Novel Soft Sensor Design in the Detection of Normal and Shear Forces

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***Abstract*—In this study, we design and create a fabricating process for a contemporary piezoresistance force sensor sensitive to normal and shear forces based on previous research on this sensor type. Designs are compared and optimized using analysis tools on 3D modeling software where design decisions before being physically fabricated. The fabrication process employs liquid metal printing where conductive strain gauges of EGaIn are encapsulated in polyurethane to form a force sensor. Experiments with applied loads in normal and shear are then conducted to verify that the sensor is capable of distinguishing between the two forces, resistance changes possess linearity, and analyze properties such as the hysteresis of the sensor. The results show that a sensor based on our fabrication process and design decisions can theoretically create a sensor capable of shear and normal force detection.**

I. Introduction

In the current age of digital technology, where A.I. and robotics are quickly becoming the norm in our society, there is an increasing need for physical robots and machines that are better suited to meet the needs and comforts of human beings. Recently, there has been an increased interest in the use of soft robotics. Soft robotics is the idea of using bendable and deformable materials in the creation of mechanical components, which offer greater ranges of motion and; conformability to a multitude of objects and are less rigid than conventional designs. This new class of robotics has a multitude of applications that extend to surgery, the creation of prostheses, improved robotic grasping [1], and more. In the application of grasping, sensors are needed so the robotic grippers to detect contact forces when grasping objects. Meanwhile, for prostheses, sensors are needed to simulate human sensation. which is vital in the development of human prosthesis [2]. A multitude of sensor types are employed for tactile sensing in robots such as piezoelectric, resistance, capacitance, optical or computer vision, and more.

Our research seeks to ascertain a new soft piezoresistive sensor designs and fabrication process for detecting the magnitude and direction of a given load, including pure shear, pure normal, and combined loads. The soft sensor could then be used in a robotic gripper to monitor contact force during grasping. The fabrication process employed will involve the use of a liquid metal alloy composed of gallium and indium. This material is chosen due to its low melting point and toxicity, aswell as the fact that it is conductive material with the properties of liquid allowing for use in stretchable electronics where traditional conductive traces like copper are much stiffer and less compliant. The liquid metal is then deposited on a substrate to form conductive metal traces which are then encapsulated in a soft elastomer. These conductive traces form a simple circuit that is sensitive to forces that cause resistance change which can be used to derive a corresponding force value. While this sensor is relatively common and thoroughly studied [3], there is more limited literature and research on soft sensor designs that can be used to evaluate the magnitude and direction of normal and shear forces of a given load.

Thus, our main research question is whether a novel soft sensor design can be created based on previous studies to find the magnitude and direction of the shear and normal components of an applied force. Using finite element analysis (FEA), conducted using SOLIDWORKS Simulation, we model and analyze several sensor designs while optimizing geometry for greater equivalent strain which correlates to a higher variability in the resistance values from the sensor. After optimization of the sensor design, the sensor is fabricated and characterized. To determine the relationship between resistance change and applied load, the resistance is monitored while applying known shear, normal, and combined loads. This information can then be used to allow for the sensor to measure a load and resolve the normal and shear components.

II. Background

To begin with, given that our sensor uses conductive paths made from liquid metal, extensive review on the properties and capabilities of the chosen material was conducted. Next, we explore possible sensor designs capable of fulfilling our sensitivity requirements in normal and shear.

A. Liquid Metal Printing

The chosen liquid metal was an alloy consisting of 75% Gallium and 25% Indium by weight. This alloying is important for lowering the melting point of Gallium from 30°C to 15.5°C [4]. Liquid metal in general is used due to our sensor type. Resistance changes on the path are induced by a force that deforms the liquid metal traces, altering the cross section and increasing the resistance [5]. Another property studied is that the metal oxidizes immediately when in contact with air which is an important consideration when using the metal [6]. This oxidation enables the metal to maintain its structure which is useful for patterning but complicates printing since the oxide layer has to yield for deposition via direct printing. Additionally, on most surfaces the liquid metal stayed as a droplet and did not wet enough to form lines or paths, so appropriate substrates had to to be identified. Viable substrates included polymers such as PET, PDMS, and polyurethane. For this study, polyurethane was selected as the substrate material.

