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Paper:

Design and Fabrication of Micro Gripper Using Functional Fluid Power

Yutaka Tanaka*,†, Ryuta Suzuki*, Kazuya Edamura, and Shinichi Yokota*****

*Hosei University
2-33 Ichigaya-Tamachi, Shinjuku-ku, Tokyo 162-0843, Japan
†Corresponding author, E-mail: y_tanaka@hosei.ac.jp
**New Technology Management Co., Ltd., Tokyo, Japan
***Tokyo Institute of Technology, Yokohama, Japan
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Gripping and holding mechanism of automated systems in manufacturing and distribution industries are required to flexibly accommodate various product shapes. In recent years, the gripping and holding mechanisms using jamming transition have been attracting attention because they can grasp objects of various shapes. The jamming gripping mechanism generally requires a mechanical vacuum pump to adjust the internal pressure of the gripping part, and it is difficult to miniaturize the system. An electro-conjugate fluid (ECF), a type of functional fluid, can generate a strong jet flow by applying a high DC voltage between the positive and negative electrodes. The ECF jet flow has a great potential to realize micro fluid power sources. In this paper, we proposed and prototyped a new type of small gripping and holding mechanism that uses the jet flow generated by the ECF and the jamming of granular material. A prototyped micro gripper had an outer diameter of 14 mm, a total length of 40 mm, and a tip diameter of 10 mm for gripping. A mathematical model of the micro gripper was derived by deformation of an elastic membrane and volume and pressure changes. It was verified by the mathematical model that the supplied pressure of the ECF hydraulic power source was large enough to realize gripping performance of the prototyped jamming gripper. The performance of the prototype micro gripper was numerically and experimentally evaluated the mathematical model. It was experimentally clarified that a maximum holding force of the prototyped jamming gripper was shown under the condition that filling rate of granular material was 50%. It was also clarified that the micro gripper with a built-in vacuum pump using the ECF hydraulic power source had a gripping force of up to 93 mN at an applied DC voltage of 4 kV.

Keywords: electro-conjugate fluid, functional fluid, jamming gripper, micro gripper, soft actuator

1. Introduction

Grippers that are attached to the tip of industrial robots to grip, hold, and transport objects are generally designed for each work object. In order to automate the system and improve work efficiency, it is desired to realize a highly versatile soft gripper that can accurately grasp objects of various materials, sizes, and shapes [1–3].

There are many studies of soft actuators and robots using new materials and phenomenon. Research on soft grippers that imitate octopus [4, 5] or tree frog suckers [6] were conducted. Seki et al. [7] prototyped a micropump using the Electro-hydrodynamics (EHD) phenomenon for small fluid-driven robots. Thongking et al. [8] proposed a flexible gripper using multi-layered dielectric elastomer actuators and gripped various objects. Matsuoka et al. [9] proposed and prototyped a soft actuator using a gas/liquid phase change phenomenon and experimentally investigated its operating characteristics. A three-fingered gripper with flexure hinges actuated by shape memory alloy (SMA) wires was designed and prototyped by Maffiodo and Raparelli [10].

In addition, many soft actuators have been proposed and prototyped that use a phase change (jamming transition phenomenon) that occurs with a change in internal pressure by encapsulating powder in a flexible film [11–14]. Empire Robotics [15, 16] has been one of the first companies to attempt to provide research directions and maximize research impact through efforts to commercialize jamming-based robotic gripper technology in products. The soft gripper using the jamming transition phenomenon for remote control of the injection needle in computed tomography (CT) has been proposed and developed by Yokouchi et al. [17]. Soft grippers and actuators based on the jamming of granular material, however, require a large-scale vacuum pump for adsorption.

