Electrostatic Force-Driven Millimeter-Class Mechanisms for Micro-Assembly Work

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Abstract

This paper describes activities of a group of students developing insect-size mechanisms at Small Mechanism Applications Laboratory (SMAL) at California State University, Sacramento. Our group focuses on a class of millimeter-size mechanisms larger than micro-electro-mechanical systems (MEMS) but much smaller than ordinary mechanisms seen in our daily life. Seeing the technological trend of electro-mechanical products getting more and more minitualized, we believe this class size of mechanisms has a wide range of future applications in manufacturing, bioengineering, the military, and many other areas. One of the difficult challenges to building this class size of mechanism is a lack of actuator technologies for miniaturization. Today's commonly used actuators for industrial automation, such as electric motors, hydraulic actuators, and pneumatic actuators, are not suited for miniaturization. At SMAL, students have been experimenting with the use of untraditional actuating sources to design miniature mechanisms. Those untraditional actuating sources include but are not limited to electrostatic force, Shape Memory Alloy (SMA), and thermal expansion/contraction. These actuating sources have potentials for simplifying mechanisms, minimizing a number of assembly components, and reducing component weights. Therefore, they are more suited for miniaturization compared to traditional actuating sources. Case studies of developing electrostatic force-driven miniature grippers and suction devices intended for micro-assembly work are described. Brief descriptions of other ongoing work are also presented.

Introduction

Things we observe in nature often motivate us in developing new technologies. From a mechanism design point of view, small insects such as ants and bees are amazing creatures with so many degrees of freedom (DOFs) of coordinated movements being contained in a tiny space. A group of students at our institution became interested in developing millimeter-size mechanisms. This is a class of mechanisms larger than micro-electro-mechanical systems (MEMS), which is usually under 1 mm but much smaller than ordinary mechanisms seen in our daily life. Under the supervision of a mechanical engineering faculty and with some internal funds, we created SMAL in January of 2014.

Millimeter-size mechanisms have many potential advantages over larger-size mechanisms. They can possibly get into tight spaces and hard-to-reach areas for maintenance and surveillance purposes. They could be cost effective due to their space efficiency and light weight, as a small amount of material is used for building mechanisms. Kuribayashi designed a Shape Memory Alloy (SMA) actuated micro-robot to work under a microscope [1]. Tanner and others developed a cable-driven robotic mechanism for minimally invasive surgery using carbon nanotube composite structures [2]. A 6-DOF micro-robot controlled by magnetic forces was created by Diller and others [3]. Micro Robotics Laboratory at University of Maryland has developed various micro-robots including a jumping robot fabricated by the silicon-PDMS MEMS process [4] and a microcontroller based mobile robot under 6 cm^3 [5]. Despite these existing applications

and activities, much more work will be needed for developing technologies for millimeter class mechanisms.

Projects under our lab are mostly for independent study projects for undergraduate and graduate students. The following technical goals have been set considering appropriate engineering challenges and resources available. These are not considered strict goals. Creativities, teamwork, and developing new ideas based on these guideline goals are encouraged.

Technical Goals:

1) The entire mechanism fitting within one cubic centimeter of space. If necessary, it is allowed to attach flexible cables for controlling the mechanism. We call this the "chop stick rule." The mechanism must be small enough to be easily picked up and moved around by a pair of chopsticks.
2) Mechanisms which can be constructed by commonly available manufacturing methods. We have a machine shop with conventional and CNC machine tools. There is also a 3D printer: Stratasys Mojo.
3) Designing mechanisms with some applications in mind. These applications include but are not limited to manufacturing, biomedical engineering, and surveillance.

We also created the following educational objectives associated with those technical goals.

Project Objectives: Through projects under SMAL, students will

a) develop out-of-the-box thinking approaches to design mechanism accomplishing the technical goals above.
b) work as a team, especially to develop standard procedures including safety rules, share resources, and exchange technical ideas.
c) obtain new experience and knowledge, which will not only be used for millimeter-class mechanisms but also for other engineering applications.
d) experience interdisciplinary work.

Two case studies describing developments of electrostatic force driven grippers and suction devices for micro-assembly applications are presented in the next two sections. A summary of other ongoing projects and future plans of our group will be given in the conclusion section.

