Sheet-based gripper featuring passive pull-in functionality for bin picking and for picking up thin flexible objects

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***Abstract*— This paper presents a novel versatile parallel gripper equipped with a sheet-embedded belt that enables passive pull-in operations. The belt is wrapped around each fingertip of the gripper, and it passively moves with the opening and closing motions of the gripper. The fingertip is made of plastic, and it is deflected when a grasping force is applied to the fingertip. This deflection enables the belt to roll up with the closing motion of the gripper, thereby passively pulling the grasped workpiece towards the gripper. This pull-in mechanism is effective in performing bin-picking tasks as well as in picking up thin, flexible objects one at a time. The softness of the sheet-embedded belt surface provides high adaptability to the shape of the object; therefore, many kinds of workpieces can be picked up. The effectiveness of the proposed gripper is experimentally demonstrated in this study.**

***Index Terms*— Gripper, soft robotics, grasping, bin picking, flexible objects.**

I. INTRODUCTION

GRIPPERS are widely used as end effectors in industrial robots and are commonly specialized to operate on a single target or perform a single task. However, the demand for high-mix–low-volume production has been increasing recently [1]. If a gripper is specialized for a single target, it must be changed based on the task at hand. Multiple grippers have to be prepared, and the time required to change the gripper reduces the efficiency of work. This can increase the total cost incurred. In this context, the development of versatile grippers that can handle many kinds of workpieces is required.

Bin picking is among the manufacturing operations considered difficult to automate [1]. This is because for grasping, stacked workpieces are unstable in comparison with the workpieces that lay flat on the table. When grasping a target workpiece from a stack of workpieces using a parallel gripper, the workpieces surrounding the target interfere with the fingertip of the gripper; thus, the fingertip often fails to make contact with the target workpiece at an appropriate position to pick it up. Therefore, sophisticated strategies are required to identify objects that can be picked up [2]–[7]. However, this software-based solution has limitations; sometimes, the system may fail to identify an object that can be picked up. An interference indicates that the contact area is limited and that a pull-in operation (Fig. 1) is required. If the target workpiece is pulled towards the gripper, it can be grasped at an appropriate position. A supporting surface such as a table cannot be used during a pull-in operation because bin picking is conducted in an environment where the targets are stacked in bulk. The easiest method of realizing the pull-in operation for bin picking involves the use of suction grippers because the suction operation corresponds to the pull-in operation. Only the suction area is required for picking up an object; thus, suction grippers can work even if the contact area is limited. However, for suction, the surface of the target is required to be smooth. In addition, if the target workpiece has a hole in it, the sufficient pressure required for suction cannot be applied to the target. Hence, the types of workpieces for which suction can be used by the gripper are limited. When suction is used on small or thin flexible objects in an environment where the objects are stacked in a bulk, the gripper can inadvertently affect multiple objects. Multiple-object picking is not desirable during bin picking, which involves the picking up of objects one at a time. Flexible objects can be damaged if the pressure is too high and the gripper is activated unexpectedly. A suction gripper is not suitable in such cases. If there is a parallel gripper that can grasp a target workpiece even if the contact area is small, bin picking and the corresponding grasp planning shall become easier.

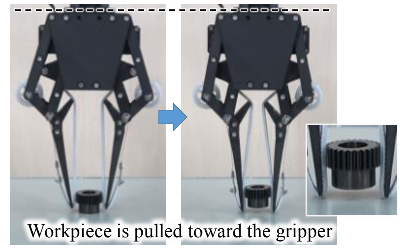

Fig. 1 Pull-in operation with the gripper developed in this study

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Considering these problems, this study proposes a novel versatile parallel gripper, equipped with a sheet-embedded belt, that enables the pull-in operation and effectively performs bin picking. The features of the proposed gripper are summarized as follows:

Passive workpiece pull-in mechanism: The fingertips of the proposed gripper are wrapped with a sheet-embedded belt that moves passively with the opening and closing motions of the grippers. The fingertips are made of plastic and deflect when a grasping force is applied. This deflection enables the belt to be rolled up with the closing motion of the gripper; thus, the grasped workpiece is passively pulled towards the gripper. Owing to this mechanism, the workpiece is pulled in with a contact area and a grasping position that are suitable for stable gripping; this is ensured even if only a part of the workpiece can be reached during bin picking.

Picking of flexible thin objects: The passive workpiece pull-in mechanism allows flexible thin objects such as paper or a cloth stacked in a bulk, to be picked up one at a time. This is possible when the top of the object comes in contact with the edges of the fingertips and the former is pulled towards the gripper by the pull-in operation.

Picking up workpieces of various shapes: The softness of the sheet-embedded belt provides high adaptability to the shape of the workpiece; thus, workpieces with different kinds of shapes can be picked up.

Reduction of the interference from surrounding workpieces: By adopting a parallel link mechanism for the opening and closing operations, the fingers can be inserted diagonally into the gap between a target and the surrounding workpieces. Therefore, the grasping operation can be performed with minimal obstruction due to the surrounding workpieces or obstacles.

