

A Torque Sensor using 3D Printed Conductive TPU

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Summary: A fully 3D printed torque sensor was realized through FDM by embedding a conductive TPU helix inside a PA12 body. Torque loading changes the helical sensing path and causes a resistance increase. The printed devices show an approximately linear response up to 3.5 Nm. Repeated cycling between zero and 1 Nm remains detectable but shows baseline drift. These results demonstrate the potential of fully 3D printed sensors and highlight the main challenges for optimization.

Keywords: Additive Manufacturing, Torque Sensor, Printed Electronics, Fused Deposition Modeling, Conductive Filament

Background, Motivation and Objective

Conductive polymers have been used in fused deposition modeling (FDM) to directly print electrical interconnects and functional sensors into structural components, enabling a high degree of integration without post-assembly. Various studies have demonstrated 3D printed strain sensors based on conductive filaments [2], as well as soft tactile sensors embedded in compliant structures [3]. In addition, torque sensing has been explored using additively manufactured structures with conductive paths, by printing metallic silver inks, although this requires specialized processes not compatible with standard FDM workflows [4]. A common limitation across these approaches is the high electrical resistance of conductive polymer composites, compared to metal wiring, and their sensitivity to environmental and mechanical influences, resulting in drift, hysteresis, and limited long-term stability [1]. In this work, we exploit these characteristics to realize a fully 3D printed torque sensor, targeting applications such as human–robot interaction where the detection of small torque variations is essential.

Description of the Torque Sensor

We propose a small inline torque sensor that exploits the helical deformation along the path of a helical conductive structure. When subjected to torque, the elastic twist response of the helix causes a change in its length, which can be measured and correlated to the applied torque through the piezoresistive material behavior. The sensor is fabricated on a standard PrusaXL printer (Prusa Research a.s.) using fiberology PA12 (Fiberlab S.A.) as the structural material, due to its wide elastic deformation capabilities and low creep. The carbon black [1] enriched filaflex conductive TPU (Recreus Industries S.L.)

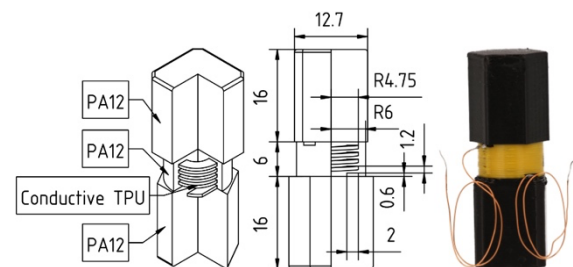


Fig. 1. Left & Middle: Dimensions (mm) of the torque sensor built from PA12 and a conductive TPU helix. Right: FDM fabricated sensor with wires.

is used for the sensor element. Filaments were dried and printed with 0.4 mm diameter nozzles at 100% concentric infill, 235 °C for TPU, and 265 °C for PA12. Specimens were stored in a dry box at room temperature after printing. As shown in Fig. 1, the helical sensing element is embedded in a PA12 cylinder between ½" sockets. In total, 115.6 mm x 1.2 mm² of conductive material are expected to give a total resistance of 21.6 to 33.6 kΩ given the previously reported processed material resistivity of 22.4 to 34.9 Ωcm [1]. The volume ratio of conductive TPU of the cylinder is 20.4%. Short pieces of 0.2 mm enameled copper wire were tinned, heated, and inserted into the straight ends of the conductive helix. An Otti Ace (Qoitech AB) source measurement unit (SMU) was connected to the specimens to record current under a constant voltage of 1.0 V to study the piezoresistive response under load. The sensor is fully clamped in the sockets up to the inner cylinder in a vice and custom test fixture shown in Fig 2. Through a retaining pin, the system can be reset and kept in a baseline state without any applied torque or twist. Without the pin, a torque of up to 5 Nm can be applied by adjusting the weight on the lever arm.

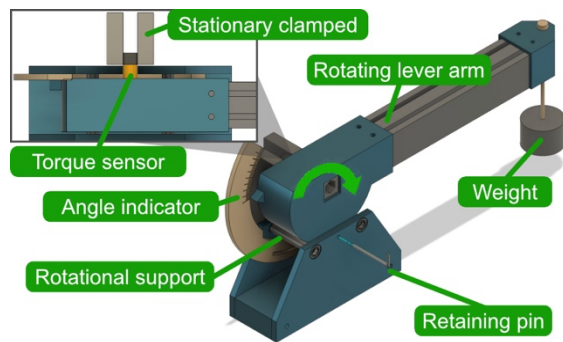


Fig. 2. Torque testing setup with an adjustable hanging mass on a lever arm inducing clockwise torque into the sensor and a 0° locking mechanism.

