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Soft pneumatic grippers embedded with stretchable electroadhesion

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Abstract

Current soft pneumatic grippers cannot robustly grasp flat materials and flexible objects on curved surfaces without distorting them. Current electroadhesive grippers, on the other hand, are difficult to actively deform to complex shapes to pick up free-form surfaces or objects. An easy-to-implement PneuEA gripper is proposed by the integration of an electroadhesive gripper and a two-fingered soft pneumatic gripper. The electroadhesive gripper was fabricated by segmenting a soft conductive silicon sheet into a two-part electrode design and embedding it in a soft dielectric elastomer. The two-fingered soft pneumatic gripper was manufactured using a standard soft lithography approach. This novel integration has combined the benefits of both the electroadhesive and soft pneumatic grippers. As a result, the proposed PneuEA gripper was not only able to pick-and-place flat and flexible materials such as a porous cloth but also delicate objects such as a light bulb. By combining two soft touch sensors with the electroadhesive, an intelligent and shape-adaptive PneuEA material handling system has been developed. This work is expected to widen the applications of both soft gripper and electroadhesion technologies.

Supplementary material for this article is available [online](#)

Keywords: electroadhesion, robotic material handling, soft electroadhesive, soft pneumatic gripper

(Some figures may appear in colour only in the online journal)

1. Introduction

Soft robots are bio-inspired and versatile soft machines made of intrinsically soft, extensible, and deformable materials [1, 2]. Soft robots usually require smart materials, structures,

and transducers to deliver desired motions and behaviours. Compared to conventional rigid counterparts, they can bring certain advantages including [3] that: (1) soft robots are able to offer safer and more robust interactions with human beings and natural environments; and (2) soft robots are more resilient and capable of passively adapting to various environments.

Soft robots are poised to revolutionize robotics in many real-life applications such as the pick-and-place of delicate objects, inspection in unknown/confined spaces, and robotic assisted living [1–4]. Soft grippers are one category of soft robots. Compared to traditionally rigid grippers, these

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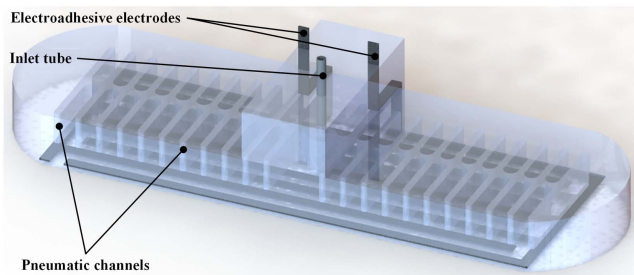


Figure 1. Schematic diagram of the PneuEA gripper in 3D.

intrinsically soft end effectors are capable of achieving highly compliant and adaptable grasping performances [1–4]. Various soft grippers have been extensively studied and implemented [1–4]. Soft pneumatic grippers (SPGs) are one of the most commonly adopted technologies and have been configured as soft bending fingers for passively compliant grasping applications [1–5]. SPGs are made of highly stretchable elastomer materials with internal fluidic channels (commonly referred to as PneuNets) [5]. They can deform upon the pressurisation of the internal channels to create a predefined motion [5]. It is difficult, however, for current SPGs to robustly grasp flat objects or to pick up objects without fully enclosing them. In addition, current SPGs cannot grasp lightweight and flexible objects on curved surfaces without distorting them.

The on-going development of soft robotics has increased the need for smart and soft transducers. Smart and soft actuators are deformable components that can be energised by external stimuli (such as electric fields) to produce desired motions and forces/torques [6]. Electroadhesive grippers are promising controllable adhesives that can be employed to grasp objects in a range of real-life applications where a wide range of surfaces (from smooth glass to rough concrete surfaces) and environmental conditions (from vacuum to humid, warm, and even dusty environments) are encountered [7]. This is because, electroadhesion [8], an electrically controllable and dynamic electrostatic attraction between an electroadhesive pad and a substrate [9], compared with other adhesion mechanisms such as magnetic, pneumatic, and bio-inspired adhesion methods [10], has certain advantages including enhanced adaptability, gentle/flexible handling, reduced complexity, and ultra-low energy consumption [7, 9, 11].

To date, very few electroadhesive grippers can robustly grasp free-form surfaces. In addition, they cannot grasp flexible objects from curved surfaces. Savioli *et al* proposed a morphing electroadhesive gripper, combining shape memory polymer with electroadhesion, to manipulate uncooperative objects [12]. The gripper's response speed was relatively slow (over half an hour) [12]. Suresh *et al* presented a curved surface gripper, combining compliant mechanical structures, gecko-inspired adhesives, and electroadhesion, to grasp various objects [13]. The gripper was developed using a delicate and complex surface and shape deposition manufacturing approach [13]. Shintake *et al* combined dielectric elastomer

actuators and electroadhesion together to fabricate soft grippers capable of manipulating various difficult-to-handle objects [14]. These soft grippers were created from precision designs with multiple electrode and dielectric layers under complex pre-stretches [14].

The great challenge for current SPGs is to grasp flat materials and to grasp without fully enclosing an object. It is also difficult for current electroadhesive grippers to manipulate complex-shaped objects. In this paper, we report the development of a novel and cost-effective PneuEA gripper by the integration of a stretchable electroadhesive gripper onto a two-fingered soft pneumatic bending actuator. As a result, the PneuEA gripper is not only able to pick-and-place delicate objects such as light bulbs and deformable objects such as volleyballs, but also flat objects such as porous clothes, CDs, and plastic plates. This gripper demonstrates the enhancement of both technologies and may significantly promote the application of electroadhesion and soft pneumatic gripper technologies.