Case Study 1: Electrostatic force–driven grippers

Gripper design

For one of the projects, a group of a few students decided to develop a miniature 1-DOF gripper. We believed that this study would set a foundation for multi-DOF millimeter class mechanisms that we hope to develop in future. Considering the technical goals described in the previous section, there are a few fundamental challenges that we don't usually encounter for ordinary mechanism design, one of which is generating joint actuation forces within this limited space. Most commonly used actuators for industrial automation are electric motors, hydraulic actuators,

and pneumatic devices. There is no commercially available hydraulic and pneumatic devices that can fit into the space in our consideration. There are some millimeter-size electric motors. However, it is still difficult to design a millimeter-scale mechanism with this kind of motors when many other mechanical components, such as speed reducers, and mechanical joints/links are considered.

We considered several untraditional actuating sources. In the field of MEMS, electrostatic force is very commonly used [6,7]. Electrostatic force requires very low electric power and generates a reasonable amount of force when two charged elements are very close. Use of electrostatic force also allows us to make mechanism design very simple. Some major disadvantages of electrostatic force are requiring very high voltage and actuation force rapidly decreasing as the distance between two charged elements increases. SMA-based actuators [8, 9] have been used for many applications including small mechanisms for their excellent output force to size ratio. One of the major disadvantages prohibiting SMA from applications such as material handlings and assemblies is its slow time response [10]. The class of Electroactive Polymers (EAP) [11, 12, 13] is another possible actuating source for miniature mechanisms.

Although, we would like to explore many different actuating sources over time, for this project we consider the electrostatic force based actuation. Knowing well-established electrostatic force applications for MEMS, we feel that it is reasonable to extend this technology to millimeter class mechanisms.

We propose a design of an electrostatic gripper based on the parallel plate actuator principle [14, 15]. The attraction force F of the parallel plate actuator illustrated in Fig. 1 is given by [14],

$$F = \frac{\varepsilon A V_S^2}{2d^2} \qquad (1)$$

where A is the surface area of each conductor plate (assuming both conductor plates having the same surface area of A), V_S is the DC supply voltage, and d is the distance between two conductor plates. Also in the equation, ε is the absolute permittivity of the dielectric material separating two conductor plates and it is given by

$$\varepsilon = \kappa \varepsilon_0 \qquad (2)$$

where κ is the relative permittivity of the dielectric material and $\varepsilon_0 = 8.8541878176 \times 10^{-12}$ F/m is the vacuum permittivity.
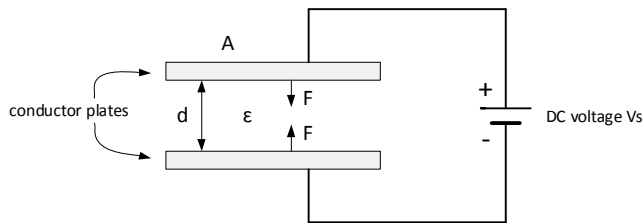

Fig. 1: Parallel plate actuator

There is a spring element between these two parallel plates. More about the spring element will be explained later. For a gripper design, it is appropriate for each of these conductor plates being enclosed in an electrically insulated case so that the gripper does not create a short circuit when it is completely closed or when it is grasping an electrically conductive object. Fig. 2 shows a concept of parallel plate actuator with insulated cases. It is assumed that the surface area A of the conducting plate, the insulating material, and the thickness of the insulating materials are the same for both conductor plates.

The output force F_c based on this concept is given by [16]:

$$F_c = \frac{\varepsilon_1 \varepsilon_2 A V_S^2}{2(\varepsilon_1 d_1 + \varepsilon_1 d_2)(d_1 + d_2)} \qquad (3)$$

where d_1 is the distance between two gripper surfaces indicated in Fig. 2, d_2 is the total thickness of the case material, ε_1 and ε_2 are the absolute permittivities of the dielectric material and the case materials respectively, and they are given by

$$\varepsilon_1 = \kappa_1 \varepsilon_0 \qquad (4)$$
$$\varepsilon_2 = \kappa_2 \varepsilon_0 \qquad (5)$$

where κ_1 and κ_2 are the relative permittivities of the dielectric material and the case materials respectively.
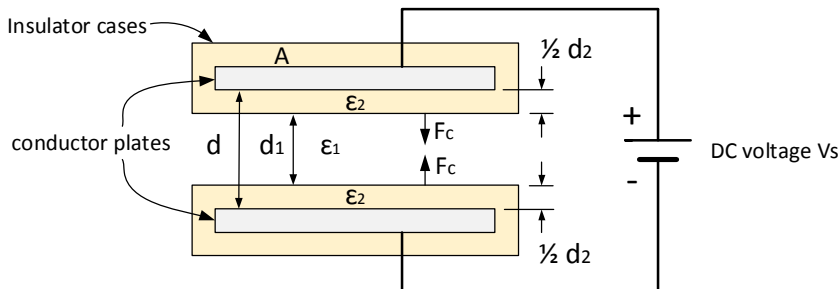

