Flexible Electronic Skin: From Humanoids to Humans

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With robots entering our lives in a number of ways, their safe interaction, while operating autonomously, has gained significant attention. We no longer speak of robots as only the industrial tools needed for repetitive tasks such as picking and placing, or robots kept away from people. Not that such tasks are unimportant, it is that significant progresses have been made in these application areas and now the focus is gradually shifting toward robots handling real-world objects under arbitrary circumstances, working safely alongside humans, and assisting them. The physical interaction by touching is important during such tasks to get an estimation of contact parameters (e.g., force, soft contact, hardness, texture, temperature, etc.) and this makes the tactile/touch sensors and haptic feedback critical for robot technology, which is opening up more and more applications [1] This trend will continue as we enter the era of smart factories, Industry 4.0, social robots, telesurgery, and so on, where robots are intended to work closely with human. Robotics is set to become the driving technology underpinning a whole new generation of autonomous devices and cognitive artifacts, providing a link between the digital and physical world. In fact, we are looking at a profound evolution, where artificial intelligent (AI) systems could be extended into robots with new embodiments for applications such as brain-controlled robots and haptic avatars [2]. New automation concepts such as human–robot collaboration (HRC) and cyber–physical systems (CPSs) are recognized as having the potential to impact and revolutionize the production landscape. A rich sensorization will be critical to such advances endowed with a large number of different sensors types (touch, temperature, pain, electrochemical, gas sensors, idiothetic sensing, etc.). Critical to these advances are the ways in which the technological advances are managed or made to develop electronic skin (e-skin) and the way it is employed to understand various dimensions of physical interaction in unconstrained environments [3].

This special issue provides state-of-the-art coverage of the theoretical, scientific, and practical aspects related to flexible electronic skin.

Developing appropriate technological building blocks (e.g., cameras, touch sensors, miniaturized actuators, etc.) for human–robotic interactions has been the focus of academic and industrial robotics research since the 1970s. In context with touch sensing, the early focus was on developing sensors using various transduction mechanisms (e.g., resistive, capacitive, optical, piezoelectric, magnetic, etc.). A large number of experimental devices and prototypes reported in the literature show a good diversity among the types of sensors that were developed in the 1980s. Particular attention was given to the development of tactile sensing arrays for the object recognition. The creation of multifinger robotic hands, in the late 1980s, increased the interest in tactile sensing for robotic manipulation and the works utilizing tactile sensing in the real-time control of manipulation started to

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appear [4]. Similarly, the multifinger prosthetics hands, in the 1990s, increased the interest in tactile feedback, although the major focus was on methods such as EMG-based control, and this continues till date. These early solutions for tactile sensing focused on the application in rigid-body robotics, while robotic is evolving toward softer and compliant robots. This means the e-skin should be soft, curvy (to conform to the robot's body), and over large areas. In this regard, the early solutions are nowhere close to the complexity of the e-skin system needed today. With the above features, the e-skin research is strongly linked to advances in electronics as it is one of the drivers for flexible electronics. In general, there is a large and ever-growing demand for flexible electronics and sensing, although the market is heavily dominated by flexible displays, flexible solar cells, and electronic paper [5], [6].

To realize e-skin, it is necessary to overcome the technological bottlenecks related to the integration of electronics and sensing components over: 1) large areas and 2) flexible and soft substrates. These features are also needed to fulfill the requirement of other e-skin applications such as health monitoring. The modest beginning in this direction was made with technological solutions such as distributed off-the-shelf electronics integrated with sensors on flexible printed circuit boards (FPCBs). From the point of view of robotics' research, this has already showed the potential benefits. For example, in addition to the hand-based manipulation and exploration, the FPCBs-based large-area tactile skin has allowed the researchers to explore the robot's whole-body contacts to plan and execute movements in unstructured environments. In terms of e-skin technology, the field has now advanced toward more attractive alternatives with sensory patches based on printed nanowires, graphene, and ultrathin chips [7].

While some of these advances in e-skin technology are driven by research in areas such as large-area display, the former has also triggered advances in several new applications [5]. For example, today, large-area flexible electronics is being explored for health monitoring. Several variants of sensory patches have been reported recently, particularly in the context of mobile health or self-health management. With the myriad type of chemical and physical sensors, these e-skin patches allow real-time monitoring of various physiological parameters such as blood pressure, heartbeat, and so on. The wearable sensory patches have also been reported for real-time monitoring of chronic diseases (e.g., diabetes) from body fluids such as sweat or tear [8]–[10]. The disposable and wearable solutions enabled by these advances are aiding positive changes in health monitoring practices at the global scale. These conformable ultrathin sensory patches are sometimes referred as "second skin," "epidermal electronics," or "electronic tattoo" as they enrich our capacity to sense ambient conditions by augmenting the five natural sensory modalities.

