Embedded Feedback System for Upper Limb Prosthetics

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Abstract— This paper proposes an embedded tactile sensory feedback system for the upper-limb prosthesis. The feedback system delivers tactile information extracted from tactile sensors to the user through electrocutaneous stimulation. The proposed system has been tested experimentally on three healthy subjects. Results demonstrate the correct feedback of the tactile information when the subjects were able to identify the location and the contact pressure level applied to the sensor arrays with a recognition rate of 86%. The system can provide feedback with a delay of around 32 ms while consuming 300 mW opening up interesting perspectives for wearable feedback systems for prosthetics.

Keywords— Embedded sensory feedback system, tactile sensors, Interface Electronics, electro-cutaneous stimulation.

I. INTRODUCTION

Commercial upper limb prostheses, such as myoelectric ones, are commonly used in daily life activities. Such prostheses include a feedforward system that replaces the basic motor function for users by decoding muscle activity through surface electromyography (EMG) [1]. Nonetheless, the prosthetic systems still lack a wearable sensory system to restore somatosensory feedback. Restoring the sense of touch requires a system that is in contact with the environment and provides reliable information about touch when e.g. manipulating an object or touching the surrounding (e.g. slippage [2]). Sensory feedback systems are usually composed of: i) tactile sensing arrays, ii) Interface Electronics (IE), and iii) stimulation system. The stimulation system delivers sensory information from tactile sensors through electrical stimulation on the forearm of an amputee. The system must be robust and embedded to be integrated into a prosthetic hand or used by patients with sensory deficits. As such, the system should include flexible tactile sensors of high electro-mechanical frequency bandwidth, with hopefully spatial resolution of 1mm for fingertips.

In the literature of closed-loop feedback systems, much activity and diversity in both systems and philosophies regarding feedback design are obvious. Some researchers developed sensing systems [3], while others proposed PC controlled stimulation systems [4]. Few studies in the literature proposed embedded-real time feedback systems that incorporate the two systems. Pamungkas and Ward. [5] developed a sensory feedback system based on sixteen polymer film force sensors fitted to the fingers and palm of a prosthetic hand. Six electrotactile feedback channels were used for force feedback. A host PC was used to monitor the sensor data and to deliver appropriate pulses to the six electrodes. Whereas Franceschi et al. [6] and Hartman et al. [7] investigated the possibilities of communicating tactile information such as touch position from artificial skin (PVDF based sensor array) through a host PC. Information from an array of 64 piezoelectric sensors is translated into electro-cutaneous stimulation patterns and conveyed to the subject through 32 electrodes or concentric electrodes attached to the subject's arm skin.

The speed in communicating sensation information has not been widely reported on when examining the performance of a sensory feedback system. A healthy nervous system can take approximately 14-25 ms to deliver tactile information to the brain [8]. A change in the dynamics of a prosthetic feedback system (e.g., response time constants, pure time delays) affects the overall system behavior, even its stability. One example of this is the integration of advanced haptic intelligence within the feedback loop. The authors in [9] examined a multi-modal sensory feedback system with three amputees. Sensory information from five piezoelectric barometric sensors was mapped into stimulations through vibrotactile or mechanotactile feedback. The developed system can communicate sensory information to the remaining stump of the amputees within 85 ms. Schoepp et al. [10] used a microcontroller (ATmega32u4) to map force level from two SingleTact sensors into one tactor fixed on the upper arm. The system operates with a time delay of 200 ms between touch instant and activation of the tactor.

With respect to previous PC-based systems presented in the literature e.g. [6]-[7], the main contribution of this paper is the demonstration of an embedded sensory feedback system that can artificially convey to the user the position and the level of any touch applied on a flexible distributed electronic skin. The system is portable and capable of delivering the tactile information to the user within a delay comparable to the healthy nervous system [8]. The system was preliminarily tested on three healthy subjects.

