Sensor systems

Exploration of Electrical Impedance Tomography and Grid-Based Soft Sensors for Distributed, Large Deformation Strain Sensing Based on a Fiber-Elastomer Composite

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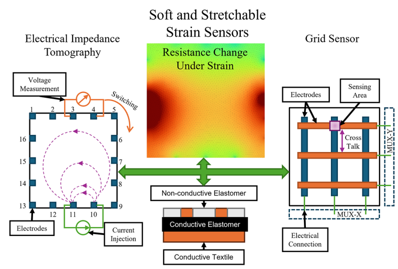
Abstract—This letter presents a comparative analysis between two setups utilizing carbon black-filled elastomer with conductive textile electrodes: electrical impedance tomography (EIT) and a grid-based configuration. Both setups represent cutting-edge approaches in the field of stretchable sensor technology. Both enable the estimation of stretch displacements, surface normal forces, and multipoint contact locations, exhibiting robustness across diverse contact conditions. So far, both approaches have only been employed for flexible and soft but not stretchable force or touch sensors, as well as with rigid metal electrodes. The presented sensors leverage the softness and flexibility of textiles and elastomers and their drastically different conductivities. This letter aims to provide insights into the comparative strengths and limitations of EIT and grid-based fully stretchable strain sensors.



Index Terms—Sensor systems, conductive elastomers, electrical impedance tomography (EIT), soft sensors, spatially resolved strain sensing, stretchable sensors.

I. INTRODUCTION

Stretchable elastomer strain sensors have potential applications in various fields, including human–machine interfaces, healthcare monitoring, soft robotics, and wearable devices [1]. They can be utilized for motion detection, such as in gloves, and for controlling avatars in virtual environments [2]. In addition, these sensors can monitor and distinguish small human motions with high accuracy and sensitivity, including facial expressions and vocal signals [3]. They are also suitable for textile-based, wearable, human body motion-sensing applications [4]. Overall, the potential applications of stretchable elastomer strain sensors span a wide range of fields, making them versatile and valuable for various practical uses with adjustable sensitivities [5].

Currently, various options for spatially distributed sensing are being researched. Promising approaches include electrical impedance tomography [EIT, Fig. 1(b)] and grid-based [also called matrix-based, Fig. 1(c)] approaches, due to the lower number of required connections when measuring at high spatial resolution in comparison with individual sensors [see Fig. 1(a)]. When evaluating a surface with $m \times n$ measurement points, also $m \times n$ sensors and connections are required. In contrast, with a grid-based setup only $m + n$ electrodes overlap and form sensing elements at each crossing but measures have to be taken to eliminate cross talk between neighboring electrodes. EIT-based sensors only require a limited number of electrodes on the boundary to achieve high spatial resolution [6].

Therefore, several approaches for soft and flexible pressure sensors have been presented in the last years based on EIT and grid setups [7]. Both require extremely soft yet highly conductive electrodes in the sensor structure, which is challenging [8]. First, the electrodes should not restrict the stretchability of the sensor, and second, the contact and connection resistance should be as low as possible. However, the systems in literature are flexible but often a strain-limiting layer is incorporated, such as thermoplastic films [9] or glass fiber textiles [10]. Lee et al. [11] presented an interesting EIT-based setup where the sensing element can be stretched to 50% strain but the electrodes are rigid metal clamps, which are not integrated into the sensor. Thus, it could only be used as a pressure sensor for practical applications.

Developing a truly stretchable, soft strain sensor with integrated electrodes based on piezoresistive elastomers would be valuable for multiple reasons. First, it provides a way to measure locally distributed strain maps with minimal restrictions in human motion monitoring or soft robots. In addition, it also presents a possibility to advance the understanding of carbon particle-filled elastomer materials and their electromechanical properties. Because depending on the carbon particle type and dynamic loading conditions, the strain-resistance behavior of these materials can be nonmonotonic [12]—sometimes called shoulder phenomenon—or even inverse [13].

In this letter, we explore and compare the spatially resolved strain measurement on fully stretchable fabric elastomer composites with EIT and grid setups. Thereby, demonstrating advantages and disadvantages of both approaches and the remaining challenges. So far most publications evaluated only one of the two approaches and used stiff electrode materials leading to soft but unstretchable sensors.

II. MATERIALS AND METHODS

A. Sample Preparation

The samples consist of the following three basic materials.

