Low Creep 3D-Printed Piezoresistive Force Sensor for Structural Integration

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***Abstract*—Attempts in research to equip robotic end-effectors with tactile sensing facilitate an advanced environment perception and provide the means for dexterous interaction. Sensing at the fingertips can be realized using force sensors. In this work, we present an additively manufactured universal force-sensor offering structural integration to accomplish fast adaptation to application-specific needs. The piezoresistive sensor consists of commercially available conductive polylactic acid (PLA). Its geometry is based on rigid PLA spring elements to overcome the inherent limitations of elastomers. A curved shape increases the length of the deformation element, thus, the sensitivity, while retaining the flexibility necessary to allow for a displacement-induced change of the electrical resistance. The sensor features an additional integrated spring, which enables the adaptation of the mechanical stiffness and therefore of the measurement range. We use thread-forming screws to achieve a robust and enduring electrical connection between wires and the conductive polymer. The characterization of the sensor takes place in a universal testing machine with an applied load up to 5 N. The resistance measured gives a nearly linear characteristic and is proportional to the displacement. We obtain a sensitivity of 6.5 Ohm/N and a relative change of resistance of 6%. Low creep (0.12%) during phases with constant load reveals an advanced geometry-induced mechanical behavior. Thus, our printed piezoresistive PLA sensor demonstrates the suitability of conductive rigid materials for their tailored application as force sensors in robotics.**

***Index Terms*—printed, piezoresistive, force sensor, robotics, tactile sensing, structural integration, creep, sensitivity**

I. Introduction

In modern robotics, the necessity of reaching a dexterous interaction with the environment requires more research effort towards bio-inspired control and environment acquisition [1], [2]. In particular for robotic grippers, a human-like motion and an environmental perception through tactile sensing is desirable [3], [4]. The sensing property of robotic end-effectors can be achieved through equipping them with force sensors [5]–[8]. One of the easiest and common ways to measure force on a surface are force-sensitive resistors (FSRs), which decrease in resistance with increased force on the polymer thick film [2]. Although FSRs were proven to be suitable for a force estimation to control a soft robotic hand [9], they inhibit creep, low accuracy, and non-linear behavior [10]. Such sensors are commercially available and have predefined specifications, such as geometry. Furthermore, the application to the robotic end-effector requires additional steps for their integration.

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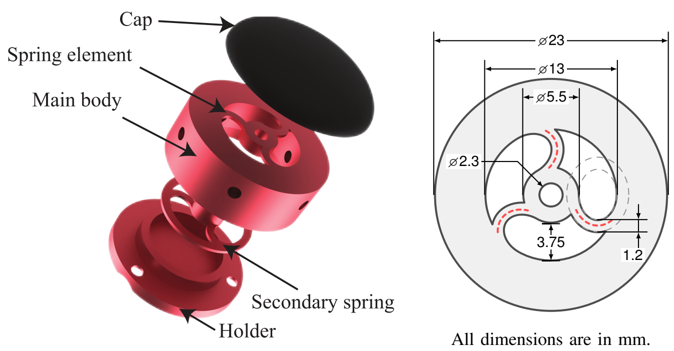

Fig. 1: Exploded 3D model of the additively manufactured sensor's structure with a detailed technical drawing of the active sensor part. The dimensions for the spring elements are carefully optimized for a solid print without unwanted gaps. The curved shape is selected instead of a straight bar in order to increase the length of the deformation element, thus, receiving a higher sensitivity with the same sensor size. The neutral fiber of the spring element (red, dashed) with 5.5 mm gains 48% in length compared to a straight bar with 3.75 mm.

