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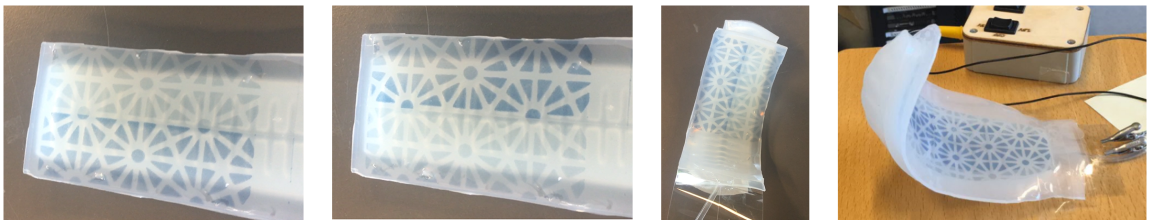

Fig. 1. Examples of two different soft-robotic actuators with build in electrochromic displays produced with the ChromaBot method.

Soft robotics - robots built from highly compliant materials that resemble soft biological materials - have recently become more popular especially in industry settings, given their ability to handle fragile objects. One problem however of these devices is that they can only communicate intend or the need for help through movement. To overcome this limitation, in this paper we present ChromaBot, a method towards prototyping soft robotic actuators with integrated printed electrochromic displays. Our method only degrades the longevity of the soft robotic actuator in an acceptable manner while at the same time allows for a more expressive soft robot. We present detailed instructions on how to prototype ChromaBot as well as an initial analysis of the durability, both of the display as well as of the actuator.

CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)**; • **Computer systems organization →** Robotics.

Additional Key Words and Phrases: Human-robot interaction; soft robotics; display; electrochromic displays

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1 INTRODUCTION

Soft robotics have in the last years emerged as a new class of robotic actuators. Their defining characteristic is that they are built from highly compliant materials with Young moduli that are close to soft biological materials [19]. Besides other [14], the most prominent application for soft robots is to be used as a robotic gripper, as their softness allows to grab irregular shaped and fragile objects[1]. Given their softness they are also particularly well suited for human

[1]https://www.festo.com/group/en/cms/12745.htm

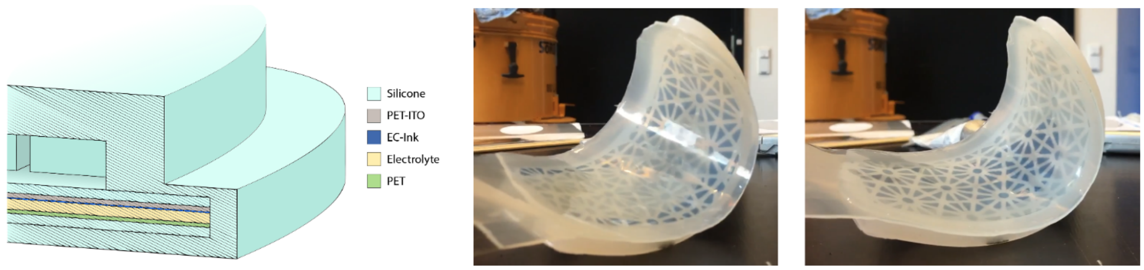

Fig. 2. Left: Composition of the ChromaBot layers using a co-planar stack with PET-ITO as top- and normal PET as bottom layer all encapsulated by silicone. Right: The evaluation prototype with a simple pattern that is split in two states and each activated.

robot collaboration as the danger of injuring the human collaborator is rather small [3, 14, 15]. However, they have limited capabilities to communicate, their intention and future actions to a human collaborator. If the soft robot fails in completing its task and cannot self-correct its behavior, a human may be needed to assist it and the current state of soft robotics only allow for the usage of movement [13, 15] or external augmentations such as sound [1] to communicate such issues. This multi-modal interplay of different interaction partners with asymmetric communication capabilities is a general issue in HRI [2, 5], however, with rigid robots, it is easy to attach e.g., displays that can assist in communication. Adding rigid components to a soft robotic actuator would decrease its main defining characteristic. While flexible OLED or E-ink displays are becoming more common they still require "hard" electronics for the display drivers and their high-price point make them less suited for prototyping. The field of printed electronics has recently developed to a point at which thin and flexible displays can be printed at comparable low costs [7, 17]. In this paper we present ChromaBot, a method towards prototyping soft robotic actuators with integrated printed electrochromic (EC) displays. Through an experimental prototyping approach we developed a construction method, that degrades the longevity of the soft robotic actuator in an acceptable manner while at the same time allows for a more expressive soft robot.

