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Distributed Pressure Sensing using Carbon Nanotube Fabrics

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***Abstract*—A nano-engineered fabric capable of densely distributed pressure sensing is presented. Piezoresistive carbon nanotube-latex thin films were spray-coated and integrated with fabric to form robust, flexible, and deformable sensors. Spatial pressure sensing was achieved and validated experimentally using an electrical impedance tomography algorithm, which was able to estimate the resistivity distribution of the fabric and its changes due to applied pressure at different locations.**

***Index Terms*—Fabric, healthcare, impedance tomography, nanocomposite, patient monitoring, pressure sensing.**

I. INTRODUCTION

INDIVIDUALS with spinal cord injuries or with limited mobility are at the greatest risk of developing painful, life-threatening pressure ulcers, which are localized injuries to the skin/tissue due to prolonged applied pressure. Pressure ulcer care in the U.S. costs ~$11 billion annually, with individual costs up to $70,000 for each ulcer [1]. Thus, preventing their occurrence is much more effective than treating them [1]. A strategy is to monitor pressure distribution along the body and to alert patients to shift their position when needed.

Typically, discrete sensors are used to measure distributed pressure, for example, by using strain gages or fiber optics [2, 3]. However, these devices can be bulky and rigid, which can cause user discomfort. Moreover, dense sensor networks need to be instrumented for mapping pressure distributions at sufficient resolution, which adds costs and complicates data acquisition. Due to these drawbacks, flexible, sensitive, and robust pressure sensors made with nanostructured materials have been proposed, such as skin patches based on interlocking nano-fibers and polymers [4]. Unfortunately, their fabrication can be cumbersome and expensive, making them difficult to be scaled up for practical applications.

This study presents a washable, carbon nanotube-based, pressure-sensitive fabric. Distributed sensing is achieved using an electrical impedance tomography (EIT) algorithm. This letter begins with the fabrication technique, followed by the validation tests and corresponding pressure mapping results.

II. EXPERIMENTAL DETAILS

A. Sensor Fabrication

Fabrication of the distributed pressure sensors was achieved by integrating piezoresistive multi-walled carbon nanotube (MWCNT)-latex thin films with flexible fabric. The first step entailed preparing the thin film sensing element by following the procedure presented in [5]. MWCNTs were dispersed in 2 *wt.*% poly(sodium 4-styrenesulfonate) (PSS) aqueous solution with minute quantities of N-methyl-2-pyrrolindinone (NMP). Dispersion was attained by high-energy probe sonication for 1 h. Then, Kynar latex solution and 18 MΩ·cm deionized water were added in appropriate quantities so that 1 *wt.*% films were obtained. Films were deposited by spraying the MWCNT-latex ink onto 210×300 mm^2 fabric transfers using a Paasche airbrush. Films were air-dried for at least 4 h, and copper tape electrodes were attached along the boundaries. Second, to assemble the fabric-based sensors, MWCNT-latex films were transferred onto waterproof, 100% polyester woven fabric by ironing. Then, another layer of iron-on adhesive was applied on top of the film (Fig. 1a) to form a strong, waterproof, and integral sandwiched structure (Fig. 1b).

B. Pressure sensing characterization

To investigate the electromechanical response of the fabric sensors, they were subjected to three-point bending tests. The two ends of the fabric were gripped, while different pressures were applied at the midpoint of the fabric (Fig. 2). Pressure was determined from force measured using a spring balance, while sensor resistance was recorded simultaneously using an Agilent 34401A digital multimeter (DMM).

C. Distributed pressure sensing using EIT

Distributed pressure sensing was achieved by coupling the fabric sensors with an EIT algorithm. In short, EIT uses sets of known electrical current excitations (applied at specimen boundaries) and corresponding boundary electrode voltage measurements for solving the inverse problem to reconstruct the resistivity distribution of the conductive fabric sensor [6].

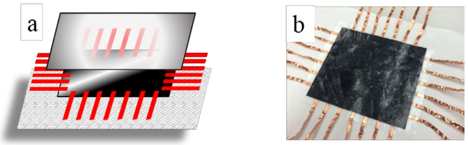

Fig. 1. (a) The nanocomposite is integrated with fabric using iron-on adhesives. (b) A picture of an actual fabric-based sensor is shown.

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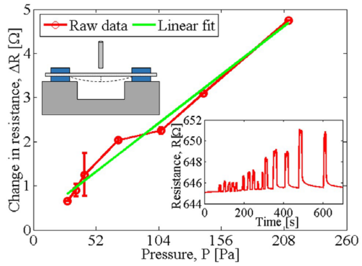

Fig. 2. The fabric sensors were subjected to three-point bending tests (left inset). From the resistance time history (right inset), the average change in sensor resistance (and standard deviations as error bars) is plotted as a function of pressure and fitted with a linear line.

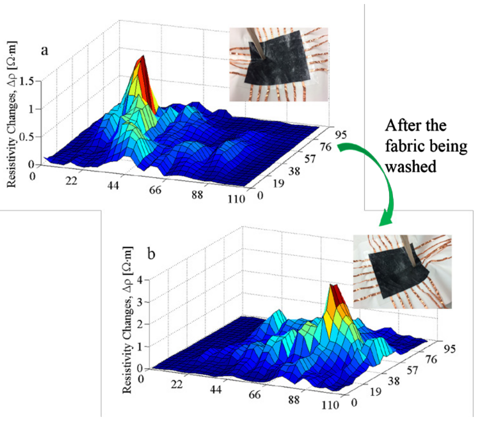

Fig. 3. A fabric-based sensor was subjected to applied pressure points (see insets). EIT results successfully mapped pressure distribution (*i.e.*, its location and severity) both (a) before and (b) after washing.