Review papers have thoroughly characterized the metal's behavior on surfaces and its behavior is heavily dependent on the surface it is in contact with, the liquid metal has a tendency to form droplets and roll right off of most surfaces [7]. However, papers have shown that the material can have wettability to various polymers [6], enough to form clean enough lines for creating conductive traces in the fabrication of sensors. Furthermore, papers have also shown that the specific parameters that are vital to printing liquid metal include the pressure used to deposit the metal, speed of the print, height above the surface being printed on, and all these variables being heavily dependent on the dimensions of the needle being used to administer the metal like length and tip diameter [4].

B. Sensor Designs

The chosen sensor type given our fabrication process was a piezoresistive sensor that uses strain gauges and senses forces through changes in resistance [4]. Utilizing liquid metal to form the strain gauges instead of traditional more rigid alloys can allow the creation of more stretchable soft sensors. When deciding between sensor designs there were multiple possible considerations that had the potential to meet our goals.

In a study on an artificial hair cell, sensor liquid metal traces were encapsulated in a PDMS (polydimethylsiloxane) substrate and a vertically pointed hair cell shaft which was very effective in 2D force detection in the x and y plane but lacked adequate compressive sensitivity for normal force [8]. Other papers studied a fingertip sensor capable of distinguishing between normal and shear-force components through analysis of mechanical deformations when a load is applied [9], however the full capabilities of the sensor have yet to be explored and studied along with limited data on detecting both the shear and normal force simultaneously as opposed to each individually.

Next, we considered sensors with bump designs and encapsulated liquid metal, which based on the literature appeared to have relatively consistent success with sensitivity in the x, y, and z plane but can distinguish between normal and shear magnitude and direction. In a paper on a 3D force sensor researchers were able to construct a piezoresistive resistive sensor with a bump on the top of four resistors that transfers force to mechanical stress and deformation [10]. Experiments of different applied forces demonstrated the ability to accurately detect them three-dimensionally.

Additionally, piezoresistive resistance sensors with the use of both film carbon nanotubes and PDMS have been used to accurately simulate human skin and discriminate between normal and shear forces in the application of sensor design for human prosthesis. While sensors of this design are ideal they overly-rely on adhesion of the different films [11], an aspect of grasping robots our research focus intends to deviate from due to its physical limitations. Instead, our research opted to fabricate sensors of a single soft elastomer to encapsulate the liquid metal. Papers on novel soft sensor designs for normal and shear detection have used strain gauges that measure forces using voltage drops of applied forces on the gauge transferred via the bump [12], this was a low cost and relatively straightforward design but lacked measures to ensure linearity among changes in resistance if it were to be applied in our study. Researchers were able to solve some of the linearity complications among multiple resistors with the use of a spherical bump to transfer force as opposed to them being cubical shaped [13]. Furthermore, studies have also extrapolated mathematical functions that have shown to derive sensitivity of forces in the x,y, and z plane [14]. Our research builds on previous designs to create a new sensor that more efficiently measures forces three-dimensionally and can distinguish the magnitude and direction of shear and normal forces.

III. Methodology

A. Design Comparison

Based on an extensive review of the literature, two piezoresistance sensors were conceptualized. These sensor designs were chosen based on their ability to maintain linearity within sensor changes and have effective capabilities in sensing shear and normal forces.

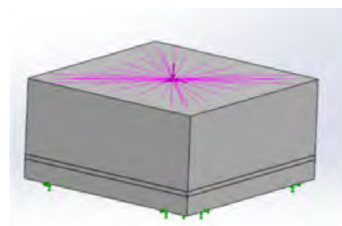

Fig. 1. Applied force constraints and bottom fixture of 3D modeled sensor without bases

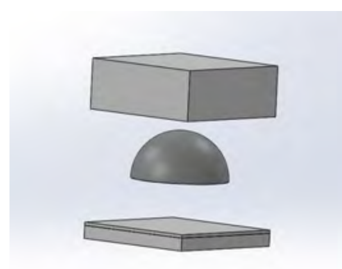

Fig. 2. Exploded view of model without the bases

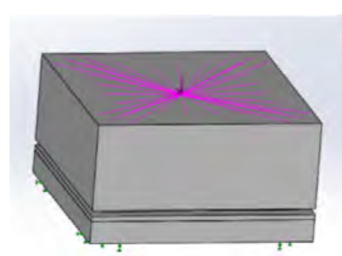

Fig. 3. Applied force constraints and bottom fixture of 3D modeled sensor with bases

