The 6th International Conference on
Engineering Mechanics and Automation (ICEMA 6)
Hanoi, October 15÷16, 2021

Fabrication and Investigation of Flexible Strain Sensor for Sign Language Recognition System

Chi Tran Nhu
Faculty of Electronics and Telecomunications
VNU – University of Engineering and Technology
Hanoi, Vietnam
trannhuchi@vnu.edu.vn

Phu Nguyen Dang
Faculty of Electronics and Telecomunications
VNU – University of Engineering and Technology
Hanoi, Vietnam
phund@vnu.edu.vn

Van Nguyen Thi Thanh
Faculty of Electronics and Telecomunications
VNU – University of Engineering and Technology
Hanoi, Vietnam
vanntt@vnu.edu.vn

Ha Tran Thi Thuy
Faculty of Electronics
Posts and Telecommunications Institute of Technology
Hanoi, Vietnam
hatt@ptit.edu.vn

Van Dau Thanh
School of Engineering and Built Environment
Griffith University
Queensland QLD 4222, Australia
v.dau@griffith.edu.au

Tung Bui Thanh
Faculty of Electronics and Telecomunications
VNU – University of Engineering and Technology
Hanoi, Vietnam
tungbt@vnu.edu.vn

***Abstract*—In this study, an ultra-stretchable and highly sensitive strain sensor is successfully fabricated by 3D printing technology with a mixture of aqueous sodium chloride and silicone rubber. This strain sensor has dimensions of 50x10x10 mm, with a fluidic channel (6 mm) inside. The physical and mechanical properties of sensor were characterized by gauge factor measurement. Experimental results show that the resistance of the sensor changes when an external force deforms the ionic liquid shell; exhibiting impressive stretchability with wide range strain (100%), good bending properties and high sensitivity with a stable gauge factor of 2.1. Besides, the sensor also is investigated with a vertical pressing force. Initially, the resistance of the sensor increase slowly and it then jump rapidly to the saturation value at the force of 40 N. For application of sensor, the proposed sensor is applied to recognize the sign language through attaching five strain sensors on the fingers. The obtained result shows the sensor can detect the movement of the fingers and convert 10 letters of sign language into the voice with high accuracy, about 98%. On the other hand, the result also demonstrates the proposed sensor has high potential in healthcare, human motion monitoring and electronic skin.**

Keywords—strain sensor, gauge factor, 3D printing technology, sign language

I. INTRODUCTION

Strain sensor, the resistive or capacitive properties of which change as the strain or curvature applied to them are varied. The change in these electrical properties basically occurs due to the change in the device geometry in response to the applied mechanical stimulus. These sensors are used widely to measure mechanical deformation of structures [1], [2]. A strain sensor is characterized by a gauge factor or the sensitivity to strain. As the most commonly used strain sensor, metallic foil gauges have a gauge factor of approximately 2. Meanwhile, strain sensors based on semiconductor give much higher sensitivity. For example, single crystalline silicon demonstrates intrinsic gauge factors as high as 200 [3]–[5]. However, as an intrinsically stiff and brittle material, silicon is just suitable for small deformation measurement, i.e., strain less than 0.1%.

Recent studies have focused on the development of strain sensors for large deformation measurement for replacing the traditional strain sensors in various applications such as medical applications and soft robotics [6]. These sensors are developed with different fabrication strategies including but not limited to lithography [7], [8], 3D printing [9], [10], laser engraving [11]–[13], and mould based techniques [14]–[17]. Besides, various conductive agents are used such as eutectic Gallium-Indium (eGaIn) [10], [11], [14]–[21], carbon [7], [8], [13], [22]–[27], ionic fluids [12], [28]–[34] and optical fibers [35]. Also, several base substrates with varying viscosity and softness properties have been employed in the design of these sensors; polydimethylsiloxane (PDMS), soft silicone rubbers and hydrogels are among the most commonly used materials in these studies. However, emerging among them, the sensors that the ionic fluids combine with with elastomer (PDMS, Silicone), to make the sensor more elastic and suitable for soft applications are a trend now. Because they are low cost, easy to use and environmentally friendly.

