Soft mechanical sensing technologies in soft robotics and wearables

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***Abstract*— Soft mechanical sensing is crucial for allowing soft robots to operate in unstructured environments, and for developing smart wearables, unobtrusive for the user. Here, we present some recent achievements in soft sensing technologies, exploiting different transduction mechanisms. In all cases, the materials, the designs, and the signal processing strategies aim to the integrated fabrication of soft robots and wearables with sensing capabilities.**

***Keywords*— soft tactile sensor, wearable sensing, tactile skin**

I. INTRODUCTION

In robotics in general, artificial soft tactile sensing must be developed to enable robots to gather external information of various types (i.e. pressure, texture, slippage, etc.), static or dynamic, local or distributed. In soft robotics the challenge is to provide such information through a soft system in the body of the robot, so that by compliant physical interaction the robot ‘knows’ the outer world and can perform intelligent and safe interactions within it. Equally important is the perception of position and movement in space, for achieving soft autonomous systems (i.e. going beyond open-loop control) that smoothly interact and implement movements, reacting to unexpected events. In fact, modelling accurate behaviour of a soft robot is a quite challenging task, due to the complex behaviours of the constituent materials. Also their position/configuration can be passively changed by unknown external loads. Thus, a soft robot cannot perform a task accurately with open-loop control, and tactile sensing is unavoidable for controlling robots in real-world scenarios. Across all the different needed sensing capabilities, soft mechanosensing provides key sensory feedback. This kind of soft transduction is also useful for wearable sensing that play an increasingly important role in healthcare systems. Detection of human movement requires lightweight, flexible systems to detect mechanical parameters (like strain and pressure) not interfering with user activity, and that he/she can wear comfortably. Our group is active in developing innovative technologies and solutions for soft perceptive robots and wearable systems, ranging from fundamentals studies on transducer mechanisms to complex architectures. In the following section, some recent examples of soft tactile systems are briefly presented, based on different transduction mechanisms.

II. SOFT MECHANOSENSING TECHNOLOGIES

A. *Capacitive soft sensing for wearables*

The capacitive mechanism has been widely exploited for soft tactile sensors, electronic skins and soft strain sensors. The main advantages are high sensitivity, good linearity, and robustness to temperature and humidity variations. Recently, applications in wearables and soft robotic systems have started to grow rapidly because of the development of stretchable conductive electrodes. Especially in the case of wearable systems, one of the main issues for these sensors is their sensitivity to external electromagnetic fields and to the proximity with conductive objects. Thus, shielding techniques are needed. As an example, we recently developed three-electrode strain sensors, shown in Fig 1, and integrated into smart wearable systems for the movement analysis of lower limbs [1]. Due to the sensing element arrangement and to the real-time processing, knee flexion-extension can be monitored in its full range of motion with RMSE less than 4°, while for the ankle 3 DOFs can be monitored simultaneously.

Fig. 1. Shielded strain capacitive sensors, based on three-electrode architecture (top panel), integrated into smart wearable braces for knee and ankle movement monitoring [2].

B. *Inductive*

Recently, soft inductive sensors are emerging for their high sensitivity and versatility [3]. Different mechanisms can correlate mechanical deformations and inductance variations (i.e. self-/mutual inductance, eddy-current effect, or magnetic reluctance). To date, soft inductive tactile sensors have been developed based on both the Eddy-current effect [3] and the magnetic reluctance of magnetorheological elastomer [4] (MREs), which represent a step forward in finding a robust, resilient, high-performance sensing solution (as demonstrated in the hammer strike). On the other hand, self-inductance of helical coils has been utilized for extension/contraction [5], [6] sensing of pneumatic artificial muscles (PAM) and bending angle sensing in wearables [7]. Recently, the authors developed a new sensing mechanism for folding angle and bending curvature measurement through self-inductance variations of planar coils undergo deformation, the Soft Inductive Angle Sensing (SIAS) [8].

As illustrated in Fig. 2, the SIAS operates through magnetic field coupling in space, and it is independent from electrical and mechanical properties of the conductive traces and substrate materials and insensitive to local defects in fabrication or integration. Unlike the strain-based angle sensing approaches, the SIAS is velocity-independent, and hysteresis-free, ensuring accurate measurement in real-world applications. Experimental results also indicate that the SIAS is extremely stable (0.08° drift in 10000 folding cycles) and ultrasensitive (resolution of 0.001°).