The contents are organized as follows: In section 2, the concept design and fabrication details of the PneuEA gripper are described; A customized experimental platform and the related experiment procedures to measure the electroadhesive forces are presented in section 3, plus several material handling case studies; The design and development of an intelligent PneuEA material handling system are illustrated in section 4, before conclusions and future work presented in section 5.

2. Design and manufacture of the PneuEA gripper

2.1. PneuEA gripper concept design

The proposed PneuEA is a synthesis of a soft and stretchable electroadhesive gripper and a two-fingered soft pneumatic actuator. A schematic diagram of the gripper in 3D is presented in figure 1. This easy-to-implement design was based on low-cost and easy-to-procure commercial conductive silicon rubber sheets and dielectric silicon elastomers.

The fabrication procedure of the proposed gripper is straightforward and can be seen in figure 2. Specifically, the PneuEA gripper fabrication procedure contains three major steps: (1) manufacturing the soft pneumatic actuator, as shown in figures 2(a), (2) manufacturing the stretchable electroadhesive gripper, as shown in figures 2(b), and (3) integrating the soft pneumatic actuator with the electroadhesive gripper, as shown in figure 2(c).

2.2. Two-fingered soft pneumatic gripper design and fabrication

A standard soft lithography approach was employed to fabricate the soft pneumatic gripper used in this paper [5]. The two-fingered design was adopted. Two moulds, as shown in figure 2(a), were 3D printed using a LulzBot TAZ 6 3D printer (Aleph Object Inc., US) and a 3 mm diameter ABS filament. One was the actuator mould with negative fluidic channels. This was used to create the main body of the soft

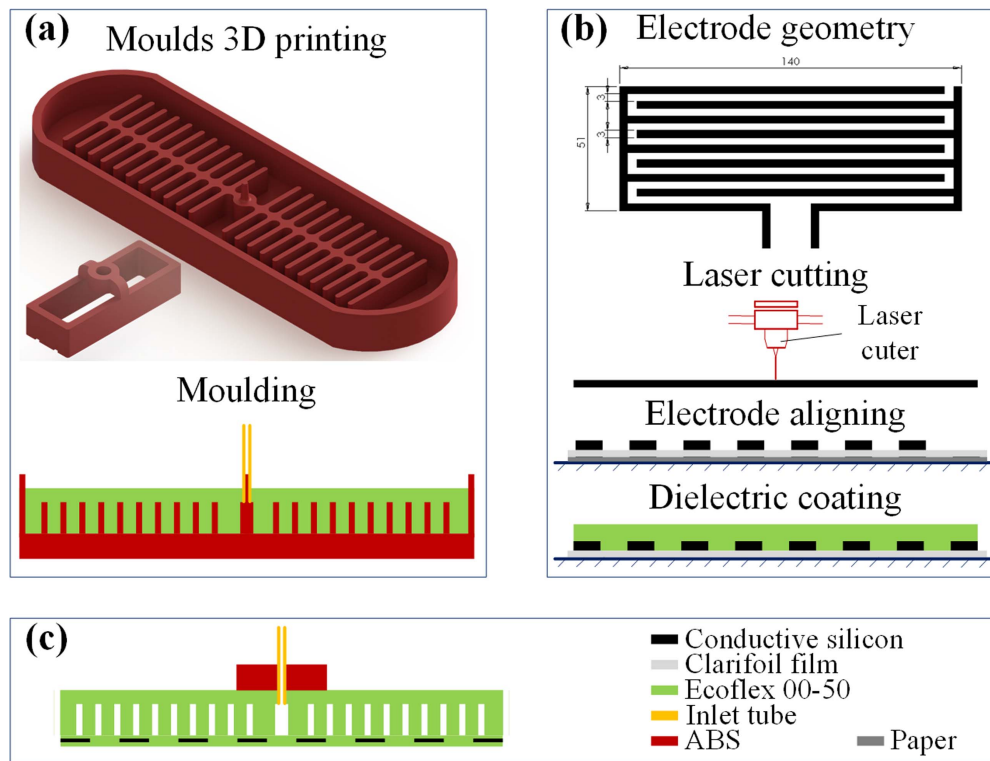


Figure 2. The fabrication procedure of the PneuEA gripper: (a) soft pneumatic actuator fabrication, (b) stretchable electroadhesive actuator fabrication, and (c) integration of the soft pneumatic actuator and the electroadhesive.

pneumatic actuator. The other was the connector mould for holding and securing the tube and electroadhesive electrode wires.

Silicone Ecoflex 00–50 (a Smooth-On Inc. product purchased from Bentley Advanced Materials, UK) was prepared by mixing equal weights of the provided parts using a wood stirrer for 2 min and then degassed in a vacuum oven (Fis-treem International Ltd, UK) at -900 mbar for about 5 min to extract any trapped air bubbles. An inlet tube was plugged in the central tip of the actuator mould. The Ecoflex 00–50 was then carefully poured in the gripper main body mould to create the two-fingered soft pneumatic actuator with imprinted features, and then left to cure at room temperature for 4 h on a flat glass substrate. The curing process can be accelerated by putting the part in the oven at 50 degree celsius. When the Ecoflex 00–50 was fully cured, the main body of the soft pneumatic actuator was demoulded from the actuator mould and placed on a clean and flat glass substrate.