The remainder of the paper is organized as follows: Section II introduces the experimental setup with the details of the system blocks. In Section III, system tests and specifications are described. The sensory feedback system demonstration and results are presented and discussed in Section IV and Section V respectively. Finally, we conclude the paper in Section VI.

II. SYSTEM ARCHITECTURE

The sketch of the proposed system is shown in Fig.1. It consists of a) the tactile sensor arrays with three sensing patches, b) an interface electronics [11], c) a master Bluetooth module [12], and d) a fully programmable 24-channel electro-

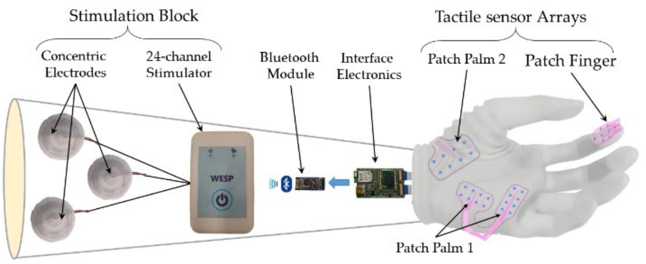


Fig. 1. Sketch of the sensory feedback system

cutaneous stimulator equipped with three concentric electrodes. In the following the details of each part.

A. *Tactile Sensor Arrays*

Fully screen-printed flexible sensor arrays based on P(VDF-TrFE) poly(vinylidene fluoride trifluor-oethylene) piezoelectric polymer sensors have been fabricated by JOANNEUM RESEARCH [13]. A circular bottom electrode is screen-printed on a transparent and flexible (175 µm thick) DIN A4 plastic foil (Melinex® ST 725) substrate. P(VDF-TrFE) is then screen-printed onto the bottom electrodes, followed by screen printing the top electrodes (Either PEDOT: PSS or carbon have been used as top electrodes). A UV-curable lacquer layer is deposited on top for overall sensor protection. Finally, a pooling procedure aligns along the thickness direction of the randomly oriented dipoles contained in the P(VDF-TrFE) crystallites. Sensor's technology has been validated previously in [14]. The sensors are flexible and low cost and have a frequency range of 1 Hz-1 kHz, and a measurable pressure range of 0.23-1.41MPa [15]. A complete set of skin patches for the fingers and the palm has been designed and fabricated as illustrated in Fig. 2.a. The presented sensing patches are composed of three sensor arrays (32 sensors in total), i.e. palm left1 (16 sensors), palm left2 (8 sensors), and single finger (8 sensors). The three patches were chosen following the number of channels offered by the IE (described in the next section). Besides, the choice is based on the assumption that the index finger and the palms are commonly used during grasping. Fig. 2 shows the shape and size of the three sensing patches.

B. *Interface Electronic*

The IE acquires and digitizes the tactile signals (i.e. charges) of 32 input sensors simultaneously. It comprises three main components: a current offset circuit, a 32-channel analog-to-digital converter (DDC232), and a low-power ARM cortex-M0 microcontroller [11]. The offset circuit enables the IE to handle the bipolar signals generated by PVDF-based sensors by level shifting the input reference. Then the DDC232 converts the shifted signals for the 32 input sensors at 2K Samples/ second. Finally, the ARM processor performs three tasks: first, it controls the DDC232 converter to retrieve the digitized data; second, it processes the data to identify the position of the touch and the charge level; third, it translates the processed data into electrotactile commands and transmits them to the stimulator through the Bluetooth module.

Based on previous experiments [15], the IE can detect a linear relationship between the input charge and the applied force. Based on these results, three intervals of charge were selected as the identification of three force levels. The IE was programmed to detect the force level and map it into its corresponding level of stimulation.