A. Related works

Many types of grippers have been developed; these include prismatically shaped grippers [8], grippers with a food shaping function [9], human-synergy-based underactuated robotic hands [10], jamming grippers [11], grippers with variable-friction surfaces [12], modular open-source robotic hands [13], and suction-enabled robotic hands [14]. Recently, soft materials have been utilized to improve the grasping stability by using elastic deformation to adapt to the shape of the target object, as surveyed in [15], [16]. The examples include a gripper with a snake-like function [17], a robot hand with a squid- or starfish-like function [18], deformable fingertips filled with fluid [19], and an underactuated gripper with deformable fingertips and ratchet mechanism at the joints [20]. The advantage of soft touch was utilized for grasping soft and fragile objects [21], whereas the drawback of low load capacity was improved by introducing rigid components into the inside of the soft bodies [22]. Some grippers use a silicone sheet in the area that makes contact with the workpiece. Furuta et al. [23] developed a gripper with a high gripping power and versatility by attaching a silicone sheet to a two-link finger with a built-in torsion spring and passively changing the shape of the sheet. However, a pull-in operation is not possible, and the system is wide, which is not ideal for operation in a bulk environment. Grippers, with drivable belts on their fingertips, have been developed to enhance the dexterity of in-hand manipulation [24]–[26]. However, the belts used in this study are rigid, and adapting to the shape of the target object using soft materials was not considered. Tincani et al. [24] presented an underactuated robot hand with an active surface and demonstrated how the active surface can enhance the dexterity. Ma et al. [25] attached a drivable belt to one finger, whereas a multi-DOF (degree of freedom) finger was utilized as the other finger to perform primitive in-hand manipulations with a supporting surface (a table). The pull-in operation was included as one of the primitives, and its importance was demonstrated. Kakogawa et al. [26] developed a gripper that could passively switch between grasping and pull-in operations with a single actuator using a differential mechanism. The gripper could grasp thin flexible objects, but they were required to be pushed against a supporting surface, such as a table, with a force large enough to enable the pull-in operation. Therefore, it is difficult to use this approach for bin picking. Different from these belt-based structures, fin-ray structures [27] can perform the pull-in operation through the finger deflection activated by the contact with objects on the middle area in the finger. However, the structure is not suitable for bin picking because bin picking requires the grasping operation with small contact areas (only utilizing fingertips), whereas the activation of deflection requires contact with the middle area of the finger. The underactuated gripper [20] can also perform the pull-in operation; however, a contact with the supporting surface is required to enable the pull-in. Furthermore, owing to its large size, it cannot operate in a narrow space. Hence, the gripper is also not suitable for bin picking. A detailed comparison is presented in Table I. Considering these issues, this study presents a passively moving surface that enables the pull-in operation that can be used for bin picking. In addition, grasping thin flexible objects without the help of a supporting surface is demonstrated.

The passive pull-in mechanism has several advantages over the active pull-in mechanism. The number of actuators is minimized, and thus, the cost and size of the gripper are also reduced. Consequently, the structure of the gripper is simplified, and the fabrication is facilitated. The payload for a robotic arm and the effort required to control the gripper are also reduced. To the best of our knowledge, no study has developed a gripper mechanism for bin-picking yet. Therefore, this study is aimed at achieving this target.

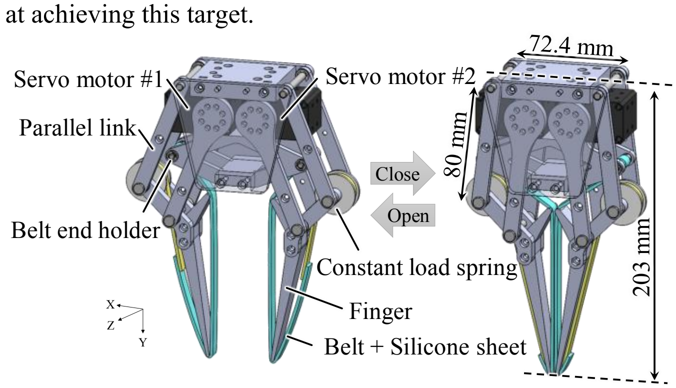

Fig. 2 CAD model of the developed gripper

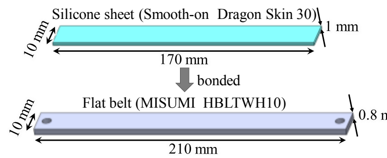

Fig. 3 Structure of the sheet-embedded belt

II. Sheet-Based Gripper with Passive Pull-in Function

A. Functional requirements

1. The gripper can perform a pull-in operation that passively works without the help of a supporting surface.
2. The finger is thin enough to be inserted in the gap between the target and the surrounding objects.
3. Differently shaped workpieces (with a width of 90 mm or less) and thin flexible objects can be grasped.
4. There is a minimal number of actuators.