2.3. Electroadhesive design and fabrication

An inter-digital electrode geometry was adopted in this work and designed in Solidworks, with an effective electrode area of $51\text{ mm} \times 140\text{ mm}$, electrode width and space between electrodes of both 3 mm, as presented in figure 2(b). Various stretchable electroadhesive manufacturing methods have been reported such as mixing carbon black powers with Ecoflex elastomeric dielectric materials [15]. The stretchable electrodes can also be manufactured from the aforementioned soft

lithography approach such as pouring prepared conductive PDMS [16] into a 3D printed mould featured with a certain electrode geometry. In this paper, the electrodes for the electroadhesive attached onto the soft pneumatic gripper were fabricated by laser cutting of an electrically conductive silicone sheet (J-Flex, UK), which was low-cost and easy to be fabricated. The J-Flex conductive silicone sheet has a thickness of 0.5 mm, hardness of 75° Shore A, volume resistivity of $4.3\ \Omega\text{cm}$, and elongation of 150%.

After the laser cutting, the two electrodes were thoroughly cleaned and dried. The same electrode geometry was printed onto a white paper which was then adhered onto a flat aluminium plate. A $30\ \mu\text{m}$ thick glossed cellulose acetate film (Clarifoil, Celanese Acetate Ltd, UK) was adhered on the top of the printed paper. The electrodes were then manually aligned with the printed pattern. Please note that a thin layer of adhesive (Elmer's Products Inc., UK) between the electrode and film may be useful for preventing the Ecoflex penetrating into the gaps between them. After electrode alignment, a 0.2 mm thick layer of Ecoflex 00–50 was blade coated on the top of the electrodes and left to cure at room temperature for 4 h.

The Clarifoil film was flexible but inextensible. This limiting layer can be used to restrict the soft finger extension upon actuation. In this way, the bending response of the soft finger can be approximately predefined via the geometry of the ribbed internal channels and the properties of the material used. The Clarifoil film can also be peeled off from the

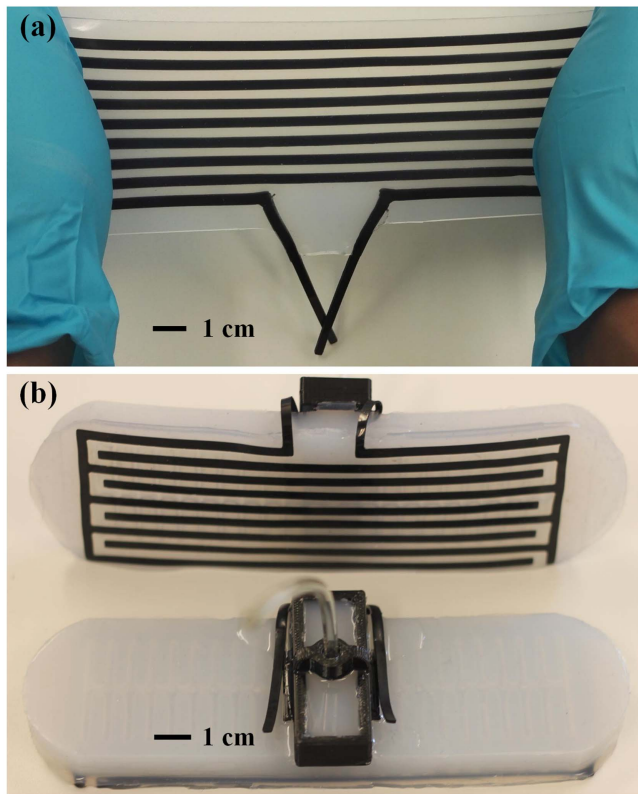


Figure 3. PneuEA gripper: (a) the soft electroadhesive shown stretched by hand and (b) the two-fingered all-elastomer PneuEA prototype.

gripper. The side with the film peeled off can then be coated with a layer of Ecoflex 00–50 material, making an entirely soft, flexible and stretchable electroadhesive gripper, as demonstrated in figure 3(a).

2.4. PneuEA gripper fabrication

Stretchable electroadhesive pads are needed for all-elastomer PneuEA grippers. In order to produce an all-elastomer PneuEA gripper, a compliant electroadhesive pad shown in figure 3(a) should be generated. When the Ecoflex 00–50, on top of the J-flex electrodes, was fully cured, the Clarifoil film was peeled off from the electroadhesive gripper. The Ecoflex 00–50 side of the electroadhesive gripper was carefully placed on a clean and flat glass substrate. A layer of freshly mixed and vacuum degassed Ecoflex 00–50 was then poured on the top of the electroadhesive gripper. After 10 min, when there was no visible air bubbles, the main body of the soft pneumatic actuator produced in section 2.2 was carefully laid down on top of the uncured Ecoflex 00–50 layer, as shown in figure 2(c). The careful bonding between the soft pneumatic actuator and the electroadhesive gripper ensured a perfect sealing between the two parts. When the adhesive layer was fully cured, the two-fingered all-elastomer PneuEA gripper was completed, as shown in figure 3(b).

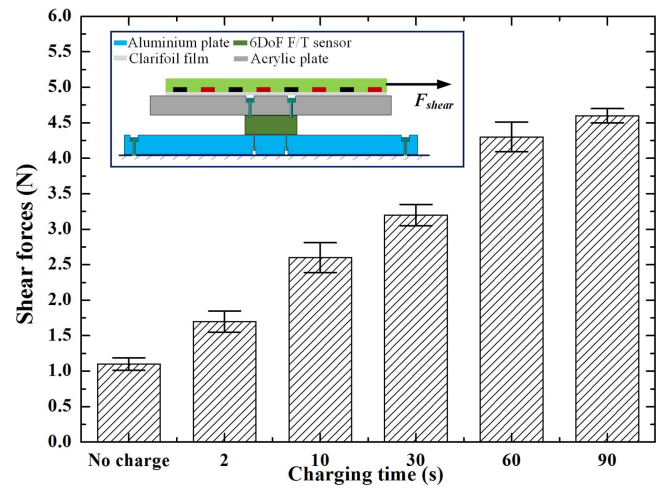


Figure 4. Shear forces of the electroadhesive gripper under 0 V (no charge) and 4.8 kV when charging for 2 s, 10 s, 30 s, 60 s, and 90 s. The error bars show the standard deviation of the five results of each test.