In this paper, we introduce a low-cost, high-sensibility and ultra-stretchable strain sensor based on the ionic liquid of glycerin and sodium chloride (NaCl). Besides, a compact conditioning circuit is also designed for evaluating the strain sensing performance of the sensor. Based on the proposed sensor, a wearable application of the sensor has been demonstrated by using the sensor for detecting the motion of fingers.

II. PRINCIPLE OF FLUIDIC STRAIN SENSOR

In this study, we use a silicone rubber shell fill with a mixture of glycerin and sodium chloride. Glycerin is used in this mixture because it can protect electrodes from being frustrated by ionic liquid and increase the viscosity of the liquid. Silicone glue is applied at the interface between the electrodes minimize leakage of the mixture to the outside.

The proposed sensor is a type of resistive form. At rest state, the sensor has the length (l) and diameter (d). The resistance of the sensor can be measured by the following equation:

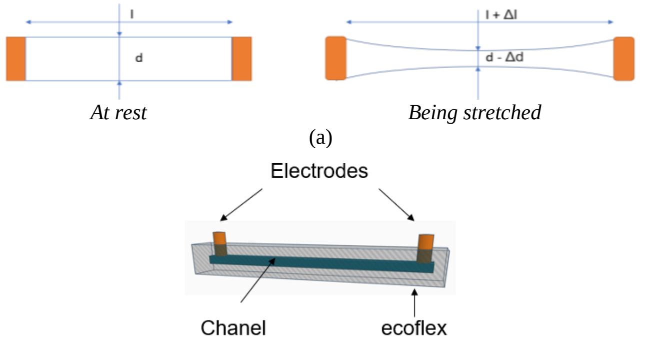
$$R = \rho \frac{l}{\frac{\pi d^2}{4}} \tag{1}$$

When the tube is stretched, the length of the sensor increases to $(l + \Delta l)$ while the section area is decreased $(d - \Delta d)$, as shown in the Fig.1a. The resistance of the sensor is changed to:

$$R = \rho \frac{l + \Delta l}{\frac{\pi \left(d - \Delta d\right)^2}{4}} \tag{2}$$

As can be seen from the formula (2), the resistance of the sensor rise when the silicon tube is stretched. As we know, when sodium chloride is dissolved in water, they will be turned into cations (Na^+) and anions (Cl^-), which are all electrical carriers. In normal condition, these ions move randomly in the electrolyte solution, but when we apply a DC (direct current) voltage to the liquid, it will change the rule of carrier's motion and make the measurement unstable. Positive electrode will attract anions while negative one will attract cations. This motion creates a current inside ionic liquid. That is the reason why we can use them as conductive material. Therefore, an alternating current source is used to improve the accuracy of measurement.

From the analyzed principle, we design the structure of the sensor. There is a conductive channel wrapped by two layer of silicone (eco-flex) in order to obtain the sandwiched channel structure. The electrodes are put at two ends of the channel to cover the holes and to connect to an external measurement circuit, as shown in the Fig. 1b.



At rest *Being stretched*

(a)

(b)

Fig. 1. Proposal of fluidic strain sensor. (a) Principle of the fluidic strain sensor, showing the geometry of the sensor at rest and when being stretched. (b) The structure of the sensor.

III. EXPERIMENTS

A. *Sensor Fabrication*

The proposed strain sensor is fabricated using a substrate as base material. The substrate is Smooth-On's EcoFlex 0010, which is an extremely soft, low-viscosity two component, addition cured room temperature vulcanizing silicone rubber. For the first part of the sensor, EcoFlex is mixed 1A:1B by weight, and poured into a 3D printed (Objet 500, 3D Printing Systems) mould (A) with the channel pattern and a total height of 50 mm. The mould is put in a vacuum chamber and degassed for 5 minutes in order to remove any air bubbles trapped inside the mixture. Before the sensor part can be demoulded, it is left to cure at high temperature (80 degree) for 2 hours, in LVO 2030 vacuum drying oven. For the second part of the sensor, a thin layer (2 mm) of EcoFlex is also fabricated similarly. However, it is only left to cure at room temperature for 15 minutes instead of putting the oven. Then the first layer is carefully placed onto the thin layer with the patterned surface facing down, preventing the channel from being filled by the semi-cured silicone, and the sensor is left to cure in the oven at 80 degree. After 2 hours, the sensor is taken out of the oven and demoulded, as shown in the figure 2.

