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A 3D-printed stretchable strain sensor for wind sensing

Mohammed Al-Rubaiai^{1,4}, Ryohei Tsuruta², Umesh Gandhi², Chuan Wang³, and Xiaobo Tan¹

¹ Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824, United States of America

² Toyota Motor North America, Ann Arbor, MI 48105, United States of America

³ Department of Electrical and Systems Engineering, Washington University in St. Louis, St. Louis, MO 63130, United States of America

E-mail: alrubaia@msu.edu, ryohei.tsuruta@toyota.com, umesh.gandhi@toyota.com, chuanwang@wustl. edu and xbtan@egr.msu.edu

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Abstract

Stretchable strain sensors with large strain range, high sensitivity, and excellent reliability are of great interest to applications in soft robotics, wearable devices, and structure-monitoring systems. Unlike conventional template lithography-based approaches, 3D-printing can be used to fabricate complex devices in a simple and cost-effective manner. In this paper, we report 3Dprinted stretchable strain sensors that embed a flexible conductive composite material in a hyperelastic substrate. Three commercially available conductive filaments are explored, among which the ETPU from Rubber3D Printing, Sweden, shows the highest sensitivity (gauge factor of 20), with a working strain range of 0%-12.5%. The ETPU strain sensor exhibits an interesting behavior where the conductivity increases with the strain. In addition, the resistance change of the ETPU sensor in a doubly-clamped configuration in response to a wind stimulus is characterized, and the sensor shows sensitivity to wind velocity beyond 3.5 m s^{-1} . The experimentally identified material parameters are used in finite-element modeling and simulation to investigate the behavior of the 3D-printed stretchable strain sensor when subjected to wind loading. In particular, the model-predicted sensor output at different wind speeds, obtained with the computed sensor strain and the experimentally characterized strain-resistance relationship, achieves good match with the experimental data.

Keywords: 3D-printing, strain gauge, flow sensing, finite-element modeling

(Some figures may appear in colour only in the online journal)

1. Introduction

Wind velocity measurement is essential for many applications, such as flight dynamics, wind turbine operation, meteorology, sailing, and farming [1–3]. For instance, it is a major factor in determining the drying rate [4], spreading of pollens [5], dispersal of pathogens [6], designing air-conditioning strategies for buildings [7], and operating wind turbines [8, 9]. Several types of commercial wind velocity measuring devices, also known as anemometers, are available with different working principles.

⁴ Author to whom any correspondence should be addressed.

Vane and cup anemometers [10] are mechanical rotating devices usually mounted on a DC-generator, which converts the wind velocity to an electric current signal. They are widely used at meteorological stations and airports due to their robustness; their main drawbacks are mechanical wear, producing performance degradation, and the presence of a sensing threshold due to bearings friction [11, 12]. An alternative class of devices are acoustic anemometers, where the measurement of wind velocity is based on the time of flight of sonic pulses between pairs of transducers. Compared to mechanical anemometers, they are faster, practically immune to wear, and measurements from pairs of transducers can be combined to capture the velocity in



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3-dimensional flows [13]. However, they are usually big and expensive, which limits their widespread use.

Pressure anemometers are based on the measurement of air pressure, which is proportional to the square of wind speed. They are divided into plate and tube anemometers. The pressure plate is the oldest; it consists of a flat plate suspended from the top so that the wind deflects the plate. The pressure tube, also called Pitot tube, can provide accurate wind speed measurement; however, the tube is susceptible to blockage by the water droplets and ice crystals [14]. Another class of wind velocity sensors is thermally based, where a heated element is exposed to the wind and the quantity of the air velocity is determined by the gross heat loss. One major example is the hot-wire anemometer, which consists of a stretched wire, usually made of tungsten or platinum, placed in the flow and heated with a current. As the electrical resistance of the wire is dependent upon the temperature, a relationship between the resistance of the wire and the flow velocity can be established [15, 16]. Due to the absence of moving parts, thermal anemometers are less prone to wear than mechanical sensors. However, the wire is fragile and consumes an electric power (from 10 to 40 mA to operate) [17].