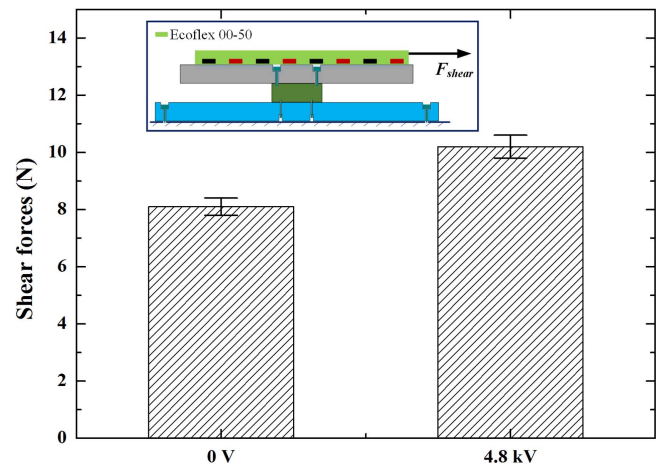


Figure 5. Shear adhesive forces of the soft electroadhesive gripper under 0 V and 4.8 kV.

3. Experimental results and discussions

3.1. Force measurement of the electroadhesive gripper

A shear electroadhesive force testing platform was used to quantify the electroadhesive performance, as shown in figure 4, where a 6-axis force/torque (F/T) sensor (tolerance of ± 0.05 N, ATI Industrial Automation, UK) was used to record the adhesive forces. Bolted connections were adopted between the flat acrylic plate and the F/T sensor. The surface of cured Ecoflex 00–50 is adhesive and attracts dusts, debris, and particulates easily. In order to eliminate the intrinsically adhesive forces produced by Ecoflex 00–50 and highlight the electroadhesive force generated by the electroadhesive pad, the bottom of the electroadhesive gripper was bonded to the Clarifoil film. The electroadhesive gripper was firstly gently laid flat down on the

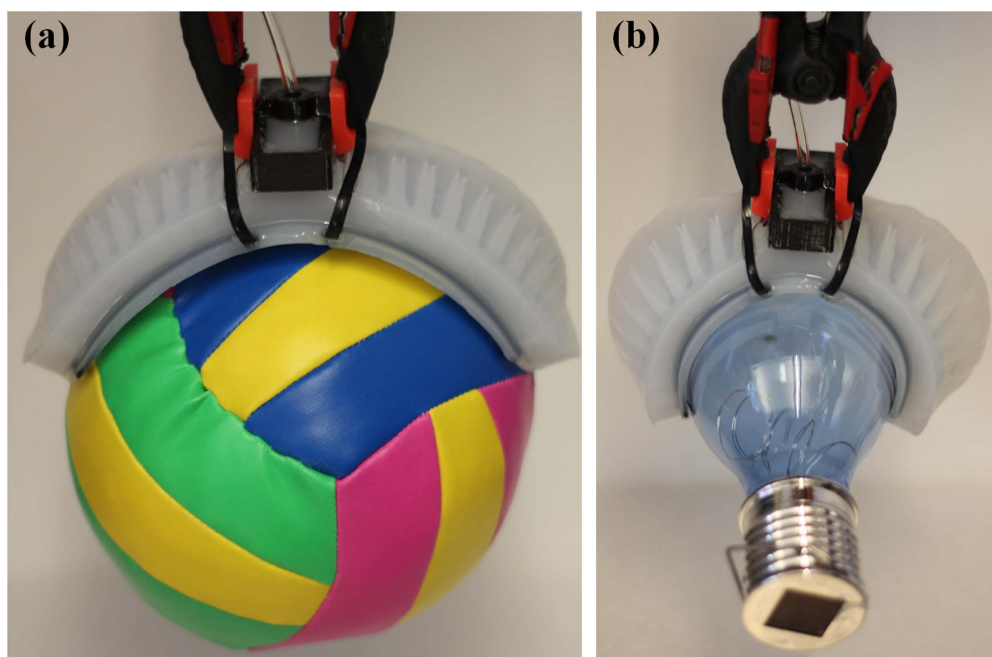


Figure 6. Safe grasping of: (a) the soft volleyball (80 g) and (b) the decoration light bulb (42 g), using the PneuEA gripper with electroadhesion off and pneumatic actuation on.

acrylic plate and then pulled away when no voltage was applied. As can be seen in figure 4, there was a 1.1 ± 0.09 N shear adhesive force between the electroadhesive gripper and acrylic substrate due to Van der Waals forces and some small amount of suction forces.

The electroadhesive gripper was then energized at 4.8 kV by two high voltage converters (EMCO High Voltage Corporation, US) connected to a direct current power supply unit (Instek GPD 3303, GW Instek). The pad was charged for 2, 10, 30, 60, and 90 s before pulling away from the acrylic substrate to investigate the relationship between the charge time and electroadhesive force obtainable and to find the charge time needed to achieve the adhesive forces close to maximum. Five tests were conducted for different charging times. Previous results showed that 90 s' pad charging can usually bring adhesive forces that are close to the maximum value [7, 9]. The results shown in figure 4 manifest that the electroadhesive forces increased with increasing the charging time. Also, the adhesive force obtained after charging 60 s was close to the result when the pad was charged for 90 s. Only a relative difference of 7% was shown. All the following tests were performed, therefore, based on charging the electroadhesives for 60 s.

