2017 11th Asian Control Conference (ASCC)
Gold Coast Convention Centre, Australia
December 17-20, 2017

Development of Universal Parallel Gripper Using Reformed Magnetorheological Fluid

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Abstract—**This paper describes the development of an innovative universal parallel gripper using a reformed magnetorheological (MR) fluid. The gripper has two fingertips, constructed using an elastic membrane enclosing the reformed MR fluid, which is stiffer than typical MR fluid. We developed a mechanism that moves a permanent magnet in order to control the viscosity of the reformed MR fluid, and an innovative elastic membrane to increase durability. The developed robot gripper grips and releases objects precisely, without excessive force, because the elastic parts can fit to the target shape. The gripper is driven quietly and can grip fragile and soft objects of various shapes. We performed numerous experiments to measure the gripping capacity of our gripper, and showed that it possesses force control, while also being able to move at high speeds.**

I. INTRODUCTION

Industrial robots can adapt widely to various tasks, such as handling, welding, and painting, by exchanging end effectors. In particular, the end effector used for gripping and conveying an object is called a *gripper*. A jamming gripper is a type of gripper that uses an elastic membrane containing powder and an air compressor [1-3]. They can grip objects of various orientations and shapes without the need for a gripper replacement, thus improving work speed. However, these grippers use a change of air pressure in order to grip objects, resulting in limitations due to the environment in which the gripper is used.

However, grippers using magnetic force do not suffer from this limitation [4]. The reformed magnetorheological (MR) fluid gripper can grip and release objects quickly by controlling magnetic force. It is driven silently and is not limited by environmental restrictions. However, since the gripper exerts some pressure against a target object in order to grip it, it is not suitable for bulk-picking operations or gripping fragile objects. To solve this problem, a parallel gripper was developed in this study [5]. This gripper has two fingertips constructed using an elastic membrane enclosing the MR fluid. First, the gripper pinches the target object and the shape of the elastic membrane conforms to the shape of the object. Subsequently, the object is gripped because the MR fluid is solidified by the electromagnet. The gripper can grip objects with irregular shapes, such as vegetables and fruits. However, it requires a magnetic density over 0.3 [T] [6] in order to sufficiently solidify the MR fluid, which is a problem that creates a trade-off between the increase in volume and weight of the electromagnet versus the gripping performance.

In this study, we developed an innovative parallel gripper using a reformed MR fluid, to overcome the aforementioned trade-off. Our MR fluid is generated by adding nonmagnetic particles to a typical MR fluid, making it is stiffer than typical MR fluids, under the same magnetic field. In addition, we overcame a problem wherein the compact electromagnet cannot generate a magnetic field of over 0.3 [T] due to the mechanism that moves the permanent magnet. We developed an innovative elastic membrane with a high durability by designing suitably its thickness. The newly developed robot gripper grips and releases objects precisely without excessive force, because the elastic parts are able to fit to the target shape. The gripper is driven quietly and can grip fragile and soft objects of various shapes. We constructed a real-world robotic system using our parallel gripper and demonstrated that our gripper can grip various objects at high speeds.

II. RELATED WORK

Various universal gripper types have been developed; such as: multi-fingered, sucker, and flexible bag types. Hirose et al. [7], Rubinger et al. [8], and Doller et al. [9] proposed multi-fingered grippers that can control joints. Deimel et al. [10] and Ilievski et al. [11] also developed multi-fingered grippers, but they focused on soft materials. Takahashi et al. [12] built a biomimetic sucker type gripper by taking inspiration from the octopus. The resulting gripper could grip and absorb objects through a suction apparatus. A flexible bag type gripper uses a deformable "bag" to grip objects. These kinds of grippers have been thoroughly investigated, and are divided into many sub-categories [13]. Internal expansion grippers, proposed by Setiawan et al. [14], grip objects by first taking them inside the grippers' structure and then expanding their deformable bags. In contrast, hemispheric bag grippers grip objects by using the force induced by external pressure. Multiple hemispheric grippers have been developed [1-3], and we proposed a gripper that uses an MR fluid, and is independent of the external environment [4].

The gripper proposed in this study is included in the complex gripper category. This category describes multi-fingered flexible bag grippers. Choi et al. [15] built a gripper using air inside the bags. Even though it was very effective in gripping objects of various shapes, the durability of the bag was low because of continuous stretching. Murayama et al. [16] used incompressible fluids and

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succeeded in gripping fragile objects. However, their gripper was sensitive to vibrations during the transport of objects. In contrast, we used MR fluids, similar to the gripper proposed by Pettersson et al [5]. Our gripper differs from theirs, as we created a reformed MR fluid and developed an innovative mechanism to control its stiffness.

