Xiang, C., Guo, J., & Rossiter, J. (2019). ContinuumEA: A soft continuum electroadhesive manipulator. In *2018 IEEE International Conference on Robotics and Biomimetics (ROBIO 2018): Proceedings of a meeting held 12-15 December 2018, Kuala Lumpur, Malaysia.* (pp. 2473-2478). [8664717] Institute of Electrical and Electronics Engineers (IEEE). https://doi.org/10.1109/ROBIO.2018.8664717

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Conference Paper · December 2018

DOI: 10.1109/ROBIO.2018.8664717

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Proceedings of the 2018 IEEE
International Conference on Robotics and Biomimetics
December 12-15, 2018, Kuala Lumpur, Malaysia

ContinuumEA: a soft continuum electroadhesive manipulator

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***Abstract*— Soft robotic gripping technologies are highly important for pick-and-place of difficult-to-access, difficult-to-handle, and delicate materials. Electroadhesion (EA) is an electrically controllable, energy-saving, highly adaptable, and lightweight material handling technology. Current EA grippers are not able to handle objects in difficult-to-access places such as confined pipelines. We present ContinuumEA, a combination of a soft continuum arm and an EA end effector, for pick-and-place of objects in complicated environments. We embed both a camera and an EA gripper into the end effector of a multi-segment soft continuum arm to demonstrate capabilities of soft-and-safe movement, object search by visual feedback, and 3D movement and placement of objects using EA gripping. ContinuumEA has the potential to extend the gripping performance and capability of current EA grippers and increase their use in material handling applications in challenging environments.**

I. Introduction

Reliable robotic grasping and manipulation technologies are required to enable manufacturing automation [1]. A robotic gripper usually consists of an end effector (for grasping functionality) and a manipulator/arm (for robotic manipulation functionality). Robotic grasping methods have been classified into four categories: 1) impactive methods, including jaws and clamps, 2) ingressive methods, including pins and hackles, 3) astrictive methods, including suction, magnetoadhesion, and electroadhesion (EA), and 4) contigutive methods, including chemical and thermal adhesion [2]. Robotics manipulators include conventional/rigid arms and soft ones.

EA [3, 4] is an electrically controllable adhesion between an eletroadhesive gripper and a substrate. After applying a high voltage (usually via direct current power sources and in a range of kilovolts) to the electrodes embedded in the EA pad, EA force can be generated by a high-electric-field induced polarization or electrostatic induction depending on the substrate material type [2]. Since the first EA patent [4], EA technologies have been extensively used in electrostatic chucking in the semiconductor industry, EA grasping of delicate objects [5,6] and fibrous materials [7], robotic climbing [8], and perching [9]. This is due to the fact that EA has advantages, compared to other grasping methods aforementioned, including enhanced adaptability (can be used on a wide range of surfaces and environments), gentle/flexible handling (especially picking up delicate objects), reduced complexity (both in terms of mechanical structure and control system), and low energy consumption [10]. Current EA grippers are, however, not able to handle objects in difficult-to-access places such as confined pipelines. Also, there is no fully autonomous or teleoperated EA material handling systems published so far.

Robotics is undergoing a paradigm shift from conventional to soft robotics which enables highly adaptive and safe interactions due to the employment of compliant and soft materials and structures. Soft grippers and manipulators are important examples of soft robotics applications. They are highly useful for pick-and-place of difficult-to-access (e.g. in unstructured and uncertain well-defined environments), difficult-to-handle, and delicate (or fragile) materials. Various soft grippers and robotics arms have been extensively studied [11-14]. Pneumatic driven soft robotic arms are one of the most popular due to the fact that they can be controlled and fabricated in a cost-effective way and have passively compliant grasping abilities. Soft pneumatic arms (SPA) include Pneunets, McKibben, and bellow types. Customized Pneunet structures usually require customized molds and casting procedures [15]. McKibben muscles consist of a two-layered actuator, made of an inner elastomeric bladder surrounded by an external woven braided shell [16, 17]. They can be used as robot grippers [18], and continuum robots [19-21]. Commercially available McKibben muscles are also expensive. Bellow actuators, made of a flexible corrugated rubber tube and two end-parts, on the other hand are cost-effective and easy-to-fabricate. In order to address the aforesaid need for EA material handling applications in confined environments, we combined a soft robotic arm made of six bellow actuators and a camera embedded in an EA gripper. This delivers a novel and exciting concept, ContinuumEA, a soft EA robotic arm, which is promising to new approach to fully autonomous EA grasping and manipulation tasks in confined environments.