An electrical conjugate fluid (ECF) [18] can realize a very small size of hydraulic power source with a simple structure and no moving parts by using the ECF jet flow generated by applying a high voltage between the electrodes. Yokota et al. [19–22] proposed and prototyped a gyroscope, gyro-motor, and micro-motor using the ECF jet. They clarified that the ECF was suitable for

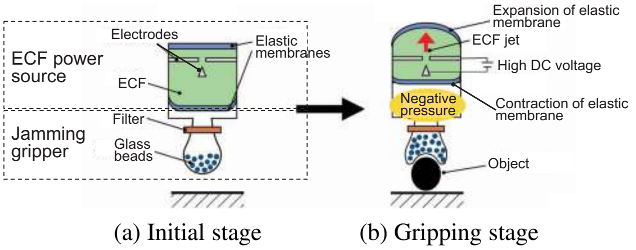


Fig. 1. Structure and principle of micro gripper with the ECF power source and the jamming gripper.

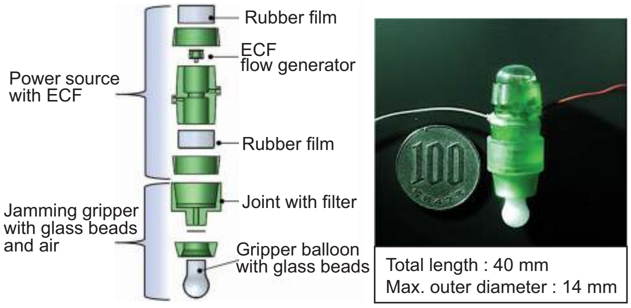


Fig. 2. Structure of the prototyped micro gripper.

miniaturization of actuators. Kim et al. [23] proposed and prototyped a high-power ECF hydraulic power source by integrating the electrodes of the ECF micropump using MEMS technology. Kim et al. [24] have also proposed a micro-lens that moves an elastic membrane using the fluid power of an ECF micropump. Tokida et al. [25] have proposed and developed a flexible actuator with an elastic film using the ECF jet generator. A suction actuator with a pressure source has been proposed and developed by using the ECF jet hydraulic power source [26].

The ECF jet has a great potential to realize micro fluid power sources. In this paper, the principle and mathematical model of a newly prototyped micro gripper with a built-in small hydraulic pressure source using the ECF jet have been proposed and prototyped. The jamming-based gripper has been applied to the development of the micro gripper. Evaluation results of operating performance for the micro gripper has been reported.

2. Structure and Principle of the Micro Gripper

2.1. Structure and Principle

Figure 1 shows a principle of a micro gripper using functional fluid power. The micro gripper consists of an ECF hydraulic power source with an ECF jet flow generator and a small jamming gripper. The top and bottom of the ECF hydraulic power source body are covered with an elastic thin film made of silicon and the internal ECF moves up and down in the body. The jamming gripper is a bag made of silicon elastic film and glass particles (particle size of 90–106 μm) are filled inside the elastic film with a spherical tip. A filter is installed at the boundary of the connection between the ECF hydraulic power source and the jamming gripper to prevent backflow of glass particles in the elastic film with the spherical tip of the jamming gripper.

From the initial stage shown in **Fig. 1(a)**, an object is pressed against the tip of the gripper to deform it according to its shape. After that, a voltage is applied between the electrodes inside the ECF hydraulic power source, a fluid pressure is generated by the ECF jet, and the upper elastic film expands and deforms. The ECF below the electrode moves to the top of the electrodes. As a result, the space below the ECF hydraulic power source expands,

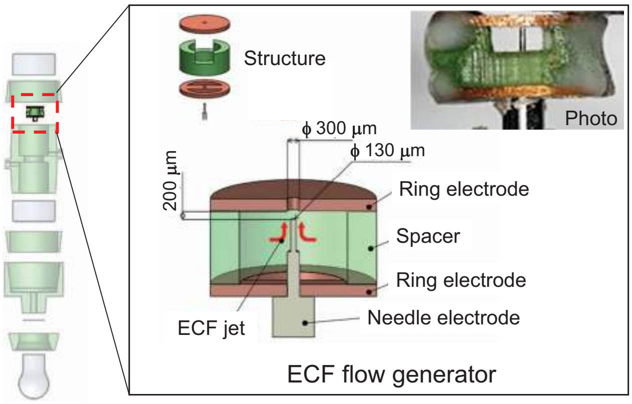


Fig. 3. Structure of the ECF jet flow generator in the ECF power source.

