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BIO-INSPIRED SYSTEMS

FROM ARTIFICIAL SKIN TO BIOLOGICAL INTELLIGENCE

ASME

ARTIFICIAL SKIN

SOFT ELECTRONICS & SENSORS FOR BIO-INSPIRED ROBOTS AND WEARABLE COMPUTING

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In order to match the versatility and robust mechanical properties of their natural counterparts, bio-inspired robots must be soft and elastically deformable [1]. This not only requires new classes of "artificial muscle" actuators but also artificial nervous tissue and skin to support stretchable electronic connectivity, sensing, and automation. In recent years, a broad range of materials, composites, and so-called "deterministic" micropatterned architectures have been introduced to support soft and stretchable electronic functionality [2]. These include conductive textiles, wavy circuits, graphene and nanotube films, filled elastomer composites **(Figure 1)**, and liquid metal microfluidics **(Figure 2)**. A common feature of these materials and architectures is their intrinsic mechanical compliance, stretchability, and low mass density. Such properties are especially important in wearable systems for personal computing and human motor assistance. By matching the mechanical properties of skin and nervous tissue, these materials can be mounted to the body or embedded in clothing without causing discomfort or injury. However, replacing rigid (and semi-rigid, i.e. flexible but inextensible) electronics with stretchable materials introduces new

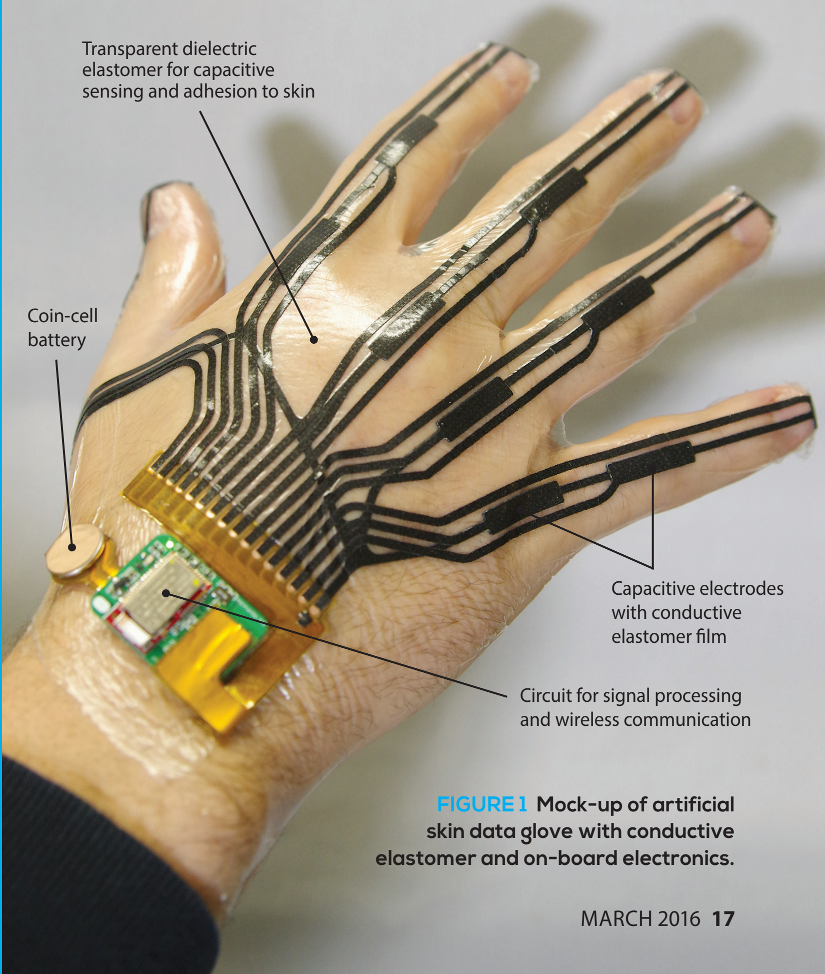

FIGURE 1 **Mock-up of artificial skin data glove with conductive elastomer and on-board electronics.**

challenges in dynamic state estimation and feedback control. As they deform, soft circuit and sensing elements can exhibit dramatic changes in electrical conductivity, capacitance, or inductance. This electro-elasto coupling has important implications in circuit design and sensing functionality. Addressing these effects in soft bio-inspired systems represents a new and exciting opportunity to merge the mechanics of materials with sensing and controls.

