Compliant bipolar electrostatic gripper using 3D-printed-layered elastic probes

Pasomphone Hemthavy1,3, Kenta Kudo1, Kento Kawano1, Kunio Takahashi1 and Shigeki Saito1,3

1 Department of Transdisciplinary Science and Engineering, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo 152-8552, Japan
2 Department of Mechanical Engineering, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo 152-8552, Japan
3 Author to whom any correspondence should be addressed.

E-mail: pasomphone@tse.ens.titech.ac.jp and saito.s.ag@m.titech.ac.jp

Abstract

A 3D-printed-layered structure for forming the compliant bipolar electrostatic gripper is proposed. A prototype gripper module, which consists of an array of elastically deformable bipolar micro-probes, is fabricated using a conventional 3D printer. Experiments are conducted to examine the attractive force and the pick-and-place performance of the prototype. Experimental results show that the prototype module can generate the maximum attractive pressure of 87.1 Pa, which can pick and hold a piece of xerographic paper of 31.2 mg successfully. The effects of residual charges and the probe-tips flattening process on the attractive force are also discussed.

1. Introduction

Over last several decades, electrostatic chucks (ESC) have been widely utilized for various industry applications, such as in printing industry, coating industry, and semiconductor manufacturing industry. For example, in the fabrication process of semiconductors, ESC plays an important role in clamping and transporting silicon wafers efficiently [1–7]. By exploiting interdigitated electrodes arrangements, which is either embedded within or attached on the surface of a dielectric layer, the ESC can achieve a firm contact to handle a silicon wafer. However, they have disadvantages such as their handling ability is limited to such objects having smooth, clean, and flat surface because the electrostatic force is dependent on the gap distance between the ESC and the object.

To challenge the handling of objects with rough surface researchers have combined the ESC with the biomimetic dry adhesives technology, which is thought to rely on van der Waals forces, resulting in expanding the ESC to the electro-dry-adhesion. For example, gecko-like adhesive, i.e. fibrillar height in the order of tens micro-meter, has been added on the substrate of interdigitated electrodes [8, 9]. However coplanar grippers would have limitation on absorbing the surface-roughness, although it can conform to the shape of the object.

Comparing to coplanar ESC’s, probe-like compliant ESC structure consisting of elastic beams with bipolar electrodes in each, as shown in figure 1 (a), can have advantages: 1) the ability to absorb surface-roughness of the object by utilizing the mechanical compliance of the beams, 2) dense distribution of electrostatic field by designing the size, gap, and electrode patterns of the beams without changing the gap distance between the ESC and the object, 3) peeling motion by simple rotation mechanism. The ideas of development of probe-like compliant ESC’s can be dated back to the last decade [15, 16], with expectations that they can have broader feasibilities of handling objects with rough surface of a high aspect ratio, such as Micro Electro Mechanical Systems (MEMS), as well as thin and fragile objects. To date, our research group has been challenging the
development of probe-like compliant electrostatic grippers, such as studies on monopolar polymeric fibers with a conductive part at the core [17], and bipolar micro-pillar gripper [18, 19]. The studies show that a prototype consisting of bundled fibers is able to exert a force to conductive objects with rough surfaces, and the compliance of the structure plays an important role in the conforming ability of the gripper to rough surfaces. However, the fabrication of the compliant bipolar elastic beam still remain a challenging problem, because specific and precise equipment/facility and complicated procedures are required for the fabrication.

To overcome the fabrication difficulties the authors propose the use of a 3D-printed-layered structure to form the compliant bipolar electrostatic gripper, which consists of an array of elastically deformable bipolar micro-probes. The proposed fabrication method is considered to have advantages, such that the alignment of the electrodes of the probes can be easily realized using a conventional 3D printer, high electroadhesion can be relatively easy to achieve by increasing the number of the probes of the proposed module (figure 1(a)), and integrating the proposed module to form a gripper of multi-layers. The proposed fabrication method also has degrees of freedom in forming the shape of the probes. The experimental results and discussions about the attractive force measurement, the effects of residual charges and the probe-tips flattening process on the attractive force, as well as the pick-and-place performance of the proposed gripper module are presented.