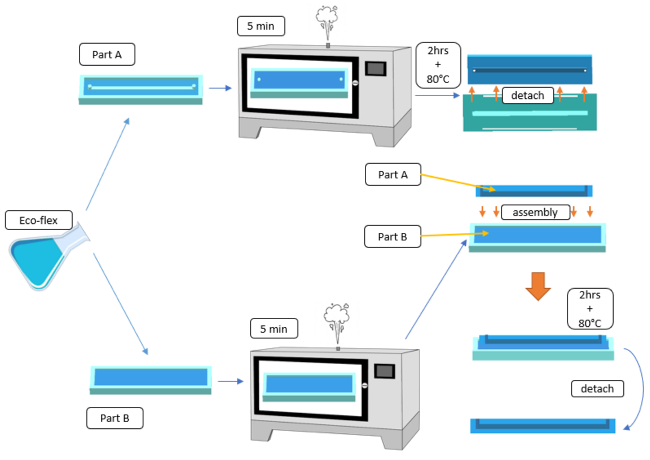


Fig. 2. The process of the strain sensor fabrication

The last step of sensor fabrication is filling the channel with a conductive liquid, namely a mixture of sodium chloride, water and glycerin. The channel is filled using a syringe fitted with a 25G needle. Gold-coated electrodes are inserted at two ends of the tube to make good contact with the liquid. Silicone glue is applied to the interface be-tween the electrode and the contact point for leaking prevention purpose as shown in the figure 3.

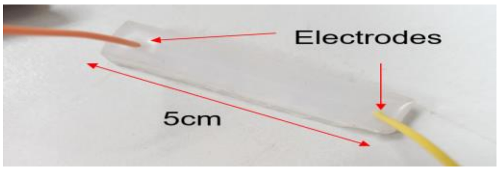


Fig. 3. A fabricated prototype of ionic liquid resistance strain sensor.

B. *Experimental measurement of strain sensor*

Resistance change can be measured by applying a current source to the resistor and measure the voltage drop. As mentioned above, with this ionic liquid resistive sensor, using the DC causes electrolysis at the two electrodes that can destroy the sensor. Furthermore, the parasitic capacitance between the electrode and the conducting liquid makes the measurement unstable [5]. Therefore, an AC source is utilized instead of the DC current source in this study to improve the accuracy of the measurement. The resistance of the sensor is measured by 4-point resistance measurement method using Howland current source as presented in Fig. 4. We can calculate the resistance of the sensor by using equation $R_s = \frac{V_s}{i_s}$, where the output signal amplitude (V_s) is determined by a conditioning circuit including an instrumentation amplifier and a peak detection circuit. The current value i_s through the sensor is determined by the reference resistor R_{ref} in the Howland current source as depicted $i_s = \frac{V_i}{R_{ref}}$. The current i_s depends only on R_{ref} and does not depend on the change of the resistance of the sensor when the sensor is stretched.

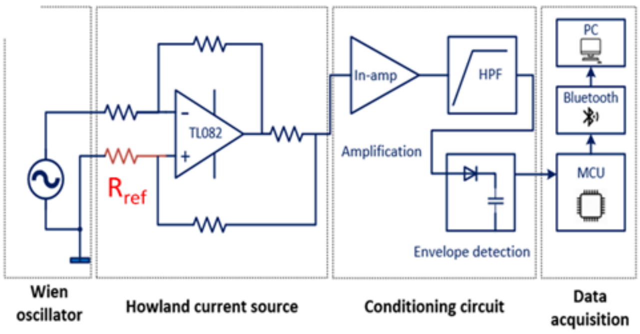


Fig. 4. Block diagram for strain gauge measurement

The current source is set to 2.0 μ A and Wien circuit generated a sinusoidal oscillator with a frequency of 1 kHz. Input and output signals are observed through an oscilloscope, a liquid crystal display in the board monitor the resistance and voltage of the sensor. Arduino development KIT is used to display results in LCD and transfer measured values to a data acquisition computer.