The remainder of this paper are organized as follows: the design and fabrication of the ContinuumEA is described in section II. The EA shear force and normal force is tested section III. A a case study of an intelligent ContinuumEA material handling system is illustrated in section III. Conclusions, outlining the key findings and main contributions, and future work are summarized in section IV.

II. ContinuumEA design and fabrication

A. ContinuumEA design

There is no EA gripper currently available for grasping objects in difficult-to-access areas. In this paper, a novel

*Research supported by EPSRC Fellowship projects under grant reference numbers: EP/M020460/1 and EP/M026388/1. Jonathan Rossiter is also supported by the Royal Academy of Engineering as a RAEng Chair in Emerging Technologies.

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solution is proposed by combining an EA gripper with a robotic bellow-based soft continuum arm. The schematic diagram of the proposed ContinuumEA can be seen in figure 1, consisting of three main parts: a soft continuum arm, an EA gripper, and a camera. The soft continuum and deformable arm can be used for entering challenging and confined environments. The EA gripper can be used for pick-and-place objects. The camera can be used as a visual guide for searching for target objects to be picked up.

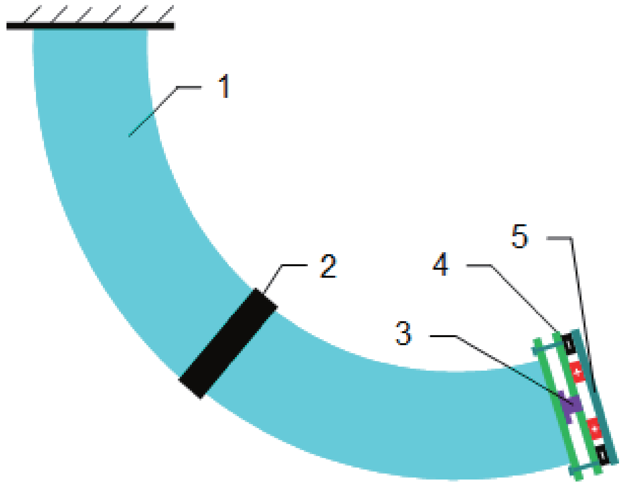

Figure 1. Schemactic diagram of the ContinuumEA: 1. Soft continuum arm, 2. Segment connector, 3. Camera, 4. Electrodes, 5. Object to be gripped.

B. Design and fabrication of the robotic bellow-based continuum arm

The bellow-based continuum arm in this paper has two sections, which enables a workspace much larger than a single section. Its 3D diagram can be seen in figure 2.

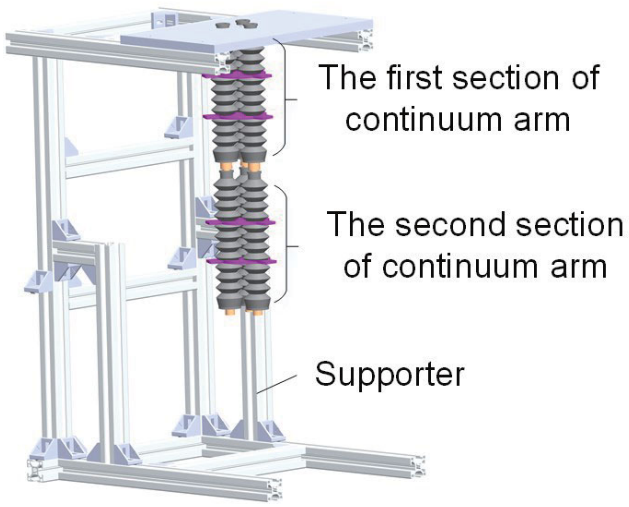

Figure 2. Schematic diagram of the Continuum arm.

