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Development of Universal Gripper with Viscous Variable Fingertip

NISHIDA Takeshi

Department of Information Systems Engineering, Faculty of Faculty of Environmental Engineering,
The University of Kitakyushu, Fukuoka, Japan
(Tel: +81-93-695-3260; E-mail: t-nishida@kitakyu-u.ac.jp)

Abstract: I developed a universal gripper for industrial robots using reformed magnetorheological (MR) fluid and consisting of two fingers able to grasp small objects. The fingertips are composed of an elastic membrane enclosing the reformed MR fluid. The fingers have a diameter smaller than 25 mm, and a magnetic flux circuit structure for changing the magnetic flux density in less than 0.1s by 0.24 T or more. A rotation mechanism of the permanent magnet allows the control of the solidification of the fingertips. Several experimental results show the effectiveness and performance of the developed universal gripper.

Keywords: universal gripper, reformed magnetorheological fluid, industrial robots

1. INTRODUCTION

Many of industrial robot's tasks consist of using a gripper to grasp and manipulate a target object. To manipulate many different targets, there are many types of grippers with different shapes and sizes. However, the ”one gripper for one object” approach requires the design, construction, and maintenance of complex industrial systems for robots faced with different targets in a short time. In addition, the low shape adaptability of the gripper not only becomes a bottleneck of multi-product variable production but also requires high accuracy of the sensor and accurate three-dimensional recognition technology of the object.

To improve the shape adaptability of industrial robot grippers, various universal grippers have been proposed [1–3]. The universal grippers proposed in many studies can be roughly classified as active or passive to grasp objects. Since many active universal grippers are being developed inspired by human hands, they are composed of fingers with many joints [4–9]. Although they have high grasping performance and manipulation abilities, they usually require complex control.

On the other hand, passive universal grippers can adapt passively to the shape of objects. A snake-like gripper [10] that conforms to the object shapes is well known as early research, and a universal gripper consists of an elastic membrane filled with granular matter able to grasp many objects without any information about the target is also well-known research [11, 12]. Furthermore, as an extension of these studies, a jamming gripper utilizing positive and negative air pressure has been developed to accurately grip and release the target [13]. Unlike active universal grippers, passive universal grippers have generally a low cost and are easy to use. Yet, their grasping ability can sometime be lacking in situations where it is not easy to grasp the object from above or when the shape of the object does not allow the gripper to have a good grasping location.

Multiple universal grippers using air pressure have been proposed such as a gripper that first press its flexible membrane against the object and then enclose it by inflating the inside of the membrane [14], a gripper using elastomer and pneumatic pressure [4], a modular soft gripper [15], and a gripper mimicking octopus' sucker that absorbs target objects due to elastomer deformation with negative pressure [16]. Alternatively, some grippers are using an incompressible fluid such as [17]. However, all these grippers fall short in their usability because they use a compressor as an actuator, meaning that they cannot perform well in dusty or hot and humid environments. In addition, their response speed of the gripping and releasing actions is slow compared to the active grippers.

A combine type universal gripper of active and passive has been proposed [18]. They designed a parallel gripper where the fingers are made of electromagnets and a membrane containing a magnetorehological (MR) fluid able to change its viscosity. The gripper [18] is capable to safely grasp objects that does not possess uniform shape like vegetables by controlling the magnetic flux density with electromagnets. The relationship between the magnetic flux density and the viscosity change of the MR fluid is nonlinear, and its viscosity saturates at a magnetic flux density of about 0.3 T [19]. However, it is difficult to generate a magnetic flux density of 0.3 T with a relatively small electromagnet that can be installed in a small size robot gripper, so the MR fluid cannot increase its viscosity to its upper limit. This hinders the development of gripper miniaturization utilizing MR fluid. Furthermore, since the membrane used for the fingers was in polyurethane resin having no long-term durability performance, there is a fatal restriction on industrial application.

