Pilot Study: Response of a Piezoelectric Polymer based Sensing system to Indentation

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***Abstract*—This paper proposes an investigation of the response of a sensing system based on PVDF (Polyvinylidene fluoride) piezoelectric polymer sensors to indentation. A 3-axis Cartesian robot has been used to perform indentation experiments at different speeds and normal loads. Overall, the sensing system reveals a viscoelastic behavior as both the indentation speed and normal load affect sensor response. Preliminary results show that by applying signal processing techniques it is possible to relate sensor response to the indentation speed and applied load. This pilot study paves the way toward extracting time-varying contact force information from sensor outputs.**

***Index Terms*—Tactile sensing systems, PVDF sensors, Signal analysis, Signal processing**

I. Introduction

Over the past decade, extensive research has been devoted to developing tactile sensors based on piezoelectric polymers, especially polyvinylidene fluoride (PVDF) and its (TrEE) Trifluoroethylene copolymers [1]. This is due to the feature set exhibited by these materials, including their high sensitivity and wide frequency range ($\leq$ 0.5Hz to 1KHz) covering the whole frequency bandwidth of the human skin [2], except for measuring slowly varying stimuli. Those materials proved as good candidates for flexible tactile sensors, suitable for dynamic tactile sensing and to be integrated into artificial electronic skins [2]–[6].

Piezoelectric polymers generate electrical signals as a response to applied stresses. Electrical signals produced in the form of output voltages have been analyzed to evaluate the sensing performance [7]. However, most of the existing research has focused on the sensor fabrication side [8]–[10]. Nevertheless, what is important in real applications where sensor signals are expected to drive sensory feedback for motor control is to interpret the time response of the whole sensing system to extract contact information [11]. As a matter of fact, the transduction of the applied mechanical stimuli into electrical signals is the result of how the structural and functional (PVDF piezoelectric polymers, in this case) components of the sensing system are integrated into a very specific electromechanical sensing structure [12]. Only a few papers presented studies to interpret the electrical response of piezoelectric-based devices to mechanical stimuli. To give an example, in [13] the e-skin is composed of two polyimide films sandwiching a sensor array built of a single PVDF film with a few top electrodes and a common bottom electrode. Sensor signals are interpreted as a function of how the sliding motion over the e-skin surface affects the strain profiles over time driving sensor outputs. In [14] contact force distributions are reconstructed from PVDF sensor signals, although the study is static. To start addressing the difficult task of the reconstruction of time-varying contact forces from sensor outputs, in this paper we focus on a specific type of stimulus, i.e. indentation of the sensing structure with a soft indenter. This can be seen as a first step towards studying haptic interactions of sensorized soft fingers with objects. A cartesian robot has been used to indent a single sensor at different combinations of normal forces and speeds. We have implemented a method based on well-known signal processing techniques in the time domain to study the sensor output as a function of the applied normal load and its speed. This paper illustrates the setup, the experiment, and the related results.

II. Materials and Methods

A. Tactile sensing system

The tactile sensing system utilized in this experiment was previously presented in [15]. It is composed of two parts: the piezoelectric sensing array (i.e., the electronic skin patch) and the Embedded Electronics (EE). A fully screen-printed flexible sensor array based on P(VDF-TrEE) poly(vinylidene fluoride trifluoroethylene) piezoelectric polymer sensors was shielded following the procedure presented in [15]. The EE presented in [16] is based on a 32-channel analog-to-digital converter (DDC232), and a low-power ARM cortex-M0 microcontroller. In the present study, the EE was configured to collect and process tactile data from 8 sensors at 2 K samples/s. The 2 kHz sampling rate was used to capture the full bandwidth of the sensor working in thickness mode ($\leq$ 0.5 Hz -1 KHz), which is beneficial for detecting discrete events corresponding to contact onset/release that are characterized by a steep increase/decrease in the sensor signal [16].