As mentioned above, a pull-in operation that can be performed without a supporting surface is important for bin picking. In bin picking, the target and the surrounding workpieces can interfere with each other; thus, the surrounding pieces must be pushed aside when picking up objects. Inserting the finger in a gap around the target is necessary. Here, we focus on relatively small parts and enhance the versatility of bin picking by setting a requirement (3). For a low cost, convenient control and fabrication, and further applications, the structure of the gripper must be simple, and the number of actuators used must be minimized. Here, we assume that the actuators shall be used only for the opening and closing motions.

B. Design of the gripper

Fig. 2 illustrates the CAD model of the developed gripper. To reduce the transmission parts, two servo motors (Dynamixel XM430-W350-R) that operate synchronously were installed to perform the opening and closing motions. The parallel link mechanism was also adopted to ensure that the pull-in operation is passively driven by these motions. The two fingers of the gripper are fixed to the mechanism; therefore, the fingers diagonally approach the target and the surrounding workpieces. For the pull-in operation, the sheet-embedded belt structure is attached to the gripper so that the former can be wrapped around the latter. The sheet-embedded belt establishes a contact surface with the workpieces. Fig 3 illustrates the sheet-embedded belt structure. It is constructed by bonding the silicone sheet (Smooth-on Dragon Skin 30, thickness: 1 mm, width: 10 mm) on a non-stretchable belt (Misumi HBLTWH10). One end of the sheet-embedded belt was attached to the belt end holder, whereas the other was connected to the constant load spring (Accurate CR-5: 5.88 N, width: 8 mm) to control the belt tension constant irrespective of the width of the gripper opening. The belt end holder was fixed to the base of the gripper, whereas the constant load spring was fixed to the joint. The guides were installed at the top and bottom of the finger (corresponding to the tip) so that the sheet-embedded belt could move along the finger without protruding from the finger area. The links and fingers were 3D printed (Markforged Mark Two).

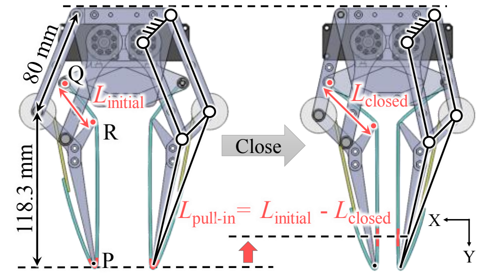

Fig. 4 Pull-in amount based on the closing motion of the gripper—This is the foundation of the principle of the passive pull-in function.

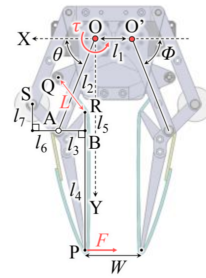

Fig. 5 Nomenclature for the gripper

III. Passive Pull-in Mechanism

A. Design

Fig. 4 demonstrates the principle of the pull-in mechanism. Let P, Q, R, and S be the tip position of the finger, the point of the belt end holder, the point of the top of the finger, and the position of the constant load spring, respectively. The length QR increases with the closing motion. The sheet-embedded belt is pulled upwards relative to the finger by the change in length $L_{pull-in}$; thus, the belt is pulled in towards the base of the gripper. In this case, the constant load spring stretches by a value $L_{pull-in}$. In addition to this mechanism, fingertip deflection plays an important role in realizing the pull-in operation. If all the components of the gripper are rigid, the pull in of the sheet-embedded belt stops when a rigid object comes in contact with the finger at the fingertip (point P). In contrast, if the finger is elastic, the fingertip is deflected according to the force exerted at the tip. Then, the sheet-embedded belt is pulled in by an amount corresponding to the amount of the deflection. In this study, by utilizing a plastic material to construct the gripper components, the proposed gripper performed fingertip deflection and passive pull-in operation. In the sections that follow, we shall discuss the extent to which a rigid object can be pulled in.

B. Kinematics and statics

The basic formula for analyzing the pull-in amount is presented here. The gripper structure is symmetric; only the left finger is considered here. Fig. 5 presents the nomenclature for the gripper. We considered a planar space where the origin O is located at the driving joint of motor #1. Let θ be the rotational angle of the motor and l_i $(\mathrm{i} = 1, \cdots 4)$ be the lengths of sections OO', OA, AB, and BP, respectively. The fingertip position $(P_x \quad P_y)^{\mathrm{T}}$ is given by

$$\begin{bmatrix} P_x \\ P_y \end{bmatrix} = \begin{bmatrix} l_2 \cos\theta - l_3 \\ l_2 \sin\theta + l_4 \end{bmatrix} \tag{1}$$

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If l_1 is the distance between the driving joints of the motors, the gripper opening width W is obtained from (1) as follows:

$$W = 2P_x + l_1 = 2(l_2 \cos\theta - l_3) + l_1 \tag{2}$$

If we solve (2) with respect to θ under the assumption that $0 \leq \theta \leq \pi$, we obtain the following equation:

$$\theta = \cos^{-1}\left(\frac{W - l_1 + 2l_3}{2l_2}\right) \tag{3}$$

By differentiating (1) with respect to θ, the result is as follows:

$$\begin{bmatrix} \Delta P_x \\ \Delta P_y \end{bmatrix} = \begin{bmatrix} -l_2 \sin\theta \\ l_2 \cos\theta \end{bmatrix} \Delta\theta \tag{4}$$