In our previous work [20], we modified the MR fluid by mixing it with nonmagnetic particles of different sizes and materials. The final modified MR fluid attained a higher viscosity rise with respect to the input of magnetic flux density. We further improved our gripper by testing different surface processing and eventually applying a matte finish on the membrane surface resulting to performance improvements [21]. However, our previous grippers have difficulties to grasp objects placed on a flat surface or loaded in bulk because they require a certain clearance around a gripping object. A parallel gripper using soft fingertips to grasp objects is proposed [22]. It is including micro-grippers inside the fingertips; the complicated architecture has different gripping mode.

In this paper we propose a novel universal parallel gripper using a modified MR fluid combining the advantage of active and passive universal grippers. Our developed gripper aims to be a step toward the miniaturization of grippers, it has four principal novelties:

- The design of a fingertip membrane and the adaptation of modified MR fluid for increasing the grasp ability.
- A compact magnetic circuit using a rotating neodymium magnet capable of controlling generation and disappearance of a strong magnetic field.
- The use of hydrogenated nitrile butadiene rubber (HNBR), which was the best material that we found to resist to MR fluid's oil swelling, for the fingers' membranes.
- The control of gripping force by current measurement of motor used for parallel chuck.

The developed gripper shown in Fig. 1 can grasp various shaped objects, light and heavy one, hard or fragile.

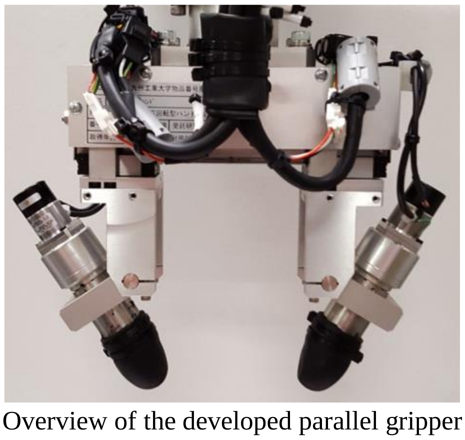
2. GRIPPER DESIGN

The proposed gripper is made of a mechanical part constituting the parallel gripper, two mechanisms controlling the dispersion of the magnetic fields, and two fingers made of a membrane enclosing a modified MR fluid. In the following section we will focus on the developed mechanism and the fingers as it is our main contribution.

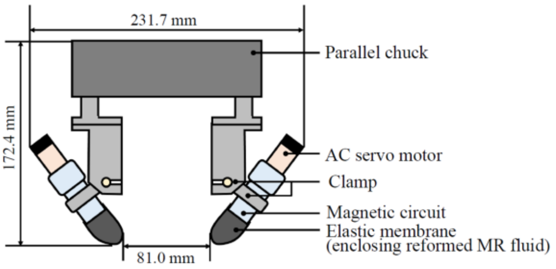
2.1 The modified MR fluid

Our gripper possesses two fingers entirely made of soft material. A finger is made of a soft membrane enclosing a modified magnetorehological (MR) fluid, and we therefore named them MR fingers. To realize the pinching work of human, we set the diameter of the MR fingers to less than 25 mm.

The principle underlying the solidification of the modified MR fluid under a magnetic field is shown in Fig. 2. The modified MR fluid consists of iron particles with diameters of a few micrometers, nonmagnetic particles, oil, and additives that prevent the precipitation of the iron particles. When a magnetic field is applied, the iron particles align themselves along the lines of magnetic flux and form a columnar structure, and the nonmagnetic particles enter the crevice between the iron column structures. When an external force is applied, the nonmagnetic particles act as an aggregate of the columnar structure of the iron particles. When a force greater than the shear stress of the modified MR fluid is applied externally, the columnar structure is destroyed and deformed. Then, when the magnetic field is removed, the iron particles revert to the random distribution state. This fluid is prepared by mixing the MR fluid and the nonmagnetic particles, and it has the following features: the solidification force with a fluxed magnetic flux density is more than two times as strong as that of the MR fluid, and the specific gravity is approximately one-half that of the MR fluid [20]. By controlling the magnetic flux, it is possible to vary the viscosity of the fingers.



(a) Overview of the developed parallel gripper



(b) Structure of the developed parallel gripper.

Fig.1 Developed parallel gripper.