B. Experimental Setup

A single skin patch including 8 sensors was tested using the experimental setup shown in Fig. 1. The skin patch was coupled to a rigid plate for sensors working in thickness mode [2] and then fixed on a strain gauge load cell (Tedea Huntleigh, Model 1042). To study the response of the sensing system in a controlled environment, a 3-axis Cartesian robot was used to perform a series of indentation actions on a single sensor through the z-axis. The z-axis is driven by a stepper motor and is controlled by modulating the z-coordinates and indentation speed. To modulate the load on the surface of the skin patch gradually, a 700 g weight was mounted on the z-axis and hung to a spring as shown in Fig. 1. A soft spherical indenter fixed

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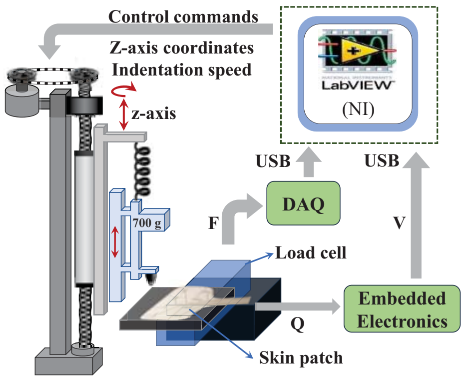

Fig. 1. Block diagram of the experimental Setup.

on the bottom of the weight (see Fig. 1) was used to indent the surface of the skin patch in a position corresponding to the epicenter of a single sensor on the outer surface. The force stimulus was processed and conditioned using a DAQ (NI, US), while the PVDF sensor response was conditioned by the EE. Data acquisition, visualization, collection, and control of the Cartesian robot were implemented using a graphical user interface (GUI) developed with NI LabVIEW on a host PC.

The aim of this work is to study the sensor response to a change in the applied load (max 700 g) at different indentation speeds to characterize the overall viscoelastic behavior of the whole sensing system and set the basis to reconstruct time-varying normal contact forces from sensor outputs. Before each test, the experimenter adjusted the x-y coordinates of the Cartesian robot to align the indenter with the sensor. Therefore, a sequence of mechanical inputs was applied, and the electrical response of the stimulated sensor and the output of the reference load cell were measured continuously. The indentation procedure comprised the following steps: indent (initial load: 3.7 N), increase the load to a target value (target load), decrease the applied load, then release the indenter. The aforementioned sequence was repeated for 7 target loads (N) $\{4.5, 5.5, 6.5, 7.5, 8.5, 9.5, 10.5\}$ each repeated at 7 indentation speeds (mm/s) $\{2.4, 3.2, 4.02, 4.8, 5.6, 6.4, 7.2\}$ therefore generating a dataset composed of 49 combinations of target loads and indentation speeds. Fig. 2.a shows an example of the indentation sequence at an indentation speed of 7.2 (mm/s) and a target load of 10.5 (N) and Fig. 2.b shows the corresponding PVDF sensor response.

III. Tactile Signal Processing

As mentioned, the experiment involves stimulating the surface of the skin patch with a soft indenter aligned with the axis of a single sensor at a certain combination of speed and target load. Each of the combinations was repeated for 10 trials. The analysis was performed by averaging the 10 trials for each of the aforementioned combinations. It should be noted that the load cell alone was first solicited by indentation in order to identify the frequency of spurious vibrations coming from the environment (172, 2 Hz), which was removed from the dataset using a notch filter implemented in MATLAB.