In order to measure the shear adhesive forces of the all-elastomer electroadhesive, the Clarifoil film was removed and a fresh layer of Ecoflex 00–50 was coated and left to fully cure. After 5 h, the all-elastomer electroadhesive gripper was then tested on the same acrylic plate in shear direction under application of 0 V and 4.8 kV for 60 s. The results presented in figure 5 manifest that, with electroadhesion, the shear adhesive forces of the all-elastomer electroadhesive were 26% larger than without electroadhesion. This suggests that, with

electroadhesion, soft pneumatic grippers are able to grasp heavier objects. Note that all the tests were conducted in a clean and closed chamber. In addition, all the tests were conducted when the relative humidity was $53 \pm 1\%$, temperature was 21.3 ± 0.1 °C, and ambient pressure was 1019.5 ± 0.2 hPa.

3.2. Case studies: grasping various objects

As is the case with other soft grippers, the two-fingered soft gripper presented here can be pneumatically actuated to grasp objects with complex geometries and delicate nature. Without exploiting its electroadhesion capabilities, examples for safely grasping a soft ball (80 g) and a decoration light bulb (42 g) are presented in figure 6. The soft nature of this class of grippers allows conforming to the geometry of the target object without damaging the surface.

The PneuEA gripper was also tested in grasping various thin and flat materials that would be challenging for conventional soft pneumatic grippers. As demonstrated in figure 7, the PneuEA gripper successfully picked up a plastic PVC ID card (6 g, dielectric constant of 3), a porous cotton-polyester cloth (0.5 g, dielectric constant of 2), and a CD (15 g). It is shown in figure 5 that there is a 8 N intrinsic shear adhesive force when the electroadhesion of the PneuEA gripper is off. It is relatively difficult, however, to release some lightweight and flat objects once picking them up. Without external release mechanisms, the objects would adhere to the gripper indefinitely, which is undesirable and makes the grasping process uncontrollable. Fine powder was applied to the gripper surface to remove its intrinsic adhesion. As shown in the supplementary video 1, available online at stacks.iop.org/SMS/27/055006/mmedia, the

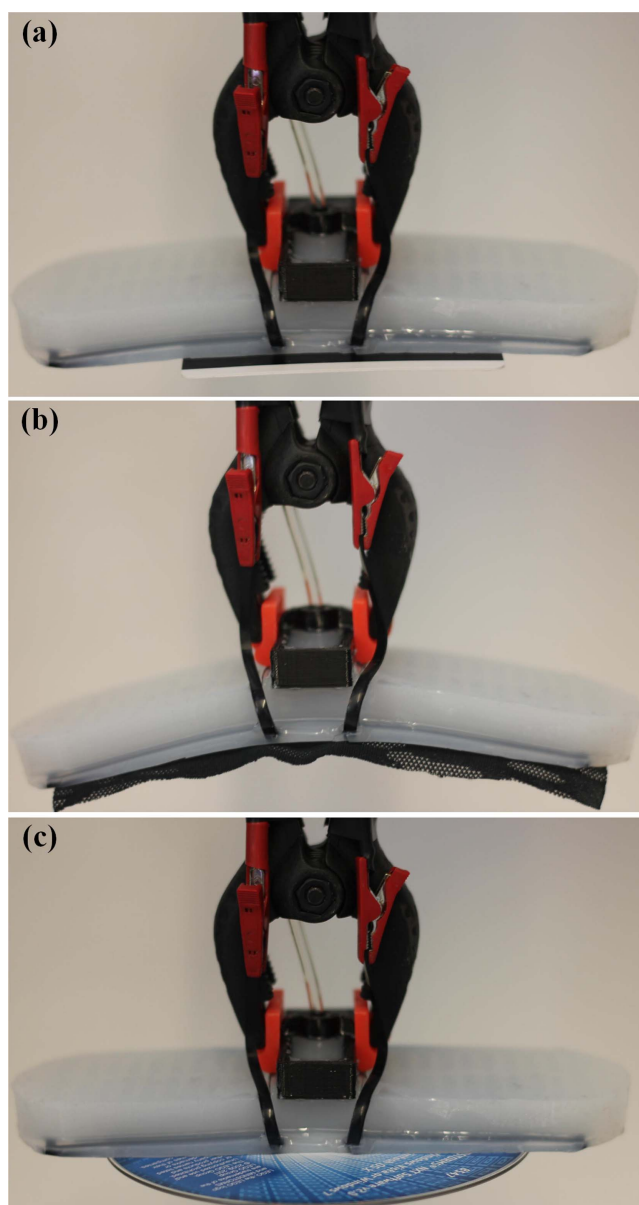


Figure 7. Grasping of flat materials: (a) plastic ID card, (b) porous cloth, and (c) CD, using the PneuEA gripper with electroadhesion on and pneumatic actuation off.

proposed gripper cannot pick up the ID card, the cloth, and the CD without applying electroadhesion. By exploiting electroadhesion, the proposed gripper was able to pick-up and release them successfully and controllably.

One unique benefit of the proposed PneuEA gripper was that, as showcased in figure 8(a), it can grasp flexible and thin materials (such as the porous cloth) from curved surfaces (such as a glass ball) with different radii, as demonstrated in figures 8(b) and (c). This is a novelty of the proposed PneuEA gripper. The grasping strategy in this case exploited both the pneumatic and electroadhesive actuation. Firstly, the PneuEA gripper conformed to the surface by adjusting its internal air pressure. 4.8 kV was then applied to enable the

electroadhesion of the gripper to attract the cloth. After this, the cloth was lifted up. The cloth was finally released by turning off the voltage, which can be seen in the supplementary video 1. In addition, the PneuEA gripper was able to grasp a layer of flexible material from a stack due to the embedded electroadhesion, which can be seen in the supplementary video 1.