From the principle of virtual work and (4), we obtain the following:

$$\tau = -F_x l_2 \sin\theta + F_y l_2 \cos\theta \tag{5}$$

where F_x and F_y denote the forces applied to the fingertip (P) in the x and y directions, respectively, and τ denotes the corresponding motor torque. Rewriting (5), we obtain

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix} \frac{\tau}{l_2} \tag{6}$$

Similarly, the position of the point R, $(R_x \quad R_y)^{\mathrm{T}}$, is given by

$$\begin{bmatrix} R_x \\ R_y \end{bmatrix} = \begin{bmatrix} l_2 \cos\theta - l_3 \\ l_2 \sin\theta - l_5 \end{bmatrix} \tag{7}$$

where l_5 denotes the distance between B and R. The joint torque corresponding to the force applied to R in the x and y directions, F_{Rx} and F_{Ry}, respectively, is as follows:

$$\tau_R = -F_{Rx} l_2 \sin\theta + F_{Ry} l_2 \cos\theta \tag{8}$$

The position of point S is given by

$$\begin{bmatrix} S_x \\ S_y \end{bmatrix} = \begin{bmatrix} l_2 \cos\theta + l_6 \\ l_2 \sin\theta - l_7 \end{bmatrix} \tag{9}$$

where l_6 and l_7 denote the distances between A and S along the x and y directions, respectively.

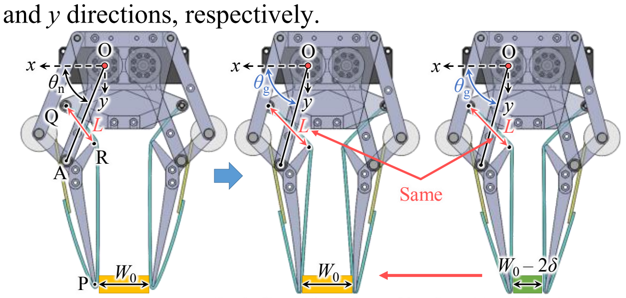


Fig. 6 Deflection effect

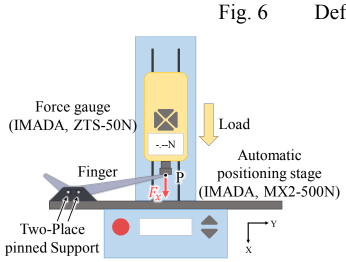


Fig. 7 Experimental setup for investigating the relationship between the load and deflection of a gripper mechanism

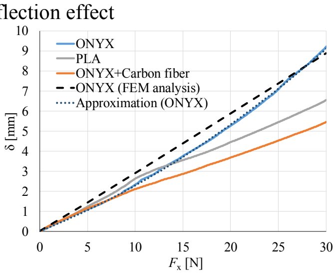


Fig. 8 Relationship between the load (F_x) and deflection (δ)

C. Pull-in length

From (1), (7), and (9), the distances SP and PR can be obtained as follows:

$$\begin{bmatrix} SP \\ PR \end{bmatrix} = \begin{bmatrix} \sqrt{(l_3 + l_6)^2 + (l_4 + l_7)^2} \\ l_4 + l_5 \end{bmatrix} \tag{10}$$

Thus, these distances are constant even when the gripper is open or closed. However, from (7), the distance RQ is given by

$$RQ = \sqrt{(l_2 \cos\theta - l_3 - Q_x)^2 + \left(l_2 \sin\theta - l_5 - Q_y\right)^2} \tag{11}$$

where Q_x and Q_y denote the x and y coordinates of point Q. RQ changes with the opening and closing motions. Therefore, the pull-in operation is activated by the change in distance RQ. Here, we focus on RQ to derive the pull in amount. From (3), distance RQ can be obtained as a function of gripper width W.

$$RQ = \sqrt{(l_2 \cos\theta_n - l_3 - Q_x)^2 + \left(l_2 \sin\theta_n - l_5 - Q_y\right)^2} \tag{12}$$
$$\theta_n = \cos^{-1}((W_o - l_1 + 2l_3)/2l_2)$$

Here, we consider the effect of deflection in the finger to derive the change in the sheet-embeeded belt distance RQ, as shown in Fig. 6. We consider a case wherein the width of the grasped (rigid) object is W_o and the deflection caused by the fingertip load is δ. If the gripper width is set to $W_o - 2\delta$, the practical gripper width reaches W_o. In this case, distance RQ corresponds to the RQ at the controlled state in which the gripper width is $W_o - 2\delta$ and no load is applied to the fingers. The distance can be expressed as follows:

$$RQ = \sqrt{\left(l_2 \cos\theta_g - l_3 - Q_x\right)^2 + \left(l_2 \sin\theta_g - l_5 - Q_y\right)^2} \tag{13}$$
$$\theta_g = \cos^{-1}((W_o - 2\delta - l_1 + 2l_3)/2l_2)$$