The rotational support minimizes bending loads but still allows for small height expansion. The expected rotational displacement θ (twist) of the cylinder can be calculated with eq. (1) using the material's shear modulus G , cylinder length $L = 6$ mm and polar moment of inertia $J \approx 2.04 \cdot 10^{-9} \text{ m}^4$, given the diameter of 12 mm.

$$\theta = \frac{TL}{GJ} \quad (1)$$

Due to material heterogeneity and FDM-induced uncertainties, G cannot be determined precisely but is assumed constant in the linear-elastic regime. For reference, isotropic PA12 ($G = 0.5 \text{ GPa}$) [5] yields $\theta \approx 1.7^\circ$ at $T = 5 \text{ Nm}$.

Results

The torque sensors show an initial baseline resistance R_0 of $20.4 \pm 0.7 \text{ k}\Omega$ after printing ($n=6$) and were split into two sets for experimental study. During stepwise increasing static loading, the sensor shows a linear response up to a torque of 3.5 Nm with high resistive sensitivity of 15.3% and deformation of 7.3° (see Fig. 3). Further loading beyond 3.5 Nm causes saturation of the resistance and eventually irreversible resistance change. However, rotational deformation does not stop beyond 3.5 Nm and continues linearly up to 10.5° at 5 Nm. Cyclic loading tests in the linear range alternating between 0 Nm and 1 Nm torque (see Fig. 4), are detectable by a 3% difference but show a linear decrease in both the loaded and unloaded resistance readings throughout repeated cycles.

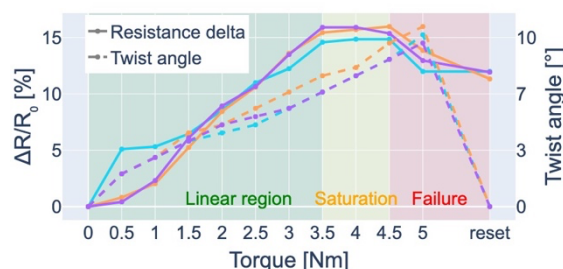


Fig. 3. Resistance and twist change under increasing static torque from 0-5 Nm for specimens 1-3.

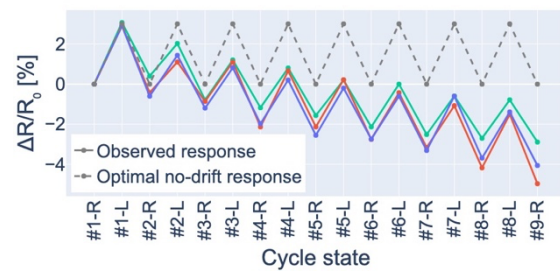


Fig. 4. Resistance change over repeated loading to 1 Nm (L) and forced relaxation to 0 Nm and 0° (R) for specimens 4-6 compared to an optimal theoretical behavior without drift.

The results indicate that conductive TPU can be used for small fully 3D printed torque sensors. However, resistance drift under repeated cycles limits the application to single-use scenarios. Additionally, the twist deformation of several degrees is undesirable for inline torque sensing. The current sensor geometry was derived from theoretical considerations but has not yet been optimized with respect to electrical recovery, mechanical stability, and long-term cyclic behavior. Future work should therefore explore alternative geometries, heat sintering [2], the influence of axial loading, and alternative transduction principles such as capacitive sensing.

References

- [1] M. Nowka, K. Ruge, L. Schulze, K. Hilbig, T. Vietor, Characterization of the Anisotropic Electrical Properties of Additively Manufactured Structures Made from Electrically Conductive Composites by Material Extrusion, *Polymers* 16, 20, 2891 (2024); doi: 10.3390/polym16202891
- [2] D. N. Pagonis, A. Stavros, I. Iakovidis, S. Dimitrellou, G. Kaltsas, A 3D Printed Strain Sensor Employing Conductive TPU for Marine Applications, *Eurosenors 2025*; doi: 10.5162/EUROSENSORS2025/MP1
- [3] R. Antunes, L. Lang, M. L. de Aguiar, T. A. Dutra, P. D. Gaspar and N. J. Matos Pereira, Self-Sensing Soft Finger Produced from Conductive TPU for Adaptive Grasping and Force Sensing Applications, *ICARSC 2025*, pp. 39-44; doi: 10.1109/ICARSC65809.2025
- [4] L. Stiglmeier, T. Wendt, N. Hangst, P. Gawron, S. Rupitsch, A guideline for the fabrication of fully 3D-printed torque sensor elements – demonstrated based on a real example, 22. GMA/ITG-Fachtagung Sensoren und Messsysteme 2024, 213–220 (2024); doi: 10.5162/sensoren2024/C1.2
- [5] Polyamide 12 - Nylon 12 - PA 12, <https://www.azom.com/properties.aspx?ArticleID=753>, access on April 19th, 2026.