Each section of the continuum arm consists of three bellow actuators (a1, a2, a3 for section 1 and b1, b2, b3 for section 2), which are arranged in parallel and arranged 120° apart. The cross-section view can be seen in figure 3 (A). The distance between the center of the bellow and the center of the continuum arm is 39 mm. Each bellow is 200mm long in rest position and each bellow fold has a minimum diameter of 22 mm and maximum diameter 38 mm. The bellow operates as a linear actuator. When inflated, the bellow will lengthen. The movement of each section of the continuum arm is controlled by relative inflation of the three bellows. Hence, the continuum arm can realize both bending and elongation movements. The working space and the operation principle can be shown in figure 3 (B) - figure 3 (G).

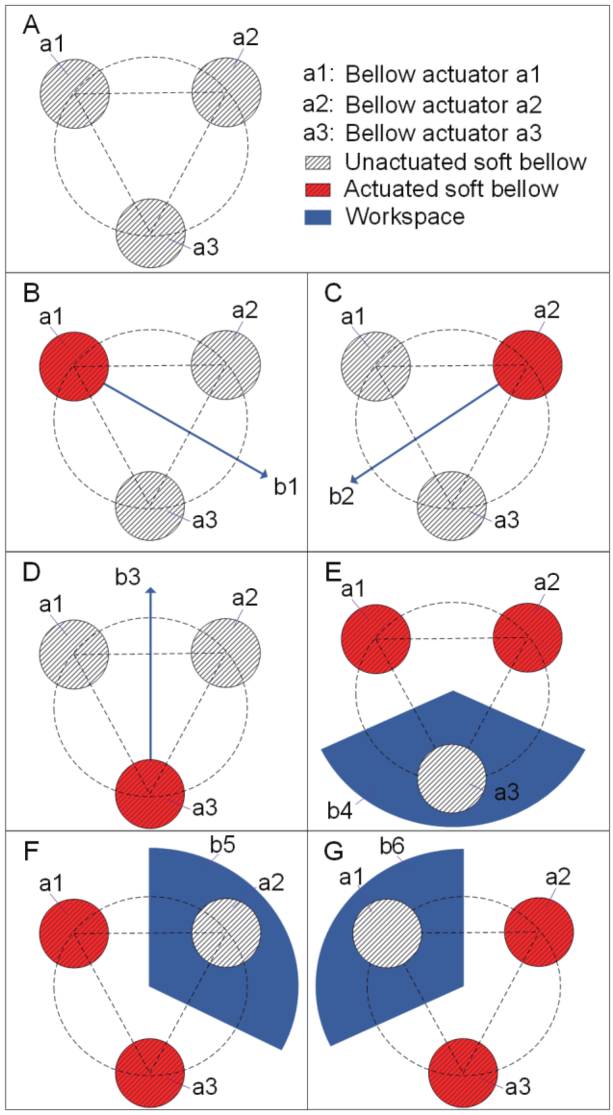

Figure 3. The working space and the operation principle of each section of Continuum arm.

From figure 3 (B) - figure 3 (G), it can be seen that through controlling these three bellow actuators, it can attend the corresponding regions. Figure 3 (A) shows the cross-section view and the legend. In figure 3 (B), bellow a1 is actuated, and the bending direction is b1. In figure 3 (C), bellow a2 is actuated, and the bending direction is b2. In figure 3 (D), bellow a3 is actuated, and the bending direction is b3. In figure 3 (E), bellow a1 and a2 are actuated, and the bending direction is b4. In figure 3 (F), bellow a1 and a3 are actuated, and the bending direction is b5. In figure 3 (G), bellow a2 and a3 are actuated, and the bending direction is b6.

