

<u>Abstract</u>

A high flexibility strain sensor based on ionic liquid is developed with the utilization of an aqueous sodium chloride solution encapsulated within a natural rubber tube and copper-coated fibers as electrodes are inserted into both ends of the tube to make good contact with the aqueous sodium chloride solution as a mean for piezo resistive enormous strain estimation. When an external force (tensile or compressive or transverse) is applied to the natural rubber tube, the electrical and geometrical properties of the aqueous sodium chloride solution inside the natural rubber tube changes, resulting in an adjustment in resistance of the strain sensor. The fabricated aqueous sodium chloride solution/elastic natural rubber tube strain sensor was experimentally characterized and the exploratory outcomes demonstrate that the fabricated ionic fluid strain sensor is profoundly adaptable (i.e. can be stretched over 100%, twisted over 180 degrees and over with a steady gauge factor of 2.15 for a prolongation of over 30%), profoundly versatile (i.e. can retain its unique shape in the wake of being stretch several times) and exceptionally sensitive to strain.

Moreover, the flexible strain sensors exhibited the capability of multiple deformation forms including strain and bending, which exhibited their application in the detection of finger touching, finger, wrist and elbow joint movement, throat muscle movement and pulse waveforms. The flexible strain sensor has a linearity rate of 0.99 which means is linear and accuracy rate of 0.00004 which makes it accurate. Another highlight was the easy, low-cost, scalable fabrication strategy, setting the stage for the practicable and widespread utilization as a flexible sensor. These unprecedented merits provide precise and reliable detections of subtle vital signals. Mechanical characterization and analysis of the fabricated flexible strain sensor has been conducted and the parabolic strain response is verified.

The design, fabrication process and experimental testing of the flexible strain sensor based on aqueous sodium chloride solution and elastic natural rubber tube are presented in this report.

Keywords: Strain sensor, Gauge factor (GF), Ionic liquids, Flexibility, Piezo resistivity, Multi-segment/fragment.

1. Introduction

Strain is one of the most fundamental concepts from the study of mechanics of materials and is paramount importance to the stress analyst^[1, 2]. Physical sensing platforms that detect and monitor the surroundings and communicate with the acquired physical data, such as strain form the fundamental building blocks of a multiple of advanced applications, including wearable consumer electronics, soft robotics, smart medical prosthetics and electronic skins, and real-time healthcare monitoring ^[3-6]. Traditional strain gauges have limited flexibility and cannot withstand large deformations, therefore making them not suitable for these advanced applications. Tremendous in-rows have been made by researchers, scientists and engineers in the fabrication of flexible strain sensors to measure and analyze large deformations and strains over the years. Recent engineering of flexible strain sensors for the measurements of large deformations and strains have been centered intrinsically on conductive polymers, conductive filler doped elastomers ^[1], and liquid metal alloy based sensors^[7] and ionic liquids based sensors^[8]. Further research into conductive filler doped elastomers have revealed that they suffer from significant non-linearity and hysteresis at larger strains^[4] and liquid metal alloys have a high intrinsic conductivity, which results in small resistance variations and bad electrical performance^[2]. But in contrast, ionic liquid based strain sensors can be engineered such that the strain sensor has the desired linearity and hysteresis at large strains, low intrinsic conductivity, which results in high resistance variations and good electrical performance^[9, 10]. In this research, a simplified fabrication process of an aqueous sodium chloride solution encapsulated in an elastic natural rubber tube is proposed. The proposed strain sensor is fabricated using the piezoresistive mechanism (electrical resistance transduction

method), where the external strain applied causes a change in the electrical resistance of the sensing element which in this strain sensor is an aqueous sodium chloride solution. This ionic liquid (aqueous sodium chloride solution) based strain sensor is reliable and avoids most flexible strain

2. Materials

sensors void problems.

Table salt (sodium chloride) of 98% purity was acquired from a chemical laboratory in Beijing, an elastic natural rubber tube of over 200% elasticity was acquired from a merchant store in Chengdu, a copper coated wire of 98% purity was bought from a copper wire manufacturer in Shanghai, distilled water was acquired from a chemical laboratory in Chengdu, rubber glue acquired from the open market in Mianyang and syringe and needle from the school laboratory.

