Piezoelectric polymer transducer arrays for flexible tactile sensors

Lucia Seminara, Luigi Pinna, Maurizio Valle

Department of Telecommunications, Electronic, Electric and Naval Engineering, University of Genoa
Genoa, Italy

Laura Basiricò, Alberto Loi, Piero Cosseddu, Annalisa Bonfiglio

Dept. of Electrical and Electronic Engineering, University of Cagliari, Cagliari, Italy

Alberto Ascia, Maurizio Biso, Alberto Ansaldo, Davide Ricci, Giorgio Metta

Dept. of Robotics, Brain and Cognitive Sciences, Istituto Italiano di Tecnologia, Genoa, Italy

***Abstract*— The paper focuses on the manufacturing technology of modular components for large-area tactile sensors, which are made of arrays of polyvinylidene fluoride (PVDF) piezoelectric polymer taxels integrated on flexible PCBs. PVDF transducers were chosen for the high electromechanical transduction frequency bandwidth (up to 1 kHz for the given application). Patterned electrodes were inkjet printed on the PVDF film. Experimental tests on skin module prototypes demonstrate the feasibility of the proposed approach and reveal the potentiality to build large area flexible and conformable robotic skin.**

I. INTRODUCTION

A large number of touch sensors using various modes of transduction, materials and innovative structures, have been reported over the last two decades and more [1-3]. A touch sensor must have fast response, high spatial density as well as it has to be robust, with low hysteresis and able to measure forces in a wide range with high resolution. However, the lack of a system approach appears to be the most notable reason for the "sense of touch" not yet being an effective part of robots.

The overall system performance depends not only on its individual elements but on the integration strategy too, and a mix of technological and system issues, such as wiring complexity, distribution of tactile sensors in 3-D space, handling of large tactile data amount, must be faced using a system approach.

The degree of complexity of the problem increases when dealing with a large number of system components, such as those which make a robotic skin for large body areas. An investigation of these issues until now has been limited by the lack of tactile sensing technologies enabling large scale experimental activities, since so far skin technologies and embedded tactile sensors have been mostly demonstrated only at the prototypal stage.

To support this aim, our research team focuses on the investigation of methods and technologies enabling the implementation of skin sensors for large areas that can be placed on existing robots. To mimic the complex behavior of the human skin a multimodal system would be required, which employs different kinds of transducers, to cover the 0 - 1 kHz range of the stimulus frequencies required for the application [4].

The present research is concentrated on the integration of piezoelectric transducers into a robotic skin patch. Films of polyvinylidene fluoride (PVDF) and its copolymers exhibit piezoelectric and pyroelectric properties [5-6] with a fast dynamic response (1 Hz – 1 kHz range). Moreover, they possess the property of flexibility which allows them to easily conform to the curved surfaces of the robot body. The reduced weight and low cost make the PVDF films natural candidates for large area tactile sensors.

Piezoelectric films need to be provided of electrodes to collect the charge developed upon mechanical contact. Among the different technologies to deposit patterned metal layers on the polymer films, inkjet printing has been chosen. The appeal of this technology lies in providing non-contact, additive patterning and maskless approach [7]. Other attractive features are the reduced material wastage, low cost, and scalability to large area manufacturing.

The tactile system requires the handling of various problems starting from technological issues related to the design and manufacturing of transducer arrays moving towards system issues like skin integration, embedding into the robot architecture and data processing. This paper is focused on the manufacturing of triangular patches of piezoelectric transducer arrays, using an inkjet printing technology to create patterned metal contacts on the PVDF film.

II. MATERIALS AND TECHNOLOGY

A. Piezoelectric transducers

PVDF is synthesized by addition polymerization of the CH_2=CF_2 monomer. The polar β phase is obtained by mechanical stretching of PVDF films [5] in the 1-direction. The piezoelectric effect originates from induced polarization. The dipoles in a semi-crystalline polymer such as PVDF must be reoriented through the application of a strong electric field (of the order of 100 V/µm) in the thickness direction at elevated temperature [8].

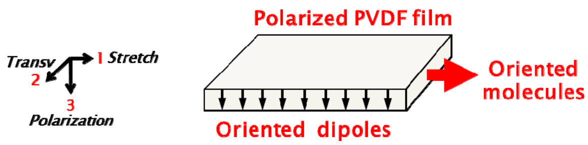

Figure 1: Polarized PVDF film. It is oriented with axis 1 along the stretching direction – axis 2 in the in-plane orthogonal direction and axis 3 along the through-thickness direction.

Commercial bare 110µm-thick PVDF sheets from Measurement Specialties Inc.[1] have been purchased already stretched and poled.

