2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
Macau, China, November 4-8, 2019

Design and Development of Compactly Folding Parallel Open-Close Gripper with Wide Stroke

Akinari Kobayashi, Jun Kinugawa, Shogo Arai, and Kazuhiro Kosuge

***Abstract*— A novel compact parallel gripper with wide stroke is proposed in this paper. Conventional parallel grippers with linear guide mechanisms have been widely utilized as end effectors of robots, especially in industrial fields, because of its simple mechanism and low cost nature. However, the width of the gripper is larger than the stroke due to the mechanical structure of its linear guide mechanism. When objects with various dimensions need to be grasped by a gripper, the width of the gripper is determined by the largest distance between fingers necessary for grasping all of the objects. This makes the collision avoidance of robot difficult even when handling a small object compared to the width of the gripper. The novel compact gripper proposed in this article has three features: long finger stroke with compact dimensions, fingers' parallel motion along a single linear trajectory, and driven by a single actuator. The finger backlash and the gripping force of the proposed mechanism are analyzed, and the parallel gripper with the mechanism is designed based on the analyses. A prototype gripper with minimum width 64 mm, whose maximum fingers stroke is 121 mm, is developed, and experimental results illustrate the performance of the developed gripper.**

I. INTRODUCTION

Grasping mechanisms have been studied actively in robotics fields, because the grasping is a fundamental function for most of industrial robots to execute tasks, such as pick-and-place and assembly of objects. Grasping is performed using a mechanism, such as a robot hand and a gripper attached to the end of a manipulator to fix geometric relation between the manipulator and the grasped object. The grasping performance of the mechanism is one of the most significant factors affecting the performance of the robot system.

A lot of research of fully actuated multi fingered robot hands has been carried out so far [1]–[3]. Most of the research aimed to achieve versatility and dexterity similar to human hands. Research of underactuated multi fingered robot hands has been also carried out as an object-shape-adaptive grasping mechanism with less number of actuators compared to the fully actuated mechanisms. The implementation methods of underactuated mechanisms are generally classified into three types: using tendon [4]–[6], linkage mechanism [7]–[10], and mechanical elements such as gears [11]–[14]. Most of the research of the underactuated mechanism is focusing on reducing the control complexity of multi fingered robot hands.

A. Kobayashi, J. Kinugawa, S. Arai and K. Kosuge are with Department of Robotics, Graduate School of Engineering, Tohoku University, 6-6-01 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-8579, Japan {kobayashi, kinugawa, arai, kosuge}@irs.mech.tohoku.ac.jp

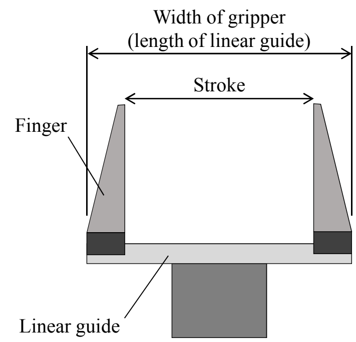


Fig. 1. Stroke of conventional parallel gripper with linear guide mechanism. The gripper stroke depends on the length of the guide mechanism, as well as the width of the gripper. The stroke could not be larger than the width of the gripper.

Because of the control simplicity and low cost nature, parallel grippers have been widely used as end effectors of industrial robots. Many types of grippers with various open-close mechanisms have already been commercialized [15]. To expand the applicability of the grippers, grippers with additional functions, such as suction gripping [16], [17], in-hand manipulation [18], [19], have been studied. The parallel gripper whose fingers move along a single linear trajectory is particularly easy to use because both fingers' position from the linear trajectory is kept the same and constant.

Conventional parallel grippers have linear guide mechanisms to make both fingers' motion along a single linear trajectory. The width of the gripper is larger than the stroke due to the mechanical structure of its linear guide mechanism as shown in Fig. 1. The collision free space of the motion of the robot which the gripper is attached to depends on the dimensions of the gripper. The tasks in narrow workspaces, such as bin picking and shelf picking, require a compact gripper with large fingers' stroke. When grasping objects with different dimensions is performed using a single gripper, the width of the gripper is determined by the largest dimension of the objects; on the other hand, a gripper with large width is undesirable from the collision free space of the robot motion point of view. Because of this issue, the parallel grippers have been usually utilized for tasks to handle the same or a similar dimensions of objects, not for tasks to handle of objects with different dimensions. Grasping of the same or a similar dimensions of objects can be realized by a compact gripper with a compact linear guide mechanism having short stroke.

This paper addresses the issue of the parallel grippers using the linear guide mechanism and proposes a novel parallel open-close gripper. The width of the proposed gripper depends on the fingers opening width, that is, the gripper becomes small when it grasps a small object and becomes large when it grasps a large object. The proposed gripper can be applied to tasks handling objects with different dimensions without restricting the collision free motion space.

The following sections are organized as follows. Section II describes three features of the proposed mechanism. Section III. A. proposes the basic structure of the parallel open-close mechanism and section III. B. analyses the finger backlash and the gripping force of the proposed mechanism. Section IV describes the design of the developed gripper with the proposed mechanism. In section V, experiments using the developed gripper are carried out to illustrate the performance of the developed gripper. Finally, Section VI gives conclusions of this paper.

