Sensors and Actuators A 253 (2017) 188–197

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Multi-mode strain and curvature sensors for soft robotic applications

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ARTICLE INFO

Article history:
Received 16 June 2016
Received in revised form
17 November 2016
Accepted 23 November 2016
Available online 29 November 2016

Keywords:
Soft robotics
Soft sensors
Flexible sensors
Stretchable sensors
Liquid metal
Sensor arrays

ABSTRACT

In this paper we describe the fabrication and testing of elastomer-based sensors capable of measuring both uniaxial strain and curvature. These sensors were fabricated from Sylgard 184, which is a transparent silicone elastomer. We created microchannels directly in silicone elastomer substrates using a laser to ablate material. The sensing element was an alloy of gallium and indium, which is liquid at room temperature, contained within the laser-created microchannels. As the substrate deformed, the microchannel deformed within it, resulting in a measurable change in electrical resistance. By fabricating two matching resistive strain-sensing elements on opposite sides of the sensor, we were able to unambiguously measure uniaxial strain and curvature by observing the common mode and differential mode changes in resistance, respectively. There was very little coupling between modes, demonstrating the utility of the differential sensor design. We characterized the sensor in terms of its response to strain and curvature, its noise, and its stability over time. We believe that this type of sensor has application in soft sensory skins and can observe pose in soft robotic systems.

1. Introduction

Soft robotics is a new class of intelligent systems that move in ways very different than traditional rigid devices. Proposed applications of research in the field are roughly grouped into two related classes of soft robotic systems: mobile soft robots [1–4] and wearable robots [5,6]. Instead of being comprised of rigid joints and links, where motion is predominately localized at the joint, soft robots rely on continuum deformations to achieve motion [7–9]. This deformation is the source of the unique capabilities of soft robots. The drawback is that the distribution of deformation throughout the body significantly complicates the state observation problem. In order to achieve control of these soft systems, we must observe the current state [10–13]. In order to place sensors on the bodies of these systems, we need sensors which are materially compatible. Traditional sensors have high stiffness compared to the materials used in soft robots, necessitating the development of a new class of soft sensors made from the same low-stiffness materials found in the soft robots themselves.

In this paper, we present a multi-mode sensor which uniquely determines strain and curvature, as shown in Fig. 1. Our sensors were fabricated from Sylgard 184 silicone elastomer substrates containing microchannels filled with a gallium–indium alloy that is liquid at room temperature. Substrate deformation resulted in changes in the geometry of the liquid-metal-filled microchannels, resulting in a change in resistance. By measuring this change in resistance, we were able to determine the strain and curvature state of the sensor element. The liquid metal components described here and in previous work are strain sensors with an added stress concentrator to enhance their response to curvature. By combining two of these strain/curvature sensors, we demonstrate a device which can differentiate between positive curvature, negative curvature and strain. Individually, each element of the devices in this paper behaves according to the theory described in [14,15], which we revisit in our theoretical discussion below. In previously published devices, uniaxial strain and bending produced the same sensor output, resulting in ambiguous measurements. In the current case, the outputs from two sensing elements are used together to measure "common-mode" and "differential-mode" signals, which correspond to strain and curvature, respectively. The theoretical basis for this capability is described in a later section. In addition, the sensor described in this work is able to measure curvature without relying on a model of the underlying host object.

We anticipate that dual-mode strain and curvature sensors will be applicable across a wide range of soft systems, but will be particularly useful in thin devices such as soft sensory skins where significant strain and bending occur simultaneously. Our long-term goal is to develop multi-modal *active sensory skins*. In these devices, sensors and actuators are combined into a fabric or elastomer substrate which can then be attached to a deformable body to impart

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http://dx.doi.org/10.1016/j.sna.2016.11.031
0924-4247/

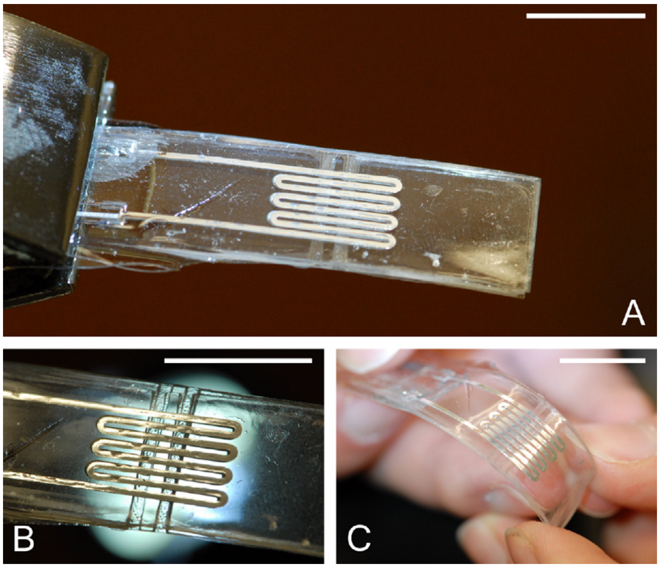

Fig. 1. Overview of a differential multi-mode sensor. (A) The top of the sensor. (B) The sensor with backlighting, highlighting the location of the stress concentrator channels behind the liquid-metal-filled microchannel. (C) The high deformability of the device resulting from the material properties of the elastomer substrate. The scale bar in the upper right corner of each figure is 6.25 mm.

motion. The sensor element presented in this work is one element which could be included in these future devices. In order to measure curvature across a surface, an array of curvature sensing elements, such as those discussed in this paper, would be required. The exact design of that sensor array would require an understanding of the spatial characteristics of the curvature field to optimize sensor placement. In a surface-based sensory array, only the deformed state of the surface of a deformable body will be known, and even with that the deformation field will only be known at the location of the sensors in the array. We suggest that boundary element methods from computational mechanics would be applicable to solving this problem, but this is outside the scope of the current work.

