Recent Progress in the Development of Soft Robots

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Abstract

Soft robots, are mobile machines largely constructed from soft materials and have received much attention recently because they are opening new perspectives for robot design and control. This paper reports recent progress in the development of soft robots, more precisely, soft actuators and soft sensors. Soft actuators play an important role in functionalities of soft robots, and dielectric elastomers have shown great promise because of their considerable voltage-induced deformation. We developed soft inflated dielectric elastomer actuators and their networks, with the advantages to be highly deformable and continuously controllable. When it comes to control of soft robots, soft sensors are of great importance. We proposed a methodology to design, analyze, and fabricate a multi-axis soft sensor, made of dielectric elastomer, capable of detecting and decoupling compressive and shear loads with high sensitivity, linearity and stability.

Index Terms: soft robots, soft actuators, soft sensors, dielectric elastomer

1. Introduction

Soft robotics has become a hot research field in the past decade. Rigid robots often encounter difficulties operating in unstructured and highly congested environments. On the contrary, the use of soft materials in robotics, driven not only by new scientific paradigms but also by many applications, is going to overcome these basic assumptions and makes the well-known theories poorly applicable, opening new perspectives for robot design and control.[1] Rather than relying on sliding or rolling motion as in traditional mechanics, soft robots produce their mobility based on the deformation of elastic members. This enables the integration of multiple functions into simple topologies, by embedding soft actuators and soft sensors to build fully functional and distributed structures capable of complex tasks.

Generally, a soft robot system includes soft bodies that may consist of elastic and/or rigid parts, soft actuators and soft sensors. A basic requirement of a soft robot is to generate large enough deformation, especially when the interaction with the environment is involved. The current examples of soft robots offer some solutions for actuation and control, though very first steps.[2] The biggest challenges in soft robotics currently are the design and fabrication of soft bodies, development of robust soft actuators capable of withstanding large deformations and delivering considerable stiffness, and soft sensors applicable to complex loading conditions with a large detection range, etc.

This paper will briefly report our recent progress in the development of soft actuators and soft sensors. Specifically, dielectric elastomer balloon-like actuators are developed, showing to be highly deformable and continuously controllable. Also, a multi-axis soft sensor is developed, made of dielectric elastomer, with the capability of detecting both compression and shear loads.

2. Soft actuators

Soft robots are able to operate with several different modes of actuation (say, pneumatic, electrical, etc). Dielectric elastomers, capable of deforming in response to an external electric field, have shown great promise for soft actuators due to their large voltage-induced deformation. Here we focus on dielectric elastomer actuators.[3,4]

2.1. Networked dielectric elastomers actuators

Balloon-like dielectric elastomer actuators have received much attention since the inside air of high pressure can provide prestretch to greatly improve the actuation performance.[5] The deformation of dielectric elastomers, however, is strictly restricted because of material failures such as loss of tension and electric breakdown. With these regards, we developed networked dielectric elastomer balloon actuators, coated with compliant electrodes and interconnected via a rigid chamber, as shown in ***Figure 1***. For the networked system, the input voltages are independently applied to the balloons, resulting in the output deformations of the balloons. The networked design is able to greatly postpone the occurrence of material failures and thus remarkably enlarge the actuation range.[6]

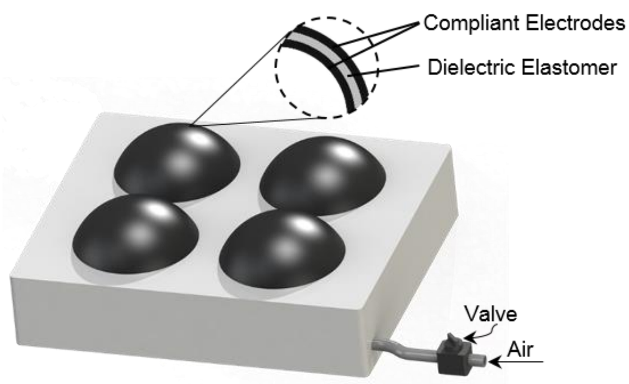

Figure 1. Illustration of networked soft inflated actuators, interconnected via a chamber. Each actuator, coated with compliant electrodes on its surfaces, is independently connected to a high voltage.