2.2 Procedure of target gripping

Our developed 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 force controlled parallel chuck by current measurement of motor while the modified MR fluid is fluidized; (3) a magnetic flux is inputted to the modified 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 parallel chuck is opened and releases the object, and the magnetic flux is turned off. The high adaptation to the object shape makes large contact area or contact at concave points on object, which increases friction leading to stable grasping. Large friction allows grasping to be realized by small contact forces. Therefore, softness at surfaces is preferable for delicate grasping of fragile objects. Further, the improvement of the viscosity of the modified MR fluid can generate a high drag against the inertial force of the object generated by the quick action.

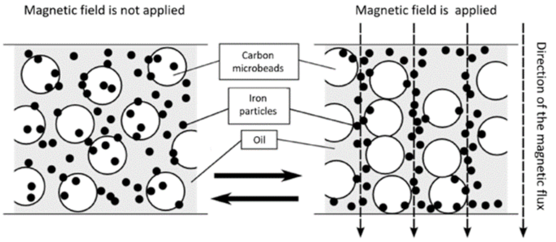


Fig.2 Solidification mechanism of the reformed MR fluid.

2.3 Relationship between magnet flux and MR fluid

Petterson et al. developed a gripper using MR fluid [18], and electromagnets were used for the control of the viscosity of MR fluid. However, the electromagnet capable of generating a magnetic flux close to 0.3 T necessary for the saturation of the solidification of the MR fluid is large and heavy, so it occupies most of the payload of the robot. Therefore, it was impossible to sufficiently solidify the MR fluid in the above research. This tradeoff between the weight and strength of magnetic flux has been overcame in our previous research [21]. In that research, we developed a mechanism to change the distance between MR fluid and neodymium magnet by using servo motor. However, since a strong magnetic flux of the neodymium magnet is always existing, problems such as precipitation of iron particles of the MR fluid and leakage of magnetic flux to the surroundings have been left. In this research, we solve these remaining problems by developing a compact magnetic circuit having little or no leaks of magnetic flux of the neodymium magnet when solidification of MR fluid is not necessary.

2.4 Membrane

The material of the flexible membrane must be selected considering various requirements, such as flexibility, durability, thickness, swelling resistance against oil, water resistance, etc.

At first, to reduce a swelling of oil content in the reformed MR fluid to the soft membrane, we conducted experiments to search for the best material. We conducted swelling tests about the following materials: silicon rubber (Q), HNBR, fluoro-rubber (FKM), an assemblage of nitrile-rubber (NBR) and polyvinyl chloride (PVC), an assemblage of Q and fluoro silicon (FQ), and an assemblage of NBR and ethylene-propylene-diene rubber (EPDM). In this experiment, we tested each soft membrane materials by enclosing the reformed MR fluid inside the membranes, then dipping them in a fluid at 100°C for 70 hours and then recording their variation of cubic volume. The results can be seen in Table 1. The NE material swelled and melted immediately after the start of the experiment. We observed that among these materials it was the HNBR one that was having the best performances with the reformed MR fluid, and we selected the HNBR material. We selected hydrogenated nitrile rubber (HNBR) for the membrane material.

Next, with reference to the results obtained from studies on robot hands with fingernails [23], we developed a soft membrane simulating the fingertip by changing the thickness of the rubber as shown in the Fig. 3. To help the fingers to keep their shapes during the grasp, the membrane shape emulates the existence of a nail by reinforcing the opposite side of the grasp of the membrane. The thickness of the soft membrane of the cylinder is 2 mm and the thickness of the part touching the target object is 0.5 mm. While grasping, the fingernail supports the opposing force from the target object. Besides, to help the MR finger to stick with the target object we applied a matte finish polishing treatment on the curved surface that is touching the target object. Finally, the upper part of the soft membrane cylinder is connected to the mechanism delivering magnetic flux to control the viscosity of the fluid.

Table 1 Experiment for MR fluid resistance.

