Dexterous textile manipulation using electroadhesive fingers

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ICRA 2021

doi: 10.1109/IROS51168.2021.9636095

2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
September 27 - October 1, 2021. Prague, Czech Republic

Dexterous textile manipulation using electroadhesive fingers

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***Abstract*—Handling of fabric is a crucial step in the manufacturing of garments. This task is typically performed by trained workers who manipulate one sheet at a time, thus introducing a bottleneck in the automation of the textile industry. This paper seeks to address the challenge of picking fabric up by proposing a new method of achieving ply-separation. Our approach relies on a finger-tip sized (2 cm^2) electroadhesive skin to lift fabric up. A pinch-type grasp is then used to securely hold the separated sheet of fabric, enabling easy manipulation thereafter. The ability to successfully pick up and manipulate a variety of commercial fabrics with diverse materials, shapes, sizes and textures is demonstrated. The ability to handle fabrics 100s of times larger than the electroadhesive skin is unique to our approach. Additionally, we demonstrate the manipulation of non-flat fabrics, a challenge that has not been previously addressed by electroadhesive approaches. We believe that this method introduces a smarter way of handling flexible and limp materials, showing great potential towards automation of garment manufacturing.**

I. INTRODUCTION

The manufacturing industry is a key driver of growth in the application of robotics and automation technologies [1]. The textile industry, manufacturing of garments in particular, presents many opportunities and challenges which have not been met by traditional methods of automation [2]. This is in part due to the flexible, stretchable and fragile nature of the objects involved. Some of the processes in the manufacturing of garments such as loading and unloading of fabric onto rollers, cutting into templates, and sewing have been automated [3]. However, a bottleneck in the automation of garment manufacturing is the separation of pre-cut pieces of fabric from a stack and their subsequent manipulation. This is a crucial step and often involves fabric pieces varying in shape, size, thickness, material, stiffness, and surface texture among many other parameters. They are therefore picked up one layer at a time by trained human workers. An automated method for reliably separating one ply from another would boost productivity by resolving this bottleneck. It is this challenge which we address in this paper.

Several approaches have been proposed in the literature to achieve separation of fabric plies from a stack [4], [5], [2]. Conventional grippers based on impactive prehension struggle to pick-up thin flexible sheets [6]. Rigid grippers can damage fabrics made of soft materials. A commonly employed technique is the use of air pressure. The simplest

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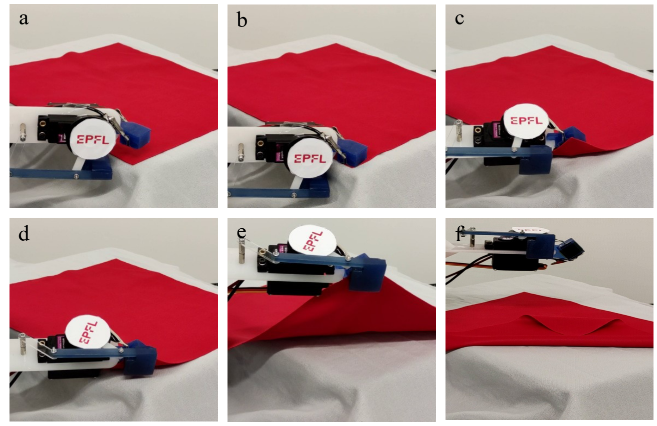

Fig. 1. A sequence of images showing the process of separating and picking up a fabric ply. (a) The gripper approaches the fabric to be picked up. (b) The finger with the EA skin adheres to a corner of the fabric. (c) The gripper performs a rolling motion to cause the separation of the top ply. (d) A pinch-type motion is executed to firmly hold the fabric. (e) The fabric is then manipulated as desired. (f) The gripper releases the fabric by opening up the fingers and turning off electroadhesion.

example is the use of a passive suction cup. An improved adhesion may be obtained by actively applying a negative pressure at the end effector [7], [8]. These approaches perform poorly for all porous fabrics. Non-contact grippers based on Bernoulli's principle of airflow have also been proposed to move single plies of fabric [9] and leather [10]. In this case, a high velocity stream of air creates a local region of low pressure which results in a lifting force on the fabric. Vibration of the deformable fabric and potential blocking of the airflow are limitations of this approach.

