5.1: Electroactive Fabrics for Distributed, Conformable and Interactive Systems

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Abstract

Posture and gesture analysis and body kinematics monitoring is a field of increasing interest in bioengineering and several connected disciplines. We propose wearable systems able to read and record posture and movements of a subject wearing them. We used strain gage sensors, deposited directly onto textile fibers realizing, in contrast with different strategies, truly wearable and unintrusive systems.

Keywords

Sensors, electroactive polymer, smart textiles

INTRODUCTION

The fabrication of electronic systems onto substrates which are not only flexible, but also conformable to the human body represents a break-through in many areas of application such as virtual reality, teleoperation, telepresence, ergonomics and rehabilitation engineering [1].

The possibility to realize sensing textiles by coating traditional fabrics with smart materials (piezoresistive, piezoelectric and piezocapacitive polymer) has opened the way to implement a new type of man-machine interface technology.

These fabrics enable the realization of wearable sensing garments capable of recording proprioceptive maps with no discomfort for the subject and negligible motion artifacts caused by sensor-body mechanical mismatch.

As discussed in this paper, elastic fabrics covered with an epitaxial layer of conducting polymer or with carbon filled rubber show piezoresistive properties and they can be used to realize sensorized garments such as gloves, leotards, seat covers and related artifacts capable of reconstructing and monitoring body shape, posture and gesture.

MATERIALS AND FABRIC PREPARATION

Sensors have been realized starting from conventional fabrics coated with a thin layer of polypyrrole (PPy, a Π-electron conjugated conducting polymer) or by a mixture of rubber and carbon.

PPy is a conducting polymer that combines good properties of elasticity with mechanical and thermal transduction. PPy coated Lycra fabrics were prepared using the method reported in reference [2].

Sensors based on carbon filled rubber (CFR) were realized either by directly printing the carbon/rubber mixture onto fabrics or by weaving CFR coated fibers. Threads and fabrics of this type have been obtained as an experimental product (Smartex Srl, Prato Italy).

SENSOR CHARACTERIZATION

The sensors were characterized in terms of quasistatic and dynamic electromechanical transduction properties. Thermal and aging properties of the sensing fabrics have also been assessed.

The sensor mechanical characterization was performed by exerting uniaxial stretching through rigid links connected to a DC motor and by reading the corresponding variation of electrical resistance. The motor was driven and controlled by an encoder connected to a PC. Quasistatic characterization was executed by applying small increments of stretching, while the dynamic one was performed with step-wise stretching.

A simple thermal characterization procedure was performed to determine how temperature influences the piezoresistive properties of the sensors. To do this we measured the electrical resistance of samples at different temperatures by putting them into an electronically controlled thermostatic cell.

Resistance versus time for unstrained samples was measured to evaluate their aging behavior.

RESULTS AND DATA ANALYSIS

PPy coated fabrics

The characterization on PPy coated fabrics has pointed out a gage factor ($GF=\Delta R/\varepsilon R_0$, where ΔR is the variation of the sensor resistance, R_0 its rest value and ε is the applied strain) of about -13 (negative and similar to nickel) and a temperature coefficient of resistance (TCR) of about 0.018°C^{-1}. The numerical value of GF was calculated from a linear interpolation of data (before saturation) reported in Figure 1.

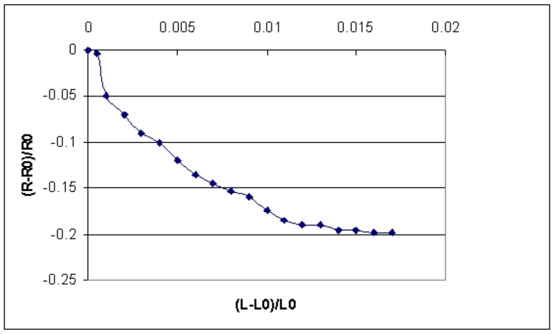

Figure 1. Quasistatic response in terms of percent change in electrical resistance versus uniaxial strain for a PPy based sensor.

Despite the fact that high GF value is suitable for strain gage implementation, two serious problems affect PPy coated fabric sensors. The first problem resides in the strong variation with time of the sensor resistance. The second problem is the high response time of the sensors; in fact after sudden application of a mechanical stimulus the resistance reaches steady state in several minutes (see Figure 2); this makes these fabrics unusable in most applications.

