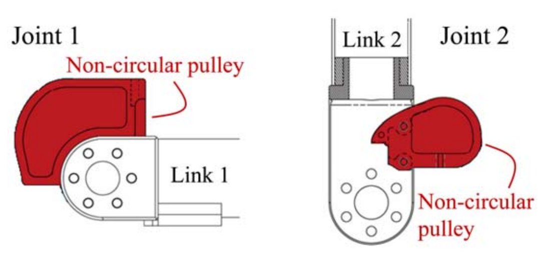

Fig. 11. Non-circular pulleys for the weight compensation

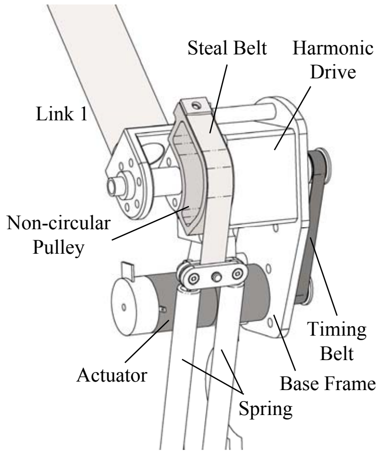

Fig. 12. Joint diving mechanism with the non-circular pulley and the springs

pendulum with the end mass of $0.302kg$.

Fig.11 shows derived shape of the non-circular pulleys based on mass property analysis. We adopt a steel belt as the flexible part because the steel belt with sufficient strength is very thin ($0.1mm$ thickness) and its elongation is negligible small.

J_1 and J_2 joint have basically the same driving mechanism. Fig.12 shows the detailed mechanism for J_1. The actuator output torque is transmitted by a timing-belt to the input shaft of the harmonic reduction gear unit. The output of the harmonic unit drives the non-circular pulley fixed to the link structure. The non-circular pulley winds the steal belt and stretch the spring to generate compensation torque.

Note that the joint stiffness does not essentially decrease by introducing the spring because the spring is connected parallel to the joint actuation.

IV. Experiment

A. Evaluation of the hand

The pick-and-place task was carried out to evaluate the gripper mechanism where the gripper was mounted at the tip of a commercially available manipulator [11] whose repeatability of ±0.1mm is guaranteed. The target task was the following sequence.

1) Pick up a discoid object from the horizontal parts box
2) Insert the object into a slot of the vertical parts box
3) Pick up the object from the vertical parts box
4) Put the object on the horizontal parts box

The diameters of the discoid objects are $\phi 13 - \phi 55$mm and the thickness are $3 - 8$mm. The materials of the discoid objects are aluminium, brass and glass. We assumed that the position of the parts box and the discoid object were given and all joints of the arm and hand was driven by a position-based teaching and playback control.

The first prototype gripper succeeded to perform the task with the discoid object of ϕ31mm. Notably, the gripper mechanism delicately pick the object up from the vertical parts box by slowly rotating the fingertip cylinder (Fig. 13). We observed that the finger distance passively changed according to the relative height of the object. We also tested the same task without the passive compliance and found that the actuator current hit the limitation of the motor driver. This result indicates the passive compliance in the grasping motion is important for succeeding the task.

However the first prototype had a large play in the fingertip joints and thus, the gripper could not perform the task using the discoid object of ϕ13mm and ϕ55mm with high reproducibility.

On the contrary, the second prototype with a less mechanical play could succeed the task with all diameters. In the case of ϕ55mm, the subsidiary passive rollers were very effective to prevent the object from falling because the subsidiary passive rollers suppress the pitching rotation of the discoid object.

B. Evaluation of the arm

We measured the performance of the developed arm using the following criteria [12]. Here we show the results only, because of space limitations.

- Maximum static torque: 11.7mNm
- Position repeatability: 0.07mm
- Pose stabilization time: 0.7sec
  (where the position error is less than ±0.3mm)
- Trajectory tracking accuracy:2mm
  (where the averaged speed is 0.5m/s in a linear trajectory)
- Standard cycle time: 1.2sec
  (where the trajectory tracking accuracy is less than 5mm)

The standard cycle time is widely use to evaluate the performance of the industrial robots. The one-way trajectory is composed of an elevation of 25mm, a horizontal transition of 300mm and a lowering of 25mm. By introducing the WCM, the required maximum static torque is drastically reduced to 26%, indicating that the small output actuator is sufficient to keep the static posture. The performance of the position repeatability is close to the commercially available industrial robots.

C. Evaluation of the integrated system

The gripper mechanism and an additional wrist yaw joint were installed at the end of the arm and the pick-and-place task was carried out. The task sequence and the basic assumptions were the same described in Section IV.A. We performed a repetitive experiment using the discoid object of ϕ31mm, ϕ40mm and ϕ54mm. We tested the task with various cycle time to investigate the minimum cycle time. Figs. 14 and 15 demonstrate the pick-and-place sequences where its cycle time was set to 15.0 sec.

