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Conductive compliant mechanisms: Geometric tuning of 3D printed flexural sensors

Frederik Grønborg, Tiberiu Gabriel Zsurzsan, Anders Egede Daugaard, Jon Spangenberg, David Bue Pedersen

*Department of Civil and Mechanical Engineering, Køppels Allé, Building 404, 2800 Kgs. Lyngby, Denmark
†Bjørn Thorsen A/S, Saltholm Park 1, 2900 Hellerup, Denmark
‡Department of Electrical and Photonics Engineering, Øresteds Plads, Building 343, 2800 Kgs. Lyngby, Denmark
§Department of Chemical and Biochemical Engineering, Saltofs Plads 228A, 2800 Kgs. Lyngby, Denmark

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A B S T R A C T
Additive manufacturing of thermoplastic conductive polymer composites offers interesting opportunities for customizing compliant flexural sensors. The study aimed to show that additive manufacturing could be used to fabricate flexural sensors for evaluating the effect of sensor geometry on the sensor output. Prior literature has primarily focused on material optimization rather than geometrical design. The results of this paper show that the signal amplitude between geometrically different flexural sensors with the same footprint can increase ~28 times. In addition, the bending force is found proportional to the signal amplitude. Thus, concentrating the bending to a small section increases the signal amplitude but also increases the effect of material relaxation broadening the hysteresis loop. This study highlights the importance of considering the geometrical design when fine-tuning additive manufactured flexural sensors. In future work, it is paramount to improve reproducibility, signal linearity, and investigate the effects of geometry on other sensor parameters.

1. Introduction

Additive Manufacturing (AM) has opened a new avenue for sensors, as the fabrication technology offers customization for a given application. This attribute has recently been exploited for applications such as wearables and soft robotics [1–3]. Additively manufactured strain sensors are used to translate physical movement into measurable quantities. The working principle is that the sensing medium under strain changes its electrical impedance [4]. Different AM methods have distinct advantages such as available materials, printing speeds, and precision [5]. Methods like inkjet and aerosol printing have shown promising results for fabricating flexible sensors and electronics [6–8]. Extensive research has been put into optimizing the conductive performance of sensors by material constituent alteration. Still, there is little knowledge of the fundamental aspects of the effect of sensor geometry on the sensor output.

Conductive Polymer Composites (CPCs) are an attractive material choice for sensors with large strain sensing capabilities [1]. The possibility of processing CPCs via AM and conventional processing equipment, like extrusion, injection molding, or fiber spinning [2], makes them ideal for incorporation into many products and applications. This enables smart production strategies to prepare both parts seamlessly [9]. Thermoplastic CPCs can be fabricated into filaments and used for Material Extrusion Additive Manufacturing (MEX), also known as Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF) [10]. In this process, the filament is guided into the print head, where it is plasticized and extruded out through the hot-end as a thin strand [11]. The material is selectively deposited into 2D slices that conclusively form the 3D objective [12]. MEX has been used to produce CPC sensors for a broad range of applications, such as a multiaxial force sensor [13], a bending sensor for finger movement [14], a sensorized pneumatic actuator [15,16], a soft prosthetic hand [17], and a void fraction sensor of two-phase flow [18]. Still, all have simple structures that do not explore the influence of geometry on the sensor.

The strain sensing ability of CPCs originates from changing the conductive pathways in the polymer composite. By imposing external stress on the CPCs, the percolated network will be strained or reformed [19] and the electrical response will depend on the type of conductor in the net [20,21]. The CNTs are relatively long and can, therefore, at low loading, form a conductive network. Compounds based on well-dispersed CNTs are typically appropriate for high strain applications due to the entanglement of the long CNTs. Conductive Carbon Black (CCB) is another material that has been used to produce CPC sensors [22–25]. CCB consists of agglomerates of spherical particles held together by weak interactions that are easily affected by strain [25],

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which makes CCB ideal for low strain applications. Most prior literature, rightfuely, focuses on evaluating their materials in pure strain. The results from pure strain are easy to evaluate and compare, but realisticmly many applications of flexural sensors will be a mixture of tensile and compressive strains experienced during bending. For CCB networks the resistance increases when the particles move further apart. In pure strain, this is easy to understand, but it is harder to grasp for the combination of compressive and tensile strains occurring in beam bending.