3. Fabrication

The fabrication of the strain sensor starts by the preparation of the aqueous sodium chloride solution (ionic liquid) and this is done by mixing 2grams of sodium chloride in 200 milliliters volume of water. Then, the elastic natural rubber tube is filled with the prepared aqueous sodium chloride solution with the syringe and needle. The copper coated wire electrodes are inserted into both ends of the elastic natural rubber tube making sure that the system is air tight (devoid of air). The elastic natural rubber tube (inner diameter of 0.5mm and length of 5mm) is then sealed with a rubber epoxy to prevent air from entering the system and cured. The finished flexible aqueous sodium chloride solution/elastic natural rubber tube strain sensor has a length of 10mm and an outer diameter of 0.5mm, and shown in Fig 1.



Fig 1. The flexible aqueous sodium chloride solution/elastic natural rubber strain sensor.

4. Design/Experiment

An aqueous sodium chloride solution is encapsulated in an elastic natural rubber tube with an initial length (l_o) and diameter (d_o) , as shown in Fig. 2.a. When an external axial strain is applied to the fabricated strain sensor, the length of the elastic natural rubber tube $(l_o + \Delta l)$ will increase, whereas the cross-sectional area of the elastic natural rubber tube $(d_o + \Delta d)$ will decrease (necking), as shown Fig. 2.b.



Fig 2. The fluidic principle of an ionic liquid strain sensor.

Now to characterize the piezoresistive behavior of the fabricated flexible strain sensor, the strain sensor is

mechanically tested different under mechanical strains or loads using an INSTRON universal testing machine with a VM 600-2 digital readout unit attached used for measuring the deformation (displacement) of the fabricated samples of the aqueous sodium chloride solution/elastic natural rubber tube when stretched. The changes in the electrical resistance of the fabricated flexible strain sensor relative to the various applied strains are measured by using a TH 2826 LCR meter which is connected to the copper coated wire electrodes of the fabricated flexible strain sensor and the results are analyze. The effect of various parameters such as the concentration of the aqueous sodium chloride solution, the length of the elastic natural rubber tube and the diameter of the elastic natural rubber tube have on the fabricated flexible strain sensor are also experimentally calibrated in this research and analyzed.



Fig 3. A self-designed Instron movable platform used to apply strain along the longitudinal direction of the fabricated flexible strain sensor.

5. <u>Results and Discussion</u>

Data obtained after testing the fabricated flexible strain sensor of length 0.005 meters and diameter 0.0005 meters several times over a period of time.

Table 1- Data for the characterization of the fabricated sample strain sensor when mechanically (tensile) tested.

Deform. (m)	Strain	Stress (N/m ²)	Load (N)	
0.001	0.2	11.19	0.02	
0.002	0.4	39.165	0.07	
0.003	0.6	61.546	0.11	
0.004	0.8	78.33	0.14	
0.005	1.0	95.116	0.17	



Fig 4. The deformation-applied load curve showing the relation between the applied load and the rate of deformation.



Fig 5. The stress-strain curve showing the relation between the stress and the strain of the fabricated sample

Hooke's Law states that the force needed to compress or extend a spring is directly proportional to the distance you stretch it^[11]. As an equation, Hooke's Law can be represented as

$$F = k \Delta L$$

Substituting Fmax=0.17N and Δl max=0.005m into Hooke's law equation;

$$k=\frac{F}{\Delta L}=\frac{0.17N}{0.005m}=34N/m$$

The modern theory of elasticity generalizes Hooke's law to say that the strain (deformation) of an elastic object or material is proportional to the stress applied to it.