1) Elastomer—Ecoflex 00-20 (KauPo Plankenhorn e.K., Spaichingen, Germany).

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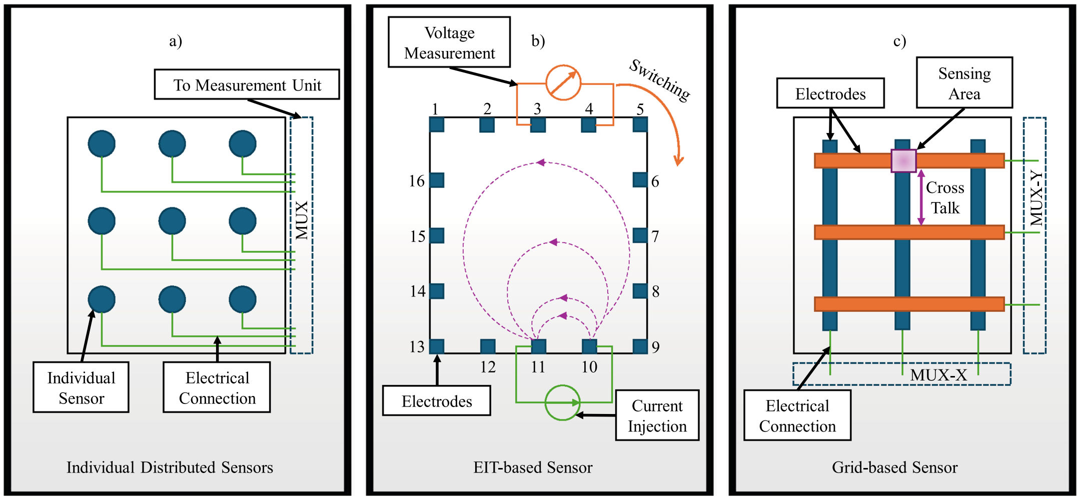

Fig. 1. Options to acquire spatially-resolved data in soft elastomer strain or pressure sensors. (a) Individual sensing elements. (b) EIT. (c) Grid-based sensor.

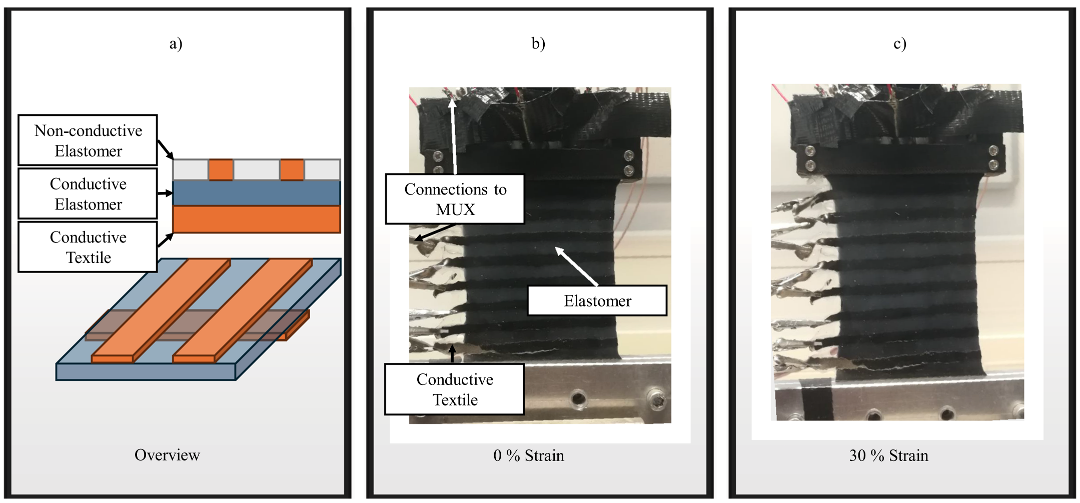

Fig. 2. Overview of the grid sensor. (a) Schematic of the conductive elastomer, conductive fabric and encapsulating nonconductive elastomer in the cross-section. (b) Tensile testing setup at 0% strai. (c) Grid sensor sample strained to 30% strain.

2) Carbon black—Vulcan XC72-R (WorlÃ©e-Chemie GmbH, Hamburg, Germany).
3) Conductive textile—Med-tex P130 (Statex Produktions-und Vertriebs GmbH, Bremen, Germany).

