



ReC-Gripper: A Reconfigurable Combined Suction and Fingered Gripper for Various Logistics Picking and Stowing Tasks

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Abstract—This article presents a gripper comprising finger and suction with reconfigurable attributes. With the reconfiguration feature, the proposed gripper has a configuration suitable for different working environments of logistic order picking. The finger part of the gripper was configured with the parallelogram remote center of motion (RCM) mechanism to implement reconfigurable features. With the RCM mechanism, the gripper implements the function of zeroed offset, which removes the gap between the finger and the suction gripper, and the function of the supporting finger. In order-picking tasks, the gripper shows higher grasping stability and practicality than existing grippers. First, the design of the mechanism and model constituting the gripper is described. Afterward, a quantitative evaluation of the performance of this gripper compared to the existing ones in the bin and shelf environment is conducted. In this section, the gripper shows 32.912% improved performance in representative tasks. Finally, the practical aspects of this gripper are described through a quantitative evaluation.

Index Terms—Robotic hands, Logistics grippers, mechanism design.

I. INTRODUCTION

OVER the past years, the demand for logistics automation has increased significantly [1]. Specifically, order picking involves fulfilling customer orders with a wide range of products in small quantities. Traditionally, this task heavily relied on human labor due to its requirement for high work flexibility [2]. The order picking task involves repetitive load transportation, which can lead to significant worker fatigue. Hence, there is active ongoing research focused on automating this task. For order picking automation, it is important to recognize and stably handle various types of items quickly. On the basis of manipulating goods, multidisciplinary studies on environment recognition using vision cameras, motion planning algorithms, and grippers have been proposed [3].

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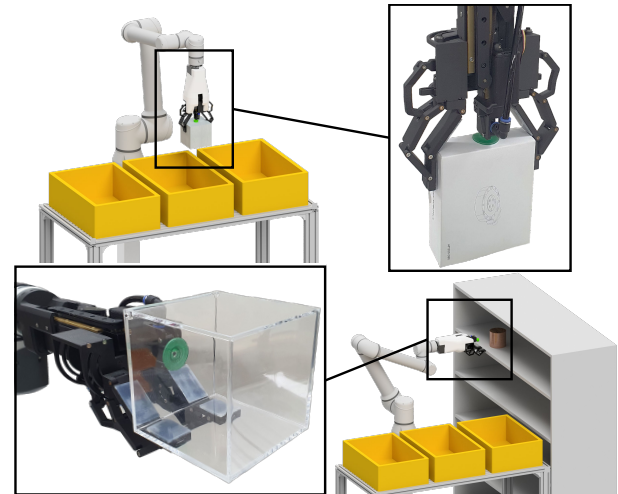


Fig. 1. Proposed ReC-Gripper which can execute picking and stowing for order picking at logistics environment.

Among these studies, the grippers are attached to the manipulator's end and handle objects like a human hand. It has a direct physical interaction with the object to be gripped and significantly impacts the productivity of order picking and handling stability.

Existing grippers are mainly categorized into suction grippers and finger-type grippers. The suction gripper grips an object through negative air pressure [4]. The advantage of suction grippers is that complex gripping mechanisms are not required, unlike finger-type grippers [5]. It can only seal and grip various objects by utilizing the compliance of the suction cup. However, the suction grippers have a common problem in that payload and grip stability are lowered depending on the contact state between the suction cup and the object. Moreover, the deformable characteristics of the suction cup cause air leakage depending on the angle between the direction of the suction and that of gravity, resulting in instability of grip. To alleviate these limitations, studies on grippers that can change the direction of the suction cup have been proposed [6], [7], [8]. These studies successfully showed that grip stability can be enhanced by changing the direction of the suction cup. However, the compliance of the suction cup still aggravates grip stability by the motion and external impacts of the manipulator. The finger-type gripper is made of a rigid or soft material and grips an object using frictional force generated

when a finger contacts an object. This feature enables the finger-type gripper to hold porous or irregular shapes that are difficult to seal or a deformable object that is vulnerable to external forces [9], [10]. In addition, the gripping method that covers the object with two or more fingers makes it possible to ensure high reliability for the gripped object. Contrary to the suction gripper, the finger-type gripper experiences a reduced success rate in grasping the object depending on the level of clutter around it [11].

Recently, integrated grippers have been developed to compensate for the disadvantages of each hardware [12], [13], [14], [15], [16], [17], [18], [19]. The integrated grippers are mainly composed of suction and a finger-type gripper. These grippers grasp an object through suction first, then bring it between the fingers, and finally assist the gripped object through the fingers. However, existing integrated grippers encounter two issues. First, they had a gap between the center of the finger-type gripper and the suction gripper. Second, the finger's capability is limited to compensate for the suction cup's deformable feature. Here, the center of the circular sealing element of the suction cup is defined as the center point of the suction gripper. The center of the contact surface of the fingertip of the closed finger is defined as the center point of the finger gripper. Even the integrated grippers having the first issue [12], [13], [14], [15] successfully showed that they can grasp many kinds of objects, but the existence of a gap between each gripper disturbs the objects from being grasped. This is because the grasping failure caused by the gap between the two grippers is greatly affected by the large or small size of the object. In addition, the grip motion of the fingers may apply a force in a direction that interferes with the grasped state of the object that the suction gripper already grasped. This lack of assistive grasping of the fingers causes the object to drop when manipulating it. Although there are other integrated grippers without the first issue [16], [17], [18], [19], they usually face the second issue when the end-effector works horizontally approaching an object. The representative works of order picking is picking or stowing goods in the bin or shelf environment [20]. The horizontal workspace is a drawback for fingers of integrated grippers in a shelf environment where items are shifted vertically, either from top to bottom or vice versa. These grippers grasped both sides of an object to prevent tilting of the object with only the frictional force of the finger gripper. However, the unexpected acceleration while manipulating the object makes it difficult to prevent the tilting of the object. In summary, the gap between the suction and finger gripper, referred to as the offset, presents a drawback in bin environments. Also, friction force-based grasping, employed by existing grippers, has limitations in shelf environments.