II. FEATURES OF PROPOSED GRIPPER

In order to solve the problem of conventional parallel grippers with linear guide mechanism which are commonly used in factory automation systems, we discuss the three desired features of the novel gripper: (A) long finger stroke with compact size, (B) fingers' parallel motion along a single linear trajectory, and (C) a single actuation degree of freedom.

A. Long finger stroke with compact size

Conventional parallel grippers whose fingers move along a single linear trajectory are designed using linear guide mechanisms, such as linear rails and linear shafts. Such guide mechanisms contribute to the highly accurate fingers' linear motions with high stiffness.

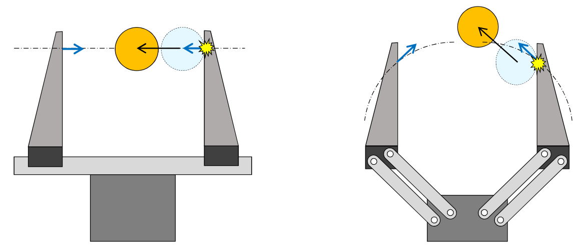
On the other hand, the size of the linear guide mechanism is longer than the finger stroke. As a result, the width of the gripper could not be smaller than the finger stroke as shown in Fig. 1. A gripper with long finger stroke which can handle objects with a variety of dimensions could not be applied to tasks in a narrow or crowded workspace, because of the restriction of collision free space of the robot with the gripper.

We are going to propose a novel parallel open-close mechanism whose width is smaller than the finger stroke.

B. Fingers' parallel motion along a single linear trajectory

Four bar parallel linkage is one of solutions that satisfies the first concept. Actually, four bar parallel linkage is widely used as the open-close mechanism of off the shelf robot hands and grippers. With this mechanism, the gripper can open and close fingers with keeping their orientations constant. Normally, the grasping flat surfaces of fingers are parallel to each other. The width of the gripper with four bar parallel linkage can be designed smaller than its finger stroke. However, each finger moves along an arc trajectory due to four bar parallel linkage mechanism, which could cause grasping failure or error.

Consider the case where the gripper is attached to a manipulator and the target object pose is estimated using a vision system. For grasping the target object, the manipulator is moved to the grasping position of the target object based on the estimated pose, then the gripper is closed to grasp the target object. When the gripper grasps the target object, both fingers could not touch the object simultaneously because of the pose estimation error and the calibration error between the manipulator motion coordinate system and the vision system coordinate system.



(a) Gripper with linear guide mechanism. (b) Gripper with parallel four bar mechanism.

Fig. 2. Comparison of two types of parallel gripper: with linear guide mechanism and with parallel four bar mechanism, when only one finger contacts with a grasping object.

Fig. 2 compares the arc trajectory finger motion gripper and the linear trajectory finger motion gripper when one finger contacts with the object first. The motion of the object is generated by the contact between the finger and the object. When the fingers move along the linear trajectory, the contact force applied by the contact finger to the object generates the object motion toward the other finger as shown in Fig. 2 (a). When the fingers move along the arc trajectories, the contact force generates the object motion toward a tangential direction of the contact point of the arc trajectory of the contact finger as shown in Fig. 2 (b). The object motion component parallel to the grasping surface direction could cause the error between the final grasp pose and the planned grasp pose. In general, the smaller and lighter the object is, the larger the error is caused by the contact. The grasp could result in failure if the object position in the direction parallel to the grasping surface drastically changes because of the contact.

We are going to propose a novel parallel open-close mechanism whose fingers move along a single linear trajectory without using the linear guide mechanism.

C. A single actuation degree of freedom

Existing widely-used parallel grippers usually have only one actuation degree of freedom and are driven by one actuator. The parallel grippers with a single actuation degree of freedom have some advantages. The grippers can be designed compact and light weight, and can be controlled easily.

We are going to propose a novel parallel open-close mechanism driven by a single actuator without using the linear guide mechanism for fingers motion along a linear trajectory.

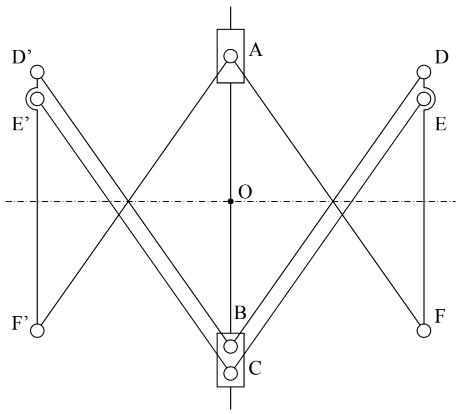


Fig. 3. Proposed parallel open-close mechanism.

