From hydrogels to 3D-printable tactile sensors: advancing durability, performance and sustainability

The continuous technological growth of our society is driving a widespread adoption of autonomous machines, soft robots, and, consequently, flexible integrated electronic circuitry. In this context, soft tactile sensors play a pivotal role in enabling seamless human-machine interactions, although identifying materials that simultaneously provide high sensitivity, stretchability, and mechanical robustness remains challenging. Hydrogels have the potential to meet this need due to their intrinsic softness, flexibility and tunable properties. Nevertheless, their practical implementation is still limited due to the difficulty of simultaneously achieving optimal sensing performance, appropriate mechanical properties and long-term stability under environmental conditions.

This work investigates three interconnected research themes aimed at advancing hydrogel-based tactile sensors: additive manufacturing of complex hydrogel architectures to improve their sensing performance, strategies for reducing water evaporation to enhance sensors long-term stability, and the transition towards more sustainable, naturally derived hydrogels for next generation wearable applications.

Typical hydrogel-sensors rely on planar geometries, but here it is demonstrated that three-dimensional structuring can improve sensing performance by enabling a precise control over the mechanical properties of hydrogel sensors, highlighting the outstanding potential of additive manufacturing in this field. Nevertheless these hydrogel sensors suffer from dehydration, resulting unusable, within few days. To address this limitation, a conductive organohydrogel, in which water is partially replaced with a low-volatility organic solvent, was developed starting from the previously optimized 3D-printable hydrogel formulation. The resulting material enables the fabrication of flexible, high-performance 3D-structured sensors with operational stability extending up to six months after fabrication.

Beyond performance optimization, this work eventually explores the use of more sustainable materials derived from natural sources. A conductive and stretchable sensor made by gelatin, cellulose and lignin showed promising potential for wearables applications, not only to measure deformation but also temperature and humidity, while displaying optimal degradability when placed in soil after a few weeks, ideal for developing transient electronics to face the growing e-waste issue.

Overall, this thesis provides an overview of the advances achieved in hydrogel-based tactile sensors over the past four years, highlighting the challenges and future opportunities for their transition toward robust, durable, and sustainable wearable technologies.