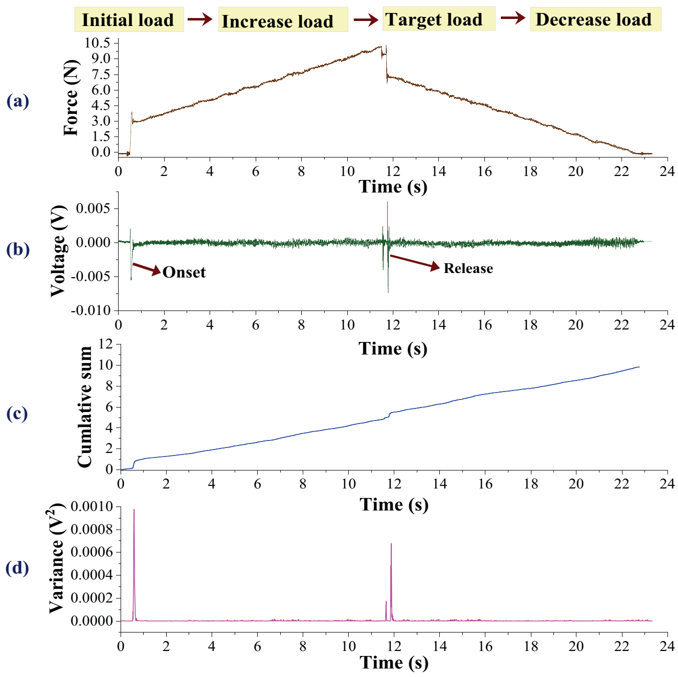

Fig. 2. Response of (a) the reference load cell and (b) PVDF sensors to an indentation sequence at a target load of 10.5 N and indentation speed of 7.2 mm/s. (c) The cumulative sum of the PVDF signal. (d) The Variance of the Cumulative sum shown in (c).

A. Event detection: Onset of contact and contact release

Due to their high cutoff frequency, the main potential of such PVDF sensors is to be capable of instantaneously detecting abrupt changes in contact forces, eg discrete events like the "onset of contact or contact release" (OCCR). The goal of analyzing peaks in the sensor response (Fig. 2.b.) is to determine how information about the applied load and speed is coded therein. On the contrary, slow changes in contact forces - as in between the OCCR events - are not detected by PVDF sensors if they are associated with frequencies lower than their low cutoff frequency (around 0.5 Hz). Two quantities are used to automatically detect an OCCR event, to further retrieve information about the time behavior of the load on time scales where the sensors are not sensitive to contact information, i.e., in between the onset and release peaks. The first one is the cumulative sum computed as in (1):

$$S_k = \sum_{i=0}^{k} |x_i| \tag{1}$$

where S_k is the cumulative sum, x_i is the i_{th} sample of the sensor signal. Steeper increases in S_k indicate abrupt changes in the signals corresponding to the OCCR events, as illustrated in Fig. 2.c.

The second is the variance applied to the windowed cumulative sum and computed as in (2):

$$Var_j = \frac{1}{w} \sum_{i=(j-1)*w}^{j*w-1} (S_i - \mu_j)^2 \tag{2}$$

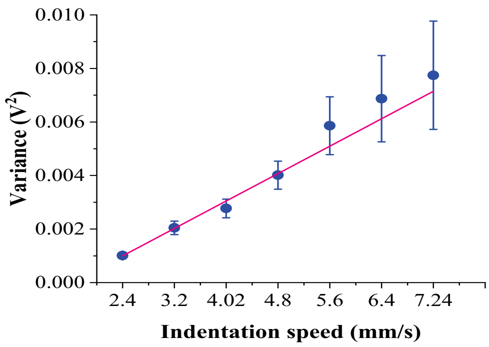

Fig. 3. Variance of the Press event vs the indentation speed.

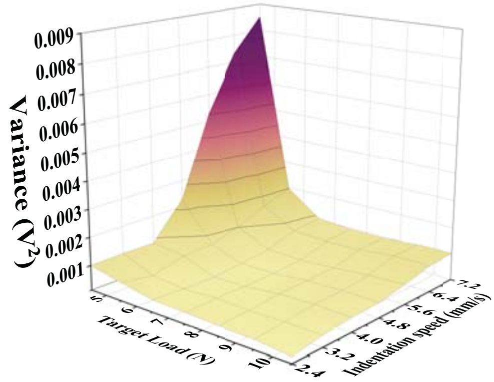

Fig. 4. Variance of the release event vs target load and indentation speed.

where w is the window size, $j = 1, 2, ..., \frac{N}{w}$ is the index of the window and N is the number of samples in x, S_i is the i_{th} element of the cumulative sum and μ_j is the mean of the j_{th} window. This last quantity detects the steeper changes in the cumulative sum as depicted in Fig. 2.d, allowing us to identify the OCCR events in the tactile sensor data and in the cumulative sum by a simple thresholding mechanism.