With the emerging use of additive manufacturing in rapid prototyping and in commercial production [11], the possibility of integrating sensors directly into the mechanical structure arises [12]. The sensor integration is available through a pause and built-in during the print [11], [13]–[15]. Another approach is attaching a printed sensor element to the robotic end-effector [16]. While there are off-the-shelf commercial force and torque sensors available for integration, printed sensors offer a high fabrication freedom as well as fast adaptation to application-specific needs. Combining these two approaches is achievable by using printable materials appropriate for sensor functionalities [17], [18] and leads to a fully-integrated and customizable sensor [19], [20]. Many groups have investigated 3D-printed flexible sensors using conductive composite materials varying their composition and ingredients to meet the applicable behavior [2], [21]. A monolithically printed hand with integrated distributed pneumatic sensors [5] showed a nearly linear static characteristic but revealed a hysteresis of up to 50%. The majority of custom tactile sensors are either

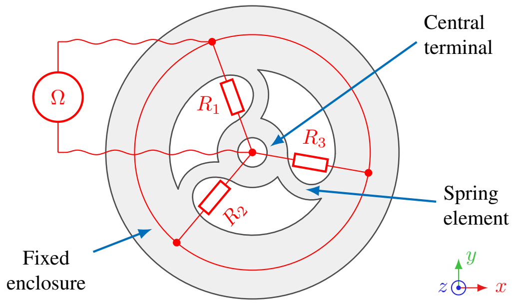

Fig. 2: Top view of the sensor's mechanical structure (gray) with the electrical circuit equivalent and ohmmeter connected for the sensor output acquisition (red). The resistors are placed beside the corresponding spring elements for the sake of clarity.

capacitive or resistive [8] and consist of conductive elastomers. Overall, most of the elastic piezoresistive compounds are inherently limited by their hysteresis in the sensor output that reduces sensitivity and repeatability [8].

Rigid materials overcome these inherent limitations of elastic compounds [22], however, undergo less deformation when a force is applied. In order to raise the sensitivity, the force has to be applied on a flexible structure of rigid material, which ensures the restoring force. The most common material used in fused filament fabrication (FFF) is polylactic acid (PLA), which bears rigid mechanical properties. This polymer is commercially available as conductive compound with slightly different mechanical properties compared to pure PLA [23]. In this work, we present a fully-printed PLA based force sensor for the integration into the fingertips of a printed robotic hand to provide tactile sensing when manipulating objects. The sensor is tested with respect to sensitivity and linearity.

II. Materials and Methods

The sensor geometry (Fig. 1) is designed in Autodesk Fusion 360 (Autodesk Inc., San Rafael, CA, USA) and prepared for FFF using the open source software PrusaSlicer (Prusa Research a.s., Prague, Czech Republic). The slicer takes the object model as a 3D volume input and calculates the optimized print head movement for each 2D xy-layer. We

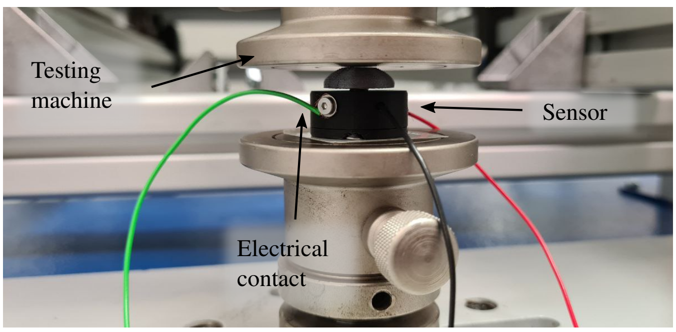

Fig. 3: Measurement setup with the sensor mounted into the universal testing machine. The bottom is fixed with adhesive tape to the lower plate, the upper parallel plate is moving downwards to apply the load onto the cap of the sensor. Resistivity is measured between the central terminal (black wire) and the sensor base at two points (green and red wire), respectively.

visually inspect the derived paths layer by layer, in particular at the sensor spring element, and tune the geometry once for a solid print without unwanted gaps. The first layer thickness is 0.2 mm, whereas throughout the rest of the layers, a thickness of 0.1 mm is selected for a higher vertical resolution. We fabricate the sensor using a 3D printer (Prusa MK3s, Prusa Research a.s.) with a nozzle diameter of 0.4 mm, extruder temperature of 220 °C, and bed temperature of 60 °C.