C. *EA end effector design and fabrication*

An EA pad is used as a gripper for the soft continuum arm, and the design of the EA pad can be seen from [22]. The fabrication procedure and the dimension parameters of the electroadhesive pad can be seen in figure 4. The width of the electrode and the distance between two electrodes were both 5 mm. The EA fabrication procedure contains three simple steps that are enumerated as follows:

a. Firstly, a Cricut 2D computer-controlled material cutter (Provo Craft & Novelty, Inc., USA) was utilized to cut a low-cost electrically conductive silicon sheet (J-flex, UK).

b. Secondly, an A4 paper with an electrode shape was printed and a transparent plastic mask was placed on top of it. Then, the pre-cut EA electrode was arranged on the top of the transparent plastic mask according to the shape of A4 paper.

c. Finally, the EA electrode was connected to an acrylic plate using adhesive (Sil-poxy, Smooth-On Inc., USA). After 20 minutes for curing, the fabrication process of electrode was finished.

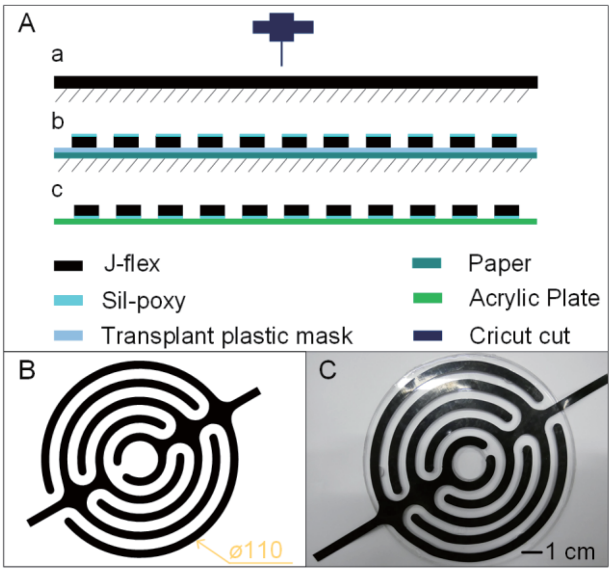

Figure 4. The EA fabrication procedure: A. the fabrication process of EA, B. the structure of EA, and C. the protoype of the EA pad.

III. Experimental Results

A. *EA force measurement and results*

To determine the relationship between force and applied voltage, the normal and shear forces of EA have been tested. Firstly, an electroadhesive normal force testing platform was established. The schematic diagram and test procedure of the normal force test can be shown in figure 5 (A). An inline miniature S-Beam load cell (Applied Measurements Ltd., UK, accuracy of ± 0.05%) was used to measure the normal adhesive force. A linear rail (X-LSQ150B-E01, Zaber Technologies Inc., USA) was used to pull the EA from an acrylic sample after 30 seconds of charging time. A Ultravolt high voltage power supply 5HVA24-BP (Advanced Energy Industries, Inc., USA) was used to provide a range of voltages to the EA pad. An NI USB-6343 X Series DAQ device (National Instruments, UK) was used to record the adhesive forces and control the output voltage of the high voltage amplifier. The designed EA pad was used to test the output forces, and the thickness of acrylic sample was 5 mm. For each experiment, three repetitive tests were conducted. The average of the three results and their standard deviation were reported. The test results can be seen in figure 5 (A).