Elastomer-based sensors with encapsulated liquid metals such as those described in this work are well represented in the literature. Previously reported soft sensory devices based on elastomers substrates include joint angle and curvature sensors [14,15], pressure sensors [16,17] capacitance-based multi-element force sensors [18,19], liquid-metal/conductive fluid hybrid strain sensors [20–22], and multi-mode resistance-based devices measuring in-plane strain and out-of-plane pressure [23]. The current work furthers the previously developed devices by being able to differentiate between positive curvature, negative curvature and strain, while still being highly stretchable and capable of undergoing large deformations. Additionally, the current work is able to measure curvature without knowing the geometry of, or even requiring, an underlying host. This is in contrast to previous work which used deflection of a mechanical joint to induce strain in a liquid metal sensor, and required re-calibration on a per-host basis [14,15]. Finally, the current work expands upon the previous example of multi-layer liquid metal sensors by placing strain gauges in parallel, rather than orthogonally [23]. This allows us to measure curvature, while the previous work was used to measure biaxial strain. These sensing modalities could be combined in devices with even more sensor layers in the future.

Beyond elastomers, other types of materials can be used to sense curvature based on strain measurement. These include multilayer composites based on carbon film/polymer electrolyte [24], conductive polymers [25], and piezoceramic systems [26]. Extending even further, Bragg fiber gradings are another common curvature sensing modality [27–30]. Changes in magnetic field have also been used to measure curvature [11]. These approaches to sensing curvature provide a range of sensitivities and accuracy. Depending on the application, the relative importance of accuracy, repeatability, integration and stretchability will vary. We believe that elastomer-based, and in particular silicone-elastomer-based sensors, have the greatest potential for integration into active sensory fabrics and sensory skins due to their low stiffness, high stretchability, lack of rigid components, and chemical resistance.

2. Liquid metal embedded elastomer sensor body fabrication

The devices we present in this paper are soft, flat, transparent devices comprised of layers of patterned silicone elastomer. The complete device is shown in Fig. 1, which shows the liquid-metal-filled microchannels and stress concentrator features. The bodies of the devices were manufactured from Sylgard 184 (Dow Corning) film with gallium indium alloy (EGaIn, Sigma-Aldrich) filled microchannels. This configuration contained two strain gauges placed back-to-back. The devices described in this work were fabricated in four major steps: substrate preparation, substrate patterning, microchannel filling, and interfacing. The fabrication sequence is shown in Fig. 2.

Sylgard 184 (polydimethylsiloxane, PDMS) substrates were prepared by spin-coating the uncured polymer onto 3 in. × 2 in. glass slides (Fig. 2:A1 and B1). Before applying liquid polymer, a film of mold release (Ease Release 200, Mann Technologies) was applied to the slide. Four layers of elastomer were applied to achieve uniformity. These layers were applied at 500 rpm, and spun for 180 s using a Specialty Coating Systems Spincoat G3-8. The elastomer layers were allowed to cure for at least 4 h at 60° between applications. The resulting elastomer substrates were 273 ± 8.25 μm (95% confidence) as measured by a Zeta Instruments Zeta 20 3D microscope.

The blank substrates were patterned using a Universal Laser Systems VLS 2.30 laser system fitted with a 30W CO_2 laser operating at 10.6 μm (Fig. 2:A2 and B2). The pattern created by the laser is shown in Fig. 3. This image contains a mixture of "thru" and "blind" features. Thru features are cuts made by the laser that pass completely through the elastomer layer into the glass substrate. Blind features only remove part of the thickness of the elastomer layer. The depth of the cut is controlled by adjusting laser power. Our approach of directly patterning features into the Sylgard 184 film is different than previously published approaches that used a mold to create channels. This direct approach has the advantage of not requiring the fabrication of a mold, which removes several processing steps and decreases design iteration time. However, the laser ablation process results in deposits of soot and debris on the surface of the substrate. Unless this material is removed, it interferes with bonding between elastomer layers. Further, small particles remaining in the microchannels can either cause wicking of liquid elastomer into the channel, resulting in a filled channel, or can block the channels themselves. For these reasons, a thorough cleaning process is required after patterning. First, the substrates were cleaned by sonication in a Liquinox detergent solution (Alconox) for 10 minutes in a Branson Bransonic 1800 bath ultrasonicator to remove the bulk of the soot left over from the patterning process. Second, we used a Kimwipe (Kimberly-Clark) with toluene to manually remove soot from the microchannels. We note that toluene aggressively swells Sylgard 184, and so the minimal amount required to wet the Kimwipe was used. Third, we sequentially rinsed the substrates in acetone, isoproponol, ethanol, and distilled water to remove film contaminants. Finally, we dried the clean patterned substrates at 60 °C to remove moisture.