From the discussions above, there is a need for low-cost, low-complexity, and robust wind sensors. In this work, we explore 3D-printed soft strain sensors for achieving this purpose. Soft strain sensors have received much attention in recent years, with applications in infrastructural and health monitoring, wearable electronics, and soft robotics [18-20]. A popular approach to create flexible and highly stretchable strain sensors is to mix conductive additives with soft silicone rubber materials [21]. Generally, materials with large elongation and good flexibility, including thermoplastic polyurethane (TPU) [22, 23], rubber [24, 25], ecoflex [26, 27], and poly(dimethylsiloxane) (PDMS) [28, 29], are widely selected as a substrate for the fabrication of strain sensors with a wide strain range. Concurrently, electrically conductive fillers, such as carbon nanotubes [30, 31], intrinsically conductive polymers [32, 33], and nanometals [34, 35] are often used in the composites to provide the electrically conductive property. Many methodologies, such as planar-printing, lithography, coating, and lamination techniques, can be used to create soft strain sensors, but they are often limited by factors such as high cost, limited extensibility, poor durability and lack of scalability.

In this paper, we propose using a material extrusion-based 3D printing technique with a dual-extruder configuration for fabricating soft wind sensors directly with a bottom-up approach, which is expected to be lightweight and low-cost. In particular, the soft strain sensors are printed through dual-extrusion, one for the conductive sensing element and the other for a hyper-elastic substrate. This technique does not involve any core to define and mold the geometry, and it facilitates rapid customization of the sensor geometry by adjusting the printing parameters in the 3D printing software. Comparing to more advanced multi-material 3D-printers (such as the Connex series of Objet), material extrusion-based printers are much more affordable, with a larger array of material choices. Three different commercially available conductive filaments, Conductive Graphene PLA from Graphene 3D Lab, USA,



Figure 1. Schematic diagram of dual-extruder 3D-printer.

Conductive PLA from Proto-Pasta, USA, and ETPU from Rubber3D Printing, Sweden, are used to fabricate stretchable strain sensors, which are subsequently characterized for extensibility and strain-sensing performance. These strain sensors show different limits in strain measurement from 6% to 25% with gauge factors (GFs) ranging from 0.2 to 20. And the sensor with the highest sensitivity, made from a conductive thermoplastic polyurethane ETPU, is used to in a doublyclamped configuration, to characterize the sensor output (resistance change) as the wind speed is varied in a wind tunnel. Finite element method (FEM)-based modeling is further conducted on the wind sensor to compute the sensor strain distribution under different wind speeds, where experimentally characterized material stiffness values are used. Along with the characterized resistance-strain relationship, the modeling is shown to be capable of predicting the measured sensor output. This work thus shows the feasibility and promise of the proposed soft strain sensors for wind sensing.

Part of this work, in its preliminary form, was presented at the ASME 2018 Conference on Smart Materials, Adaptive Structures, and Intelligent Systems [36]. This manuscript represents significant improvement and extension over [36]. New results in this paper include characterization of mechanical properties (Young's moduli) for all printed materials, more thorough experiments on sensor characterization, FEM modeling and simulation, and experimental validation of the model. In addition, the presentation has been improved throughout the paper.

The remainder of the paper is organized as follows. The characterization of material properties and the procedure of 3D-printing the sensors are first presented in section 2. Then the characterization of strain-sensing behaviors is discussed in section 3. FEM modeling and simulation results are described in section 4, followed by experimental characterization and model validation of wind-sensing for the ETPU strain sensor

Table 1. Filaments used for sensor fabrication.					
Filament name	Company	Volume resistivity (Ohm cm)	Tensile strength (MPa)		
Conductive graphene PLA	Graphene 3D lab	0.6 [39]	2350		
Conductive PLA	Proto-Pasta	15 [40, 41]	1000		
ETPU	Rubber 3D printing	800 [42]	47.6		
X60	Diabase	∞	5.885		



Figure 2. 3D-printed wind sensors with different shapes.

in section 5. Finally, concluding remarks are provided and future work are discussed in section 6.

2. Material characterization and sensor fabrication

The sensors are fabricated with a low-cost, desktop 3D-printer (QIDI TECH I, QIDI TECHNOLOGY, China) with a customized dual-extruder setup. The use of dual extruders enables the integration of two different materials. The printer has a nozzle diameter of 0.4 mm and a layer resolution of 0.1 mm, figure 1 shows a schematic diagram of dual-extruder 3D-printer. The software SIMPLIFY3D 4.1 is utilized for controlling the 3D-printer and adjusting the printing parameters. Detailed settings for the 3D-printing are provided in the appendix (table A1).