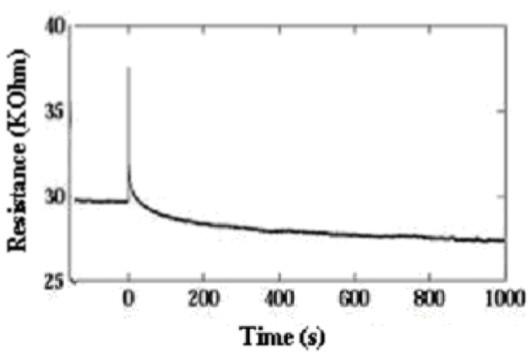

Figure 2. Response in terms of change in electrical resistance under stepwise stretching for a PPy based sensor.

Both limitations have been partially overcome by the following "ad hoc" coding procedure. Analyzing the resistance responce in the range of 1 second after the imposition of a step-wise deformation, it is possible to derive the applied strain in an aging invariant way. We consider a right-angled triangle (Figure 3) where the cathetus height is equal to the excursion of the response peak and the slope of the hypotenuse is equal to the time derivative of the resistance calculated at the middle point between the the peak and the final value of the range. It has been demonstrated [3] that the area of this triangle codifies for the strain independently of the sensor resistance aging.

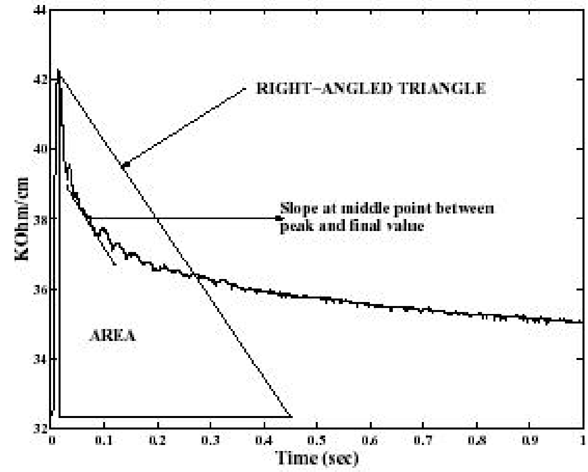

Figure 3. PPy sensor resistance per unit of length vs time after the application of the mechanical strain. The triangle we consider to be useful in data treatment is also traced.

Carbon filled rubber coated fabrics

The characterization on CFR coated fabrics has pointed out a GF of about 2.5 and a TCR of about 0.08C^{o-1}. The numerical value of GF was calculated from a linear interpolation of data (before saturation) reported in Figure 4. These values are quite similar to those of metals and are suitable for the use of such sensors in wearable applications.

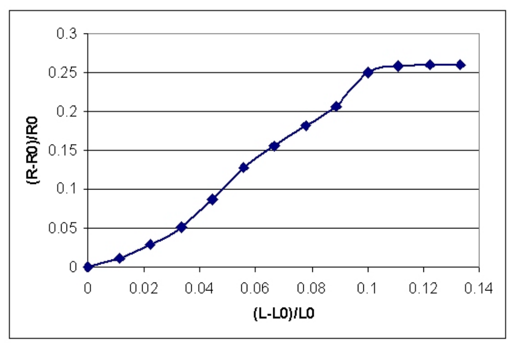

Figure 4. Quasistatic response in terms of percent change in electrical resistance versus strain for a CFR based sensor.

CFR fabrics age very slowly and they behave like low pass filters with a bandwidth from DC to 8 Hz. In Figure 5 we report the response of this type of sensors to a step-wise stretching [4].

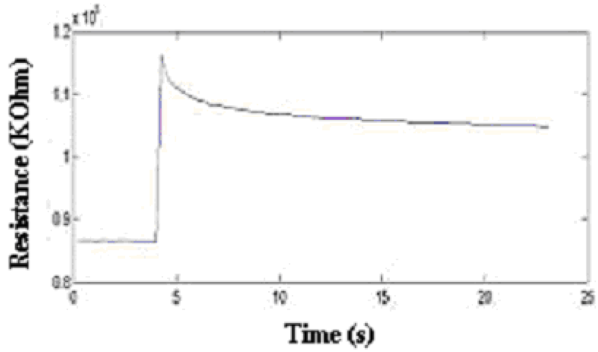

Figure 5. Response in terms of change in electrical resistance under stepwise stretching for a CFR based sensor.