Figure 2 shows the overview of the experimental setup, and some experimental results. Initially the balloons are pumped until the net pressure reaches 2kPa. Thereafter, the system is sealed and then voltages are applied. When only one balloon is activated, the activated balloon deforms largely (say, about 3 times the volume of the prestretched state), the inside pressure drops accordingly, and the others shrink (***Figure. 2b***). The underlying reason for large deformation is that the three passive chambers effectively slow down the drop of inside pressure, sustain the mechanical stresses of the actuated membrane, and thus postpone the occurrence of material failures. When three balloons are activated, the inner pressure drops and the unactivated balloon to shrinks greatly (almost flat, see ***Figure 2c***). This actuation mode typically explores the minimum volume of the balloon.

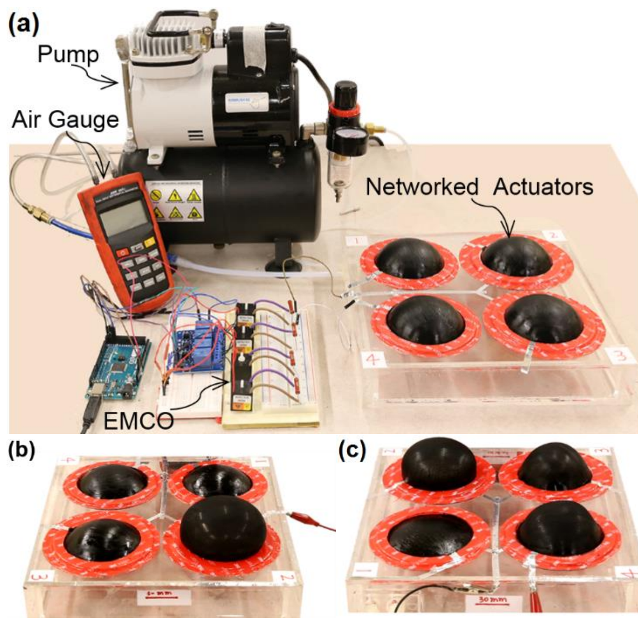

Figure 2. Experimental results: (a) system setup; (b) one balloon is activated; (c) three balloons are activated.

2.2. Dielectric elastomer actuators for soft WaveHandling systems

We developed a soft handling system, aiming to offer a soft solution to delicately transport and sort fragile items like fruits, vegetables, biological tissues in food and biological industries. The system consists of an array of hydrostatically coupled dielectric elastomer actuators. ***Figure 3*** conceptually shows one 'unit' of the system, where one active dielectric elastomer and one passive membrane are coupled together via an air mass. When the dielectric film is activated by an external electric field, the passive membrane will deform accordingly, due to the variation of the internal pressure. The assembly of such 'unit' constitutes the WaveHandling system and the controls of multiple active membranes enable movements of the system (see ***Figure 4***).

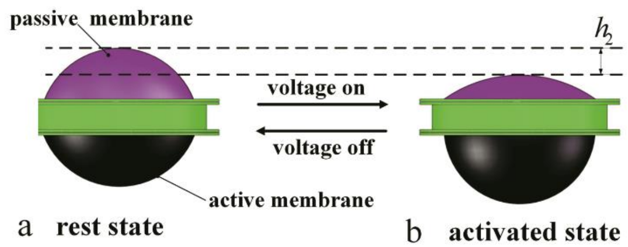

Figure 3. Hydrostatically coupled dielectric elastomer actuators: (a) rest state and (b) activated state.