III. Reformed Magnetorheological Fluid

MR fluid is functional fluid that can change its viscosity due to a magnetic field, and mainly consists of oil and 5 to 10 µm iron particles. It also includes a surfactant to spread and to prevent iron powder from settling in the oil. By applying a magnetic field, the viscosity of the MR fluid increases 10^5–10^6 times, and the response is very quick; less than 1 [ms] [6]. When there is no magnetic field, the iron particles are suspended in the oil and the MR fluid behaves as a simple fluid. When a magnetic field is present, the iron particles gather along the lines of magnetic flux and form a chain structure [17]. The solidification mechanism of the MR fluid is shown in Fig. 1. As a result, the shear stress and viscosity of the MR fluid increases. When the magnetic field is removed, the chain structures are broken and the MR fluid behaves as a simple fluid. Moreover, the reformed MR fluid includes nonmagnetic particles. The solidification mechanism of the reformed MR fluid is shown in Fig. 2. As shown the figure, when the magnetic field is applied to the reformed MR fluid, the iron particles form chain structures along the line of magnetic flux, and the nonmagnetic particles fill the gaps in each chain and support the structure. Because of this mechanism, the reformed MR fluid solidifies more firmly than ordinary MR fluids. The characteristics of the reformed MR fluid change with the size and the material of the nonmagnetic particles. The relation of the mixing ratio of the MR fluid and nonmagnetic particles and its performance is described in the literature [4]. In this study, we created a reformed MR fluid by using carbon micro beads as the nonmagnetic particles, and constructed MR fluid grippers.

IV. MR Parallel Gripper

A. Design concept

We developed an innovative parallel gripper with two fingertips, equipped with a small MR fluid gripper in order to grip a fragile object while adhering to the characteristics of the MR fluid gripper. As previously mentioned, a magnetic flux density over 0.3[T] is required to sufficiently solidify the MR fluid. Although the MR fluid gripper uses an electromagnet

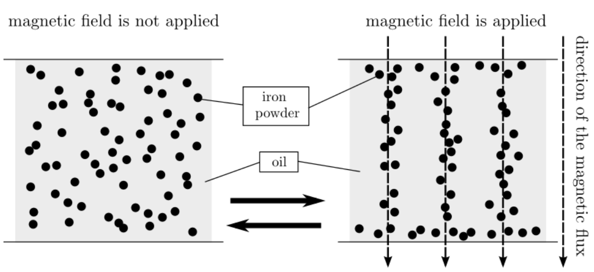


Figure 1. Solidification mechanism of the MR fluid.

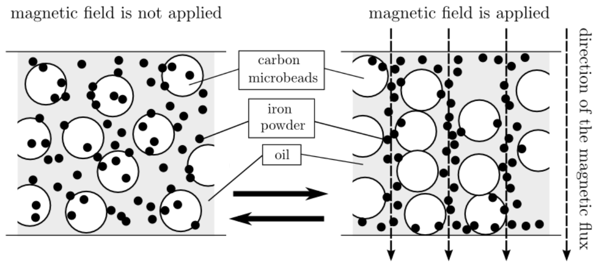
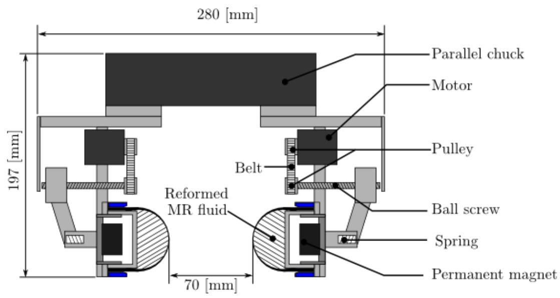


Figure 2. Solidification mechanism of the reformed MR fluid.