Mechanical grippers that mimic the motion of the human hand have also been proposed to pick up flexible objects [11], [12], [3]. A strategy relying on friction between fingers of a robotic hand and the fabric has been used to form a crease by repeated rubbing of the fabric, then grabbing the crease [13]. Optimal positioning of fingers to create taller creases to facilitate pinch-type grasping has been investigated [14]. While the range of materials that such grippers can handle is large, the deformation of the fabric while it is picked up poses major problems in subsequent tasks such as laying the fabric flat on the work surface.

A third approach relies on piercing the fabric to lift it up [15]. Pins attached to a robotic end effector have been used to pierce the fabric [16]. Commercial solutions that use needles also exist [17]. A toothed wheel was reported in [18] to handle flexible composites. Similarly, a roller with bristles has been used to separate sheets of cotton fabric [19]. A soft gripper with micro-needles was demonstrated recently, which picked fabric up by penetrating through the fibres and pinching the

doi: 10.1109/IROS51168.2021.9636095 Accepted article

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cloth [20]. A concern with these approaches is the possibility of damage through separation of fibres and tearing. Thickness of the cloth affects performance of the gripper. Piercing through multiple layers at a time is yet another concern.

Adhesive surfaces have also been used to pick up sheets of fabric [21]. Over time, adhesives are prone to contamination from dust and stray fibres, thereby reducing their ability to stick. Localised freezing is another method used to separate fabric from a stack [22], [23]. In this case, the fabric is wet before grasping. The surface of the end effector is maintained at a low temperature, freezing the fabric locally upon contact. A drawback of this approach is the damage caused to fibres when frozen. Staining of the fabric by permeation of the liquid through the fibres is also undesirable. Localised heating may also be employed if suitable to the material being handled. For example, the surface of a carbon fibre sheet can be made tacky by heating it [24]. However, post processing (smoothing) is required to remove the damage caused by heating and subsequent deformation.

Strategies based on electroadhesion (EA) [25] have been proposed as a solution to the problem of grasping fabrics [26], [27]. One of the earliest examples uses a roller with an EA skin for ply-separation [28]. A more recent study used four flat EA pads placed in a circular arrangement on a moving platform [29]. By varying the distance between the pads, fabric sheets of different sizes are picked up. Commercial solutions such as the EA gripper from Grabit Inc. are used in the textile and aerospace industry to handle flat, flexible materials [30]. Benefits of EA compared to alternative approaches are: handling a wide variety of materials and thicknesses, no damage to fibres, fast operation and pickup directly from the top surface. The comparatively lower forces generated by electrostatic fields and the requirement for the fabric to be flat for effective adhesion are a hindrance to more widespread use.

In this paper, we report a novel method of ply-separation and manipulation of fabric sheets using a two fingered gripper that is equipped with one EA skin (Fig. 1). Our approach uses the EA force to very locally (2 cm^2) cause separation of plies. Subsequently, the separated fabric sheet is grasped between the two fingers of the gripper. In comparison to other electroadhesive grippers [28], [30], where successful grasping requires a mechanism that is as big as or even bigger than the fabric sheet that is being picked up, our scalable method requires only a small EA skin, the size of a human finger-tip, to handle fabric that is hundreds of times larger in size. Another advantage is that our method can handle nonflat fabrics. This expands the usability of EA to processes that deliberately set a non-flat topology in the fabric, such as in thermoforming of contours. Since a gripper with fingers is employed, there is the possibility of manipulating the fabric after it has been picked up, which is not possible with the other approaches.

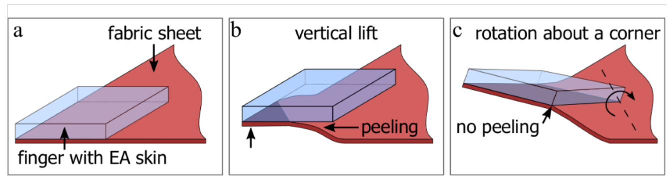

Fig. 2. (a) An illustration of the finger with EA skin adhering to a corner of the fabric sheet. (b) During a vertical lifting motion, the fabric detaches from the finger due to peeling. (c) A rotation about the inner corner of the finger prevents peeling and keeps the fabric attached.

