SensorNets: Towards Reconfigurable Multifunctional Fine-grained Soft and Stretchable Electronic Skins

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Abstract

SensorNets is a bioinspired electronic skin integrated with multimodal sensor networks for interactive media applications, from wearables, self-aware objects, to intelligent environments. It is developed by connecting miniaturized flexible printed circuit boards as two-dimensional sensor arrays with stretchable interconnects. The system is embedded in between soft deformable layers, such as textiles or rubbers. The result is a soft sensate surface that can be distributed and conformally wrap and adapt to curved structures. Each node contains a microprocessor together with a collection of nine sensors and a light-emitting diode, providing multimodal data that can be used to detect various deformation, proxemic, tactile, and environmental changes. We show that the electronic skin can sense and respond to a variety of stimuli simultaneously, as well as open up a possibility for sensor-rich virtual and augmented reality-based visualization and interaction.

Author Keywords

Flexible-stretchable electronics, sensor networks, smart materials, deformable interfaces, spatiotemporal mapping, sensor visualization.
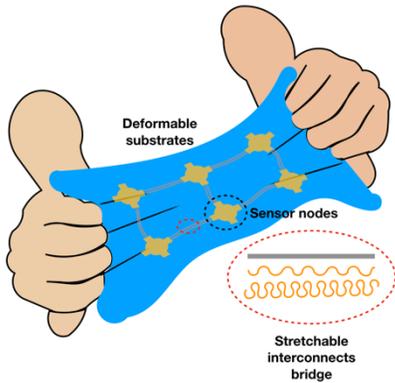
Figure 1: SensorNets concept illustration.

(a)

(b)

Figure 2: a) SensorTape vs SensorNets, b) Illustration of large-area 2-D sensor networks on fabric (scale bar, 3 cm).

CSS Concepts

• **Hardware~Sensors and Actuators;** Sensor applications and deployments; Human-centered computing~Mixed/augmented reality.

Introduction

Recent developments in materials science, fabrication technology and biomedicine have pushed forward the field of flexible and stretchable electronics to bridge the gap between electronics and the human body, particularly the human somatosensory system [1,2]. The somatosensory system consists of sensory neurons and receptors spread around the periphery, such as in the skin, muscle, and organs, to the brain and spinal cord as the central nervous system. The human skin, for example, is a remarkable example of large-coverage and fine-grained sensing system, as it incorporates multiple sensing modalities (e.g. temperature, nociception, mechanical, chemical, and *et cetera*) into a dense substrate. In addition to sensing, it also serves many other functions, such as for radiation and pathogen protection, thermal regulation, and waterproofing in a seamlessly deformable form-factor [3]. The somatosensory network also processes data through two-way complex interactions at many levels throughout the nervous system, from the skin, around the spinal cord, to the brain's cortex [4].

Inspired by the complexity and mechanics of our biological skin and the somatosensory system, SensorNets presents an effort towards high-density multifunctional electronic skin (e-skin) network in a soft and stretchable form-factor. This e-skin can augment contact and non-contact sensing to an object or surface, for applications ranging from robotics, wearable health monitoring and rehabilitation, gaming, to telepresence. The array of sensor nodes also offers opportunities for the exploration and testing of e-skin network, communications, scalability, as well as human-computer interaction capabilities of large and dense sensor network deployments [5-7].

Related Work

There has been a significant effort conducted in skin-inspired spatiotemporal sensing, but the emphasis is still currently on specific modalities and fabrication technologies [8,9]. Direct deposition [10], transfer-print [11], and ink-jet, three-dimensional (3-D), or screen-printing [12] techniques have been demonstrated to fabricate electronics in stretchable substrates such as textiles, polydimethylsiloxane (PDMS), or Ecoflex. Stretchable interconnect principles have also been applied, including pre-stretching of a substrate, meander-like designs, or synthesizing intrinsically stretchable metals [13]. Most of these approaches, however, require sophisticated machinery and specialized fabrication process. Several HCI work also result in novel multimodal sensing surfaces [14-17]. Nevertheless, their connections tend to be centralized and multiplexed, with a large amount of wirings, restraining them from large-scale, scalable deployment, and widespread adoption [18].