Fig. 2: Parallel plate actuator with insulating cases

Based on the model illustrated in Fig.2, we designed a gripper based on the compliant mechanism [17] concept. Use of the compliant mechanism concept significantly simplifies the mechanism design by reducing a number of mechanical components. It also eliminates the problem of non-smooth motion for overcoming static friction, which is typically seen in ordinary joint mechanisms. We used a Stratasys Mojo 3D printer to produce such a compliant mechanism gripper. The design of the 3D printed gripper is shown in Fig. 3. One of the reasons to consider 3D printing for producing miniature devices is ease of manufacturing. The entire compliant gripper body shown in Fig. 3 is a one-piece ABS component including all mechanical features including the gripper plates and spring loaded joints. Aluminum foils which act as conductor plates and electrical leads to these foils are not included in the figure. Aluminum foils were inserted into the slots shown in the figure. Electrical leads are inserted into the base portion of

the gripper. The lead and the aluminum foil were clamped together by the base unit for solid electrical connection and then the lead is fixed to the base with a light amount of epoxy. The thickness of the ABS layer covering the conductor plate is 0.5 mm. Each of the bridges that act as compliant joints have the square cross section of 0.17 mm x 0.17 mm. This is the smallest cross section geometry that the 3D printer can produce according to its specification. The gripper fits within the one cubic centimeter space.
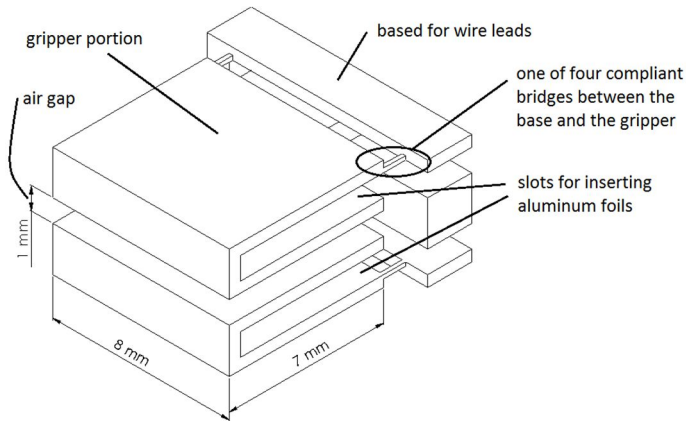

Fig. 3: Design of a 3D-printed ABS gripper body

A finite-element analysis (FEA) was conducted to predict the amount of gripper displacement. It is assumed that the gripper is operated in ambient air under atmospheric pressure. The gripper does not exactly produce parallel plate movement. However, the force value calculated by Eq. 3 when the air gap is 1 mm is used as the approximation of the output force. The maximum input voltage is limited to the dielectric strength of air, which is about 3 MV/m. Fig. 4 shows the displacement predicted by FEA when the input voltage of 4500 V is applied to the gripper shown in Fig. 3. Using the relative permittivity of 1.0 and 2.5 for air and ABS, the force value calculated by Eq. 3 is 0.17×10^{-3} N. The deflection force of aluminum foils (approximately 0.016 mm thick) is neglected. Approximately 0.4 mm of total displacement is predicted.
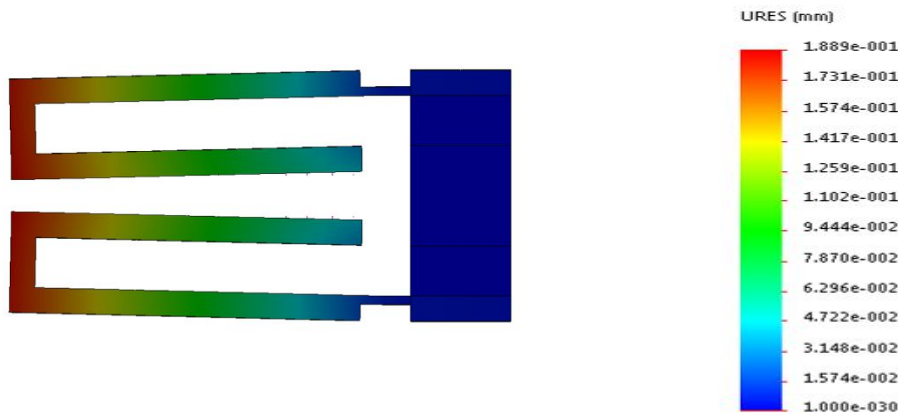