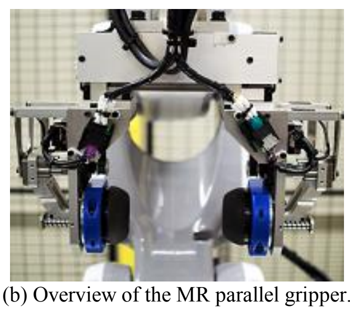
to generate the magnetic field, it is difficult to reduce the volume of an electromagnet with a high magnetic flux density. Therefore, we adopt permanent magnets (neodymium) with a stronger magnetic flux density than electromagnets and their moving mechanism. With this mechanism change, we succeeded in reducing the size of the MR fluid gripper and developing an innovative parallel gripper that has two fingertips. In this paper, we call it the *MR parallel gripper,* and its overview is shown in Fig. 3. This gripper carries a target object as described in the following procedure: (1) The industrial robot approaches the target with the gripper; (2) the gripper clamps the target by means of the parallel chuck while the MR fluid is fluidized; (3) the permanent magnets approach the MR fluids and the fingertip part hardens and holds the object securely; (4) the gripper and industrial robot carries the object to the set point; and (5) the gripper releases the object.

B. Driving structure

The parallel chuck of this gripper consists of a servo motor and ball screw. In order to grip low-rigidity objects, we designed it to feedback control the torque of its fingertips by measuring the electric current of the servo motor. The two MR fluid gripper parts in the gripper are opposite each other, and



(a) Structure of the MR parallel gripper.



(b) Overview of the MR parallel gripper.

Figure 3. Developed MR parallel gripper.

the viscosity of MR fluid is controlled by moving the permanent magnets horizontally. The flow of controlling the viscosity of MR fluid by moving the permanent magnets is shown in Fig. 4. The structure of the permanent magnet is shown in Fig. 5(a). The permanent magnet moves horizontally by rotating the ball screw via the belt from the motor in the root of the fingertip. The fingertip is equipped with a spring, to decrease the force of separating the permanent magnet from the MR fluid. The fingertip becomes stiff when the permanent magnet approaches the MR fluid and soft when the permanent magnet recedes.

C. Magnet part

The magnet part consists of a neodymium magnet and an iron yoke, to reduce leakage flux and increase magnetic density. The maximum magnetic flux density of the magnet part is 0.521 [T]. It is designed so that the magnetic flux density exceeds 0.3 [T] when it approaches the MR fluid.

D. Elastic membrane

The detail of the fingertip is shown in Fig. 5 (b). The elastic membrane is made of hydrogenated nitrile butadiene rubber (HNBR). HNBR is suitable for enclosing MR fluids, and has excellent durability for industrial use. The surface of the elastic membrane has been designed with a matte finish. This matte finish reduces sticking between the object and the elastic membrane, and improves the release performance. The elastic membrane is sandwiched and fixed by tubular parts made of stainless steel and a part made of plastic, with sufficient force to ensure that the MR fluid does not leak out. Moreover, in order to withstand over one million repetitions of use, the part of the membrane to be pinched has a thickness of 3 [mm], and the part in contact with the object has been designed to be 1 [mm] thick, for flexibility.

E. Cover design

If using the apparatus at factories, a dustproof cover must be equipped. If sand iron adheres to the moving part of the attached permanent magnet, it may be damaged. Therefore, we designed and developed a cover for the parallel gripper. The parallel gripper equipped with the cover is shown in Fig. 6.

V. Experiments

A. Gripping objects of various shapes

We conducted experiments to evaluate the perfomance of the developed parallel gripper by using objects of various shapes. The specifications of the objects used are shown in Table 1. We set constraints on the size of the objects for the experiments; i.e., their sizes had to be less than 70 [mm], which is the stroke length of the parallel gripper. The overview of the process in which the parallel gripper grips the objects is shown in Fig. 7. We confirmed from the experimental results that the developed parallel gripper is able to grip all of the objects shown in Table 1. Moreover, in order to check the stability of gripping, we applied a force to move the object while the gripper was gripping the target.

Next, we conducted gripping experiments using objects with complex shapes and varying materials. The overview of the gripping of the objects is shown in Fig. 8. It was found from these experiments that the developed parallel gripper is able to adapt to complex shapes and various materials. Moreover, in these experiments the objects were never scratched. Furthermore, in this experiment, it was confirmed that stable gripping could be achieved without strictly setting the position of various objects. Therefore, it can be said that the parallel

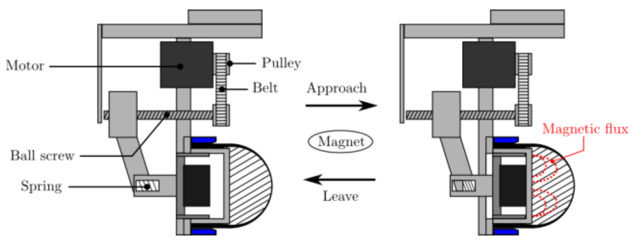
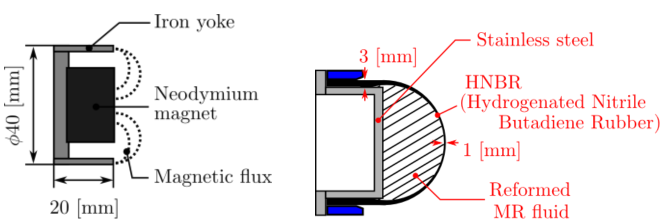


Figure 4. Solidification control of the MR fluid by moving a permanent magnet.



