

GripFlexer: Development of hybrid gripper with a novel shape that can perform in narrow spaces

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Abstract— In recent years, the role of robots across industries has become increasingly diverse, and they are now required to perform complex missions beyond simple repetitive tasks. However, robots used in confined spaces that humans cannot reach or in disaster field missions have challenges in performing various tasks due to their small size. In this study, we developed a compact hybrid gripper that fuses a multi-finger gripper and a jamming gripper to perform various tasks in a confined environment. Such a hybrid gripper can have both the strengths of a multi finger gripper that can perform various tasks and a jamming gripper that can effectively handle irregular small objects. In this study, we developed a hybrid gripper "GripFlexer" based on theoretical analysis and confirmed its performance through experiments by taking the task of turning a circular doorknob, which is one of the most difficult tasks in disaster sites, as the final target task. We also confirmed that the two grippers of GripFlexer can interact by showing performance improvement effects when two grippers are operated simultaneously.

I. INTRODUCTION

Natural disasters are becoming more frequent around the world due to rapid climate change, which has led to a need for robots that can operate in confined spaces where humans cannot enter [1-2]. To meet this need, small robots with advantages in traveling on rough terrain, such as snake robots and insect robots, are being developed for use in confined spaces, rather than bulky robots like existing quadrupedal and wheel-based robots [3-4]. Accordingly, manipulators and grippers that perform actual missions are also being developed with a focus on miniaturization and shock absorption [5-6].

Traditional grippers are primarily developed for industrial applications and are designed to perform specialized tasks with a high probability of success [7-8]. Gradually, the diversity of tasks that robots need to perform has increased, and several studies have been conducted to enable a single robot to perform multiple tasks. To this end, industrial robots with enough available space are being developed to deploy multiple grippers and use the appropriate gripper depending on the situation [9]. However, field robots used in rugged terrain and confined spaces need to perform multiple tasks with a single gripper. Various attempts have been made to overcome the limitations of existing grippers that can only perform specific tasks [10-11].

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Grippers can be manufactured in various forms, such as parallel grippers, multi-finger grippers, and jamming grippers, and the driving method is also very diverse, such as pneumatic [12], cable [13], hydraulic, and linkage structure-based [14]. To be used in confined spaces, gripper bodies and actuating parts must be compact and capable of gripping objects of various shapes. This work presents the 'GripFlexer', a hybrid gripper that combines two different types of grippers to fulfill the specified conditions.

The first gripper to be incorporated into GripFlexer is an under actuation multiple finger gripper. Han et al. attached a three finger under actuation gripper to a snake robot, a mobile robot for confined spaces, and drove it [15], and it has the advantage of enabling a compact design due to the reduction of the number of actuators, which is suitable for use in confined spaces. In this study, we aim to develop an extreme under actuation gripper that drives a multi-finger gripper with a single motor to maximize these advantages. Li et al. [16] fabricated a five-finger under actuation robot hand that utilizes springs and cables to operate with only one motor. Like that robot hand, we can develop an under actuation gripper mechanism that can grasp various objects by setting the cable path using springs. In addition, by utilizing a flexible joint called paired-Cross Flexure Hinge (p-CFH) for shock absorption of finger-based grippers, the fingers can adapt to various impacts occurring in rough terrain [17].

The second gripper that is incorporated into the GripFlexer is the jamming gripper. The jamming gripper, which uses a pneumatic pump with a relatively small force to grip objects, can be attached to the end of a mobile robot such as a snake robot to perform various tasks [18]. In particular, the jamming gripper can play a big role in the mission in rugged terrain, where there are many small obstacles such as rocks, broken parts, and objects that are difficult to grasp with a finger-based gripper, such as small valves. In addition, jamming grippers have the effect of increasing friction during operation, which increases the gripping force when driven in conjunction with a multi finger gripper [19].

The purpose of this study is to develop GripFlexer, a small hybrid gripper that integrates two grippers. This allows for the gripping of large and heavy objects with a multi-finger gripper and small objects with a jamming gripper. Additionally, it improves gripping stability and force through compound drive when it is difficult to perform with a multi-finger gripper. This will make it possible to grip objects of various shapes based on the jamming gripper in narrow disaster sites, and by driving the hybrid gripper together, it is possible to overcome the limitation of gripping power due to the small size of the gripper.