$$E = \frac{stress}{strain}$$

Substituting stress max=95.116 and strain max=1.0 into the equation;

$$E = \frac{95.116Nm^{-2}}{1} = 95.116Nm^{-2}$$

During the uniaxial tensile test, it is found that the specimen exhibits a lateral contraction. Further, for linear elastic materials, there is a definite ratio between the lateral and longitudinal strains which is given by;

$$\frac{\varepsilon_T}{\varepsilon_L} = \frac{\Delta D/D}{\Delta L/L} = -v$$
$$-v = \frac{0.00025m/0.0005m}{0.005m/0.005m} = 0.5$$

Table 1. Data for fabricated sampled flexible	
strain sensors when tested mechanically	

Strain	0	0.01	0.02	0.03
Δ^{R_1}/R_1	0	0.0253	0.0434	0.0635
Δ^{R_2}/R_2	0	0.0261	0.0495	0.0704
Δ^{R_3}/R_3	0	0.0267	0.0501	0.0709
Δ^{R_4}/R_4	0	0.027	0.0504	0.0712
Δ^{R_5}/R_5	0	0.027	0.0504	0.0712





Fig 6. The strain-change in relative resistance curve shows the relation between the strain and the change in relative resistance of the fabricated sample strain

sensor.

Linearity: The linearity of the fabricated strain sensor is a measure of the proportionality between the actual values of a variable being measured to the output of the instrument over its operating range. The linearity of the fabricated flexible strain sensor is an expression of the extent to which the actual measured curve of a sensor departs from the ideal curve. The linearity is the property of a mathematical relationship or function which means that it can be graphically represented as a straight line. Linearity is a quantitative assessment of how strongly related a set of data is. Linearity ranges from 0 (not related at all) to 1 (completely related) and gives a useful numerical gauge to be used alongside a numerical plot. The linearity of the fabricated strain sensor is determined either graphically or by calculations.

$$Linearity = \frac{Sxy}{(\sqrt{Sx}) \times (\sqrt{Sy})}$$

Where x is the corresponding x-axis values and y is the corresponding y-axis values. Defining the variables mathematically;

$$Sxy = \Sigma(xy) - \frac{(\Sigma x)(\Sigma y)}{n}$$

Where $\Sigma(xy)$ the summation of multiplying each x-value with its corresponding y-value, Σx the summation of all x-values, Σy the summation of all y-values and n the total number of data pairs in sample data.

$$Sx = \Sigma(x^2) - \frac{(\Sigma x^2)}{n}$$
 And

$$Sy = \Sigma(y^2) - \frac{(\Sigma y^2)}{n}$$

From table 1. Sxy= 0.0003585, \sqrt{Sx} =

0.01414 and $\sqrt{Sy} = 0.02536$, we have

$$Linearity = \frac{0.0003585}{(0.01414) \times (0.02536)}$$

Linearity = 0.999

From the strain-relative resistance curve, the graphical representation and the calculation done shows clearly that the fabricated flexible strain sensor is linear.

Accuracy: it is the ability of a measurement to match the actual value of a quantity being measured and is measured as the ratio of the highest deviation of a value represented by a sensor to the ideal value. The smaller a fraction of the measurement itself the deviation represents, the more likely your measurement is to be accurate, although it is necessary to know the true value to be absolutely confident of this (the closer the result is closer to zero than one, the more accurate the fabricated flexible strain sensor).

Table 2. The mean and deviations deduced from the recorded data during the characterization of the fabricated flexible strain sensor.

	Mean	Deviation
Δ^{R_1}/R_1	0.03305	0.00311
Δ^{R_2}/R_2	0.0365	-0.00034
Δ^{R_3}/R_3	0.03693	-0.00077
$\Delta^{R_4}/_{R_4}$	0.03715	-0.00099
Δ^{R_5}/R_5	0.03715	-0.00099
Average	0.03616	0.00002

$Accuracy = \frac{\Sigma[average deviation]}{no. of measurements}$

 $Accuracy = \frac{0.00002}{5} = 0.000004$

The data collected from the experimental testing of the fabricated flexible strain sensor gives an experimental accuracy of 0.000004 which is very minute and closer to zero. This indicates that the fabricated sample strain sensor is precise and accurate.