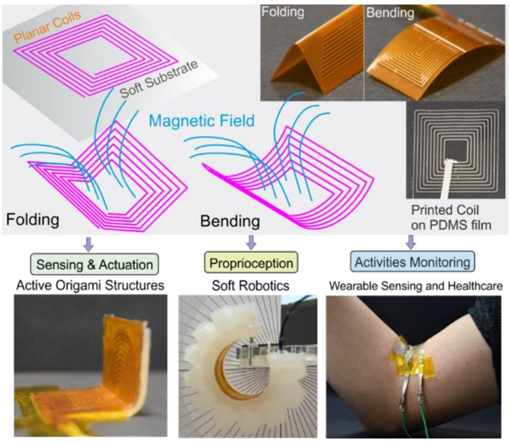

Fig. 2. Illustration of the working principles of folding angle and bending curvature sensing via planar coils and three case studies (active origami, soft robotics, and wearables).

In this work, a numerical analysis tool was developed to rigorously investigate the inductance variations of planar coils undergo folding and/or bending deformations.

Extensive experiments were performed to evaluate the sensing performance comprehensively. And three case studies were demonstrated to highlight further some promising features of this sensing mechanism, like easy-to-implement, versatility, high performance. The first case study is a flexible bilayer sheet made of a flexible planar coil and a shape memory polymer (SMP) sheet, in which the coil was used for simultaneous actuation (via thermal heating) and folding/unfolding angle sensing (self-inductance of the coil). And the flexible and soft LM coils were also attached to a soft bending actuator and the inner side of the elbow for proprioception and wearable angle sensing, respectively.

C. *Optical*

Optical-based tactile systems are an up-and-coming solution for soft robotics. In this case, the light emitted by a LED is transmitted through a soft optical fiber or waveguide. If integrated into a soft system (i.e. a robot or an exoskeleton) movements and tactile interactions cause a deformation in the transmission medium, consequently a variation of detected light intensity on the other end of the waveguide. This technology enables high resolution and large sensing areas, broad sensitivity range and high reliability with low susceptibility to EMI. A large-area skin can be obtained by combining several emitter/detectors. Besides, the sensing area can be completely free of rigid sensing elements and electronic boards that can be located on the periphery. This approach allows to tune and exploit the mechanical properties of the soft substrate. Furthermore, this happens to be a solution in every kind of application in which the sensing area undergoes large deformations and cyclic indentations that are well tolerated by the bulk material. In contrast, the more fragile electronics is less prone to be involved. On the other hand, this technology has been generally less exploited since materials must fulfill optical transparency and elasticity requirements. Moreover, it requires typically complex signal processing algorithm and, by consequence, higher computational power. One possible approach is based on back-projection reconstruction techniques [9], but it is computationally demanding, making difficult real-time reconstruction. Instead, a promising alternative method exploits the recent development of machine learning and artificial intelligence [10]. In this way, the algorithmic complexity can be distributed between the soft material interface and the software to achieve a real-time reconstruction of the pressure map within the sensing area. This approach makes it possible to extract multiple mechanical cues from an extended soft skin or a sensorized 3D body.

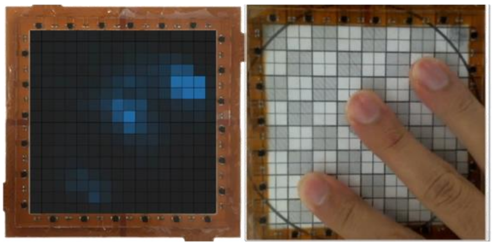

Fig. 3. Example of online multi-touch reconstruction on an optical-based tactile skin with IR LEDs (emitters) and phototranssitors (detectors) located alternatively at the perithery of the active area.

III. CONCLUSION

Mechanical sensing can be developed by using soft materials by means of known transduction principles (e.g. capacitive) in layouts providing low-noise and precise measurements, in spite of inherent non-linearity. However, what is most attractive in the field is exploiting material deformability in order to invent new transducers by known phenomena (e.g. inductive, optical) enabling new human-machine interfaces and robotic applications.

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