II. PRINCIPLE OF OPERATION

The gripper used in this study consists of two fingers (Fig. 1a and 3). One finger is rigid and is equipped with an electroadhesive skin. This finger is used to lift a corner of the fabric. The second finger is able to move towards the rigid finger to perform a grasp and away from it to release the fabric being held. A four-bar mechanism drives the movement of the second finger.

Achieving sufficient adhesion with the fabric sheet and maintaining it while lifting it up are crucial to successful separation of plies. The weight of the fabric, bonding between layers and the elastic restoration forces oppose the lifting up of the sheet. As a consequence, the position on the fabric at which the gripper attempts to lift it up must be carefully chosen. Lifting the fabric up at a corner requires less force than lifting it along an edge or in the interior. A second important factor to consider is the peeling of the fabric from the EA skin as it is being separated from the rest of the stack. A simple vertical lifting motion of the corner is ineffective. As the corner is being lifted by electroadhesion, the remainder of the fabric exerts an opposing force which can result in the peeling away of the adhered region of the fabric (Fig. 2b). This peeling starts from the interior of the fabric and proceeds towards the corner. To counteract this detrimental phenomenon, a robot-controlled rotating motion of the fixed finger was employed, in a direction opposite to that of the propagation of peeling (Fig. 2c). Our strategy for grasping fabric sheets can be described in the following steps (also shown in Fig. 1).

- *Step I: Approach*. The gripper approaches the fabric sheet. The movable finger is in an open and retracted position to provide the rigid finger with unobstructed access to the object and ample space for manoeuvrability. (Fig. 1a).
- *Step II: Adherence*. The end effector is positioned such that the finger with the electroadhesive skin rests on a corner of the fabric (Fig. 1b). A potential difference is applied across the electrodes within the EA skin. The fabric then adheres to the finger by means of electroadhesion.
- *Step III: Ply-separation*. The end effector performs a rotating motion. The part of the textile that is adhering to the EA skin is lifted up. The top ply is thus separated from the work surface or the plies lying below (Fig. 1c).

- *Step IV: Grasping*. After successful separation of the ply, it is held securely in a pinch-style grasp. This is achieved by moving the opposing finger towards the fabric to perform the pinch (Fig. 1d).
- *Step V: Manipulation*. The firmly grasped textile can then be manipulated as desired. In Fig. 1e, it is picked up from the work surface and folded.
- *Step VI: Release*. To release the fabric, electroadhesion is switched off and the finger pinching the fabric is moved back to the open position. This releases the fabric from the end effector at the location of choice (Fig. 1f).

III. METHODS

A. Design of the gripper

We built a prototype to demonstrate this new method of grasping fabrics (Fig. 3). The fingers were 3D printed in a LCD-based stereolithography printer using a photo-curable resin. This fabrication method produces flat surfaces for the fingers, a required feature to affix the electroadhesive skin and to achieve complete mating of the fingers when closed. The fingers were attached to an acrylic frame. A servo motor (MG995, Tower Pro) fastened to the frame enabled the movement of the finger. The position of the finger was controlled using a microcontroller board (Arduino Uno). The gripper was mounted to a robot arm (P-Rob 3, F&P Personal Robotics) for precise positioning and handling of fabrics.

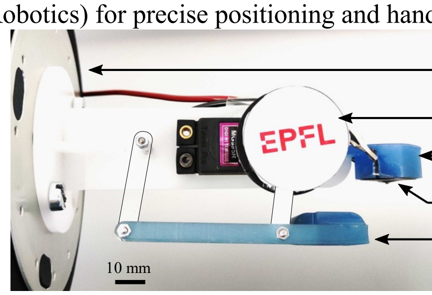

Fig. 3. A picture of the gripper with the functional components labelled.