Fig. 4: The gripper displacement predicted by FEA when Vs = 4500 V

Experiments

Experiments were conducted to validate the performance of the proposed gripper design. The experimental setup is shown in Fig. 5. This experimental setup is used for most of the single-input miniature electrostatic force driven mechanisms and devices developed under our lab including the gripper and the suction device, which is explained in the next section. The high DC voltage power generator, Ultravolt 20A12 – P4, was used to generate input voltage to an electrostatic-driven mechanism or device. By applying a DC control signal voltage of 0 to 5 volts, the device can generate up to 20 KV of DC output. A Hewlett Packard E3630A DC power supply was used to provide the constant power supply of 12 V DC and a Kikusui PMC35-1A DC power supply was used to provide the control signal DC voltage to the Ultravolt 20A12 – P4.
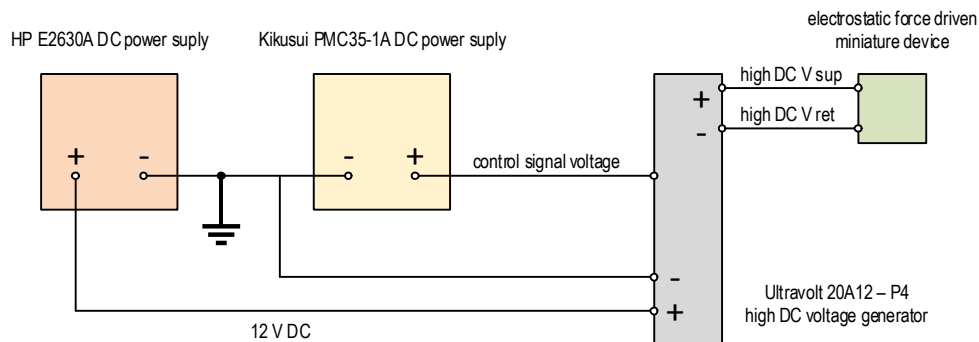

Fig. 5: Schematic diagram of experimental setup for electrostatic force–driven mechanisms

Safety is the ultimate concern especially using the extremely high voltage circuitry. Wiring work must be done with extreme care especially paying attentions to short circuits. Fortunately most of electrostatic force driven mechanisms use very low electric power despite extremely high voltage. The maximum output power of the Ultravolt 20A12 – P4 high DC voltage generator is 4W. Expected electrical current for operating electrostatic-force mechanisms is well below 10 mA. According to the OSHA electrical hazard guideline [18], possible electric shock for this level of current to the human body is relatively minor without any direct injury. Electric shock due to a capacitor discharge is also a great concern [19]. However, capacitance of most of the miniature devices we design is too small to cause any serious injury.

We tried to produce the gripper model shown in Fig.3. Although we have been extremely satisfied with the overall performance of the Stratasys Mojo 3D printer for many other student projects, it failed to produce the compliant bridge portion of the part. This printer produces a model with support material. The compliant bridge portion was covered by support material when it came out of the printer. After a washing process, the bridge portion disintegrated and the gripper portion was separated from the base portion. We are not certain if the printer simply could not produce the bridge portion or if the printer produced it, but it was too week and destroyed in the washing process.

After some trials and errors, we could produce a similar gripper but larger in size (20 mm x 20 mm for the gripper portion). This gripper was successfully operated for repeated open-close actions. Photos of open and close statuses of this gripper are shown in Fig. 6.
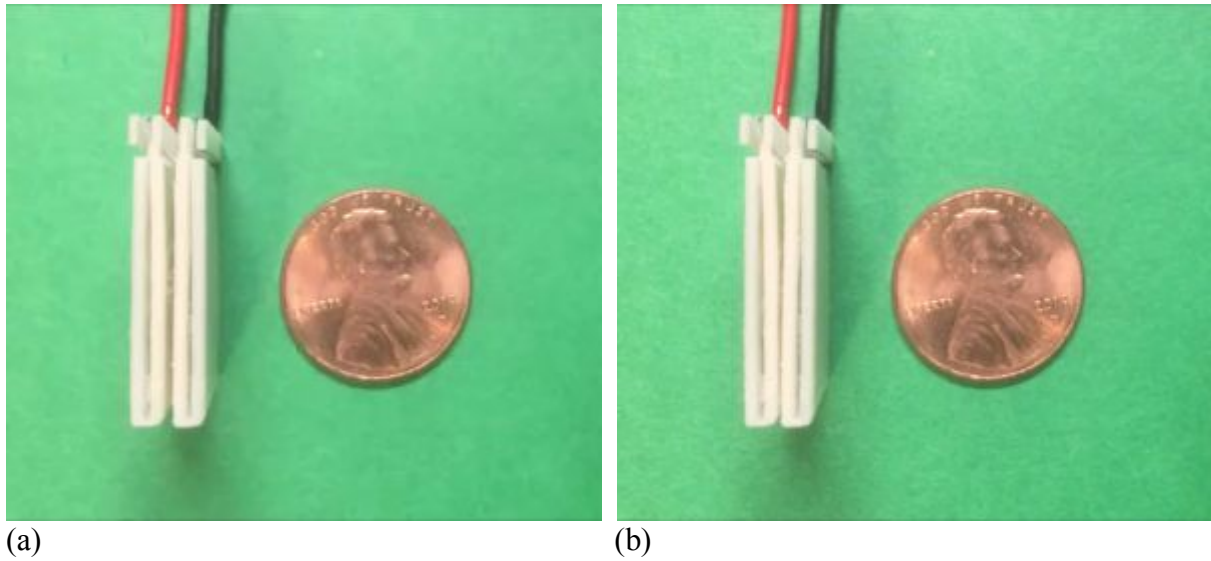
(a)   (b)