4. Design and development of an intelligent PneuEA material handling system

4.1. Intelligent electroadhesive gripper design and fabrication

The proposed PneuEA aforementioned requires the user to determine when to activate both the pneumatic pump and the PneuEA action. In order to automate this process, extra sensors are needed to stop pressuring the gripper when the gripper is in contact with surfaces. Flexible resistive sensors can be used to enhance the intelligence level of soft grippers [17]. These commercial sensors, however, are not customizable and not stretchable. In this paper, two customized touch sensors, made of two coplanar J-flex conductive electrodes, were designed and embedded in the gripper, as shown in figure 9.

Rather than laser cutting the J-flex sheets used in section 2.3, a Cricut 2D computer-controlled material cutter (Provo Craft & Novelty, Inc., USA) was utilized to generate both the electroadhesive electrodes and touch sensor electrodes, providing a much easier and neater stretchable electrode cutting solution. Firstly, the 0.5 mm J-flex sheet was adhered to a 0.3 mm thick A4 size PVC sheet. Secondly, the sheet was cut by the Cricut cutter based on the electrode design shown in figure 9. Thirdly, the unwanted electrode areas were manually removed. Since there was a good adhesion between the J-flex sheet and the PVC sheet, the wanted electrode area remained on the PVC sheet. Then, Ecoflex 00–50 coating and bonding were the same with the procedures mentioned in sections 2.3 and 2.4. Baby powders were applied on top of electroadhesive surface to remove the intrinsic adhesion of the Ecoflex.

The schematic diagram of the sensor design is shown in figure 10(a). Once electrode of the touch sensor was connected to a 10 V and 1 kHz sine wave excitation from an analog output of a NI DAQ device. The other electrode of the touch sensor was connected to an analog input. When an object was touching the touch sensor, a sudden change of the sensor reading was captured by the NI DAQ device, as seen in figure (b). A touch was then detected when V_{AI} was greater than the threshold, $T = 10$ V.

4.2. Intelligent PneuEA material handling system development

Based on the intelligent PneuEA gripper shown in figure 9, an intelligent PneuEA material handling system was developed. The schematic diagram of the system is presented in figure 11(a). A bipolar 5 kV Ultravolt high voltage power

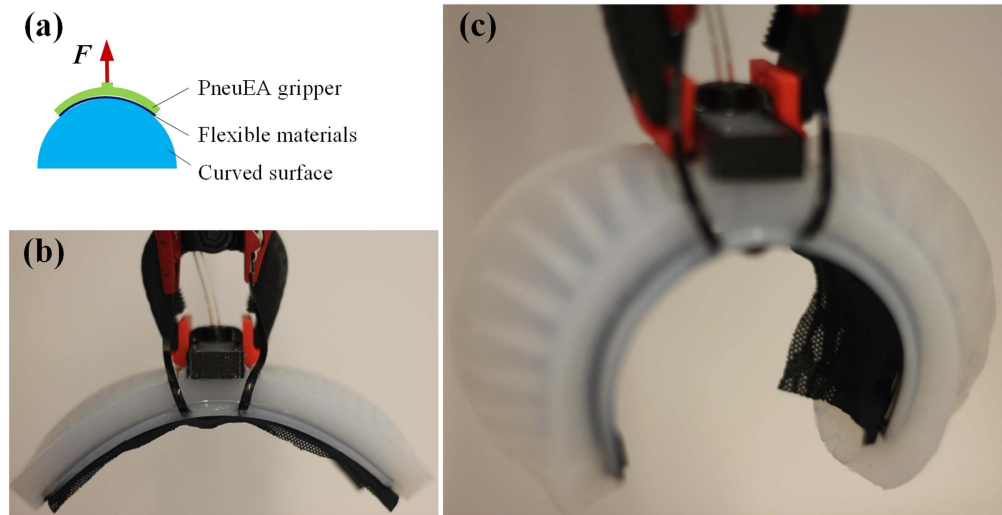


Figure 8. Grasping of flexible materials from curved surfaces: (a) schematic diagram, (b) grasping of the cloth from a glass ball, and (c) grasping the cloth from a glass ball with a different radius, using the PneuEA gripper with electroadhesion on and pneumatic actuation on.

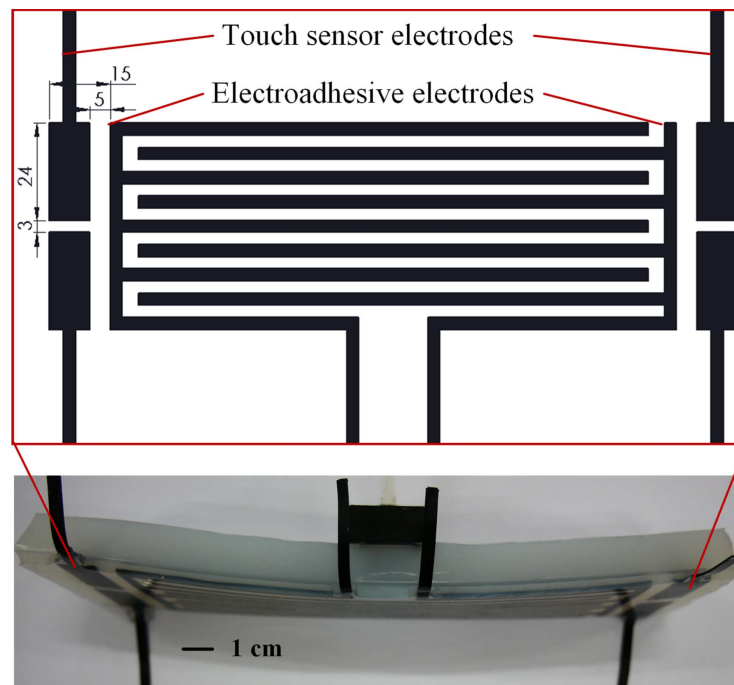


Figure 9. The intelligent PneuEA gripper embedded with two touch sensors.

