Enabling Soft Mechanosensing via Vat Photopolymerization 3D Printing: Materials, Design and Integration

Soft sensors are usually made of compliant materials that match the mechanical softness of the soft robots on which they need to be integrated. Various manufacturing techniques can be exploited to produce soft sensors, with mold-casting representing a popular choice within the soft robotics community. This method relies heavily on manual operation and multiple steps, being time-consuming and resulting in low reproducibility and scalability. Moreover, a lack of mechanical and/or chemical compatibility between the diverse elements can hinder proper adhesion, compromising the sensor's integrity and performance. Three-dimensional printing, or additive manufacturing (AM), offers a compelling solution to these limitations. Unlike conventional subtractive manufacturing, AM builds objects by adding material in layers based on a digital design, allowing for the creation of intricate geometries. This inherent design freedom, coupled with the ability to use compliant materials, positions AM as a promising alternative to develop advanced soft sensors. In particular, it unlocks new possibilities such as: (i) fine-tuning the properties of soft sensing through 3D printed design, including bioinspired architectures (*e.g.*, porous morphologies and 3D mechanoreceptors-like features); and, (ii) achieving superior integration between sensors and actuators.

The experimental work presented in this thesis lies in this framework, as material science and engineering play a crucial role in advancing the field of 3D printed soft mechanical sensors. In particular, a delicate equilibrium between materials' properties, printability, and design is needed to enhance the advantages of AM and to justify the related challenges. These aspects motivated the careful study of materials' composition and fabrication parameters. Our goal was to tackle these challenges by proposing innovative materials and fabrication approaches that can be employed and easily adapted by the soft robotics community, assisting the transition to a holistic approach in which material science, mechanics, and electronics can converge into functional sensing systems. Moreover, within the development of the presented sensors, we took into account their possible integration in soft robots. Even if the integration itself goes beyond the scope of this thesis, it drove the transition towards more suitable transduction mechanisms and solutions.

In particular, this thesis explores the potential of 3D photopolymerization printing for the fabrication of soft mechanical sensors, leveraging various materials, designs, and both resistive and optical transduction mechanisms.

Initially, the research focuses on resistive sensors due to their simplicity. The thesis presents an innovative method for developing porous conductive cryogels through Digital Light Processing (DLP) printing and a freeze-drying process. This methodology has enabled the fabrication of tactile sensors with honeycomb morphologies, which have been exploited to modulate the sensor response. Specifically, the mechanical and electromechanical properties have been tuned by leveraging the "double porosity" principle, determined by the cryogel pores and the cells of the 3D-printed geometry. This work addresses the issue of the scarcity of intrinsically conductive materials suitable for 3D printing, allowing for the creation of sensors with complex architectures and a tunable response in the 0-4 N compression force range. Moreover, this method, which enables the fabrication of features as small as 100 µm, proves to be versatile for various applications.

However, a key aspect of this research is the development of soft sensors while considering their future integration within a robotic system. From this perspective, resistive sensors present limitations due to wiring complexity and potential signal interference. This has motivated the exploration of optical sensors, which offer advantages in terms of integrability, simplified connectivity, and noise reduction.

Therefore, this thesis also investigates the development of optical sensors through the 3D printing of transparent resins. This approach has been studied using both Stereolithography (SLA) and DLP printing. In the first case, by controlling the orientation of the printed layers and incorporating specific surface patterns, it was possible to fabricate bending sensors with a tunable response. Additionally, a proof of concept was developed to demonstrate the integration of these sensors into soft structures, highlighting the possibility of printing flexible robots whose bodies themselves serve as sensing units. A key aspect of the study was the role of the printed layers in determining the optical properties of the material. This concept was also investigated via DLP printing, with particular attention given to the influence of layer thickness on optical properties and sensor response.

Finally, the thesis explores bioinspired designs, drawing inspiration from the skin of an elephant’s trunk and Triply Periodic Minimal Surfaces (TPMS). The use of DLP 3D printing enabled the replication of key aspects of the trunk’s skin, including the mechanical mismatch between layers and the presence of dermal papillae-inspired structures. The integration of TPMS lattices further allows for the modulation of mechanical properties. These preliminary results lay the foundation for the development of fully bioinspired mechanical sensors.

In conclusion, the findings presented in this research expand knowledge in the field of soft sensing and provide the groundwork for the development of bioinspired, fully integrated robots with advanced sensing capabilities.