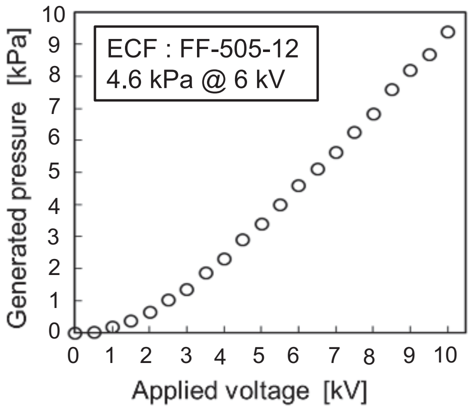
the volume increases, and the internal pressure drops below the atmospheric pressure. As the pressure drops, the particles inside the jamming gripper undergoes a phase change and solidifies. Finally, the jamming gripper holds and grips the target object during the gripping stage shown in **Fig. 1(b)**.

Figure 2 shows the overall configuration and shape photograph of the prototyped micro gripper. The total length and the outer diameter of the micro gripper are 40 mm and 14 mm, respectively.

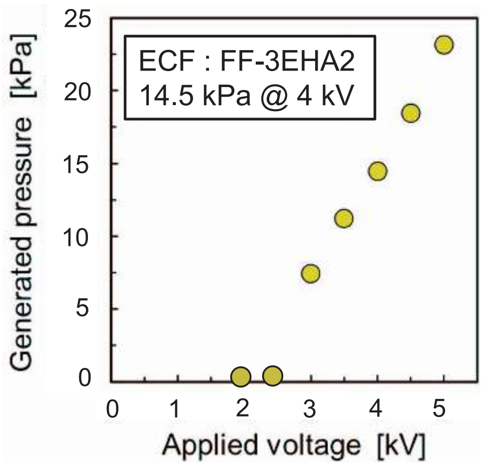
2.2. Performance of the ECF Jet Flow Generator

Figure 3 shows the structure of an ECF jet flow generator inside the ECF hydraulic pressure source. The ECF jet flow generator consists of a ring-shaped negative electrode with a hole diameter of 300 μm in the center, a needle-shaped positive electrode with a tip diameter of 130 μm, and a ring-shaped plate with two crescent inflow holes. Each plate of the electrodes has a thickness of 300 μm. The needle-shaped electrode is inserted into the ring-shaped plate with the crescent inflow hole. The needle-shaped positive electrode and the ring-shaped negative electrode are arranged by adjusting the distance between the electrodes with a non-conductive spacer so that the distance between the electrodes is maintained at 200 μm.

Figure 4 shows the experimental results of the generated pressure according to two types of the ECF when a



(a) FF-505-12



(b) FF-3EHA2

Fig. 4. Static characteristics of generated pressure for the ECF jet flow generator.

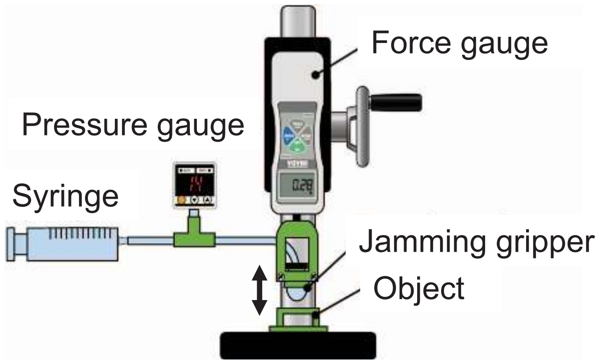


Fig. 5. Experimental setup for measurement of the jamming gripper.