Hence, from (12) and (13), the pull-in length is given by

$$L_{pull-in} = \sqrt{\left(l_2 \cos\theta_g - l_3 - Q_x\right)^2 + \left(l_2 \sin\theta_g - l_5 - Q_y\right)^2} - \sqrt{(l_2 \cos\theta_n - l_3 - Q_x)^2 + \left(l_2 \sin\theta_n - l_5 - Q_y\right)^2} \tag{14}$$
$$\theta_g = \cos^{-1}((W_o - 2\delta - l_1 + 2l_3)/2l_2),$$
$$\theta_n = \cos^{-1}((W_o - l_1 + 2l_3)/2l_2)$$

D. Relationship between the deflection and load at the fingertip

The relationship between the fingertip load and deflection δ is difficult to derive analytically. In addition, the material used affects the relationship; therefore, it must be selected carefully to obtain the desired pull-in operation. Here, we derive the relationship experimentally and select the material most suitable for the pull-in operation. Fig. 7 illustrates the experimental setup for the investigation. We prepared a hand-made jig that fixed the finger with the two pins in the same way as the finger is fixed to the parallel link of the gripper. The jig was attached to the base of the automatic positioning stage (Imada, MX2-500N). A force gauge (Imada, ZTS-50N) was attached to the driving part of the positioning stage. The fingertip was pressed by the force gauge at a constant speed of

10 mm/min. We prepared three fingers made from PLA, ONYX, and ONYX+carbon fiber, respectively. Fig. 11 presents the results. As described above, a large deflection offers a large pull-in length. In addition, an inflection in the relationship can indicate a change in the material property, and it may result in a fracture of the finger [21]. Thus ONYX was selected. If ONYX is selected, the relationship between the load and deflection is approximated as follows:

$$\delta = 0.0038F_x^2 - 0.191F_x \tag{15}$$

where F_x denotes the fingertip load and corresponds to F_x in (5). The coefficient of determination was $R^2 = 0.9996$, indicating that (15) approximates the relationship effectively. FEM analysis was also conducted to study the relationship between F_x and δ when utilizing ONYX, based on the material properties [28]. Fig. 11 includes the calculation results. The tendency of the profile and the values were similar to those of the experimental results, which validated the experimental analysis.

E. Deviation of the pull-in amount

Based on the above analyses, we derive the pull-in amount. From (14) and (15), the pull-in amount can be derived if the width of the object and the fingertip load are given. Force sensors were not embedded in the finger; then, we estimated the fingertip load from the motor torque. It is possible to install sensors such as force sensors at the fingers for estimating the pull-in amount and facilitating bin picking. However, the sensors require wiring that can cause the disconnection of wires owing to the opening and closing motions. Therefore, herein, we do not consider installing any sensors on the fingers to facilitate the maintenance and enhance durability. The motor torque was set to 2 Nm by assuming that we controlled the current value of the motor to the value corresponding to 2 Nm. The constant load spring applies force on the fingertip. Therefore, the effect of the constant load spring must be included. From the geometrical relationship between points S, P, and R, the applied forces in directions SP and PR are counterbalanced. Additionally, these forces are applied from the initial state. Thus, we do not have to consider the deflections by these forces; we only have to consider the force applied on the finger at R in direction RQ. From (11), the force is given as follows:

$$\begin{bmatrix} F_{Rcx} \\ F_{Rcy} \end{bmatrix} = \begin{bmatrix} (l_2 \cos\theta_g - l_3 - Q_x)/RQ \\ (l_2 \sin\theta_g - l_5 - Q_y)/RQ \end{bmatrix} F_c \tag{16}$$

where F_c denotes the constant load of the spring. Then, from (8), the corresponding motor torque τ_{RC} can be derived as follows:

$$\tau_{RC} = \left(F_{RCx}(l_3 + Q_x)\sin\theta_g - F_{RCy}(l_5 + Q_y)\cos\theta_g\right)l_2 F_c/RQ \tag{17}$$

We estimated that the motor torque corresponding to the grasping force was $2 - \tau_{RC}$. From (6), the corresponding F_x is given by

$$F_x = -(2 - \tau_{RC})\sin\theta / l_2 \tag{18}$$

From (13), (15), and (18), θ_g corresponding to δ can be derived by solving the following equation with respect to θ_g:

$$l_2 \cos\theta_g + 0.0038(2 - \tau_{RC})^2 \sin^2\theta / l_2^2 + 0.191(2 - \tau_{RC})\sin\theta / l_2 = W_o/2 - l_1/2 + l_3 \tag{19}$$

Given W_o, by substituting θ_g (obtained by solving (19)) in (14), the pull-in amount can be derived. The results of the calculation are presented in Fig. 9.

