

Proceedings

# A Soft Pneumatic Actuator with Integrated Deformation Sensing Elements Produced Exclusively with Extrusion Based Additive Manufacturing <sup>†</sup>

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**Abstract:** In recent years, soft pneumatic actuators have come in the spotlight because of their simple control and the wide range of complex motions. To monitor the deformation of soft robotic systems, elastomer-based sensors are being used. However, embedding of sensors into soft actuator modules by polymer casting is time consuming and difficult to upscale. In this study, it is shown how a pneumatic bending actuator with an integrated sensing element can be produced using extrusion-based additive manufacturing method, e.g. fused deposition modeling (FDM). The advantage of FDM against direct printing or robocasting is the significantly higher resolution and the ability to print large objectives in short time. New, commercial launched pellet-based FDM printers are able to 3D print thermoplastic elastomers of low shore hardness that are required for soft robotic applications, to avoid high pressure for activation. A soft pneumatic actuator with the in-situ integrated piezoresistive sensor element was successfully printed using a commercial styrene-based thermoplastic elastomer (TPS) and a developed TPS/carbon black (CB) sensor composite. It has been demonstrated that the integrated sensing elements could monitor the deformation of the pneumatic soft robotic actuator. The findings of this study contribute to extending the applicability of additive manufacturing for integrated soft sensors in large soft robotic systems.

**Keywords:** piezoresistive sensor; soft robotics; additive manufacturing; fused deposition modeling; pneumatic actuator

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## 1. Introduction

The integration of piezoresistive elastomer strain sensors in soft robotic actuators enables the monitoring of the deformation and motion of the robotic modules. The monitoring of the deformation can be used for a closed loop control of self-sustaining locomotion and obstacle recognition [1]. However, integrating piezoresistive elastomer-based sensing elements in soft robots using conventional casting methods is time consuming and difficult for automatized fabrication. Fused deposition modeling (FDM) allows the automatized fabrication of soft robotic actuators [2]. Additionally, FDM is compatible with conductive composites based on thermoplastic elastomers and carbon fillers [3].

It is well-known that in order to achieve good piezoresistive properties, high concentration of conductive filler is required [4]. Nonetheless, because of high filler concentration, the filaments get brittle and commercial FDM printers cannot be used anymore. New commercial launched pellet-

based printers are able to print brittle materials and can be used to fabricate soft robotic actuators with integrated sensing elements.

In this study, piezoresistive elastomer sensors with a conductive filler content of 50 wt.% have been printed in situ on an elastomer substrate with a pellet based FDM. The sensor behavior of the 3D printed elastomeric strips was investigated under dynamic and quasi-static cycling conditions. Finally, a conventional pneumatic actuator module with integrated strain sensing element was printed and bending deformation was evaluated.

## 2. Materials and Methods

### 2.1. Preparation of the Conductive Pellets for the Piezoresistive Sensing Element

The preparation of the conductive composite was described in detail elsewhere [5,6]. In short, a TPS elastomer and carbon black were acquired from Kraiburg TPE (Waldkraiburg, Germany) and TIMCAL (Bodio, Switzerland), respectively. The two components were mixed in a 1:1 mass ratio, using a torque Rheometer from Thermofisher (Karlsruhe, Germany). The resulting composite was extruded into filaments with a diameter of 1.75 mm, using a capillary rheometer from NETZSCH (Selb, Germany). Finally, the electrically conductive filaments were cut into 3 mm pellets.

### 2.2. Printing of the TPS Structures with Integrated Sensing Elements Using Pellet-Based FDM

For the printing of the support structures, a TPS elastomer with shore hardness 18A (Kraiburg TPE, Waldkraiburg, Germany) was used. The design of the pneumatic actuator was performed using a CAD software based on an open-source design for molds of a pneu-net bending actuator [7].

The temperature used during the printing was 250 °C and the printing speed was 15 mm/s. The extrusion multiplier used for the printing was 10. A heated printing bed was used at the temperature of 45 °C.