Fig. 6: Photos of a 3D-printed electrostatic gripper, (a) open, (b) closed

We also handcrafted another gripper with a design described in Fig. 7. Although more labor intensive to produce than a 3D-printed gripper, it is significantly smaller (8 mm x 6 mm for the gripper portion) with much more displacement in open-close action as seen in Fig. 8.
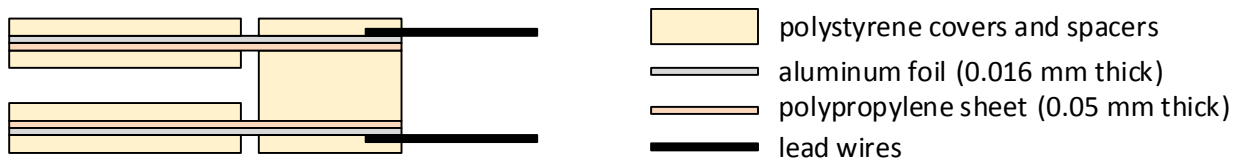

polystyrene covers and spacers
aluminum foil (0.016 mm thick)
polypropylene sheet (0.05 mm thick)
lead wires

Fig. 7: Design of a handcrafted miniature electrostatic gripper

(a)   (b)
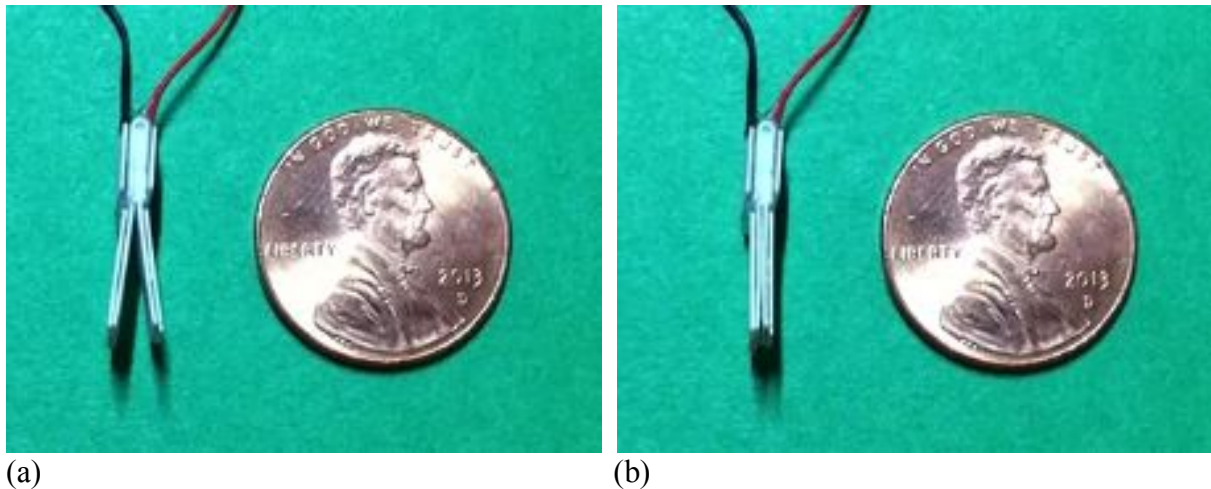
Fig. 8: Photos of a hand crafted electrostatic gripper, (a) open, (b) closed

Further design considerations for electrostatic miniature grippers

Technologies for 3D printing are rapidly advancing for higher precision, more material options and lower costs. Although a 3D-printed gripper proposed in Fig. 3 could not be produced this time, we believe 3D printing will be a viable manufacturing option for producing electrostatic force–driven miniature mechanisms in the near future.