All three materials are commercially available and frequently used in the soft robotics and flexible electronics community due to their stretchability, conductivity, and ease-of-use. Therefore, the materials were chosen for their properties better reproducibility of our results. The conductive elastomer was produced by mixing 30g of Ecoflex part A with 4.516 g of carbon black, equivalent to 7 wt.% of the final mix. Both were mixed together with 15 g of OS-10 (Dow Chemical, MI, USA), which reduces the viscosity and evaporates later. These components were mixed with a planetary-centrifugal speed mixer (Thinky ARE-250, Thinky Corp, Tokio, Japan) and three 8 mm steel balls at 2000 r/min for 4 min. Then, 30g of Ecoflex part B was added and mixed again for 4 min. Afterward it appeared to be a homogeneous mixture, which was then blade-cast with a set thickness of 1 mm (PG-031-200, Thierry GmbH, Stuttgart, Germany) and cured at 60°C. The conductive textile electrodes were manually cut to strips of 5 mm width and applied to the textile according to the 8 × 8 grid leading to a total sensing area of approx. 60 mm × 60 mm. Next, pure nonconductive ecoflex was used to overcast the electrodes and the conductive elastomers to form one joint sample [see Fig. 2(a)]. An overview of the grid-based testing setup at its starting position [see Fig. 2(b)] and at 30% strain [see Fig. 2(c)]. The setup for the EIT sample is similar, only with the electrodes equally spaced around the edges of the sample on all four sides.

B. Electromechanical Testing Setup

The samples were tested on a tensile testing machine (TIRATEST 2703, TIRA GmbH, Schalkau, Germany), which was equipped with a 100 N force transducer (type S2M by HBM GmbH, Darmstadt, Germany) and 3D-printed clamps made of acrylonitrile butadiene styrene. All conductive textile electrodes were connected to stainless steel micro crocodile clips. The sample was clamped in a nontensioned state. After prestraining the sample with a force of 0.1 N to straighten it, the sample was strained to 10%, 20%, and 30%. Each strain level

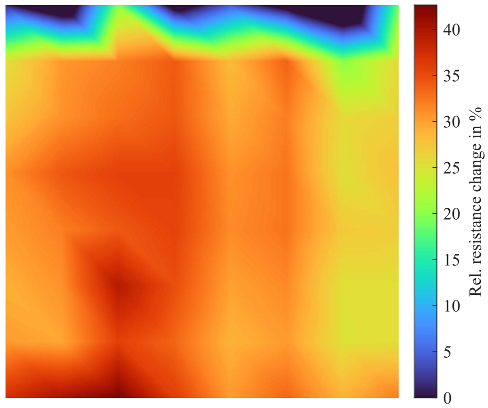

Fig. 3. Results of calculated resistance distribution based on the grid sensor signals.

was held for 30 s with the measurements starting after 15 s of the static period. As visible in Fig. 2(c), elastomers, and consequently, the evaluated samples show significant transversal contraction and locally varying strain. This should result in a nonuniform change of the resistivity [14].

For the impedance measurements a Sciospec ISX-3 EIT (Sciospec Scientific Instruments GmbH, Bennewitz, Germany) was used. It consists of an electrical impedance analyzer and an any-to-any multiplexer, allowing flexible injection and measurement patterns for EIT and grid evaluation. The measurements were performed at a frequency of 1 kHz excitation frequency with current injections of 20 μA and corresponding voltage measurements both for the EIT and grid approach. Unused connections are in a high impedance state (>10 TΩ). The EIT was performed with an adjacent injection pattern. Acquiring one frame lasted 830 ms for the EIT setup and 1600 ms for the grid setup with a shorter measurement time being beneficial due to the relaxation-induced resistance changes that occur even at static strain levels.

C. Reconstruction Approach

Evaluation of the grid-based sensor was conducted by taking the applied current and measured voltages between an electrode pair to calculate a base resistance. Then, relative resistance changes were calculated for each electrode pair and the continuous resistance change derived through interpolation. For EIT, the reconstruction parameters are critical due to the ill-posed inverse problem, which has to be solved. EIDORS, a reliable open-source MATLAB tool was used for the reconstruction [15]. We employed a standard one step Gauss–Newton difference solver with a Laplace prior and a hyperparameter of 1. This is a difference solver where the state at 0% strain was used as the reference.