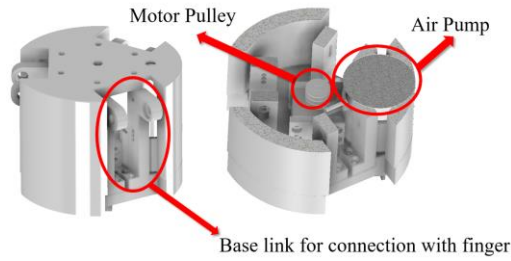


Fig. 1. 3D design of the manufactured base part.

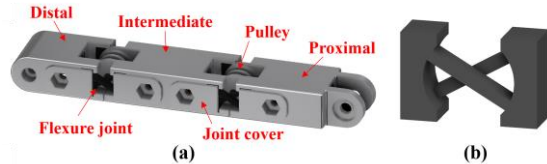


Fig. 2. Design of the finger. (a) Assembled finger. (b) Flexure joint.

Rotating a circular doorknob is considered one of the most challenging tasks for a small gripper to perform. This was chosen for the following reasons. First of all, when mobile robots operating in narrow spaces are used in indoor environments, they are likely to encounter obstacles such as closed doors. Most doors are opened and closed by rotating a torsional spring-based handle, and circular handles must overcome torsional stiffness using only the frictional force between the gripping object and the handle. Therefore, this study aims to build GripFlexer to perform this task. The overall organization of the paper is as follows. Section II describes the design of the GripFlexer. Section III contains the theoretical analysis of the stiffness of p-CFH, which will be used as the joint of GripFlexer, and the statics analysis of multi-finger gripper. Section IV describes the experiments on the trajectory analysis and shock absorption of the fingers, and the gripping experiment of the GripFlexer. Finally, Section V concludes the paper with a discussion of the experimental results and the significance of the developed gripper.

II. GRIPPER DESIGN

A. Finger & Base Design

A motor with a stall torque of 12 *kg-cm* (1000:1 Micro Metal Gearmotor HP 6V, Pololu, USA) and a motor pulley with a diameter of 6.2 *mm* was used to actuate the three fingers. The main body is cylindrical with a diameter of 72 *mm*, and the three fingers are arranged radially to efficiently grasp circular objects. Details on motor selection and finger length selection are described in section III. The selected motor's fixture is positioned in the middle of the main body to enable cable actuation in three directions. To avoid obstructing the cable's path, we positioned the pump to drive the jamming module inside the base. A 4 *mm* diameter hose connects the pump to the jamming module. The geometry of the finished base is shown in Fig. 4. The skeleton of the base is made of aluminium and the motor and pulley are made of Veroclear resin using a 3D printer (Objet30 pro, Stratasys Inc, Los Angeles, USA).

Fig. 2(a) displays the finger design developed in this study, which comprises three links: distal, intermediate, and proximal, connected by the flexure joint shown in Fig. 2(b). The lengths of each link are 25 *mm*, 33.6 *mm*, and 30 *mm*, respectively, and

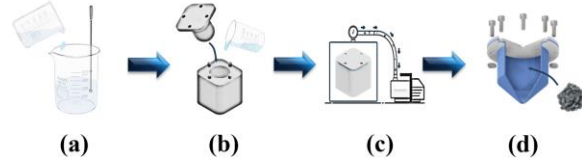


Fig. 3. Production process of jamming module.

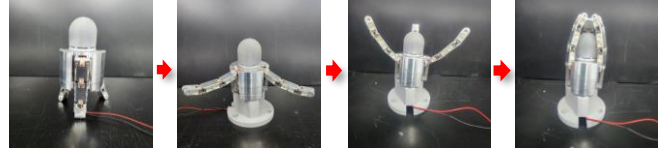


Fig. 4. Shape and operation of the GripFlexer.

can be actuated up to 40°. The main frame is made of aluminium, while the joint cover and pulley are fabricated using polyjet 3D printing. The flexure joint was 3D printed using nylon through FDM printing (Zortrax SA, Olsztyn, Poland), which is characterised by high flexibility and impact resistance. In addition, the cable path of the finger is organised as described in section III-B. The gripper works well when the three fingers are bent at the same angle to grasp a symmetrical object, such as a circular doorknob.