(a) Structure of magnet.

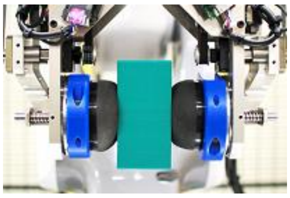
(b) Detail of fingertip.

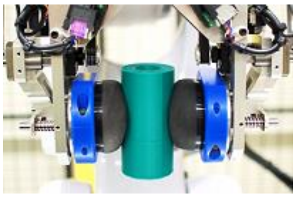
Figure 5. Components of fingertip.

Figure 6. Overview of parallel gripper equipped with cover.

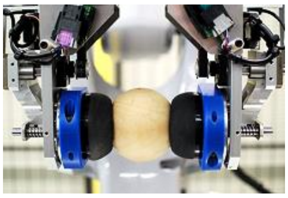
TABLE I. The objects used for evaluating the gripping performance with respect to the shape.

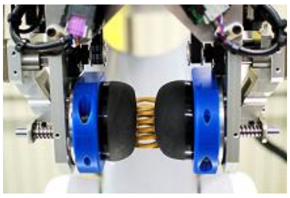
Shape	Prism	Column	Sphere	Spring
Material	ABS	ABS	Wood	SWP-A
Weight [g]	23	16	66	29





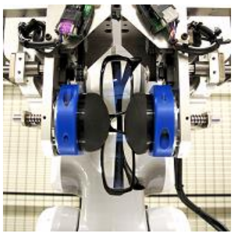
(a) Prism. (b) Column.

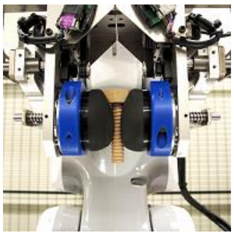




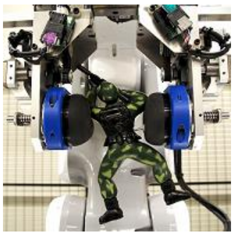
(c) Sphere. (d) Spring.

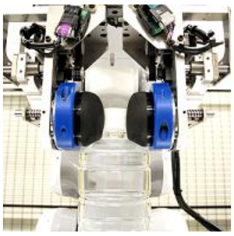
Figure 7. The gripper grips various objects.





(a) Glasses. (b) Bolt.





(c) Figure. (d) Bottle.

Figure 8. Gripping objects of various shapes.

gripper has a durability of holding against position aberration of the target.

B. *Improvement of gripping performance by MR fluid*

We conducted experiments to confirm the improvement in gripping performance by the MR fluid. In this experiment, the objects shown in Table 1 are used. The improvement in holding performance of the gripper was verified by applying the magnetic field to the MR fluid. We measured the gripping force by the following procedures: (1) the target object was connected to a force gauge and was clamped by the gripper; (2) the permanent magnet was positioned close to the MR fluid and solidified it; (3) the force gauge was read and the force when the gripper released the object was measured as the gripping force. Moreover, the gripping performance was evaluated in case the solidification of the MR fluid did not influence gripping performance, by skipping the second procedure. Here, the gripping force represents the drag against the downward tension, including the force of gravity. The experimental result is shown in Fig. 9. It can be seen from the results that the gripping forces increased against objects of all shapes by solidifying the MR fluid. Specifically, the Sphere and the spring were more stably gripped than the prism and the column. This is because an increase in the area of the elastic membrane coming into contact with the object helped to improve the grasping stability. In addition, it was observed that the elastic membrane slightly ate into the spirals of the spring and this phenomenon contributed to a stable grip.

C. *Gripping performance change by orientation of objects*

The change in the gripping performance of the gripper according to the change in orientation was evaluated by using a wood block, as shown in Fig. 10. The gripping performances in the orientation gripping the face and the corner of the block were evaluated. The gripping force in each orientation was measured by the same method as mentioned above. The gripping forces were 47.7 [N] and 100.5 [N] at the orientation shown in Fig. 10 (a) and (b), respectively. It is found from these experiment results that the gripping force increases when the elastic membrane deforms largely and wraps around the object.