Sensorized electronic skins are an essential element in wearable computing and co-robotic systems that engage in physical interaction with humans. These include strain and bend sensors for joint proprioception and gesture monitoring, pressure sensors for monitoring surface tractions, and tactile sensors for detecting light touch and data entry. A variety of sensing architectures and materials are currently being explored in the Soft Machines Lab (SML) at Carnegie Mellon University. This work incorporates conventional microelectronic and flex circuit technologies and also builds on principles and practices in the emerging fields of *soft robotics* and *soft-matter engineering*.

FIGURE 2 **Tactile sensor with laser-patterned traces of eutectic gallium-indium (EGaIn) liquid metal (LM) embedded in silicone elastomer.**

ARTIFICIAL SKIN FOR SOFT ROBOTS

Like their counterparts in nature, soft bio-inspired robots are primarily composed of lightweight elastic materials that can easily deform and adapt their shape to contacting surfaces [1, 3]. This compliance and mechanical versatility allows soft robots to grasp delicate objects and navigate through tightly confined spaces with limited sensing and closed-loop control. Quadrupeds, undulators, and snake-like robots represent a particularly exciting class of soft bio-inspired systems that could have a revolutionary impact on unmanned, autonomous field exploration, particularly in unmapped or unstructured environments.

Examples of soft robot quadrupeds are presented in **Figure 3**. The quadruped limbs contain artificial muscles that are typically powered with pneumatics/inflation [4,5] or shape memory alloy. Ionic-polymer metal composites (IPMCs), dielectric elastomer actuators (DEAs), combustion, motor-driven cables, and series elastic actuators represent other common sources of actuation in bio-inspired robotics [6-8]. The latter two are particularly popular for humanoid robots that engage in physical human interaction during assistive co-robotic tasks.

Just as soft robots depend on artificial muscles for actuation, they also require artificial skin and nervous tissue for sensing, wiring, and signal processing. As with technologies for wearable computing, these sensors and circuits must be soft, lightweight, and stretchable so that they don't interfere with the mechanics of the host. Therefore it helps to turn to recent advancements in wearables in order to identify materials and sensing architectures for soft and elastic functionality.

SENSORS FOR NEXT-GENERATION WEARABLES

Wearable computing is a rapidly growing sub-domain in the electronics industry and has the potential to transform how we work, play, get information, and interact with others. There are already thousands of wearable electronic devices on the market, with millions of users and projections for hundreds of millions more within the next 5-10 years [9]. Although most existing wearables are constructed from conventional solid-state microelectronics, there is increasing interest in incorporating novel materials and architectures. One

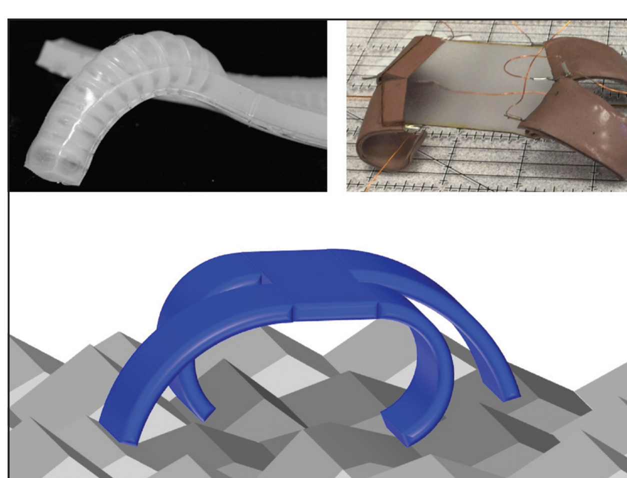

FIGURE 3
Soft quadruped robots with artificial muscle limbs powered by (above left) pneumatics [4,5] or (above right) shape memory alloy.