Considerable research has been done to optimize sensor materials and mimic conventional serpentine strain sensor measuring grids using AM, yet only one prior work [26] has been found to deviate from the conventional measuring grids. To evaluate the effect of sensor geometry, three sensors with different-sized deforming measuring areas are manufactured and evaluated. The study aims to show how the geometry of flexural sensors can be optimized in the design phase. The three sensors were compared on a purpose build experimental test equipment that allows for cyclic loading of the sensors whilst measuring the resistance of the sensors.

2. Methodology

2.1. Filament fabrication

The conductive filament was produced via a two-step process (as seen in Fig. 1) to ensure good dispersion and a stable filament. The filament was a 50/50 wt% blend containing Cabot Cabelec CC6057 conductive concentrate (Density: 1130 kg/m3, Conductive Carbon Black content: 40%, Melt Flow Index: 1 g/10 min at 230 °C & 5 kg) and SABIC PP 579S (Density: 905 kg/m3, Rockwell Hardness, R-Scale: 104, Melt Flow Index: 47 g/10 min at 230 °C & 2.16 kg). The blend was compounded on a Thermo Fischer Eurolab 16, twin-screw extruder with a set of co-rotating parallel screws containing four kneading zones. All materials were pre-dried and fed in the first barrel segment. The blend was compounded with a 1.5 kg/h output rate and a temperature profile as seen in Fig. 1. The compounding process was allowed to stabilize and run-in extrude was discarded. After run-in, the extrude was cooled in a water bath and pelletized. In process 2, the pelletized extrude was dried for 4 h at 80 °C in a forced convection dryer before filament extrusion on a Haake Polylab single screw extruder with a temperature profile from the nozzle of 230–215–200–180 °C. This was done since a more stable extrude can be achieved on a single screw extruder. The extrusion process was allowed to stabilize before producing the filament and the run-in material was discarded. The filament was water-cooled and had a diameter of 1.70 ± 0.05 mm.

2.2. Design and manufacturing of flexural sensors

Three sensor designs (see Fig. 2) were manufactured by MEX. The designs were inspired by compliant mechanisms and were meant to illustrate the function of a flexural joint rather than the serpentine design seen for traditional strain sensors. The Simple Flex design (i.e., the simple cantilever beam) functions as a reference design. Extended Flex and Short Flex were designed to bend around a fixed point with a greater or smaller bending area, respectively. The hypothesis was that concentrating the bending to a smaller area would increase the strain on the conductive network and thereby increasing the signal amplitude. All three sensor designs were manufactured in sets of three.

The MEX machine was equipped with a direct drive extruder, a heated build plate, and an enclosed build volume. Along with the heated bed and enclosure, multiple precautions were taken to reduce the warpage of the printed parts. Table 1 summarizes the main process parameters. The filament was stored in a sealed container with a desiccant drying medium and guided through a Teflon tube from the container to the material extruder inside the build chamber. Post-processing of the printed parts consisted of cautiously removing the brim.
Fig. 2. Sensor design and dimensions.

Fig. 3. SEM images of (a) the cryo-fractured cross-section of the filament and (b) the cross-section of the MEX-produced sensor.

Fig. 4. Impedance spectroscopy of the filament.

Table 1
<table>
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<tr>
<th>FDM process parameters</th>
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<tr>
<td>Nozzle diameter</td>
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<td>Nozzle temperature</td>
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<tr>
<td>Build plate temperature</td>
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<td>Layer height</td>
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2.3. Characterisation

The bending characterization of the sensors was carried out on purpose-built test equipment (see Fig. 5). This apparatus was configured to bend the sensors between 0 and 54.9° for 100 cycles and log the resistance in 0.9° increments. Two test runs were performed on each sample. The first test run showed a signal drift for the first 80 cycles before reaching a plateau and was therefore discarded. The drift is expected to stem from resistive heating as it is common in CPCs [27,28]. The second test run showed stable results and was used for the subsequent analysis. To improve contact between the sample sensors and the testing apparatus copper tape was added to the contact on the sample sensors. The sensors were mounted in POM vice grips with two copper contact pads aligned to the flanges of the sensors. The soft POM vice grips with copper strips conformed to the uneven surface of the sensors to reduce contact resistance. The three sets of sensors of each design
were tested for reproducibility. The background noise was digitally filtered using a Savitzky-Golay filter with a 9-point window length, as demonstrated for similar materials by Atitallah et al. [29].

