A BIOMIMETIC SENSING SKIN: CHARACTERIZATION OF PIEZORESISTIVE FABRIC-BASED ELASTOMERIC SENSORS

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This article presents a deformable poroelastic bidimensional elastomeric architecture that responds to deformations along various directions thanks to an integrated sensorized fabric. The sensors exploit the piezoresistivity of the loaded rubbers as a principle of strain transduction. Using this architecture, sensors have been characterized in terms of their quasistatic and dynamic electromechanical transduction properties.

1. Introduction

Key points for biologically inspired artificial implementations are the materials, the sensing elements and the control.

Rigid structures are evolving toward flexible architectures characterized by redundant sensing and actuation nets. Development and selection of materials is mandatory. The new breakthroughs made in the past few decades in material science in order to develop intelligent materials built in compliance, non-linearity and softness allow to mimic the multi-component and bi-phasic nature of biological tissues [1]. Moreover, intelligent algorithms allow dynamics to be effectively reconstructed [2,3,4]. In this work we present a electromechanical characterization and modelling of piezoresistive fabric-based elastomeric sensors which properties are suitable for applications in various sectors: health care, rehabilitation and biomimetic robotics [3,4].

2. Sensors

The artificial sensing skin is a 3D latex foam, under which lies a sensing layer.

The sensing layer responds to simultaneous deformations in different directions by means of a piezoresistive network which consists of a Conductive Elastomers (CEs) composites rubber screen printed onto a cotton lycra fabric. CE composites show piezoresistive properties when a deformation is applied and can be easily integrated into fabric or other flexible substrate to be employed as strain sensors (figure 1). They are elastic and do not modify the mechanical behaviour of the fabric. CEs consist in a mixture containing graphite and silicon rubber. Resistance, Gauge Factor, Temperature Coefficient Ratio and Reactive Properties have been classified [3]. In the production process of sensing fabrics, a solution of CE and trichloroethylene is smeared on a lycra substrate previously covered by an adhesive mask. The mask is designed according to the desired topology of the sensor network and cut by a laser milling machine. After the deposition, the cross-linking process of the mixture is obtained at a temperature of 130°C. Furthermore, by using this technology, both sensors and interconnection wires can be smeared by using the same material in a single printing and manufacturing process.

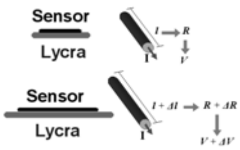

Figure 1 – Transduction principle of the strain sensor

3. Methods

From the technical viewpoint, a piezoresistive woven sensing fabric is a system whose local resistivity is a function of the local strain.

In a discrete way, it can be thought of as a two dimensional resistive network where single resistors have a non-linear characteristic that depends on the local strain. The integral impedance pattern is a function of the overall shape of the sensorised fabric and allows mapping between the electrical space and the shape space. For the characterisation of the sensors in terms of their quasi-static and dynamic electromechanical transduction properties sensors were serially connected. In this case, a current is superimposed in the circuit and high impedance differential voltages are acquired from each sensor. A block scheme of the acquisition hardware is presented in figure 2. Two multiplexers allow a sensor to be selected and the relative signal is acquired by a differential amplifier. A microprocessor drives the whole system, performs the analogous/digital conversion and exchanges data via USB interface. The device is provided with an automatic calibration subsystem which allows gain and offset to be tailored to each sensor.

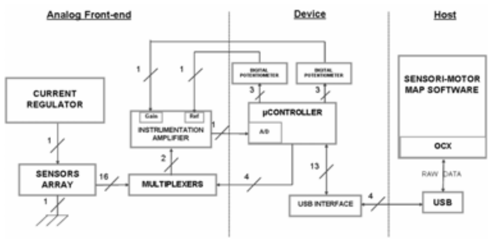

Figure 2 – Block schema of the acquisition hardware

A pushing punch driven by a stepper motor was used to apply alternate mechanical deformations (by indentation) to each fabric based sensor. Several tests were carried out, by using rectangular-wave mechanical stimulations (series of pressure impulses). In order to model the electromechanical response of each sensor, an equivalent circuit based on the equivalence between the electrical response (current variation) of the circuit and the response (resistance variation) of the sensor was proposed.

4. Results

Each sensor was tested by applying a series of pressure impulses (figure 3a) and by acquiring the voltage drop across the sensor as its response (figure 3b).

Pressure impulses result in a typical differential voltage behaviour showed in figure 3b. Sensor response shows a peak in correspondence to every mechanical transition. Data acquired were filtered, peaks were detected and relative maximum and minimum, and time constants were selected as features (figure 3b).

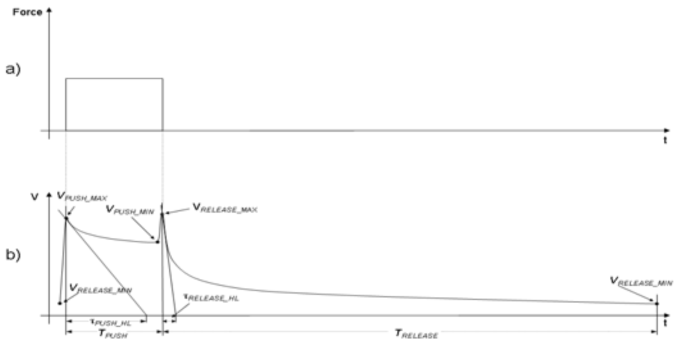

Figure 3 – a) A pressure impulse; b) sensor response a pressure impulse and selected features

Sensor responses during constant pressure time intervals were approximated by decreasing exponentials, assuming the local minimum as the steady-state value. This approximation results as true as long is the pressure time interval. In order to remove the contribution of high order exponentials, first order time constants were calculated discarding the first 5% of each curve. This choice allowed quantization errors introduced by the acquisition device in response to rapid transitions to be avoided and sensor steady state deformation, related to slower frequency components, to be maintained.

