Abstract— An electro-conjugate fluid (ECF) is a kind of functional fluid, which produces a jet flow (ECF jet) when subjected to high DC voltage. It is known that a strong ECF jet is generated under nonuniform electric field, for example, the field with a pair of needle and ring electrodes. This study introduces the ECF jet to develop a novel flexible robot hand. First, we characterize the ECF jet generator which could be a micro fluid pressure source of the robot hand, and confirm the effect of the variation of electrode parameters and the number of electrode pairs on its performance. Next, we investigate the characteristics of the robot finger which mainly consists of the ECF jet generator, a flexible rubber finger and an ECF tank. The robot finger is integrated with the pressure source (ECF jet generator) and the tank, and is successfully driven. Finally we developed a five-fingered flexible robot hand and demonstrate that the robot hand can grasp some objects with various shapes without any complex controller. The height, the width and the mass of the robot hand are approximately 60 mm, 40 mm and 15 g, respectively.

I. INTRODUCTION

Application areas of robotics and mechatronics have been spreading especially in the last two decades, which means robots are now widely used not only in industrial fields but in the field more close to our daily lives. Hence, a robot hand is getting much interest of researchers in the field of medical, amusement and man-machine cooperation etc. A common subject for such robot hands is to be small enough in size, lightweight and flexible which means passive compliance.

However it is difficult to realize a robot hand fulfilling these requirements through the use of conventional power source. For example, a servomotor, which is widely used as a power source for robot hand, produces an accurate motion, but plural servo motors are required as increasing the number of degree of freedom [1]-[2]. Therefore servomotors are inappropriate actuator when downsizing and lightening a robot hand. Also, constructive flexibility is difficult to be realized with this kind of actuator. Another example is a pneumatic soft actuator [3]-[4]. It mainly consists of a fiber-reinforced rubber tube and a pneumatic power source. The actuator could be flexible, however, it requires a bulky power source besides the actuator itself. Therefore the entire system must be large. A shape memory alloy (SMA), an ultrasonic motor (USM), an ionic polymer-metal composite (IPMC), etc. have recently received attentions as power source for a robot hand [5]-[7].

A SMA is a kind of alloy having a shape memory effect (SME). Even though the alloy may deform in the low temperature phase, it recovers its original shape by the reverse transformation upon heating to a critical temperature called the reverse transformation temperature. Since it has a great power density, it may be an appropriate power source for downsizing and lightening a robot hand. But its response time and heat generation could be a problem for practical applications. A USM is a kind of new actuator, which is driven by an ultrasonic vibration of a stator. It has an excellent performance and many advantages such as high torque at low speed, compact in size, no electromagnetic interferences and so on. However, USM itself does not have constructive flexibility and it requires complicated control systems to give USM robot hand compliance. An IPMC is one of the electroactive polymers (EAP). It mainly consists of a thin polyelectrolyte film, chemically plated on both surfaces with a noble metal (typically platinum or gold). It shows a large deformation in the presence of low voltage applied and exhibits low impedance. However, it is limited in the working environments because it requires water or wet condition to operate.

As noted above, it is assumed that in order to realize a robot hand fulfilling the above requirements (small in size, light-weight and flexible), a novel power source is necessary. Hence in this study, we pay an attention to an electro-conjugate fluid (ECF). The ECF is a kind of dielectric fluid, which generates a powerful jet flow when subjected to high DC voltage. The ECF could be an appropriate fluid power source for downsizing and lightening a robot hand, because ECF jet becomes more powerful as the electrode pair becomes more compact (the power density increases as the size decreases), and construction of the electrode pair is simple [8]. Furthermore, using ECF jet pressure together with soft material such as a rubber enables an actuator to have constructive flexibility.

Hence, the purpose of this study is to realize a robot hand that is small enough in size, lightweight and flexible by using ECF as a power source.
II. ELECTRO-CONJUGATE FLUID

The electro-conjugate fluid is a dielectric fluid, which works here as a smart/functional fluid. Applying a high voltage of several kilovolts between electrodes inserted into the fluid with an interelectrode gap of several hundred micrometers, we can observe a powerful jet flow (an ECF jet) between the electrodes as shown in Fig. 1 and this phenomenon observed with the electro-conjugate fluid is called an ECF effect in particular [8]. The ECF jet may be observed especially under a non-uniform electric field produced, for example, by a needle–ring electrode pair as shown in Fig. 1. Although a high voltage is required to generate the jet flow, the current is quite low at several microamperes.