FIGURE 4 Materials and architectures for wearable computing (clockwise from top left): iSkin with conductive silicone elastomer [10]; wireless dataglove with adhesive electronic skin; wavy copper traces for stretchable functionality [11]; UIUC Electronic Tattoo [12].

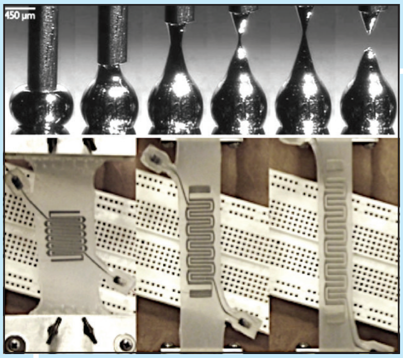

FIGURE 5 (top) Eutectic gallium-indium (EGaIn) alloy is a "moldable" liquid that forms a nanometer-thin oxide skin in air [15]. (bottom) A fluidic channel of EGaIn embedded in silicone deforms with the surrounding elastomer [17].

popular approach is to use elastomeric composites in which rubber is embedded with percolating networks or films of micro/nano-scale conductive filler. Early efforts have focused on structured carbon black (see top insets in **Figure 4** [10]) and metal powders, while more recent attention has shifted to co-polymer blends, silver flakes, carbon nanotubes, and graphene [2]. Another emerging technique is to interface solid state sensors with wavy circuits and other so-called "deterministic architectures" that achieve stretchable functionality through pre-buckling, wrinkling, helicity, or serpentine shapes (e.g. bottom insets in **Figure 4** [11,12]).

In recent years, there has also been increasing interest in using soft microfluidics. This includes soft silicone elastomers that are embedded with microfluidic channels of ionic solution [13]. Stretching the elastomer or applying pressure to the surface alters the geometry of the channels and changes its electrical resistance. By monitoring this change in resistance, the elastic deformation can be inferred. An alternative is to replace the ionic fluid with liquid-phase metal alloy. As far back as the late 1940s, liquid metal (LM) electronics have been used for stretchable wiring and stretch sensing – most notably the mercury-based strain gauge developed by Reginald Whitney for biomechanical measurements [14]. In 2007, researchers at Harvard University discovered an approach to LM-based soft microfluidic electronics involving a safe alternative to mercury [15]. This is accomplished with eutectic gallium-indium (EGaIn; see inset of **Figure 2**). EGaIn is an alloy composed of 75% Ga and 25% In (by wt) that is liquid at room temperature, has high electrical conductivity ($\sigma \sim 3\times10^6$ S/m), low toxicity, and negligible vapor pressure. As shown at the top of **Figure 5**, the liquid oxidizes in air and forms a nanometer-thin oxide skin