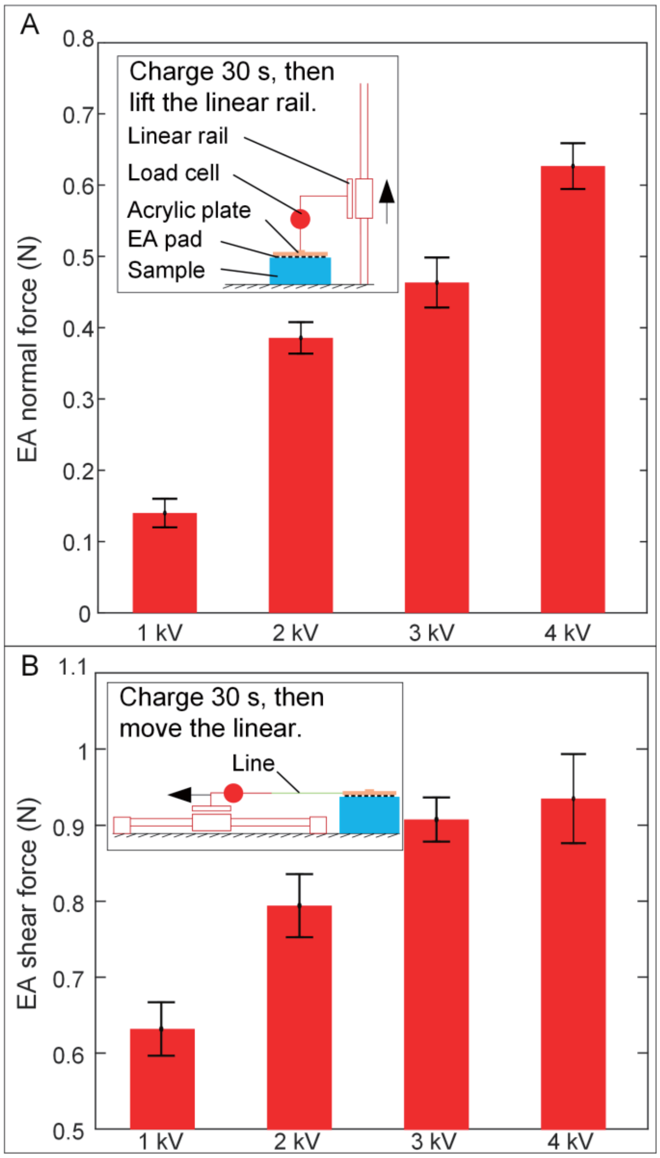

Figure 5. EA force measurement and results: A. EA normal force measurement setup and results and B. EA shear force measurement setp and results.

Secondly, an electroadhesive shear force testing platform was designed. The schematic diagram and test procedure of the shear force test can be seen in figure 5 (B). The linear rail was used to pull the EA in parallel with the surface of the acrylic sample after 30 seconds of charging time. The average of the three results and their standard deviation are shown in figure 5 (B).

Figure 5 shows that both shear EA forces and normal EA forces increase as the applied voltage increases. All the tests were conducted when the relative humidity was 54 ± 1% with ambient temperature being 25.1 ± 0.1°C.

B. *Case studies*

Based on this design of the soft continuum arm and the EA gripper, an intelligent and tele-operated ContinuumEA material handling system was developed. The schematic diagram of the system can be seen in figure 6. A high voltage power supply, HVA (E60, XP power, Singapore), was used to activate the EA actuator. The image acquisition was implemented through a USB camera module (Ailipu Technology Co., Ltd, China). Each soft bellow actuator length was controlled by two solenoid valves (S070, SMC Pneumatics, Japan) to allow inflation, deflation and holding of the soft bellow actuator. Twelve solenoid vales were used to fully control the continuum arm. An air compressor (Werther International S.p.A., Italy) supplied the air for all the bellows. When this arm lifts something heavy, the movement speed of the arm will be affected. Based on the image feedback from the camera, the operator will correct the movement of the arm in real-time.