Then, EIT utilizes a finite element model (FEM) of the fabric-based sensor (meshed with four-node quadrilateral elements) and the weak-form of Laplace's equation. A Gauss-Newton algorithm iterates and updates spatial resistivity distribution until the predicted boundary voltage response from FEM, as compared to experimental voltage data, is within a prescribed error threshold, upon which the spatial resistivity distribution of the fabric can then be estimated and outputted [6].

Validation of distributed pressure sensing was done using fabric-based sensors with 28 boundary electrodes (Fig. 1b). An Agilent 34980A multifunctional switch was programmed using *MATLAB* to apply direct current (using a Keithley 6221 current source) across a pair of electrodes, while its built-in DMM measured voltage at the remaining adjacent pairs of electrodes. Next, a rod was used to manually apply pressure at localized regions on the fabric. The switch was then employed for interrogating the fabric-based sensor, and a total of 28 sets of excitations and voltage responses were obtained for each test. The raw data was used as the input to the EIT algorithm for estimating the spatial resistivity distribution [6], which can be equated to pressure, since the film was pre-calibrated to applied strains and pressure, as will be discussed next.

III. RESULTS AND DISCUSSION

A representative result of a fabric-based sensor subjected to different magnitudes of applied pressure is shown in Fig. 2. One can observe from Fig. 2 that sensor resistance increased in tandem with increasing pressure, and the correlation between applied pressure and resistance change is linear, as evident from the fitted linear least-squares regression line shown in Fig. 2. Sensor response also remained stable and repeatable over multiple cycles of applied pressure.

Upon validating pressure sensitivity of the MWCNT-based fabric, large fabric-based sensors with 28 boundary electrodes (Fig. 1) were subjected to pressure sensing tests. As mentioned earlier, a rod was used to apply pressure at highly localized locations on the fabric (Fig. 3a inset), and the corresponding EIT pressure mapping result is shown in Fig. 3a. First, EIT resistivity maps clearly show localized increases in resistivity near the vicinity of applied pressure, which validates the use of this technique for sensing locations of applied pressure. Second and as expected, applied pressure causes an increase in resistivity due to localized induced tensile strains, which is consistent with the results shown in Fig. 2. In general, this approach requires fewer sensing channels (*i.e.*, only along sensor boundaries) than technologies that require a dense network of transducers at every location. Densely distributed pressure sensing is possible using a continuous fabric-based sensor. To utilize this sensor in practice, they can be applied onto bed mattresses, wheel chair cushions, and garments, among others. When immobilized patients lie or sit on the fabric, an alert can be generated if the patient suffers from pressure "hot spots", notifying them to shift their position. Furthermore, a fabric-based sensor was subjected to 10 min of hand-washing (including twisting). After air-drying for 3 h, it was re-calibrated and tested. The sensor could successfully measure pressure distributions after being washed (Fig. 3b).

IV. CONCLUSIONS

In this study, a distributed pressure sensor was fabricated by integrating MWCNT-latex films with flexible fabric. An EIT algorithm was used for mapping the resistivity changes of the sensor. Since film resistance varied linearly with applied strains and pressure, EIT directly outputted the 2D pressure distributions. The lab tests confirmed the fabric-based sensor's distributed pressure mapping capabilities, and the sensor is flexible, simple, low-cost, noninvasive, and washable.

REFERENCES

[1] W. V. Padula, M. K. Mishra, M. C. F. Makic, and P. W. Sullivan, "Improving the quality of pressure ulcer care with prevention: a cost-effectiveness analysis." *Medical Care*, vol. 49, no. 4, 2011, pp. 385-392.

[2] A. Massaro, F. Spano, A. Lay-Ekuakille, P. Cazzato, R. Cingolani, and A. Athanassiou, "Design and characterization of nanocomposite pressure sensor implemented in tactile robotic system," *IEEE Transactions on Instrumentation & Measurement*, vol. 6, no. 8, 2011, pp. 2967-2975.

[3] M. Nishiyama, H. Sasaki , S. Nose , K. Takami , and K. Watanabe, "Smart Pressure Sensing Mats with Embedded Hetero-Core Fiber Optic Nerve Sensors," *Materials and Manufacturing Processes*, vol. 25, 2010, pp. 264–267.

[4] C. Pang, C. Lee, and K. Y. Suh, "Recent advances in flexible sensors for wearable and implantable devices." *Journal of Applied Polymer Science*, vol. 130, no. 3, 2013, pp. 1429-1441.

[5] L. Wang, K. J. Loh, Spray-coated carbon nanotube-latex strain sensors. *Science Letters Journal*, vol. 5, no. 234, 2015, pp. 1-10.

[6] J. Gonzalez, S. Gupta, and K. J. Loh, "Multifunctional cement composites enhanced with carbon nanotube thin film interfaces." *Proceedings of IEEE* (*in press*).