The e-skin technologies offer unprecedented opportunities for tackling several pressing societal challenges. For example, when wrapped around surgical tools (e.g., tool used in pinhole surgery), the flexible sensory patches could allow surgeons the feel the tissues or palpate the internal body parts. Coupled with advances in the Internet of Things (IoT), virtual reality, augmented reality, Industry 4.0, organ on chips, and artificial intelligence/deep learning, the e-skin is believed to hold a great promise in achieving a new level of human connectedness. As robots become ubiquitous, the special requirements they place on technologies not currently driven by robotics, e.g., communications protocols, battery technology, materials, and sensors, will begin to drive and influence developments in those technologies [11].

The above-mentioned opportunities come with several challenges that remain to be resolved. Major challenges are related to comfortability, signal acquisition and transmission, and energy autonomy of the transducer devices. Majority of these technological bottlenecks lie at the interface between the wearable device and the skin or robot and tactile skin. Proper choice of materials and morphological features aligning with biological skin or robotic platform would be needed to overcome the technological challenges. e-skin requires heterogeneous integration between a wide variety of material systems and smart functional structures [12]. Functionalities and applications dictate the use of various materials and functional structures. In addition, the "second skin" type e-skin systems require biocompatibility, conformability, stretchability to various levels, sustainability to various strains due to body motion, minimal discomfort, adequate adhesion, adequate shelf life, and service life, lightweight, water vapor permeability.

The challenges will also lie in realizing the soft e-skin system with transduction sites of different bandwidths, dynamic range, resolution, sensitivity, and mechanical characteristics, using materials and neural models that can take into account different adaptation characteristics of skin receptors [2]. Possibly, the circuits interfacing the huge amounts of distributed sensors will also need to be looked into as the constraints on power consumption, spatial and time resolution, and compatibility with flexible and soft materials make the circuit design no less challenging.

Furthermore, with technological advances over the past few years, particularly in the field of flexible and soft electronics, we have achieved closer to mimicking some of the abilities and morphology of real skin with sensors and electronics embedded in soft substrates [13]. However, just copying skin morphology or capturing a few parameters that we experience is not enough. The challenge is how to reproduce the functions while accepting the fact that the shape (morphology), at the microlevel and the macrolevel, affects the functions [14], [15] Therefore, we need to focus on the functionalities as well and in this regard, there is also a need to find the ways to extract the information from sensor data [16] The e-skin requires a holistic approach starting from the way data are acquired, encoded, and eventually acted upon.

I. OVERVIEW OF THIS SPECIAL ISSUE SENSING TECHNOLOGIES

The e-skin in context with robotics and the "second skin" in wearable and health monitoring type applications have flexible electronics in common. This special issue connects these intertwined areas through 11 articles presented in three sections—Section I-A focusing on e-skin-related works in robotics, Section I-B presenting the articles related to health monitoring, and Section I-C with articles on bridging or common topics such as flexible energy systems. The 11 high-quality contributions from well-known experts in the field have been conceived to be accessible to nonspecialists while reporting, at the same time, the latest contributions for the research communities of the areas they cover. With the articles dealing with theoretical, scientific, and practical aspects, the SI is aimed to consolidate the research in the fast-emerging field of e-skin type systems. This broad coverage may draw the attention of academic researchers, application experts and practitioners, and possibly stimulate new collaborations.

A. Four Articles Address the State of the Art of e-skin in Context With Robotics and Prosthetics

The article "Large-area soft e-skin: The challenges beyond sensor designs" by Dahiya *et al.* presents the state of the field of large-area tactile sensing in robotics and prosthetics, particularly in relation with the challenges lying beyond sensors designs such as the handling of large tactile data using distributed local processing in neural-like fashion, neuromorphic tactile sensing, the bendable hardware e-skin solutions for robotic interaction with the environment, the energy autonomy of e-skin, and the printed nanowires-based manufacturing processes for large-area e-skin with high-performance devices. This article will complement several past surveys, where various types of tactile sensors are discussed.

