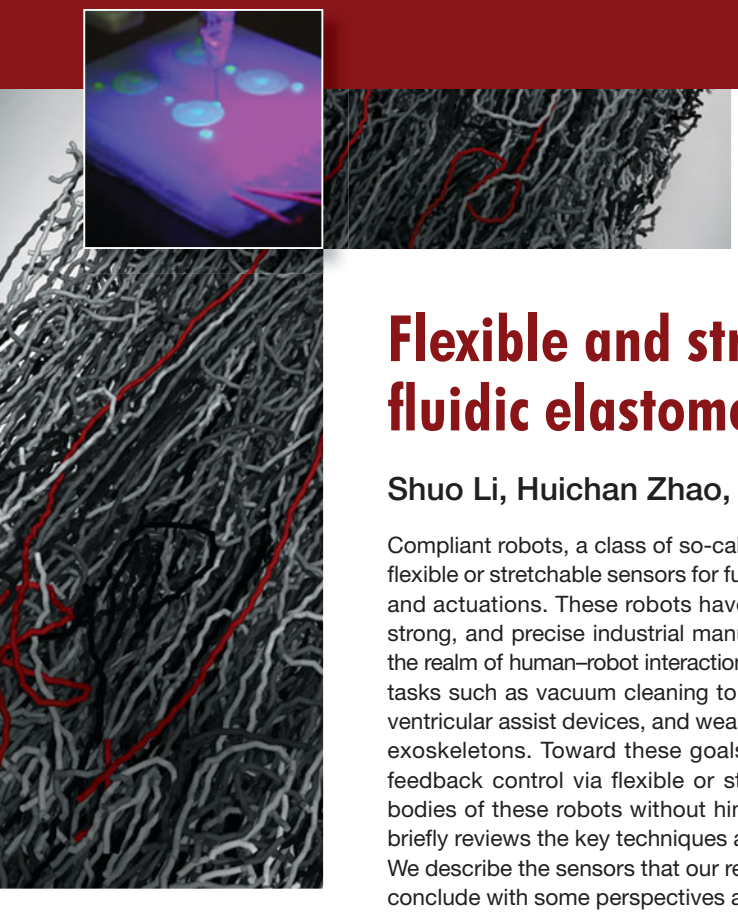


Flexible and stretchable sensors for fluidic elastomer actuated soft robots

Shuo Li, Huichan Zhao, and Robert F. Shepherd

Compliant robots, a class of so-called soft robots, made from elastomeric materials, require flexible or stretchable sensors for functional sophistication beyond that of open-loop controls and actuations. These robots have expanded the scope of research in robotics from fast, strong, and precise industrial manufacturing toward new needs of adaptation and safety—the realm of human–robot interactions (HRIs). HRIs include circumstances ranging from existing tasks such as vacuum cleaning to the far-reaching goal of direct contact with the heart for ventricular assist devices, and wearable robots as an intermediate task for force-augmenting exoskeletons. Toward these goals, many efforts are being made to impart sensation for feedback control via flexible or stretchable sensors that can be integrated with the soft bodies of these robots without hindering their motion or reducing their safety. This article briefly reviews the key techniques and tradeoffs for designing and fabricating these sensors. We describe the sensors that our research group uses for fluidically powered soft robots. We conclude with some perspectives about future directions of sensing integration for improved autonomy and interaction with humans in close proximity.

Introduction

Soft robotics, an emerging subfield of robotics, aims to provide simpler and more robust interactions with humans in complex and unpredictable environments. For our purposes, we define soft from a human perspective—as a structure that would deform readily upon the application of a contact pressure, which would typically cause harm to a user. There are two ways to achieve softness, extrinsically or intrinsically. Here, we will consider only the latter case: Robots that are soft regardless of their shape and are composed of elastomeric organic materials[1–4] with tangent elastic moduli below 1 MPa (similar to that of the human skin epidermal layer of ~100 kPa).[5] These robots are able to demonstrate natural, continuous deformation with their mobility only limited by the extensibility of the constituent materials.[1] Examples of the complex motions they demonstrate from simple fabrication and control inputs include bending, twisting, extension, and conformation to arbitrary geometries using infinite passive degrees of freedom.[6,7]