Gauge Factor: A fundamental parameter of the strain gauge is its sensitivity to strain, expressed quantitatively as the gauge factor. The gauge factor or strain factor of the fabricated strain sensor is the ratio of relative change in electrical resistance R to the applied mechanical strain ε of the fabricated strain sensor. The gauge factor is the ratio of fractional change in electrical resistance to the fractional change in length (strain).

 $G.F = \frac{relative \ change \ in \ resistance}{strain}$

$$G.F = \frac{0.06944 - 0.02642}{0.03 - 0.01} = 2.15$$

The gauge factor of the fabricated flexible strain sensor when tested under an applied strain of 37.5% is 2.15 which is exceed the standard gauge factor of ionic liquid strain sensors. This clearly shows that the fabricated flexible strain sensor proposed in this report is highly sensitive to large deformations and strains.

Effect of the concentration of aqueous sodium chloride solution on the fabricated flexible strain sensor: Three different aqueous sodium chloride solutions with concentration ratios of 1:2:3 in percentage were prepared representing 2:4:6 grams of sodium chloride mixed with 200 liters of water and used in fabricating three different samples of flexible strain sensors.

$$ASC \% = \frac{W(g)}{V(ml)} \times 100$$

Where ASC is the percentage of aqueous sodium chloride solution, W is the weight of sodium chloride (salt) in grams and V is the volume of water which is always constant (200ml) in milliliters. These three different concentrations of aqueous sodium chloride solutions were used as the sensing element to fabricated three different samples of aqueous sodium chloride solution/elastic natural rubber tube strain sensor of the same length (0.05m) and diameter (0.08m), and tested mechanically.

Table 3- Data for three fabricated samples with different concentrations of sodium chloride solutions.

Strain	0	0.01	0.02	0.03
$\Delta^{R_{1\%}}/R_{1\%}$	0	0.0544	0.079	0.095
$\Delta^{R_{2\%}}/R_{2\%}$	0	0.0574	0.082	0.098
$\Delta^{R_{3\%}}/R_{3\%}$	0	0.0602	0.085	0.101



Fig 7. The strain-change in relative resistance curve shows relation between the strain and the change in relative resistance of three different concentration of fabricated sample strain sensor when mechanically

tested.

 $Gauge Factor (1\%) = \frac{0.095 - 0.0544}{0.03 - 0.01}$ Gauge Factor (1%) = 2.03 $Gauge Factor (2\%) = \frac{0.098 - 0.0574}{0.03 - 0.01}$ Gauge Factor (2%) = 2.03 $Gauge Factor (3\%) = \frac{0.101 - 0.0602}{0.03 - 0.01}$ Gauge Factor (3%) = 2.04

From fig 5 and the calculation of the gauge factor of the three different samples, it was observed that no matter how high the concentration of the sodium chloride solution is, the gauge factor of the fabricated sampled strain sensors still revolved around two, which is the ideal gauge factor and our theoretical path of the fabricated flexible strain sensor. Therefore we can conclude that, the concentration of ionic liquid in an ionic liquid strain sensor doesn't have a major impact on how sensitive the sensor is to external stimuli, which in this case is strain.

Effect of the inner diameter of the elastic natural rubber tube on the fabricated flexible strain sensor: Three different samples of aqueous sodium chloride solution/elastic natural rubber tube strain sensor of inner diameters 0.5mm, 0.8mm and 1mm are fabricated, and tested mechanically. A concentration of 2% and a length of 0.05m is kept constant for all three fabricated samples strain sensor.

Table 4- Data for three fabricated samples with different inner diameters on natural rubber tubes.

Strain	0	0.01	0.02	0.03
$\Delta^{R_{0.5}}/R_{0.5}$	0	0.0148	0.038	0.055
$\Delta^{R_{0.8}}/R_{0.8}$	0	0.0186	0.041	0.059
Δ^{R_1}/R_1	0	0.0206	0.044	0.061





Fig 8. The strain-change in relative resistance curve shows the relation between the strain and the change in relative resistance of three different diameters of fabricated sample strain sensor when mechanically tested.