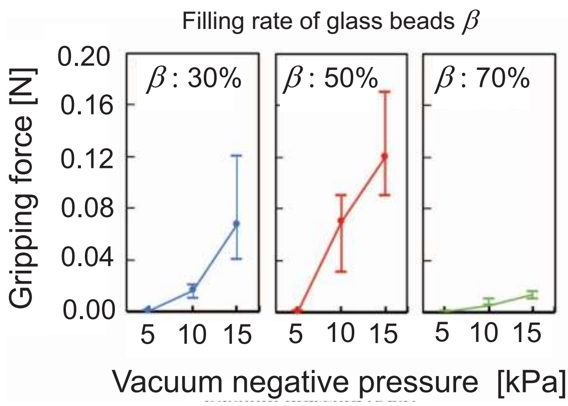


Fig. 6. Experimental gripping performance for the jamming grippers.

voltage is applied to the ECF jet flow generator. There are many types of ECF for commercially available. In our experiments, a type of FF-505-12 was selected as the fluid with high stability and a type of FF-3EHA2 was selected as the fluid with obtained large output. **Figs. 4(a)** and **(b)** show the results of using the FF-505-12 and the FF-3EHA2 for ECF, respectively. The generated pressure of the FF-3EHA2 could not be obtained because the generated flow was not stable until the applied voltage was 2.5 kV. The generated pressure was almost proportional to the applied voltage. In the case of FF-505-12, a generated pressure of 4.6 kPa was obtained when 6 kV was applied, and in the case of FF-3EHA2, a generated pressure of 14.5 kPa was obtained when 4 kV was applied.

2.3. Performance of the Jamming Gripper

The jamming gripper consists of a flexible membrane filled with a granular material that can passively adapt to the shape of the target object. By adjusting the air pressure in the membrane, the jamming gripper can rapidly harden or soften for gripping objects of various sizes and shapes. When the particles are in unjammed state, the gripper can be pressed against the target object, whereby the particles can flow to match the shape of the object. Air can then be evacuated from within the membrane, inducing a jammed state in the particles to grip the object rigidly.

Figure 5 shows an experimental device for measuring the gripping performance of the small jamming gripper. In the measurement experiments, the jamming gripper with the tip diameter of 7 mm was fixed to the tip of the force gauge using a jig. A cylindrical object with a diameter of 2 mm and a length of 15 mm was pressed against the flexible membrane tip of the jamming gripper to deform according to the shape of the object. After that the object was gripped while gradually decreasing the internal air pressure of the membrane from the atmospheric pressure using a syringe. Then, while pulling the object upward by the force gauge, the maximum force was measured until separating the object and the tip of the gripper. The experimental conditions are the filling rate of glass particles β inside the jamming gripper and the negative pressure p_g set by the syringe.

Performance measurement experiments were carried out on five handmade small jamming grippers. As the particle size that fills the flexible membrane, 100 μm nominal glass beads were selected based on the results of preliminary experiments. In the experiments for gripping performance, five cases of the jamming grippers were measured. Experimental measurement results were shown in **Fig. 6**.

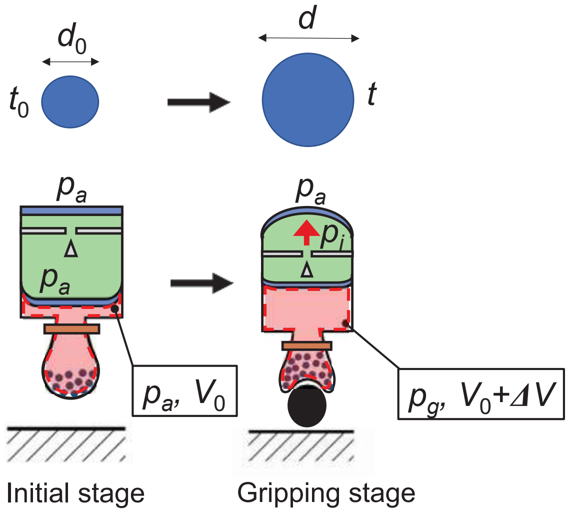


Fig. 7. Mathematical model of the micro gripper.

In **Fig. 6**, plots are arithmetic mean value, and horizontal error bar of upper and lower is maximum and minimum of the measured values, respectively. Since the prototyped jamming gripper was handmade, there were variations in the five measurement results. The object gripping force of the prototype jamming gripper increased almost in proportion to the negative pressure p_g. The maximum gripping force was shown under the condition that the filling rate of glass particles β was 50% of the membrane volume. It was also confirmed that the pressure changes of 15 kPa showed the average gripping force of about 120 mN. The effects of particle size and filling rate on the gripping performance are for further study.