B. Fabrication of EA skin

The electroadhesive skin in this study was fabricated in a manner similar to that described in [31]. Briefly, the process involves four steps. First, a 170 µm thick layer of silicone (SYLGARD 184, Dow) was cast on a flat surface. After it cured, a 15 µm thick layer of conductive silicone was cast on top of it. This layer has carbon powder (KETJENBLACK EC300J, AkzoNobel) mixed with silicone in a 10% proportion by weight. Once cured, the electrode pattern was cut out using a laser engraver. Finally, a third layer of silicone, 30 µm thick was cast to encase the electrodes. The overall size of the EA skin was 12 mm × 18 mm, about that of a human fingertip. The width of the electrodes was 330 µm and the spacing between them was 550 µm.

C. Characterisation of fabric samples

The electroadhesion-based strategy for grasping was tested on eight different fabric materials. These are shown in Fig. 4 and designated as S1-S8. The samples are commercial blends of materials such as elastane and polyamide, commonly used in the manufacturing of garments. Samples S1-S4 have a close-knit structure, S5-S7 have a mesh-like structure and S8 is a tufted woven fabric with a velvet-like surface. The average density of the samples was 200 g/m^2.

Surface roughness: The areal surface texture of these samples was analysed using a confocal microscope (VKX1000, KEYENCE) according to the ISO 25178 specification. The surface roughness parameters are presented in table I. The arithmetic mean height (Sa) represents, as an absolute value, the difference in height of each point compared to the arithmetical mean of the surface. The maximum height parameter (Sz) is defined as the sum of the height of the highest peak and the depth of the lowest trough.

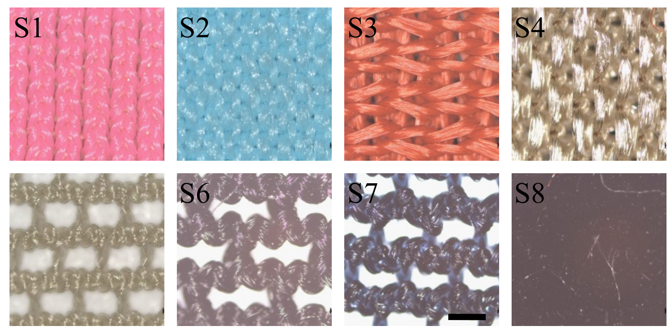

Fig. 4. The eight samples of fabric that were used in the study, as seen under a microscope. The various patterns of fibres are clearly visible. Scale bar = 500 µm

TABLE I

SURFACE ROUGHNESS PARAMETERS OF THE TESTED FABRIC SAMPLES

Property	S1	S2	S3	S4	S5	S6	S7	S8
Sa (µm)	30	22	77	57	107	164	134	69
Sz (µm)	450	354	716	791	412	806	929	1139

Measurement of adhesive stresses: Adhesion of the fabric to the EA skin is crucial to achieve successful separation of the fabric from whatever it is resting upon. While adhesion can be modelled in simple cases [25], the applicability to rough surfaces is not clear. Hence, a series of experiments was conducted to determine adhesive stresses on the fabric samples both in the shear and normal directions.

To measure the electroadhesive stress due to shear, a set of experiments was conducted as follows. The fabric sample was affixed to a horizontal platform. The EA skin was laid on top of it. A nylon nut was affixed to the exposed surface of the skin. One end of an inextensible string was wrapped around the nut. The other end of the string was attached to a load cell (Nano 17, ATI). A linear translation stage moved the load cell horizontally, thus pulling the EA skin across the surface of the fabric sample. The speed of movement was 0.1 mm/s. The total normal force on the EA skin due to its own weight and that of the nut was 0.37 g. Shear force between the contacting surfaces was measured with no voltage applied, and with a voltage of 1000 V, 1200 V and 1500 V. Each experiment was repeated three times for every fabric sample. Shear stress is

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computed by dividing the measured shear force by the area of the EA skin.