One of the fundamental challenges of electrostatic force driven devices is to produce enough output force for required tasks. Based on the output force given by Eq. 1 for a parallel-pate based mechanism, the following four options to increase the output force are:

1) Bringing two charged elements as close as possible (reducing d)
2) Increasing surface area of conductors (increasing A)
3) Using a dielectric material with a high relative permittivity value (increasing ε)
4) Increasing the input voltage V_S

Option 1 works in favor of small size mechanisms such as MEMS and millimeter-class mechanisms that are under our consideration. As we consider small mechanisms, Option 2 in general is not a practical option. Option 3 should not be overlooked. Considering the gripper model of Fig. 3 with the 4500 V input voltage, the output force was calculated for a wide range of relative permittivity values of case materials using Eq. 3. The result is shown in Fig. 9. It is noted that the output force can be significantly increased by using case material of higher relative permittivity value although it reaches at a plateau level after a relative permittivity value of around 10. The ABS used for our project has the relative permittivity of 2.5 with the output force of 0.17×10^{-3} N. If a material such as neoprene with the relative permittivity value of 6.7 [20] is used the output force for the same model of the gripper is 0.20×10^{-3} N, which is 18% of increase.
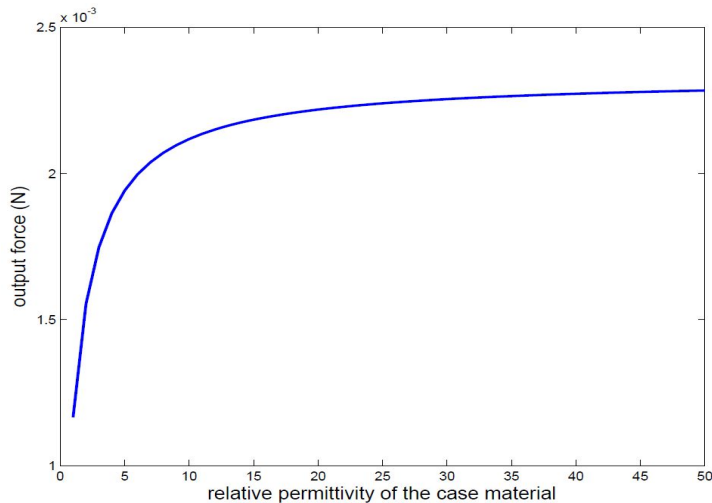

Fig. 9: Output force of the gripper model of Fig. 3 when different case materials are considered.

Option 4 is a very attractive option especially as the force increases squarely to the input voltage. The most limiting factor of the input voltage is the dielectric strength of the dielectric material between two conducting plates. For our project, it is assumed that grippers are operated in

ambient air with the dielectric strength of about 3 MV/m. ABS used for the 3D printed gripper has the dielectric strength of about 5 MV/m. For simplicity of fabrication, some portions of the conductor plates were exposed to air. If the conductor plates were completely enclosed in ABS cases, higher input voltage could have been applied. The dielectric strength of vacuum is over 40 MV/m [21]. In a vacuum environment, such as inside a confined vacuum container or a space environment, it is possible to operate electrostatic force–driven miniature mechanisms with a completely different order of output force.

There are some electro-adhesion grippers for industrial applications [22, 23]. Those multi-finger grippers typically use electro-adhesion pads made of very flexible material like flexible silicon. The shape of the pad can be adapted to almost any contour of a grasping object. They are not necessarily intended for miniature mechanisms but they could be scaled down. The electrostatic suction devices in the next case study are based on this electro-adhesion principle.