B. Load Analysis

In order to assess how the PVDF sensor response could be compared to the behavior of the load cell, a linear regression was applied on the increasing and decreasing phases of the load cell response (Fig. 2.a). and of the cumulative sum of the sensor response (Fig. 2.c), located between the OCCR events extracted with the methodology described above. Since the cumulative sum was computed using the absolute values of the signals, the resulting slopes are positive. Therefore, we also considered the absolute values of the slopes for the decreasing behavior of the load cell signal. The resulting slopes were compared to assess if the load cell and sensors showed similar trends at different indentation speeds.

IV. Results and Discussion

The approach outlined in section III-A detects the OCCR events using the variance outcomes. The first analysis is based on evaluating the relationship between the indentation speed and the variance of the onset of the contact event. Fig. 3 shows that an increase in the indentation speed results in a linear increase of the variance amplitude, leading also to an increase in the standard errors.

The second analysis examines the effect of the target load and indentation speed on the variances of peaks related to contact release. Fig. 4 shows a 3D presentation of the variance of the contact release event as a function of the indentation speed and target load. The 3D plot demonstrates that at fixed target load an increase in the indentation speed results in an increase of the variance. On the other side, the relation between the variance peak amplitude and the target load is non-linear and inversely proportional, i.e. at fixed indentation speed an increase in the target load leads to a decrease in the variance amplitude.

The last analysis consists of assessing the similarity in the response of the load cell and the PVDF-based sensing system to a change in the applied load, as described in III-B. The results presented in Fig. 5 show that the PVDF sensor and the load cell present a similar increasing behavior in the slope while the indentation speed is increasing.

V. Conclusions and Future Work

In this paper, signal processing techniques were used to study sensor response to indentation stimuli at a variable indentation speed and load. Such preliminary results characterized the response of the PVDF sensor to a change in the indentation speed and a change in the load. Moreover, the variance of the release event is an interesting feature towards reconstructing information on the time-varying normal force. Although more extensive experimentation is needed to reconstruct meaningful information from sensor data, our preliminary experiments and analysis can be considered as a first step towards extracting high-level time-varying tactile information from PVDF sensors (e.g. Force and slippage). Moreover, the work proposed in this paper paves the way towards developing real-time processing techniques to be implemented in the Embedded electronics of the sensing system.

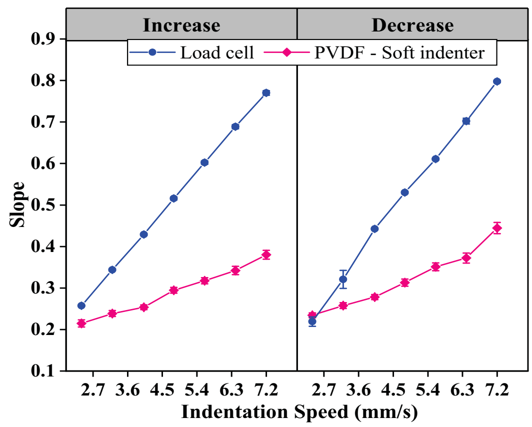

Fig. 5. Slopes of Increase in load (left) and decrease in load (Right) vs indentation speed.

REFERENCES

[1] P. Saxena and P. Shukla, "A comprehensive review on fundamental properties and applications of poly (vinylidene fluoride)(pvdf)," *Advanced Composites and Hybrid Materials*, vol. 4, pp. 8–26, 2021.

[2] L. Seminara, M. Capurro, P. Cirillo, G. Cannata, and M. Valle, "Electromechanical characterization of piezoelectric pvdf polymer films for tactile sensors in robotics applications," *Sensors and Actuators A: Physical*, vol. 169, no. 1, pp. 49–58, 2011.