III. CONCEPT

This study introduces the electro-conjugate fluid to a novel flexible robot hand as a power source. Fig.2 shows a conceptual view of the robot hand, composed of flexible fingers filled with the electro-conjugate fluid, ECF jet generators and an ECF tank (palm of the hand). When high voltage is applied to each ECF jet generator, the ECF moves from the tank to each finger, resulting in making the inner pressure of finger increase. Because the finger is appropriately reinforced with fibers, it bends when pressurized.

There are several similar fingers/hands using pneumatic pressure [9][10], however, the proposed robot hand differs from these fingers/hands in the following points. First, the working fluid is completely enclosed in the robot finger itself. Second, the actuator and the pressure sources are integrated in the hand. Finally, the configuration is quite simple in comparison with the pneumatic robots, which require compressors outside. Hence, we believe that the proposed robot hand has advantages for integration, downsizing and lightening. Furthermore it is believed that the configuration of the robot hand is very simple so that the robot hand overcomes the difficulty of spaghetti cord problems of other robot hands.

The following sections detail each component of the robot hand.

A. ECF jet generator

1) Configuration: The ECF jet generator could be a micro pressure source. There can be several types of electrode pairs which may generate the ECF jet, a bar-shaped electrodes pair, a ring and needle electrode pair, etc. In this study, we adopted

![Fig. 1. Schematic diagram of ECF jet](image1)

![Fig. 2. Concept of robot hand](image2)

![Fig. 3. ECF jet generator](image3)

![Fig. 4. Relationship between pressure and applied voltage](image4)

![Fig. 5. Relationship between flow rate and applied voltage](image5)
the pair of ring and needle electrodes because this pair can easily be located in the channel and it generates relatively high pressure [11]. Fig. 3 shows the schematic illustration of the ECF jet generator we designed. It is mainly composed of a needle-ring electrode pair, an electrode spacer, a frame, and covers. The electrode pair is of a brass ring, a tungsten needle, a needle mount made of brass. The other parts are made of engineering plastic. The spacer keeps a gap of the electrode pair to an appropriate distance. The electrode pair and the spacer which are inserted into the frame are fixed by covers as shown Fig. 3 (b).

The previous study by Abe et al. [8] has reported that there is a close correlation between dimensions of electrode pair and ECF jet flow. Furthermore the study has indicated that ECF jet becomes relatively powerful when diameter of needle electrode, inner diameter of ring electrode and electrode gap are 0.13mm, 0.3mm and 0.2mm, respectively. Therefore we adopted these parameters in this study. Additionally the ECF jet generator has two electrode pairs (two pairs of needle and ring bore) as shown in Fig. 3 so that it may increase the flow rate. The diameter and the height of ECF jet generator are 5.0 mm and 3.4 mm, respectively.

2) Influences of electrode gap and number of electrode pairs on pressure and flow rate: As mentioned above we designed the electrode gap to be 0.2 mm as in the previous study [8]. Ref. 8 uses Dibutyl decane-dioate (DBD: New Technology Management Co. Ltd., Japan) as the working fluid in the experiments. However, we use FF-101EHA2 (New Technology Management Co. Ltd., Japan) in this study as the working fluid which is known to produce more powerful jet flow than DBD. Hence, we confirmed the influences of electrode gap on the pressure and flow rate characteristics of the ECF jet. Furthermore we also measured the pressure and flow rate characteristics of the ECF jet generator having different number of electrode pair (needle-bore pair) because the ECF jet generator we designed has two electrode pairs as mentioned above. The experimental results are shown in Fig. 4 and Fig. 5. The physical properties of FF-101EHA2 and DBD are shown in Table I.

First, we mention about the influence of the variation of electrode gap and number of electrode pairs on the ECF jet pressure (Fig.4). It can be seen that the generated pressure quadratically increases against the applied voltage and the generated pressure increase as the electrode gap becomes short. In case the electrode gap is smaller than 0.2 mm, there occurred an intermittent electrical discharge between electrodes.