To measure the electroadhesive stress normal to the surface of the fabric, the following experiment was conducted. The EA skin was fixed to a horizontal platform. The fabric sample was affixed to a load cell (LRF400, Futek)) mounted on a vertical motorised stage. A voltage of 500 V, 1000 V, 1200 V or 1500 V was applied to the EA skin. The sample was first moved towards the skin until a maximum force of 80 mN was recorded on the load cell. This step ensured consistent contact between the EA skin and the sample. The sample was then moved away from the EA skin until it broke contact. The force was recorded throughout the motion of the sample. The speed of movement was 0.1 mm/s. Care was taken to ensure that surfaces of the sample and the EA skin were parallel to each other to maximise contact area. For each fabric sample, the experiment was repeated thrice at every voltage level. Normal stress is computed by dividing the measured normal force by the area of the EA skin.

D. Picking fabric up

The grasping and manipulation strategy based on electroadhesion was implemented to pick sheets of fabric up. First, each sample was tested to check if successful separation from the work surface could be achieved using the steps described in section II. In these experiments, the fabric sheet (about 200 mm × 300 mm) was placed on the work surface, which was a table covered in a large piece of cloth. Tests were performed at an electroadhesion voltage of 1.5 kV.

Next, the ability to manipulate the fabric after picking it up was demonstrated by folding the sheet in half upon grasping a corner. The robot arm was pre-programmed to perform this motion. This task was tested on sheets of various sizes; a 200 mm × 200 mm sheet made of fabric S2 and a 60 mm × 300 mm strip made of fabric S1.

To evaluate if our grasping strategy works non-flat sheets of fabric, a test specimen of material S4 was deliberately crumpled to have multiple creases. Only a small portion of the fabric remained flat near a corner. The same set of motions used for the other experiments was repeated to pick the sheet up.

To test if the strategy successfully separates the top ply from a stack, two sets of experiments were performed. These were set up to replicate commonly encountered scenarios in the manufacturing of garments, in particular processes that use stacks of the same material and those that require multiple materials to be handled one after the other. In the first set, four sheets of the same fabric (S2), were placed on top of each other. The gripper was programmed to pick up the top most sheet. In the second set of experiments, three sheets of different fabrics (S4, S5 and S2) were placed on top of each other. The goal here was to sequentially pick each sheet up by a corner and fold it to the centre.

IV. RESULTS

A. Characterisation of fabric samples

The measured electroadhesive stress on the various samples is presented in Fig. 5a and b. For every fabric, both the shear stress and normal stress due to electroadhesion increase with higher actuation voltages. Fabrics with a rough surface (e.g. S7 and S8) have lower adhesion in the normal direction compared the smoother fabrics. The effect of the surface roughness is also seen in the measured shear stress. The tufted fabric (S8) for example, has a higher shear stress both at no actuation voltage (dry friction) and when adhering to the EA skin as compared to the smoother, closely knit fabrics (e.g. S1, S2).

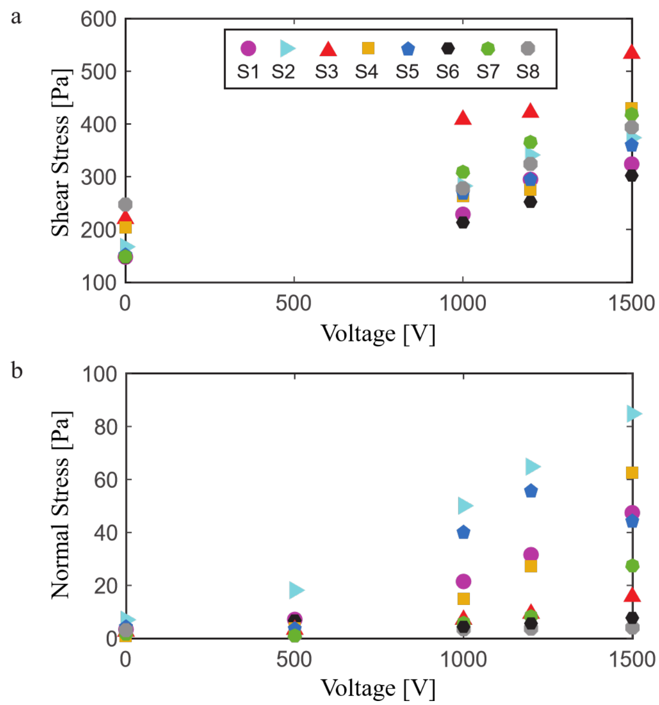

Fig. 5. (a) Electroadhesive shear stress vs. applied voltage and (b) electroadhesive normal stress vs. applied voltage for the eight fabric samples. The data shows mean of three trials at each actuation voltage for every type of fabric.