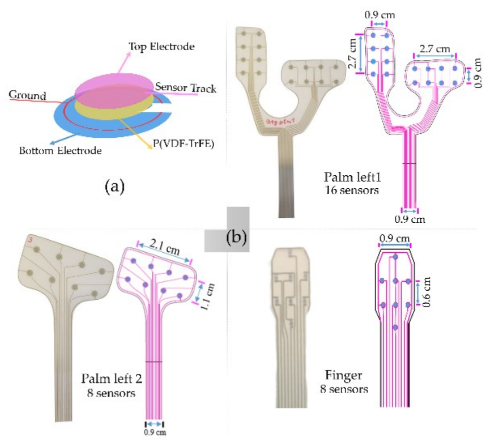


Fig. 2. Design of different sensing patches. (a) Cross sectional view of a single sensor unit. (b) Top: Palm Left 1 -16 taxels, taxel diameter = 2mm. Bottom left Palm Left 2 -8 sensors, taxel diameter = 2mm. Bottom right: Finger -8 sensors, taxel diameter = 1mm.

C. *Stimulation Block*

The stimulation block employs a 24-channel programmable battery-powered stimulator (WESP, Tecnalia Serbia [16]). It generates current-controlled waveforms with a current magnitude in the range of 0-10mA with 0.1mA step, a frequency from 1 to 400 Hz, and a pulse width from 50 to 500 µs. The WESP produces simultaneous charge-balanced biphasic continuous electrostimulation pulses in any combination of electrodes or individually in each electrode. Three self-adhesive concentric electrodes (CoDe 1.0, OT Bioelettronica, IT) were used to deliver the electrical stimulation to the user.

III. System Performance

This section presents the system, performance represented by the measurements of the time latency, and power consumption.

A. *Power consumption*

The IE is supplied by a 5 V power source [11]. The IE acquires, preprocesses data, and sends corresponding commands to the stimulator. The measured power consumption is of about 300 mW in continuous mode, where the IE sends commands to the stimulator continuously.

B. *Time Latency*

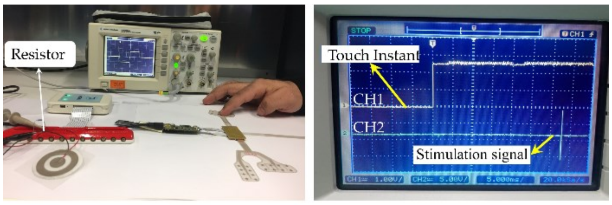
The total delay from the applied pressure to the stimulation is the summation of the delays starting from the sensor, to the IE different tasks until the activation of the stimulation. A 2.2 kΩ load resistor was connected between the stimulator electrode and the oscilloscope probe to visualize the stimulation signal. Fig. 3 shows the setup and the response of the system when a touch is applied to one of the sensor arrays. The total time latency is around 32 ms. This indicates that the response of the system is fast enough to transmit the desired signal without a perceivable delay.

IV. Experimental Setup and Protocol

To test the effectiveness of the system, localization and identification tests have been performed. The localization tests the subject's ability to localize the touched sensing patch while the intensity identification tests the subject's ability to distinguish between touch pressure values.

A. *Experimental setup*

Three healthy subjects (3 males, 28 ± 8 years) participated in the experimental tests. The experimental setup of the conducted tests is shown in Fig.4. The three sensing patches were fixed on a table and connected to the IE. The subject was comfortably seated on a chair in front of a table in a quiet



(a) (b)

Fig. 3. (a) Picture of the system responding to a contact on one sensor array. (b) CH1 signal represents a touch event on the sensor array; CH2 signal is the corresponding electrical stimulation waveform.

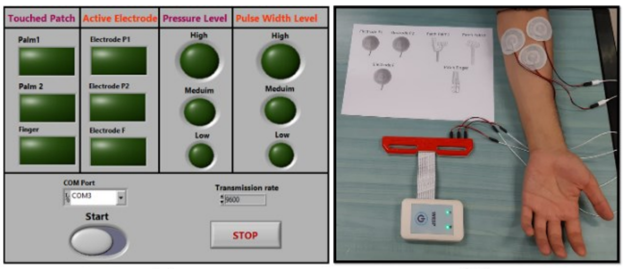
environment to avoid distraction. With the forearm on the table, the three electrodes were put on the volar side and aligned with the position of the sensor patches in the prosthetic hand. A sheet of paper was placed in front of the subject with a schematic drawing of the position and names of the electrodes. The experimental procedure was then explained to the subject. For each electrode, the subject received stimulation at a comfortable intensity to familiarize him/her with electro-coutaneous stimulation. The electrode locations remained fixed during the experimental sessions because they affect the perceptual thresholds.