During a series of pressure impulses, the time constants of the deformation phases presented an average value of 9.32 seconds, while the time constants during the deformation recovery showed an average value of 4.72 seconds.

Figure 4a shows the acquired signal during pressure deformations (continuous line) and the extracted exponential discharging law (dashed line); figure 4b shows the quadratic error. Close to the mechanical transitions the differences between the signal and the exponential law is high; during the constant pressure phases the differences are very low (< 3×10^{-5} V).

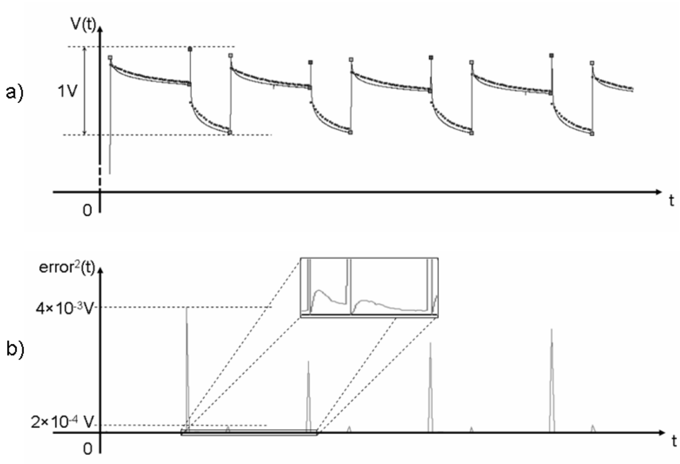

Figure 4 – a) acquired signal during pressure deformations (thin line) and extracted exponential law (bold dotted line); b) quadratic error

In order to model the first-order components of the sensor response (resistance variation) to a rectangular stimulation (applied deformation), the equivalent circuit represented in figure 5 was considered.

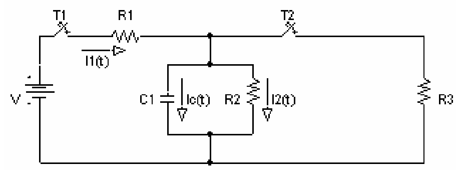

Figure 5 – Proposed equivalent electric model of each sensor

The power supply V is the electrical analogous of the imposed deformation. The switch T1 (initially open) is closed and open in correspondence of, respectively, the beginning and the end of the imposed deformation. The switch T2 (initially open) is closed when T1 is open again. Following a simple analysis of this circuit, it is easy to recognise that the variation of the charging and discharging currents of the circuit in consecutive phases of stimulation are analogous to the variation of the resistance of the sensor during, respectively, its deformation and the following release. The circuit parameters R_1, R_2, R_3 and C can be derived by using the features, extracted from reference experimental signals, listed in Table 1.

Feature of the variation of the sensor resistance	Feature of the variation of the charging/discharging currents of the circuit	Symbol
Initial peak [kΩ]	Initial peak [A]	$I_1(0)$
Steady-state value for the deformation phase [kΩ]	Steady-state value for the charging phase [A]	$I_1(\infty)$
Time constant of the first-order exponential components for the deformation phase [s]	Time constant for the charging phase [s]	τ_1
Time constant of the first-order exponential components for the release phase [s]	Time constant for the discharging phase [s]	τ_2

Table 1 – Considered analogous features

A circuit voltage of 1 V was assumed as the analogous of a deformation of 1 mm, while a circuit current of 1 A was assumed to correspond to a variation of the sensor resistance of 1 kΩ. Values of the features listed above were extracted from ten cycles of a reference experimental signal and were used to derive the circuit parameters by means of the following system of equations:

$$\begin{cases} \tau_1 = C(R_1 /\!/ R_2) \\ I_1(0) = \dfrac{V}{R_1} \\ I_1(\infty) = \dfrac{V}{R_1 + R_2} \\ \tau_2 = C(R_2 /\!/ R_3) \end{cases}$$

The solution of this system provided, for the considered ten cycles of stimulation, the results reported in figure 6.

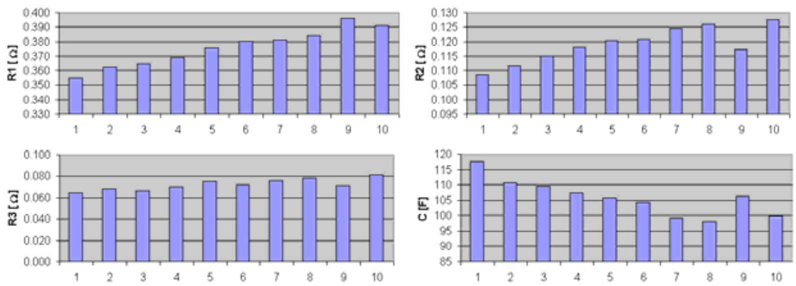

Figure 6 – Values of the parameters of the equivalent electric model extracted from ten cycles of a reference experimental signal

In consideration of the limited number of tests considered so far, definitive assessments and interpretations of the trends reported in figure 6 are premature at the moment. Accordingly, we are approaching a second phase of tests, in order to validate such an electrical equivalent model by subjecting each sensor to an extensive campaign of measurements, by applying deformations consisting of rectangular-wave signals with variable amplitudes, frequencies and duty-cycles.

5. Conclusions

In this paper sensors exploiting the piezoresistivity of the loaded rubbers as a principle of strain transduction have been preliminarily characterized in terms of their quasistatic and dynamic electromechanical transduction properties. Moreover, in order to model the first-order components of the sensor response to a rectangular stimulation, an electrical equivalent circuit was proposed.

References

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