Our previous work demonstrated the concept of modular and reconfigurable sensors and electronics platforms as "Sensate Media" [5] in various form-factors, from rigid Z-Tiles [19] and ChainMail [20], flexible sensing floors [21], spherical Tribble [22], to cuttable papers [23] and tapes in SensorTape [24].
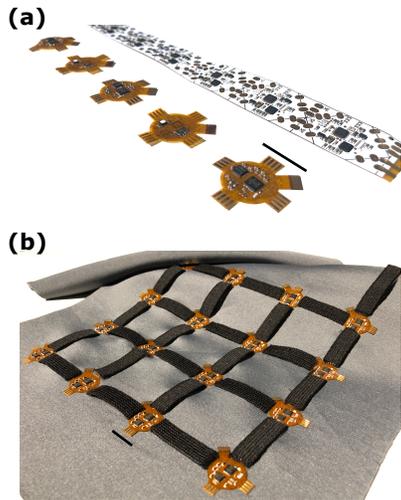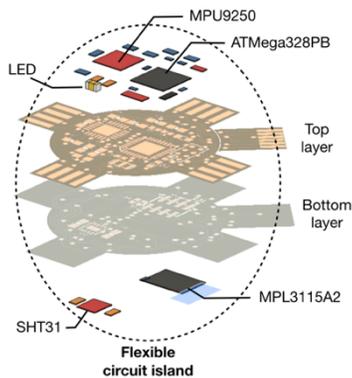
Figure 3: Exploded view of a sensor node.

Sensor Modules

MPU9250, Invesense: 9-axis Accelerometer (± 2-16g, scale 16-bit), Gyroscope (± 250-2000°/sec, 16-bit), Magnetometer (± 4800uT, 14-bit), and On-chip temperature (-40–85°C, 4%). *Applications*: tap, touch, deformation (bend and stretch), proxemic magnetic field, and temperature sensing.

SHT31, Sensirion: Humidity (0-90%, accuracy ±1.5%) and Temperature (0-90°C, 0.2°C) *Applications*: environmental, human body (skin), and air flow sensing.

MPL3115A2, NXP Semi: Pressure (20-110kPa, 20-bit), Altimeter (-698-11775m, 20-bit), and On-chip temperature sensing (-40-85°C, 1°C). *Applications:* environmental, altimetry, and tactile pressure sensing.

Table 1: Sensor module characteristics and applications.

However, none of these work is soft, malleable, or stretchable. Recent trends show the possibility of soft modular electronics [25,26]. Still, there is currently not many stretchable electronics work with self-aware and sensor-rich capability, specialized networking architecture, and extensive interaction and application study outside the physiological sensing, which is the basis of this work that we will further develop.

Device Design

As illustrated in Figure 1, SensorNets consists of a flexible printed circuit board (PCB) islands (3 x 3 cm size) as the sensor node connected with each other through stretchable interconnects. Each node consists of a microprocessor that communicates with several sensors and a light-emitting diode (LED). We designed and fabricated two-layer flexible polyimide PCB (Figure 3) with copper traces (120 μm thickness), and additional polyimide stiffener (75 μm thickness) for rigid electronic chips support. We incorporated flexible flat cable (FFC) pad with six-pins in-system programming (ISP) signals for programming as in [27]. Each node also has four pads (VCC, SDA, SCL, and GND) in all directions for Inter-Integrated Circuit (I^2C) communication between all sensor nodes as slaves with the central node (Teensy 4.0 or Arduino) as a master. After assembling all of the components on the PCB, we attached each node to the stretchable fabric (Neoprene) using fabric adhesive (Platinum Bond, Aleene's) and laser-cut some holes in the fabric for sensor modules that require exposure to the environment.

In comparison to the SensorTape (Figure 2a), SensorNets design and architecutre allow two-

dimensional (2-D) connection between each sensor node. SensorNets deformability allows it to conform and adapt to large 2 to 3-D surfaces, as shown in Figure 2b. The stretchable interconnects can be realized using several methods. One method, as demonstrated in our work, uses four serpentine stranded wires woven in an elastic ribbon textile (E12L2, Ohmatex). This conductive elastic ribbon can be stretched to up to 30 % with an impedance of 0.4 Ω/m. The encapsulation or outer shell can also be customized with other types of materials. The stretchability here is achieved by the structure of the interconnects. Since copper wires are used, there is not much compromise between the length and the resistance of the interconnects. The stretchable interconnects can be connected reliably to each side of the I^2C pads through soldering. Another possible technique relies on the fabrication of conductive elastomer matrix, such as using silver (Ag) nanoparticles and polymers or liquid metal (GaIn) intrinsically stretchable interconnects.