supplies (Advanced Energy Industries, Inc., USA) was used to energize the electroadhesive gripper. A Zaber linear rail (X-LSQ150B-E01, Zaber Technologies Inc., USA) was used to pull the PneuEA gripper up and down. An inline miniature S-Beam load cell (Applied Measurements Ltd, UK) was used to inform the gripper whether it touches the substrate or not. A NI USB-6343 X Series DAQ device (National Instruments, UK) was used to control the output voltage of the high voltage amplifier and the switching of an air pump (Cool Components Ltd, China) via a solenoid valve (The Lee Company, USA). Grasping of a flexible fabric from a curved substrate is demonstrated in figure 11(b) and the supplementary video 2, available at stacks.iop.org/SMS/27/055006/mmedia.

The movement and control flow chart of the intelligent PneuEA material handling system is presented in figure 12. Firstly, the linear rail moved down to approach the object to be grasped and stopped when the force sensor reading was over F ($F = 4\text{ N}$ here in this study). Secondly, air was pressurized into the gripper so that it can conform to the flexible object on a curved substrate. The air pump stopped when the reading of both touch sensors was over a threshold T ($T = 10\text{ V}$ here in this study). Then the electroadhesion was turned on and 4.8 kV was applied for a period of t ($t = 5\text{ s}$ in this study). After this, the linear rail moved up to pick up the object and stopped when it reached its original position. The electroadhesion was finally turned off and the object was released.

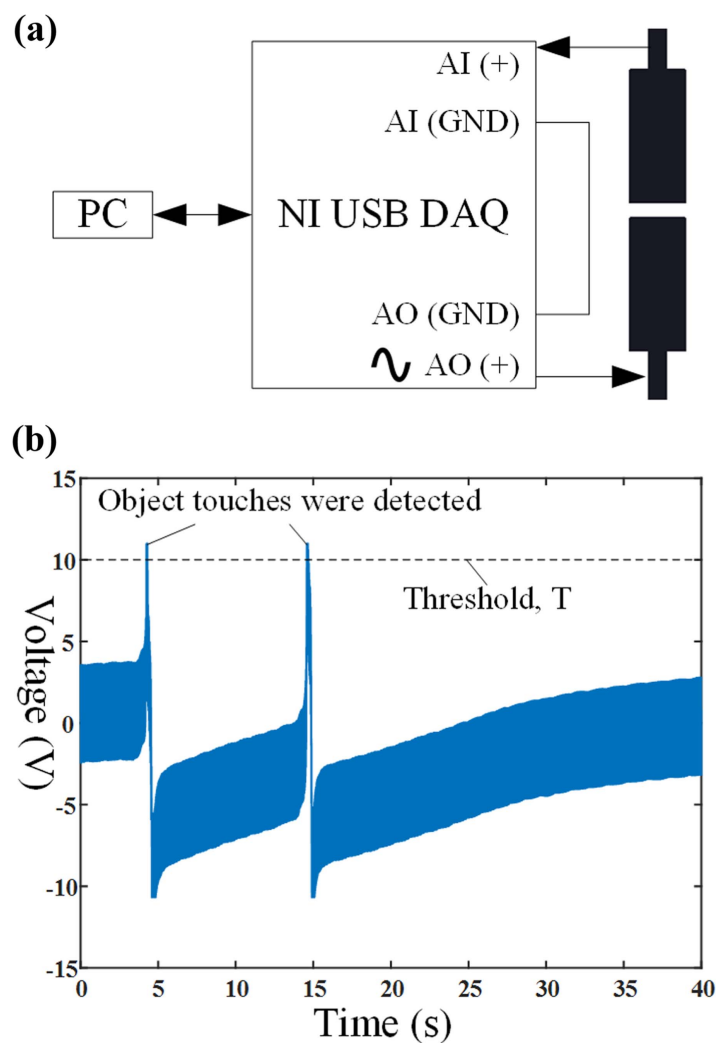


Figure 10. The soft touch sensor: (a) schematic diagram and (b) sensor reading when there is no object and there is an object touching the sensor.

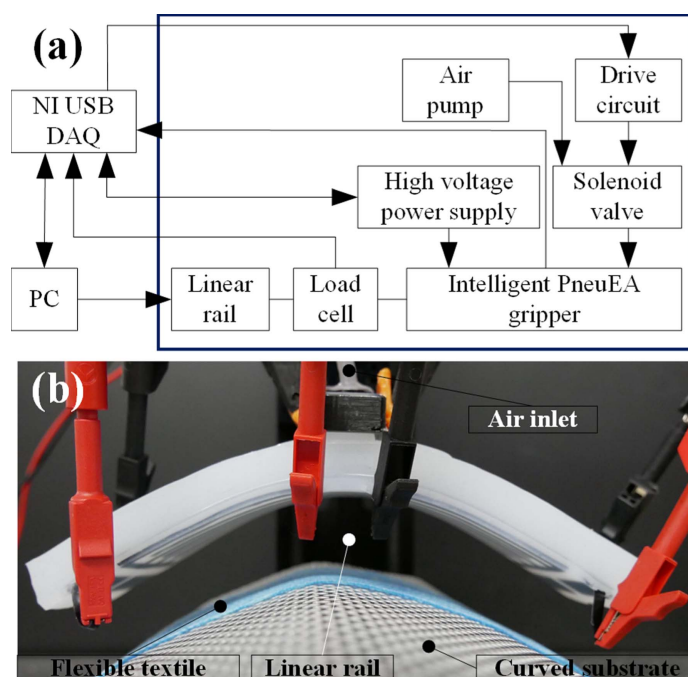


Figure 11. The intelligent PneuEA material handling system: (a) schematic diagram and (2) the physical material handling setup.