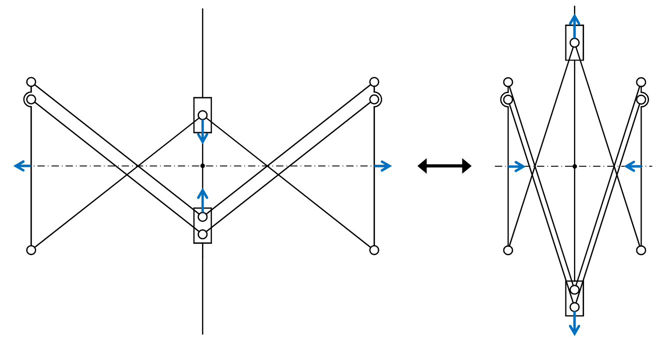


Fig. 4. Open and close motions of proposed mechanism.

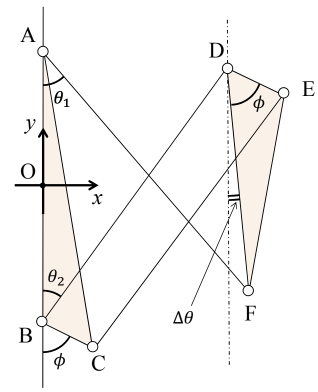


Fig. 5. Analysis model of finger backlash for proposed mechanism.

III. MECHANISM AND ANALYSIS

In this section, we propose a parallel open-close mechanism which satisfies the three features described in the previous section. We analyze the proposed parallel open-close mechanism from the point of view of the finger backlash and the gripping force. In the following, l with two suffixes express a distance between two points, for example, l_{AB} means the distance between points A and B.

A. Parallel open-close mechanism

Fig. 3 describes the proposed parallel open-close mechanism. The mechanism consists of two prismatic joints, AO and BO, nine revolute joints, A, B, C, D , E, F, D', E', F', and eight links, AF, BD, CE, DF, AF', BD', CE', D'F'. The revolute joints E and E' are located on the links DF and D'F' respectively. The revolute joint A is attached to the prismatic joint AO and moves along the line AO. The revolute joints B and C are attached to the prismatic joint BO and moves along the line BO together.

We assume that joints A and B moves symmetrically about the point O along the line AB by designing an appropriate actuation mechanism. The linkage structure is symmetric about the line AB, thus we only consider the right side of the structure in the following analyses. The lengths of the links AF, BD, and CE are the same, and the lengths of the links BC and DE are the same. Therefore, the link BC is parallel to the link DE and the link BD is parallel to the link CE.

The proposed mechanism opens and closes by the two prismatic joints motions driven by one actuator. The open and close motions are shown in Fig. 4. The links DEF and D'E'F' are extended and used as fingers. The links DEF and D'E'F' moves horizontally with their orientations kept parallel to each other and parallel to the line AB because of the link structure and the symmetric motion constraint of the prismatic joints.

B. Analysis of mechanism

1) Fingers backlash: The link structure has been designed for the finger link DEF (D'E'F') to move along the linear trajectory perpendicular to the line AB with its orientation parallel to the line AB. Any actual mechanical part has shape error from the ideal part shape, no matter how accurately the part is fabricated. The revolute joint consists of a bearing which has a gap. The gap in the bearing could not be eliminated. The gaps in bearings of the joints and the shape errors of parts generate backlash and motion error of the finger link. In the following part of this subsection, we analyze the backlash of the finger link DEF based on the link model with the gaps in bearings of the joints and the shape errors of parts. In this paper, the backlash of the finger link DEF is measured by the the orientation error of the finger link DEF.

Fig. 5 describes the linkage model used for analysis of finger backlash. For the calculation of joints position, we define the o-xy coordinate system as shown in Fig. 5, where the origin of the coordinate system is located at the point O, the middle point of the link AB. θ_1 and θ_2 represents the angle $\angle$BAF and $\angle$ABD, respectively. θ_1 is equal to θ_2, if there were no gaps in bearings and no shape errors of parts. In Fig. 3, the joint C is located on the line AB, but it turns out that this configuration causes a large backlash of the finger link when there are gaps in bearings and shape errors of parts. We are going to solve this issue by locating the joint C out side of the line AB. We introduce the angle ϕ to determine the position of the joint C with respect to the line AB.

The revolute joints B and C are fabricated on the same prismatic joint, and the revolute joints D and E are fabricated on the same link structure by precise machining. Assuming that the machining error is negligible, the lengths of the link

BC and the link DE are the same, although gaps in bearings are not negligible. Then, we have

$$l_{\mathrm{BC}} = l_{\mathrm{DE}}. \tag{1}$$

To make the analysis simple, the effect of gaps in bearings is treated as the difference of the link length BD and CE , assuming that the lengths of the links BD and AF are the same. We also assume that the $\angle$FDE is equal to ϕ, because the difference of the link length BD and CE is enough small to be negligible compared to the link length BC and DE. Then, we have

$$l_{\mathrm{AF}} = l_{\mathrm{BD}}, \tag{2}$$

$$l_{\mathrm{CE}} = l_{\mathrm{BD}} + \Delta l, \tag{3}$$

where Δl represents the difference of the length of the link BD (AF) and the link CE. Because of the length difference Δl, link DF are not parallel to link AB; link DF has the angle difference $\Delta\theta$ to the line which pass through the point D and is parallel to the line AB. $\Delta\theta$ is the finger backlash of the proposed mechanism. When l_{CE} is equal to l_{BD} (l_{AF}), $\Delta\theta$ is equal to zero and θ_1 is equal to θ_2.