3. Mathematical Model of the Micro Gripper

In this section, when the ECF hydraulic power source and the small jamming gripper are integrated to manufacture the micro gripper, it is investigated by a mathematical model whether the volume change by the ECF hydraulic power source can obtain sufficient gripping performance by the small jamming gripper.

A mathematical model of the micro gripper between the initial and gripping stages are shown in **Fig. 7**. Physical variables for the mathematical model are tabulated in **Table 1**. If Laplace's law for thin-walled elastic spherical shells [27] is applied to the deformation of the ECF hydraulic power source due to an elastic membrane, the following Eq. (1) is derived.

$$\Delta p = p_i - p_a = \frac{4\sigma t}{d}, \quad \dots\dots\dots\dots \quad (1)$$

where p_i is a pressure generated by the ECF hydraulic power source (internal pressure of a thin-walled elastic spherical shell), p_a is a pressure outside a spherical shell (atmospheric pressure), σ is a tensile stress acting on the elastic membrane, t is a film thickness, and d is an inner diameter of the spherical shell.

Table 1. Physical variables for mathematical model of the micro gripper.

Variables	Numerical values
Diameter of elastic membrane: d	
Initial diameter of elastic membrane: d_0	11.5 mm
Diameter ratio ($= d/d_0$): α	
Tensile stress of elastic membrane: σ	
Elastic film thickness: t	
Initial elastic film thickness: t_0	0.2 mm
Young's modulus of elastic membrane: E	2 MPa
Internal pressure by ECF power source: p_i	
External pressure (atmospheric pressure): p_a	100 kPa
Internal pressure in jamming gripper: p_g	
Initial volume of jamming gripper: V_0	
Volume change of jamming gripper: ΔV	

Assuming that the elastic membrane is incompressible like rubber and the Poisson's ratio is 0.5 [28], the tensile stress σ acting on the elastic membrane is given by the following Eq. (2).

$$\sigma = 2E\frac{d-d_0}{d_0}, \quad \dots\dots\dots\dots \quad (2)$$

where E is the Young's modulus of the elastic membrane, and d_0 is the initial inner diameter of the spherical shell.

Since the elastic film is assumed to be incompressible, the volume does not change before and after deformation. Therefore, if the initial film thickness is t_0, the film thickness t is given by the following Eq. (3).

$$t = \left(\frac{d_0}{d}\right)^2 t_0. \quad \dots\dots\dots\dots \quad (3)$$

If the inner diameter ratio d/d_0 is α, the pressure difference Δp is given by the following Eq. (4) using Eqs. (1)–(3).

$$\Delta p = \frac{8Et_0}{d_0}\left(\frac{1}{\alpha^2} - \frac{1}{\alpha^3}\right). \quad \dots\dots\dots \quad (4)$$

Figure 8 shows the relationship between the pressure difference Δp and the inner diameter ratio α using Eq. (4). Here, the calculation was carried out that the value of the Young's modulus E for the elastic film was 2×10^6 Pa with reference to the Young's modulus value of general rubber [29], the value of the initial thickness t_0 for the elastic film was 2×10^{-4} m by actual measurement, and the value of the initial inner diameter d_0 for the spherical shell was 11.5×10^{-3} m from the design value.

When pressure difference Δp rises, the inner diameter ratio of the spherical shell increases. It can be seen that the thin-walled elastic spherical shell expands to 1.5 times the initial inner diameter d_0 of the spherical shell at pressure difference of 41.2 kPa.

