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# Soft piezoresistive sensor model and characterization with varying design parameters

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ABSTRACT

Recent robots target safety, reconfigurability and interactivity by addressing the "softness" of the hardware either by endowing additional degrees-of-freedom or through inherent compliancy. These robots require distributed sensing with flexibility and softness that would not interfere with the robot's agility. There have been various sensing solutions using soft conductive materials including conductive silicone, liquid metal-filled micro-channels, and conductive-ink based sensors. However, we still lack a comprehensive study on their potentials, drawbacks, and the different parameters that affect their response.

We present our design, fabrication process and characterization results for conductive silicone polymer and carbon ink-based curvature sensors. These sensors are flexible, mechanically robust under large strains, scalable, and easy to fabricate in large numbers. We propose an equivalent mechanical system to model sensors' response. This model is unique for its extensive characterization of these polymer based sensors. Based on the characterization results, we systematically categorize and compare the performance of conductive silicone and carbon ink-based sensors with different design parameters.



## 1. Introduction

Applications that require interacting with humans and operating in unknown environments are motivating more compliant systems with many discrete or continuous degrees-of-freedom (DoF). New methods for soft and scalable actuation [1–3] and sensing [2] have made this transformation from rigid body robots to soft and reconfigurable systems possible. But the capabilities and limitations of these emerging components have not been thoroughly studied. Fig. 1 presents two examples of applications that benefit from an array of flexible low-profile sensors. These applications are based on origami robot, Robogami, [4] which is a low profile robotic sheet that can reconfigure its form by folding actively (in the case of the crawler robot [2] Fig. 1(a)) or deform passively and provide feedback on the shape (the case of the facial rehabilitative device [5] Fig. 1(b)). In both of examples, accurate feedback on the joint angle is necessary. In this research, we elaborate on the performance analysis of soft and flexible curvature sensors that can be used in such applications. We report on the major characteristics of the two classes of sensors and suggest a model to explain their behavior. Using the result of the characterization tests, we compare the performance of these sensors. The design of the sensors are based on the requirements for the Crawler robot Fig. 1(a) which is a preliminary study toward more complicated robots such as the rehabilitative device in Fig. 1(b).

Flexible strain sensors work on different principles including the change in the capacitance [6–8] or resistance [9] in a solid-state material or change in the resistance caused by the shape change in liquid metal-filled micro-channels [10]. Between these, the piezoresistive based sensors have a very simple fabrication process and need a rather primitive auxiliary circuit. This makes them highly scalable [11] and more appropriate for arrays of sensors consisting of many sensing elements.

In general, the piezoresistive material is made from conductive particles in a non-conductive soft polymer matrix. One family of these sensors are made by impregnating different rubbers with carbon particles [12,13]. This conductive paste can later be molded into a desired shape as suggested in [2]. The ease of fabrication in large arrays is one of the main advantages of this type of sensor. Another family of strain sensors are based on a carbon layer deposited on polymer sheets [14]. The carbon layer usually contains a hard polymer as the matrix. In this research the performance of these two families of sensors will be studied in detail.

The behavior of the carbon particle-based sensors can be studied on micro-scale [15–18] or on macro-scale [19–21]. The study of the interaction of carbon particles and the polymer matrix on the micro-scale is interesting for understanding the nature of different phenomena and optimizing the component choices. In the

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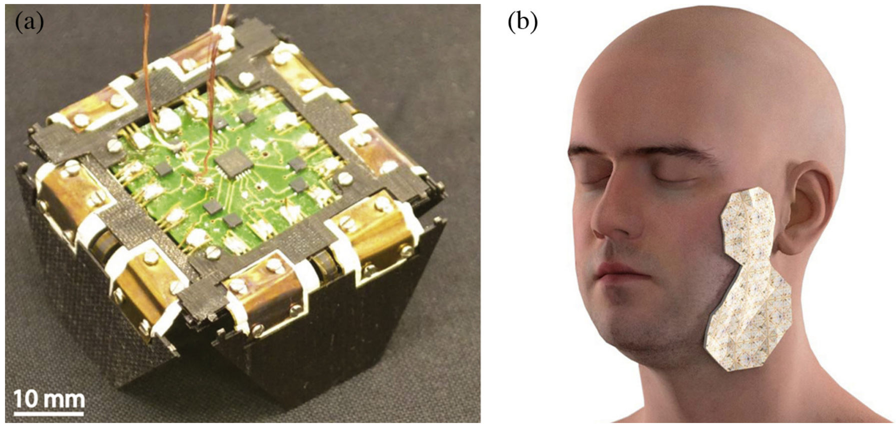