Three types of electrically conductive filaments (conductive graphene PLA, conductive PLA, and ETPU) and one stretchable filament (X60 from Diabase, USA) were first mechanically characterized before fabricating the sensors. Additional information of each filament is listed in table 1. The resistivity value of each conductive material is provided by the manufacturer. And as shown in this work, the resistance of each shows strong dependence on the strain. The stiffness of each material is measured using a tensile testing machine (model



Figure 3. Experimentally characterized curve for the (a) conductive graphene PLA, (b) conductive PLA, (c) ETPU, and (d) X60 filament.

SFM–20, United Testing Systems Inc., USA) at 25 °C. The specimen geometries followed specifications outlined in ASTM D412–15a [37] for the X60 filament and ASTM D–638 [38] for the three conductive filaments. All samples were printed



Figure 4. Experimental setup for characterizing the change of resistance with the mechanical strain applied by the linear slider. (a) Schematic, (b) actual setup.

with a thickness of 2 mm. The tension specimens were tested in batches of five for each material, and the values of Young's modulus were averaged over the five trials. The Young's modulus was calculated from the stress-strain ratio below the proportional limit of the material. Figures 3(a)-(d) shows the stress-strain graphs for all materials, and one can see that the ETPU has the lowest modulus among the conductive materials, and the X60 filament shows a typical hyper-elastic curve, which makes it a good candidate as a substrate to the sensors. Note that each material was subjected to a different range of strains, as determined by the stretchability of the corresponding material. Both ETPU and X60 have excellent stretchability (over 200% and 500%, respectively), while conductive graphene PLA and conductive PLA show much less stretchability. Table 1, lists the measured Young's modulus for each material.

In this work we explore a basic design where the conductive sensing element is printed on top of the ultra-flexible substrate. One could also consider using the substrate to completely encapsulate the sensing element. Figure 2 shows the dimensions of the sensors, with 0.5 and 0.25 mm being the thicknesses for the hyper-elastic and the conductive filaments, respectively. Since conductive graphene PLA and conductive PLA are relatively stiff, both a straight line design and a serpentine design are investigated. The serpentine design allows the sensor to be stretched more before breaking, but its sensitivity will be lower [43]. During the tests, we 3Dprinted both designs for each one of the conductive filaments, but it turns out that the Conductive Graphene PLA and Conductive PLA-based sensors in the straight line configuration would peel off the X60 substrate under the smallest deformation we could apply, so for these materials, only the results for the serpentine design are presented.



Figure 5. Normalized resistance change for the (a) conductive graphene PLA sensor (serpentine), (b) conductive PLA sensor (serpentine), (c) ETPU sensor (serpentine), (d) ETPU sensor (linear) during five stretching/releasing cycles.

3. Characterization of strain-sensing behavior

The proposed approach uses the change of resistance in response to tension to measure the wind velocity. Therefore, it is important to characterize the strain-sensing performance of the printed sensors. Figure 4 shows the experimental setup for this purpose. The setup consists of two clamps, one fixed and the other mounted on a linear guide slider, the position of which can be adjusted via a stepper motor. The control of the movement of the slider during the experiments and the data acquisition were coordinated with a microcontroller (model number A000073, Arduino). Each sensor is mounted with the



Figure 6. Stretching/releasing cycle tests of change in resistance with 4% applied strains for the (a) conductive graphene PLA sensor (serpentine), (b) conductive PLA sensor (serpentine), (c) ETPU sensor (serpentine), (d) ETPU sensor (linear).

two clamps and its resistance is measured with via a voltage divider circuit as the sensor is stretched with the slider. During the experiments, the maximum strain applied before the sensor is mechanically broken, is 4% for the Conductive Graphene PLA and Conductive PLA-based sensors in the serpentine configuration, 25% for the ETPU-based sensor in the serpentine configuration, and 12.5% for the ETPU-based sensor in the linear configuration and the stretching speed for all the experiments is 0.33 mm s^{-1} .

The resistance change ratio $\Delta R/R_0$, where R_0 is the initial electrical resistance and ΔR is the change in electrical resistance, is measured as a function of quasi-static uniaxial strain. For each sensor, the normalized resistance change



Figure 7. GF value for the linear, low-strain range (<2%) for the (a) conductive graphene PLA sensor (serpentine), (b) conductive PLA sensor (serpentine), (c) ETPU sensor (serpentine), (d) ETPU sensor (linear).