2. Design and fabrication

2.1. Structure and behavior of compliant bipolar electrostatic gripper

The proposed structure of compliant bipolar electrostatic gripper module is schematically illustrated in figure 1(a). The module is composed of an array of elastically deformable bipolar micro-probes, in which an electrically insulative layer is sandwiched between two conductive layers used as electrodes. In order to handle an object, the module is connected to an external manipulator at its root (fixed end) to control its displacement while being supplied by two DC voltages. The probe-tips (free end) of the module are used for attracting (gripping) target objects by means of electrostatic force.

When two DC voltages are applied to the module’s electrodes in the way shown in figure 1(a), the module can attract target objects by two mechanisms depending on electrical properties of the objects as follows: (1) when the object is a conductor attracted to the probe-tips, provided that short circuit is avoided, e.g. by coating a thin insulative layer on the probe-tips, the electrostatic attractive force is generated by induced charges in the object and the probe-tips (figure 1(a)). An equivalent series connection of parallel capacitors can be used to derive the attractive force, which is proportional to the square of the applied voltage and inversely proportional to the square of the thickness of the insulative layer [1, 2, 20]. (2) when the object is a dielectric, the electric fields cause polarization of bound charges in the object (figure 1(a)) which gives rise to the generation of electrostatic attractive force. The attractive force can be generally expressed as proportional to the gradient of the squared electric field [21, 22]. However, it can not be obtained analytically for general cases, since the exact profile of the electrostatic field in the object is required for the calculation. A numerical investigation of the attractive force of this case was conducted in a previous work of our research group [18].

2.2. Mechanical compliance of the probes

To consider the mechanical compliance of the gripper, we focus on a single probe, as shown in figure 1(b). Here the probe is considered as a cantilever beam of length $L$, whose root is fixed at angle $\varphi$ measured from the horizontal line. It is assumed that the cantilever is linearly elastic with relatively small deflections and the axial stress can be negligible. The cantilever can be moved vertically (along z direction in figure 1(b)) by a displacement given to its root. The reference position ($z = 0$) of the root is defined at the point the probe-tip touches the object surface without any applied voltage. The displacement, $z$, is defined positive downward, i.e. as
the cantilever approaches the object. The concentrated force, \( F \), acted on the probe-tip by the object is defined positive upward, i.e. repulsive force. Therefore, the attractive force would be reversed in direction. The \( x \) and \( y \) axes are set as shown in figure 1(b).

The relation between the curvature of the cantilever and a bending moment, \( M \), due to the concentrated force, \( F \), is given as

\[
\frac{d^2y}{dx^2} = \frac{M}{EI} = \frac{F \cos \varphi}{EI} (L - x),
\]

where, \( EI \) is the flexural rigidity of the cantilever.

Equation (1) can be solved for the deflection of the cantilever at its tip, \( \delta \), which satisfies two boundary conditions, \( y(0) = 0 \) and \( y'(0) = 0 \). As a result, the deflection, \( \delta \), is obtained as

\[
\delta = y(L) = \frac{FL \cos \varphi}{3EI} L^3.
\]

Since the bending deflection of the cantilever occurs in the same direction as the given displacement, \( z \) and \( \delta \) have the same sign convention, expressed as \( z = \delta \cos \varphi \). Combining this expression with equation (2) yields

\[
F = \frac{3EI}{L^3 \cos^2 \varphi} z.
\]

Equation (3) shows a linear relation between the force and the displacement. The coefficient \( k = \frac{3EI}{L^3 \cos^2 \varphi} \) expresses the stiffness, i.e. the reciprocal of the compliance, of the cantilever. The stiffness, however, is an essential factor in design process to determine dimensions of each individual probe of the gripper module. In this research, prismatic cantilever beams (probes) of rectangular cross-section are selected for the members of the gripper module. Derived from equation (3), we should increase the length and decrease the cross-sectional height of the probe to gain more compliance because they are involved by the cube of their magnitude.