We also investigated the actual pull-in amount using the experiment illustrated in Fig. 10. The workpieces we prepared were 3D-printed rectangles (material: PLA) with dimensions $W \times 20$ (D) $\times 10$ (H) mm where W was 30, 40, ⋯, 90 mm; the width was prepared in intervals of 10 mm. We measured the pull-in amount when each workpiece was picked up with the developed gripper. The motor torque was maintained at 2 Nm by controlling the corresponding current value of the motor. The experiment was conducted five times per workpiece. Fig. 9 summarizes the experimental and calculation results obtained. The calculation results nearly agreed with the experimental results. The estimation error of the load calculated indirectly from the motor current and the softness of the sheet surface are considered the reasons behind the small difference between the calculation and experimental results. It was theoretically and experimentally shown that the finger deflections enable the pull-in operation.

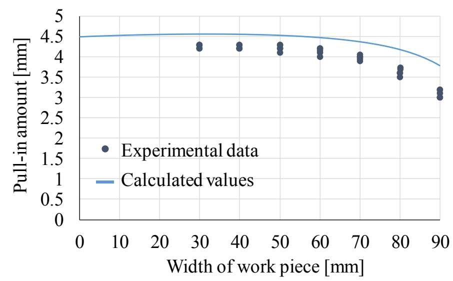


Fig. 9 Calculation and experimental results of the width of the grasped workpiece vs the pull-in amount

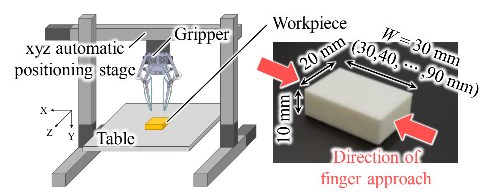


Fig. 10 Experimental setup to investigate the pull-in amount

IV. EXPRTIMENTAL PERFORMANCE EVALUATION

We conducted several experiments to evaluate the performance of the developed gripper for bin picking.

A. Pull-in function

We investigated the efficacy of the pull-in mechanism provided by the sheet-embedded belt by analyzing the amount of contact required for pick up. For comparison, we prepared the gripper without the sheet-embedded belt (hereafter, "nominal gripper"). Its grasping structure was the same as that of the gripper developed, and the sheet on the surface of the sheet-embedded belt was bonded to the contact surface of the nominal gripper. The experimental setup was the same as the one used to investigate the pull-in amount (see Fig. 10). The workpiece to be picked up was a 3D-printed rectangle (material: PLA) with a size of 30 (W) × 20 (D) × 10 (H) mm. The experimental procedure is summarized in Fig. 11. First, the gripper was maintained at the point where the centers of the gripper palms coincided with the geometrical center of the workpiece and the fingertip height corresponded to the height of the upper surface of the workpiece; the fingertip did not come in contact with the object at all. We set the point of the required contact amount as zero, e.g., $d_y = 0$ mm. Second, the gripper was lowered at 0.5 mm intervals, and at each step, we investigated whether the workpiece could be picked up 10 times. We evaluated the success rate of the pick up at each step. Fig. 12 presents the results for which the gripper with the pull in operation required a contact amount of only 1 mm for grasping; this was 2 mm less than that needed for the nominal gripper. The results indicate that the proposed pull-in mechanism works effectively for picking up workpieces when the allowable contact area is limited.

B. Picking-up performances

We conducted pickup experiments with several kinds of objects in different environments to determine the effectiveness of the developed gripper. The experimental setup is presented in Fig. 13; the developed gripper was attached to the tip of a universal robot (UR5). The control was manual.

First, to determine the effectiveness of having a sheet-embedded belt with a soft surface, we picked up several kinds of objects on a table. Fig. 14 illustrates the successful picking up of several objects, which indicates that the developed gripper can grasp objects of various shapes owing to the softness of the sheet.

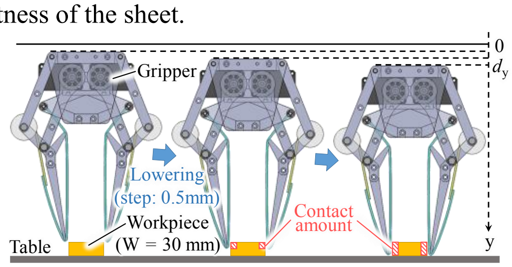
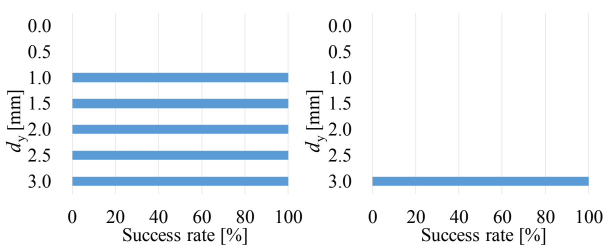