A Zeiss- EVO MA10 Scanning Electron Microscope (SEM) was used for characterization of the conductive network microstructure. The filament was cryo-fractured, and the manufactured sensor specimen was cryo-microtomed before microscopy.

Impedance spectroscopy was performed using an Agilent 4924A Precision Impedance Analyzer in voltage excitation mode, at 0.5 V amplitude. The frequency was swept between 40 Hz and 110 MHz. The filament was cut into samples of 10 cm in length, and three different samples were measured.

3. Results and discussion

3.1. Filament characterisation

From the cryo-fractured surface of the filament, the structure of the conductive network can be seen as shown in Fig. 3a. The CCB is the lighter particles. In Fig. 3b, the conductive network can be recognized in the cross-section of the manufactured sensor. The network does not show any significant alignment post fabrication of the sensor.

From an electrical standpoint, impedance spectroscopy was used to investigate the behavior of the fabricated filament. This method measures changes in material electrical impedance and its related phase through a frequency-swept sinusoidal excitation signal and its resulting current response. The resulting impedance magnitude and phase are shown in Fig. 4, with all three samples having identical responses. The response characteristic is exceptionally flat, meaning that the filament behaves electrically like an ideal resistor throughout the whole measured spectrum. At frequencies above 15 MHz, the increase in impedance magnitude and its associated phase increase are the results of measurement wire inductance, which starts to dominate. The volume resistivity is calculated using:

\[ \rho = \frac{R \cdot \pi r^2}{l} \]

where \( R \) is the bulk resistance of the sample, \( l \) is its length and \( r \) is the filament radius. The resulting volume resistivity is 8 \( \Omega \cdot \text{cm} \).

3.2. Manufacturing and sensor characterisation

All three sensors were produced using the same slicing settings and three of each sensor were produced. The sensors are meant to function as flexural joints and to work as integrated buttons, limit switch, or rough position sensor. Thus, the purpose of the investigation was not to make the optimal design, but to investigate the possibilities for using sensor geometry to control the sensor output. A better understanding of the relationship between sensor geometry and output will open new possibilities to integrate sensors into flexural joints in compliant mechanisms.
The physical bending behavior of each sensor type is seen in Fig. 5. The three sensors have different lengths of bending sections but are designed within the same footprint and thus the difference is the concentration of deformation. In Fig. 6, the characteristic signal is seen for the three designs, and the apparent difference between the three sensor designs is easily observed in the signal. The average relative change in resistance at the maximum bending angle for the three designs is 0.77%, 0.16%, and 4.30% for Simple, Extended, and Short Flex sensors, respectively. Consequently, the Simple Flex response is 4.9 times higher than that of Extended Flex and Short Flex is 5.6 times higher than Simple flex and 27.7 times higher than Extended Flex. Even though they consist of the same material and undergo the same amount of bending, they have vastly different output amplitudes. This can be regarded as a mechanical amplification when the strain is concentrated in a small section. The three sensors are designed such that Extended Flex has strain over a much greater area than Simple Flex and Short Flex has a more concentrated strain in a small area. The result of concentrating the bend over a smaller length is an increase in the signal amplitude.

The forces during beam bending consist of compression and tensile strain under and above the neutral axis, respectively. In the compression zone of the beam there would be new conductive pathways forming in the conductive network with a resulting decrease in resistance. On the contrary, in tensile zone the conductive pathways would be broken leading to higher resistance. For Short Flex, the tensile strain from bending seems to be the governing effect on the conductive network through a full bending cycle (0°–54.9°–0°), as only a small initial decrease in resistance is observed. Simple Flex both has a decrease and increase in resistance for half a bending cycle (0°–54.9°). The initial decrease in resistance could mean that the signal is governed by the compression in the beam. Thus, creating more conductive pathways in the sensor. After an initial decrease in resistance for the first 20–25°, the Simple Flex shows an increase in the resistance indicating that the tensile strain and breakage of conductive pathways now is the governing effect. The same behavior is then seen in the unbending from 54.9°–0° where the strain lessens, and the signal follows the same trend backward. This behavior is not clearly observed for the Extended Flex. Another mechanism that should be mentioned as it can potentially affect the signal output is the layered structure (cf. Fig. 7) of the additively manufactured sensors. These layers can decrease the resistance of the sensor during bending by the collapse of voids. The fusing of the layers is a result of the MEX process and could be controlled through printing-speed and -temperature

Fig. 7. Image of the sensor cross-section showing the unfused layers. The arrows highlight two of the voids that could collapse during bending.