Therefore, this study proposes a gripper that can overcome the disadvantages of the integrated gripper mentioned above. To overcome these problems, we implement a reconfigurable feature to our gripper by using the remote center of motion (RCM) mechanism. Already some grippers showed superior performance which could grasp diverse objects by reconfiguring their finger position [21], [22]. However, in logistics, using a suction-based gripper is crucial because of its efficiency

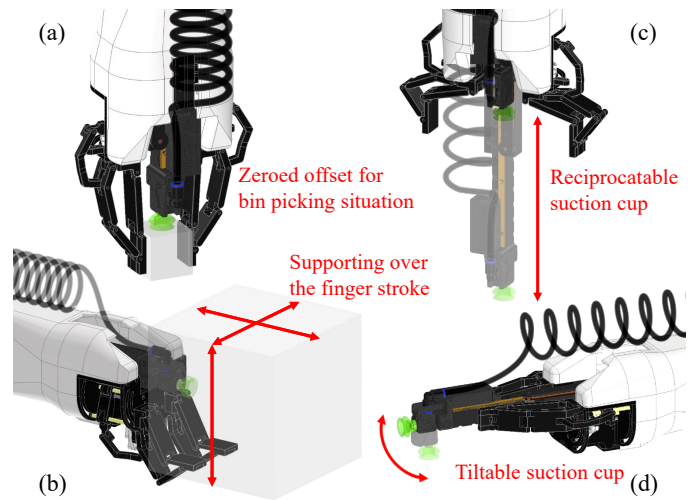


Fig. 2. Equipped several functions at the gripper. (a) Zeroed offset for bin environment, (b) Supporting finger utilized in shelf environment, (c) Suction gripper that can reciprocate, (d) Suction cup which can tilt to 90°.

when grippers approach a target object with their thin bodies.

Therefore, it is essential to integrate two types of grippers while leveraging their respective advantages. To achieve this, we introduce two key innovations: zeroed offset, which eliminates the gap between the finger and the suction gripper, and supporting finger, which provides support to the underside of an object as shown in Fig. 1. As a result of these enhancements, the gripper exhibits improved performance in both picking and stowing tasks within a logistics environment.

The key contributions of this work can be summarized as:

- With the RCM mechanism, the gripper can achieve reconfigurability, including zeroed offset and supporting fingers, allowing it to adapt to various logistic tasks.
- Through evaluation of the performance in a real-world environment, We showed that our gripper's reconfigurable ability is suitable for each environment.

II. GRIPPER DESIGN

A. Equipped Functions

As shown in Fig. 2, the following functions are used to respond to various tasks that could occur in order picking.

- Zeroed offset
- Supporting finger
- Reciprocatable suction cup
- Tiltable suction cup

Through these functions, the proposed gripper has the following advantages. a) This function eliminates the gap between the gripping point of the finger and the suction gripper. Therefore, even a thin object can be grasped by the suction with the fingers, so it has high adaptability for various-sized objects compared to existing integrated grippers. b) Through this physical ability, the finger supports the lower surface of the target object. Existing grippers grip both sides of an object when gripping the object in a shelf environment, but if the frictional force applied by the gripper is not enough, then the thing slips. The object's weight deforms the suction

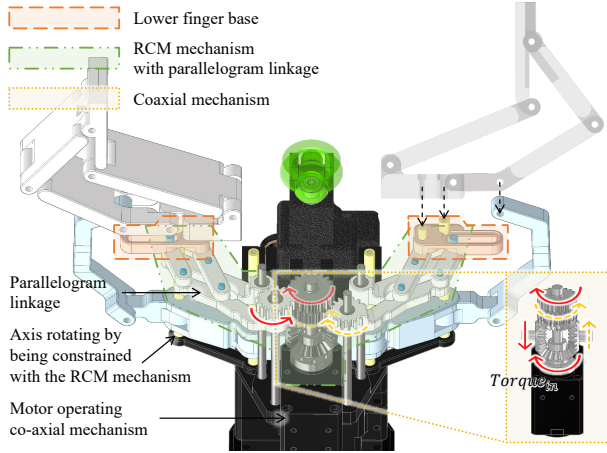


Fig. 3. The finger rotating mechanism is operated by the co-axial mechanism and the reconfigurable mechanism. This allows the fingers to rotate in opposite directions synchronously.

cup, resulting in air leakage. However, this gripper solves this problem by assisting the lower surface of the object and mechanically preventing the deformation of the suction cup. c) This feature allows the suction cup to move back and forth. Accordingly, the manipulator can use the working space more efficiently than simply using a long suction gripper. In addition, this allows the suction cup to get in tight spaces, and the extended suction prevents the finger gripper from collisions with the surrounding environment. d) This function could change the direction of the suction cup. When the suction gripper lifts an object, this function aligns the suction cup toward gravity to prevent air leaking. In addition, if the posture or surface of the object recognized by the vision camera is impossible to grip, existing grippers change the target object or rarely topple the object. However, by adjusting the angle of the suction cup, it is possible to access grasping points that are difficult to access with conventional grippers.