Variants of soft robots can be categorized by the actuation mechanisms used. In this article, we limit our focus to fluidic elastomer actuators (FEAs).[8] The fabrication technique of these robots involves intentionally embedding interconnected channels in silicones or other elastomers.[1,9–11] By simply pressurizing via either gas (pneumatic)[12–15] or liquid (hydraulic),[7,16,17] the channels inflate in regions with lowest stiffness and generate complex shapes and motions in three-dimensional (3D) space.[1] Recently, our group developed a new class of FEAs based on molding stochastic networks of open-cell organic elastomeric foams. Using this technique, we can now form complex 3D actuators without the need for 3D printed fugitive channels (ink scaffolds that can be removed afterward),[18,19] or even without 3D printing at all.[20]

A characteristic of most soft robots is that they demonstrate complex motions through simple open-loop control,[21] realizing complex tasks such as walking on irregular terrains,[9] grasping unpredictable shapes,[22] and manipulating fragile objects.[1] This control mechanism, simple as it is, is unable to achieve accuracy, or actively interact with its environment—eliminating the possibility of autonomy.[23] In order to continuously regulate the output signals based on external circumstances, closed-loop controls are necessary, where sensors are used to obtain information from the environment (exteroception) and also to monitor their internal states (proprioception).[23] These data are subsequently provided to the controller to self-correct errors and yield smart human–robot interactions.[24] Hence, sensors with high repeatability and resolution, fast speeds,

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doi:10.1557/mrs.2017.4

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and mechanical compatibility with soft robots are required to achieve these goals.

Flexible and stretchable sensors for FEA soft robots

A key challenge of creating sensory apparatus for soft robots is to work with highly deformable and mechanically nonlinear materials.[25] Conventional sensors lack the compliance and extensibility to remain electrically functional under large strains. In this section, we briefly discuss some recent developments in flexible and stretchable sensors that have been or can be readily employed in FEA soft robots based on their sensing mechanisms.

Resistive sensors

Resistive sensors operate via dimensional changes (e.g., length or cross-sectional area) that cause a change in current flow through electrically conductive materials embedded in an insulating elastomeric matrix. A typical embodiment of these sensors is liquid-phase conductors embedded in molded microchannels of soft silicone elastomer. By patterning the microchannels into different shapes, it is feasible to apply this principle in multiple sensing modes, including applied force,[26,27] strain,[26,28,29] and curvature.[30] Stacking several layers of the sensing elements also enables a blend of sensing types such as normal and shear forces.[31] The fabrication of this class of sensors includes, but is not limited to, soft lithography,[26,30–33] 3D printing,[29] and planar printing/coating.[14,28,34–36] The conductors generally comprise stretchable, mostly organic composites, including those with a continuous phase (e.g., eutectic gallium-indium,[26,27,30–33] conductive polymers,[36] and hydrogels)[37] and those that possess a dispersed phase with solid particles (e.g., carbon black,[29,38] carbon nanotubes,[34] and silver nanoparticles[28] and nanowires[35]).

Capacitive sensors

Capacitive sensors, consisting of a thin dielectric layer sandwiched between a pair of conductors, provide an alternative approach to measuring strain,[39–41] force,[39,41–44] bending,[45] and shear.[43,44] As capacitance variation only relies on the change in dielectric thickness and effective overlapping surface area, compared to resistive sensors, this method overcomes hysteresis and other issues caused by the electrical resistivity of conductors, demonstrating higher sensitivity, higher repeatability, and better temperature stability.[46] Most capacitive sensors are produced by aligning conductive films on an elastomeric substrate. Frutiger et al., however, have recently demonstrated a fiber-shaped capacitive sensor fabricated via multicore-shell printing.[40]

We recently used stretchable capacitors for feedback control of soft robots. Robinson et al. demonstrated a highly extensible organic capacitive skin comprising hydrogel electrodes and silicone dielectrics directly 3D printed on soft pneumatic actuators.[47] This overlaid structure enabled both tactile sensing from external compression and kinesthetic sensing from internal pressurization (**Figure 1**).[47] Larson et al. recently presented a hyperelastic light-emitting capacitor (HLEC) composed of a silicone dielectric embedded with ZnS phosphors and sandwiched between transparent hydrogel electrodes.[48,49] These HLECs act as sensors of internal and external stimuli and display pixels that can accommodate uniaxial strains up to 480% without compromising illumination.[48] We used this intrinsically compliant and extensible configuration to construct an electroluminescent skin for a soft mobile robot to impart both tactile sensing and optical signaling (**Figure 2**).[48]