Fig. 8. Hysteresis loops for the three designs and comparing each of the reproduced sensors.
to exaggerate this behavior by introducing more unfused areas giving more ways to tailor the sensor signal.

For every sensor, a hysteresis loop of relative resistance versus bending angle was plotted, based on the averaged value of 100 test cycles, as shown in Fig. 8. It is seen that for the Simple Flex and Short Flex sensors there is a noticeable effect of recovery during the unbending of the sensors. The delayed response to the signal broadens the hysteresis loop and is an important factor to consider for any application. The Extended Flex sensor shows a small response that is almost linear. Less strain on the polymer means faster recovery and less hysteresis. Extended Flex is a useful design for signal transmission or low power transmission. From Fig. 8 the reproducibility of the signal can be seen for each sensor. The reproduced signals from each sensor are recognizable for each batch. The difference in signal shape is attributed to production inconsistency.

For the Simple Flex sensor, the length of the sensing part is 40 mm, which is the length between the fixture points. Thus, this sensor must deflect 57 mm when bent to an angle of 54.9°. The two other sensors have a geometry that gives the Extended Flex sensors a bending section length of 77 mm and 8 mm for the Short Flex sensor giving deflections of 110 mm and 11 mm, respectively. The force needed to bend a cantilever with an end load, can be calculated from the deflection equation:

\[ F = \frac{3EI_{\text{max}}E}{L^3} \] (2)

Where \( F \) is the force, \( I \) is the moment of inertia, \( \delta_{\text{max}} \) is the max deflections, \( E \) is the modulus of elasticity, and \( L \) is the length. From this, it is seen that the force needed to bend the Extended flex sensor is only about one-quarter of the force needed to bend the Simple Flex. On the other hand, it requires 25 times the force to bend the Short flex sensor compared to Simple Flex. Interestingly, the calculated bending forces have approximately the same proportions as the relative change in resistance discussed earlier. It could indicate that the calculated forces in beam bending could be used to approximate the signal amplitude of compliant flexural sensor segments. This is very useful when designing more complex sensor geometries and especially when combined with multi material fabrication.

From the results it is seen that it is indeed possible to maximize the signal amplitude of the sensors without changing the size of the sensor “footprint”. This knowledge is useful for designing integrated sensors for rough positioning and binary on/off functions. In multi-material AM designs the findings can be used optimize the deforming joints in integrated buttons to improve the signal for a given space.

4. Conclusion

It was demonstrated that the flexural sensor response is highly linked to the length of the bending sections. Three compliant flexural sensors based on simple cantilever beam bending provided three different signal amplitudes that were proportional to the calculated forces needed to bend them. Interestingly, even though all three designs were bent to the same degree they show vastly different signal outputs. The Short Flex sensor was 5.6 times higher than Simple flex and 27.7 times higher than Extended Flex. The Simple Flex design showed both a decrease and increase in resistance from 0° to 54.9°, whereas Short Flex mostly shows an increase in the same range. This behavior indicates that the sensor signal is governed differently by the internal compressive- and tensile- strains depending on how concentrated the bending is. Concentrating the bending in a small section (Short Flex) increases the signal amplitude, while distributing the bending over a larger section (Extended Flex) decreases the signal amplitude. The hysteresis loops showed that with higher forces exerted in the bending area (Short Flex) the effects from material recovery increase and broaden the hysteresis loop. The MEX process enables rapid evaluation of sensor design, and it was shown that the signal was reproducible for each sensor. The relative proportion between the flexural sensors signal amplitude could be estimated by how the force needed to bend the sensors. Understanding and predicting how these geometries might influence the sensor performance helps to create application-specific sensor designs.

The designs presented in this study are not optimal geometries, but rather a demonstration of how sensor geometry can be actively used in designing the sensor output. This gives new opportunities to combine and implement sensors into compliant mechanisms. It is also a demonstration of using MEX to rapidly evaluate these geometries in the development of flexural sensors. Improving sensor reproduction and linearity of the signal output are important aspects of the future work. Improvement could be made through investigating the effects stemming from the MEX process on other performance parameters such as response and recovery time. Simultaneously comparing the experimental results to theoretical results for better implementation in compliant mechanisms through simulations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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