Case Study 2: Electrostatic suction devices

Design of electrostatic suction devices

In this section, we present another case study conducted by our group. This is an example of a project where many of resources were shared with the above case study but at the same time distinctively different ideas were developed by another group of students. In this project, we developed electrostatic suction devices based on the electro-adhesion principle [22, 23, 24, 25] illustrated in Fig. 10.
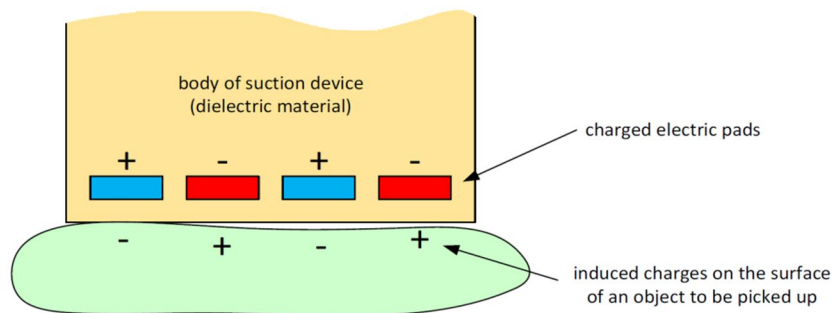

Fig. 10: Electrostatic suction device with induced electric charges on a contact object

Under this principle, electrostatic force is generated between charged electric pads inside the suction device and induced electric charges on the contact object. We developed the following two types of electrostatic suction devices: (1) unipolar and (2) bipolar suction devices as shown in Fig.11. For both cases, the bottom surface facing downward is the contacting surface with an object to be picked up. For the unipolar case, one charged pad (either positive or negative) and the picking up object is separated by the insulation layer of the suction device. For the bipolar case, two charged pads (one positive and the other negative) are arranged side-by-side. The Mojo 3D printer was used for this project as well to produce those two types of suction devices. For each type of suction device, aluminum foils and wire leads were inserted into slots shown in the figure. Wire leads were fixed to the body of the suction devices with epoxy.
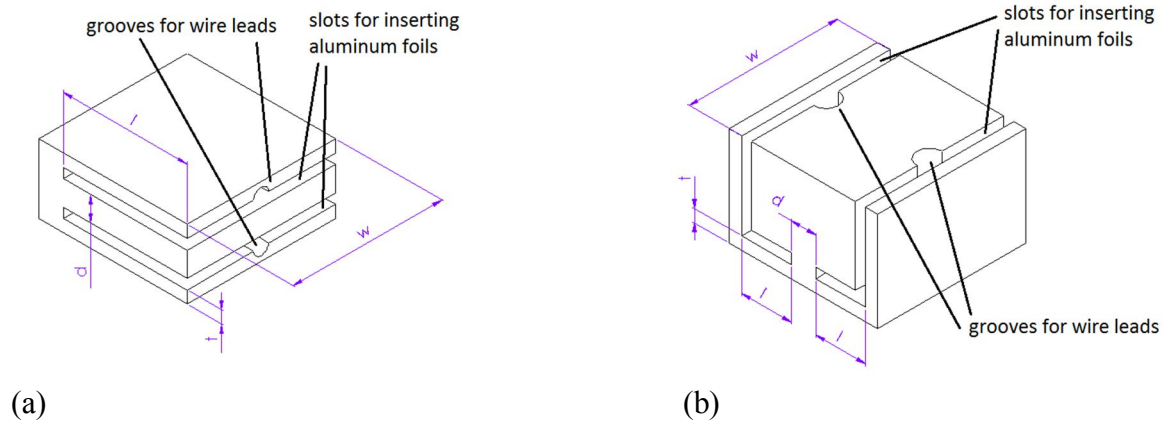
Fig. 11: Design of 3D-printed suction devices, (a) unipolar type, (b) bipolar type

Experiments

Experiments were conducted to study performances of electrostatic suction devices produced. Exactly the same experimental setup shown in Fig. 5 was used except an electrostatic force–driven gripper being replaced with a suction device.

Based on the nomenclature (d, t, l, and w) shown in Fig. 11, the following notations were developed to indicate the type and size of a suction device: # - d - t - l - w, where # indicates either the unipolar (u) or the bipolar (b) followed by dimensions in millimeters.