Material	Volume change ratio [%]
Q	32
HNBR	1.9
FKM	4.0
NBR+PVC	30
Q+FQ	36
NE	-

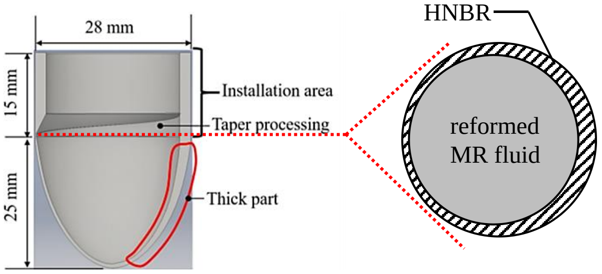
The MR fluid in the flexible membrane was filled to such a degree that a depression of about 1 mm could be formed at the contact portion of the flexible membrane with the object. The resulting MR finger is by itself a small universal gripper.

2.5 The mechanism

To change the viscosity of the modified MR fluid, it is necessary to control the magnetic flux therein. In order to the miniaturization of the gripper which can generate and annihilate of a high magnetic flux density we developed a mechanism controlling the magnetic flux in the reformed MR fluid with a rotating permanent magnet.

The mechanism we developed consists of a neodymium magnet inserted between a pair of iron yoke in the radial direction as shown in Fig. 4. The neodymium magnet has a diameter of 15 mm, a height of 25 mm, and a hole diameter of 4 mm. As for the iron yokes, they have a height of 28 mm, a thickness of 3 mm, and a cylinder shape of 100 deg. The magnet is rotated by a servo motor for change the magnetic flux density applied to the reformed MR fluid.

As shown in Fig. 5, the yokes and neodymium magnet relative position can vary from 0 deg to 90 deg. When it is decided that the relative position is of 0 deg, the reformed MR fluid is not provisioned with magnetic flux since all the magnetic fluxes are passing through the yokes. On the other hand, when the relative position of the iron yoke and the magnet is of 90 deg, the magnetic fluxes from the N pole are flowing in the direction of the length of the N pole of the yoke through the reformed MR fluid and are coming back to the S pole of the magnet after entering to the S pole of the yoke. Since the magnetic permeability of the



(a) Cross section view. (b) Cross-section view.

Fig.3 Shape of rubber.

reformed MR fluid is lower than the one of the air or the iron the magnetic field is guaranteed to flow through the fluid.

Therefore, by rotating the neodymium magnet by 90 [deg], the magnetic flux density in the reformed MR fluid can be changed from 0.24 T to zero. In order to turn the magnet, we used an AC servo-actuator (harmonic drive system, RSF-5B-100-E050-C) and an AC servo-driver (HA-680-4B-24). The resulting mechanism can change the magnetic flux density within 0.1 s. This speed response translates directly to the grasping speed of the gripper.

2.6 Magnetic field inside the MR fluid

To evaluate the performance of the developed mechanism, we simulated the magnetic field in the MR fingers when the relative angle between permanent magnet and iron yoke was changed from 0 deg to 90 deg by COMSOL Multi Physics [24]. The figure of fingertip including modified MR fluid was modelized as a cylinder of diameter and the height 25 mm. In this simulation, we assumed that the permanent magnet was neodymium, and that the remanence of the magnetic flux was 1.26 T. For the magnetic permeability of the reformed MR fluid, we set it to 3 times the magnetic permeability of the air.

The results are shown in Fig. 6. When the relative angle of the iron yokes and the magnet is 0 deg, the magnetic flux is flowing in the horizontal level with an arc shape in the iron yoke. On the other hand, at 90 deg, the magnetic flux is flowing from the iron yoke to the MR fluid and then comes back to the opposite iron yoke.

2.7 Parallel gripper

For the stable gripping and releasing of weak and small targets, a parallel gripper is made using two MR fluid fingers in oppositions. An AC servo motor has been adopted to control the opening and closing of the parallel chuck. The tilt angle of each MR finger can be adjusted up to 60 deg as shown in Fig. 7.