B. Detailed Design

This gripper was developed using one multi-stage prismatic joint module of the gripper used in the following study [23]. The mechanism can reciprocate a length of 250 mm and this part is used as a suction gripper. As shown in Fig. 3, the part that adjusts the finger's position or drives the grasp is located at the bottom of the suction gripper. The finger gripper uses the parallelogram RCM mechanism to rotate fingers. According to Fig. 4, the finger is attached to points G and H contained in the lower finger base, and the angle of θ_{output} which is the resultant angle of the finger varies as θ_{input} changed. The value of θ_{input} is controlled by the co-axial mechanism with the motor, resulting in two opposite directions of rotation on both sides. θ_{output} is calculated as follows: l_{DG} , l_{EG} , l_{ED} , which are the length of the linkage that joins each point. θ_{output} could be easily controlled because it has a constant linkage size and is related to θ_{input} .

$$\theta_{output} = \cos^{-1} \left(\frac{l_{EG}^2 + l_{DG}^2 - l_{ED}^2}{2l_{DG}l_{EG}} \right) - \phi_f \quad (1)$$

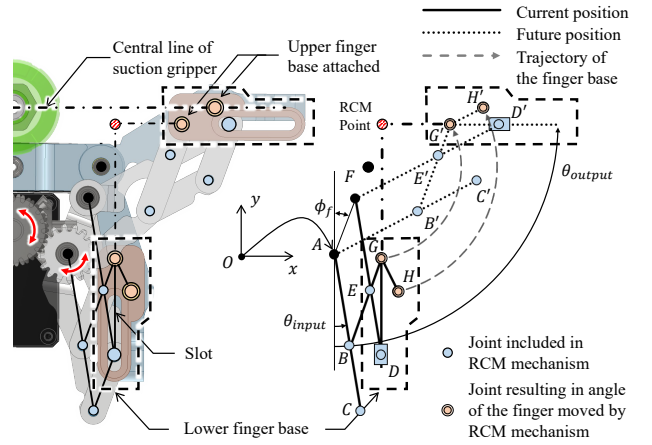


Fig. 4. Movement of linkages that rotate lower finger base to reconfigure gripper structure. The torque provided by the co-axial mechanism rotates the finger base from below to the side of the suction.

TABLE I
SIZES OF LINKS CONSISTING RECONFIGURABLE MECHANISM

ϕ_f	l_{AB}	l_{AC}	l_{AF}	l_{EG}	$d_{H/DG}$	d_{GH_y}
20 [°]	28 [mm]	48 [mm]	18 [mm]	10 [mm]	5 [mm]	10 [mm]

$$l_{DG} = \sqrt{l_{EG}^2 + l_{ED}^2 - 2l_{EG}l_{ED} \cos(\pi - (\phi_f + \theta_{input}))} \quad (2)$$

When the fingers are located on both sides of the suction gripper, the zeroed offset is satisfied. The center of the finger, which is point H' , is located on the same line as the central line of the suction gripper. According to Fig. 4, the lower finger base rotates to both sides of the suction gripper based on the RCM point. we define d_s as the distance between the suction line from point A , and $d_{H/DG}$ as the physical distance between point H from the line DG , which is same as $d_{H'/D'G'}$.

$$d_s = H' = RCM_y + d_{H'/D'G'} \quad (3)$$

The position of y of RCM point is calculated as follows: ϕ_f is the angle between axis y and line AF .

$$RCM_y = l_{A-RCM} \sin\left(\frac{\pi}{2} - \phi_f\right) \quad (4)$$

l_{A-RCM} follow the triangle proportionality theorem. we define each length as follows: l_{A-RCM} , l_{AC} , l_{BC} , l_{EG} , and l_{AF} denote the length of each linkage connecting each point. θ_{input_B} is the angle of θ_{input} when the fingers are located at both sides of the suction gripper. Table I presents the size of each linkage constructing the RCM mechanism.

$$l_{A-RCM} = \frac{l_{AC}}{l_{BC}} l_{EG} + l_{AF} \quad (5)$$

The gripper configuration suitable for the shelf environment is that the fingers rotate downward to support the lower surface of the object. An object standing on a shelf is gripped by suction at the center of the volume and supported by fingers at the bottom. During this process, the fingers are positioned lower, so the greater the distance between the fingers and the suction cup, the larger the object can be held. The RCM mechanism increases the distance and it can be calculated as follows. we

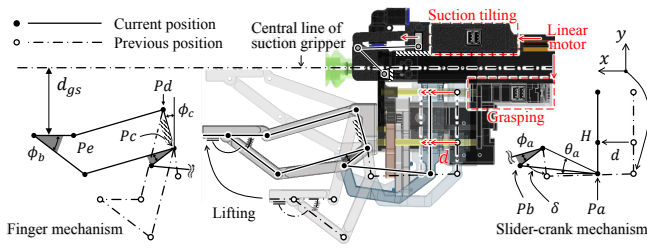


Fig. 5. The grasping and suction tilting mechanism. This allows the finger to match the d_{gs} between the center and the lower side of the object.