Second, we mention about the influence of the variation of electrode gap and number of electrode pairs on the ECF jet flow rate (Fig.5). It can be seen that the flow rate doubles with two electrode pairs compared with the case with one electrode pair. Furthermore it is also confirmed that the flow rate increase as electrode gap becomes short.

3) Pressure-flow rate relation: Using the ECF jet generator shown in Fig. 3, we confirmed the relationship between pressure and flow rate of ECF jet generator. Fig. 6 shows the experimental result. The ECF jet generator has a typical
dropping characteristics as can be seen in Fig. 6. The maximum pressure and flow rate was 33.6 kPa and 53.0 ml/min with the applied voltage of 6.0 kV.

4) Characteristics with ECF jet generators arranged in series: Characteristics of ECF jet generators when arranged in series are confirmed by experiment. The experimental results are shown in Fig. 7 and Fig. 8. In this experiment we used two ECF jet generators in total (“Jet a” and “Jet b”), and we arranged Jet b at the upstream of Jet a. A distance between the rear end of needle electrode of Jet a and ring electrode of Jet b is 1.4 mm. Owing to this arrangement, ECF jet may be possibly generated to unwanted direction (from Jet a to Jet b); therefore we coated the rear end of needle electrode with an insulator. Fig. 7 and Fig. 8 show that the characteristics of two ECF jet generators are nearly equal. Fig. 7 also shows that the generated pressure doubles by arranging two ECF jet generators in series. The maximum pressure was 60.5 kPa with the applied voltage of 6.0 kV. On the other hand, Fig. 8 shows that the flow rate slightly decreased by arranging two ECF jet generators in series.

B. Flexible finger

The flexible finger is in Fig. 9 and Fig. 10, showing a basic configuration and an actual view of motion, respectively. The finger is composed of a silicone rubber tube, a silicone rubber cap and aramid fibers. The tube has plural fibers on its circumferential surface with even intervals, and also has a fiber along its axis.

Expansion of tube, which is caused by the increase of inner
pressure, is transformed to an expansion along its axis because of the fibers on circumferential surface. However, the expansion along its axis is also restrained by the fiber, which is placed along the tube. Therefore, as the inner pressure increases, the finger bends as shown in Fig. 10 (b).

The length and the inside diameter of the flexible finger are 25 mm and 5 mm, respectively. The thickness of the tube is approximately 100 μm. The distance between the fibers is 2 mm.

IV. ECF ROBOT FINGER

A. Configuration

The ECF robot finger we developed is shown in Fig. 11. The basic configuration and principle of operation of the robot finger are the same as the robot hand we proposed in Sec. III. It mainly consists of the ECF jet generators, the flexible finger and an ECF tank. Inside the robot finger is filled with ECF, and the ECF is shared by the flexible finger, the ECF jet generators and the ECF tank. The ECF is injected into the robot finger through an injection tube shown in Fig. 11. Namely when assembling, we connected the opposite side of the injection tube to an external ECF tank and placed all components into a vacuum chamber to remove air from inside the robot finger. After injecting the ECF into the robot finger, the injection tube is clamped by a valve and the tube is cut. Therefore the finger, the ECF jet generators and ECF tank are all integrated. As shown in Fig. 11, wirings connect the electrode pair in each ECF jet generator to high voltage power source. ECF may not leak from the robot finger because ECF is completely enclosed inside. The ECF tank is made of silicone rubber tube. The silicone rubber tube is approximately 100 μm thick and is large enough as compared to the flexible finger, so that it may not effect on the finger performance.

B. Experiment

The basic driving performances of the robot finger were confirmed by experiments. The experimental results are shown in Fig. 12, Fig. 13, Fig. 14 and Fig. 15, respectively indicating the motion of the robot finger, the step response in the x- and y-direction, and the trajectory of fingertip in the x-y plane. We measured the displacement of fingertip with every 0.1 s in the rectangular coordinate system defined in Fig. 12 in order to confirm step response of the finger. The time indicated in Fig. 15 means the converged time of tip displacement at each applied voltage. From this experiment, we confirmed that the robot finger could be driven by the ECF jet as we proposed. This means the concept of the robot hand we proposed is reasonable.