B. Jamming Design

The gripper developed in this study is intended for use in disaster sites and narrow spaces. It proposes a new design that complements the characteristics of finger-type grippers and jamming-based grippers. The combination of these two types of grippers provides the ability to perform difficult tasks in narrow spaces and effectively grip objects of various shapes. The jamming gripper, which can be attached to a finger-type gripper, was fabricated using the process shown in Fig. 3.

To grip unstructured objects, the gripper requires a chamber made of a flexible material. Dragonskin 20A silicone solution was used to construct the chamber. (a) The outline of the jamming gripper is formed by pouring the silicone mixture into a mold. (b) Once the mixture was in the mold, the air inside was evacuated using a vacuum chamber. (c) The molded chamber was equipped with a pressure-retaining attachment, and flexible rubber particles were added as internal granules to create a jamming gripper. (d) The jamming gripper is capable of adapting to irregular shapes, such as stones and debris, that may be encountered when working in confined spaces.

By integrating the individually fabricated jamming module, finger, and base, the final form of the gripper proposed in this study was achieved (Fig. 4). The interaction of each part in this process is expected to significantly enhance the final function and performance of the gripper.

C. Circuit Configuration

To ensure effective control and coordination between the jamming module, finger, and base modules, we developed an integrated drive circuit as shown in Fig. 8. The drive circuit simultaneously controls the operation of the jamming gripper and the finger gripper, and allows the user to easily switch the gripper's operating mode according to the shape of the object or the working environment. In addition, the drive circuit senses the drive current and position value of each gripper, enabling verification of gripping force and position. The design and implementation of this drive circuit is expected to

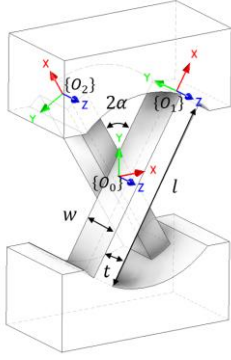


Fig. 5. Coordinate system of the flexure joint

enhance the efficiency of grippers in performing complex tasks and improve their ability to respond to emergency situations at disaster sites. This will ultimately expand the range of applications for grippers and make them more versatile in various situations and environments.

III. ANALYSIS

A. p-CFH Joint Stiffness Analysis

The finger joint is designed as a p-CFH structure. This structure has the advantage of shock absorption like a conventional flexure joint, and the stiffness in the direction other than the main rotation direction is higher than a conventional flexure joints to prevent rotation in other directions when driving the cable. Fig. 5 shows the flexure joint configuration of the hybrid gripper developed in this study. The flexure joint was designed so that cantilever beams with length of l , thickness of t and width of w were crossed at an angle of 2α . The stiffness of the flexure joint can be obtained by obtaining the stiffness of the cantilever beam and then synthesizing it using coordinate system transformation.

First, the compliance matrix of the cantilever beam can be obtained through Castigliano's second theorem and has the following form (1).

$$\mathbf{C}_{cantilever} = \begin{bmatrix} C_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & C_{22} & 0 & 0 & 0 & C_{26} \\ 0 & 0 & C_{33} & 0 & -C_{35} & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & -C_{53} & 0 & C_{55} & 0 \\ 0 & C_{62} & 0 & 0 & 0 & C_{66} \end{bmatrix} \quad (1)$$

where E and G are the elastic modulus and shear modulus of the material, respectively. The stiffness matrix of the cantilever beam is obtained by taking the inverse of (1).

The compliance matrices of the two cantilever beams are expressed as (1) in each coordinate system, and they can be expressed in the O_0 coordinate system by coordinate system transformation.

Since a flexure joint can be considered as a parallel connection of two cantilever beams, the stiffness of a flexure joint can be expressed as the sum of the stiffness of the two cantilever beams as follows:

$$\mathbf{K}_{flexure} = \mathbf{T}_1^{-T} \mathbf{K}_{cantilever} \mathbf{T}_1^{-1} + \mathbf{T}_2^{-T} \mathbf{K}_{cantilever} \mathbf{T}_2^{-1} \quad (2)$$

where \mathbf{T} is the adjoint transformation matrix that converts from the coordinate system of each cantilever beam to the O_0 coordinate system. The stiffness matrix of the flexure joint can

be obtained from (2), and since it is designed to replace a revolute joint, the rotational stiffness with respect to the z-axis moment is the main design variable. Since two flexure joints are used symmetrically between each link, the z-axis rotational stiffness of each link can be calculated as twice the flexure joint rotational stiffness. Where the z-axis rotational stiffness of the flexure joint is calculated to be 0.0328 Nm/rad . Therefore, the z-axis rotational stiffness (K_θ) of the finger joint is 0.0656 Nm/rad .