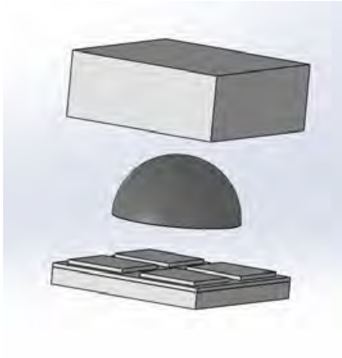

Fig. 4. Exploded view of model with the bases

B. Parametric Study

Through 3D models of sensors on Solidworks, an inputted force of one newton along the top is analyzed to observe the amount of strain in normal and shear directions. The constraints for the top force included a distributed force coupling centered around the center most node to accurately replicate a force being applied uniformly on the top surface. The amount of strain the sensor experiences correlated with higher resistance changes as greater deformation in strains increases measured resistance from a given force. The equivalent strain of the entire surface of where the strains would theoretically be placed have static simulations performed on both sensor designs. Each model used material that simulated with material that had properties comparable to polyurethane for the bottom and top layers and a harder epoxy-based shape memory polymer to form the semi-sphere meant for transferring force over from the top layer to the strain. The design with the highest strain was then chosen based on the analysis results, which was the 4 base design.

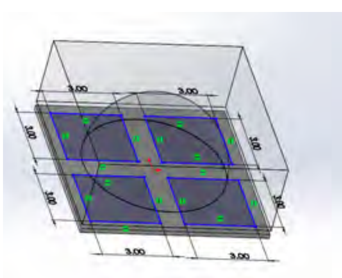

Fig. 5. Dimension view of 3D model of sensor with bases

To improve our design the chosen model was put through a parametric study to observe which parameters when changed would maximize strain experienced by the device. The contact area of the bases in contact with the semi-sphere was altered to be larger or smaller to demonstrate that reducing the area would increase the stress concentration on the base in both shear and normal directions. Using this test as a general guide when physically fabricating the sensor, smaller base sizes underneath the strain gauges should be favored as to receive a higher resistance change when detecting forces.

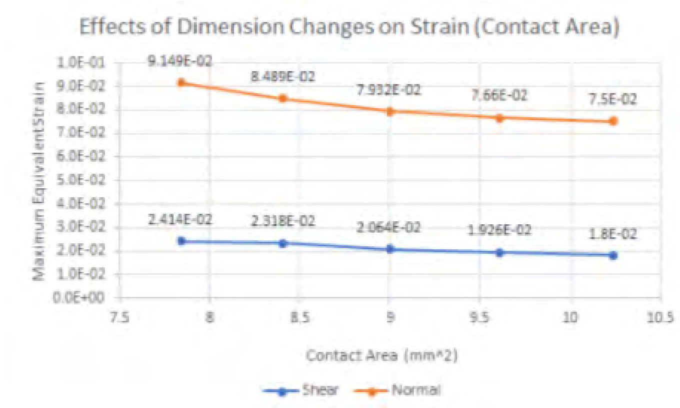

Fig. 6. Parametric study data on the effects on maximum equivalent strain from changing the base areas

Starting at 3mm x 3mm, the contact area was both increased and reduced to observe the trend in maximum equivalent strain over multiple sizes under a one newton force. Maximum strain proved to be higher on bases that had smaller areas.

C. Printing Conductive Trace

The method used to print the metal ink EGaIn was with the use of a 3D printer with the metal being deposited with the use an air pump assisted syringe and needle. Speeds of the print were adjusted through a mechanical bed that moved in the y-direction and the needle holder in the x-direction. Using the air to push out the liquid metal at a specific flowrate was used to match the speed of the needle to form complete and consistently shaped lines along a path. The needle above the substrate had to be adjusted enough above the surface to freely allow the liquid to flow and form a line, yet not too close as to disrupted the flow of liquid metal.