[3] Y. Wu, Y. Ma, H. Zheng, and S. Ramakrishna, "Piezoelectric materials for flexible and wearable electronics: A review," *Materials & Design*, vol. 211, p. 110164, 2021.

[4] Y. Abbass, L. Seminara, M. Saleh, and M. Valle, "Novel wearable tactile feedback system for post-stroke rehabilitation," in *2021 IEEE Biomedical Circuits and Systems Conference (BioCAS)*. IEEE, 2021, pp. 1–6.

[5] Y. Amin, C. Gianoglio, and M. Valle, "Embedded real-time objects' hardness classification for robotic grippers," *Future Generation Computer Systems*, 2023.

[6] Y. Xin, H. Tian, C. Guo, X. Li, H. Sun, P. Wang, J. Lin, S. Wang, and C. Wang, "Pvdf tactile sensors for detecting contact force and slip: A review," *Ferroelectrics*, vol. 504, no. 1, pp. 31–45, 2016.

[7] Y. Su, C. Chen, H. Pan, Y. Yang, G. Chen, X. Zhao, W. Li, Q. Gong, G. Xie, Y. Zhou *et al.*, "Muscle fibers inspired high-performance piezoelectric textiles for wearable physiological monitoring," *Advanced Functional Materials*, vol. 31, no. 19, p. 2010962, 2021.

[8] W. Deng, T. Yang, L. Jin, C. Yan, H. Huang, X. Chu, Z. Wang, D. Xiong, G. Tian, Y. Gao *et al.*, "Cowpea-structured pvdf/zno nanofibers based flexible self-powered piezoelectric bending motion sensor towards remote control of gestures," *Nano Energy*, vol. 55, pp. 516–525, 2019.

[9] X. Chen, J. Shao, H. Tian, X. Li, C. Wang, Y. Luo, and S. Li, "Scalable imprinting of flexible multiplexed sensor arrays with distributed piezoelectricity-enhanced micropillars for dynamic tactile sensing," *Advanced Materials Technologies*, vol. 5, no. 7, p. 2000046, 2020.

[10] J. Zhang, H. Yao, J. Mo, S. Chen, Y. Xie, S. Ma, R. Chen, T. Luo, W. Ling, L. Qin *et al.*, "Finger-inspired rigid-soft hybrid tactile sensor with superior sensitivity at high frequency," *Nature Communications*, vol. 13, no. 1, p. 5076, 2022.

[11] C. Gianoglio, E. Ragusa, P. Gastaldo, and M. Valle, "Trade-off between accuracy and computational cost with neural architecture search: A novel strategy for tactile sensing design," *IEEE Sensors Letters*, 2023.

[12] L. Seminara, L. Pinna, A. Ibrahim, L. Noli, S. Caviglia, P. Gastaldo, and M. Valle, "Towards integrating intelligence in electronic skin," *Mechatronics*, vol. 34, pp. 84–94, 2016.

[13] K. Shin, E. Choi, M. Sim, M. Kang, J.-W. Choi, S. Cha, H.-J. Kwon, H. Kang, and J. E. Jang, "Fundamental insights into the electrical signals of a piezoelectric sensor in a sliding condition," *Nano Energy*, vol. 100, p. 107487, 2022.

[14] L. Seminara, M. Capurro, and M. Valle, "Tactile data processing method for the reconstruction of contact force distributions," *Mechatronics*, vol. 27, pp. 28–37, 2015.

[15] Y. Abbass, M. Saleh, S. Dosen, and M. Valle, "Embedded electrotactile feedback system for hand prostheses using matrix electrode and electronic skin," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 15, no. 5, pp. 912–925, 2021.

[16] Y. Abbass, S. Dosen, L. Seminara, and M. Valle, "Full-hand electrotactile feedback using electronic skin and matrix electrodes for high-bandwidth human–machine interfacing," *Philosophical Transactions of the Royal Society A*, vol. 380, no. 2228, p. 20210017, 2022.