Linear electro-elastic constitutive equations are commonly used to describe the coupling of dielectric, elastic, and piezoelectric properties in piezoelectric materials [9]. Under the assumption of the thickness mode operation

$$D_3 = d_{33}T_3 + \varepsilon_{33}E_3 \quad (1)$$

where *D, T, E* are respectively electric displacement, stress tensor and electric field, while *d* and *ε* are the piezoelectric and permittivity matrices.

As a charge amplifier is used to measure the output charge from the piezoelectric film [10], the electric field E_3 across the PVDF sensor can be considered to be negligible because of the virtual ground at the operational amplifier inverting input. The charge generated by the PVDF sensor can be obtained by integrating the electrical displacement over the loading area A_c:

$$q = \iint_{A_C} D_3 dA_3 = d_{33}A_C T_3 = d_{33}F_C \quad (2)$$

where F_c is the applied force and $T_3 = F_c / A_c$ is assumed to be uniform over the loading area. The frequency behavior of the d_{33} piezoelectric coefficient for PVDF films has been reported in a previous publication [11].

B. *Deposition technology of metal contacts on piezoelectric films*

Metal contacts were patterned on both sides of PVDF films by means of inkjet printing. In particular a Fujifilm Dimatix 2800 (DMP2800) Drop On Demand piezoelectric inkjet printer was used. In this system the deformation of a piezoelectric crystal induced by a voltage stimulus generates a single ink droplet ejection from the print head nozzle allowing the complete control of the ejection of ink droplets. Drawbacks of the thermal inkjet technology, i.e. nozzle clogging due to thermal evaporation of high-volatile solvents, are limited. We used a DMC-11610 cartridge containing 16 nozzles with a diameter of 21.5 µm and each nozzle generates 10 pL drops of ink. For all the metal contacts we used Cabot Conductive Ink 300 (CCI-300), a metal ink (provided by Cabot Corporation) made of silver nanoparticles in a liquid vehicle composed of ethanol and ethylene glycol. Before filling the cartridge the CCI-300 has been subjected to 15 min ultrasonic bath to avoid silver nanoparticles agglomeration and then filtered with a 0.2 µm nylon filter.

During printing, PVDF films were kept at 60°C in order to promote faster solvent evaporation. Two different patterns were printed on the two sides of the substrate: the first consists in a triangular-shaped (3 cm side), continuous and homogeneous ink layer, which acts as the ground contact; the second pattern was printed on the other side of the substrate, once the first was dried, and consists in 12 circles with a diameter of 3 mm each, also arranged in a triangular shape. Fig. 2 shows both layouts.

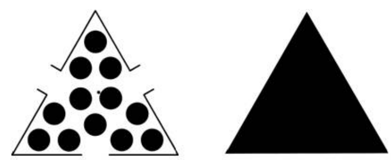

Figure 2: Layout of the inkjet printed patterns: circular taxels (left) and continuous ground contact (right).

A plasma treatment step has been used before the printing process to increase electrode adhesion to the polymer film, enhancing sensor robustness and reliability.
After deposition, samples have been annealed at 60°C in an oven for several hours. We observed that annealing at temperatures above 60°C leads to a huge deformation of the polymer films.

C. *Design and fabrication of the tactile sensing system*

The proposed robot skin is a distributed system composed of a large number of spatially distributed tactile elements (i.e., taxels), organized in a number of patches (Fig. 3), which are surface compliant structures designed to cover large parts of a robot body [12] .

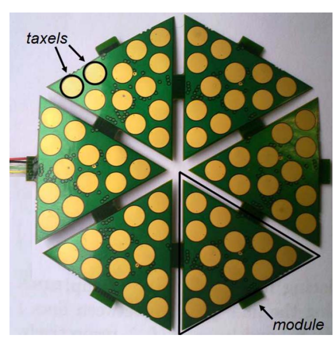

Figure 3: Hexagonal patch made up of six triangular PCBs.

Since complex contact phenomena are likely to be distributed over large robot body surfaces (i.e., the palm, the forearm or the torso), each patch is organized in a number of the above cited triangular modules, each module comprising of a 2D tactile sensing array as well as of embedded and

[1] http://www.meas-spec.com/default.aspx

dedicated electronics. In the current implementation, piezoelectric transducers have to be integrated on the flexible PCB substrate and an elastomer coating is directly polymerized on top as protective layer (Fig. 4).