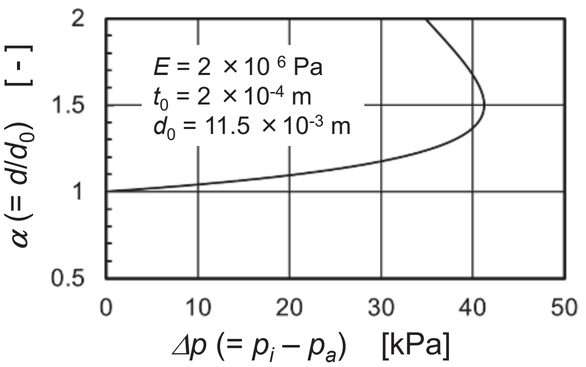


Fig. 8. Diameter change of the elastic membrane for pressure of the ECF power source.

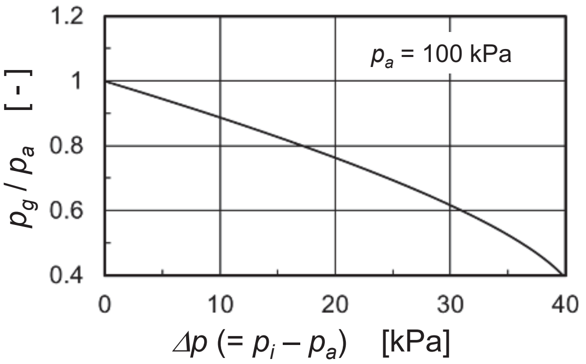


Fig. 9. Negative pressure change in the jamming gripper for pressure of the ECF power source.

Next, it is considered that the expansion of the spherical shell of the upper elastic membrane by the ECF hydraulic power source directly corresponds to the increase in the volume of the lower part. The volume change rate of the jamming gripper part $\Delta V/V_0$ is given by the following Eq. (5) as a function of the volume change of the spherical shell.

$$\frac{\Delta V}{V_0} = \left(\frac{d}{d_0}\right)^3 - 1. \quad (5)$$

As for the pressure change due to the volume change of the jamming gripper, the following Eq. (6) is derived between the initial stage and the gripping stage, assuming that the volume change of air is an isothermal change.

$$p_a V_0 = p_g (V_0 + \Delta V). \quad (6)$$

From Eqs. (5) and (6), the internal pressure of the jamming gripper based on the atmospheric pressure p_g/p_a is given by the following Eq. (7).

$$\frac{p_g}{p_a} = \left(\frac{1}{\alpha}\right)^3. \quad (7)$$

Figure 9 shows the relationship between the internal pressure of the jamming gripper and the generated pressure of the ECF hydraulic power source obtained from Eqs. (4) and (7). It was estimated from the mathematical model that when the generated pressure p_i of the ECF hydraulic power source was about 15 kPa at the gauge pressure, the internal pressure of the jamming gripper decreased by about 20% with respect to the atmospheric pressure p_a. This pressure change is large enough to realize the gripping performance of the prototype jamming gripper described in Section 2.3.

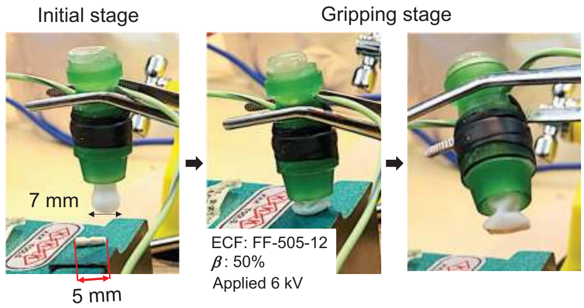


Fig. 10. How to grip the target object by the micro gripper.

4. Experimental Evaluation for Gripping Performance of the Micro Gripper

An experiment was conducted to quantitatively evaluate the gripping performance of the micro gripper integrated the ECF hydraulic power source and the small jamming gripper.

Figure 10 shows how to grip the target object. The jamming gripper had the outer diameter of 7 mm at the tip, the filling rate of glass particles of 50%, and the ECF FF-505-12 was used as the functional fluid for the ECF hydraulic power source. The response time of the thin rubber film by the ECF jet flow in the ECF hydraulic power source was about 0.6 s from the analysis of the video for the expansion process. The object to be gripped was a wooden cylinder with a diameter of 1 mm and a total length of 5 mm. The tip of the jamming gripper was deformed and gripped the object.