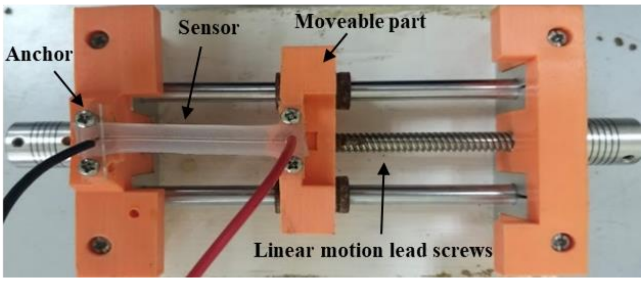


Fig. 5. Tensile strain generating platform

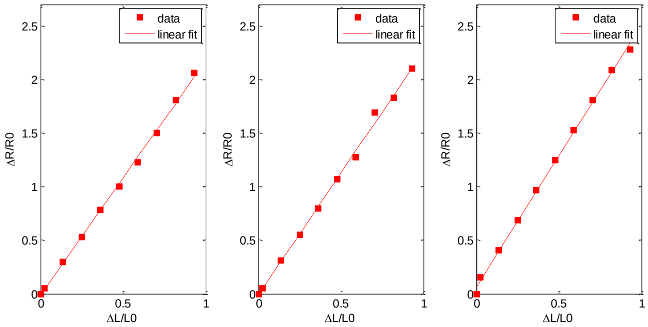
A tensile strain generating platform is designed and fabricated using 3D printing technology (Objet 500 printer from Stratasys) to apply strain to the sensor. It stretches the sensor easily and conveniently (Fig. 5). By fixing one end and pull another end by controlling the screw rod parallel to the sensor. A ruler is used to indicate the exact length of the sensor when being stretched. Signals from two electrodes are taken to the measurement circuit board to determine the resistance of the sensor. The sensors were fabricated in three different mixtures, namely 1%, 2% and 3% of NaCl. In addition, the sensor is also experimented with a force being applied to the sensor vertically. Experiment setup is established as shown in the figure 7a, with a mixture of 2% NaCl. The force is applied in the middle of the sensor with the contact area being 8*10 mm, a scale that put under the sensor as an applied force measuring device. Their properties are experimentally characterized and presented in the next session.

IV. RESULTS AND DISCUSSIONS

In this study, we use Gauge factor as a fundamental parameter of the strain sensor. The Gauge factor is the relationship between can be defined as:

$$\mathrm{GF} = \frac{\Delta R / R_0}{\varepsilon} \tag{3}$$

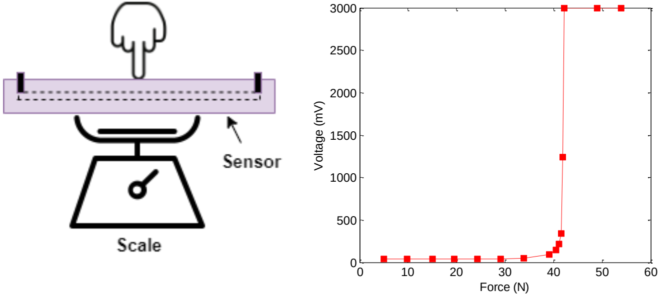
where ε is the applied strain, is the representative parameter to access sensitivity. The strain gauge of this kind of sensor was evaluated at different conductivities of the liquid. Experiment results are presented in Fig. 6 showing the change of sensor resistance due to the longitudinal strain of three different mixing ratios (1%, 2%, and 3% of NaCl). All the measurements are conducted at room temperature of around $25^o C$. As can be seen, the proposed sensor can be stretched up to 100% and the resistance of the sensors increased linearly with the applied strain. The Gauge factor of the sensor is quite stable in the range from 2.01 to 2.4. This obtained result is same as previous studies [12], [33]. Furthermore, the results also show the resistance of the sensor increase gradually with the applied force being less than 40N, while it rises quickly when the force is bigger. The resistance of the sensor reach its limit point as the applied force is around 42N and this value still remain unchanged whether the force increase significantly, as shown in the Fig. 7b. This result can be explained that the length of the sensor rise and the diameter of a part of the sensor area where it is applied by the force decrease dramatically lead to the resistance of the sensor increase. When the applied force is over the limit value, the channel will be block and the ions can not move between two electrodes. Therefore, the resistance of the sensor is infinity.