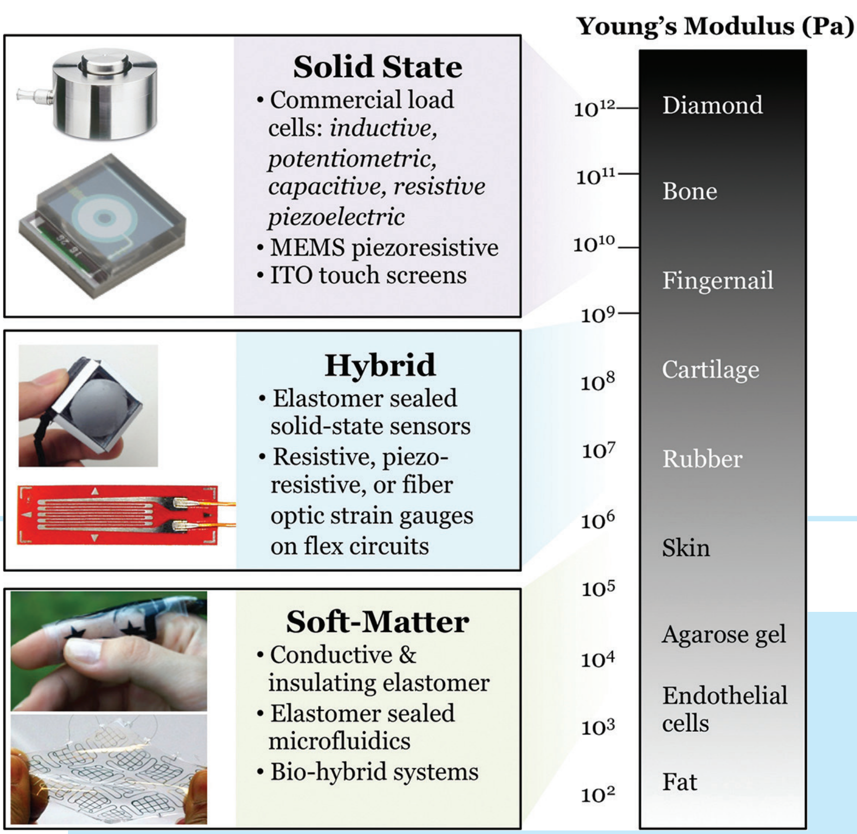

FIGURE 6 Pressure and strain sensing technologies for robotic grippers. Soft robotic applications require "soft-matter" and "hybrid" technologies that match the mechanical compliance (e.g. Young's Modulus) of soft biological tissue.

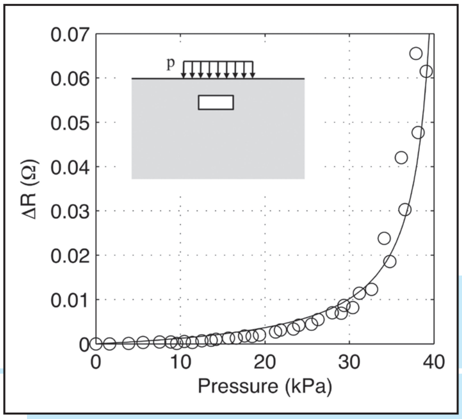

FIGURE 7 **Change in electrical resistance (ΔR) of an EGaIn channel in response to surface pressure (p) applied to the surrounding silicone [18].**

that allows the droplet to hold its shape and be molded. Such oxidation and moldability allows EGaIn to be patterned with a variety of techniques based on soft lithography, additive manufacturing, and laser rapid prototyping [16]. It also enables wetting to soft silicones and urethanes so that the liquid channels can conform to stretch and other deformations (bottom **Figure 5**, [17]).

Lastly, there are opportunities to integrate conventional sensing technologies with soft materials and deterministic architectures. Referring to **Figure 6**, these *hybrid* technologies combine the sensing mechanisms (resistive, capacitive, inductive, optical) of solid-state devices with the soft, flexible, and stretchable functionality of elastomeric and thin-film technologies. Such integration is especially important for precision sensing and measurement of vitals for personal healthcare monitoring. For example, a pulse oximetry or glucose monitoring chip mounted to a wavy or soft microfluidic circuit can be embedded into a bandage or clothing and placed virtually anywhere on the skin. Current technical challenges include electrical interfacing between solid-state chips and soft-matter circuits and antennae as well as power for RF transmission.

Figure 6 also shows the difference in Young's modulus for different sensing technologies and how they compare with materials in nature. Young's modulus scales with the force required to elastically deform a material and is only defined for small (<1%) strains. In the case of soft and biological materials, there are other essential metrics for capturing elastic and rheological properties, including strain limit, shear modulus, and dynamic (shear) viscosity. Moreover, mechanical compliance and deformability represent just a few of the many properties that a sensor must exhibit for applications in soft robotics and wearable computing. Attention must also be given to the influence of materials selection and sensor architecture on dynamic range, sensitivity, bandwidth and allowable sampling rate, signal-to-noise ratio, and hysteresis.