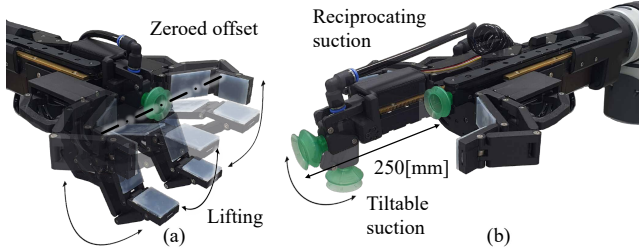


Fig. 6. (a) Reconfigurable gripper and grasping and lifting motion, (b) Features of suction gripper.

define d_{S-H} as the distance between point H from the central line of the suction gripper and d_{GH_y} as the distance of point G and H in the y direction.

$$d_{S-H} = -G_y + RCM_y + d_{GH_y} + d_{H/DG} \quad (6)$$

Following the above equations, the gripper can enlarge the distance between the fingers and the suction cup. As the fingers are located below, the ability to grasp is changed to the ability to adjust the distance between the suction cup and the finger. As Fig. 5, the finger's movement is implemented by a linear motor and slider-crank mechanism. Accordingly, the distance can be adjusted according to the object's size. We define the distance as d_{gs} and the grasping size, d_{H-P_a} is the distance between points H and P_a , and d_{S-H} is already calculated at (6). d_{gs} could also be used to control the gripper stroke.

$$d_{gs} = d_{S-H} + d_{H-P_a} - P_{ey} \quad (7)$$

P_{ey} is the position of y of P_e and can be calculated as follows: $l_{P_a P_e}$ is the length of each linkage that joins each point and δ is shown in Fig. 5.

$$P_{ey} = P_{dy} - l_{P_a P_e} \cos(\delta + \phi_a) \quad (8)$$

δ can be calculated as follows: P_{cy} is the position of y of P_c , P_{cx} and P_{ax} are position of x of each points.

$$\delta = \tan^{-1} \left(\frac{P_{cy}}{P_{cx} - P_{ax}} \right) \quad (9)$$

Accordingly, the gripper can adjust the grasp size and support the object mechanically using a non-backdrivable linear motor. Tiltable suction is implemented to be adjusted according to the angle of the crank in the slider-crank mechanism. Therefore, the gripper implements the four required functions mentioned above in the configuration as shown in Fig. 6. In total, the gripper force range is 5N–20N, the finger's friction coefficient is 0.45, and the gripper stroke is 180mm.

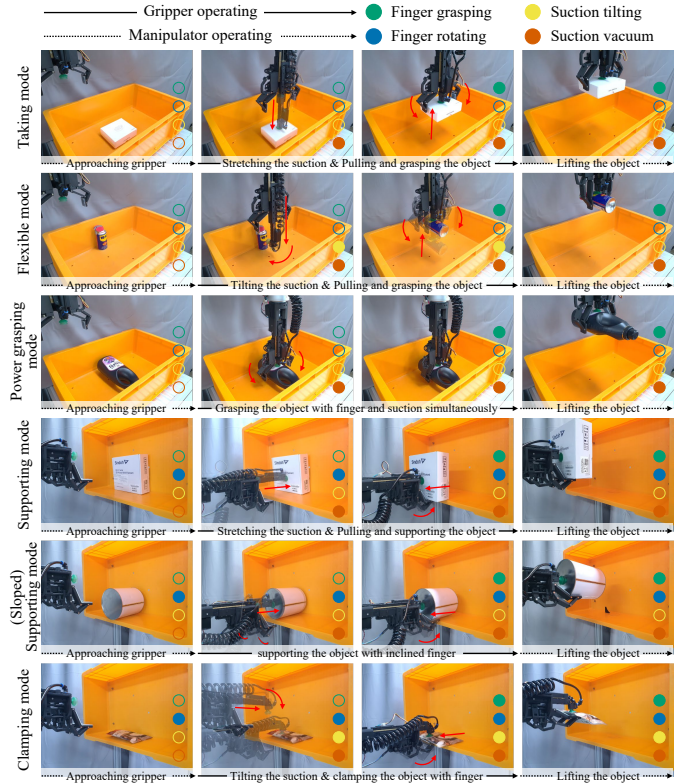


Fig. 7. Five types of the grasp method and sloped supporting method were carried out by combining four kinds of functions. Four colored circles mean that a filled interior indicates that the corresponding function is active, and vice versa when it is frame-only.

III. GRASP METHOD

As shown in Fig. 7, this gripper implements various grasp modes through the design presented in Section II. The first is the Taking mode which can be used in bin and shelf environments. The object is gripped through suction, then brought between the fingers, and assisted grasping is performed using the fingers. With zeroed offset, the proposed gripper utilizes the finger gripper with a suction gripper. The second is a supporting mode, which complements the deformable characteristics of existing suction grippers in the shelf environment. Through the rotation of the fingers implemented using the RCM mechanism, the gripper can support the lower surface of the object. Additionally, since the angle of the finger is controlled according to the θ_{output} , the cylindrical objects can be gripped by determining the finger angle suitable for them. The third is the flexible mode, which is used to avoid excessive movement of the manipulator when the grasping point of suction is not detected on the upper surface of the object. For example, when a thin object is standing in a bin, conventional suction grippers and manipulators move excessively to grab the object. However, as shown in Fig. 7, this gripper can grip the object by rotating the suction cup. The fourth is the clamping mode, which is a grasp method using all the functions of this gripper. This lets the gripper grip an object by rotating the suction tip and the finger base. It is mainly useful for holding thin and wide objects and wide objects such as plastic packs. First, the gripper draws the objects through suction and then