(a) (b) (c)

Fig. 6. Experimental results show the change of resistance due to strain of each sodium chloride ratio in ionic liquid mixture 1% NaCl (a), 2% NaCl (b), 3% NaCl (c).

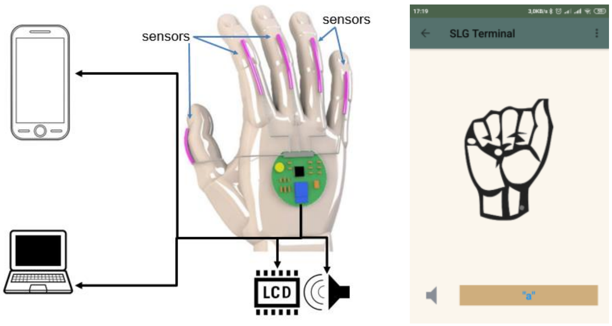
Besides, the hysteresis of the sensor is also investigated with the force applying vertically. The time is recorded when the finger start moving from the sensor. The sensor back to the original state which there is no force applying to. The results show that the hysteresis is inversely proportional with the magnitude of the applied force. It is around 14.2 ms and 25.2 ms with the strong and light applied forces, respectively.



(a) (b)

Fig. 7. The property of the strain sensor when being pressed. (a) Experiment setup and (b) The obtained signal of sensor with the vertical applied force.

Furthermore, the proposed sensor design was applied in a finger motion detection experiment. Five sensors were attached on a human hand for finger movement detection (Fig. 8). For collecting information from five sensors, an analogue-switching IC was integrated in the measurement circuit for applying AC source to the sensors as well as sharing the signal conditioning circuit. The amplitude of the signal reflects the bending of the fingers marked in the figure. By combining the signal obtained from the sensors, the movement of the fingers can be realized. There is an on-board micro-controller (Atmega 328) for data collection and processing. After the data is analyzed and decoded into the language, it will be transferred to a speaker and display on a LCD screen. Besides, these data also are transmitted to the computer and smartphone through the HC05 Bluetooth module.



(a) (b)

Fig. 8. Proposed strain sensors are applied to recognize sign lanuguge. (a) The block digaram of sytem. (b) An application on the smartphone

On the computer and smartphone, we developed an application which can connect to the system through the Bluetooth communication (Fig. 8b). As can be seen, the application plays the voice through the speaker being available on the device. On the other hand, the letter also is displayed in a textbox and a hand shape respresenting sign language. These help people can hear and see the letter which a mute person want to communicate. With each letter, the resistance change of sensors is investigated repeatedly about 10 times to obtain the average value and limited range. The sensors are attached in order from thumb to little finger. From the obtained data, an algorithm is built to convert the digital signal into the voice. Firstly, the system is initialized to enable the communication and other function blocks. Then the system get the data from five sensors and save them to a temporary memory before being pass through the average filter. After that, the obtained data is decoded into the letters. The waiting time (1 second) make sure that the system is not confused with a quick movement of the hand. Finally, the data that is processed will be transferred to the executable block, including the speaker, smartphone and computer as show in the Fig. 8b. To evaluate the accuracy of the system, we conducted to experiment repeatedly about 15 times with each the letter. The result shows the average accuracy rate is 98%, as shown in the table I.