B. Finger Statics Analysis

This section describes the statics analysis of the p-CFH-based under actuation finger that was performed to calculate the specifications required to perform the target task. Since the p-CFH has a similar motion to a pin joint, the most efficient way to drive the pin joint with a cable and the force transfer rate were analyzed theoretically. In addition, we theoretically analyzed the normal force applied to each point given the contact points between the under actuation finger and the object, and derived the minimum conditions to perform a specific target task.

When driving a joint with a cable, the cable path should be set to deflect the joint center to one side. Since the finger in this study needs to be bidirectional, it is assumed to follow the same path as shown in Fig. 6. When the joint moves by θ , the change in the length of the red colour cable that is pulled and the length of the purple colour cable that is stretched is constant at $r\theta$. This allows the tension on both cables to be maintained during bidirectional drive. If the path of the cable is set as shown in Fig. 6, the relationship between the tension of the cable and the torque of the joint can be obtained as (5), (6). By the law of conservation of energy, the force relationship of the cable in the joint is shown in (3), and the relationship between l and θ is shown in (4), and finally (5) can be derived. As a result, this is equal to the force pulled by the distance from the center of rotation to the point of force. In addition, if a stiffness is introduced into the joint by the p-CFH, the force transmitted to the joint can be calculated using (6).

$$\tau \frac{d\theta}{dl} = F \quad (3)$$

$$\Delta l = r\Delta\theta \quad (4)$$

$$\tau = rF \quad (5)$$

$$\tau = rF - k_\theta\theta \quad (6)$$

This study aims to develop a gripper to perform various tasks in a small space, and the most difficult task to perform using a gripper in real life is to turn a circular doorknob. The reason why the circular doorknob is the most challenging is that it does not directly use the force generated by the actuator, but uses the friction force generated by the force to turn the doorknob. We assumed that the gripper has a specific contact point for each finger as it grips the circular doorknob. To find the friction force, we first analyzed the normal force applied to each contact point. Based on (6), we can derive the force equilibrium expression for the total sum of the force on the joint of the under actuation finger and the force F of the actuator as shown in (7). In addition, since the angle of the joint is fixed, the force equilibrium equation due to the normal force (F_1, F_2) on both sides can be derived as (8). By combining the two equations, the normal force can be obtained

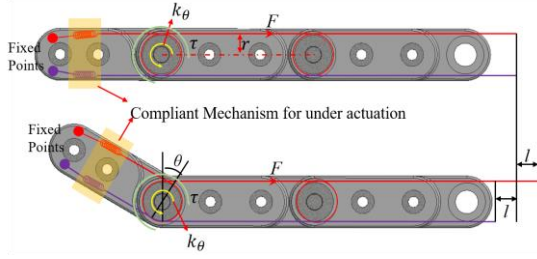


Fig. 6. Cable path for under-actuation mechanism and parameter setting for force analysis

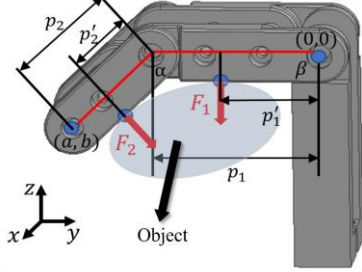


Fig. 7. Parameter settings for static analysis of underactuated finger.

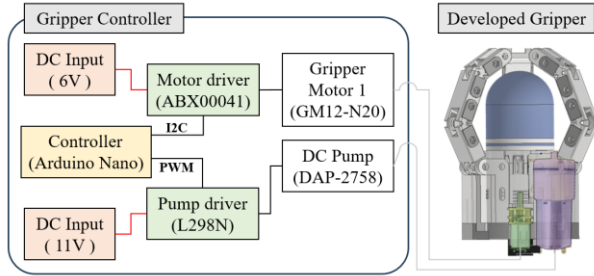


Fig. 8. Circuit diagram of GripFlexer.

by matrix operation as shown in (9). Each variable is visualized in Fig. 7.

$$p'_1 F_1 + p'_2 F_2 = rF - k_\theta \theta_1 - k_\theta \theta_2 \quad (7)$$

$$(p_1 - p'_1) F_1 - p'_2 F_2 = 0 \quad (8)$$

$$\begin{bmatrix} p'_1 & p'_2 \\ p_1 - p'_1 & -p'_2 \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = \begin{bmatrix} rF - k_\theta \theta_1 - k_\theta \theta_2 \\ 0 \end{bmatrix} \quad (9)$$

$$\frac{x^2}{9} + \frac{y^2}{9} + \frac{z^2}{6.25} = 1 \quad (10)$$

TABLE I. CONSTANTS USED IN GRIPPER STATICS ANALYSIS.