TABLE II
EXPERIMENTAL CONDITION FOR SHAKING IN SHELF ENVIRONMENT

Experimental object	Grasp method	Frequency of shaking	Shaking degree	Maximum speed
Box & Cylinder ($d = 100\text{mm}$, $W = 1\text{kg}$)	- Previous - Supporting	1 [Hz]	± 15 [$^\circ$]	0.46 [m/s]

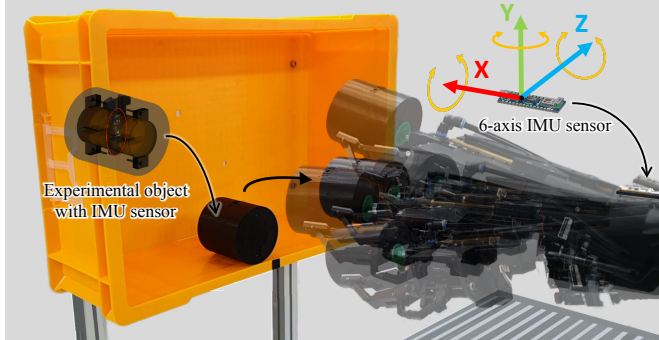


Fig. 8. Experiment environment to evaluate grasping stability at the shelf.

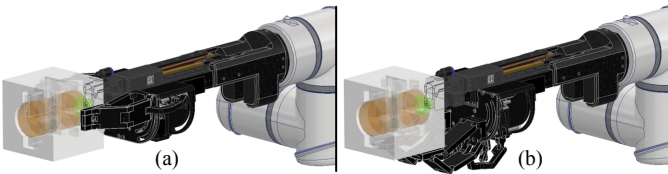


Fig. 9. Grasping pose of the gripper according to (a) previous grasp mode, (b) supporting grasp mode.

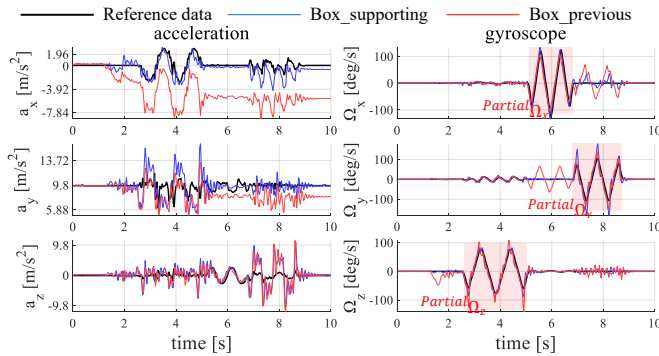


Fig. 10. Measured data with two types of grasp mode and reference data.

grips them by biting them with its fingers. The last is the power grasping mode, which can grasp objects that are heavy to lift in taking mode. Unlike the taking mode, which draws an object through suction, it moves the object after catching it by operating both the suction and finger gripper. When several objects are mixed in the bin, light items are quickly moved by the taking mode, and then heavy objects are grasped through the corresponding method when space for the finger to access is secured. As a result, the power grasping mode is algorithmically selected last.

IV. EXPERIMENTS

The gripper's ability is confirmed through cooperative work with a manipulator that pretends order picking. First, a

TABLE III
COMPARISON OF STABILITY ACCORDING TO THE GRASP METHODS

Target object	Box		Cylinder		Box		Cylinder	
Grasp method	Previous		Supporting		Supporting		Supporting (sloped)	
Unit	RMSE	Partial RMSE	RMSE	Partial [%]	RMSE	Partial [%]	RMSE	Partial [%]
a_x	0.493	-	0.109	-77.880	-	0.097	-80.316	-
a_y	0.188	-	0.164	-12.616	-	0.148	-21.090	-
a_z	0.257	-	0.261	1.574	-	0.225	-12.573	-
Ω_x	19.564	31.303	11.076	-43.385	-25.788	9.823	-49.792	-42.495
Ω_y	19.288	29.622	15.387	-20.224	11.544	8.743	-54.668	-37.687
Ω_z	13.961	20.490	7.838	-43.860	-32.912	8.101	-41.976	-33.065
Tilted angle [$^\circ$]	-36.394	-	-5.203	-85.701	-	-4.132	-88.644	-

quantitative evaluation method proves the grasping stability of the proposed gripper compared to existing grippers. Afterward, a qualitative evaluation presents the possibility of using the gripper in an actual order picking environment. In these evaluations, we manually operate the manipulator to ensure consistent grasping size and position of the subject and manipulator, while setting the manipulator's velocity and acceleration to maximum.

A. Quantitative Evaluation

The proposed gripper is used for picking and stowing work in the bin and shelf environment of order picking. The ability required for each task is to move the object stably without dropping and tilting it in the bin and shelf environment.

1) *Shelf Environment*: In a shelf environment, grippers change an object's position vertically from top to bottom or vice versa. Therefore, it is essential for the proposed gripper to confirm how objects are grasped stably. As shown in Fig. 8, the gripper grasps a subject on the shelf and brings it out to open space to avoid collision with the surrounding environment. Then, the manipulator shakes $\pm 15^\circ$ according to the end-effector's xyz -axis. The suction gripper exerts 25N and the finger exerts 10N on the subject, eliminating even small gaps between the finger and the subject. The 6-axis inertial measurement unit (IMU) sensor is inserted in the subject, measuring the subject's states such as oscillation and tilted angle and it is defined as measured data. The same sensor is attached to the manipulator whose data plays the role of reference data. As shown in Fig. 9, the gripper changes its shape and grabs and shakes the subject with the two methods, which are Fig. 9(a) the previous method used by the existing gripper, and Fig. 9(b) the proposed supporting method.