TABLE I. EXPERIMENT RESULTS WITH 10 DISTINGUISHED LETTERS

No.	**Letter**	**Correct**	**Error**	**Accuracy (%)**
1	A	13	2	86.67
2	B	15	0	100.00
3	C	14	1	93.33
4	D	15	0	100.00
5	E	15	0	100.00
6	F	15	0	100.00
7	V	15	0	100.00
8	W	15	0	100.00
9	Y	15	0	100.00
10	l	15	0	100.00
Total		**147/150**	**3**	**98.00**

V. CONCLUSIONS

A highly stretchable, low-cost, and hysteresis-free strain sensor was achieved by combining the ionic liquid of Water/NaCl/Glycerin with silicone shell, which is shaped by 3D printing technology. Furthermore, a measured system was also designed and fabricated to investigate the sensor. Several tests were performed in order to characterize the sensor. The results showed that the proposed sensor has a stable gauge factor of 2.1. The resistance of the sensor did not increase linearly with vertical applied force. The magnitude of vertical applied force effect to the hysteresis of the sensor.

Moreover, an application in sign language translation was developed based on the proposed sensor by attaching some sensor on the fingers. The result showed the sensors could detect 10 letter with high accuracy (98%). With obtained results, the proposed sensors showed outstanding durability, low latency, and ultra-stretchability. These excellent performance capabilities make the proposed sensor applicable for precise and quantitative strain sensing in various wearable electronic applications, such as human motion detection, personal health monitoring.

REFERENCES

[1] V. T. Dau, T. Yamada, D. Viet Dao, B. Thanh Tung, K. Hata, and S. Sugiyama, “Integrated CNTs thin film for MEMS mechanical sensors,” Microelectronics J., vol. 41, no. 12, pp. 860–864, Dec. 2010, doi: 10.1016/J.MEJO.2010.07.012.

[2] B. T. Tung, H. M. Nguyen, D. V. Dao, S. Rogge, H. W. M. Salemink, and S. Sugiyama, “Strain sensitive effect in a triangular lattice photonic crystal hole-modified nanocavity,” IEEE Sens. J., vol. 11, no. 11, pp. 2657–2663, 2011, doi: 10.1109/JSEN.2011.2157122.

[3] T. T. Bui, D. V. Dao, T. Toriyama, and S. Sugiyama, “Evaluation of the piezoresistive effect in single crystalline silicon nanowires,” Proc. IEEE Sensors, pp. 41–44, 2009, doi: 10.1109/ICSENS.2009.5398124.

[4] K. Nakamura, D. V. Dao, B. T. Tung, T. Toriyama, and S. Sugiyama, “Piezoresistive effect in silicon nanowires - A comprehensive analysis based on first-principles calculations,” 20th Anniv. MHS 2009 Micro-Nano Glob. COE - 2009 Int. Symp. Micro-NanoMechatronics Hum. Sci., pp. 38–43, 2009, doi: 10.1109/MHS.2009.5352099.

[5] S. Yang and N. Lu, “Gauge Factor and Stretchability of Silicon-on-Polymer Strain Gauges,” Sensors 2013, Vol. 13, Pages 8577-8594, vol. 13, no. 7, pp. 8577–8594, Jul. 2013, doi: 10.3390/S130708577.

[6] S. Russo, T. Ranzani, H. Liu, S. Nefti-Meziani, K. Althoefer, and A. Menciassi, “Soft and stretchable sensor using biocompatible electrodes and liquid for medical applications,” Soft Robot., vol. 2, no. 4, pp. 146–154, 2015, doi: 10.1089/soro.2015.0011.

[7] X. Z. Niu, S. L. Peng, L. Y. Liu, W. J. Wen, and P. Sheng, “Characterizing and Patterning of PDMS-Based Conducting Composites,” Adv. Mater., vol. 19, no. 18, pp. 2682–2686, Sep. 2007, doi: 10.1002/ADMA.200602515.

[8] N. Lu, C. Lu, S. Yang, and J. Rogers, “Highly Sensitive Skin-Mountable Strain Gauges Based Entirely on Elastomers,” Adv. Funct. Mater., vol. 22, no. 19, pp. 4044–4050, Oct. 2012, doi: 10.1002/ADFM.201200498.