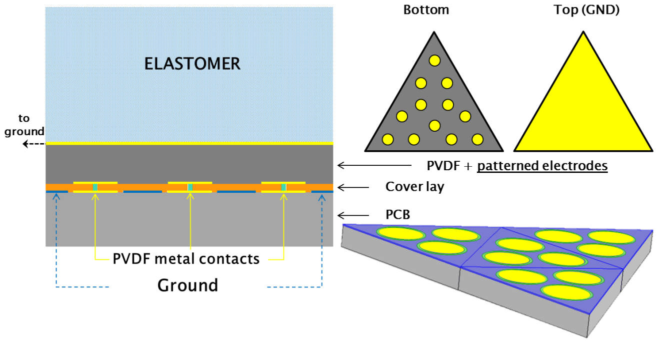

Figure 4: Right: the PCB substrate contains the lower PVDF electrodes (yellow) surrounded by a ground plane (blue). Left (section): robot skin module.

Patterned PVDF film triangles were glued on the PCB by the use of conductive Epoxy (CW2400, all-spec industries). The optimal amount of conductive glue has been determined by preliminary tests. In order to obtain a constant pressure on the whole triangle for the gluing process, 1 kg weight has been used. The System has then been wired by soldering metal wires on the taxel terminations on the PCB back side. The temperature of the PVDF film during soldering has been checked by a thermo camera. Particular care must be used at this stage to avoid the risk to heat the polymer film above the Curie temperature. By carefully working, it is possible to solder a wire at 200°C without heating the polymer at a higher temperature than 60°C (Fig. 5).

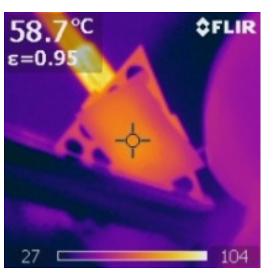

Figure 5: PVDF temperature during soldering (thermoimage).

In order to optimize the thickness of the protective layer, freestanding PDMS (Sylgard 184) films have been prepared with different thicknesses. A 2,5mm layer thickness has been finally chosen as optimally meeting the application requirements.

A completely assembled and 'ready for testing' prototype device (with the exception of the protective film) is shown in Fig. 6.

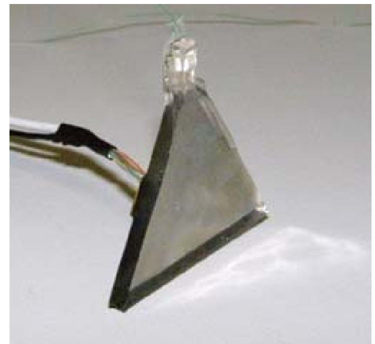

Figure 6: Skin module prototype based on piezoelectric polymer arrays.

III. ESPERIMENTAL TESTS

The electromechanical behavior of skin prototypes was extensively evaluated using the setup shown in Fig. 7.

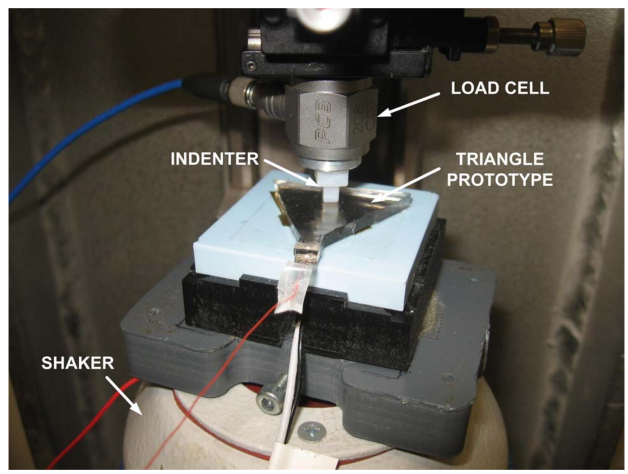

Figure 7: Mechanical setup for the electromechanical characterization of skin module prototypes.

The mechanical chain of the experimental setup is mainly constituted by a mechanical shaker, the triangular skin module (protective layer included) and a load cell. Controllable compressive forces are applied and the charge developed by the PVDF film is measured. The objective of the tests is to validate the proposed approach and assess the performance of the "skin module - interface electronics" tactile sensing system. Different sets of triangular prototypes have been manufactured and tested. A 4 mm x 4 mm square indenter has been mounted on the shaker to stimulate one taxel at a time.

By varying the amplitude of the applied stimulus at a fixed frequency (= 6Hz), 4 different taxel electromechanical responses have been compared (Fig. 8). The curves report the measured charge (mean of peak values) when the single PVDF taxel is subjected to a sinusoidal force applied on top of the elastomer coating. Each sensor behavior is pretty linear over a dynamic range of more than 2 orders of magnitude. The differences between the slopes of the four curves may be due both to variations in the protective layer thickness or to not perfect centering of contact forces over the taxel. However, the overall reproducibility of results shows that the proposed approach is promising.