Magnetic sensors

Magnetic sensors based on the Hall effect measure the magnetic flux density around a magnet and generate an output voltage in response to a deformation.[49] Tuning the position and orientation of the magnet with respect to the Hall element would result in mapping of measured data for sensing curvature of a bending segment [50,51] and determining multiple other object properties (object tracing, contact localization, and

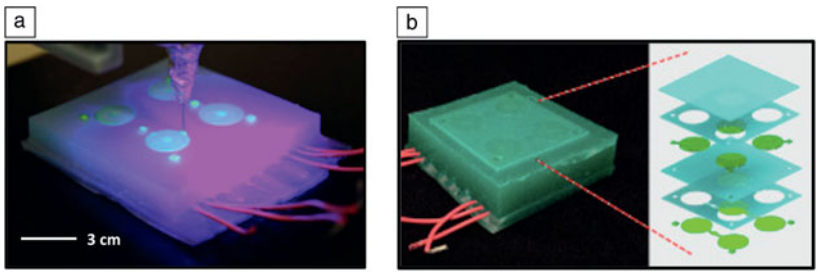


Figure 1. (a) Three-dimensional printing of a capacitive sensor on top of a pneumatic actuator for tactile and kinesthetic sensing; (b) exploded view of the printed layers with green showing conductive hydrogel and blue showing insulating silicone.[47]

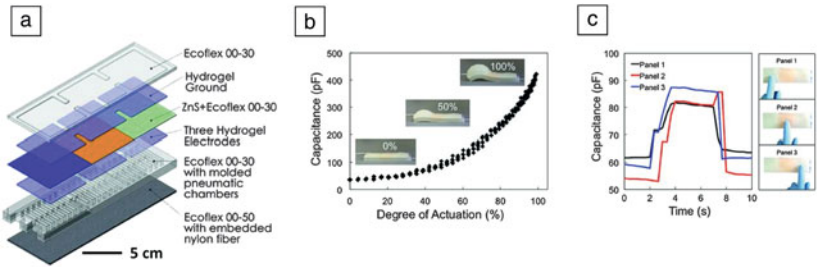


Figure 2. (a) An exploded view of electroluminescent skin integrated in a soft mobile robot with capacitance measurements that demonstrate sensing for (b) internal and (c) external stimuli. (Ecoflex 00-30 is a commercially available silicone elastomer; ZnS is an electroluminescent phosphor powder [~25 μm]). The intensity of illumination indicates relative capacitance change and serves as a tool for optical signaling in a soft, mobile robot.[48]

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detecting exerted force).[52–54] The integration of these sensors in soft robots, however, is constrained by the stiffness of the miniature magnet and the semiconductor-based Hall element, which are rigid components assembled with metal circuit traces printed on a plastic substrate.[51,52] Their parts require molding to an inextensible central layer of the bending actuator that may lead to practical issues such as pressure leakages due to a mismatch of moduli at the interface.[52]

Optoelectronic sensors

Optoelectronic sensors, in particular, fiber-optic sensors, detect applied deformations in a path between a light source (usually a light-emitting diode [LED]) and a photodetector by translating the shift in the physical characteristics of light (e.g., intensity, frequency, and phase) to electrical signals through a waveguide medium. Owing to the high quality and low price of fibers and optoelectronic components, optical sensors have found broad implementation in sensing curvature,[55,56] shape,[56–58] and force,[59–61] as well as contact localization.[61] The main advantages of this sensing scheme are (1) nonelectrical method of operation that shows immunity to electromagnetic interference; (2) low density and good flexibility; and (3) easy interface with data systems.[62]