As shown in Table II, the test subjects are sorted into a box-shaped object and a cylinder-shaped one whose size is $100 \times 100 \times 100 \text{mm}^3$ ($w \times d \times h$) and weight is 1kg. The data from the sensors are plotted in Fig. 10. These results suggest that if the shaking or tilting of the gripped subject was less, it would represent a small difference between the reference data and the measured data, and it means that the subject is stably grasped. The summary of the experiment is that the previous method cannot prevent the subject from tilting while shaking the grasped box. Conversely, the supporting mode can quietly prevent the subject from tilting. In the case of grasping a cylindrical subject, even the previous grasp method drops the subject. To compare the difference of data from Fig. 10 in overall duration, we use the root mean squared error (RMSE)

TABLE IV
EXPERIMENTAL CONDITION FOR SHAKING IN BIN ENVIRONMENT

Experimental object	Grasping method	offset size [mm]	Shaking degree	Maximum speed
Box & Cylinder (d = 100mm, W = 1kg)	- Aligned	0, 25, 50, 75	± 15 [°]	0.46 [m/s]
	- Unaligned			

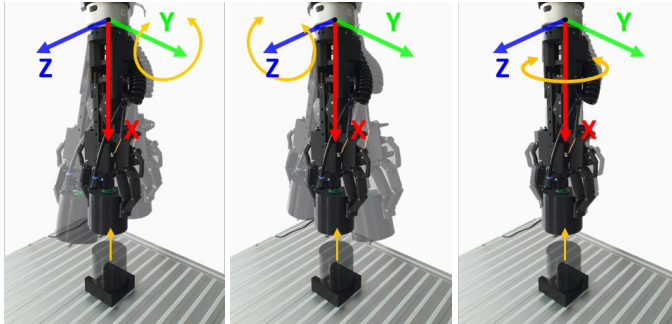


Fig. 11. Experiment environment to evaluate grasping stability at the bin.

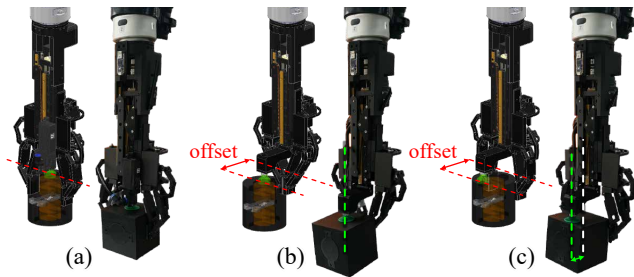


Fig. 12. Grasp method according to offset type of gripper (a) aligned grasping of the proposed gripper, (b) aligned grasping of previous grippers, (c) unaligned grasping of previous grippers.

value between the two data and these are summarized in Table III.

The table expresses the calculated values of the proposed supporting method as a percentage compared to the existing method. RMSE values of a_x , a_y , and a_z are used to calculate the degree of tilted angle during shaking. In particular, RMSE values of Ω_x , Ω_y , and Ω_z show the gyroscope value relative to each axis, and the small value of those means that the selected method could grasp the subject stably with small oscillation.

In particular, their partial values focus only on a short period of time when the manipulator is shaken in each axis and represent the values measured during that time. Consequently, RMSE values about the gyroscope of the supporting method show a more stable grasp on every axis during a long duration. Although the partial RMSE for Ω_y of the supporting method indicates a weakness concerning y-direction shaking, it is important to note that many tasks in a shelf environment involve vertical operations. In terms of grasp stability during vertical operations, Ω_z demonstrates a notable improvement of 32.912%. Experiments confirm how well the supporting method prevents unexpected acceleration by the motion in shelf order picking.

2) *Bin Environment*: The gripper moves an object in a vertical pose at the bin environment, as shown in Fig. 11. To describe the situation of order picking, the gripper grasps

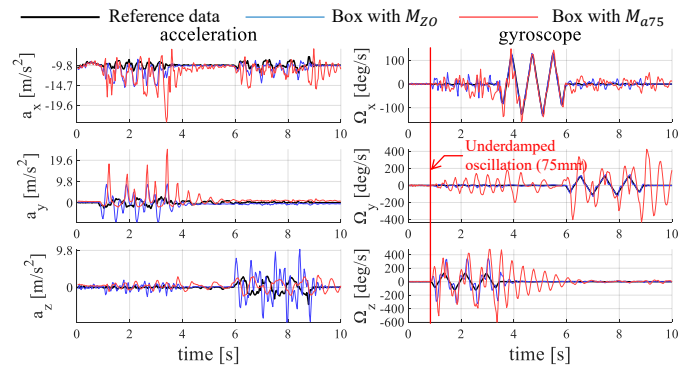


Fig. 13. Measured data with two types of grasp mode and reference data.

the object by taking mode. After grasping the object, the manipulator shakes $\pm 15^\circ$ relative to the end-effector's xyz -axis, just like the experiment implemented at the shelf. Likewise, data from sensors are classified into measured and reference data. To compare the proposed gripper with existing ones, the suction cup could be replaced with the modified part that makes the gripper get the offset. Consequently, we can conduct experiments under conditions imitating various offsets found in existing grippers.