SENSORS ARRAYS

This technology consents the realization of large sets of sensors distributed over a garment. The advantage offered by this technology is clear: a large quantity of information can be obtained, leading to a great versatility in device implementation. On the other hand, reading a large number of sensors, one per channel (single sensor reading), increases dramatically the complexity of the electronic acquisition system. In order to address this problem, we have studied several topologies of interconnection of sensors to reduce the number of sampling channels and tracks. By connecting sensors arrays in electrical networks and reading their borders only (by a multiplexed acquisition), it is possible, in principle, to reconstruct a resistance variation of the value of an inside-located sensor.

Three types of interconnection have been studied. Two strategies use for each sensor a bipolar model (variable resistance, see Figures 6 and 7); the third one uses a quadripolar model (4 variable resistances, see Figure 8).

The two bipolar strategies consist in connecting arrays of sensors in series (Figure 6) or parallel (Figure 7) networks. Pairs of sensors (whose distance is negligible in respect to the geometric dimension of the net) on the fabrics are connected rows by columns. The inevitable crossing of wires makes necessary to electrically insulate them to realize series and parallel connections.

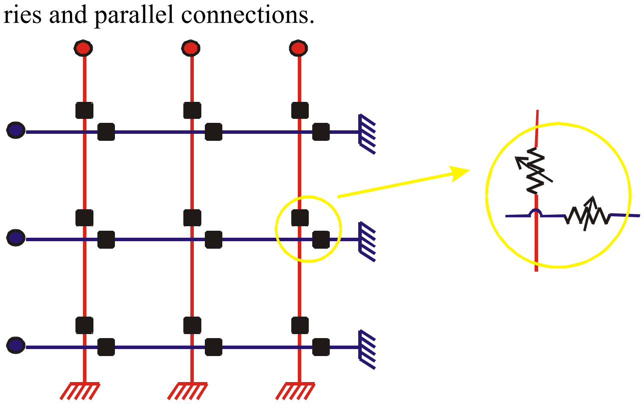

Figure 6. Series network.

The small distance between the two sensors ensures that their deformation is the same and differs from the other couples.

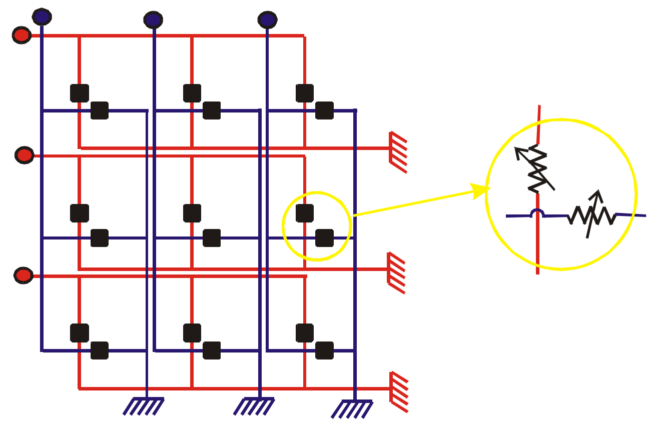

Figure 7. Parallel network

A deformation of a pair of sensors implies a resistance variation of the entire row and column identifying the couple. So, by reading a variation of a column and of a row, we can identify a precise point into the net.

In the quadripolar strategy (Figure 8) connections are realized inside each sensor and no insulated cable is needed. In this configuration, signals are read by multiplexing both the channel and the ground of each column and row. By using common techniques of resistance network analysis, it can be proved that a sensor is localized by matching the row and the column which present the maximum resistance variation.

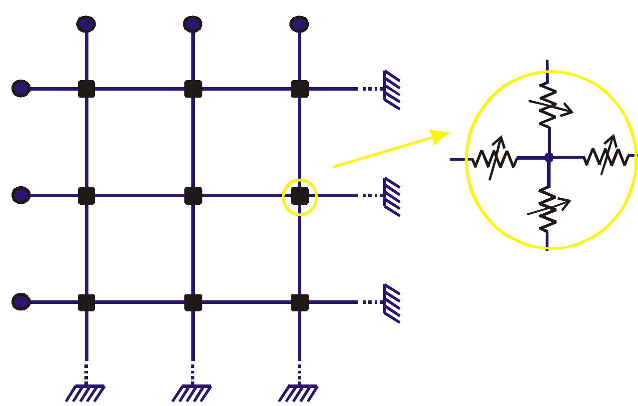

Figura 8. Quadripolar network.

For each strategy, considering a square array of sensors, a n-channels acquisition system can read a network of $(n/2)^2$ pairs of sensors for the bipolar configurations or a network of $(n/2)^2$ sensors for the quadripolar configuration. In respect to a single sensor reading, these strategies are advantageous (reduced reading channels number) if $n \geq 6$ even if they lead, as it will be discussed later on, to a loss in terms of sensors sensitivity and accuracy in signal reconstruction, causing a degradation in sensor localization.