For each subject, the Sensation Threshold (ST) and Pain Thresholds (PT) for electrotactile stimulation have been determined for the three electrodes using the method of limits [17]. The current amplitude and frequency were constant and set to 3 mA and 100 Hz respectively. While the pulse width was adjusted to regulate the intensity of stimulation. The mean ST and PT calculated among all subjects were equal to 140±50 µs and 350±50 µs respectively. Previous experiments in [4] demonstrated that stimulation with these parameters allowed good perception and modulation of the elicited tactile sensations.

The Graphical User Interface (GUI) shown in Fig. 4 has been implemented in LabVIEW. The experimenter uses the GUI for indicating the level of the applied pressure and the activated sensing patch. It is worth noting that the control of the system is completely independent of the PC, where the GUI was used for visualization only.

B. *Testing Methodology*

The stimulation parameters were chosen to maximize the differences in the intensities of the stimuli. The pulse widths for the low (LE), medium (ME) and high (HE) electrotactile stimuli were: LE = 1.2×ST, ME = LE+0.3× (HE-LE) and HE = 0.8×PT, respectively. The sketch shown in Fig. 5 illustrates the mapping of tactile information into stimulation patterns. Each subject received 9 different configurations of stimulation



(a) (b)

Fig. 4. Experimental setup (a) GUI used during training and validation phases (b) The three concentric electrodes connected to the stimulator from one side are placed on the volar forearm from the other side.

shown in Table I. Where electrode F corresponds to patch Finger, electrode P1 corresponds to patch Palm1, and electrode P2 corresponds to patch Palm2. Each experimental session was divided into three phases: pre-training, reinforced learning, and validation. During the three phases, each trial consisted of 2-second of continuous stimulation.

TABLE 1 NINE DIFFERENT STIMUALTION CONFIGURATIONS

Categories		**Pressure Levels**		
		Low (L1)	**Medium (L2)**	**High (L3)**
Touch Position	**Palm 1 (P1)**	**P1.L1**	**P1.L2**	**P1.L3**
	Palm 2 (P2)	**P2.L1**	**P2.L2**	**P2.L3**
	Finger (F)	**F.L1**	**F.L2**	**F.L3**

*1) **Phase1:*** subjects were instructed to focus on the stimulation and build a tactile mental map between sensation, level of stimulation, and the position of the activated electrode. The subjects were introduced to the nine configurations. The experimenter announced to the subject the electrode/patch that will be activated and the level of touch, then started the stimulation by touching the corresponding patch. In total 18 stimulations trails were presented (two repetitions per configuration).

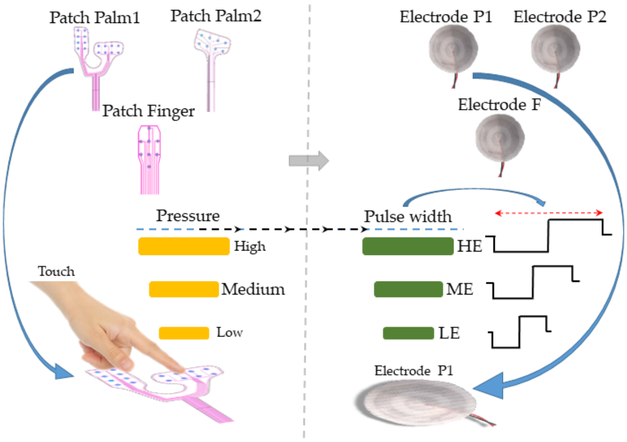


Fig. 5. Mapping of tactile information into stimulation patterns at the subject side.