Our sensor modules, as described in Table 1, enable each individual and a collection of nodes in the SensorNets to achieve somesthetic senses. The nodes can detect touch, perform proprioception, haptic perception, nociception, or even proxemic interaction with the inertial measurement units (IMU) (accelerometer and gyroscope), temperature, humidity, deformation, pressure, tactile, and magnetic field sensing.

System Implementation

The SensorNets system is composed of multiple sensor nodes, which can be distributed and assembled in various configurations. Our architecture is illustrated in
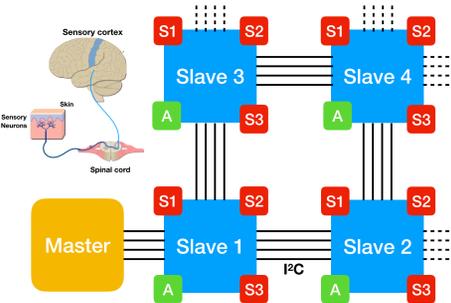
Figure 4: Sensor networks architecture inspired by the somatosensory system.

Figure 4. The network has one master, and all the sensor nodes on the fabric are slaves. Each slave contains a microcontroller (ATMega328PB, Microchip), an LED and the sensor modules. We chose this microcontroller since it has two I^{2}C (SDA and SCL) channels: one for communication to the master and other slaves, and the other one for communication to sensor peripherals (MPU9250, MPL3115A2, and SHT31).

Before distributing and connecting the slaves, we assign address on each of the sensor nodes with USB AVR programmer through the FFC connector socket. We used the I^{2}C communication bus running at 400 kHz to talk between the master and slaves. Each master can handle up to 128 sensor nodes. It deals with coordinating the communication, processing, controlling, as well as transferring all sensor data from all of the sensor nodes to the PC. The data transferred through serial can then be further processed for real-time recording and visualization by connecting it to Matplotlib, Processing, or OpenCV.

Results

As an initial prototype, we fabricated four sensor nodes with 4 cm interconnects gap. Figure 5 displays the 2 x 2 sensor nodes tested under various stimuli and conditions. The sensor data that correspond to each stimulus are shown in Figure 6. Note that in here, we only plot the sensor parameters that are relevant to their stimuli. Figure 6a shows all of the accelerometer data on each sensor nodes upon finger touch and strikes. As demonstrated, we could localize where the touch happens based on the distance of strike from each sensor node. The accelerometer and gyroscope

(MPU9250, Invesense) on each sensor node can also be used to detect deformation (bending, folding, twisting, and stretching). The deformation sensing can be performed by measuring angle or degree of the gyroscopes, as well as direction and speed of the accelerations, as illustrated in Figure 6b-e. The magnetometers can also be used to track magnet movements and location in the air (Figure 6f) for proxemic interaction [28]. We observed with the magnet we used, that each sensor node is responsive to its presence to up to 10 cm.

We modified the MPL3115A2 (NXP Semiconductors) barometer function from measuring atmospheric to tactile pressure by casting, degassing, and curing PDMS, a soft rubber agent around the chip [29]. The encapsulation enables each sensor node not only to detect light touch sensitively, but also moderate and strong presses (Figure 6g). Lastly, we demonstrated the SHT31 (Sensirion) nodes to accurately sense temperature and humidity change by exposing it to hot air (Figure 6h).