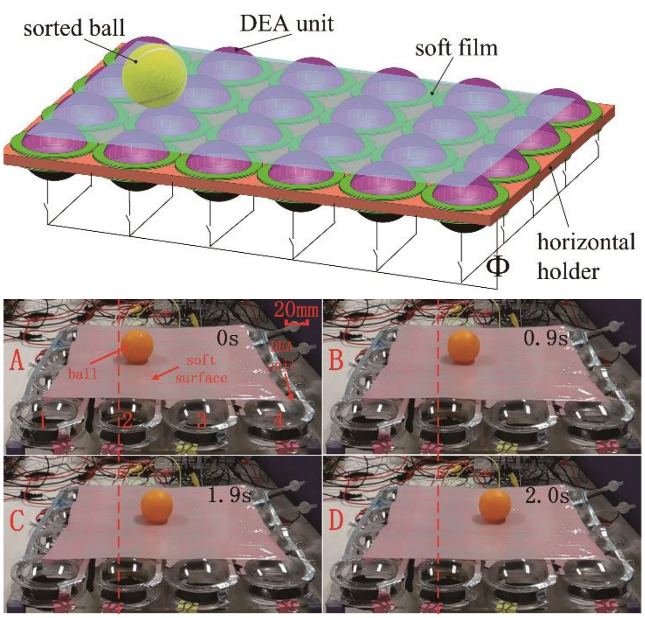

Figure 4. A soft handling system transfers a ball from one location to another location.

As a proof of design concept, a simply made prototype of the handling system is controlled to generate a parallel moving wave to manipulate a ball. The electric control, simple structure, lightweight and low cost of the soft handling system show great potential to move from laboratory to practical applications.[7]

3. Soft sensors

Soft sensors play an important role in control of soft robots, by providing feedbacks of deformations, forces, etc. There are mainly two popular avenues to convert the induced deformation to electrical signals: converting to resistance changes or converting to capacitance changes. The capacitance-based soft sensors show better performance in terms of accuracy and repeatability, and thus are adopted in this paper.

To overcome the limitations of existing soft sensor designs—rigid electrodes, low sensitivity, limited detection range, and inability in decoupling multi-axis loads, we proposed a methodology to design, analyze, and fabricate multi-axis soft sensor. The soft sensors each consist of four capacitor modules aligned in a 2×2 array. An isolated air chamber is embedded into each module to amplify the deformation (***Figure 5a***), resulting in an enhancement in the sensitivity. We investigated a compressive sensor[8] (***Figure 5b***) and two types of multi-axis sensor, i.e. the circular type and rectangular type (***Figures 5c*** and ***5d***)[9]. ***Figure 6*** shows the fabrication process and the prototypes, where the compressive sensor is made of Eco-Flex 30 (Smooth-On), while the multi-axis soft sensors are composed of polydimethylsiloxane (PDMS).

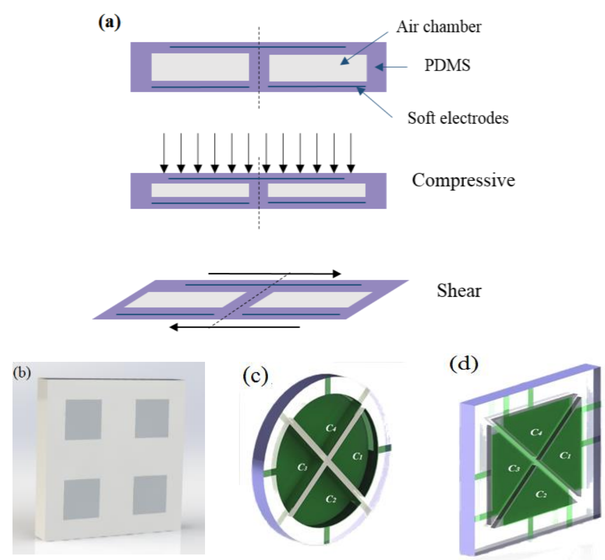

Figure 5. Soft sensor prototypes. (a) Loading conditions. (b) Compressive sensor. Multi-axis soft sensor of (b) circular prototype and (c) rectangular prototype.