### 2.3. Dynamic and Quasistatic Cycling Behavior of the Printed TPS Structures

To investigate the dynamic and quasistatic cycling behavior, a Zwick Roell Z005 tensile testing machine from (Zwick Roell GmbH & Co. KG, Ulm, Germany) was used. Pneumatic clamps with a pressure of 4 bar and a 200N load cell were used to avoid slipping behavior during the tensile testing. For the measurements of the electrical signal, a Keithley 2450 multimeter (Keithley Instruments, Solon, USA) was used. The relative resistance ( $R_{rel}$ ) was calculated using the following formula:

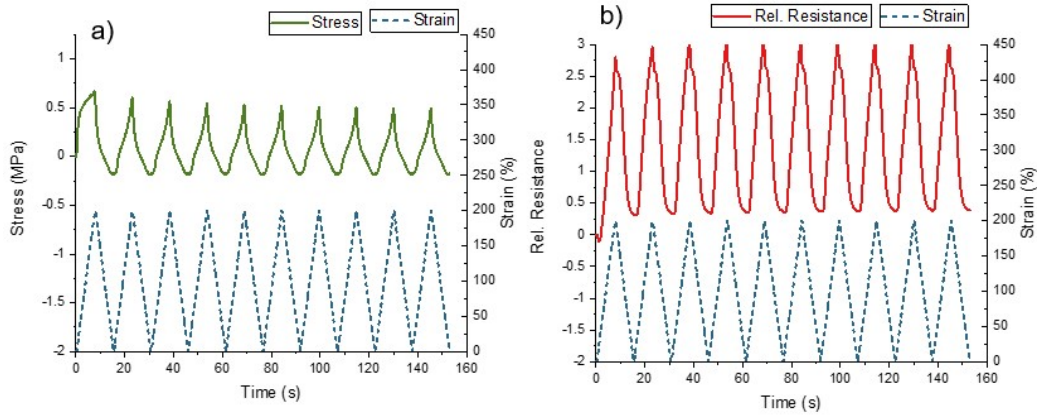
$$R_{rel} = \frac{R - R_0}{R_0} \quad (1)$$

where R is the value of the resistance during a certain strain and  $R_0$  the initial resistance value.

## 3. Results and Discussion

### 3.1. Dynamic and Quasistatic Cycling Behavior of the Printed TPS Structures

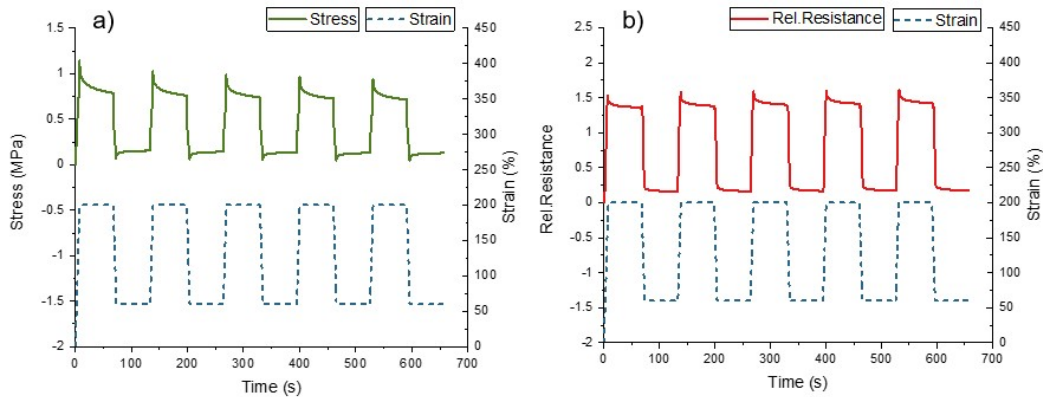
In order to investigate the response of the sensor signal under dynamic loading, the TPS strips with integrated strain sensor element were cycled between 0 and 200% strain (Figure 1).



**Figure 1.** (a) Dynamic stress and (b) relative resistance sensor signal response of the FDM printed TPS strips with the integrated strain-sensing element during cycling between 0 and 200% strain.