Fig. 11 Procedure for investigating the pull-in function



(a) With the pull-in function (b) Without the pull-in function

Fig. 12 Pick-up success rate

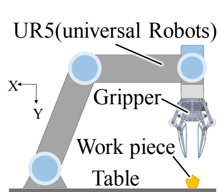


Fig. 13 Experimental setup for investigating pick-up performance

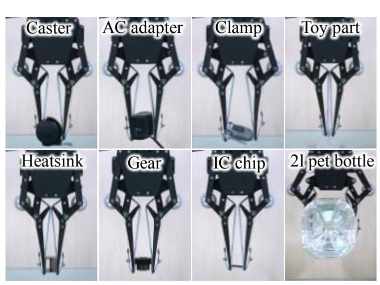
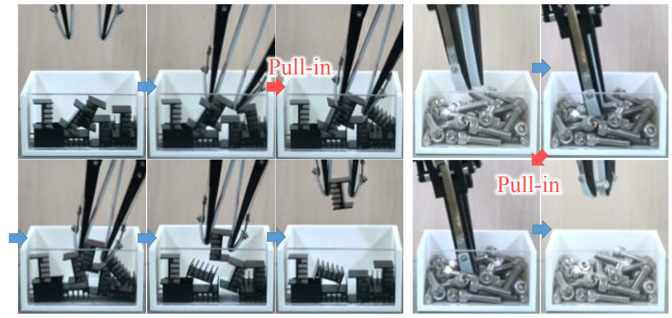
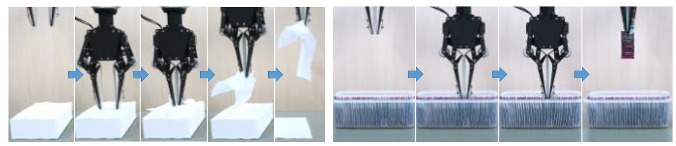


Fig. 14 Picking up several kinds of objects



(a) Heatsink (b) Hexagonal bolt

Fig. 15 Results of the bin-picking operation



(a) Picking up a single piece of tissue paper from a bundle (b) Picking up a single thin tea bag from its box

Fig. 16 Picking up a flexible sheet-type object

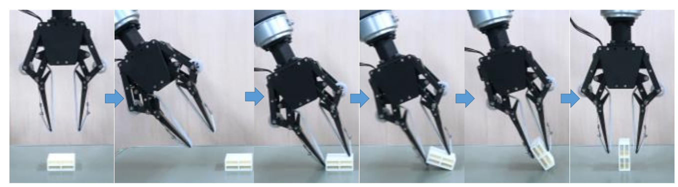


Fig. 17 Flipping operation

Second, bin-picking operations were conducted as shown in Fig. 15. The parts were able to be picked up one by one very easily because the fingers could be inserted into the gaps between the target and the surrounding workpieces easily, and very little contact was required for the pick up owing to the pull-in operation.

Third, we attempted to pick up flexible thin objects. As shown in Fig. 16(a), a single tissue paper was successfully picked up from a bundle. First, we made the bottom of the finger touch the top of the tissue paper. Then, by closing the gripper, the tissue paper was pulled towards the gripper owing to the passive pull-in function; thus, only a single paper was picked up. Fig. 16(b) illustrates how a tea bag was successfully removed from its box. The fingers were first inserted into the gap between the target and the surrounding objects. The level of insertion was low, and thus, the contact amount was also low. However, with the help of the pull-in operation, the subsequent closing motion pulled the target tea bag towards the gripper and it succeeded in picking up the single target tea bag.

Fourth, a flipping operation was performed to check whether the pull-in function can be utilized effectively for manipulation (Fig. 17). The flip operation is utilized by a human when they pick up a thin plate on a table. To perform the flipping operation, conventional approaches [25], [29]–[31] utilized multi-DOF fingers because the finger form was required to change based on the way the object was rotated. In contrast, the pull-in operation can change the relative contact position on its

TABLE I. A COMPARISON OF THE DEVELOPED AND EXISTING GRIPPERS

Preferable functions for bin picking†	**Pull-in**	**Requirement for activating the pull-in**	**Mechanism for activating the pull-in**	**Required contact amount for grasping at fingertips (Fig. 12)**	**Flexible surface**[1] **(Fig. 14)**	**Grasping in narrow spaces**[2] **(Figs. 15,16b)**	**Insertion in the gap between objects**[2,3] **(Figs. 15,16)**	**Picking up thin flexible objects**[4] **(Fig. 16)**	**Scooping**[3] **(Fig. 17)**	**Flipping operation (Fig. 17)**
Suction gripper	**Yes**	Suction	Suction	**Small**	No	**Easy**	Difficult	Requiring no hole	Difficult	Difficult
Parallel-jaw gripper (supposing thin fingertips)	No	-	-	Medium	No	**Easy**	**Easy**	Possible	Possible	Difficult
Fin-ray-based gripper‡ [27]	**Yes**	Load around the (intermediate) fin-ray area	Fin-ray structure	Large	**Yes**	Possible	**Easy**	Possible	**Easy**	Difficult
Underactuated soft gripper‡ [20]	**Yes**	Supporting surface	Ratchet mechanism	**Small**	**Yes**	Difficult	Possible	Possible	**Easy**	Possible
Underactuated gripper with active surfaces [25]	**Yes**	Motor	Motor	Medium	No	Possible	Possible	Possible	Possible	**Easy**
Underactuated modular finger with pull-in mechanism [26]	**Yes**	Load around finger surface	Differential gear	Medium	No	Difficult	Difficult	Requiring supporting surfaces	Difficult	Difficult
Developed gripper	**Yes**	Load around fingertip	Finger deflection and flexible sheet-embedded belt	**Small**	**Yes**	**Easy**	**Easy**	**Easy**[4]	Possible	**Easy**