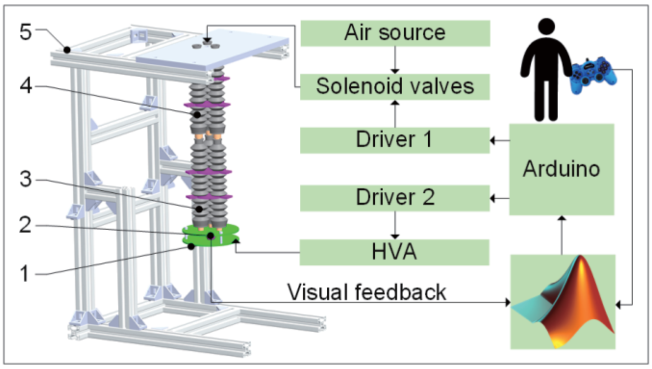

Figure 6. The principle diagram of materials handling system : 1. EA pad, 2. Camera, 3. Second section of the continuum arm, 4. First section of the continuum arm, 5. Supporter.

For a single bellow, the valves connection diagram can be seen in figure 7. An Arduino was used to control the HVA and the solenoid valves through a solenoid driver (driver 1) and an HVA driver (driver 2). The EA control commands and solenoid control commands were sent by joystick (SABRENT, USA), and all the program code was realized through MATLAB software. Grasping of several substrates within the workspace of the continuumEA is demonstrated in the supplementary video.

The control flow chart showing the movement and handling of materials for the system can be seen in figure 8. Firstly, the continuum arm was remotely controlled by the operator to search, using camera feedback, for the object which should be picked up. Once the object was located, the operator uses the joystick to control the continuum arm towards the object. When the images from the camera become dark, it means that the EA has touched the object. Then, the EA was turned on to grasp the object, and all the bellows were deflated to move the target to the designated place (rest position in this case). The EA was finally turned off to release the object to a sorting box.

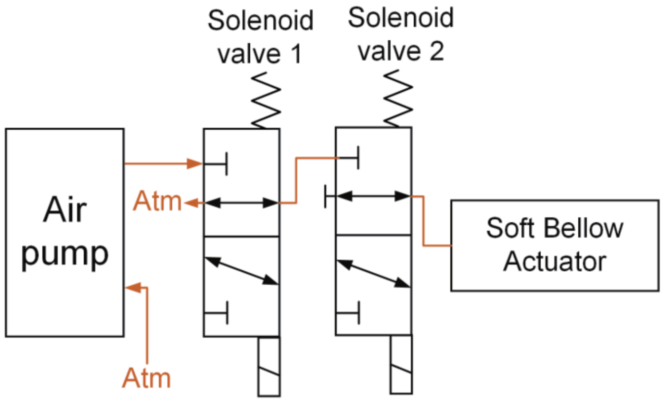

Figure 7. Valve connections. When both valves are actuated the bellow will be inflated. When only valve 2 is actuated, the bellow will be deflated. When no valves are actuated, the bellow will be held.

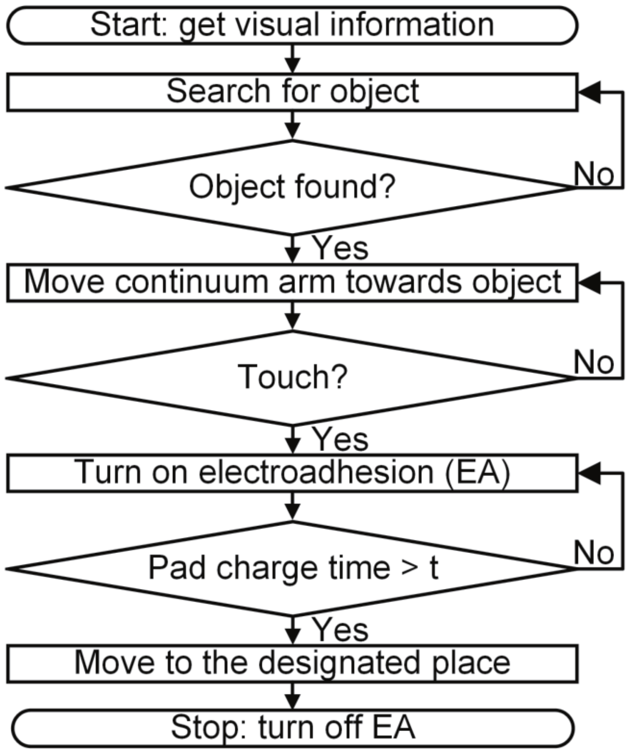

Figure 8. The movement and control flow chart of the ContinuumEA material handling system.