Based on the diameter of the needle tip (0.3112 mm) and employed substrate (polyurethane), the speed of 500 mm/min, pressure of 2.5 psi (17.24 kpa) and was successful in forming consistently straight and well formed lines that could be used to fabricate resistance strain gauges, possessing widths that were roughly 0.5 mm. Parameter adjustments that led to finding these system settings was through the constant adjustment of three variables of air pressure in the syringe, height above the substrate, and speed at which the needle and printing bed moved.

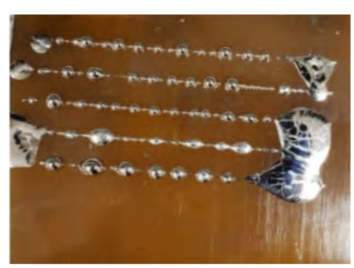

Fig. 7. Printing lines at a height of 0.3 mm above the substrate

At heights too far above the substrate there would not be enough contact for the liquid metal to be dragged and form a consistent line so ranges below 0.3 mm were used. Our method having a favorable printing height of 0.2 mm.

Fig. 8. Printing lines at a height of 0.2 mm above the substrate at increasingly higher pressures from right to left

Observing the pressure changes, higher pressures consistently formed prints with straighter and well formed however the instants of bubbling in the middle of prints were higher due to disruptions in speed not matching with flowrate. Through, these observations and tests, a pressure of 2.5 psi and 500 mm/min was discovered to most consistently form complete lines with less complications and deformities.

D. Possible Physical Fabrication of Sensor Process

Based on our modeled design and the properties of the materials used in our molding procedures, a physical fabrication process for this sensor was devised in this study.

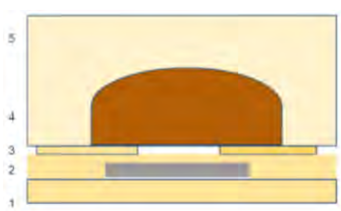

Fig. 9. Illustration of physical fabrication process

Figure 9 illustrates the steps needed to physically fabricate the proposed sensor design. The first step is to mold a base and print four separate strains on top at locations underneath where the 4 bases would be placed, then encapsulate the strain gauges in a another thin layer to preserve the print. Next, a stencil is used to form the four separate bases that are above the locations of the strain gauges. Further, a separate mold is created for the top with in an opening for the semi-sphere, after it has finished curing the harder polymer would then be put inside the semi-sphere opening and the completed base would then be aligned on top to cure together forming the full sensor.

IV. Results

Using our fabrication process and settings, a simple piezoresistance sensor was created to test if a resistor was possible with our method.

Fig. 10. Strain gauge printed at the optimal print settings prior to encapsulation

A print was first made on a polyurethane substrate, the lines were connect to a pieces of copper which is how we test resistance of the lines, and then a an additional layer of polyurethane was than used to encase the print.

Before loading a predicted resistance measurement was calculated based on the dimensions of the printed strain. The gallium-indium mixture for the gauges possessed a resistivity of roughly 0.00024.9 ohm-mm [15], they were 170 mm in length, and possessed a cross-sectional area of roughly the same shape of a semi-circle so based on the diameter of the lines being 0.5 mm the area was calculated to roughly be 0.982 mm^2.

$$R = \rho L/A$$

Using the resistance equation above and the dimensions calculated the unloaded resistance to be 0.43 ohm.

A. Weight Test

Next a series of standard weights were used to test the resistance change response of the simple sensor. A glass slide was put on top of the surface to evenly disperse the weight across of the strain and after a weight was applied on the glass the resistance value was recorded.

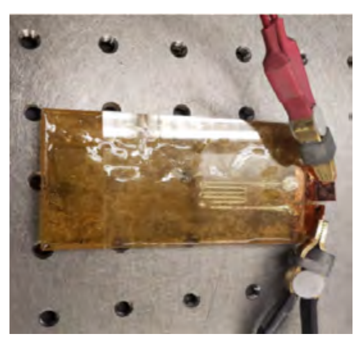

Fig. 11. Encapsulated printed strain gauge before weight and resistance test

TABLE I
WEIGHT TEST RESULTS

Mass (kg)	Resistance (Ohms)
0	0.38
0.1	0.381
0.2	0.3817
0.5	0.3839
1.0	0.473
2.0	0.647

