

# Design, fabrication and test of arrays of piezoelectric transducers for robotic tactile sensors

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## ABSTRACT

The present paper presents the manufacturing technology of a robot skin made of 2D arrays of piezoelectric transducers. Inkjet printing has been used to provide the piezoelectric film of patterned electrodes. The experimental tests on fabricated skin prototypes reveal the reliability and potentialities of the proposed technology to fabricate large area robot skin. The challenge is to obtain an effective robotic touch sensing system which not only provides fast response, high spatial resolution and wide dynamics but which is also able to cope the requirements of robustness, scalability, reproducibility, light weight and low cost necessary to build a large area skin system.

## Categories and Subject Descriptors

D.I.2 [Artificial Intelligence]: Robotics – *sensors*

## General Terms

Design, Experimentation

## Keywords

Tactile sensors, piezoelectric polymers, PVDF, ink jet printing.

## 1. 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][2][8]. 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 is dictated not only by its individual elements but by also the way they are integrated together. A mix of technology and system issues, such as wiring complexity, distribution of tactile sensors in 3-D space, handling of large tactile data, 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 0-1kHz range of the stimulus frequencies required for the application [7]. In particular, a big effort is devoted to integrate piezoelectric and capacitive transducers into multifunctional modules which are

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interconnected to form a compliant network structure to cover the curved surfaces of the robot body [11].

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 [3][10][15] with a fast dynamic response (1Hz-1kHz 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 [14]. 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 contacts on the PVDF film.

## 2. MATERIALS AND TECHNOLOGY

### 2.1 Piezoelectric transducers

PVDF is synthesized by addition polymerization of the  $\text{CH}_2=\text{CF}_2$  monomer. The polar  $\beta$  phase is obtained by mechanical stretching of PVDF films [10]. 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/ $\mu\text{m}$ ) at elevated temperature [4][5][12].

Commercial bare 110 $\mu\text{m}$ -thick PVDF sheets from Measurement Specialties Inc. [<http://www.meas-spec.com/default.aspx>] have been purchased already stretched and poled.

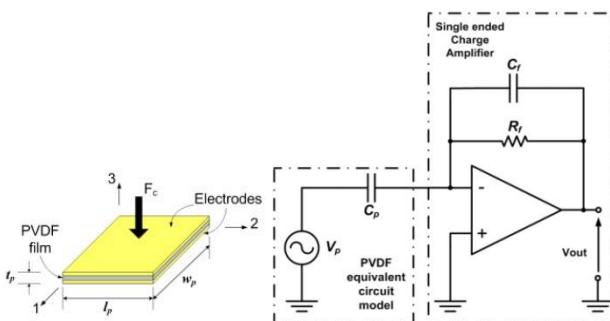


Figure 1. Thin film of piezoelectric material (green), provided of two electrodes (yellow) (left). Charge amplifier connected to the PVDF equivalent circuit model (right)

Linear electro-elastic constitutive equations are commonly used to describe the coupling of dielectric, elastic, and piezoelectric properties in piezoelectric materials [6]. Under the assumption of

the thickness mode operation (“3” corresponds to the through-thickness direction, *Errore. L'origine riferimento non è stata trovata. (left)*)

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

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

A charge amplifier (*Errore. L'origine riferimento non è stata trovata. (right)*) is used to measure the output charge from the piezoelectric film. Considering the operational amplifier as ideal, 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 [13].

### 2.2 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  $\mu\text{m}$  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  $\mu\text{m}$  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 (3cm 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. Figure 2 shows both layouts.

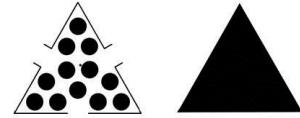


Figure 2. Layout of the inkjet printed patterns: circular taxels (left) and continuous ground contact (right).

In order to promote ink adhesion on PVDF, air plasma treatment was performed before printing process.

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.

### 2.3 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, which are surface compliant structures designed to cover large parts of a robot body [9]. 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 dedicated electronics.

In the current implementation, taxels consist of piezoelectric transducers, which have to be integrated on a flexible PCB substrate. On top of the taxel layer, an elastomer is positioned as a protective layer (Errore. L'origine riferimento non è stata trovata.).

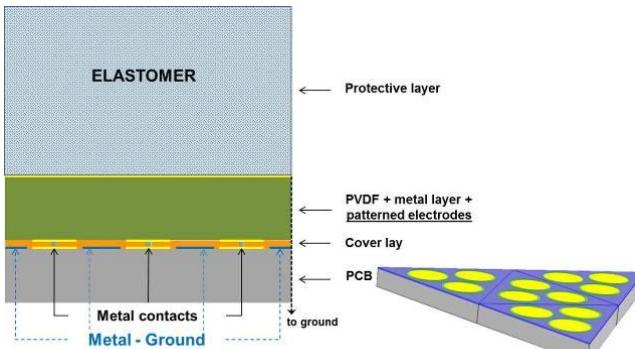


Figure 3. Right: the PCB substrate contains the lower PVDF electrodes (yellow) surrounded by a ground plane (blue). Left (section): robot skin module.