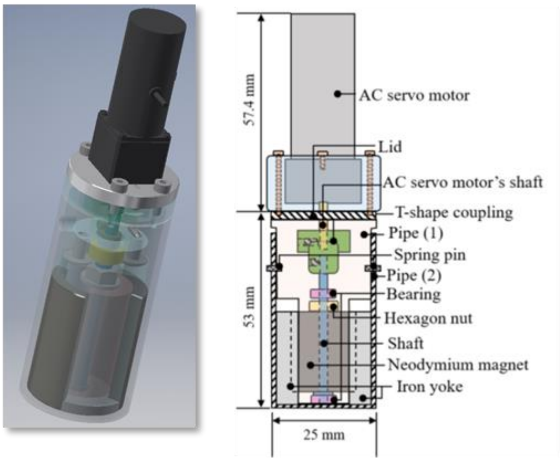
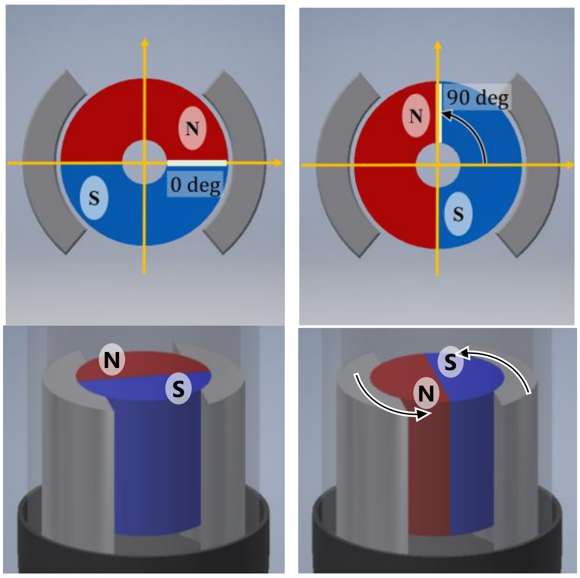


Fig.4 Structure of the developed finger of the parallel gripper. The bottom part is connected to a reformed MR fluid and an elastic membrane

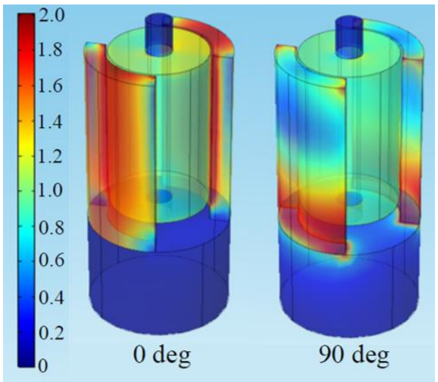
The operation sequence of this parallel chuck when mounted on an industrial robot is as follows.

1. The gripper is moved by the industrial robot so that the target object position is in between the soft membranes of both fingers.
2. The object is pinched by the parallel gripper.
3. The target gripping force is feedback controlled by

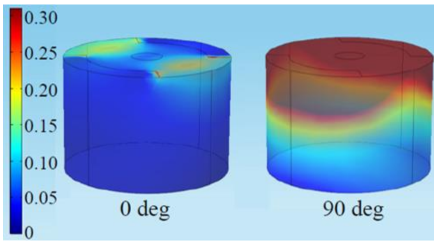


(a) 0 deg with 0 T. (b) 90 deg with 0.3 T.

Fig.5 Positional relationship between magnet and yoke view from the bottom.



(a) Simulation of the magnetic flux density in the yoke.



(b) Simulation of the magnetic flux density in the reformed MR fluid.

Fig. 6 Simulation results of magnetic flux density distribution corresponding to magnet angle. The color indicates the value of the strength of magnetic flux density [T].

using the current value in the AC servo motor.

4. The servo motors of each MR finger are rotated by 90 deg to apply a magnetic field, and the object is hold by increasing the viscosity of the soft membrane.
5. The object is transported to the target position by the robot.
6. The parallel chuck is opened at the target position and the object is released.

The two fingers enclose a part of the object and creates a firm grasp. Thus, by combining the design of a parallel gripper with the MR fingers, we developed a gripper classified in between active and passive universal gripper.

3. EXPERIMENTS

To validate the performances of the developed gripper, we conducted several experiments where the gripper had to grip many objects in different situations.

3.1 Gripping of different shape and material

The first experiment was to verify that our developed gripper was able to grip fragile objects without breaking them. We used a quail egg, a cookie, a light bulb, and a simmered boiled Japanese radish to verify the gripping performance (Fig. 8). They have various shapes with various materials, the surface is wet, slippery, or fragile. The gripper always succeeded in gripping without hurting the object. In particular, the gripper was able to grip the cookie which was placed on the workbench. Furthermore, it is difficult task for a universal gripper to stably grasp objects in liquid. However, the developed gripper succeeded in stably grasping the radish soaked in the soup.