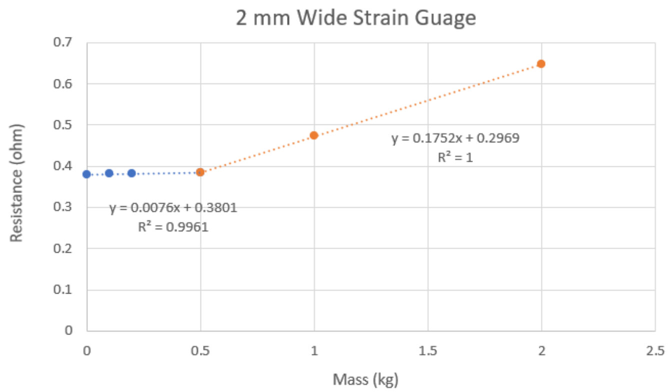

Fig. 12. Graphical representation of results with trend data before and after 0.5 kg

The results of the weight test are indicated in table 1 as seen by the chart in Figure 12 the resistance changes possess linearity which indicates the sensor can theoretically be created using our fabrication process under a specific force range. The jump in amount may seem to indicate exponential growth however looking at the trend line value before and after the jump in resistance value, this indicates the sensor likely only having linearity under a specific force range.

B. Performance of Fabricated Sensor

Using the physical fabrication process detailed the methodology, our sensor was successfully replicated.

Fig. 13. Simplified strain print before encapsulation

As seen in Figure 13 a much simpler strain gauge patterns were employed due to our current printing process lacking reliability in creating more complex strain gauges like the patterns in Figure 10. This strain pattern still proved to be capable of functioning in the exact same manner.

Fig. 14. Fabricated sensor using the procedure

Following the procedure the sensor was able to be completed however the process requires greater refinement. When molding the bases the heights were unequal so when securing the top mold to the bases, contact was not the same. One of the the base was completely unattached due to being so low and one of the bases had a bond that was very unstable. Out of the 4 bases only two of them were securely bonded to the top mold and thus only their resistance measurements were evaluated. Similar to the initial weight test, a glass slide is placed on top of the sensor and as increasing amounts of weight are applied changes in resistance are observed.

TABLE II
WEIGHT TEST ON RESISTANCE BASE 2

Mass (kg)	Resistance (Ohms)
0	0.2586
0.2	0.2606
0.5	0.2621
1.0	0.2635
2.0	0.2675
3.0	0.2685

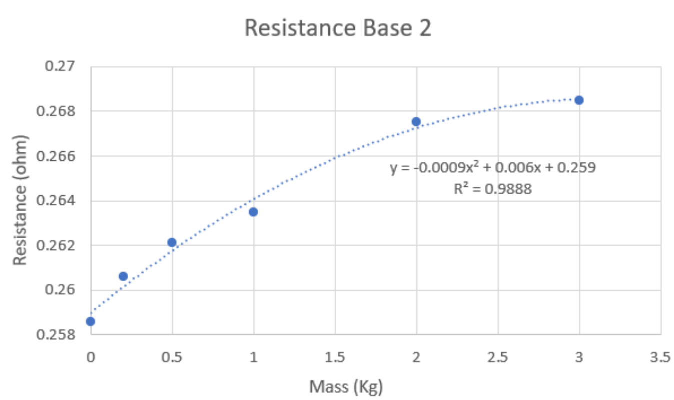

Fig. 15. Graphical results of weight test for the 2nd resistance base

For the second resistance base the change in resistance was not linear and has a line of fit most suitable for a polynomial trend. A linear trend is more ideal in that the resistance values can more reliably and easily be tied to force values.