When an offset exists at the gripper, grasp methods can be divided into two cases. One is aligning the suction cup with the center of the object as shown in Fig. 12(b), and the other case is matching the middle of the suction cup and the finger with the center of the object as shown in Fig. 12(c). The first case has the advantage that the suction cup does not deform when the object is lifted through the suction gripper because the location of the suction cup and gravity are aligned. However, auxiliary grasping of the finger for small objects is impossible due to the distance between the fingers and the suction cup. Conversely, the second case can hold smaller objects than the first case, but it can not prevent the deforming of the suction cup when the object is brought upward through the suction gripper. The first case is named aligned grasping and the other case is named unaligned grasping. As shown in Table IV, such as the experiment in the shelf environment, there are two experimental subjects. The offset size was varied with values of 0mm, 25mm, 50mm, and 75mm.

To explain the result of the experiment simply, we will address grasping objects with zeroed offset method as M_{Z0} , which is shown in Fig. 12(a), and grasping objects in an aligned method with an offset of 50mm as M_{a50} and unaligned method with an offset of 75mm as M_{un75} . And other things also follow these rules. This experiment also compares the RMSE values between reference and measured data for all cases in Table V. On the relative of the RMSE values calculated with M_{Z0} , better results are indicated in blue, and worse results are indicated in red. First, the grasp methods of the zeroed offset and the aligned grasp cases are compared. Both M_{Z0} and M_{a50} exhibit similar results when the subject is a box. However, in all the cases of a cylinder, it is evident that M_{Z0} provides greater stability. When the size of the offset is larger than M_{a50} , it can be observed that the grasping stability is very poor. Therefore, it can be confirmed that the grasping

TABLE V
COMPARISON OF STABILITY ACCORDING TO THE TESTED GRASP METHODS

Offset	0 [mm]		25 [mm]				50 [mm]				75 [mm]			
Target object	Box	Cylinder	Box		Cylinder		Box		Cylinder		Box		Cylinder	
Grasping method	Aligned	Aligned	Aligned	Unaligned	Aligned	Unaligned	Aligned	Unaligned	Aligned	Unaligned	Aligned	Unaligned	Aligned	Unaligned
unit	RMSE		Comparing with zeroed offset [%]											
a_x	0.141	0.136	-0.928	-16.379	2.436	-9.064	-3.089	-25.301	26.567	10.063	97.818	Dropped	Dropped	92.541
a_y	0.300	0.261	14.087	20.127	10.012	23.013	9.267	35.141	7.942	57.764	20.884			26.493
a_z	0.280	0.276	-4.653	-1.938	-13.601	-6.967	-4.764	-4.260	-34.366	-42.028	-37.544			-35.354
Ω_x	10.012	19.346	13.488	-32.497	-12.819	-10.925	27.414	-23.462	-25.105	14.802	117.220			11.937
Ω_y	10.093	12.814	14.487	-1.158	70.652	23.707	9.532	5.679	582.280	749.939	1111.123			833.369
Ω_z	63.022	64.065	-53.021	-54.513	2.673	1.154	-63.577	-72.788	23.590	88.586	115.339			92.431
$slope_{mit}$ [°]	-1.499	-0.967	97.152	513.525	186.179	908.129	81.877	1004.930	534.179	1480.256	170.477	125.093		
$\Delta slope$ [°]	-4.063	0.935	35.845	-25.821	525.080	232.110	-46.881	-20.114	-379.229	428.021	-113.803	-62.290		