For the ease of handling, we use a conductive compound filament (Protopasta Conductive PLA, Protoplant Inc., Vancouver, WA, USA) for the whole sensor structure despite being only necessary for the sensor spring element itself. The compound consists mainly of food packaging approved PLA and electroconductive carbon black. According to the datasheet, we expect a specific electrical resistance $\rho_{xy} = 30\,\Omega\,\text{cm}$ inside each layer and $\rho_z = 115\,\Omega\,\text{cm}$ perpendicular to the layers. The total resulting resistance will be dominated by the xy-component because of the spring element direction. Generally, material compounds with carbon black exhibit a negative pressure coefficient of resistance [8]. Conductivity in these polymer composites is dominated by the percolation mechanism where a rearrangement of the conductive path is induced by the dispersed particle motion inside of the material, which leads to a variation of resistance [24]. When the sensor spring element undergoes a deformation due to an applied force, stress in the material causes a resistance change.

The sensor's main body (⌀23 mm) consists of the fixed enclosure, the central terminal, and three spring elements interconnecting them, building one flexure spring (Fig. 2). We select a curved shape instead of a straight bar for the three spring elements in order to increase the length of the deformation element, thus, receiving a higher sensitivity with the same sensor size. The neutral fiber of the spring elements (Fig. 1, red, dashed) with 5.5 mm gains 48% in length compared to a straight bar with 3.75 mm. The sensor features two flexure springs in total, mounted parallel to each other. The first spring is part of the main body and presents the electrically relevant component. The second spring is attached to the main body through the holder and serves as an additional mechanical stiffness to control the sensor's measurement range. In fact, by changing the number of spring elements, their geometry, or thicknesses, the measurement range can be adapted without the necessity of replacing the main body. Here, we select a measurement range up to 5 N. Therefore, we use three spring elements with a thickness of 0.5 mm for both flexure springs resulting in a total sensor stiffness of 13.3 N mm^{-1}.

On top of the central terminal, a non-conductive cap is fixed with a screw. The cap transmits the applied force into the sensor itself and works as a mechanical stop to limit the spring element deformation. The spring elements' geometry is decisive for the basic sensor resistance. The sensor's equivalent output resistance (Fig. 2) consists of three single resistors in parallel for one spring element each including the central terminal's and the enclosure's resistance, respectively. When manufactured with the given specifications, the basic resistance of the sensor results to 500 Ω approximately.

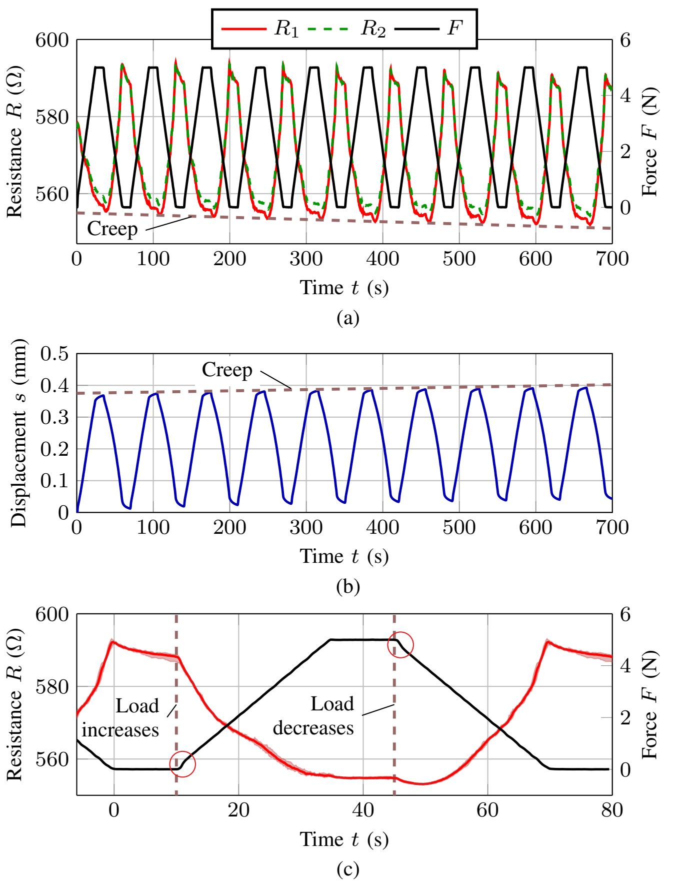

Fig. 4: Measurement results of the sensor resistance (red and green) with the applied force (black) of up to 5 N for (a) ten full load cycles and (b) the resulting displacement. (c) One average cycle with mean (red, solid) and the overall range (red, shadow) over the ten cycles with creep eliminated. For the sake of clarity, the second resistance R_2 is omitted. After phases of constant load, the force changes slightly non-linear (red circles).