Despite the developed hand-arm system was a completely open-loop control and there was no sensor to measure the position of the discoid object, the system succeeded 100 times continuous pick-and-place task. This is because that the position error of the discoid object in each trial is absorbed by the passive compliance, and the symmetric mechanism automatically centers the discoid object. The minimum cycle time is about 4.0sec which is almost the same as the human worker's speed.

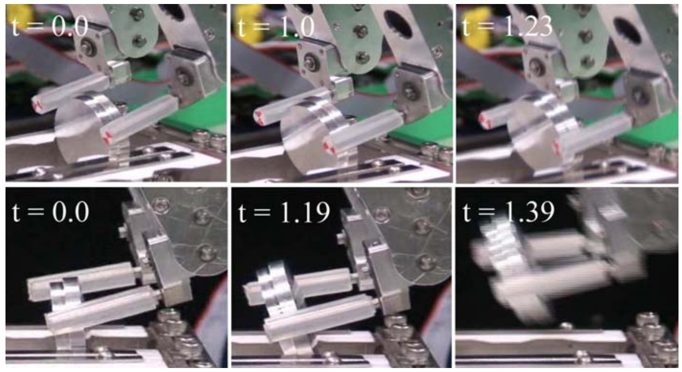

Fig. 13. Pick up from the vertical parts box using the first prototype hand (aluminium discoid, ϕ31mm, unit of t is sec)

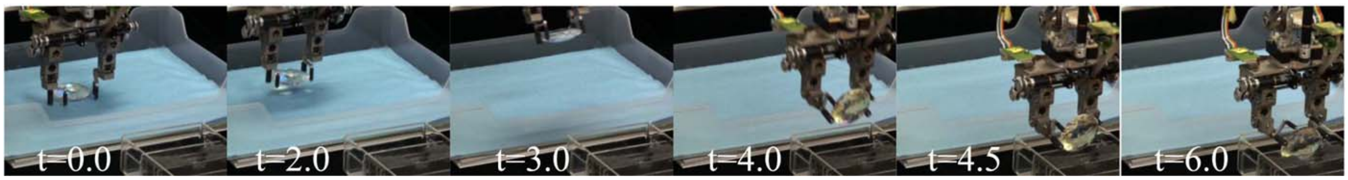

Fig. 14. Pick-and-place motion from the horizontal placement to the vertical placement by the integrated system (grass discoid, diameter:ϕ40mm, unit of t is sec)

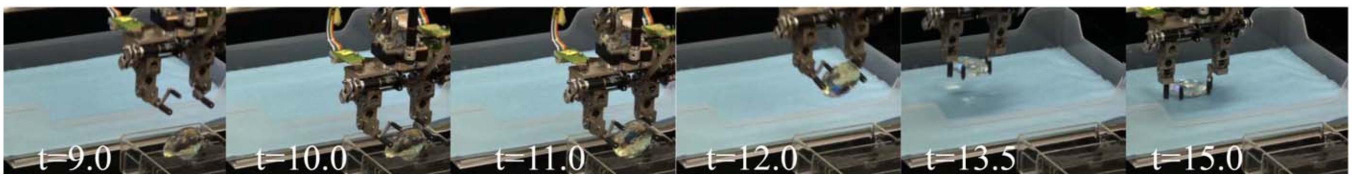

Fig. 15. Pick-and-place motion from the vertical placement to the horizontal placement by the integrated system (grass discoid, diameter:ϕ40mm, unit of t is sec)

V. Conclusion

In this paper, we have proposed a light duty arm with an active-fingertip gripper that can perform a pick-and-place task for discoid objects where the object placement is from horizontal to vertical and vice versa. We have proposed a new gripper mechanism which has the cylindrical rotational fingertips and developed two prototype models. The gripper mechanism can grasp a discoid object whose diameter is $\phi 13-55$mm. The gripper can also change the pitching angle of the discoid object only touching its edge. We also developed a light duty arm which is potentially capable of sharing the workspace with human workers. In order to minimize the required actuator power to increase safety for a neighbour human worker, we choose the lightweight materials and introduce a weight compensation mechanism with a non-circular pulley and a spring. After evaluations of the basic performances, we integrated a hand-arm system and demonstrated a sequence of pick-and-place task. As a result, the system successfully performed 100 times continuous pick-and-place without failure, whose cycle time is almost the same as a human worker.

To decrease the cycle time, we plan to increase the structural stiffness of the arm. The measurement of the actual position of the discoid object and the generation of the trajectory to do pick-and-place task using acquired object position are our important future work.

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