Applications

Deformation sensing and visualization

To demonstrate the ability of each sensor node to calculate its position relative to its peers and to sense deformations, we performed an algorithm [24] on the quaternion orientation data from the IMU on each sensor node that map them to a kinematic chain model. As shown in Figure 7, we breakdown all deformations of four sensor nodes in 4 x 1 array into bending (movement in X and Y plane) and twisting (Y and Z plane) and visualized it with Processing in real-time.
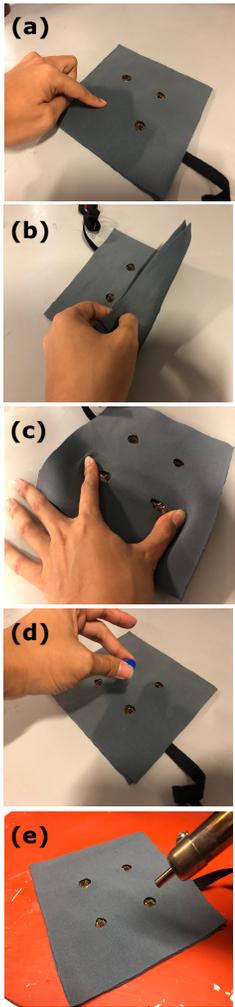
Figure 5: Different gestures and stimuli. a) tapping, b) folding, c) stretching, d) magnet approach, and e) hot-air gun.
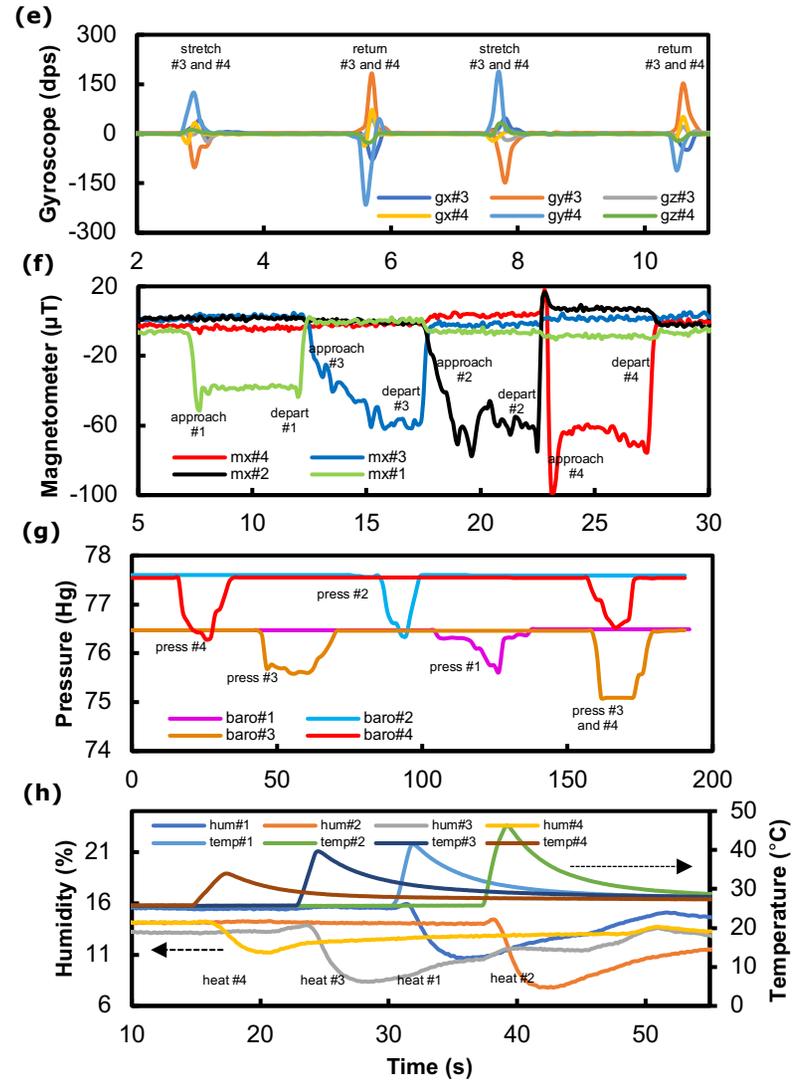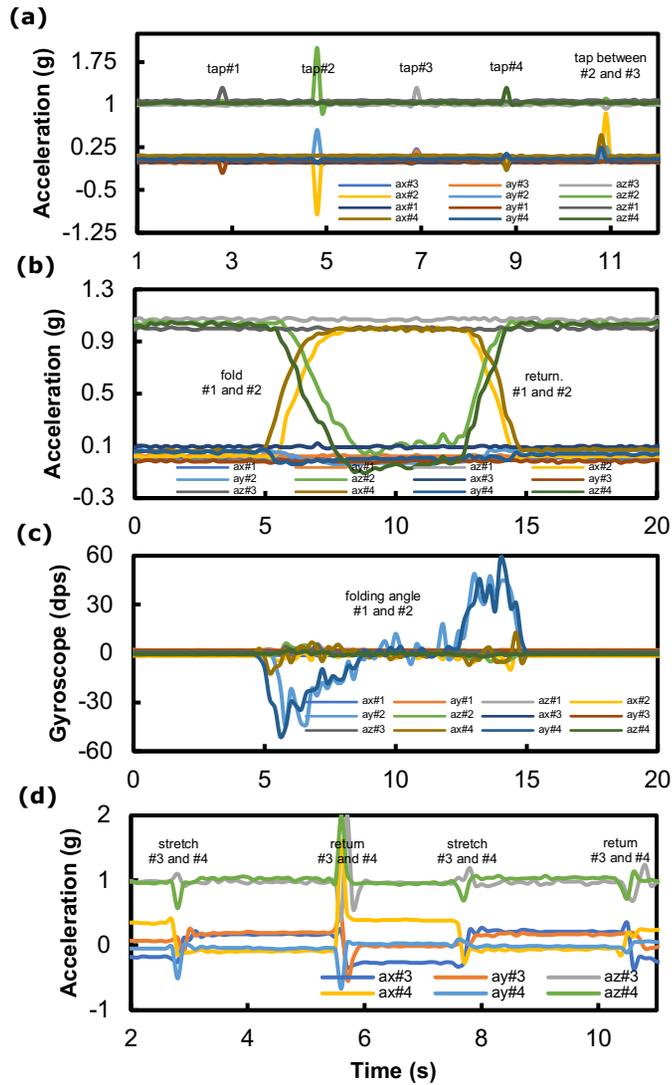