Next, we conducted an experiment to grip a wooden ball with our gripper (Fig. 9). The gripper was able to grip the sphere not only in the equatorial part but also in a more slippery situation where the gripper was grasping from the upper part of the sphere. This experiment demonstrated the robustness for positional deviation and slippery of the developed gripper.

Moreover, since it is not uncommon for robots to grasp objects in a way that generates a rotational torque to the gripper, it is important for the gripper to compensate this torque for the stabilization of the grip. To evaluate the oppositional force against the torque generated by the rotation of an object, we conducted an experiment where the gripper had to grip a cucumber with a rotational torque applied to the gripper. It should be noted that the cucumber surface was uneven. The gripper gripped the edge of the cucumber in a normal operation sequence and lifted. Thereafter, by returning the permanent magnet to 0 [deg] by the servo motor, the magnetic flux in the MR fluid was suppressed and the change in the gripping state was observed. It is found from Fig. 10 (a) that the cucumber kept the same posture that when it was put on the workbench by the high viscosity state of the MR finger. On the other hand, after attenuating the magnetic flux density in the MR fluid and the viscosity of the membrane of the MR finger decreased, the attitude of the cucumber could not be maintained after (Fig. 10 (b)). Namely, this experiment shows that the developed gripper has an opposition force against a rotational torque and can keep the position of the object when it has a high viscosity.

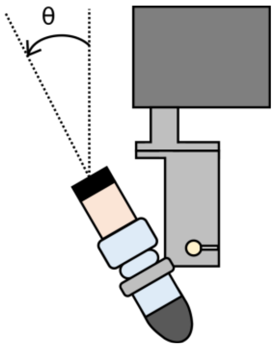


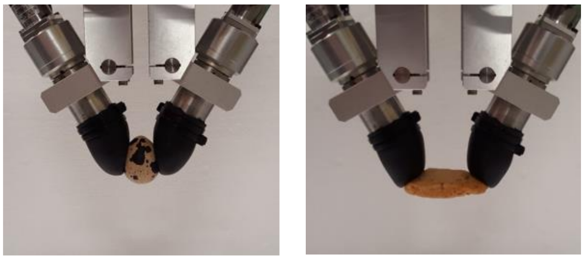
Fig. 7 The finger can adjust the angle θ up to 60 deg.

3.2 Gripping performances

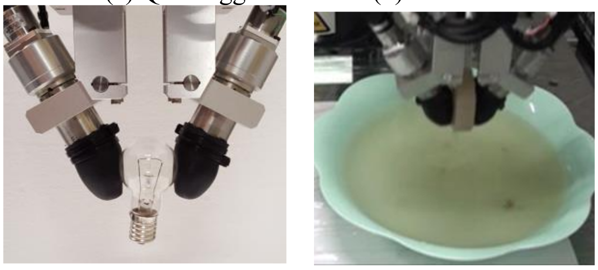
To evaluate the performances of the MR fingers when the reformed MR fluid is in a state of a high viscosity, we executed the following process:

1. Target object is griped by the parallel gripper, the target object is connected to a force gauge.
2. A magnetic field is impressed to increase the viscosity of the fingertip.
3. The force gauge was pulled vertically and the maximum force until the object was released was measured.