We previously combined EA grippers with Pneunets grippers to grip both flat and flexible materials on curved surfaces [7]. We also integrated dielectric elastomer actuation and EA into a monolothic composite gripper to grip concave objects [23]. In this paper, the design of the EA grippers is realitively straightforward, and these EA gripers can also be integrated with the bellow-based continuum arm to grasp different shaped objects. This paper presents the concept of integrating an EA pad with a soft continuum manipulator to broad the EA application range. In this case a flat and easy-to-implement EA pad was used, and as such it can only grasp flat objects. A 0.2 mm thick clear PVC sheet (Binding Store Ltd., UK) glued to a white paper was used as the target object. The square-shaped PVC sheet was 120 mm square and 2 mm thick, and weighted 5.3g. The combined grasping and articulation of the ContinuumEA are seen in figure 9.

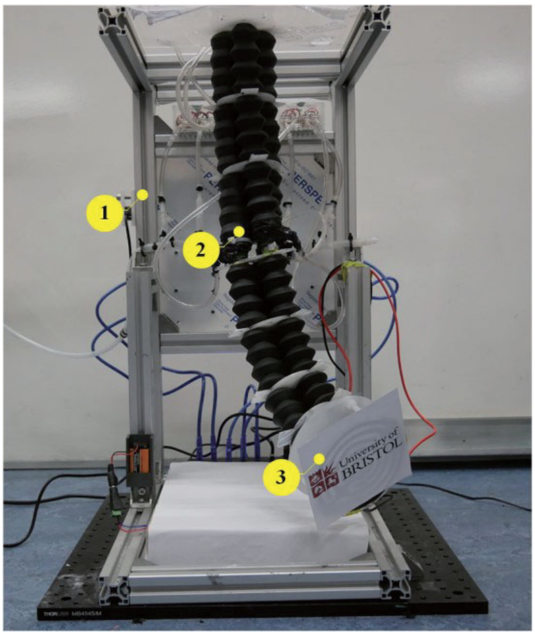

Figure 9. Simultaneous grasping and articulation of the ContinuumEA: 1. Supporter, 2. ContinuumEA, 3. PVC sheet and white paper. 4. Control system.

IV. Conclusions and Future Work

This paper presents a novel, cost-effective, and easy-to-implement soft continuum electroadhesive manipulator by the integration of a bellow-based continuum arm and an EA gripper. This combination enables the pick-and-place of difficult-to-handle and delicate materials in difficult-to-access places. This novelty offers an opportunity to significantly extend capabilities of current electroadhesive grippers.

The main contributions of this paper include: 1) the development of a soft, cost-effective, and easy-to-implement manipulator, ContinuumEA, by the combination of an EA and a bellow-based continuum arm; 2) the development of a new, easy-to-implement, and cost-effective EA fabrication approach; and 3) an easy-to-implement and real time vision-based human-computer interaction control method for the ContinuumEA material handling system.

Future work may include: 1) optimizing the design of the EA gripper and its performance, 2) addressing the dynamics and kinematics of the continuumEA, 3) integrating with soft PneuEA gripper to enhance the object gripping properties of ContinuumEA, and 4) using deep learning image processing algorithms to realize fully autonomous object recognition and grasping.

Data Access Statement

All underlying data are provided in the main text within this paper and as supplementary information (showing the ContinuumEA articulation, gripping actions, and object moving) accompanying this paper.

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