B. Picking fabric up

Fabrics with smoother surfaces (S1-S5) were all successfully picked up (see video) with the grasping routine described in section II. However, those with a high degree of variation in the surface (S6-S8) did not have sufficient adhesion to the EA skin and were not picked up.

All of the different sheet sizes tested in the study were successfully picked up (Fig. 1 and Fig. 6a-d). A sequence of images in Fig. 6 shows these fabrics before and after being picked up and folded. The fabric with deliberately induced creases was also successfully picked up, without any issues (Fig. 6e-g).

The EA based separation of plies from a stack also worked for the tested fabric (S2). The top ply adhered to the EA skin and was lifted up without affecting the plies below (Fig. 7). When tested on stacked sheets of dissimilar materials (S2, S3 and S5), the gripper had no trouble picking each top sheet up and folding it one after the other (Fig. 8).

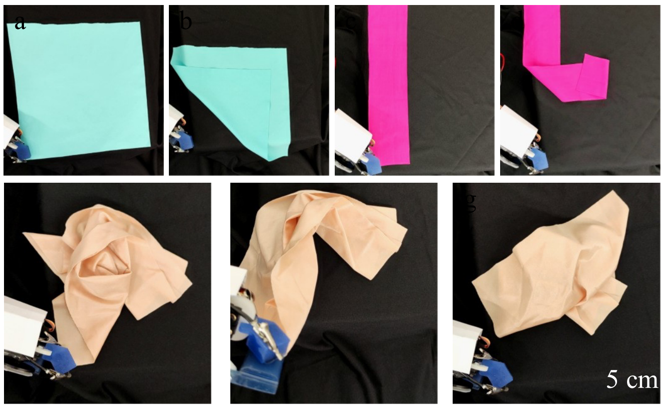

Fig. 6. Sequence of top-view images showing sheets of fabric before and after being picked up and manipulated. (a) A square sheet of fabric S2, 200 mm × 200 mm in size. (b) The same sheet after it has been folded in half. (c) A strip of fabric S1, 60 mm × 300 mm in size before it is picked up. (d) The same strip of fabric after being folded by the gripper. (e) A sheet of fabric S4 deliberately creased into a rose-like shape. (f) The same sheet after it has been picked up at the bottom left corner. (g) The sheet after the corner has been folded towards the centre. Scale bar = 5 cm

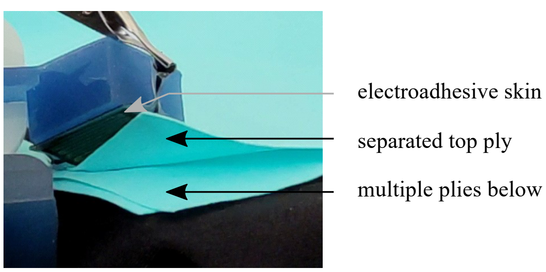

Fig. 7. Successful separation of the top ply from a stack of fabric sheets of type S2.

V. DISCUSSION

The strategy of ply-separation and grasping combining small-area electroadhesion followed by pinching reported in this study, works for a variety of materials, as demonstrated above. The method proved particularly successful in the case of smoother fabrics (S1-S5) due to high adhesion force between the fabric and the EA skin (Fig. 5a and b). The fabrics that were not successfully picked up (S6-S8) have a rough surface (note the large Sz values in table I). Fabrics S6 and S7 have a mesh-like weave which is the reason for this roughness. As a consequence, the effective area of contact between the EA skin and the fabric is many times smaller than the area of the skin itself. A smaller contact area drastically reduces the achievable electroadhesive force on these materials [32]. The issue is similar in the case of the velvet-like material (S8). This material has tufts of fibres that extend normal to the surface which reduce the contact area, resulting in a lower force of adhesion (S8 has the highest shear force at 0V, but not at other voltages). Although fabric S5 had a mesh type structure, it was less wavy (lower Sz). The gripper was able to successfully pick this fabric up, demonstrating that our strategy works for fabrics with voids, which is not possible with vacuum based grippers.

