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Experimental characterization of dedicated front-end electronics for piezoelectric tactile sensing arrays

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ABSTRACT

Embedding electronics with tactile sensors may enable electronic skin to be applied in many domains such as prosthetics, robotics, industrial automation. The complexity of electronics from size and power consumption point of view represents the main barrier towards achieving goal. This paper provides the experimental characterization of dedicated front-end electronics for piezoelectric tactile sensing arrays. Aiming to decrease the hardware complexity, the designed circuits are based on the DDC112U and an FPGA Xilinx Spartan-6 devices. An experimental setup has been implemented to acquire the signal generated from a tactile sensor. Results validate the functionality of the proposed interface when the measured voltage and charge are analyzed in terms of the input force. Experimental characterization demonstrates the correctness of the results when the signal to noise and distortion (SINAD) ratio, and the effective number of bits (ENOB) have been analyzed.

1. Introduction

Electronic systems implementing perceptive functions close to those of human senses (e.g. touch) are highly demanded in many application domains such as robotics, prosthetics, and industrial automation. Such systems should be integrated hopefully in a seamless and autonomous manner into the target devices. An example of such system is the electronic skin (e-skin) which is made of a set of autonomous and networked sensors; each sensor hosts a certain number of transducers embedded with a dedicated electronic system.

The e-skin is an arrangement of tactile sensing materials, signal conditioning and acquisition (interface circuit), signal processing and interpretation. Thus, sensing materials should be fabricated together with an interface circuits able to acquire the tactile signals at the first place, then to transmit the acquired data in order to be decoded.

A functional block diagram of the tactile sensing system is shown in Fig. 1. Tactile sensors represent the main component of the system since the chosen materials for e-skin development should reflect certain sensing capabilities to fulfill the application domains requirements [1]. The piezoelectric polymer films of Polyvinylidene Fluoride (PVDF) [2] is used because it meets the target requirements.

When mechanical stimuli are applied to the surface of tactile sensors, the front-end electronics should carefully collect the generated signals to preserve meaningful information contained in raw data. The interface circuit is in charge of signal conditioning to adapt the output signals extracted from the sensor array into voltage to be converted by analog to digital conversion circuits. These signals are progressively elaborated to extract structured information employing an embedded electronic system for tactile data decoding.

Our main goal is to develop an electronic skin (e-skin) system as illustrated in Fig. 1, integrating tactile sensors with the different components on a single system on chip (SoC). The e-skin system will be incorporated in the palm of the prosthetic hand for the restoration of sense of touch. This imposes big challenges in terms of hardware complexity and power consumption because of the small available area, the need of light weight, and energy efficient system. To achieve this goal, a series of stages should be followed starting from selecting the adequate sensing materials, then to designing the front end electronics and building prototypes to deal with the system requirements, and finally after trials and assessments to the fabrication of an Application Specific Integrated Circuit (ASIC) for the target system.

In this vein, this paper presents our recent achievements in the development of the interface electronics system for piezoelectric tactile sensing array. The work employs an FPGA device as a prototype to assess the proper functionality of the system and to experimentally characterize the implemented circuits.

2. State of the art

Modern prostheses aim at restoring the sense of touch of the lost

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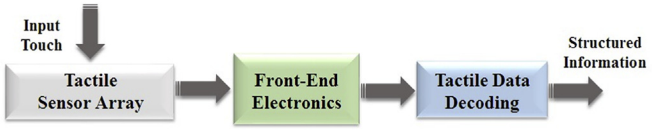

Fig. 1. Tactile sensing system.

limb. To do so, the upper limb prosthesis should be equipped with tactile sensor systems, with a huge amount of data to be acquired, processed, and conveyed to the user through electrostimulation [3]. Moreover, this has to be done respecting real time functionality. In this perspective, a dedicated embedded electronic system, with small size and low power consumption to ensure long battery lifetime, should acquire and decode tactile data in real time dealing.