Figure 8. FEM simulation setup for the 3D-printed sensor.

shows slight hysteresis with respect to the strain, as shown in figures 5(a)-(d). In each case, the resistance change versus the strain demonstrates an approximately linear relationship for low strain values, and then transitions to a saturated relationship as the strain gets higher. To characterize the cyclic stability of the strain sensors, the 3D-printed sensors are tested by measuring the resistance under repeated cycles of stretching/releasing as shown in figures 6(a)-(d). To compare the performance among all the sensors, a maximum strain of 4% is applied during each stretching/releasing cycle. The conductive graphene PLA and conductive PLA-based sensors show unstable behavior, where the value of the resistance change ratio keeps decreasing throughout the cycles strain test. While the ETPU-based sensors exhibit some transient behavior, the responses are largely stabilized after the first 600 cycles. Therefore, a preconditioning step can be implemented in sensor fabrication, during which cycles of stretching-releasing are applied, such that subsequent measurements will be reproducible. Table 2 shows the initial electrical resistance R_0 for each 3D-printed sensor.

To characterize the sensitivity of the 3D-printed sensors at different strains, the GF values are calculated using the



Figure 9. Isometric view of the wind velocity profile around the 3D-printed sensor.

Table 2. 3D-printed sensors initial electrical resistance.

#	Sensor	$R_0 \; (k\Omega)$
1	Conductive graphene PLA sensor (serpentine)	2.62
2	Conductive PLA sensor (serpentine)	27.13
3	ETPU sensor (serpentine)	4884.43
4	ETPU sensor (linear)	4761.24

following equation for each cycle:

$$\mathrm{GF} = \frac{\frac{\Delta R}{R}}{\epsilon},\tag{1}$$

where ϵ denotes the strain. The GF values of the 3D-printed sensors at different strains are plotted in figure 7. The GF of each sensor is computed based on the average of the slopes of the normalized resistance change versus the strain when the sensor is stretched and released, respectively (figure 5), for the linear, low-strain range (<2%). The ETPU-based sensor in the linear configuration shows the highest sensitivity (GF of 20) to strain, which makes it a good candidate for the proposed wind sensor. The GF for metallic foils are typically between 2 and 5 [44], which indicates the competitiveness of the 3D-printed strain sensors with respect to their metallic counterparts.

During the tests, conductive graphene PLA and conductive PLA-based sensors show an increase of resistance when the strain increases, but the ETPU-based sensors demonstrate an opposite trend. This is a non-trivial material response, and similar behavior was reported for the stretchable sensor fabricated by Xie *et al* [45]. In their work, the origin of this behavior derives from the nanoscale micro-structural rearrangements under the stretching deformation. Similar experiments are needed for the ETPU-based sensors to investigate the origin of the decrease of resistance with an applied strain.

4. Finite element modeling and simulation

In this section, we use the characterized material properties to create an FEM model of a 3D-printed wind sensor, and examine its deformation response when subjected to air flow, which will be further validated with experimental measurement. The Ansys software is used for implementation of the fluid structure interaction (FSI) setup, which couples the Ansys fluid flow module (Fluent) and the Ansys static structural module. This setup allows both solvers to run simultaneously, exchanging data when needed without outputting intermediate results. Figure 8 shows the FEM simulation setup, where the sensor is fixed from both ends and the wind load is applied perpendicularly on the sensor.

In the simulation a wind velocity range $(1-15) \text{ m s}^{-1}$ is considered and the calculated force at the fluid-structure interface is transferred to the mechanical model and applied as load. Figure 9 shows the wind velocity profile in isometric view when an air flow of 15 m s^{-1} is applied to the 3Dprinted sensor. The wind inlet is from the x-y plane marked with dashed lines. The elastic strain profile on the conductive



Figure 10. Strain distribution on the 3D-printed sensing layer at 15 m s^{-1} wind speed.



Figure 11. FEM simulation of the strain distribution on the 3Dprinted sensing layer as the wind speed increases.

layer of the sensor at 15 m s^{-1} wind velocity is shown in figure 10, which indicates that the maximum strain value is in the center of the sensor body. The deformation of the sensor will change when the wind velocity increases or decreases. For example, figure 11 shows the simulated elastic strain profile for different wind velocity values (15, 10, 5 m s^{-1}). From the figure, one can see that the deformation will decrease significantly when the wind velocity drops.