[9] J. T. Muth et al., “Embedded 3D Printing of Strain Sensors within Highly Stretchable Elastomers,” Adv. Mater., vol. 26, no. 36, pp. 6307–6312, Sep. 2014, doi: 10.1002/ADMA.201400334.

[10] A. Frutiger et al., “Capacitive soft strain sensors via multicore-shell fiber printing,” Adv. Mater., vol. 27, no. 15, pp. 2440–2446, 2015, doi: 10.1002/adma.201500072.

[11] R. K. Kramer, C. Majidi, R. Sahai, and R. J. Wood, “Soft curvature sensors for joint angle proprioception,” pp. 1919–1926, Dec. 2011, doi: 10.1109/IROS.2011.6094701.

[12] J. B. Chossat, Y. L. Park, R. J. Wood, and V. Duchaine, “A soft strain sensor based on ionic and metal liquids,” IEEE Sens. J., vol. 13, no. 9, pp. 3405–3414, 2013, doi: 10.1109/JSEN.2013.2263797.

[13] O. A. Araromi, S. Rosset, and H. R. Shea, “High-Resolution, Large-Area Fabrication of Compliant Electrodes via Laser Ablation for Robust, Stretchable Dielectric Elastomer Actuators and Sensors,” ACS Appl. Mater. Interfaces, vol. 7, no. 32, pp. 18046–18053, Aug. 2015, doi: 10.1021/ACSAMI.5B04975.

[14] Y. L. Park, C. Majidi, R. Kramer, P. Brard, and R. J. Wood, “Hyperelastic pressure sensing with a liquid-embedded elastomer,” J. Micromechanics Microengineering, vol. 20, no. 12, 2010, doi: 10.1088/0960-1317/20/12/125029.

[15] P. M et al., “Highly stretchable electric circuits from a composite material of silver nanoparticles and elastomeric fibres,” Nat. Nanotechnol., vol. 7, no. 12, pp. 803–809, 2012, doi: 10.1038/NNANO.2012.206.

[16] Y. Menguc et al., “Soft wearable motion sensing suit for lower limb biomechanics measurements,” Proc. - IEEE Int. Conf. Robot. Autom., pp. 5309–5316, 2013, doi: 10.1109/ICRA.2013.6631337.

[17] Y. L. Park, B. R. Chen, and R. J. Wood, “Design and fabrication of soft artificial skin using embedded microchannels and liquid conductors,” IEEE Sens. J., vol. 12, no. 8, pp. 2711–2718, 2012, doi: 10.1109/JSEN.2012.2200790.

[18] M. D. Dickey, R. C. Chiechi, R. J. Larsen, E. A. Weiss, D. A. Weitz, and G. M. Whitesides, “Eutectic Gallium-Indium (EGaIn): A Liquid Metal Alloy for the Formation of Stable Structures in Microchannels at Room Temperature,” Adv. Funct. Mater., vol. 18, no. 7, pp. 1097–1104, Apr. 2008, doi: 10.1002/ADFM.200701216.

[19] Y.-L. Park, B. Chen, and R. J. Wood, “Soft artificial skin with multi-modal sensing capability using embedded liquid conductors,” pp. 81–84, Jan. 2013, doi: 10.1109/ICSENS.2011.6127228.

[20] S. Zhu et al., “Ultrastretchable Fibers with Metallic Conductivity Using a Liquid Metal Alloy Core,” Adv. Funct. Mater., vol. 23, no. 18, pp. 2308–2314, May 2013, doi: 10.1002/ADFM.201202405.

[21] C. Majidi, R. Kramer, and R. J. Wood, “A non-differential elastomer curvature sensor for softer-than-skin electronics,” Smart Mater. Struct., vol. 20, no. 10, 2011, doi: 10.1088/0964-1726/20/10/105017.