An experimental equipment for measurement of gripping characteristics is shown in **Fig. 11**. In the measurement experiment, the micro gripper was first fixed to the upper part of the force gauge. Next, we attached the object to be grasped to the tip of the force gauge. We slowly moved the force gauge from below to bring it closer and pressed the tip of the gripper against the object with a force of 1 N from below to deform it. A voltage of 4 kV was applied to grip the object. After that, while slowly pulling down the force gauge, the change in force indicated by the force gauge at that time was measured with a sampling cycle of 0.1 s.

In the experiments, the jamming gripper had the outer diameter of 10 mm at the tip, a mass of glass particles of 410 mg, the filling rate of glass particles of 50%, and the ECF FF-3EHA2 was used as the functional fluid for the ECF hydraulic power source. The object to be gripped was a resin cylinder with a diameter of 2 mm and a total

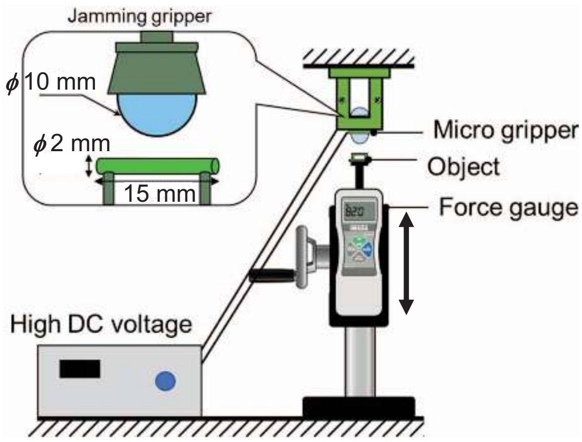


Fig. 11. Experimental setup for measurement of the micro gripper performance.

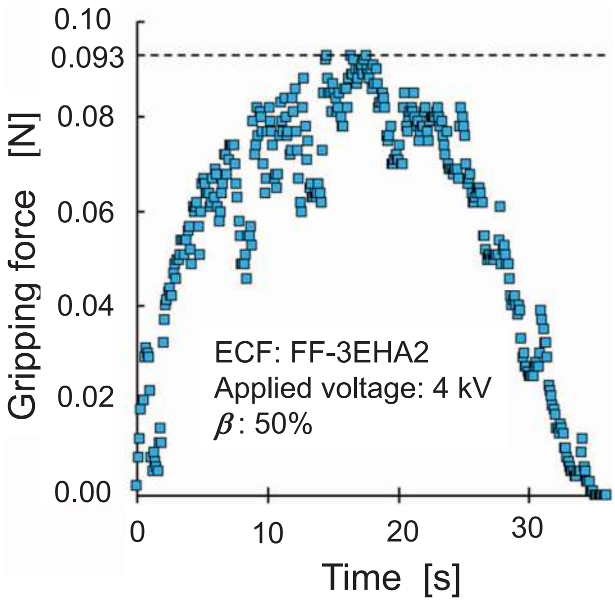


Fig. 12. Experimental measurement for gripping performance of the micro gripper.

length of 15 mm.

Measurement results of gripping performance were shown in **Fig. 12**. The gripping performance in **Fig. 12** shows the measurement results when the developed micro gripper was gripping the target object and the downward force was then applied to pull it off. Since the force gauge was manually operated in the vertical direction, the measured values fluctuated slightly. When a 4 kV voltage was applied, the gripped object did not come off even if it was pulled downward with a force of up to 93 mN. When the gripping force reached the maximum value and then continued to be pulled downward for more than 20 s, the gripping tip of the jamming gripper was gradually deformed and the contact area between the object and the gripper tip changed. As a result, the force measured by the force gauge decreased, and finally the object separated in about 35 s.

5. Conclusions

In this study, we have proposed the structure and principle of the micro gripper that integrates the drive source using the functional fluid ECF as the hydraulic power source and the small jamming gripper. The mathematical model of the operating principle was derived and the validity of the gripping performance of the micro gripper was investigated from the preliminary experiment to confirm the performance of the small jamming gripper.