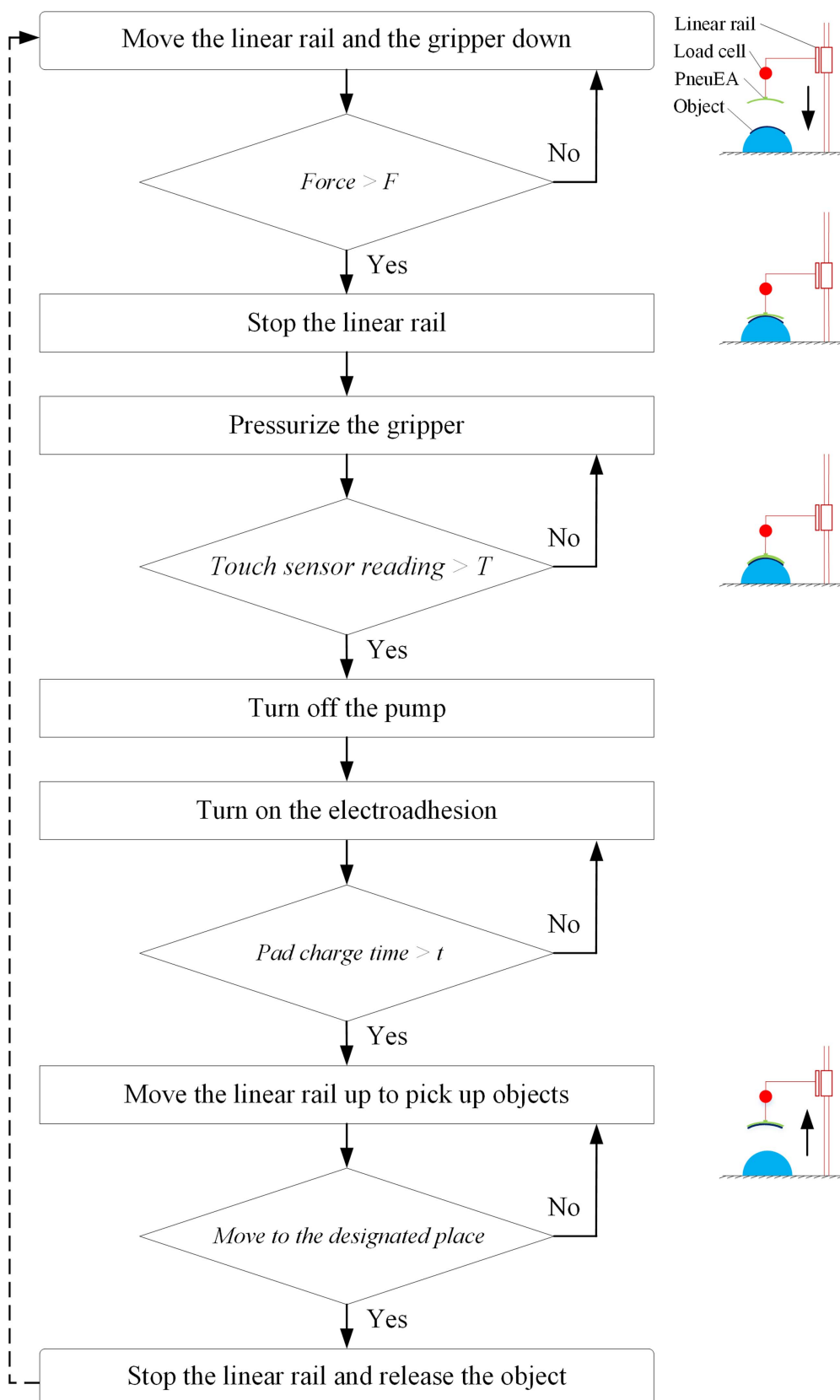


Figure 12. The movement and control flow chart of the intelligent PneuEA material handling system.

5. Conclusions and future work

The work presented in this paper has focused upon the development of a novel, cost-effective, and easy-to-implement PneuEA gripper by the integration of an electroadhesive gripper into a two-fingered soft pneumatic actuator. The proposed gripper combines advantages of both electroadhesion and soft pneumatic grippers. This combination has not only solved the limitation of soft grippers in lifting thin and flat objects but also the limitation of electroadhesion grippers in lifting objects from non-planar surfaces. As a result, the PneuEA gripper is able to handle not only flat and flexible materials but also complex-shaped objects. This may significantly extend the capability of both current electroadhesive and soft pneumatic grippers and may promote the application of both electroadhesion and soft gripper technologies. In addition, by exploiting electroadhesion, the mechanical actuation force of the pneumatic gripper can be reduced and more delicate objects can be handled.

The main contributions of this paper include: (1) the combination of electroadhesion and soft pneumatic grippers to augment the functionality of both technologies, (2) the embedding of customized soft touch sensors to make the PneuEA gripper controllable and intelligent, and (3) the development of a cost-effective stretchable electroadhesive manufacturing approach. Future work will include optimizing the design of the PneuEA gripper and its performance and integrating the intelligent PneuEA gripper to a 6DOF robot for industrial material pick-and-place applications.

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