2 METHOD & EVALUATION

We followed an experimental approach to develop a method to integrate EC displays into a soft robotic actuator. The reason for choosing EC displays is that they are easy to produce and have a proven track record in interactive artefacts [9–11] and can be integrated easily with other materials such as paper [12, 16] or be used as part of a wearable [4, 8]. We followed previous work and used the PneuNet design for our actuators [6]. PneuNet actuators are made of two layers that are merged, the extensible layer and the inextensible layer. The extensible layer - usually cast from a highly compliant silicon - contains several air chambers that, once pressurized, expands and is thereby bending the actuator given that the inextensible layer does not expand. For ChromaBot we decided to use an EC display cast in silicone as the extensible layer. Given that most current display technologies are not stretchable, it is the most logical choice to integrate the display in the inextensible layer which is supposed to be less compliant. For our approach we decided to produce the EC display in a co-planar stack following the method described in [7] using flexible PET-ITO. The reason to chose a co-planar stack over a vertical stack is, that the latter is comprised out of two layers of PET-ITO facing each other that potentially could under stress and pressure touch each other and short-circuit. With a co-planar stack there is no risk for this. We tested over 25 different combinations and building styles before we arrived at the final combination. A cross-section of the final construction of ChromaBot can be seen in Figure 2 (left). Building the inextensible layer consist of the following steps: Firstly one builds a co-planar EC display consisting of a layer of

PET-ITO, EC-ink, electrolyte and normal PET. Then a flat thin layer of silicone is produced and cured. After that the EC display is placed on it and more silicone is cast around it and on the top of it which should also be cured. The PET-ITO layer of the EC display should face the outside of the actuator leading to a clearer visible display. The PET-ITO should extend further out of the extensible layer so that the connection leads to digitally control the display can be connected (compare Figure 1 right). Lastly, another layer of silicone is placed on this to fuse the extensible layer (cast priory from silicone in a suited mold) to the inextensible layer.

We evaluated this method by constructing 10 actuators following the above described steps as well as 5 actuators without a display where the inextensible layer was build with textile (made 100% from cotton). The silicone that was used was uncolored ecoFlex 00-30 from Smooth-On. The final design of the actuator can be seen in Figure 2 (right). We used a more complex actuator with a rounded end that was 14cm long. The used design for the display was a simple pattern that was meant to enhance the aesthetics of the actuator with no specific application in mind. The switching time of the displays (meaning an activation until no visual optical change was perceivable) after they were cast in silicone was between 9-10 seconds (avg 9,67s). To test the durability of the actuator we fixated one end of an actuator to a a table using adhesive tape and exposed the actuators to continuous complete inflation and deflation cycles. After every 200 cycles we tested the switching time of the display. We measured the average time it took until no visual optical change was perceivable. We cycled the actuators through inlfation and deflation cycles until they would break (meaning that they would not inflate anymore). This occurs usually due to either the extensible or inextensible layer disintegrating or the two layers separating from each other. The actuators were pneumatically inflated by a Mitsumi air pump, to which also a valve was attached to release air from the chambers to deflate the robot. The pump and valve are controlled by an Arduino Uno with a motor shield. On average the ChromaBot actuators all lasted for over 1400 cycles of inflation and deflation (avg. 1591) before they would disintegrate, in comparison the normal actuators all lasted over 1700 cycles (avg. 1923) before breaking. The mostly observed reason for this decreased lifetime is that the silicone separates from the display making the displays move in its cavity in the inextensible layer and ultimately breaking it. In terms of display switching time no differences were found during the tests compared to the starting point.

3 DISCUSSION & CONCLUSION

Overall the ChromaBot actuators performed very well and why they did pose a decrease in durability compared to the normal actuators, it is still acceptable for prototyping purposes. While EC displays come with some disadvantage e.g. not being light emissive, given that the characteristics of electrolumiscent (EL) displays in terms of thickness and flexibility are very similar to them and that they also can be produced using PET-ITO [17] it should be possible to replace the EC display with an EL display in the ChromaBot build. This however, would need further investigation, but from a purely technical perspective it should result in similar actuator performance. It also should be mentioned that the actuators used and thereby its bend radius were rather large. This means that the PET-ITO was exposed to less stress. With smaller actuators this might change. While these limitations are not negligible, the ability to integrate digitally controlled displays is an advancement over existing approaches. We believe that ChromaBot can have a significant impact in enhancing soft robots communication channels to be more multi-modal. Our example actuators purely where equipped with a display demonstrating a pattern that was meant to be aesthetically pleasing. Besides these aesthetic or playful elements we especially hope, ChromaBot will be used to add more affordances, explanations or instructions to soft robotic actuators. It can play an active role in facilitating human robot collaboration using soft robotic actuators in the future. Furthermore, we also believe that this approach hast the potential be used for future research in shape-changing devices [18].

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