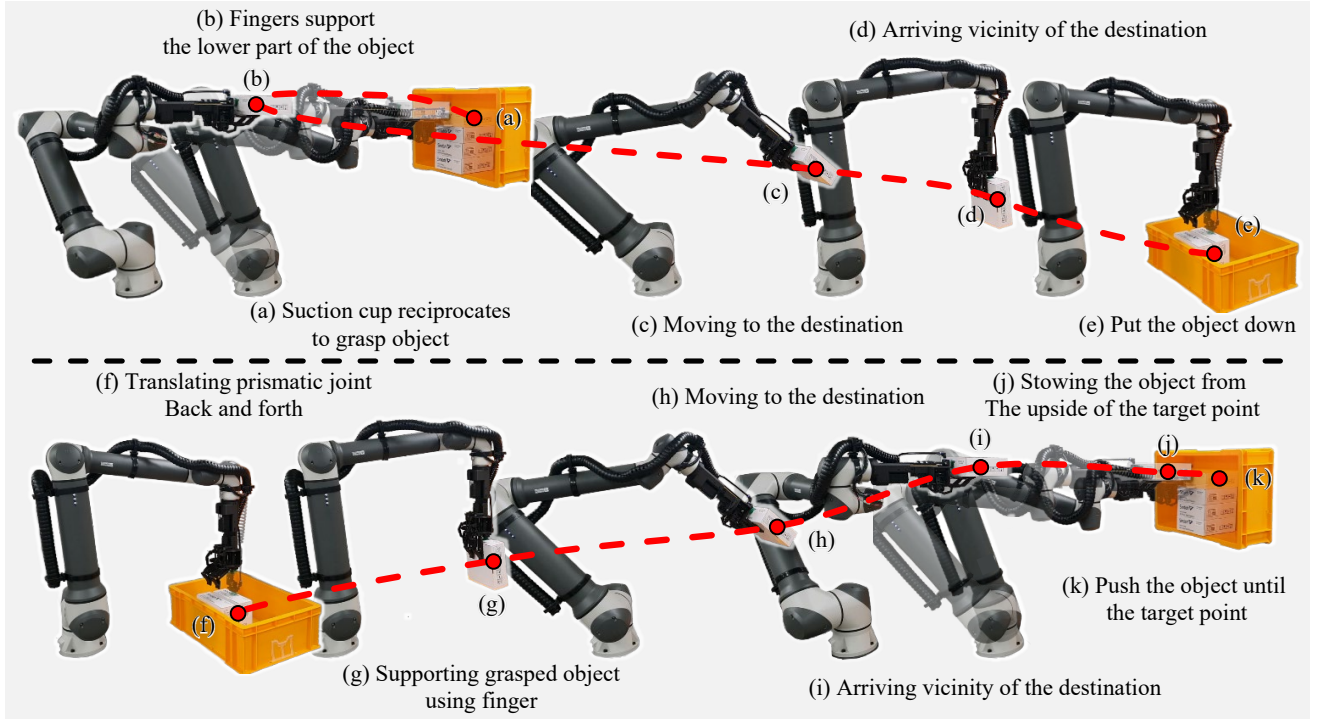


Fig. 14. Two tasks at logistic shelf environments to verify the practicality of grippers. Reliable movement of the object whose size is beyond the gripper's stroke from top to bottom and from bottom to top with less oscillation and tilting.

stability is lower than the M_{ZO} when the offset is larger than half the size of the object and the cylindrical object is gripped. Next, check the unaligned grasp case. It can be confirmed that M_{un50} is helpful for stable grasping when grasping the box. Conversely, the stability is seen to be further deteriorated when grasping the cylinder. Even when the size of the offset exceeds M_{un50} , both the box and cylinder drop during shaking. These drawbacks are totally revealed in Fig. 13, the measured data of shaking the box with M_{ZO} and with M_{un75} is expressed. The biased finger could interfere with the grasping, even though its purpose was to perform auxiliary grasping. Furthermore, if the size of the offset exceeded 50mm, the grasped object oscillated in an under-damped motion because the finger couldn't reach the subject, as shown in the grasping box in M_{a75} in Fig. 13.

Overall, it can be proved that the grasping stability is greatly affected by the presence of the offset and shape of the target object. While the existing method might yield favorable results in certain limited cases, it is essential to highlight that consistent performance was frequently observed with M_{ZO} in

a wide range of scenarios. In conclusion, opting for a gripper without an offset proves advantageous for achieving consistent performance in order picking, especially when dealing with diverse items.

B. Qualitative Evaluation

In this section, we evaluate the gripper's ability by imitating the tasks required for order picking. As highlighted in the qualitative evaluation, the main issue with existing grippers is the deformation of the suction cup. Therefore, this gripper performs the picking and stowing tasks in the shelf environment and shows practical ability compared to existing grippers. The gripper picks and stows objects mainly using the supporting fingers whose excellence has been verified in an advanced shelf experiment. The size of the subject is $200 \times 200 \times 50 \text{ mm}^3$ (wxdxh), which exceeds the finger stroke. The upper part of Fig. 14 is the picking task. As shown in Fig. 14(a), the gripper grasps the object using suction, pulling it over the

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finger. Simultaneously, the finger adjusts its distance from the suction cup based on the object's position. Then, as in Fig. 14(b), the lower part of the object is supported, and the object is moved to the destination in the process of Figs. 14(c) and (d). Even when the subject is rotated 90°, deformation of the suction cup is prevented because the lower surface is supported. Once it reaches the destination, the goods would be put down slowly to complete the picking task. Next is the stowing task, which is performed in the opposite order to the picking task. After gripping the object located at a lower position in the environment using suction, as shown in Fig. 14(f), the lower surface of the subject is supported as in Fig. 14(g). The supporting finger prevents the suction cup from deformation in the same way, the subject can be rotated 90° and moved as shown in Figs. 14(h) and (i). When reaching the destination, the object is put down the object from above, as shown in Fig. 14(j), and the suction gripper pushes the object. If we used the grasp method of existing grippers, a collision could occur in the process Figs. 14(j) and (k), because it is hard for existing grippers to prevent the subject from tilting. However, as shown in this experiment, the proposed gripper can prevent the subject from tilting using the supporting method. Therefore, it is confirmed that the proposed gripper outperforms the existing grippers and supporting fingers are suitable in the shelf environment.

V. CONCLUSION AND FUTURE WORK

This study introduced a new reconfigurable integrated suction and fingered gripper. The proposed gripper has configurations suitable for order picking by applying the RCM mechanism to the fingers. In the shelf environment, a feature called a supporting finger supports the object by supplementing the deformable suction cup. In the bin environment, grasping stability is improved by applying a feature called zeroed offset that eliminates the gap between the suction cup and the finger. The performance of the gripper compared to existing grippers was quantitatively evaluated through experiments in the bin and shelf environments. Especially in the shelf environment, picking and stowing operations were performed, showing superior performance compared to existing grippers. The main reason for these results is the finger's ability to reconfigure and supplement the suction gripper's performance through supporting finger and zeroed offset, thus maximizing overall efficiency. For future work, the mechanically passive mechanism will be considered for the gripper's finger to enhance the ability to adapt to various shaped objects [24], [25]. We plan to implement grasping strategies that can utilize the four functions of the proposed gripper using a vision sensor and a learning-based method for various automatic grasping.

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