D. *Gripping of fragile objects*

Since the developed gripper grabs a target object with the elastic membrane, and its gripping torque can be controlled, it can grip a fragile object without damaging it. We conducted

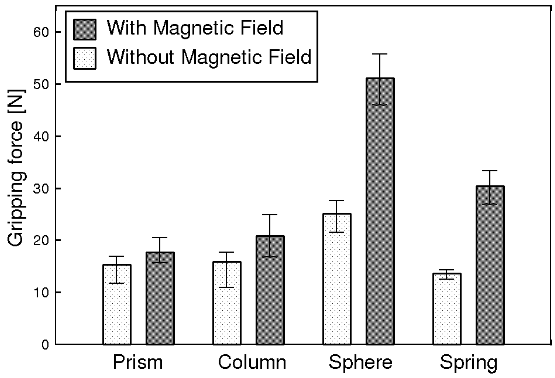
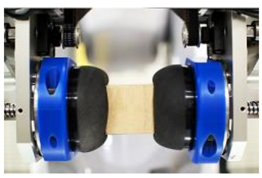
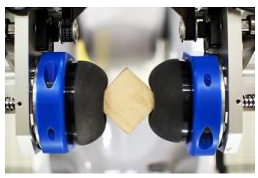


Figure 9. Improvement of gripping force for objects of various shapes due to solidification of MR fluid.





(a) The side of object. (b) The corner of object.

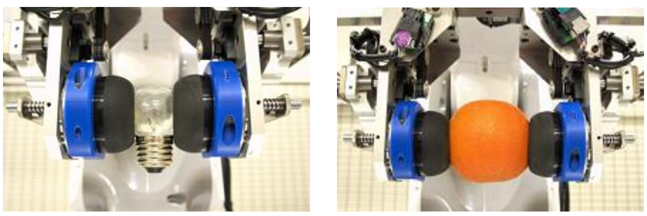
Figure 10. Change in gripping performance according to the change in grasping orientation.

gripping experiments using fragile objects; a light bulb (16 [g]) and an orange (159 [g]), in order to verify the advantage of this design. In this experiment, the clamping force of the parallel gripper was set to 17.8 [N], which is the minimum clamping force. The objects gripped by the parallel gripper are shown in Fig. 11. It can be seen from these experiments that the developed gripper is able to grip fragile objects like a light bulb and an orange stably, without damaging them.

E. Fast transport by the parallel gripper

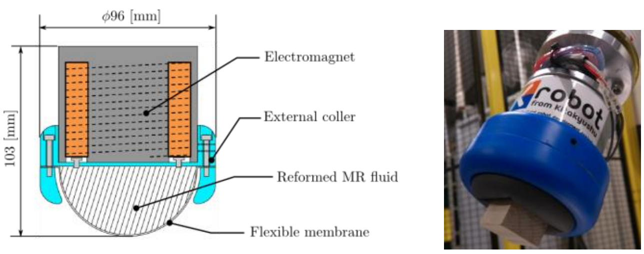
We installed the developed parallel gripper in an industrial robot and evaluated its performance with respect to fast transportation. The experimental procedure was as follows: (1) the gripper equipped on the industrial robot was moved to the gripping position and made to grip an object; (2) the object was lifted up to a height of 200 [mm]; (3) the object was transported 400 [mm] horizontally (the orthogonal direction of the clamping direction of the gripper); (4) if the object did not fall during transportation, the procedure was considered as a success. We executed this process twenty times, varying the transport speed from 200 [mm/s] to 2800 [mm/s]. The clamping force of the parallel gripper was set to 17.8 [N] and 50.0 [N]. We used a plastic bottle filled with water (644 [g]) as a target object and set its cap to the gripping point. Further, we compared the developed parallel gripper and the conventional MR fluid gripper [4]. The conventional MR fluid gripper is shown Fig. 12. In this gripper, an electromagnet is used for controlling the magnetic field. It grips objects by stiffening the MR fluid after being pressed against objects.

The experimental result is shown in Fig. 13. At first, it is found from the experimental results that the transport performance of the developed parallel gripper is better than that of the conventional MR fluid gripper. From this result,



(a) Light bulb. (b) Orange.

Figure 11. Gripping experiments on fragile objects.