From the geometrical relationship of the linkage, the position of joints C, D and E are derived as follows:

$$x_{\mathrm{C}} = l_{\mathrm{BC}} \sin\phi,\ y_{\mathrm{C}} = -\frac{l_{\mathrm{AB}}}{2} - l_{\mathrm{BC}} \cos\phi, \tag{4}$$

$$x_{\mathrm{D}} = l_{\mathrm{BD}} \sin\theta_2,\ y_{\mathrm{D}} = -\frac{l_{\mathrm{AB}}}{2} + l_{\mathrm{BD}} \cos\theta_2, \tag{5}$$

$$\begin{aligned} x_{\mathrm{E}} &= x_{\mathrm{D}} + l_{\mathrm{DE}} \sin(\phi + \Delta\theta), \\ y_{\mathrm{E}} &= y_{\mathrm{D}} - l_{\mathrm{DE}} \cos(\phi + \Delta\theta). \end{aligned} \tag{6}$$

With the equation (4) to (6), the square of the distance between joints C and E is derived as follows:

$$\begin{aligned} l_{\mathrm{CE}}^2 &= (x_{\mathrm{E}} - x_{\mathrm{C}})^2 + (y_{\mathrm{E}} - y_{\mathrm{C}})^2 \\ &= [l_{\mathrm{BC}}\{\sin(\phi + \Delta\theta) - \sin\phi\} + l_{\mathrm{BD}} \sin\theta_2]^2 \\ &\quad + [l_{\mathrm{BC}}\{-\cos(\phi + \Delta\theta) + \sin\phi\} + l_{\mathrm{BD}} \cos\theta_2]^2. \end{aligned} \tag{7}$$

Substituting the equation (3) to (7), we have the following relation:

$$\Delta\theta = \frac{\Delta l^2 + 2 l_{\mathrm{BD}} \Delta l}{2 l_{\mathrm{BC}} l_{\mathrm{BD}} \sin(\theta_2 + \phi)}, \tag{8}$$

where we assumed that $\Delta\theta$ is small, that is, $\Delta\theta^2 \approx 0$, $\cos\Delta\theta \approx 1$, and $\sin\Delta\theta \approx \Delta\theta$. By also assuming that Δl is small, that is, $\Delta l^2 \approx 0$, the following equation is derived from the equation (8):

$$\Delta\theta = \frac{\Delta l}{l_{\mathrm{BC}} \sin(\theta_2 + \phi)}. \tag{9}$$

The equation (9) shows the followings:

1) The finger link backlash is proportional to Δl. Actually, $\Delta\theta$ is equal to zero when Δl is equal to zero as mentioned before.
2) The finger link backlash is inversely proportional to a design parameter l_{BC}.
3) The finger link backlash is inversely proportional to $\sin(\theta_2 + \phi)$, where ϕ is another design parameter.

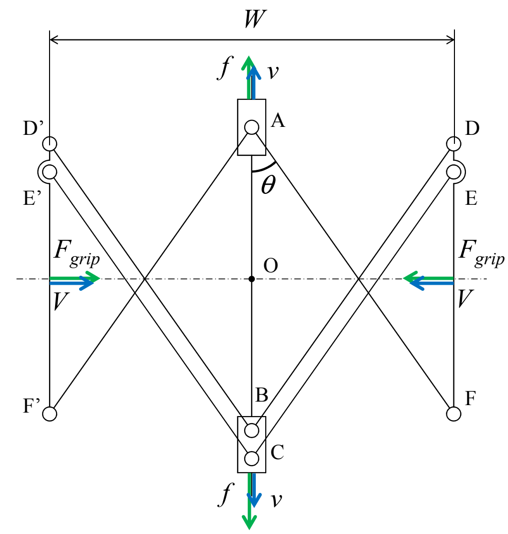


Fig. 6. Analysis model of grasping force for proposed mechanism.

l_{BC} is determined by the dimensions of the grasping mechanism and is selected as large as possible. Δl depends on the machining error of parts and gaps in bearings, which are not easy to be reduced.

θ_2 is a variable and varies according to the opening width of the fingers. ϕ should be designed to increase the absolute value of $\sin(\theta_2 + \phi)$ for a given range of θ_2. Let the range of θ_2 be expressed as follows:

$$0 \leq \theta_{\min} \leq \theta_2 \leq \theta_{\max} \leq \frac{\pi}{2}. \tag{10}$$

The optimum value of ϕ that maximizes the minimum value of $\sin(\theta_2 + \phi)$ in the given range of θ_2 is derived as follows:

$$\phi = \frac{\pi}{2} - \frac{\theta_{\min} + \theta_{\max}}{2}, \frac{3\pi}{2} - \frac{\theta_{\min} + \theta_{\max}}{2}\ (0 \leq \phi \leq 2\pi). \tag{11}$$

2) Gripping force: We analyze the gripping force of the proposed mechanism using the linkage model, assuming that gaps in bearings and shape errors of parts are negligible. Fig. 6 shows a grip force analysis model of the proposed mechanism. f and v are the force and velocity of the prismatic joints which moves symmetrically about the point O along the line AB. F_{grip} and V are the force and velocity of the finger links DEF and D'E'F'. W is the distance between the link DEF and the link D'E'F'. θ is the angle $\angle$BAF. Because of the geometric property of the proposed mechanism, the angle $\angle$ABD, $\angle$ACE, $\angle$BDF, $\angle$CEF, and $\angle$AFD are equal to the angle $\angle$BAF.