**Fig. 1.** Two examples of the applications of the flexible curvature sensor arrays: the Crawler robot [2] that uses a curvature sensor on each leg (a), and a Robogami conceptual design for an assistive device for assessing the paralysis level in the patients with facial palsy [5] (b).

second approach, a gray box model is used to explain the relation between the resistance and strain. This type of modeling is more attractive for those who are concerned with the bulk response of the sensors. Such a model is still useful in optimizing the design parameters [21] of the sensor since the elements that make up the model are representative of the characteristics of different components in the sensor [19]. To characterize the sensors, researches in both groups mostly studied cyclic loading with fixed loading rate [22,23]. Some researchers also studied the dynamic response of these sensors [19,15]. Still some effects such as drift or creep [17] were not studied thoroughly. A model in macro-scale [19] that explains all these effects would deepen our understanding and provide us with a set of figures for comparing more thoroughly the performance of different sensors.

The principal focus of this work is on presenting a sensor model in the macro-scale. We attribute physical meaning to the components in the macro-scale model based on the behavior predicted by the micro-scale models for piezoresistive materials. A review on different methods of strain sensing and models for piezoresistive materials are found in [24]. Among the micro-scale models suggested for the resistance change of the piezoresistive materials, the theory based on the destruction of the conductive paths [25,26] explains the increase in the resistance of the carbon silicone composite materials (used for fabrication of the CSC sensors) under compression. The same theory also explains the transient response observed for all sensors studied in this paper.

The major contributions of this research are:

- the investigation of the less-studied, but functionally significant aspects of the sensor behavior: the dynamic response, the drift in the sensor reading, and the accuracy, and precision of the response in cyclic loading.
- the presentation of a comprehensive mechanical equivalent model and defining characterization tests for studying the key aspects of the sensor response.
- the comprehensive study on two different types of flexible curvature sensors and introducing a set of performance measures for comparing different sensors and the effect of different designs and components on the performance.

Section 2 of this manuscript presents the fabrication process of the sensors. In Section 3, the setup for characterization tests is introduced and in Section 4, a model that can explain the behavior of the sensors is presented and a set of tests for evaluating important parameters in the model are presented. In Section 5, the results of the characterization tests are presented and the effect of material choice and fabrication process are discussed. Finally, the conclusion of this work and the future steps are presented.

## 2. Carbon polymer composite curvature sensors for distributed sensing

Choosing the sensing method and designing sensors require a comprehensive understanding of different aspects of sensor response. Here, we determine the important characteristics of the sensor response by studying the response of two types of carbon-particle-based piezoresistive sensors: carbon silicone composite (CSC) and carbon ink (CI) sensors. The literature concerning the comparison of different sensors is limited, lacking comparison based on some key aspects such as drift in sensor reading and transient response of the sensors. In this research, we compare the performance of different sensors to highlight how the design affects these aspects of the sensor response. The dimensions and the working range of the sensors are based on the requirements for the curvature sensor in robotic origami introduced in [2,29]. The bending length of the sensor for this application is 4 mm and the desired range of deformation is from fully opened (0°) to fully closed hinge (180°).

Under strain, due to relative motion of the conductive particles, that make the conductive paths, the overall electrical resistances of the CSC and CI sensors changes. Although the working principle is quite similar, the appearance, mechanical properties, and fabrication process of these sensors are very different. The main advantages of the CSC sensors are their ease of fabrication and robustness in extreme loading conditions (up to 100 % strain). The main advantage of the ink-based sensors is their better transient response, lower drift, and better accuracy as will be discussed in Section 5. In what follows, these sensors are introduced and their fabrication and integration process are presented in detail.

### 2.1. Conductive silicone composite (CSC) sensors

Composites of silicone and conductive particles are among the most appealing strain sensing material due to their maximum strain range, their ease of fabrication, and their high electrical resistance sensitivity to strain. One of the advantages of these sensors is that they can be directly integrated in the structure by molding the mixture directly on to the structure. Many different combinations of materials are suggested in the literature. Here, we study two compositions of carbon particles with different silicone rubbers. The fabrication process of the CSC sensors starts with cutting the components needed for the base. We use the laser micro-machining system, designed and introduced by the authors in [2] for all the