2.3. Prototype fabrication by 3D printing

A fused deposit modeling (FDM) 3D printer (MakerBot Replicator 2X) is used for fabricating the prototype module. The printer used is equipped with an extruder head with a nozzle of 400 \( \mu \)m diameter, the layer resolution is 100 \( \mu \)m, the XY positioning precision is 11 \( \mu \)m, and the Z positioning precision is 2.5 \( \mu \)m. Therefore, the layer solution is set to be 200 \( \mu \)m, in order to ensure that the shape of the probes can be properly printed. A conductive polymeric material (eSUN 3D filament conductive black) is used for the electrodes, while an acrylonitrile butadiene styrene (ABS) material provided by MakerBot is selected for the insulator.

Figure 2(a) depicts the schematic of the module, detailing its dimensions. The 80 mm-long bipolar probes are arranged at angle \( \varphi = 45^\circ \). The dimensions of the rectangular cross-section of each bipolar probe are 1.2 mm \( \times \) 1.6 mm, the thickness of the conductive and insulating layers are set to be 0.4 mm and 0.8 mm, respectively. Figure 2(b) shows the photograph of the entire fabricated prototype module, which consists of 11 probes. The sandwich configuration of the electrodes and the insulator can be observed. It takes 30 minutes to fabricate one prototype module.

2.4. Probe-tips flattening

The electrostatic force is generally known to be highly gap-dependent [1, 23]. Therefore, careful attention on the flatness of probe-tips is an important factor in designing an electrostatic gripper. However, the FDM 3D printer can not form a flat tip as precise as its resolution. As a result, the probe tips of the fabricated module are of

![Figure 2. (a) Schematic of the designed prototype detailing some dimensions, (b) Photograph of the fabricated prototype consisting of 11 probes, and magnified image of the tips.](image)
rounded shape, as shown in figures 2(b) and 3(c). This is because the probe tips are relatively small to be printed by a round path of the extruder head, as schematically shown in figures 3(a) and (b).

It is necessary to conduct a flattening process to decrease the curvature of the probe-tips as describe in the following procedures: (1) pressing the probe-tips against a hot glass-surface, which is heated by a laboratory hot plate (HHP-411V) with a temperature set at 200°C. (2) the temperature of the hot plate is then gradually decreased to 70°C while the probe-tips remain being pressed. As a result, the probe-tips could be partially flattened as typically shown in figure 3(d).

3. Experiments

3.1. Measurement of attractive force

An experimental setup used to measure the electrostatic force against the displacement of the prototype module is schematically depicted in figure 4(a). The setup consists of the prototype, a motorized stage (including stepping motor) connected to the root of the module to control its vertical displacement, a precision balance (sartorius TE153S, sensitivity is 0.001 gf) to measure the attractive force between the module and the object.

A slide glass (Matsunami Glass Ind., Ltd., S1111) of dimensions 76 mm × 26 mm × 0.91 mm and of weight 4.59 g is selected as the object and placed on the precision balance to measure the attractive force. Additionally, ceramic balls and an insulative spacer is inserted between the object and the balance, as shown in figure 4(a), in order that the effect of horizontal force on the probe-tips can be eliminated and preventing the balance from being interfered by the electrostatic field, respectively. The experiments are performed within a Faraday cage to prevent the measurements from effects of surrounding electric fields, and the cage is also grounded to assure its electrical potential at zero.

The experimental procedure employed is depicted in figure 4(b), which involves four phases: (i) approaching, (ii) loading, (iii) unloading, and (iv) detaching. Before starting measurements, the reference position of the module is determined by bringing the module into contact with the object surface without any
applied voltage. The contact point is judged by observing the measurement value of the precision balance. At the reference point, the displacement of the module, \( z \), is set to be zero, and is defined positive downward. The horizontal level of the module is adjusted and determined by observation with naked eyes. DC voltages of \( \pm 600 \) V are applied to the module during the experiments.