†: The number of the Figure demonstrating the corresponding functions is shown ‡: These grippers have nails, although the developed gripper does not have them.
1: This function is associated with the high adaptability to the shape of the object, and therefore, many kinds of workpieces can be picked up.
2: Small thickness of the fingertips is effective in performing these functions. 3: Nails are effective in performing these functions.
4: In this function, "easy" implies that the gripper is able to pick up the object from a bundle one by one.

fingers with the closing operation, thereby making it possible to flip the object using only closing motion of the developed gripper. First, one finger came in contact with the surface of one side of the target box while the other finger came in contact with the top of the target box. The gripper was initially tilted for the contact. The tilted gripper was then rotated while being lowered with the closing operation, which straightened the gripper and lowered the relative contact position. Using this strategy, the flip operation was conducted successfully.

V. DISCUSSION

We compared the proposed gripper with other existing grippers. Table I presents the comparison results, listing the functionalities featured by the developed gripper and other existing grippers that are suitable for bin picking or for picking up thin flexible objects. It can be inferred that the utilization of sheet-embedded belt and finger deflection provides a simple structured gripper equipped with the highest number of functions suitable for bin picking and for picking up thin flexible objects.

Next, we discuss the durability of the developed gripper. The sheet-embedded belt must be replaced after every few months. The main reason for the replacement is not the breaking of the sheet due to overload or overstress but the deterioration due to the chemical reaction with substances in the air or adhered by contact. The sheet (Die B tear strength = 18.91 N/mm) [32] and the belt (allowable tension = 40 N) [28] break primarily due to tension. The opening and closing motions exert tension on the belt but not on the sheet. The main component of the belt is polystyrene, which has high durability and a long service life. When grasping workpieces, the contact between the finger and the sheet-embedded belt also prevents the large stretching of the sheet and the belt. Therefore, the effect of contact with the workpiece on the stretching of the sheet is relatively low in comparison with the effect of deterioration. When an experiment was conducted for the extreme cases, a cut occurred in the sheet with a width of 10mm when a force of 4.5 N or more was applied on it with a cutter.

The finger is constructed by ONYX, which is a nylon mixed with chopped carbon fiber, and thus, it has high durability and a long service life. The FEM analysis based on the material properties [28] such as tensile strength (36 MPa) provides allowable loads of 75 N (F_x) and 111 N (F_y) in the x and y directions, respectively. These values are lower than the maximum fingertip force that can be generated by the motor (51 N). Hence, the maximum fingertip force can be applied, and it is large enough to grasp heavy objects, such as a 2 l PET bottle, without breaking. The fatigue or breaking issues must be considered if the deflection of the components is utilized for the grasping operation. But, if the component materials are selected appropriately, the methodology of usage of deflection works effectively.

VI. CONCLUSION

This paper presents a novel and versatile parallel gripper for bin picking and for picking up thin flexible objects. The developed gripper is equipped with a sheet-embedded belt that enables the target workpiece to be pulled towards the gripper even when the contact area is limited. When picking up a workpiece, the grasping force deflects the fingertip, the deflection rolls up the sheet-embedded belt, and the grasped workpiece is pulled towards the gripper. The pull-in operation was performed passively with the opening and closing motions. Owing to the pull-in function, workpieces were able to be picked up one at a time in conditions where the targets were stacked in bulk. Flexible thin objects such as tissue paper could be grasped when the bottom of the gripper fingertips touched the top of a thin object and pulled it towards the gripper with a closing motion. The sheet on the sheet-embedded belt is soft enough to enable a wide variety of workpieces to be picked up. The effectiveness of the pull-in function and the gripper itself were demonstrated through several experiments.

However, the developed gripper also has several limitations. The range of the width within which the gripper can perform the pull-in operation was 30–90 mm, and workpieces with widths beyond this range are difficult for the gripper to grasp. A 2 l PET bottle could be grasped; however, picking up objects heavier than the PET bottle was not attempted. The grasping forces were not optimized; however, they must be determined according to the targets. The optimization of the finger shape was also not considered. The difference in the arrangements of the left and right finger components (for example, the difference in the bulge of the sheet-embedded belt) could tilt the grasped workpiece. A larger gripper is required to pick up larger objects such as car parts. The scaling-up of the main design concept is possible. However, for realizing the scale-up, we must resolve several issues: feasibility of material selection, development of fabrication methods instead of 3D printing, and so on. The installation of sensors such as tactile sensors can be effective in applying the gripper to more complex assembly tasks. These issues are beyond the scope of this study and may thus be a part of our future work.

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