Applying the principal of virtual power, the following relation holds between f and F_{grip}:

$$fv = F_{grip} V. \tag{12}$$

From the geometric relation of the mechanism shown in Fig. 6, l_{AB} and W are expressed by

$$l_{\mathrm{AB}} = 2 l_{\mathrm{AF}} \cos\theta - l_{\mathrm{DF}}, \tag{13}$$

$$W = 2 l_{\mathrm{AF}} \sin\theta. \tag{14}$$

TABLE I: MAIN SPECIFICATIONS OF THE DEVELOPED GRIPPER

Dimensions (open state)	185 mm × 64 mm × 267 mm
Dimensions (close state)	64 mm × 64 mm × 267 mm
Finger size	32 mm × 10 mm × 80 mm
Stroke	121 mm
Max. grip force (open state)	73.8 N
Max. grip force (close state)	12.3 N
Motor model	DCX14L GB KL 18V (maxon motor)
Max. output	10.5 W
Weight	998 g

As the two prismatic joints moves symmetrically about the point O along the line AB, the time derivative of l_{AB} is equal to $2v$; thus, v is derived as follows:

$$\begin{aligned} v &= \frac{1}{2}\frac{l_{\mathrm{AB}}}{dt} = \frac{1}{2}\frac{dl_{\mathrm{AB}}}{d\theta}\frac{d\theta}{dt} \\ &= -l_{\mathrm{AF}}\sin\theta\frac{d\theta}{dt}. \end{aligned} \tag{15}$$

Similarly, as link DEF and link D'E'F' moves symmetrically and parallel to the line AB, the time derivative of W is equal to $2V$; thus, V is derived as follows:

$$\begin{aligned} V &= \frac{1}{2}\frac{dW}{dt} = \frac{1}{2}\frac{dW}{d\theta}\frac{d\theta}{dt} \\ &= l_{\mathrm{AF}}\cos\theta\frac{d\theta}{dt}. \end{aligned} \tag{16}$$

From the equation (12) through (16), the magnitude of the grip force F_{grip} is derived as follows:

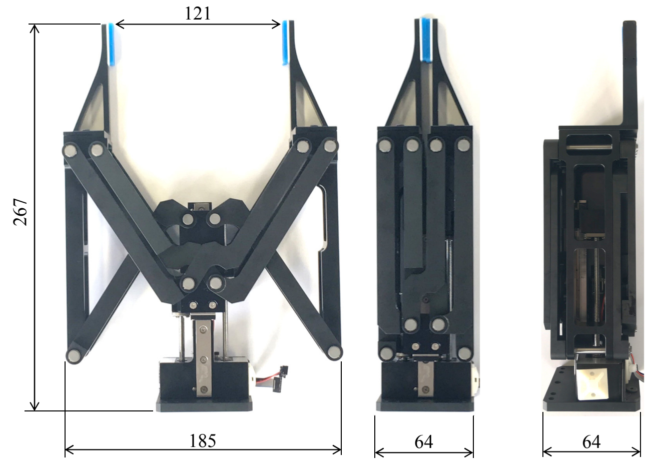
$$F_{grip} = f\tan\theta. \tag{17}$$

The equation (17) shows that the grip force depends on the actuation force of the prismatic joints and the angle θ. When the actuation force is constant, the larger fingers distance W is, the larger grip force is.

IV. GRIPPER DESIGN

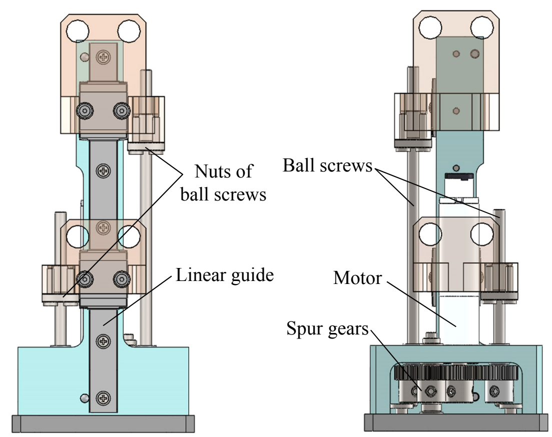
Based on the analyses of the proposed parallel open-close mechanism introduced in the previous section, we design and develop a novel compact parallel gripper with the mechanism. Specifications of the developed gripper are shown in Table I. Fig. 7 shows the developed gripper with the proposed mechanism and the specifications given in Table I. The developed gripper can open and close the fingers with 121 mm finger stroke and its width changes from 64 to 185 mm according to the opening width of the fingers.

As described in the equation (17), the grip force of the developed gripper varies according to the fingers distance even if the constant actuation force is applied to the system. The maximum grip forces are specified for two cases, for the fingers distance 121 mm, and for the fingers distance 0 mm as shown in Table I.