The experiment starts from the approaching phase, during which the module is brought towards the object (figure 4(b-i)) until it makes contact with the object. Then, further displacement is given to the module during the loading phase (figure 4(b-ii)). Finally, the module is pulled upward during the unloading phase (figure 4(b-iii)) until it detaches the object (figure 4(b-iv)). Two identical experiments are conducted here, one for the module with rounded tips and the other for the module with flattened tips. The maximum attractive force, which indicates the holding ability of the module, is measured within the unloading phase, as being discussed in the next section.

### 3.2. Evaluation of pick-and-place performance

A pick-and-place experiment of a thin dielectric object is conducted to evaluate the performance of the prototype module. The same experiment setup as used for attractive force measurement in section 3.1 is applied, however, the ceramic balls and the precision balance are excluded. Three kinds of thin objects are chosen: (1) polypropylene (PP) film, (2) tissue paper, and (3) xerographic paper. The objects are chosen to have relative permittivities of almost the same order (i.e. 2–3), however, different weight densities and surface roughness.

Figure 5 illustrates the experimental procedure, which is a sequence of four phases: (i) approaching, (ii) making contact, (iii) holding, and (iv) detaching. The object is initially placed on top of the spacer (paper stand), and the experiment starts from bringing the prototype module into contact with the object while two DC voltages of \( \pm 600 \) V are applied (figure 5(i)). Once after the module attracts the object (figure 5(ii)), by an externally given displacement, the module picks up the object and holds it (figure 5(iii)). Finally, the applied DC voltages are cut off and the module’s electrodes are grounded to detach the object (figure 5(iv)). Five trials of pick-and-place experiments are conducted for all three types of object while a video camera is used to record the experimental results.

### 4. Results and discussion

#### 4.1. Effects of probe-tip’s curvature on attractive force

Figure 6 plots the force-displacement curves measured between the prototype module and a slide glass as an object. The sequential numbering of the four phases of the measurement denoted in figure 6 corresponds to those shown in figure 4(b). The displacement is given at a rate of 10 \( \mu \)m/pulse in every 5 seconds.

The cross-marks in figure 6 denote the result for the module with rounded probe-tips, whereas the circles denote that for flattened tips. Beginning with the approaching phase, during which the module is approaching from \( z = -1.5 \) mm, almost no force is observed. When the module comes close to the object, yet before reaching the reference point (at \( z \approx -0.2 \) mm), the attractive force can be measured clearly. This attractive force, which is non-linear with respect to the displacement, signifies that the electrostatic force is dominant (to be discussed later). After the contact has occurred, further displacement is given to the module up to \( z = 0.4 \) mm, by which the module is pressed against the object (loading phase) giving rise to a repulsive force. The linear relation between the repulsive force and the displacement during the loading phase shows a hysteresis to be

---

**Figure 5.** Experimental procedures for evaluating the pick-and-place performance of the prototype module.
observed between the loading and unloading phases. The attractive force continues decreasing, and lastly at a limit of the deformation the module detaches from the object.

The maximum attractive force (denoted as $F_{\text{max.attr.}}$ in figure 6) can be extracted from the hysteresis of the force-displacement curves, that measures $-2.45$ gf for the module with flatten tips, and $-0.56$ gf for that with rounded tips. The measurement results verify that the maximum attractive force is improved by flattening process, which is 4.4 times larger than the result of rounded tips in this experiment. Consequently, it suggests that the thinner the gap exists between the tips and the object’s surface, the greater attractive force can be gained [1, 23].

