

A 3D Printed Strain Sensor Employing Conductive TPU for Marine Applications

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Summary:

This work investigates the development of a fully 3D printed strain sensor using conductive Thermoplastic Polyurethane elastomer (TPU) and Polylactic Acid (PLA) filaments. The sensor is produced solely through additive manufacturing Fused Deposition Modeling (FDM) technology. This process is particularly beneficial in maritime environments as it enables remote production, thereby reducing downtime, minimizing inventory demands, and lowering environmental impact. The use of conductive TPU compared to previously performed research employing CNT-enriched PLA filament results in expanded measuring range and reduced hysteresis, mainly attributed to the elasticity of the building material. The developed sensor maintains the key advantages of a fully 3D printed device, including robustness, a straightforward design, and a single-step manufacturing process, while offering a reliable electrical interface through standard soldering. These combined features enhance its reliability, durability, and overall suitability for structural monitoring applications in marine environments.

Keywords: Additive manufacturing, conductive TPU, strain sensor, structural health monitoring, marine engineering.

Background, Motivation and Objective

The application of 3D printed sensors in the marine industry can provide substantial benefits such as cost-effectiveness, minimal downtime, and circular economy compliance. Prior work by our research group demonstrated the feasibility of using Carbon Nanotube (CNT) enriched filaments as piezoresistive elements for FDM-printed strain sensors, which showed adequate and promising performance when subjected to bending with consecutive compression and elongation steps [1]. However, hysteresis and non-linearity were recorded especially at displacements larger than 0.6 mm, possibly attributed to the fracture of the conductive paths within the polymer matrix.

To address this challenge, the present work investigates the employment of a conductive Thermoplastic Polyurethane elastomer (TPU) filament -a composite material characterized by intrinsic elasticity and resilience- for the sensing element. The goal was to develop a fully printed sensor with improved repeatability, lower hysteresis, and better long-term reliability in strain detection applications relevant to structural monitoring of marine components. The proposed sensor consists of a monolithic body comprising of two layers: a non-conductive layer acting as a

substrate, and a piezoresistive layer on top as the sensing element. The device can be attached to a structural component to monitor mechanical stress and can be easily connected to the appropriate measurement electronics via integrated solder pads, enabling straightforward interconnection.

Description of the Developed Process

The device was fabricated exclusively using FDM additive manufacturing technology, employing a dual-material strategy; the sensing element is fabricated from a commercially available conductive TPU filament enriched with lamp black (approx. 10% w/w, Recreus Industries S.L.) while the mechanical supporting frame is printed using standard Polylactic Acid (PLA) building material (Ultimaker B.V.).

Due to the inherent elasticity of TPU, the sensor is expected to exhibit higher durability under cyclic loading conditions, along with reduced hysteresis. This improvement is attributed to TPU's ability to accommodate strain through reversible deformation and facilitate a more stable balance between the disruption and reformation of the conductive network (percolation pathways) within the piezoresistive element. In contrast, CNT-enriched PLA filament employed in previous research leads to a more rigid polymer

matrix which may result to conductive network fragmentation under strain, therefore enhancing hysteresis. All process steps, from CAD design to print parameters, including extrusion temperature, building plate temperature, print speed, layer thickness and infill pattern, were optimized for consistent extrusion and interlayer bonding within the conductive piezoresistive path and between the two structural layers. These optimizations aimed to ensure uniform electrical conductivity and enhanced mechanical stability of the device. The application of an appropriate thermal treatment step on the printed device was also investigated to enhance its sensing characteristics, in accordance with previous research results [2,3]. In brief, annealing alters the polymer microstructure, which changes from an amorphous state to a semi-crystalline state, affecting its viscoelastic behaviour; this leads to a lower and more stable resistance when no strain is applied and improved hysteresis [1].

Results

Compared to previous CNT-based printed sensors, the TPU-based prototype demonstrated a significantly expanded measuring range and noticeably improved hysteresis. It can accurately detect displacements up to 5 mm, which is more than a ninefold increase compared to the previous 0.6 mm limit. The average recorded hysteresis as a percentage of the maximum resistance variation (ΔR_{\max}) for each step of the compression-decompression cycle is reduced by approximately two thirds. Figure 1 illustrates the corresponding resistance variation (ΔR) as a percentage of the initial resistance (R_0) for each deformation step—applied for a duration of one minute—and the corresponding calculated hysteresis. The resistance variation value represents the mean value of ten consecutive measurements. The deduced mean hysteresis value (excluding the zero and maximum deformation points) is calculated at 15.9%, which is significantly lower than the 46% observed for the PLA-based piezoresistive element. Stability under cyclic loading was also investigated, as illustrated in Figure 2, with baseline drift mainly observed during the initial strain cycles. Additionally, the significant effect of thermal treatment in reducing the initial resistance of the device is highlighted, as reported in the case of CNT-enriched PLA [1], inkjet printing and screen-printing technologies [4,5].

The results indicate that elastic conductive polymer composite filaments, such as TPU, can be used effectively in single-step, 3D-printed strain sensors where resilience and consistent behavior are essential. Consequently, the previously developed process for fabricating cost-effective strain sensors using additive manufacturing

technology has been significantly improved, making remote on-site fabrication with readily available equipment more feasible. This advancement aims to reduce the need for extensive inventories and long supply chains, which is crucial for practical marine applications. Ongoing work focuses on optimizing the geometry of the strain sensor and embedding it within Glass Fiber Reinforced Polymer (GFRP) composites for structural health monitoring and maintenance purposes.

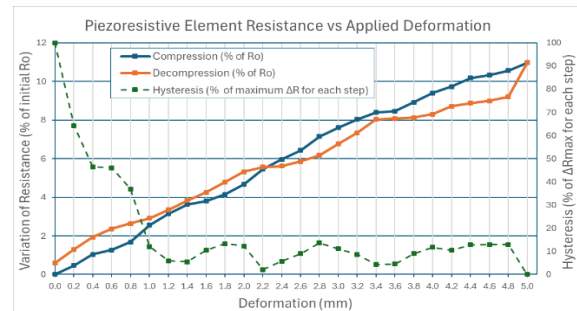


Fig. 1. Calculated hysteresis and resistance variation (ΔR) as a percentage of the initial resistance (R_0) recorded for each step of deformation.

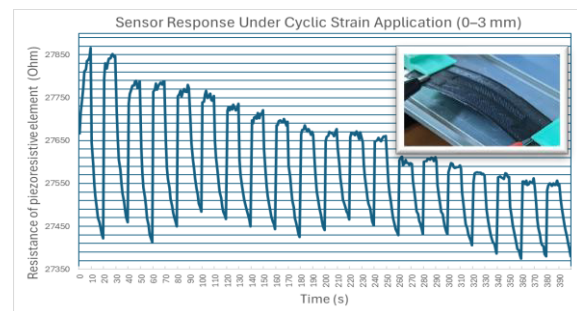


Fig. 2. Sensor response under twenty consecutive cyclic strain applications (3 mm of displacement).

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