The fabrication technology to assemble the different building blocks (PCB – PVDF film – protective layer) and to take signals out is described in the following.

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, 1kg 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 working carefully it is possible to solder a wire at 200°C without heating the polymer at a higher temperature than 60°C (Figure 4).

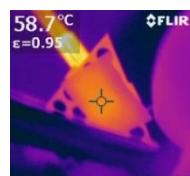


Figure 4. PVDF temperature during soldering (thermoimage).

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 Figure 5.

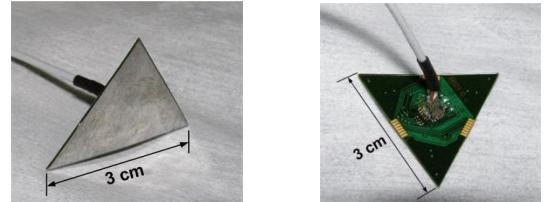


Figure 5. A triangular skin module (no protective layer).

### 3. EXPERIMENTAL TESTS

Figure 6 shows the complete apparatus for the experimental tests on the skin prototypes.

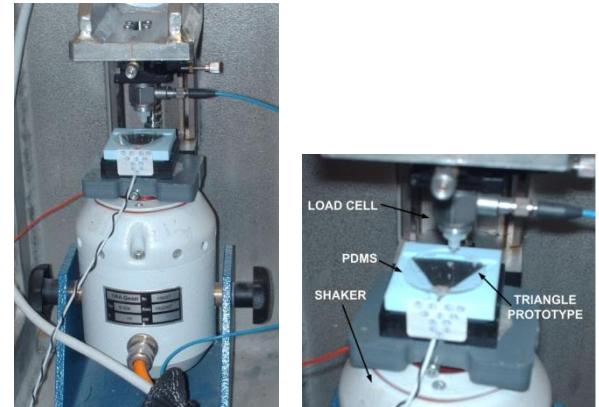


Figure 6. Mechanical setup to characterize the electromechanical behavior of skin prototypes.

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. A “three-stage” charge amplifier circuit with 3 orders of magnitude dynamics has been fabricated. 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. Figure 7 shows some preliminary results.

By varying the amplitude of the applied stimulus at a fixed frequency, 3 different taxel responses can be compared (Figure 7 - top). The most similar behaviors are associated to taxels 4 and 7 belonging to the same triangle (T1), while the third one is associated to taxel 12 of another triangle (T2). The different sets of lines correspond to the 3 output stages of the electronics. The first set correspond to the charge amplifier (CA) output, the

second one to the CA output voltage amplified 16 x and the third one to the CA output voltage amplified 256 x.

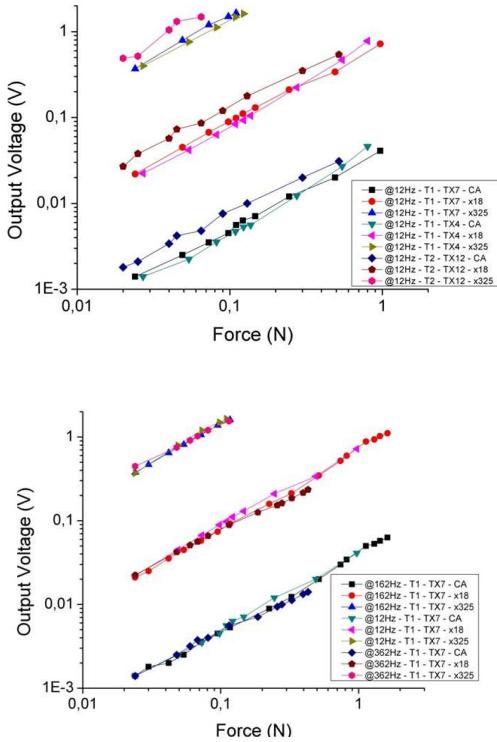


Figure 7. Electrical response of 3 different taxels (top). Response linearity: same taxel, different stimulus frequencies (bottom).

Fig. 7 – down, on the other hand, shows the response of the same taxel for three different stimulus frequencies belonging to the range of interest for the present application. Again, the different sets are associated to the different output stages. As it can be seen, a good linearity is achieved over the whole explored range.

#### 4. 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. The presented manufacturing technology of skin patches can be scalable to cover large areas of the robot body.

#### 5. ACKNOWLEDGMENTS

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