5. Experimental characterization and model validation of wind-sensing performance

A wind tunnel (X–Stream, Pitsco) is used in experimentally characterizing the response of the 3D-printed ETPU strain sensor under different wind speeds. This wind tunnel has a low-restriction flow straightener, combined with a 6:1 compression ratio intake bell, which converts turbulent air flow into smooth, laminar flow for repeatable test results. The system has a total length of 180 cm and a test section of 30 cm. As shown in figure 12, the wind tunnel is equipped with a handheld control unit to adjust the velocity of the air moving through the test chamber (up to 18 m s^{-1}), and a manometer to indicate the actual velocity.

The sensor is clamped to a standard precision dovetail Zaxis stage (ZDTLS80, Misumi USA) via a custom-made 3Dprinted platform and a standard precision dovetail XY-axis stage (XYDTS90, Misumi USA). The two stages are fixed on a setup plate (Misumi USA). This setup is fixed at the center





Figure 12. Wind velocity experiment: (a) wind tunnel and (b) structure for holding the sensor.



Figure 13. Normalized resistance change for the ETPU sensor (linear) during five stretching/releasing cycles. A curve is plotted in between the stretching, and releasing cycle which represents an approximation of the normalized resistance–strain relationship.

of the test champer while its resistance change is measured. Only the ETPU-based sensor in the linear configuration is tested in this experiment due to its high GF (20 in the strain range of 0%-2%) relative to the other 3D-printed sensors.

To compare the simulated result with the FEM simulation, the experiment in figure 5(d) was repeated with lower strain cycle of (1.25%) and a fitting is found to capture the straindependent normalized resistance. This approximation enables one to map the elastic strain from the FEM simulation to the experimental normalized resistance. The curve fitting between the normalized resistance $\Delta R/R$ and the elastic strain ϵ is as follows: $\Delta R/R = 0.094 34\epsilon^2 - 0.261\epsilon + 0.000 012 54$ as shown in figure 13. Figure 14 shows the normalized resistance as the wind velocity is increased and then decreased. It can be seen that the FEM simulation is able to capture the normalized resistance all the way up to the maximum wind velocity, approximately 15 m s⁻¹, produced by the wind tunnel.



Figure 14. Measured and FEM prediction of the electrical resistance variation with respect to the wind velocity for the ETPU filament-based wind sensor in the linear configuration.

6. Conclusion and future work

In this paper we reported 3D-printed stretchable sensors with application to wind sensing. Among the three explored conductive materials, ETPU was shown to be most promising due to its larger strain range and higher sensitivity. In particular, ETPU-based sensors show a wide workable strain range of 0%—12.5%, and high sensitivity (GF of 20 in the strain range of 0%-2%). This strain sensor provides the advantages of low cost, simplicity in fabrication, robust mechanical properties, and versatility in applications. Its ability in measuring the wind velocity inside a wind tunnel was demonstrated, where the sensor showed sensitivity to the wind velocity beyond 3.5 m s^{-1} . The mechanical characterization results were then used in FEM simulation of the 3D-printed stretchable sensor, where FSI simulation was used to couple the wind load with the mechanical deformation of the sensor. The simulation results on the elastic strain behavior of the sensor showed good match with experimental measurements conducted on a prototype in the wind tunnel experiment.

For future work, we will conduct additional mechanical characterization and scanning electron microscopy experiments to understand the particular strain-resistivity behavior of ETPU material. The wind-sensing behavior of the material will be further studied to measure both wind direction and velocity via wind tunnel experiments and finite-element modeling, based on which the optimal design of the sensor in terms of dimensions and geometry will be pursued.

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Appendix. 3D-printer properties

Table A1. 3D-printing settings.				
Parameter	Value	Unit		
nfill	100	%		
Number of shells	2			
Layer hight	0.25	mm		
Extruders temperature	200	°C		
Build plate temperature	60	°C		
Speed while extruding	800	mm min ⁻¹		
Raster orientation	0	Degree		
Filament diameter	1.75	mm		

0.4

mm

ORCID iDs

Nozzle diameter

Mohammed Al-Rubaiai https://orcid.org/0000-0003-2335-0196

Chuan Wang ⁽⁾ https://orcid.org/0000-0002-5296-0631

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