In addition, another important observation is that, during the approaching phase the module jumps to contact before reaching the reference position ($z = 0$), where the attractive force is measured at $-0.25$ gf. Considering the weight of the glass object ($4.59$ gf), this attractive force is considerably too small to lift the object, however, it can make the probes bend into contact with the object before reaching $z = 0$. In order to verify the dominant attractive force, an additional experiment is conducted using the same experimental setup and sample without applied voltage. The experiment reveals that neither jump-to-contact nor hysteresis phenomenon could be observed. Therefore, it is experimentally evident that the dominant attractive force is due to the electrostatic force generated between the probe-tips and the object’s surface.

### 4.2. Effects of residual charges on attractive force

Figure 7 shows two results of the force-displacement curves measured between the prototype module and a slide glass as the object for discussing the effect of residual electric charges on attractive force. In this experiment, residual electric charges are generated by applying the DC voltages to the module and turning them off after 1 minute. The displacement is given at a rate of $5 \mu$m/pulse in every 2 seconds, and no ceramic ball was used.

The cross-marks, as shown in figure 7, denote the measurement result due to residual charges, while the circles denote the result due to applied DC voltages. The non-linear variation in the force observed in the loading and unloading phases is attributable to the effect of horizontal forces acting on the probe-tips.

The maximum attractive force is measured at $-0.70$ gf and $-0.30$ gf for the case with applied voltages and residual charges, respectively. The result reveals that even after the applied voltages had been turned off, the maximum attractive force still remained at about 40% of that with applied voltages. The maximum attractive pressure generated by the prototype module can be calculated by dividing the maximum attractive force with applied voltages ($-0.70$ gf) by the effective area of the module ($78.7$ mm$^2$), which is obtained in magnitude of $87.1$ Pa.

If no initial electric charges exist in the module, the residual force is expected to be zero. However, once the module is supplied with some amounts of voltages, free charges are trapped in the module because of its equivalent capacitive circuit. From a manufacturing point of view, the residual force may cause harmful effects upon manipulated targets, thus there have been previously several studies on this topic for various types of the electrostatic chuck [1, 3, 5, 6]. Especially, in case the manipulated target is such a relatively soft and thin material.
Figure 7. Measurement results of force against displacement. The cross-marks denote the force due to residual charges after the DC voltages have been turned off, the circles denote the force while the DC voltages being applied to the prototype module.

Table 1. Three kinds of objects chosen for pick-and-place evaluation and their results.

| Object               | Weight (mg) | Success rate |
|----------------------|-------------|--------------|
| PP film (50 μm thick)| 5.9         | 5/5 (100%)   |
| tissue paper         | 10.2        | 5/5 (100%)   |
| xerographic paper    | 31.2        | 5/5 (100%)   |

Figure 8. Snapshots of the pick-and-place evaluation for (a) polypropylene film, (b) tissue paper, and (c) xerographic paper. Dashed boxes are illustrated to indicate the position of each object because of their low contrast. All of the objects can be picked up, held, and placed successfully.
with light weight and rough surface, which is the focus point of this paper, the residual charges can not be
neglected, or rather, they may cause a noticeable problem with detaching process.

4.3. Pick-and-place performance

Three kinds of thin dielectric objects, which are (a) polypropylene film, (b) tissue paper, and (c) xerographic
paper, are cut into a rectangular shape of about 8 mm × 55 mm. The weight of the objects are listed in table 1.

Five trials of pick-and-place experiments are conducted for each object, and a video camera is used to record the
experimental results. Figures 8(a)–(c) shows the snapshots of the pick-and-place experiments for the
polypropylene film, tissue paper, and xerographic paper, respectively. The evaluation is implemented by
counting the success rate of the pick-and-place performance, which is counted only if both the picking and
placing are successfully performed. As a result, all of the objects in this experiment can be successfully (100%)
manipulated, as shown in column 3 in table 1. The experimental results imply that the proposed gripper module
has the ability of handling thin objects.