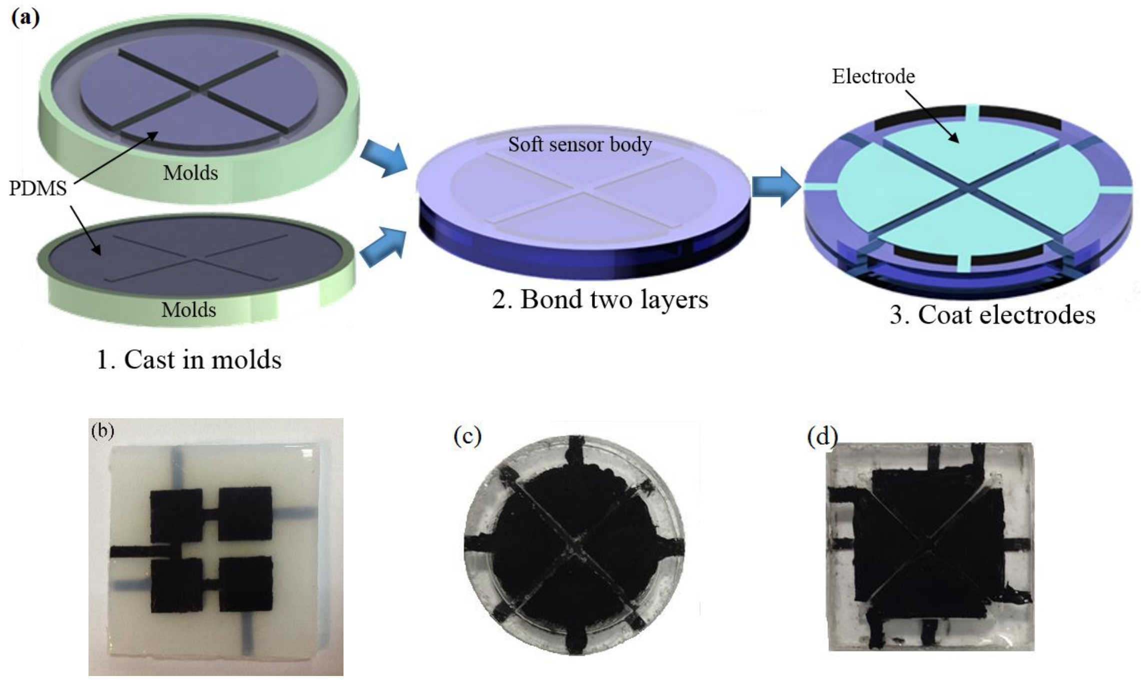

Figure 6. Fabrication process and samples. (a) Fabrication process of circular prototype. (b) Circular prototype. (c) Rectangular prototype.