First, we mention the displacement in the x-direction (Fig.13). The finger starts moving to the x-direction at 0.3 s after applying each voltage and the primary displacement is in negative direction with each voltage. When the applied voltage is relatively low as 4.0 kV and 4.3 kV, the finger remains negative displacement. On the other hand when applied voltage is higher than 4.7 kV, the displacement

<table>
<thead>
<tr>
<th>Object</th>
<th>Mass(g)</th>
<th>Diameter(Upper part):</th>
<th>Dimension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small cup</td>
<td>6.4</td>
<td>40</td>
<td>Height:45</td>
</tr>
<tr>
<td>Large cup</td>
<td>4.7</td>
<td>60</td>
<td>Height:45</td>
</tr>
<tr>
<td>Tape</td>
<td>12.7</td>
<td>45</td>
<td>Height:18</td>
</tr>
</tbody>
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becomes positive after approximately 1.0 second. The main reason for the primal negative displacement is that the flexible finger slightly contracted along its axis at the initial stage. It is also confirmed that the rise time in the x-direction with 6.0kV step input is 1.94s as can be seen in Fig. 13.

Next, we mention the displacement in the y-direction (Fig.14). The finger starts moving to the y-direction at 0.3 s after applying each voltage. When applied voltage is relatively high as 5.7 kV and 6.0 kV, the displacement in the y-direction have slight peaks. It is also confirmed that the rise time in the y-direction with 6.0 kV step input is 0.83s as can be seen in Fig. 14.

Finally, we mention the trajectory of fingertip in the x-y plane (Fig. 15). As can be seen in Fig. 15, the length of the trajectory increases against the voltage applied, because the generated pressure by the ECF jet may increase quadratically against the applied voltage. However the trajectories of the fingertip are almost corresponding even if the applied voltage change.

V. ECF ROBOT HAND

A. Configuration
Using the flexible fingers and the ECF jet generators, we developed a robot hand shown in Fig. 16. Inside the robot hand is filled with ECF, and the ECF is injected into the robot hand in the means similar to Sec. IV. The robot hand has five flexible fingers. Each finger is connected to two ECF jet generators, which are arranged in series and placed in an ECF tank (palm of the hand). Namely one robot hand has ten ECF jet generators in total, and each two ECF jet generators are arranged in series. In the following, the two ECF jet generators arranged in series is called Jet A, Jet B, Jet C Jet D and Jet E, each of them is connected to little finger, ring finger, middle finger, index finger and thumb, respectively.

The height and the width of the robot hand are approximately 60 mm and 40 mm, respectively. The mass of the robot hand is 15.2g.

B. Driving experiment
Characteristics of the robot hand were confirmed by experiment. In the experiment, we applied the voltage of 6.0 kV to each ECF jet generator. Fig. 17 shows an actual view of robot hand motion. Fig.16 shows the initial state. Fig. 17 (a) shows the motion when 6.0 kV is applied to Jet A, Jet B and Jet E. Fig. 17 (b) shows the motion when 6.0 kV is applied to all ECF jet generators. The robot hand can make multiple actions as the input voltage is selectively applied to the ECF jet generators.

C. Grasping experiment
Grasping experiments are carried out, and as can be seen in Fig. 18, we demonstrate that the robot hand can grasp some objects having various shapes. Table II shows the objects we used. The fingers are flexible so that the robot hand can grasp some objects even without a complex controller.

However it is required for the hand to generate much larger force in order to grasp variety of objects. The force can be enlarged by placing several electrode pairs in series, resulting in increasing the pressure by the ECF jet. Note that, the electrode pair required is extremely compact compared with the robot hand itself. Furthermore, it is also possible to improve the response of the robot finger by placing several electrode pairs in parallel, this means, the flow rate of the ECF jet flow increase.

VI. CONCLUSION
This study proposed a small, lightweight and flexible robot hand using ECF. First, we proposed the concept of the robot hand. Second, we investigated the characteristics of the ECF jet generator, which is used as the pressure source for the robot hand. Third, we developed the ECF robot finger and confirmed our concept is reasonable. Finally, we developed the ECF robot hand and demonstrated that the robot hand can grasp some objects with various shapes without any complex controller.

Our future study focuses on the improvement of the finger configuration and the ECF jet generator, and controlling the ECF robot hand.

REFERENCES