TABLE III
WEIGHT TEST ON RESISTANCE BASE 4

Mass (kg)	Resistance (Ohms)
0	0.2644
0.5	0.267
1.0	0.272
2.0	0.282
3.0	0.287

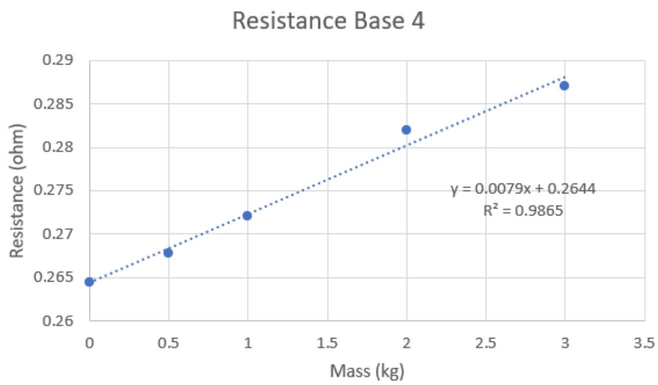

Fig. 16. Graphical results of weight test for the 4th resistance base

The resistance change as shown in Figure 16 possess linearity which is a more ideal trend in the sensor. A linearly increasing sensor indicates more predictably the force associated with the resistance forming a reliable and an accurate sensor.

V. DISCUSSION

A. Hysteresis

When performing weight test for the first encapsulated strain gauge the sensor possessed a notable hysteresis. It was noted that for the weight of 1 kg when initially applied had a resistance value of 0.3947 ohm however only returned to 0.3947 ohm when the weight was removed. For the 2 kg weight a similar effect was observed where the resistance when the weight was applied was 0.647 ohm and the resistance after the weight was removed fell to 0.401 ohm. Given enough time the resistance values eventually fell to its original amount.

While, this implies that the sensor may only be usable in a specific force range due to the fact that the sensor to have repeatable results. This also could be mitigated through the fabrication process. The resistance value of strain changes because of the deformation in the cross-section size, when the force is elevated the strains are intended to return back to its original shape, one of the benefits of using liquid metal was the materials heighten capacity to perform this function.

However, factors like the the encapsulation layer being to excessive may hinder the liquid metal's ability to return to its shape in reasonable amounts of time or defects in the material due to not riding enough air bubbles trapped in the polyurethane before it finished curing. In the full sensor fabrication many of these errors were corrected and the hysteresis was dramatically reduced. Upon removal of weight, the sensor fell from a heighten value to its original resistance value immediately.

B. Discrepancies in Resistance Change Trend

A notable discrepancy in the resistance change among the bases tested is the difference in increase trends as the weights were applied. Since the force applied was intended to to be uniformly normal the increase in resistance should atleast follow the same trend this may be use to the inconsistency in base height which caused small shifts in the force being imparted on the strain gauges. Another reason may be the starting weight of the top mold. Theres is a force limit to the detection of liquid metal sensors in that the cross-sectional change in the strain reaches a plateau so resistance changes taper off after a force is reached as the cross-sectional area of the strain gauges no longer change. This limit might have been reached earlier on base 2 causing an increase in resistance to taper off earlier than in base 4.

C. Challenges and Future Implications of Research

The main causes of continual error and complications within this research was our fabrication method, particularly the liquid metal. The Gallium-Indium mixture was chosen due to a multitude of physical properties such as its ability to conduct electricity, staying a liquid at room temperature, and possessing low toxicity. However, the metal oxidizes quickly once in contact with air and requires extremely refined parameters to form consistent and complete prints. The repeatability of prints was limited with our printing method which largely involved matching speed with the flowrate of the liquid metal. Research in the future may involve the production of sensors with a more reliable printing method and then studying the performance of those sensors.

Additionally, the weight test employed judges the sensor only in the normal direction however when forces are applied in the shear direction noticeable resistance changes are observed. This indicates that the sensor design possess sensitivity in both directions. Further experimentation can be employed to determine if similar properties like hystersis and linearity are shared in both normal and shear.

VI. CONCLUSION

To conclude, our study details a viable sensor design and physical fabrication to create a sensor capable of normal and shear force detection. Based on a review of the literature a sensor design was chosen and modified through CAD software. These sensor designs were analyzed and compared with one another to establish which design had greater potential in force sensing capabilities. Using Gallium-Indium liquid metal piezoresistor sensors were able to be fabricated with a printer setup adjusted for parameters suited for material employed. Based on our printing setup simple encapsulated sensors were able to be fabricated which showed that printing liquid metal into resistance sensor was possible. With these findings in mind this study was capable of developing a viable plan to physically fabricate the sensor design while showing that it was theoretically possible for it to operate satisfactory given simulation data and preliminary builds and experiments. Additionally, further research is required in the full development of this sensor to definitively prove that our fabrication process is viable and that the sensor design and build is effective at sensing normal and shear forces.

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