 $Gauge \ Factor \ (0.5) = \frac{0.055 - 0.0148}{0.03 - 0.01}$ $Gauge \ Factor \ (0.5) = 2.01$ $Gauge \ Factor \ (0.8) = \frac{0.059 - 0.0186}{0.03 - 0.01}$ $Gauge \ Factor \ (0.8) = 2.02$ $Gauge \ Factor \ (1) = \frac{0.061 - 0.0206}{0.03}$ $Gauge \ Factor \ (1) = 2.02$

From fig 6 and the calculation of the various gauge factor of the fabricated samples, it was observed that no matter the size of the inner diameter of the elastic natural rubber tube, the gauge factor of the fabricated sampled strain sensors still revolved around two, which is the ideal gauge factor and theoretical path of fabricated flexible the strain sensor. Therefore we can conclude that, the size of the inner diameter of the material used in the fabrication of an ionic liquid strain sensor doesn't have a major impact on how sensitive the sensor is to external stimuli, which in this case is strain.

Effect of the Length of the Natural Rubber Tube on the Fabricated Strain Sensor: Three different samples of aqueous sodium chloride solution/elastic natural rubber tube strain sensor of lengths 80mm (A), 100mm (B) and 150mm (C) were fabricated and mechanically tested. A concentration of 2% and a diameter of 0.08m is kept constant for all three fabricated samples strain sensor.

Table 5- Data for three fabricated samples with different lengths on natural rubber tubes.

Strain	0	0.01	0.02	0.03
$\Delta^{R_{80}}/R_{80}$	0	0.0251	0.0483	0.067
$\Delta^{R_{100}}/R_{100}$	0	0.0241	0.0462	0.065
$\Delta^{R_{150}}/R_{150}$	0	0.0236	0.0452	0.064





Fig 9. The strain-change in relative resistance curve shows the relation between the strain and the change in relative resistance of three different lengths of fabricated sample strain sensor when tested.

Gauge Factor $(A) = \frac{0.067 - 0.0251}{0.03 - 0.01}$ Gauge Factor (A) = 2.09

Gauge Factor (B) = $\frac{0.065 - 0.0241}{0.03 - 0.01}$ Gauge Factor (B) = 2.04 Gauge Factor (C) = $\frac{0.064 - 0.0236}{0.03 - 0.01}$

Gauge Factor (C) = 2.02

From fig 7 and the calculation of the various gauge factor of the fabricated samples, it was observed that no matter the length of the elastic natural rubber tube, the gauge factor of the fabricated sampled strain sensors still revolved around two, which is the ideal gauge factor and theoretical path of the fabricated flexible strain sensor. Therefore we can conclude that, the length of the material used in the fabrication of an ionic liquid strain sensor doesn't have a major impact on how sensitive the sensor is to external stimuli, which in this case is strain.

<u>Attachment of fabricated strain sensor to</u> <u>targeted systems</u>

The fabricated flexible aqueous sodium chloride solution/elastic natural rubber tube strain sensor holds incredible guarantee for different imaginative applications in fields such as medicine, healthcare, environment, and biology. Taking into account that most wearable systems, healthcare electronics, and laboratory-on-a-chip testing tools can be required to come into contact with arbitrarily curved interfaces, the flexibility of the sensor is essential for improving their interactions with target systems and improving the reliability and stability of the tests. For practical applications and to meet new expectations, this fabricated strain sensor is structured in the quest for exceptionally economical, multifunctional and biocompatible flexible sensors. The fabricated flexible strain sensor can be attached directly to the skin position or to a rubber material or a silk material that will be worn around the skin position under investigation. The possible applications of the fabricated flexible strain sensor are gesture identification, gait detection, expression identification, rehabilitation. phonation and deglutition detection. The fabricated flexible strain sensor can be

attached to the hand, limb, knee, throat, foot, wrist, fingers, toes, waist, neck and elbow.