Descriptions	Values	Units
Radial arrangement diameter of finger	25	mm
Rotational stiffness of doorknob	0.2	Nm/rad
Maximum rotation angle of doorknob	$\frac{2\pi}{3}$	rad
Friction coefficient between silicone and steel	1	-

The lengths of the two links responsible for gripping were set to $p_1 = 30\text{mm}$ and $p_2 = 20\text{mm}$, which are large enough to wrap around the circular doorknob. In addition, the shape of a typical circular doorknob is assumed to be ellipsoid, and the reverse design is performed as shown in (10). When gripped by the finger, its cross-section appears as an ellipse and the contact point can be specified. From the tangent equation of the ellipse, we can find $p'_1 = 14.6\text{mm}$ and $p'_2 = 15.5\text{mm}$. Substituting this into (9), we can find the normal force at each point, and using this value and the friction coefficient, we can find the friction force. In addition, the rotational stiffness and

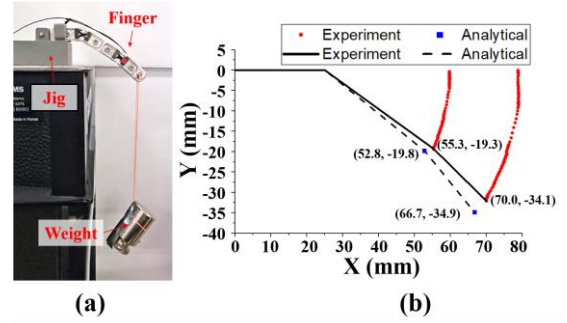


Fig. 9. Experiment setup to validate the stiffness of the finger.

maximum rotation angle of the circular doorknob were calculated, and all the constants are summarized in Table II. Since three fingers of the same shape are driven by one actuator, it is assumed that the force of the actuator is applied equally to all three fingers. As a result, it was found that a force of more than 100N was required to rotate a circular doorknob using a single actuator.

IV. EXPERIMENT

A. Finger trajectory and impact experiment

To verify the results of the stiffness analysis, an experiment was performed as shown in Fig. 9(a). The trajectory of each joint was analyzed by attaching a 100 g weight to the end of the finger. In the theoretical analysis, the trajectory of the finger was examined when a load was applied to the pseudo-rigid body model with a stiffness of K_θ at each joint. Fig. 9(b) shows the experimental results. The final position of the fingertip was calculated to be (70.0, -32.1) in the experiment and (66.7, -34.9) in the theoretical analysis. This confirms that the stiffness analysis performed well.

To verify the shock absorption performance of the flexible hinge joint, a comparison experiment with a finger consisting of a pin joint was performed. To measure the acceleration applied to the fingers, wireless IMUs (EBIMU24GV2, E2BOX) were fixed on the second link of each finger to acquire data. For the experiment, the two types of fingers were fixed vertically on a vibration-proof table as shown in Fig. 10(a), and then a 100 g weight was dropped from a height of 40 cm to apply an impact. The results were analyzed for the amount of impact, focusing on the acceleration in the Z-axis direction of the IMU. The results can be seen in Fig. 10(b). For the analysis, we utilized the Head Injury Criterion (HIC), a numerical representation of the impact force. The HIC value is defined as [20].

TABLE II. RESULT OF HIC36 (N = 3).