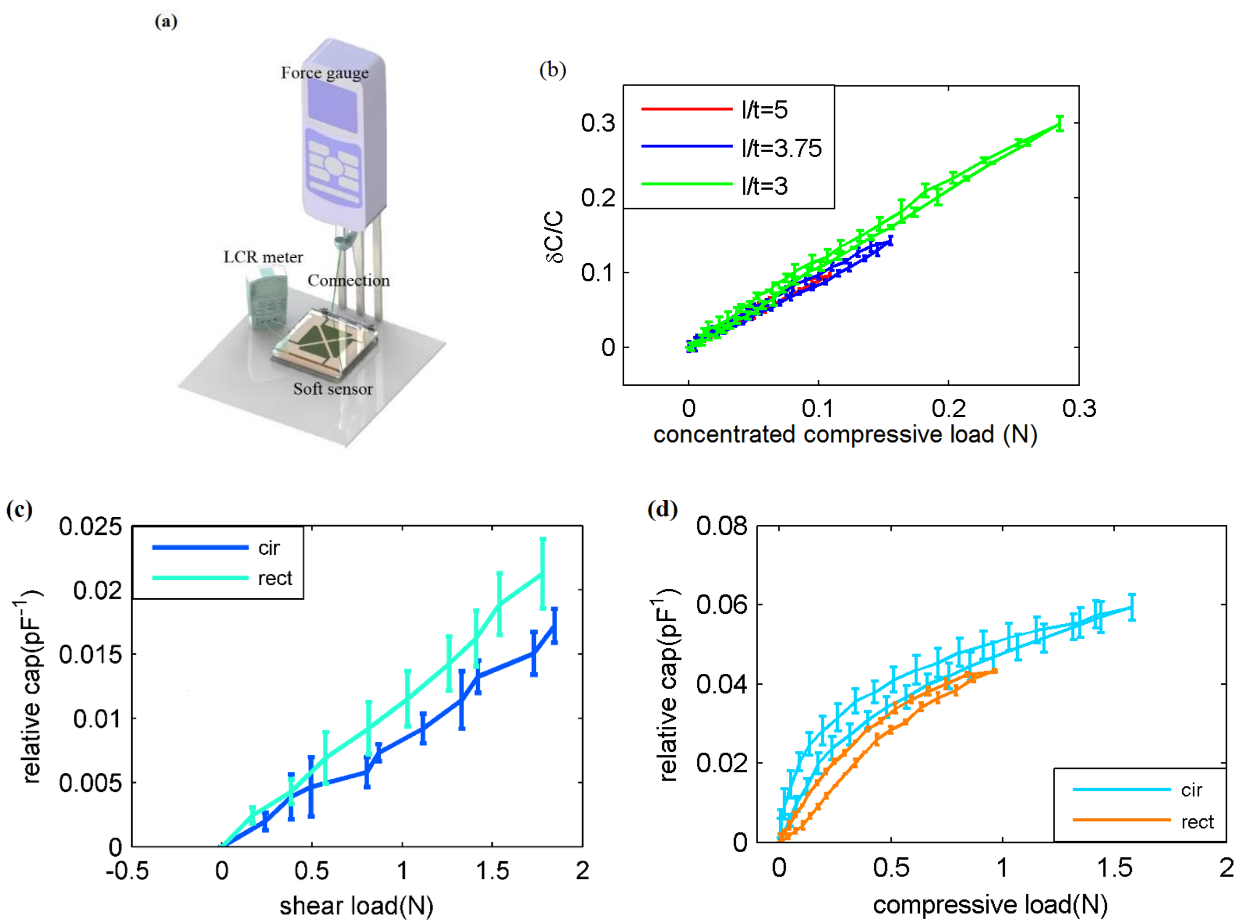

Figure 7. Experimental setup (a) and results for compression sensor (b), and multi-axis sensor under shear (c) and compression (d).

The experiments are carried out on the Mark-10 testing system. Specifically, the concentrated compression loading condition is applied via a conical punch and the shear loading is applied via two plates wherein the sensor is sandwiched. ***Figure 7a*** shows an overview of the experimental setup, where the force gauge can measure the applied force (in forms of either compression or shear), and the LCR meter measures the capacitance of the soft sensor that keeps increasing with the applied force.

Figures 7b-7d show the responses of the compressive sensor under compression and the multi-axis sensor under both compression and shear loading, where the circle design is denoted by 'cir', the rectangle design is denoted by 'rect', and denotes *I/t*, the aspect ratio of the soft sensor and its value is determined empirically. It is specially noticed that the capacitance increases monotonously with the loading and shows good repeatability within a large enough detection range.

4. Conclusion

This paper has briefly reported our recent progress regarding soft robots, from the networked dielectric elastomer actuators and Wavehandling system driven by soft actuators, to soft sensors capable of detecting both compressive and shearing loadings. These advancements basically represent a further step toward the development of soft robots. In the future work, we hope to integrate the soft actuators and sensors into soft bodies to build soft robots in terms of specific functionalities, such as a soft gripper.

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