Figure 6: Sensor data results from: a) finger tapping, b-c) folding, d-e) stretching, f) magnet approach, g) finger pressure, and h) hot-air exposure.
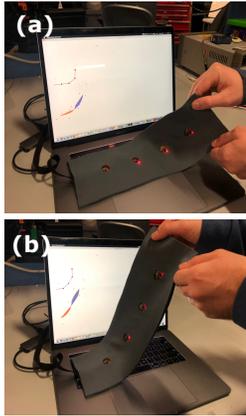
Figure 7: Real-time visualization of deformation sensing.

Figure 8: Three different visualizations of the LEDs when turned on. a) shows brightness intensity, b) the sensor streams, and c) a mole game.

Sensor nodes localization and AR-based interaction

Augmented Reality applications provide a way to overlay digital information on top of physical objects. Work such as LightAnchors [30] uses a computer vision algorithm to identify the location and states of LED in the environment and maps information on top of them without markers. We developed a simple AR application for LED tracking, localization, and information mapping to each sensor node using OpenCV blob detection algorithm.

Figure 8 shows three examples of AR-based visualizations. In Figure 8a, the application identifies the brightness intensity of each LED in a 2 x 2 matrix that is on and overlays that information above each node. Figure 8b demonstrates an example of overlaying and mapping digital information about the sensor data on every node. We also envision an application in gaming, in which a "whack-a-mole" interactive avatar appears (Figure 8c) above the sensor node that the user hits by reading the value from the pressure sensor.

Future Work and Improvements

The future development of SensorNets will focus on several aspects. First, we will further miniaturize every sensor node, add other sensor modalities to expand the applications, and to realize a prototype with a dense and large number of sensor nodes. We will look closer on to mapping stretch events, detecting and classifying various gestures, and interpolating data from many sensor points. Future work may also extend our system with more actuators, enriching its capability as a multimodal interface.

We will explore several materials to enable cutting and reconnecting of the stretchable array [23,29] and develop manufacturing techniques to increase our throughput while simplifying our fabrication and assembling flow. We are also interested in studying other network protocols and localizations that can make our system more efficient and accurate, and in incorporating duty-cycling and wake-up interrupts to minimize the overall power consumption [32]. Finally, we will continue our efforts in developing novel visualization and interactions for on-skin sensing, self-aware objects, and intelligent environments based on a 2-D array of e-skin networks.

Acknowledgements

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