The sensor signal response, between different cycles, had a drift of 1%. The TPS strips exhibited a monotonic response without a plateau or uncertainty in the sensor behavior. A buckling behavior during cyclic tensile measurement was visually observed and correlated with negative stress values, shown in Figure 1a. Buckling occurred for the FDM printed TPS strips at 57% strain.

In order to measure the relaxation behavior of the sensor, a quasi-static cycling experiment with a dwell time of 60 s at maximum and minimum strain was performed. In order to avoid the effect of mechanical buckling below 57% strain, quasi-static experiments with a pre-strain of 60% were selected (Figure 2).

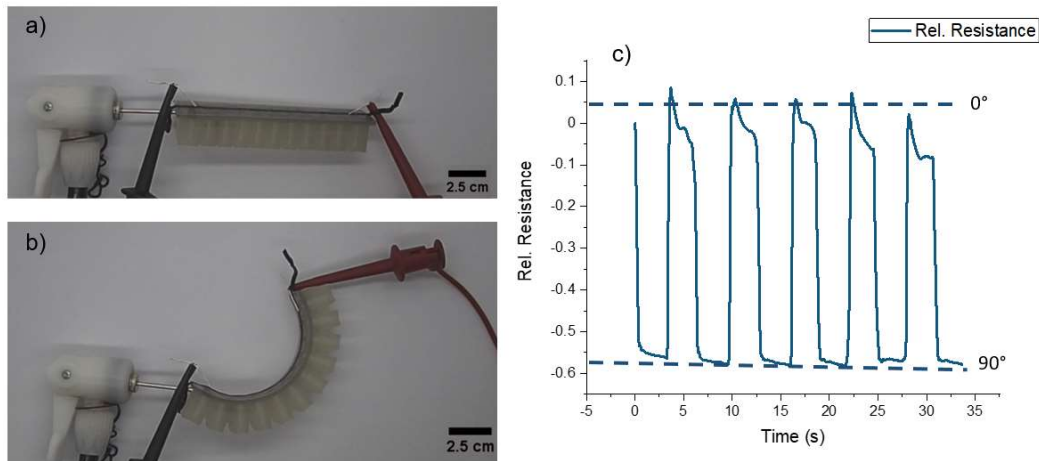


**Figure 2.** Response of (a) the stress and (b) electrical sensor signal during the quasi-static tensile testing for the printed TPS strips with integrated sensing element.

At 60% strain, the mechanical and electrical relaxation of 88% and 13% could be observed, respectively. At 200% strain, 29% and 32% could be detected for the mechanical and electrical relaxation, respectively.

### 3.2. Sensor Performance of a 3D Printed Pneumatic Actuator

To avoid high pressure for the activation of the pneumatic actuator, an elastomer with low shore hardness is required. A conventional pneumatic bending actuator consists of air chambers connected by a long thin airway. Once the compressed air is pumped into the actuator, all the chambers will inflate and the actuator bends. Due to the design requirement of such actuators, the strain sensor has to be integrated into the compression side (Figure 3).



**Figure 3.** The pneumatic bending actuator with the integrated sensing element in position (a) 0°, (b) 90°, (c) the sensor signal during cycling measurement between 0° and 90°.

As expected, a negative piezoresistive behavior was observed, due to the compression. Nonetheless, the sensing element exhibits a monotonic response and it is possible to distinguish between the two positions (0° and 90°) of the bending actuator.

#### 4. Conclusion

In this study, TPS tensile strips and a soft pneumatic-based bending actuator with integrated piezoresistive sensing elements was successfully fabricated using a multi-material pellet-based FDM printer. The TPS strips have to be used with a pre-straining to avoid buckling and an uncertainty of the sensor signal below 57% strain. For the actuator, a thermoplastic elastomer (TPS) of shore hardness 18A was used. As expected, for the bending actuator a negative piezoresistive behavior of the sensor was observed, because the sensor element was used in compression mode. The results are promising but the sensor response has to be implemented into an actuation algorithm to achieve closed loop autonomous soft robotic structures.

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