Contents	<i>p</i> -CFH finger	Pin Joint Finger
Average $\text{HIC}_{36} (m^2 s^{-4})$	4.84	20.33
Std dev. Of $\text{HIC}_{36} (m^2 s^{-4})$	0.89	6.71

The HIC_{36} indicator, set to $\Delta t_{\max} = 36\text{ms}$, was used in this study to evaluate the impact of robotic systems [17][21]. A smaller value of this metric indicates that fewer impacts were delivered, as it represents the total sum of the impact volume over time. Table III shows the results of the impact evaluation. The results indicate that the multi-degree-of-freedom finger with flexible hinge joints had approximately four times fewer metrics for impact. Flexible hinge joints have a significant advantage in shock absorption compared to pin

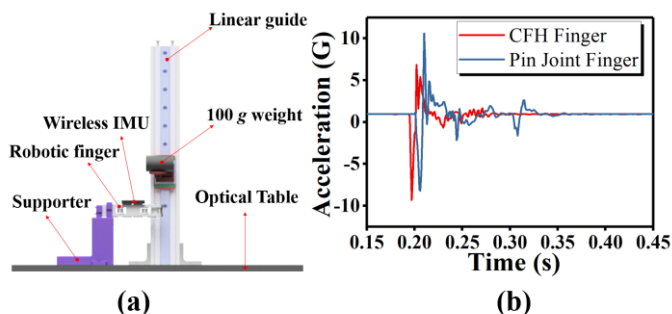


Fig. 10. Experiment setup for shock resistive experiment.

joints. This makes flexible hinge joints suitable for use in confined space grippers that are subject to various impacts.

B. Grasping Experiment

By conducting various gripping experiments on the fabricated gripper, we analyzed its feasibility in small spaces and the effectiveness of the hybrid gripper. Therefore, all the experiments except the last one were divided into two ways: finger-only driving and finger and jamming together.

The first experiment focused on gripping and rotating a circular doorknob, which was the main target task in this paper. To conduct the experiment, we built a door with a circular doorknob and checked the success rate of opening and closing it. In addition, we also conducted an experiment on opening and closing a lever type doorknob, which is widely used as a torsional spring-based doorknob, along with a circular doorknob. We performed 10 repetitions to analyze the success rate of the opening and closing task. As a result, we found that the rotation of the circular doorknob, which had a success rate of 30% when gripping using only fingers, had a success rate of 80% when the hybrid operation using both fingers and jamming was performed. In the case of the lever type doorknob, the rotation success rate was 100% in both the finger-only and hybrid drive experiments. Since this experiment only shows the performance of opening and closing a single doorknob, we cannot reliably check the opening and closing performance of many doorknobs with different stiffness. Therefore, we conducted an experiment to measure the quantitative force of the gripper when turning a circular doorknob.

A PLA model of a circular doorknob was made with a 3D printer (Carbon X1, Bambu, China) and attached to a commercial F/T sensor (AXIA 80, ATI, USA) to analyze the torque generated on the doorknob when the gripper grasps the doorknob and rotates it. A total of five experiments were performed and measurements were taken until the slip occur between the gripper and the doorknob model. The setup of the experiment is shown in Fig. 11(a). The results can be seen in Fig. 11(c), and the F/T sensor results for the first experiment with the two gripping strategies can be seen in Fig. 11(b). As a result, we found that the hybrid drive can generate torque of up to 0.56 Nm . For the doorknob used in this paper, the torque required for rotation was 0.416 Nm , confirming that the hybrid gripper can rotate sufficiently. The success rate of the round doorknob task increased from 30% when using multi-finger alone to 80% when using finger and jamming together, and the maximum torque value generated during force measurement increased by an average of 43.3%. These findings show that the role of the jamming gripper is not limited to simply

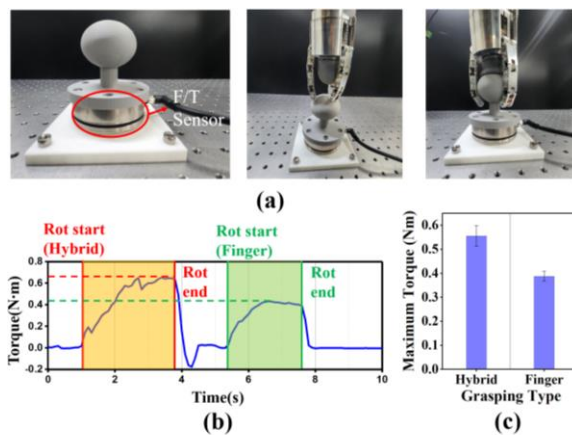


Fig. 11. Torque measurement experiment result when rotating the circular doorknob using GripFlexer.