*2) **Phase 2:*** one of the stimulation configurations was randomly selected and delivered to the subject (three repetitions per configuration). The subjects were asked to guess the configuration, and verbal feedback about the correct response was provided by the experimenter.

*3) **Phase 3:*** the protocol of phase 2 was repeated, except that each stimulation configuration was delivered five times (45 stimulation trials in total) and the subjects did not receive the verbal feedback about the correct answer.

The Recognition Rate (RR) has been selected as a metric to recognize the ability of the subject in identifying the touch positions and the value of the applied pressure. RR is defined as

$$RR = \frac{number\ of\ correctly\ identified\ trails}{number\ of\ total\ trails} \times 100 \qquad (1)$$

V. Experimental Results

Three subjects took an experiment on recognition of touch position and applied pressure. The average RR has been calculated using the following equation: RR = mean ± standard deviation was 86.66 ± 2.22 %. The confusion matrix presented in Fig. 6 is used to evaluate the overall performance and identify prevalent classification errors. The confusion matrix demonstrates a visible diagonal line standing for a correct class (position) recognition. Whereas typical errors were observed due to the misjudgments of the level of the stimulus at electrodes P1 and P2 (the 2×2 squares along the main diagonal) and less frequently of the electrical stimulus at electrode F (the parallel diagonals above and below the main diagonal) for one level up or down from the presented (correct) level. The subject's answers were therefore distributed within several levels around the correct stimulus. Subjects were significantly better in discriminating low and high levels of pressure i.e. pulse width values with respect to the intermediate level. One reason is the small difference between two consecutive levels of pulse width. Which in turn depends on the PT and DT of each electrode separately. These results indicate the ability of the system in delivering meaningful information to the subjects. The high accuracies in discriminating different touch positions and levels demonstrate the feasibility of an embedded system in coding different touch modalities for example light and strong touches.

VI. Conclusion

This paper presented a portable sensory feedback system incorporating tactile sensors, interface electronics, and a programmable electro-cutaneous stimulator. The power consumption and time latency of the system have been measured. The proposed system operates in real-time with 32 ms delay (from touch to stimulation) and low power consumption of 300 mW. Although more extensive experimentation is needed to fully evaluate our system, our preliminary demonstration on three healthy subjects showed an accuracy of 86.66% RR. The results of this study are important for sensory feedback design. They have shown the effectiveness of using a real-time embedded feedback system to extract and deliver tactile information to the users. The system is an important step toward integrating a distributed sensing system into a prosthetic hand and deliver tactile information to the user. Therefore, future work will involve miniaturizing the stimulation device. Further experiments will be conducted to study the effectiveness of the system in making the user more spatially aware of the prosthetic hand and its interactions with objects.

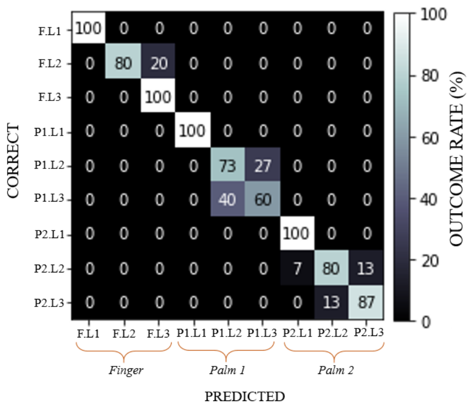


Fig. 6. Confusion matrix for the RR of 9 configurations in the validation phase. The matrix demonstrates the superior performance in recognizing touch positions.

Acknowledgment

The authors acknowledge financial support from TACTIle feedback enriched virtual interaction through virtual realITY and beyond (Tactility) project: EU H2020, Topic ICT-25-2018-2020, RIA, Proposal ID 856718.

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