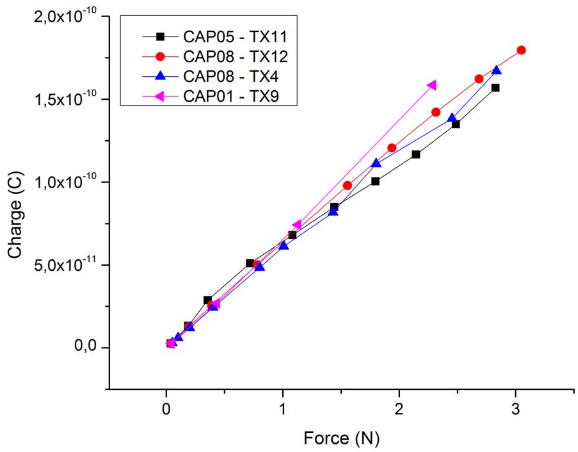

Figure 8: Charge generated by different PVDF taxels (no.11, 12, 4, 9, respectively belonging to triangles no.5, 8, 8, 1) vs applied input force (f = 6Hz).

IV. CONCLUSIONS

A large area tactile sensing system based on arrays of piezoelectric transducers has been designed, manufactured and tested. An ink-jet deposition based solution has been proposed to deposit controllable patterns of metal electrodes on the PVDF films. Preliminary results showing the linearity and reproducibility of the system response to the applied mechanical stimuli reveal the potentialities of the employed technology. This work is intended as the first step towards the integration of different transducers on the same skin module.

ACKNOWLEDGMENT

This work is supported by the European Commission project “ROBOSKIN” about “Skin-Based Technologies and Capabilities for Safe, Autonomous and Interactive Robots”, under grant agreement no. 231500.

REFERENCES

[1] M. R. Cutkosky, R. D. Howe, W. Provancher, “Force and tactile sensors,” In Springer Handbook of Robotics, B. Siciliano and O. Khatib, Eds. Berlin, Springer-Verlag. Heidelberg, Germany, 2008, pp. 455–476.

[2] R. S. Dahiya, G. Metta, M. Valle, G. Sandini, “Tactile Sensing—From Humans to Humanoids,” IEEE Transactions on Robotics, vol. 26, pp. 1-20, 2010.

[3] M.H. Lee and H.R. Nicholls, “Tactile sensing for mechatronics—A state of the art survey,” Mechatronics, vol. 9, pp.1-31, 1999.

[4] S.J. Lederman, Tactual Perception. Ed. W. Schiff., 1982, pp. 130–167.

[5] H.S. Nalwa. Ferroelectric Polymers - Chemistry, Physics and Applications, Marcel Dekker Inc. New York, NY, 1995, pp. 203-214.

[6] T. T. Wang, J.M. Herbert, A.M. Glass, The Applications of Ferroelectric Polymers, Blackie Publishing Co., 1988.

[7] M. Singh, H.M. Haverinen, P. Dhagat, G. E. Jabbour, “Inkjet printing – Process and Its Applications,” Advanced Materials, vol. 22, pp. 673-685, 2010. DOI= http://doi.acm.org/10.1002/adma.200901141

[8] B. Dickens, E. Balizer, A. S. DeReggi, S. C. Roth, “Hysteresis measurements of remanent polarization and coercive field in polymers,” J Appl Phys., vol. 72, pp. 4258-4264, 1992.

[9] T. Ikeda, Fundamentals of Piezoelectricity, Oxford Science Publications, 1996.

[10] L. Pinna, L. Seminara, M. Valle, “Interface Electronics for Robotic Systems based on Tactile Sensor Arrays,” In Proceedings of the IEEE International Conference on Electronics, Circuits, and Systems – ICECS (Beirut, Lebanon, December 11-14, 2011).

[11] L. Seminara, M. Capurro, P. Cirillo, G. Cannata, M. Valle, “Electromechanical characterization of piezoelectric PVDF polymer films for tactile sensors in robotics applications,” Sensors and Actuators A, vol. 169, pp. 49-58, 2011.

[12] A. Schmitz, P. Maiolino, M. Maggiali, L. Natale, G. Cannata, G. Metta, “Methods and Technologies for the Implementation of Large-Scale Robot Tactile Sensors,” IEEE Transactions on Robotics, vol. 27, pp. 389-400, 2011.