Mechatronics 34 (2016) 84–94

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Towards integrating intelligence in electronic skin

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ARTICLE INFO

Article history:
Received 15 October 2014
Revised 3 March 2015
Accepted 6 April 2015
Available online 29 April 2015

Keywords:
Materials integrated sensing
E-skin
Piezoelectric polymers
Tactile information processing
Electronic embedded systems

ABSTRACT

Due to its very peculiar features, the development of e-skin can be effectively tackled using a holistic approach. Starting from the definition of system specifications, the mechanical arrangement of the skin itself needs to be designed and fabricated together with the electronic embedded system, to move towards aspects such as tactile data processing algorithms and the communication channel interface.

In this paper we present the design, the implementation and the results on the way of the development of an electronic skin (e-skin) system based on arrays of piezopolymer transducers. Focus of the paper is on both the development of innovative approaches for tactile information processing and electronic system embedding into the e-skin structure. In particular, Machine Learning technologies can provide a powerful tool to tackle the pattern-recognition problems involved in the tactile sensing framework and the ability of processing data represented as N-th order tensor is the key aspect of the presented research, which can be seen as an application of an existing method (Signoretto et al., 2011). The experimental session compares two different implementations of the ML-based framework, which differ in the learning paradigm adopted, namely SVM and ELM (K-ELM). The effectiveness of the adopted pattern-recognition technologies in the classification of touch modalities has been confirmed by addressing two different binary classification problems in an experiment involving 70 participants. The computational requirements for the hardware implementation of the proposed algorithm together with an overview of what exists in the existing literature are finally discussed.

1. Introduction

The development of electronic skin (e-skin in the following) is a hot research topic due to its relevant countless applications e.g. in robotics and in biomedical systems [2,3]. The functions of e-skin are basically: (1) to convey the mechanical stimulus to the distributed sensor arrays beneath: the geometrical arrangement of e-skin patches and the geometry/composition of the protective layer contribute to an effective implementation of this task; (2) to protect the inner electronic system from damages due to interactions with the outside (e.g. impacts, humidity); (3) to acquire and pre-process sensor signals in a convenient way; (4) to extract in an effective and reliable way the meaningful and necessary information for the task at hand (e.g. automatic reflexes, contact type recognition, surface feature detection, etc.); (5) to transmit the information to the next higher level of the ICT system infrastructure (e.g. the local communication bus). Each of such operations can be organized in other tasks which jointly concur to implement the extrinsic/cutaneous tactile system. Moreover, the e-skin should be flexible (i.e. conformable to the system to be integrated in) and stretchable e.g. to support joint movements, and processing must be implemented in real time to use the tactile information in the system control loop.

Following the definition given by Dahiya et al. [4], tactile sensing involves the detection and measurement of contact parameters in a predetermined contact area and subsequent processing of the signals to extract structured and meaningful information which is subsequently transmitted to higher system levels for perceptual interpretation. In this perspective, tactile information to be extracted by the e-skin includes (i.e. cutaneous sensing):

(i) normal force sensing for e.g. grasp control, object manipulation, and orientation determination;
(ii) tensile strain monitoring for e.g. proprioception (essential for simple movements such as standing or walking);
(iii) shear force sensing for e.g. grasp control and friction determination;
(iv) vibration detection for e.g. slip detection and texture determination.

Basing on these requirements, e-skin might potentially behave as a smart artificial skin with human-like sensory capabilities

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http://dx.doi.org/10.1016/j.mechatronics.2015.04.001
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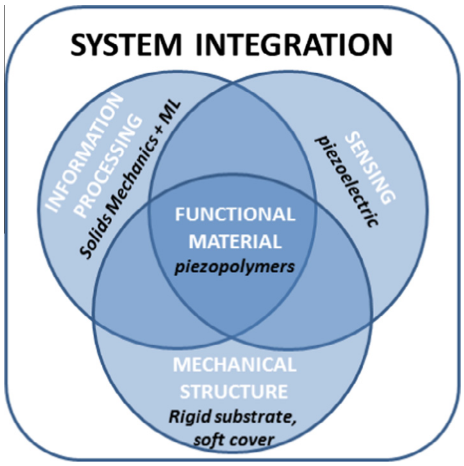

Fig. 1. Basic building elements of e-skin. White text: general, black text: our tactile system.

and could therefore offer several possibilities for robotic and medical applications, e.g. medical diagnostics and prosthetics.

The development of electronic skin starts from defining the system specifications, designing and fabricating the mechanical arrangement of the skin itself (i.e. soft or rigid mechanical support, structural and functional material layers, etc.) together with the electronic embedded system, and moving towards higher level aspects such as tactile data processing and the development of the communication channel interface.