(a) Front view when the gripper is opened. (b) Front view when the gripper is closed. (c) Side view.

Fig. 7. Front views and side view of the developed gripper.



(a) Front view. (b) Rear view.

Fig. 8. Drive mechanism of the developed gripper.

A. Drive mechanism

Fig. 8 illustrates the drive mechanism of the developed gripper. The mechanism consists of a motor, four spur gears, two ball screws which have the same lead parameter, and a linear guide with two guide blocks. The spur gears distribute the motor torque to the two ball screws, and the gears are designed to rotate two ball screws at the same angular velocity with different rotational directions. The nut of each ball screw is mechanically connected to each linear guide block, and the linear guide blocks move along the guide rail according to the motion of the ball screws. Since the rotational direction of one ball screw is opposite to the rotational direction of the other ball screw, one linear guide block moves symmetrically to the other linear guide block along the linear guide rail.

B. Joints layout

Fig. 9 shows the link structure of the developed gripper. The link parameters are listed in Table II. Based on the backlash analysis described in the previous section, the

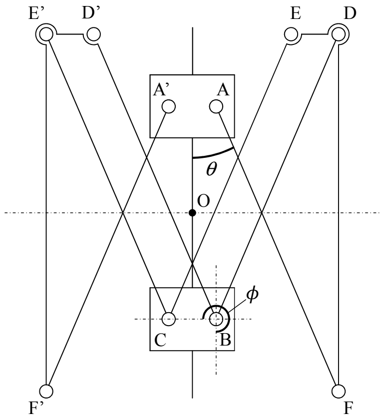


Fig. 9. Link structure of the developed gripper.

TABLE II: LINK PARAMETERS OF THE DEVELOPED GRIPPER

$l_{\mathrm{AF}} = l_{\mathrm{BD}} = l_{\mathrm{CE}} = l_{\mathrm{A'F'}} = l_{\mathrm{BD'}} = l_{\mathrm{CE'}} = 118$ (mm)
$l_{\mathrm{AA'}} = l_{\mathrm{BC}} = l_{\mathrm{DE}} = l_{\mathrm{D'E'}} = 18$ (mm)
$l_{\mathrm{DF}} = l_{\mathrm{D'F'}} = 136$ (mm)
$42.0 \leq l_{\mathrm{AB}}(= l_{\mathrm{A'C}}) \leq 97.5$ (mm)
$8.3 \leq \theta \leq 41$ (°)
$\phi = 270$ (°)

optimum value of ϕ for the range of θ shown in Table II is calculated as $\phi = 65.35, 245.35$ °. $\phi = 245.35$ ° could make the width of the mechanism more compact.

In order to minimize the height of the mechanism, joints B and C should locates on the same line which is parallel to the fingers' linear trajectory; in this case, ϕ is equal to 90 or 270°. When $\phi = 270$ °, the same joint can be used as joint B and C, which makes the mechanism compact in the width direction. When $\phi = 65.35, 245.35$ ° and θ varies from 8.3 to 41 ° as shown in Table II, the minimum absolute value of $\sin(\theta + \phi)$ is 0.96. When $\phi = 270$ ° and θ varies from 8.3 to 41 ° as shown in Table II, the minimum absolute value of $\sin(\theta + \phi)$ is 0.75. In this case, the finger backlash is 28% larger than the optimal design, $\phi = 65.35, 245.35$ °, according to the equation (9). In this paper, $\phi = 270$ ° is used to make the mechanism compact considering the 28% increase in finger backlash is negligible. l_{BC} is designed as large as possible to reduce the backlash, and to make the gripper's width under allowable size.

V. Experiments

In order to test the performance of the developed gripper, grasping experiments were conducted. 12 mechanical parts with different shapes that compose an actual industrial product were grasped using the developed gripper. Fig. 10 shows how the gripper grasped 12 kinds of the parts. The gripping width of the parts were 2 to 110 mm, and the weights were 3 to 87 mm. The experimental results show that the developed gripper can grasp the different objects with different dimensions.

Bin picking experiments using the developed gripper were also conducted. One of the parts shown in the upper left of the Fig. 10 was used as the grasping object. The parts were randomly piled up in a rectangular bin. The developed gripper was attached to a six degrees of freedom manipulator in the experiment. First, pose estimation of the piled up parts were conducted using the algorithm of [20], then, the grasp planning and motion planning were carried out, and finally, the picking operation was executed according to the planned motion. Fig. 11 shows three trials of the experiments. The experimental results shows that the developed gripper can replace conventional parallel grippers without any problems.

The developed gripper can grasp objects with various dimensions without redesigning fingers differently from conventional parallel grippers.