Besides, we executed the exact same experiments without doing step 2), and then we compared the results of both experiments to measure exactly the contribution of the reformed MR fluid. In the experiment of the grasping of targets, we used three different objects: a wooden cube of side length 30 mm, an identical wood cube which has been processed to have a gutter of depth 3 mm and width 4 mm (wood cube with groove processing), and a wood bobbin with a flange diameter of 23 mm, an inside width of 25 mm, and a shell diameter of 11.35 mm. For the wooden cube and the wood cube with groove processing, we executed gripping experiments of the objects from two opposite faces. The bobbin cube was gripped from the upper flat surface. We executed 10 times the experiment for each object and collected the results as shown in Fig. 11. First, in all experimental results, it was confirmed that when the magnetic field was applied, the gripper's gripping force improved. Next, when comparing the grasping forces about the two types of wood cube with different surface roughness, it is found that the gripping ability is increased against complicated shape objects by the adaptation ability of the membrane. We predict that this phenomenon is connected to the fact that the hardness of the soft membrane made of HNBR is 55 HA. On the other hand, the gripping force of the bobbin in a state of high viscosity of the reformed MR fluid or in a state of low viscosity were always higher than when the gripper is grasping the cubes. We conjecture that this is due to the shape constraint generated by the wrapping of the soft membrane on the bobbin to raise it. These experiments demonstrate that our developed parallel gripper is performing even better when

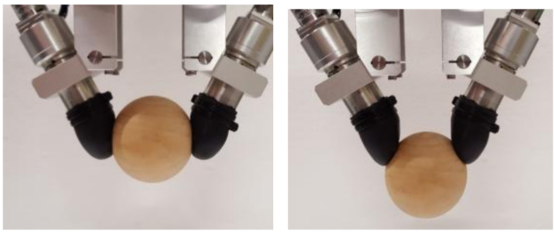


(a) Quail egg. (b) Cookie.



(c) Light bulb. (d) Simmered radish

Fig. 8 Examples of different objects being grasped by our proposed gripper. All the objects are easily broken and should usually require a force sensor to safely grasp them. However, the gripper MR fingers are made from soft components meaning that they can smoothly adapt to the shape of the object and apply a uniform force towards all the surface of the object.



(a) (b)

Fig. 9 Overview of a gripping of a wood sphere. The gripper can grasp the sphere even from a small angle due to the high viscosity of the fingers. (a) Grasp of the equatorial part of sphere, (b) Grasp of the upper part of sphere.

the fingers are wrapping around small objects.

4. CONCLUSION

We developed a novel universal robot gripper able to safely grip fragile objects as much as various shaped objects. The gripper is constituted of a parallel chuck equipping two MR fingers. The developed compact magnetic circuit which changes the magnetic density by a rotating mechanism allows the gripper to deliver quickly a high magnetic flux density to the MR fluid resulting to a high grasping force. Since the neodymium magnet is adopted, the developed gripper has a faster response speed than the conventional universal gripper and has a compact size. To demonstrate the performances of the proposed gripper, we executed several grasping experiments. The gripper was able to grip various shaped objects and even objects inside a liquid. Further, the gripper keeps the frictional force between the flexible membrane and the target object by increasing the viscosity of the fingertip after gripping the target. Therefore, even if the gripper grips the position which is different from the center of gravity, the gripped posture of the target can be kept. Finally, it was found from the last experimental results that the developed parallel gripper demonstrates higher gripping force against complex figures and surface through.

(a) High viscosity state.

(b) Low viscosity state.

Fig. 10 Overview of gripping of a cucumber for demonstration of the gripper ability to oppose the rotational torque of the grasped objects. (a) In a high viscosity state (when the reformed MR fluid is activated) the fingers can perfectly counteract the rotational torque. (b) In a low viscosity state (when the magnet is not generating any magnetic field to the reformed MR fluid) the gripper is unable to prevent the rotation of the grasped object. However, the gripper is still able to seize it, the object does not fall.

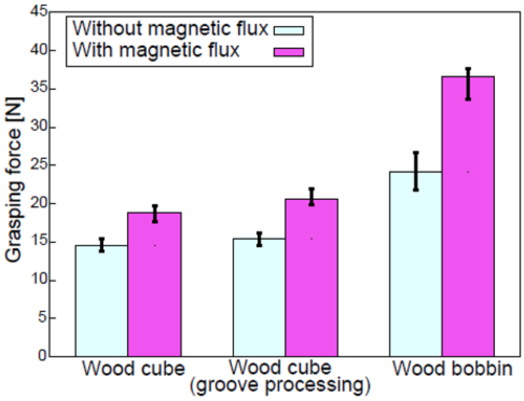


Figure 11. Changes of the gripping force due to the viscosity change of the reformed MR fluid and the shape of the target.

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