(a) Structure of MR fluid gripper. (b) Overview of MR gripper.

Figure 12. The conventional MR fluid gripper.

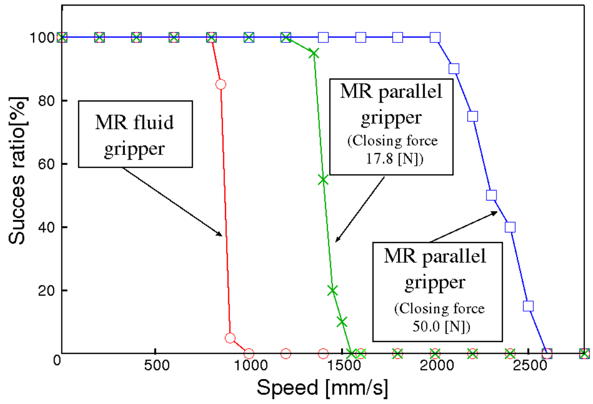


Figure 13. Experiment result of fast transport by the grippers.

it was confirmed that the gripping method for clamping the object of the developed gripper is effective for gripping an object stably. Next, it was found that the transport performance is improved by setting a large clamping force. Therefore, it was found that the developed parallel gripper grips the target by two factors: the solidification of the MR fluid after wrapping of the target by elastic membrane; i.e., "form closure," and by the clamping force; i.e., "force closure." Thus, it is considered that force closure and form closure are performed by the gripper at the same time.

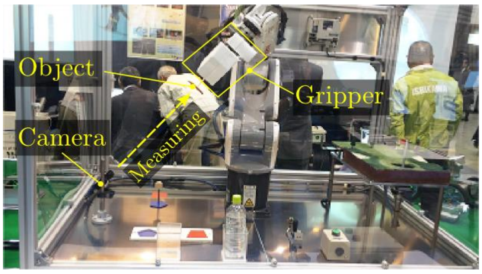
VI. Advantages for Industrial Systems

The developed parallel gripper has the following advantages.

1. The gripper simultaneously performs "form closure" and "force closure" by controlling the solidification of the MR fluid and the clamping force.
2. The gripper is able to grip complex shapes and various materials without damaging them.
3. The gripper has durability of holding the target without position aberration.
4. Stable gripping can be achieved without strictly setting the position of various materials.
5. The driving sound of the gripper is quieter than the vacuum-type robot hand.
6. The gripper can be used in dusty environments where vacuum-type robot hands cannot be.
7. This gripper withstands repeated use of one million iterations in industrial applications.

We constructed a robotic system in which the developed parallel gripper was installed and conducted demonstration program to confirm the abovementioned advantages. The overview of this demonstration program is shown in Fig. 14. In this demonstration program, the robot grips several targets, such as a golf ball, flag made of steel, non-rigid plastic bottle, and wood parts, without teaching on these individually. Specifically, we constructed a demonstration program that can move the gripper's position to the correct position with a high

(a) Gripping.



(b) Transporting and Measuring.

(c) Placing.

Figure 14. Demonstration of parallel gripper.

accuracy, even if the initial position of the wood parts had aberration.

Namely, the robot grips the target wood parts that have a position aberration as shown in Fig. 14 (a). Since the orientation of the gripping target is unknown, the position and orientation are measured by a camera, as shown in Fig. 14 (b). Finally, the gripper releases the target in the correct position with a high degree of accuracy by modifying the motion path according to the measurement. In a typical industrial robot system, the accurate measurement of the target is executed at the beginning, and the grasping and movement of the target is executed thereafter. In the constructed system, the durability of the gripper was effectively demonstrated by switching the order of accurate measurement and gripping.

VII. Conclusion

We developed an innovative parallel gripper by using a reformed MR fluid, and confirmed its various advantages in the experiments performed. The gripper simultaneously demonstrated "form closure" and "force closure" by controlling the solidification of the MR fluid and the clamping force. The gripper is able to grip to complex shapes and various materials without causing damage, and has the durability of holding objects despite position aberration of the target. The driving sound of the gripper is quieter than the vacuum-type robot hand, and the gripper can also be used in dusty environments wherein vacuum-type robot hands cannot be used. This gripper withstands repeated use of one million iterations in industrial applications. Moreover, we found that the gripping performance of the developed gripper is better than that of the conventional gripper, if a gripper moves quickly while gripping an object. In the future, we will downsize this gripper further, improve its function, and construct a mathematical model.

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