We fabricated four different suction devices that fit comfortably within one cubic centimeter of space as shown in Fig. 12. The figure also shows four different types of sample objects to be handled with those suction devices.
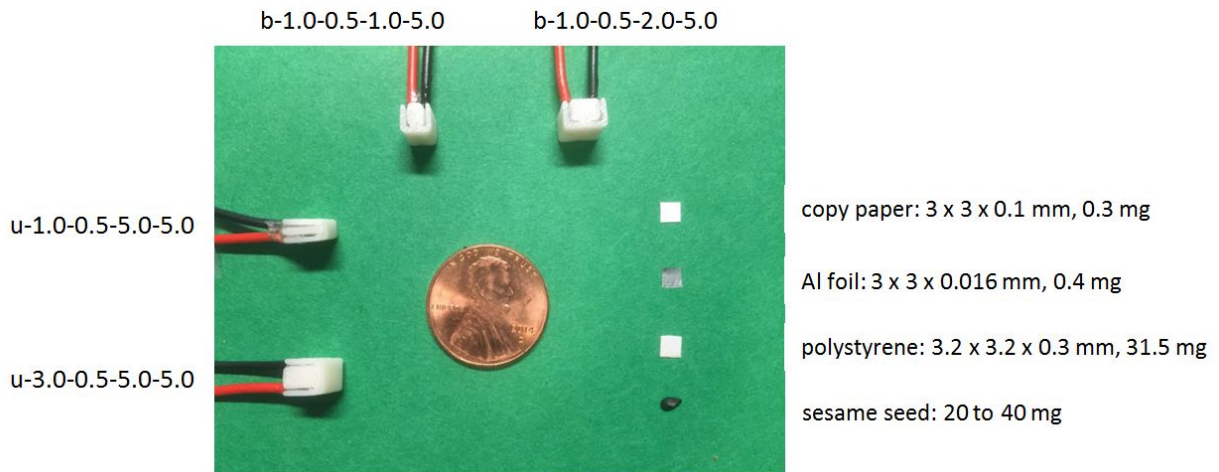

Fig. 12: Four different suction devices with sample pick-up objects

As an example of how a suction device works, Fig. 13 shows sequential photos of the b-1.0-0.5-1.0-5.0 type unipolar suction device picking up a sesame seed with approximately 1200 V of input voltage.

Fig. 13: b-1.0-0.5-1.0-5.0 type device picking up a sesame seed

Table 1 shows the results of input voltage required to pick up sample objects by these suction devices. For each device, 5 runs were conducted for each sample pick-up object. Considering possible charges accumulated to both pick-up objects and suction devices due to triboelectric charging effects and residual charges, two pickups were conducted before 5 runs of experiment.

Table 1: Input voltage required for picking up sample objects

Gripper	Input voltage required (V)							
	Paper		AL foil		Polystyrene		Sesame seed	
	Ave.	STD	Ave.	STD	Ave.	STD	Ave.	STD
u-1.0-0.5-5.0-5.0	390.5	56.0	373.2	120.7	1413.7	137.6	1178.4	75.2
u-3.0-0.5-5.0-5.0	268.1	69.7	279.3	104.5	783.6	110.1	779.2	134.7
b-1.0-0.5-1.0-5.0	473.2	35.1	411.2	89.0	928.4	157.5	1017.2	90.4
b-1.0-0.5-2.0-5.0	319.8	31.7	354.3	46.1	534.4	133.9	633.6	161.8

All suction devices were able to pick up sample objects successfully well under expected breakdown voltages of 3000 V (for all cases except u-3.0-0.5-5.0-5.0) and 9000 V (for the case of u-3.0-0.5-5.0-5.0). As seen from table values, required input voltages significantly vary depending on types of suction devices and dimensional parameters.

Further design considerations for electrostatic suction devices

Based on this case study, we believe that there are significant potentials for electrostatic suction devices for miniature material–handling applications. The Mojo 3D printer is a very effective tool to mass-produce miniature suction devices. One problem that needs to be investigated further is a phenomenon where an object sometimes "sticks" to a suction device even after the input voltage is turned off. This phenomenon has been reported by other researchers [26, 27]. Tien [27] reported that coating on electrostatic suction devices by some commercially available anti-static sprays reduce this "stick" problem.

Conclusions

This paper introduced project activities for developing millimeter class mechanisms and devices at California State University, Sacramento. Two case studies about developing electrostatic force driven miniature grippers and suction devices were described. From studies conducted, we believe that there are significant potentials for electrostatic force driven mechanisms and devices for miniature material handlings and other applications.

Since our group was formed at the beginning of 2014, two undergraduate independent projects, one graduate independent project, and two M.S. theses have been produced. Currently, there is a student working on developing electrostatic force driven miniature linear actuators. Any out-of-the-box thinking for applications beyond millimeter-class mechanisms are also encouraged. Our group recently obtained a sponsorship from a local company to develop a material-sorting device for recycling work based on electrostatic/triboelectric principles. Details cannot be disclosed due to a nondisclosure agreement (NDA) between our group and the company. However, this is an example of a meaningful side product that could not be developed without the experience of designing electrostatic force driven millimeter-class mechanisms.

We will continue working on new projects for electrostatic force–driven miniature mechanisms considering increasing output force, motion controls, and developing multi-degree-of-freedom mechanisms. Currently all students for our project activities have been Mechanical Engineering students. In the future, we will make more effort on generating interdisciplinary projects by students and faculty from different disciplines.

Acknowledgment

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