Progress in Soft, Flexible, and Stretchable Sensing Systems*

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***Abstract*— Soft sensors hold the promise of new applications in wearable electronics, soft robotics, and human-machine interaction. Commercially available sensors do not currently fill the needs of these applications. Here we present an overview of different technologies we have developed in the last two years in order to address the needs for soft sensing systems. These include fully soft sensors made of rubber with embedded micro-channels filled with a liquid metal and a barometric sensor embedded in rubber used as a high sensitivity pressure sensor. Compared to traditional rigid sensors, these highly compliant sensing skins provide valuable information with minimal impact on the host system, robustness in harsh environments, impact resistance, and are composed of low cost materials. Here we highlight sensors that measure pressure, strain, curvature and shear.**

I. Introduction

An emerging area of interest for electronic sensing systems is the fabrication of sensors from soft materials, such as rubbers. The goal is to gain valuable sensing information while minimizing the physical impact on the host system. In addition to their compliance, these sensors have the advantages over more traditional sensors including impact resistance, reduced-cost, low power, and tolerance to strains over 100%.

The following sections present two different approaches to use soft materials in sensors.

II. Type of Sensors

A. Soft Sensors

Soft sensors are made out of two main components; a soft elastomer (e.g. modulus 69kPa, capable of 900% strain) containing embedded micro-channels filled with a liquid metal (eutectic Gallium-Indium or eGaIn). This metal is liquid at room temperature and has high electrical conductivity.

1) Principle of operation

Sensors are created by a sequence of molding, lamination, then syringe filling.

Due to its compliance, the effect of pressure or strain modifies the cross-sectional area of the micro-channels, thus increasing its electrical resistance, as shown in Figure 1 [1]. Following this principle, and by modifying the micro-channel geometry, additional features, such as curvature [2] and surface shear [3] can be measured using only soft or liquid phase materials.

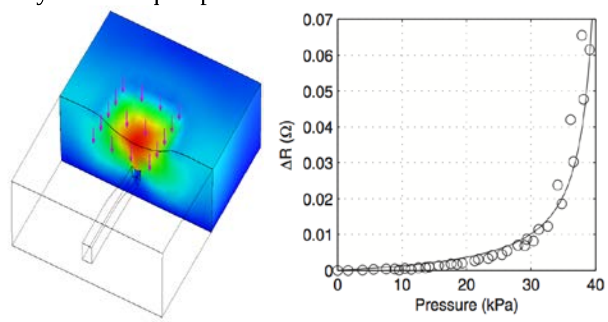

Figure 1: Soft Sensor response to pressure [1]

2) Applications

Soft sensors are natural for measurements on complex shapes such as the human body. Strain sensors and curvature sensor placed along joints can be used to capture motion [4]. This information can then be used for kinematics studies or as feedback in an adaptive soft orthotics system [5].

In the same way, pressure sensors can be used in insoles to map the pressure distribution between the foot and the ground. Pressure sensors can also be used as a tactile keypad [6] allowing a user to input data on an electronic skin.

Robotic hands for grasping can benefit from shear sensors with feedback force control. Indeed, sensing the normal and shear forces allows the hand to minimize the force needed and to detect slippage or failure.

B. "TakkTile": A barometric sensor embedded in rubber

The "TakkTile" [7] sensor is a commercially available barometric sensor adapted to sense contact forces. In order to do so, an uncured rubber is poured on the sensor. The sensor is then placed under vacuum so that the rubber infiltrates the sensor and contacts the sensing membrane.

1) Principle of operation

Once cured, force applied on the rubber above the sensor will result in an increase of the barometric pressure reading.

This method presents many advantages including robustness and high pressure sensitivity. Furthermore, using an existing barometric sensor provides the advantage of having analog to digital conversion directly on the chip. The data is transmitted over an I^2C bus communication, allowing multiple sensors on a single line.