Because of the large spectrum of materials, layups, geometries, and sensing mechanisms, there is an almost endless number of possible design combinations. In order to navigate this vast design space, it helps

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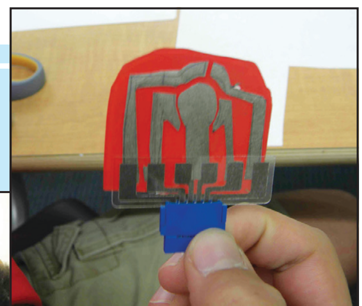
to have reliable theoretical models or computer-aided tools that accurately predict sensor performance under anticipated loading conditions. This includes multi-physics models that combine 3D elasticity, electrodynamics, and effective medium theory to predict the change in the electrical properties of a soft-matter circuit embedded in an elastically deforming medium. **Figure 7** shows an example of one theoretical model for predicting the change in electrical resistance of an EGaIn channel as surface pressure is applied to the surrounding silicone. This strong agreement is achieved without data fitting and utilizes a combination of Ohm's law along with classical solutions in linear elasticity [18]. Models like this have the potential to dramatically reduce the number of design iterations required to select appropriate materials and geometries for soft microfluidic sensing.



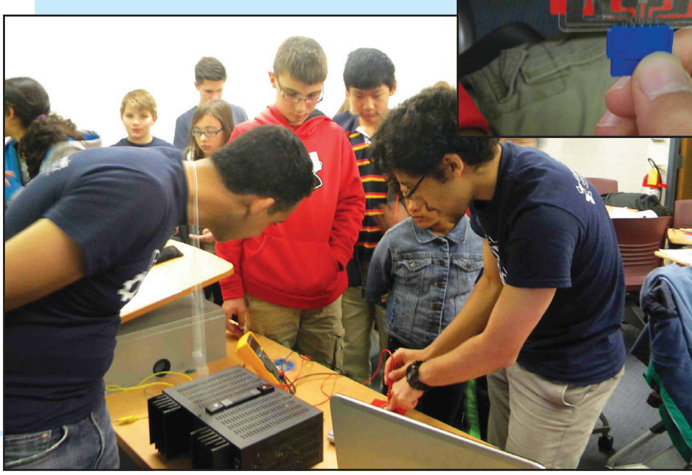


FIGURE 8 Middle-school workshop on materials for wearable computing with hands-on interactive.

OPPORTUNITIES FOR STEM OUTREACH

Because of its close connection to personal electronics and fashion, artificial skin technologies represent a good opportunity for STEM outreach at the middle and high school levels. Wearable technology is a promising path to STEM education since it is relevant to the daily experiences of teens and pre-teens, regardless of their social, cultural, and economic background. Through hands-on projects that combine e-textiles and fashion accessories with rapid prototyping and open-source electronics hardware, youth can readily connect STEM topics with arts, crafts, and personal expression [19]. Middle school students are an especially appropriate target, since they have adequate intellectual preparation for hardware prototyping but are still at the earliest stages of developing their academic interests.

Members of SML have participated in several outreach events on the theme of materials for wearable sensing. This includes an interactive in which students can produce their own wearable touchpad and use it to move a cursor or play Tetris. Instead of custom laboratory-prepared materials, we provide the students with commercially available conductive fabrics and elastomers that they can cut out and bond to a soft insulating adhesive (e.g. 3M VHB tape). An example is shown in **Figure 8**, taken from a recent workshop hosted by the Gelfand Center for Service Learning and Outreach at CMU. ■

ABOUT THE AUTHOR

Carmel Majidi was born in Wilmington, Delaware in 1980. He received his B.S. degree from Cornell University and M.S. and Ph.D. degrees from UC Berkeley. At Berkeley, he worked with Profs. Ronald Fearing and Bob Full to examine natural gecko adhesion and develop a gecko-inspired shear-activated adhesive. After completing his Ph.D. in 2007, Carmel was a postdoctoral fellow in the Princeton Institute for the Science and Technology of Materials (PRISM) and worked with Profs. Mikko Haataja and David Srolovitz (currently at UPenn) to examine the physics and morphological stability of piezoelectric nanostructures. Later, he did a fellowship at the School of Engineering and Applied Sciences at Harvard University where he worked with Profs. Robert Wood and George Whitesides to explore new paradigms in soft robotics and soft-matter electronics. In Fall 2011, Carmel joined CMU as an Assistant Professor, where he leads the Soft Machines Lab. He is a recent recipient of Young Investigator awards from DARPA, ONR, AFOSR, and NASA all for work related to soft-matter robotics and engineering.

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