VI. Conclusions

This paper has proposed a novel parallel open-close gripper whose finger stroke is larger than the width of the gripper, although the finger stroke of conventional parallel grippers is smaller than their width. The proposed parallel open-close mechanism of fingers consists of two prismatic joints driven by one actuator, nine revolute joints, and eight links connecting the joints. The finger backlash of the proposed mechanism caused by gaps in bearings and shape errors of the parts has been analyzed. The gripping force has been also analyzed applying the principal of virtual power to the proposed mechanism. Based on the analyses, we have designed and developed the parallel open-close gripper whose finger backlash is almost negligible. The developed gripper has 121 mm stroke, and its width varies from 64 mm (when the fingers are closed) to 185 mm (when the fingers are fully opened). The basic grasping performance of the developed gripper has been evaluated by grasping experiments of actual industrial parts with different shapes and dimensions together with bin picking experiments. The experimental results have shown that the developed gripper can replace the conventional parallel grippers. The use of the proposed gripper make it possible to grasp different objects without replacing the fingers.

References

[1] H. Liu, P. Meusel, N. Seitz, B. Willberg, G. Hirzinger, M. H. Jin, Y. W. Liu, R. Wei, and Z. W. Xie, "The modular multisensory DLR-HIT-Hand," *Mechanism and Machine Theory*, vol. 42, no. 5, pp. 612–625, 2007.

[2] T. Mouri, H. Kawasaki, K. Yoshikawa, J. Takai, and S. Ito, "Anthropomorphic Robot Hand: Gifu Hand III," *Proceedings of International Conference on Control, Automation and Systems*, pp. 1288–1293, 2002.

[3] L. B. Bridgwater, C. A. Ihrke, M. A. Diftler, M. E. Abdallah, N. A. Radford, J. M. Rogers, S. Yayathi, R. S. Askew, and D. M. Linn, "The Robonaut 2 Hand – Designed To Do Work With Tools," *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 3425–3430, 2012.

[4] S. Hirose and Y. Umetani, "The development of soft gripper for the versatile robot hand," *Mechanism and Machine Theory*, vol. 13, no. 3, pp. 351–359, 1978.

[5] C. Gosselin, F. Pelletier, and T. Laliberté, "An anthropomorphic underactuated robotic hand with 15 dofs and a single actuator," in *Proc. IEEE Int. Conf. Robotics and Automation*, 2008, pp. 749–754.

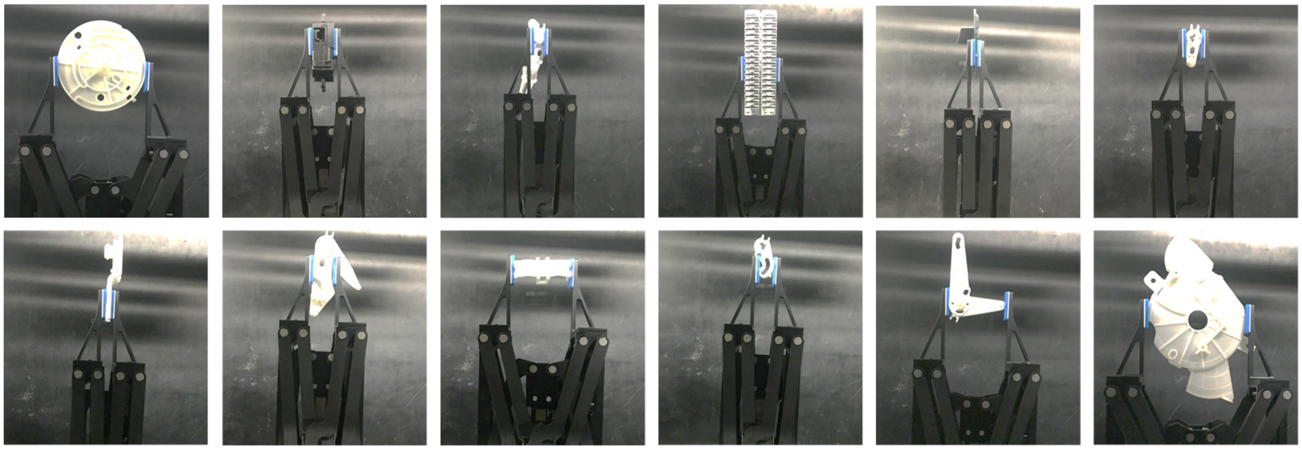


Fig. 10. Grasping test of 12 industrial parts with different shapes using the developed gripper.