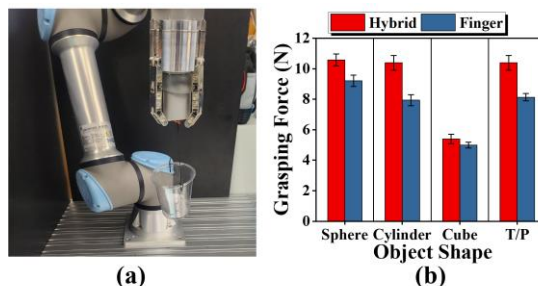


Fig. 12. Grasping force measurement experiment results.

gripping small objects, but also helps to improve the gripping power of the multi finger gripper. This confirms that the hybrid gripper can perform the rotation task of a circular doorknob, which can be rotated with a torque of 0.62 Nm or less, with a high probability.

An experiment was conducted to measure the absolute gripping performance of the gripper. The designed gripper needs to grip objects of various shapes to perform various tasks. Therefore, we created four different shapes (sphere, column, tetrahedron, and triangle) and conducted gripping experiments on them. Each sculpture was chosen to be 40mm high and 40mm in diameter, which is the size of the gripper, and a hook was installed underneath to add weight. The grippers were attached to a commercial manipulator (UR5, Universal Robot, Denmark) to grasp and lift each object, and the grip was analyzed for 3 seconds while adding weight, and if the object slipped within 3 seconds, it was considered a failed grip. The same experiment was repeated five times for each of the four models with two different gripping strategies. The experimental setup and results can be seen in Fig. 12.

The results show an average increase of 20.3% in grip force, with the largest increase in grip force for cylindrical objects. On the other hand, the cube object, which has the largest surface area, had the smallest grip increase of about 7.8%. Converting this to a force, we can see that the increase in gripping force is between 0.39 N and 2.45 N , showing a large difference. This is because the performance of the jamming module varies depending on the shape of the gripped object, and the performance is maximized when grasping small objects.

Unlike conventional finger-based grippers, the jamming gripper has the advantage of being able to grip smaller objects.

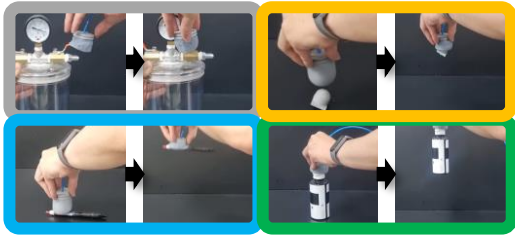


Fig. 13. Various small object grasping experiments using jamming module.

This is especially necessary in disaster situations where there are many small-sized obstacles such as pebbles and branches. To verify this, we conducted an experiment to grip small objects using the jamming gripper and finger gripper. We found that most small objects with a diameter of 3 cm or less, which are impossible to grasp using only the finger, can be grasped using jamming and perform the task (Fig. 13).

V. CONCLUSION

In this paper, we developed GripFlexer, a novel type of compact gripper that can be used in fields such as narrow spaces and disaster sites. As a hybrid gripper to be used in a narrow field, we used a new method that combines a finger type gripper and a jamming type gripper. The finger gripper was manufactured through theoretical analysis based on the task of turning a circular doorknob, which is the most difficult task for a gripper in a narrow space/disaster site. In addition, the gripper was manufactured based on a special compliance joint called p-CFH for the purpose of shock absorption and breakage prevention, so that the gripper can secure safety when put into the actual field. Jamming was done through design and bead selection to maximize the force in a limited size, resulting in a very compact gripper with all modules except the circuitry fitting within $72*72*120mm$.

This study has the following future plans. First of all, the finger size developed in this paper is set based on circular handle gripping, but in the future, we will modify the design parameters to perform all tasks by setting various tasks. And the maximum vertical gripping force of the GripFlexer was found to be 10.8 N and the maximum friction torque was found to be 0.62 N·m. This large gripping force is due to the fact that the small jamming module helped to improve the performance of power grasping by more than 20% in addition to gripping small objects, which once again validates the need for a small jamming module in the production of compact grippers. Since the gripping environment and gripping objects of GripFlexer are very diverse, it is essential to perform slip recognition and actuator torque-based force control. Therefore, we plan to attach a force controller to GripFlexer in the future to automate the performance of various tasks in practice. In addition, if the GripFlexer is used in conjunction with a manipulator on various mobile robots used in the field, it is expected that the GripFlexer will be used in a wider range of tasks in addition to the various tasks proposed in this study.

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