5. Conclusion

The experimental results of the attractive force measurement show that the proposed gripper module can
generate a maximum attractive pressure of 87.1 Pa, by which a piece of 31.2 mg xerographic paper can be
successfully picked, held, and placed. The residual charges and probe-tips flattening process are observed to have
noticeable effects on the attractive force, for which careful attention and further consideration are required to
improve the manipulation functionality of the gripper. It was also observed that, due to the mechanical
compliance, the probes can deform to adhere to the object’s surface from a possible distance. This phenomenon
suggests that the proposed compliant electrostatic gripper module has the ability to absorb the surface roughness
of the manipulated object.

Acknowledgments

This work was supported by Grants-in-Aid for Scientific Research of the Ministry of Education, Culture, Sports,
Science and Technology of Japan (16H04297).

ORCID iDs

Pasomphone Hemthavy 🇬🇧 https://orcid.org/0000-0001-7709-2642

References

[1] Yatsuzuka K, Hatakeyama F, Asano K and Aonuma S 2000 IEEE Trans. IAS 36 510–6
[2] Qin S and McTeer A 2007 J. Appl. Phys. 102 064901
[3] Kanno S and Usui T 2003 J. Vac. Sci. Technol. B 21 2371–7
[4] Nakamura T and Yamamamoto A 2017 Robot Mon Tech J 4 18
[5] Wang K, Lu Y, Cheng J and Ji L 2019 Proc. Int. Mech. Eng. Sci. C J Mech. Engineering Science 233 302–12
[6] Asano K, Hatakeyama F and Yatsuzuka K 2002 IEEE Trans. IAS 38 860–5
[7] Guo J, Tailor M, Bamber T, Chamberlain M, Justham L and Jackson M 2016 J. Phys. D: Appl. Phys. 49 (035303) 1–9
[8] Krahni J and Menon C 2012 J. Micromech. Microeng. 22 85438–43
[9] Ruffatto D, Parness A and Spenko M 2013 J. R. Soc. Interface 11 20131089
[10] Germann J, Schubert B and Floreano D 2014 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS 2014) (Chicago, IL, United
States of America, 14–18 Sept.) 3933–8
[11] Liu R, Chen R, Shen H and Zhang R 2013 Int. J. Adv. Robotic Sy 10 1–9
[12] Xiang C, Guo J and Rossiter J 2019 Smart Mater. Struct. 28 055034
[13] Shintake J, Rossiter S, Schubert B, Floreano D and Shea H 2016 Adv. Mater. 28 231–8
[14] Prabhulad H, Eckerle I S, Kornbluh R D and Pelrine R E 2019 U.S. Patent 10232383 Application No. 15/343303 http://www.
freetepatsonline.com/10232383.html
[15] Benerenques J, Urago M, Saiito S, Padakuma K and Meguro H 2006 IEEE Int. Conf. on Robotics and Biomimetics (Kunning, China, 17–20
Dec.) 1018–23
[16] Prevensilik T 2009 Tribology in Industry 31 61–6 http://www.tribology.flnk.rs/journals/2009/2009-1-2/11.pdf
[17] Saiito S, Soda F, Dhehika R, Takahashi K, Takarada W and Kikutani T 2013 Smart Mater. Struct. 22 015019
[18] Dhehika R, Hemthavy P, Takahashi K and Saiito S 2016 Smart Mater. Struct. 25 055037
[19] Dhehika R, Sawai K, Takahashi K, Takarada W, Kikutani T and Saiito S 2013 Smart Mater. Struct. 22 095010
[20] Shultz C D, Peskin M A and Colgate J E 2015 2015 IEEE World Haptics Conference (WHC) (Evanston, IL, United States of America, 22–
26 Jun.) 57–62
[21] Pohl H A 1958 J. Appl. Phys. 29 1182–8
[22] Pohl H A, Pollock K and Crane J S 1978 J. Biol. Phys. 6 133–60
[23] Sabermand V, Hojjat Y and Hasanzadeh M 2014 International Scholarly and Scientific Research & Innovation 8 1797–800 https://publications.waset.org/9999970/study-of-parameters-affecting-the-electrostatic-attractions-force