[22] K.-Y. Chun et al., “Highly conductive, printable and stretchable composite films of carbon nanotubes and silver,” Nat. Nanotechnol. 2010 512, vol. 5, no. 12, pp. 853–857, Nov. 2010, doi: 10.1038/nnano.2010.232.

[23] T. Yamada et al., “A stretchable carbon nanotube strain sensor for human-motion detection,” Nat. Nanotechnol., vol. 6, no. 5, pp. 296–301, 2011, doi: 10.1038/nnano.2011.36.

[24] D. J. Lipomi et al., “Skin-like pressure and strain sensors based on transparent elastic films of carbon nanotubes,” Nat. Nanotechnol. 2011 612, vol. 6, no. 12, pp. 788–792, Oct. 2011, doi: 10.1038/nnano.2011.184.

[25] M. A. Lacasse, V. Duchaine, and C. Gosselin, “Characterization of the electrical resistance of carbon-black-filled silicone: Application to a flexible and stretchable robot skin,” Proc. - IEEE Int. Conf. Robot. Autom., pp. 4842–4848, 2010, doi: 10.1109/ROBOT.2010.5509283.

[26] A. Firouzeh and J. Paik, “Robogami: A Fully Integrated Low-Profile Robotic Origami,” J. Mech. Robot., vol. 7, no. 2, pp. 1–8, May 2015, doi: 10.1115/1.4029491.

[27] S. Kumbay Yildiz, R. Mutlu, and G. Alici, “Fabrication and characterisation of highly stretchable elastomeric strain sensors for prosthetic hand applications,” Sensors Actuators, A Phys., vol. 247, pp. 514–521, 2016, doi: 10.1016/j.sna.2016.06.037.

[28] Y. N. Cheung, Y. Zhu, C. H. Cheng, C. Chao, and W. W. F. Leung, “A novel fluidic strain sensor for large strain measurement,” Sensors Actuators, A Phys., vol. 147, no. 2, pp. 401–408, 2008, doi: 10.1016/j.sna.2008.05.013.

[29] K. Noda, E. Iwase, K. Matsumoto, and I. Shimoyama, “Stretchable liquid tactile sensor for robot-joints,” Proc. - IEEE Int. Conf. Robot. Autom., pp. 4212–4217, 2010, doi: 10.1109/ROBOT.2010.5509301.

[30] C.-Y. Wu, W.-H. Liao, and Y.-C. Tung, “Integrated ionic liquid-based electrofluidic circuits for pressure sensing within polydimethylsiloxane microfluidic systems,” Lab Chip, vol. 11, no. 10, pp. 1740–1746, May 2011, doi: 10.1039/C0LC00620C.

[31] P. Manandhar, P. D. Calvert, and J. R. Buck, “Elastomeric ionic hydrogel sensor for large strains,” IEEE Sens. J., vol. 12, no. 6, pp. 2052–2061, 2012, doi: 10.1109/JSEN.2011.2181993.

[32] [32] J.-Y. Sun, C. Keplinger, G. M. Whitesides, and Z. Suo, “Ionic skin,” Adv. Mater., vol. 26, no. 45, pp. 7608–7614, Dec. 2014, doi: 10.1002/ADMA.201403441.

[33] C. T. Nhu et al., “Experimental Characterization of an Ionically Conductive Fluid Based High Flexibility Strain Sensor,” Lect. Notes Networks Syst., vol. 63, pp. 318–323, Dec. 2018, doi: 10.1007/978-3-030-04792-4_42.

[34] C. T. Nhu, A. Nguyen Ngoc, V. T. Dau, C. Le Van, T. C. Duc, and T. T. Bui, “Wearable Fluidic Strain Sensor for Human Motion Sensing,” Proc. IEEE Sensors, vol. 2020-October, Oct. 2020, doi: 10.1109/SENSORS47125.2020.9278685.

[35] T. A. Hampshire and H. Adeli, “Monitoring the behavior of steel structures using distributed optical fiber sensors,” J. Constr. Steel Res., vol. 53, no. 3, pp. 267–281, Mar. 2000, doi: 10.1016/S0143-974X(99)00043-7.