III. RESULTS AND DISCUSSION

The calculated resistance change of the grid-based sensor at 30% strain is shown in Fig. 3. Due to the limited space only the difference between 0%, 20%, and 30% for the EIT as well as 30% for the grid-based system are shown. Except for the top area, where the electrodes in y-direction and the conductive elastomer underneath are clamped, the resistance increases quite uniformly by approximately 30%. However, due to the cross talk and the lower resolution, it is not possible to distinguish region with lower and higher impedance change as with the EIT setup. This could also be a consequence of the electrodes, which are inside the sensing region instead of surrounding it as in the EIT system. This can be improved in the future by minimizing cross talk with specialized electronics, which have successfully been used in multiphase flow wire mesh sensors [16]. In addition, such electronics would drastically increase the speed to acquire a frame. Even with 64 × 64 electrodes, the acquisition time for one frame could be below 10 ms.

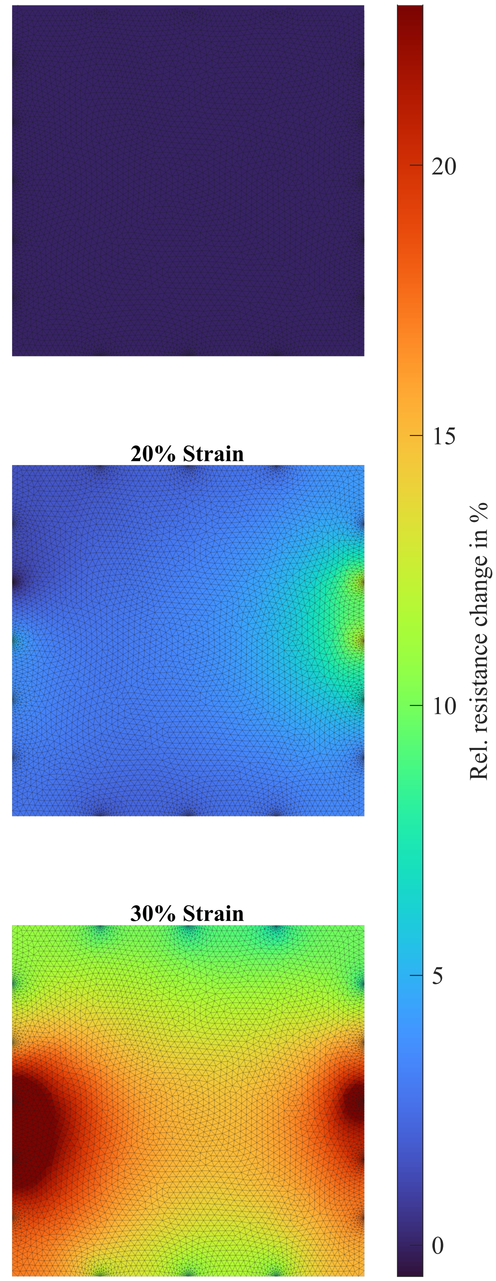

Fig. 4. Results of the EIT reconstruction at 0, 20, and 30% strain.

In comparison to the grid-based sensor, our EIT strain sensors have a drastically higher resolution. In Fig. 4 the reconstructed resistance change and the element mesh, on which the reconstruction was carried out, are depicted.

As expected, the resistance change is highest on the right and left sides because of the transversal contraction. Because the clamps restrict deformation, resistance change on the top and bottom edges is lower. Moreover, the influence of the transversal contraction becomes more prominent at increasing strain. Therefore, the local variation in resistance is small at lower strain levels but obvious at 30% strain. Moreover, a resistance change of around 20% is within expectations for a conductive elastomer with a filler content above the percolation threshold [12].

This also demonstrates a major advantage of EIT-based sensors, which is the possibility to acquire quasi-continuous resistance distributions with a small number of electrodes. However the successful reconstruction benefits from a-priori knowledge, such as about the smoothness of the distribution, which might not be available for real-world applications. In addition, EIT can be susceptible to artifacts due to incorrect reconstruction parameters or movement of the electrodes [17], which is not the case for grid sensors. In a controlled environment, such as the tensile testing experiments, the electrode positions can be tracked optically and movements can be compensated. But this would require additional sensors to be implemented in, for example, soft robotic systems. Recently machine learning methods have shown promise for soft touch sensors for robotic skins, which could also be beneficial for EIT-based strain sensors [18] and mitigate some of the mentioned challenges. This would allow to capture the underlying dynamics of the shoulder phenomenon and improve our understanding of the piezoresistivity of carbon particle-filled elastomers.

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