Connecting the conductive filament with wires is not trivial. Shih et al. push the bare wire through an elastomer and increase electrical contact with silver paste, while securing the wire mechanically at a second location [25]. In preliminary experiments this did not show sufficient reliability in combination with the conductive PLA. We use ring cable lugs on the wires and screw (M2) them directly into the holes (⌀1.9 mm) of the sensor forming a thread on insertion to ensure a durable and robust connection.

III. Experimental Setup

The prototype sensor is characterized regarding its linearity and creep (Fig. 3) using a universal testing machine (inspekt table 5 kN, Hegewald & Peschke, Nossen, Germany) with a 100 N reference force sensor (accuracy 0.02%). The holder of the sensor is fixed with adhesive tape to the lower plate of the testing machine; the upper parallel plate is moving downwards to apply the load onto the cap of the sensor. Initially, we use three full loading cycles until the mechanical stop of the sensor becomes effective. Only after this procedure, we achieve the low creep behavior measured. Loading is done force-controlled with a slope of 0.2 N s^{-1} up to a maximum force of 5 N and back to zero over ten full load cycles. The minimum and maximum force are held for 10 s, respectively. A sourcemeter (model 2450, Keithley, Cleveland, OH, USA) powers the sensor with a test current of 1 mA to measure the resistance (sampling rate 10 Hz). We acquire the resistance at two terminals (R_1, R_2) of the enclosure at the same time to check for a potential shear force on the sensor.

IV. Results and Discussion

The sensor shows a clear resistance change proportional to the applied force (Fig. 4a). Both measured resistances (red and green) resemble each other in shape, yet differ slightly in their magnitude. This is expected and explainable by the manufacturing tolerances. When the force is applied to the sensor (Fig. 4c, t = 10 s), the resistance is reduced accordingly. The resistance decreases from 587 Ω to 555 Ω with larger rates at the beginning. For the same level of the decreasing force, a similar change in resistance amplitude and rate of change is found. However, when the force on the sensor starts decreasing (Fig. 4c, t = 45 s), the resistance drops slightly at this time. We suspect this behavior to derive from the sudden and non-linear load change (red circle).

The sensitivity in our sensor prototype results in average to 6.65 Ω N^{-1}. With a relative resistance change of around 6%, we receive similar results as in other works with the same material [26], [27]. The creep during constant load phases saturates to a constant value. It is low (0.12%) compared to an elastic material [8] where the material itself is deformed instead of the geometry of our sensor. Furthermore, the shape of the displacement curve (Fig. 4b) corresponds to the shape of the resistance. The resistance change is thus proportional to the displacement. The creep of the peak resistance over all cycles (343 mΩ min^{-1}) correlates with the creep in the maximum displacement (2.3 µm min^{-1}) and is nearly linear. Therefore, the initial cyclic loading procedure can be used to reduce this characteristic at the beginning. The creep behavior of the displacement shows that this is a mechanical property of the polymer used. Nevertheless, as we expected, loading a flexible geometry of rigid material causes less creep than loading an elastic polymer.

V. Conclusion and Outlook

In this paper we present a 3D-printed piezoresistive force sensor with improved sensitivity consisting of a commercially available conductive polymer compound. The results demonstrate the feasibility of rigid material for a tunable sensor geometry to overcome the inherent limitations of elastomers, in particular creep. With the low-cost fabrication technique used, a full structural integration of this sensor into bigger 3D-printed parts is attainable. Dual head extrusion with the same conductive material and a second isolating one is already proven to work [26], [28] and will be included in our future work with the robotic hand. Beyond the scope of this work, the process enables fast tailoring for application-specific needs, e. g., in other areas of robotics as well as in predictive maintenance and reliability monitoring.

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