We have used fiberoptic sensors and FEAs for force-augmented grasping in hand orthotics—assistive devices that help rehabilitate and improve hand functions.[63,64] In this work, the sensors were incorporated in each finger actuator to monitor shape and realize closed-loop control. We used engraved plastic optical fibers to enhance sensitivity to bending, and along with an LED light source and photodetector, we embedded them into each finger actuator to enable strain sensing in a hand orthosis (**Figure 3**). Relying on the light intensity change, these solid-state optical sensors outperform most resistive and capacitive sensors in terms of precision, repeatability, and signal-to-noise ratio, and have been applied to real-time position sensation in feedback control loop for soft robotic systems. However, flexible, solid-state optical sensors are inextensible and can only be placed into nonstretching regions of FEAs. Thus, there is a need for stretchable waveguide sensors based on the same mechanism (intensity modulation of light signal).

Future perspectives

Soft robots are rapidly opening up new possibilities for safely assisting humans in everyday tasks, improving health, or imparting new abilities with applications ranging from exosuits,[65,66] ventricular assist devices,[67] orthotics/prosthetics,[64,68] and wearable devices. To realize their full potential, fundamental developments in sensory apparatus, including materials, structural designs, processing strategies, and integration schemes will be required and be indicative of progress in soft robotics. We believe that optics will play a critical role in the sophistication of soft robotics and robotics in general. A next step toward this goal is organic stretchable waveguides[68–70] and their future integration into soft robots. Current efforts have already revealed promising results in terms of fabrication and characterization of this class of sensors. A near-term goal would be decoupling signals from various deformation modalities and building smart interfaces that communicate the information to users. We believe that in the long-term, these highly extensible optical sensors, with multispectral capabilities and full 3D integration with soft robots, will circumvent issues such as hysteresis from particle-laden electrically conductive material or real estate problems from routing hundreds of conductive traces.

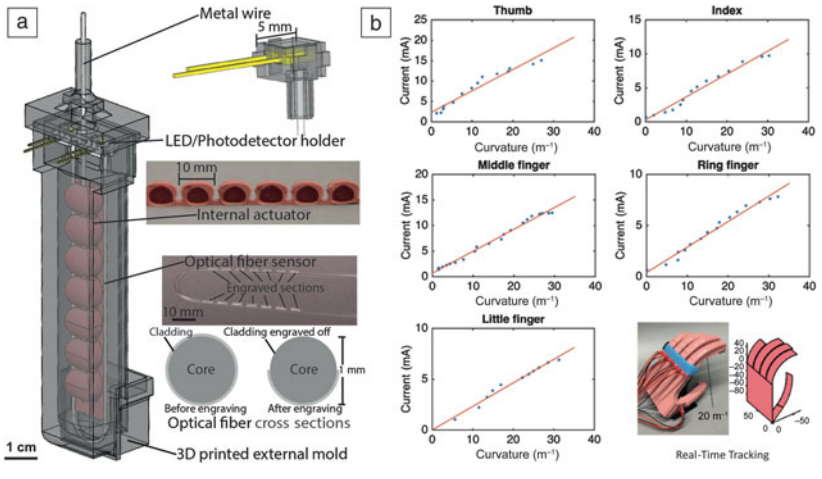


Figure 3. (a) A schematic of a hand orthosis (an assistive glove that helps restore hand functions), where various components (light-emitting diodes [LEDs], pressure chambers, optical fibers, photodetectors, nylon fabric, clamps, air-supply tubes, and optical-component holders) were monolithically cast into one finger. (b) Demonstration of integrated solid-state optical sensors that can monitor the curvatures of all five finger actuators via current output, and track real-time finger positions (bottom right inset has units in mm).[64]

Acknowledgments

The authors acknowledge support from the Air Force Office of Scientific Research, Army Research Office, National Science Foundation, and 3M Non-Tenured Faculty Award.

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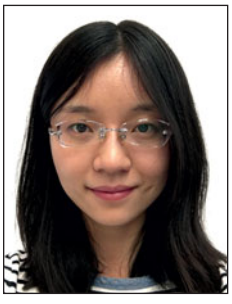
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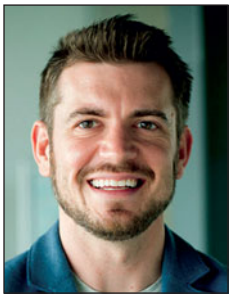


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