Recently, notable implementations of interface electronics for tactile sensors have been presented in literature. The concept for tensoresistive and capacitive force sensors interfacing with applications in modern microelectronics systems is presented in Ref. [4]. Authors show the results of PSPICE simulations for some circuit components corresponding to the realistic behavior of sensor implementation; based on the simulation results, the paper showed an optimal variant of the interface circuit. Moreover, they implemented a negative capacitance for the linearization of capacitive microsensors through the proposed circuit. Damilano et al. [5] presented a digital electronic interface for pressure sensation. Authors took advantage of the capacitive variation of commercial piezoresistive tactile sensors to extract the applied pressure. Besides, some practical considerations for the readout circuits of commercial sensors for hands exoskeletons have been presented. In Ref. [6], the mechanical imaging of soft tissues using tactile sensing systems has been investigated: the system is adequate for imaging tumors in body tissues. Soft capacitive tactile sensors with custom electronics for data acquisition and processing are presented. The results show the ability to produce images of the surface lumps providing information about the geometry of embedded lumps [7] presents an array of tactile sensors with an interface circuit demonstrating the functionality and assessing the quality of readings aiming at implementing high accuracy tactile sensor. The work in Ref. [8] developed a tactile sensing system for the fingertips of ‘iCub’ [9]. The system features 5 × 5 POSFET tactile sensing array with a readout and the data acquisition system. The design of a tactile sensing system for clothes manipulation and classification is proposed in Ref. [10]. An experimental campaign is performed on sensing modalities and the process of integrating the sensor together with an industrial gripper has been described. Pinna et al. proposed a novel approach for the design of interface electronics for tactile sensing systems based on piezoelectric polymers [11]. The paper presented an electromechanical model for the piezoelectric sensor with its experimental characterization. An architecture composed of a set of field programmable gate arrays (FPGAs) is proposed in Ref. [12]. The proposed system computes parameters of the ellipses fitting the tactile images with high speed allowing the detection of slippage. Peinado et al. implemented the electronics for tactile sensor module for robotic hand [13]. They used FPGAs to acquire and process tactile data. Authors proposed a direct sensor to FPGA interface (i.e. without using ADC converters) to get advantage from parallel computation offered by FPGAs to achieve real time embedded processing.

Concerning piezoelectric tactile sensors, a charge amplifier circuit for signal conditioning, together with a 16-bit NI USB 6341 board for data acquisition have been used in Ref. [14]. Acer et al. [15] proposed a design using TLV 2772 operational amplifier for the signal conditioning of silicone embedded distributed piezoelectric sensors. Authors in Ref. [16] proposed an interface electronics consisting of PCB charge amplifiers for signal conditioning, 4 channels ADC, two NI DAQ boards and LabVIEW tool for data acquisition.

Table 1 summarizes tactile sensing systems presented recently in literature highlighting the front end electronics complexity. Most of the proposed works are DAQ-based systems and as such they are bulky. Such systems are not able to meet the restrictions of embedded implementation i.e. small space, light weight, low power consumption and consequently cannot be mounted on prosthetic hands [23].

This paper presents a step forward in the implementation of the embedded electronic system for the upper limb prosthetics. The work employs an FPGA to control Components-of-the-Shelf (COTS) devices for direct sensors-ADC interfacing. The advantage of this approach is the ability to apply data processing algorithms [24] near to the sensors (i.e. on the FPGA).

The paper provides the experimental characterization of the dedicated front-end electronics for piezoelectric tactile sensing: it extends a previous work [25] which describes the FPGA implementation of the digital serial interface; it highlights the functional evaluation and noise analysis of the interface circuit prototype using COTS devices. The circuit adopts an analog to digital converter DDC112U from Texas Instruments Inc [26] and an FPGA Xilinx Spartan®-6. Results validate the functionality of the proposed circuits when the measured voltage and charge have been analyzed in terms of the input force. Moreover, the experimental characterization verifies the correctness of the results when the signal to noise and distortion (SINAD) ratio, as well as the effective number of bits (ENOB) have been analyzed. The proposed system represents a step towards full SoC integration for the e-skin development.

3. Interface electronics system

3.1. Interface electronics requiremennts

Mimicking the human skin, an e-skin with large sensor frequency bandwidth i.e. from zero to 1 kHz is desirable. Accordingly, the sampling rate must be greater than 2kSPS to respect Nyquist rate. Aiming to restore the sense of touch for the upper limb prosthesis, a high number of sensors in each array (32–64 per array) should be mounted on the palm. The size/weight of electronic system should be adequate to the integration in the forearm. The system should be self-powered providing a daily life operation. The system should give a response each 50 ms (time latency of the stimulator). Table 2 summarizes the requirements with some others extracted and adapted from Ref. [11]. Some of the requirements are partially satisfied by examples reported in the literature: therefore our goal is to totally satisfy these requirements for the target application.

3.2. Experimental prototype

Fig. 2 sketches the prototype of the interface circuit with a 4 × 4 tactile sensor array. The DDC112 is a dual inputs converter consisting of two identical input channels where each one implements current to voltage integration followed by a multiplexed analog to digital (A/D) conversion. Each input has two time-multiplexed integrators such as the current to voltage integration can be continuous in time. The output of the four integrators are switched to one delta-sigma (ΔΣ) converter via a four-input multiplexer. Fig. 3 shows the block diagram of the DDC112 for one input: 1) an operational amplifier, 2) a programmable feedback capacitors, 3) some switches for the integration cycle control. The switches represented in the diagram are externally controlled using the system clock (CLK), the Range0-Range2 select the feedback capacitance range, and the CONV signal. The integration capacitor collects the charge generated from the input signal reducing the output voltage of the operational amplifier. The integration is stopped on the falling edge of the CONV signal by switching from side A to side B the input signal. Before the falling edge of CONV signal while the signal on the side A has been integrating, the side B has been converted by the ΔΣ modulator.

With the DDC112 in the continuous integration mode, the output of the integrators from one side of both of the inputs is be digitized while