The results of the experiments with picking up sheets of

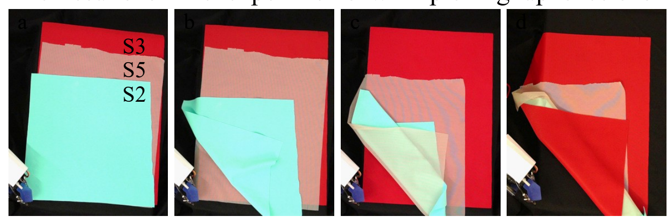

Fig. 8 Sequence of images showing the picking up and manipulation of a stack of fabric sheets one at a time. (a) The stack of sheets before manipulation. (b) The stack after the first sheet, S2 has been folded, (c) after the second sheet S5 has been folded and (d) after the third sheet S3 has been folded.

different sizes shows that our method can be scaled to fabrics of various shapes and sizes (Fig. 1 and 6), without any modification in the design of the gripper. Earlier approaches based on electroadhesion [28], [30] relied on using large and flat grasping surfaces to ensure large force of adhesion. Since our approach relies on electroadhesive forces only to achieve successful separation of plies in a localised region, and thereafter uses a pinch-type gripper to handle the weight of the whole fabric, the shape and size of the fabric have a negligible impact on the performance.

Another advantage of our method is the ability to manipulate fabrics after picking them up. In this study, we demonstrated this ability by folding the fabric after picking it up (Fig. 6 a-d). Folding is possible because only a corner of the sheet is adhering to the gripper while the rest of the fabric is free to move.

A third benefit of our approach is the ability to pick up non-flat fabrics. We demonstrated successful picking up of a crumpled fabric sheet that was arranged in a rose shape (Fig. 6e-f). Our method only requires that a small local region, the size of a fingertip, be flat to be able to pick up and manipulate the sheet. On the contrary other electroadhesive grippers rely on the entire surface being flat [28], [30].

Electroadhesion is an elegant strategy to achieve separation of plies from a stack. We demonstrated this strategy for both similar and dissimilar materials (Fig. 7 and 8). Since the electroadhesion force decays quadratically with distance, this technique is well-suited to separate a single sheet without affecting other sheets lying below. While it has been argued that the separation of plies from a stack of dissimilar materials is a more challenging task due to different polarisation densities on either side of the ply [28], such as difficulty was not observed in our experiments.

A common challenge with electroadhesion is the slow release of adhered objects after the applied voltage is switched off due to residual charges [33]. Researchers have tried to address this issue by adding actuators to enable rapid release [34]. Our gripper does not present such an issue as the aforementioned peeling due to the weight of the fabric aids in rapid de-adhesion (see section II).

VI. CONCLUSIONS

In this paper we reported a novel approach to pick fabrics up and enable their manipulation. The method relied on electroadhesion to separate a fabric ply from the work surface and a pinch-type gripper to grasp the sheet after it has been separated. A prototype end effector was used to show that the method works successfully with diverse fabrics of different shapes, sizes, materials and weave patterns.

Testing the performance of the gripper in different environmental conditions will be considered in the future. There is scope for addressing some of the drawbacks discussed with regards to handling rough materials. For example, introducing compliance could enable the EA skin to conform better to the uneven surface. Optimisation of the EA skin in terms of the materials [35] and patterning of electrodes to achieve larger adhesive forces [36], [37] is another possible solution, which is being investigated. The influence of ply thickness on grasp sucess is also being studied.

The approach presented in this paper is an important step towards improved automation in the manufacturing and handling of flexible materials.

VII. ACKNOWLEDGMENT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869963 (MERGING).

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