We also prototyped the micro gripper with the outer diameter of 14 mm and the total length of 40 mm, which consists of an ECF hydraulic power source and the small jamming gripper. As results of the gripping performance evaluation experiment, it was clarified that the micro gripper with the built-in vacuum pump using the ECF hydraulic power source has the gripping force of up to 93 mN at the applied voltage of 4 kV.

Acknowledgments

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Name:
Yutaka Tanaka

Affiliation:
Professor, Faculty of Engineering and Design, Hosei University

Address:
2-33 Ichigaya-Tamachi, Shinjuku-ku, Tokyo 162-0843, Japan

Brief Biographical History:
1985- Research Associate, Tokyo Institute of Technology
1991- Lecturer, Hosei University
1992- Associate Professor, Hosei University
2002- Professor, Hosei University

Main Works:
• "Hydro-Disk-Type of Electrorheological Brakes for Small Mobile Robots," Int. J. of Hydromechatronics, Vol.4, No.2, pp. 99-115, 2021.
• "Characteristics of Hydraulic and Electric Servo Motors," Actuators, Vol.11, Issue 1, 11, 2022.

Membership in Academic Societies:
• Japan Fluid Power Systems Society (JFPS)
• Japan Society of Mechanical Engineers (JSME)
• Society of Instrument and Control Engineers (SICE)

Name:
Ryuta Suzuki

Affiliation:
Graduate School of Engineering and Design, Hosei University

Address:
2-16 Ichigaya-Tamachi, Shinjuku-ku, Tokyo 162-0843, Japan

Brief Biographical History:
2016-2019 Undergraduate Student, Hosei University
2020- Graduate Student, Hosei University
2021- Canon Inc.

Main Works:
• "Design and Fabrication of Micro Gripper using Electro-conjugate Fluid," Proc. of Mechanical Engineering Congress Japan, J11113, 2020.

Name:
Kazuya Edamura

Affiliation:
CEO, New Technology Management Co., Ltd.

Address:
2-9-1-306 Higashi-Shinkoiwa, Katsushika-ku, Tokyo 124-0023, Japan

Brief Biographical History:

1976- Graduate Student, Tokyo Institute of Technology
1978- Chemist in Research Lab., Kyowa Hakko Kogyo Co., Ltd., etc.
1985- Product Manager, Diagnostics Department, Boehringer Mannheim Japan, etc.
1995- CEO, New Technology Management Co., Ltd.

Main Works:

- Formulation of intelligent fluids
- Electro-conjugate fluid (ECF)
- MR fluid technology
- Organic/inorganic composite particle ERF, partly author (supervision of K. Koyama)
- Development of Electro Rheological Fluid (CMC Publishing Co., Ltd., 1999)

Membership in Academic Societies:

- Japan Society of Mechanical Engineers (JSME)

Name:
Shinichi Yokota

Affiliation:
Professor Emeritus, Precision and Intelligence Laboratory, Tokyo Institute of Technology

Address:
4259 Nagatsuta-cho, Midori-ku, Yokohama, Kanagawa 226-8503, Japan

Brief Biographical History:

1975- Research Associate, Research Laboratory of Precision Machinery and Electronics, Tokyo Institute of Technology
1986- Associate Professor, Precision and Intelligence Laboratory, Tokyo Institute of Technology
1995-2015 Full Professor, Precision and Intelligence Laboratory, Tokyo Institute of Technology

Main Works:

- "New construction of an electro-conjugate fluid-jet driven micromotor with an inner diameter of 2 mm," Proc. of the Institution of Mechanical Engineers (IMechE), Part I: J. of Systems and Control Engineering, Vol.220, No.4, pp. 251-256, 2006 [Donald Julius Groen Prize 2006 from IMechE].
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Membership in Academic Societies:

- Japan Society of Mechanical Engineers (JSME), Fellow
- Japan Fluid Power System Society (JFPS), Fellow
- Japan Society of Applied Electromagnetics and Mechanics (JSAEM)