The article "A comprehensive realisation of robot skin: Sensors, sensing, control, and applications" by Cheng *et al.* presents a holistic approach that engineers the artificial skin for robots with an example of a multi-modal skin cell, showing multiple human-like sensing modalities. The article also shows how the skin cell network could be used to develop large-area skin patches to cover the surfaces of robots along with the basic strategy to efficiently handle a large amount of tactile data.

The article "E-skins: Biomimetic sensing and encoding for upper limb prostheses" by Iskarous and Thakor focuses on prosthetic applications of e-skin. The article discusses the physiology of the receptors that encode tactile, thermal, nociceptive, and proprioceptive information and the sensors designed to mimic them. The spiking response of the receptors, their relay to sensory nerves, and encoding by the brain are also discussed. Echoing the discussion in the article by Dahiya *et al.*, the authors argue how the e-skin is designed to produce neuromorphic or receptorlike spiking activity and present the computational models to mimic these sensory nerve signals.

The article "Flexible multimodal sensors for electronic skin: Principle, materials, device, array architecture, and data acquisition method" by Jeon *et al.* presents the research trends and approaches in the field of flexible and stretchable multimodal sensors for e-skin focusing on operating principles and materials suitable for pressure, temperature, strain, photo, and hairy sensor devices, and integration architectures, including multimodal single cells, three-axes tactile sensors, vertical-stacked sensor arrays, active-matrix sensor arrays, and integration electronics. The article also discusses acquisition methods for various texture sensing and machine-learning algorithms for processing tactile sensing data.

B. Four Articles Address the State of the Art of the Topics Related to e-skin Interfaces and Energy

The article "Flexible ultralow power sensor interfaces for e-skin" by Jiang *et al.* presents the present the state of the art in thin-film electronics with examples of low-cost printable transistors and biosensors. The ultralow-power design for thin-film transistors is discussed from the standpoint of reducing both operating voltage and operating current, taking into account the challenges in meeting frequency requirements. The article also presents a concept for batteryless operation of an integrated system comprising sensors and interfacing circuits enable.

The article "A fully additive low-temperature all-air low-variation printed/flexible electronics with self-compensation for bending: Codesign from materials, design, fabrication, and applications" by Chang and Ge presents the codesign between the different chains of flexible electronics supply chain to derive practical flexible electronics and sensors for applications where the substrate is expected to bend. For example, in an augmented sensing e-skin smart glove, this effort includes the authors' fully additive low-temperature all-air low-cost screen-printing process, and how to obtain consistency and repeatability. The authors also describe how to accommodate the variations of the printed elements when the substrate is bent—a self-compensating means.

The article "Energy scavenging and powering e-skin functional devices" by Dharmasena *et al.* highlights the importance of scavenging energy from human body movements and presents some of the key developments that enable energy harvesting through mechanical and thermal effects and low-light sources, as well as energy management and storage technologies, which could lead toward the construction of autonomous e-skin modules and self-powered sensing systems.

The article "Organic photovoltaics: Toward self-powered wearable electronics" by Yu *et al.* discusses recent developments in flexible organic photovoltaics (OPVs), including advances in materials, structure, and integration with additional wearable components, such as sensors and displays. The authors also describe their recent work in developing a self-powered actuator for a tactile feedback system.

C. Three Articles Address the State of the Art of e-skin in Context With Robotics and Prosthetics

The article "Physical and chemical sensing with electronic skin" by Takei *et al.* discusses current progress on flexible and stretchable transistors and sensors for e-skin such as flexible chemical sensors for sweat analysis as well as physical sensors for detecting tactile force, bending, and temperature. The emphasis is on materials, detection mechanisms, and device demonstration to realize multiplex human-interactive devices. The system integration enabling the real-time monitoring of health conditions is also discussed as a proof of concept.

The article "Electronic skins based on liquid metals" by Yang *et al.* discusses liquid metal alloys of gallium, which provide unique physical and chemical properties for e-skin, originating from their high thermal and electrical conductivities. Liquid metal alloys present great future opportunities to develop intelligent, either passive or active, e-skin of remarkable functionalities.

The article "Materials and design strategies of stretchable electrodes for electronic skin and its applications" by Hong *et al.* presents an overview of state-of-the-art technological advances in materials and design strategies for the development of stretchable electrodes. In addition, e-skin systems and their human–machine interface applications based on such stretchable electrodes are briefly reviewed. ■

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