2) Applications

In addition to grasping and manipulation, this pressure sensor can be used in harsh environments where the

*This material is based on work partially supported by the National Science Foundation (grant #DMR-0820484) and the Wyss Institute For Biologically Inspired Engineering. An opinion, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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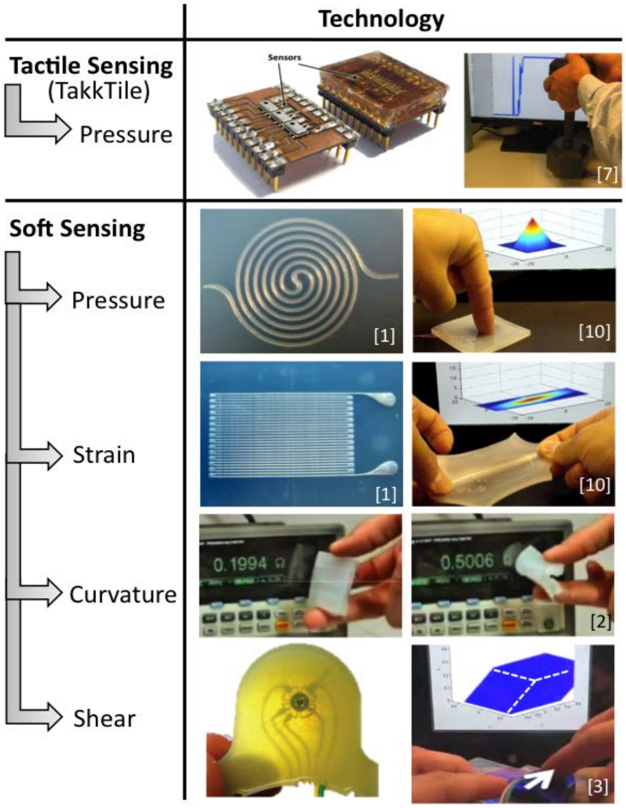

Figure 2: Examples of Sensor Technology

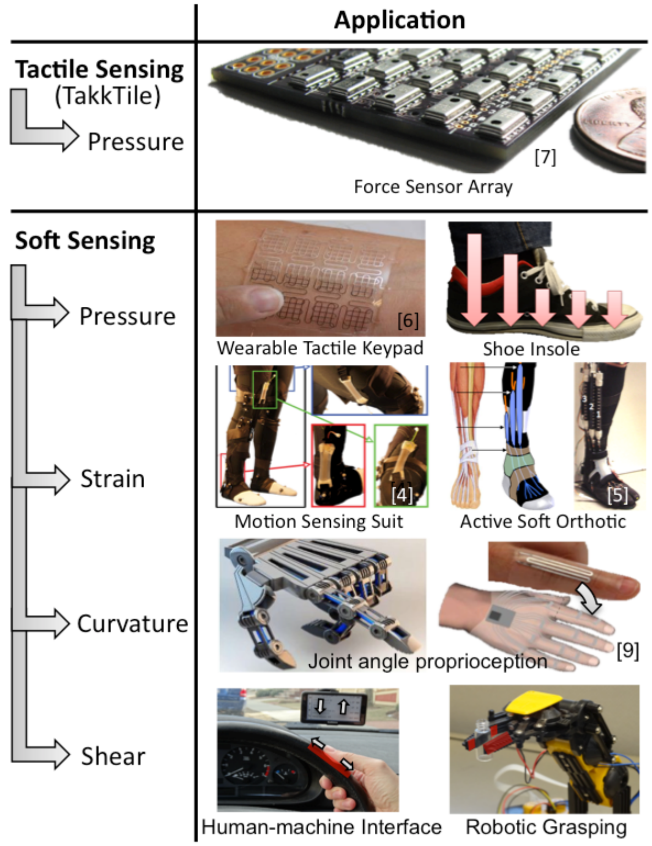

Figure 3: Examples of Sensor Applications

surrounding rubber can protect the sensor electronics from shocks and liquids. Using the communication capability through a digital bus, force-mapping applications can be done as shown in a jamming gripper example [7] where flexible sensors fit on a compliant membrane.

Figure 2 and Figure 3 show examples of the sensor technology and application described in this paper.

III. Sensor Specifications & Future Directions

Table 1 summarizes the specifications of the sensors. Although these sensors are scalable for certain specifications, typical values of the sensors are presented. The advantages of these sensors are mainly conformability to complicated 3D shapes, which makes them adaptable to various applications. The current limitation is the interface between soft materials and the rigid host structures, which can be overcome using stiffness gradient materials on the interface areas.

Our future work will focus on new technologies to build sensors out of soft elements. Some effort will also be brought in the usage of such sensors in particular in sport and medical applications.

Table 1. Typical specifications for each sensor types

	TakkTile	Soft Sensors			
	Pressure	Pressure	Strain	Curvature	Shear
Range	177 kPa	40 kPa	100% strain	150 m^{-1} curvature	50 kPa
Sensitivity/ Gauge Factor	0.05 count/Pa	GF=2.5	GF=3	0.31mΩm curvature	8.4 mV/kPa
Failure	-	-	350% strain	-	180% strain

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