Fig 10. (a) Fabricated strain sensor successfully adhered to gloves and worn over the fingers *to* be monitored. (*b*) The time-change in the voltage output graph of the strain sensor when attached to the fingers. (*c*) The deformation-change in the resistance curve of the strain sensor when attached to the fingers.



Fig 11. (a) Fabricated strain sensor successfully adhered to a bandage and a cloth and worn over the elbow to monitor the movement and motion of the elbow. (b) The deformation-change in the resistance curve of the strain sensor when attached to the elbow to monitor motion. (c) The timechange in voltage output graph of the strain sensor when attached to the elbow.

Conclusion

A novel of low-cost packaging technology for an ionic liquid-based strain sensor and a large strain sensing technique of using an aqueous sodium chloride solution encapsulated in an elastic natural rubber tube is introduced. The flexible aqueous sodium chloride/elastic natural rubber tube-based strain sensor showed high sensitivity at low strain can withstand large deformations and outstanding linearity at high strains. These unprecedented merits provide precise and reliable detections of subtle vital signals. Mechanical characterization and analysis of the fabricated flexible strain sensor has been conducted and the parabolic strain response is verified. Fig 4-5 clearly shows that the fabricated flexible strain sensor obeys the Hooke's law, the elastic natural rubber tube used in the fabrication of the flexible strain sensor is a Hookean material, the fabricated strain sensor is not a stiffer substance and very responsive to deformation because the fabricated strain sensor has a low ability to resist deformation. the stress-strain relationship is linear and the deformation is elastic in the case of the fabricated flexible strain sensor. Fig 6 show that the experiment conducted is repeatable, the fabricated flexible strain sensor is linear and accurate. The fabricated flexible strain sensor also has a gauge factor of 2.15 at an applied strain of 30%, which is around the theoretical path/standard gauge factor of strain sensors (that's 2). Fig 7-9 clearly show that the concentration of sodium chloride in the

aqueous sodium chloride solution used as the sensing element of the fabricated flexible strain sensor, the inner diameter and length of the elastic natural rubber tube used in the fabrication of the flexible strain sensor has no bearing effect on the sensitivity of the flexible strain sensor to applied strain. Fig 10-11 clearly indicates that the fabricated flexible strain sensor can be easily attached to other materials/applications to monitor strain. This ionic liquid strain sensor (aqueous sodium chloride solution/elastic natural rubber tube) may be very useful in broad applications in electronic skin, biomedical implants, human movement monitors, and so on, due to its various advantages.

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References

- [1] Room W, Hall W. Advanced mechanics of materials [J]. 2012,
- [2] Boresi A P, Schmidt R J, Sidebottom
- O M. Advanced mechanics of materials [M]. Wiley New York et al., 1985.
- [3] Wu H-C. Continuum mechanics and plasticity [M]. Chapman and Hall/CRC,

2004.

[4] Truesdell C, Noll W. The non-linear field theories of mechanics [M]. The non-linear field theories of mechanics. Springer. 2004: 1-579.

[5] Wong R D P, Posner J D, Santos VJ. Flexible microfluidic normal force sensor skin for tactile feedback [J]. Sensors and Actuators A: Physical, 2012, 179(62-9.

- [6] Ilievski F, Mazzeo A D, Shepherd R F, et al. Soft robotics for chemists [J]. Angewandte Chemie International Edition,
- 2011, 50(8): 1890-5. [7] Eringen A C. Mechanics of continua
- [7] Eringen A C. Mechanics of continua [J]. Huntington, NY, Robert E Krieger Publishing Co, 1980 606 p, 1980,
- [8] Daniel I M, Ishai O, Daniel I M, et al. Engineering mechanics of composite
- materials [M]. Oxford university press New York, 1994.
 - [9] Rogers R D, Seddon K R. Ionic
- liquids--solvents of the future? [J]. Science, 2003, 302(5646): 792-3.
- [10] Johnson K E. What's an ionic liquid?
- [J]. Interface-Electrochemical Society, 2007, 16(1): 38-41.
- [11] Rychlewski J. On Hooke's law [J]. Journal of Applied Mathematics and Mechanics, 1984, 48(3): 303-14.

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