The different e-skin tasks are far from being properly addressed and are still in their infancy even if many research groups are addressing the topic with numerous different approaches at each level of the problem [5–11].

In Fig. 1, the basic functional and structural elements to be integrated into e-skin are sketched. All these elements are correlated and the one influences the other in each skin system. In particular, all design choices affect the overall behavior of the skin system. To give an example, the core is the choice of the *functional material*, but how and where the functional material is integrated, whether the substrate is soft or rigid and the properties of the cover layer (i.e. the choice of the *mechanical structure* of the skin) affect the sensing properties of the skin together with information processing.

Main issue to be solved is how to integrate different building blocks into a system with challenging specifications. Following the approach outlined above, we developed e-skin focusing on both the integration of "intelligent" tactile information processing and its embedded real-time implementation, in the perspective of developing an autonomous system. The paper is organized as follows: Section 2 describes the functional material and the sensor array implementation. This section is meant as an introduction to the following central discussion. Section 3 presents two different tactile data processing algorithms, focusing on the Machine Learning approach. Research issues related to the effective implementation of embedded electronic systems for e-skin are illustrated in Section 4. Conclusions and future perspectives are finally reported in Section 5.

2. Tactile sensing arrays

Piezoelectric polymer films of Polyvinylidene Fluoride (PVDF) [12] have been chosen as transducers for their versatility, as meeting the requirements of mechanical flexibility, high sensitivity, detectability of dynamic contact events (1 Hz–1 kHz frequency range), wide dynamics (light/strong touch), low cost, light weight and robustness.

Two categories of sensitive surfaces can be considered. The former corresponds to *large area* skin, which is mainly characterized by robustness, wide frequency bandwidth, reproducibility, flexibility, low cost and light weight. The latter is the high spatial resolution, high sensitivity and real time *small area* encoding system.

The same functional material (PVDF) has been used for both large and small area skin, providing different functionalities in relation to the way the polymer film is integrated into the overall multilayer structure, which also includes a substrate and a cover layer.

Large area skin will be illustrated in Par. 2.1. On the other hand, Par. 2.2 will focus on one of the most promising approaches for high spatial resolution e-skin systems which is based on the POSFET device [2,14] (Piezoelectric Oxide Semiconductor Field Effect Transistor) and on the neuromorphic interface [13].

2.1. Large area sensor array technology

An array based on a PVDF polymer film has been designed having in mind *large area* requirements cited above. The tactile sensor rectangular array integrates 64 ad-hoc screen-printed electrodes and tracks on both sides of the piezoelectric polymer film (taxel/sensor radius equals 1.5 mm and pitch is 8 mm) [14]. Flaps are used to extract sensor signals through suitable crimping connectors (Fig. 2). Screen printing technology allows for ad-hoc e-skin design, optimizing taxel size and sensor pitch according to application requirements. The flexible prototype is currently glued on a rigid substrate for preliminary experimental tests. A, PDMS elastomer layer (2.5 mm thick) is integrated on top for stress transmission and sensor protection.

Exploiting the direct piezoelectric effect, charge generated by the PVDF material as a response to the transmitted mechanical stimuli is directly converted to voltage by means of a charge amplifier based front-end electronics [15]. A 64-channel charge amplifier and band-pass filter readout electronics has been realized to interface the e-skin prototype.

Recently the 64 taxel e-skin has been used to provide myoelectric prostheses for amputees with a comprehensive artificial cutaneous sensing. The e-skin enables bidirectional communication between the subject and the prosthesis. Preliminary results are reported in [16]. The aim is to test the ability of the subjects to process the artificial tactile information.

2.2. Small area sensor arrays

The POSFET device is a "sensotronic" unit comprising both transducer and transistors on the same substrate and is therefore capable of sensing and (partially) processing the tactile signal on the same device. The POSFET is composed by a piezoelectric polymer film (PVDF) spin-coated on the gate of a standard MOSFET, and it exploits the pressure generated voltage to induce a charge modulation in the underlying MOS device.

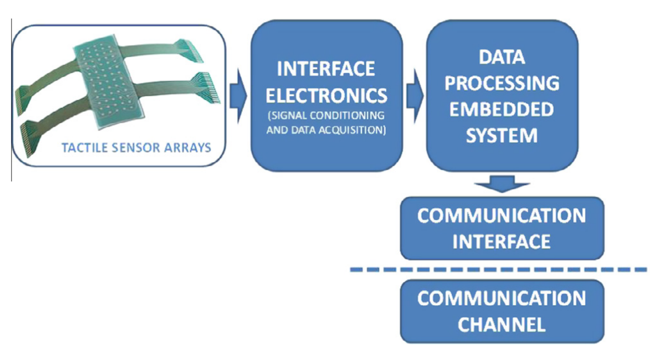

Fig. 2. Block diagram of the tactile sensing system.