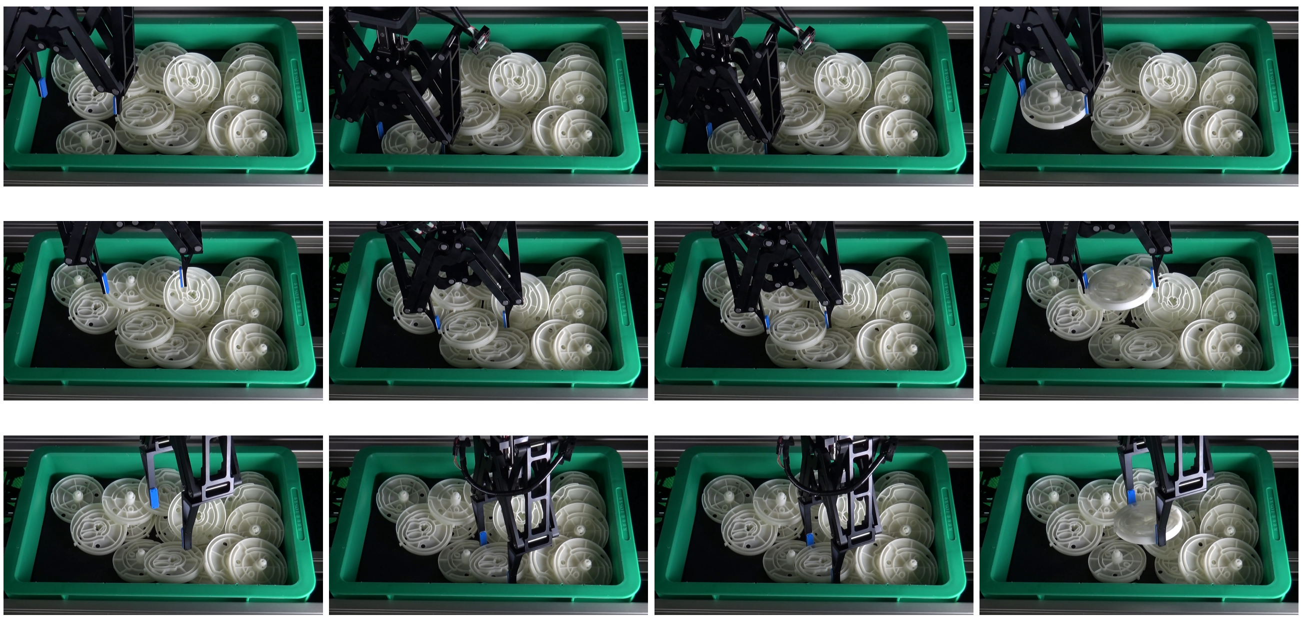


Fig. 11. Bin picking experiments of disk-shaped industrial parts with the developed gripper.

[6] M. G. Catalano, G. Grioli, E. Farnioli, A. Serio, C. Piazza, and A. Bicchi, "Adaptive Synergies for the Design and Control of the Pisa/IIT SoftHand," *International Journal of Robotics Research*, vol. 33, no. 5, pp. 768–782, 2014.

[7] N. Fukaya, S. Toyama, T. Asfour, and R. Dillmann, "Design of the TUAT/Karlsruhe humanoid hand," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, 2000, pp. 1754–1759.

[8] G. Figliolini and P. Rea, "Ca.U.M.Ha. robotic hand (Cassino-Underactuated-Multifinger-Hand)," in *Proc. IEEE/ASME Int. Conf. Advanced Intelligent Mechatronics*, 2007, pp. 1–6.

[9] L. Birglen, T. Laliberté, and C. Gosselin, "Underactuated Robotic Hands," 44 *Springer Tracts in Advanced Robotics*, 2008.

[10] K. Yamaguchi, Y. Hirata, and K. Kosuge, "Underactuated Robot Hand for Dual-Arm Manipulation," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, 2015, pp. 2937–2942.

[11] W. Townsend, "The BarrettHand grasper –programmably flexible part handling and assembly," *Industrial Robot: An International Journal*, vol. 27, no. 3, pp. 181–188, 2000.

[12] R. Niikura, N. Kunugi, and K. Koganezawa, "Development of artificial finger using the double planetary gear system," in *Proc. IEEE/ASME Int. Conf. Advanced Intelligent Mechatronics*, 2011, pp. 481–486.

[13] K. Mitsui, R. Ozawa, and T. Kou, "An under-actuated robotic hand for multiple grasps," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, 2013, pp. 5475–5480.

[14] R. Ozawa, Y. Mishima, and Y. Hirano, "Design of a Transmission With Gear Trains for Underactuated Mechanisms," *IEEE Trans. Robot.*, vol. 32, no. 6, pp. 1399–1407, Dec. 2016.

[15] F. Y. Chen, "Gripping mechanisms for industrial robots: an overview," *Mechanism and Machine Theory*, vol. 17, no. 5, pp. 299–311, 1982.

[16] K. Yamaguchi, Y. Hirata and K. Kosuge, "Development of robot hand with suction mechanism for robust and dexterous grasping," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, 2013, pp. 5500–5505.

[17] S. Hasegawa, K. Wada, Y. Niitani, K. Okada, and M. Inaba, "A three-fingered hand with a suction gripping system for picking various objects in cluttered narrow space," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, 2017, pp. 1164–1171.

[18] N. Rojas, R. R. Ma, and A. M. Dollar, "The GR2 Gripper: An Underactuated Hand for Open-Loop In-Hand Planar Manipulation," *IEEE Trans. Robot.*, vol. 32, no. 3, pp. 763–770, Jun. 2016.

[19] A. Kakogawa, H. Nishimura, and S. Ma, "Underactuated modular finger with pull-in mechanism for a robotic gripper," in *Proc. IEEE Int. Conf. Robotics and Biomimetics*, 2016, pp. 556–561.

[20] D. Liu, S. Arai, J. Miao, J. Kinugawa, Z. Wang, and K. Kosuge, "Point Pair Feature-Based Pose Estimation with Multiple Edge Appearance Models (PPFMEAM) for Robotic Bin Picking," *Sensors*, vol. 18, no. 8, 2719, Aug. 2018.