Assuming to read sensor resistance variations by voltage (V) variations with an imposed constant current, we define sensor sensitivity as $\delta V/\delta\varepsilon$ and accuracy in signal reconstruction as $\Delta V/V_{bias}$ (where V_{bias} is the voltage read for unloaded sensors and ε is the applied strain). Assuming each channel to include a certain number (k) of equal sensors and assuming the deformation of a single pair of sensors only, the expression of the voltage (V) read from the channel with an imposed constant current (i) is reported below.

For the series network we have:

$$V = ikR\left(1+\frac{\Delta R}{kR}\right)+ke = ikR\left(1+\frac{GF}{k}\varepsilon\right)+ke$$

where R is the sensor resistance, ΔR is its variation, GF is the single sensor gage factor and e is the RMS value of the resultant of intrinsic noise and interferences on each sensor.

For the parallel network we have:

$$V = i\frac{R}{k}\left(1+\frac{\Delta R}{kR+(k-1)\Delta R}\right)+e = i\frac{R}{k}\left(1+\frac{GF\varepsilon}{k+(k-1)GF\varepsilon}\right)+e$$

Table 1 shows the expressions of sensitivity and accuracy for the single sensor reading strategy and the two bipolar ones.

Table 1. Sensitivity and accuracy for different sensor reading strategies.

Configuration	Sensitivity	Accuracy
single sensor	$iRGF$	$GF\varepsilon$
series	$iRGF$	$GF\varepsilon/k$
parallel	$iRGF/[k+(k-1)GF\varepsilon]^2$	$GF\varepsilon/[k+(k-1)GF\varepsilon]$.

We observe that the parallel network presents the worst sensitivity and accuracy.

To quantify the decrease of accuracy shown by the bipolar strategies in respect to the single sensor one, it is necessary to take into account the effect of the noise and the interferences (e term). In particular it is useful to determine the maximum value of k ($k_{\max}$) able to keep a reasonable signal-to-noise ratio (SNR). Even if the analysis of the noise and interferences effect is still under study, $k_{\max}$ can be estimated assuming for example the signal variation to be ten times grater than the RMS of the resultant of noise and interferences, e=1mV, R=10K and ΔR=1KΩ: we have $k_{\max}$=100 for the series network and $k_{\max}$=10 for the parallel network. This means that the series strategy allows one to use a greater number of sensors.

For the quadripolar sensors arrays an accurate formulation on the decrease of sensitivity and accuracy in respect to the single sensor strategy needs further investigation. Preliminary circuit simulation proved that the information in terms of sensitivity and accuracy obtained with this strategy is worse than the bipolar connections one.

The reading schemes exposed above, anyway, are not simple to employ directly on a garment, for several matters. In particular, reconstruction of the status of the net is expensive from a computational point of view. Moreover, to reconstruct a position of a subject wearing a sensing garment, the knowledge of the exact position of each sensor of the net relative to his body is required. We remark that this is made difficult by the inevitable differences in subject body size and shape. This means that the discussed strategies enable sensors localization, but not gesture and posture identification. This problem can be overcome by a suitable "inversion" technique, as explained in the next section.

INVERSION TECHNIQUE

We have studied a reconstruction ("inversion") technique based on an identification phase, not of the single sensor but of the entire system. So we make a calibration of a sensors net ignoring the location of the applied deformation. This can be obtained by adopting a strategy in a certain sense functional, i.e. the final aim of our work is to know which gesture a subject holds, and not which individual sensor has modified its status. From this point of view, redundant sets of sensing fabrics patches linked in different topological networks can be regarded as a spatially distributed sensing field. By simultaneously comparing the sensing field with the value of the joints variables in the identification phase, it is possible to reconstruct postures and gestures in the data acquisition phase. The identification phase has been executed by having a subject wearing the sensing device and pointing by a handhold laser a lattice of markers fixed in a measurement environment. An entire set of sensor data has been recorded for each pointed position. This data have then been interpolated by a piecewise linear function. We have tested posture detection system over a second lattice (said of the target) in the space of the position, where data obtained by the sensors have not been used to interpolate the piecewise linear function, but only to check the device precision.

In Figure 9, as an example, abduction-adduction angle and flexion-extension angle of the gleno-humeral joint are reported respectively in the abscissa and the ordinate. Each piecewise line is the solution of the equations holding for significant sensors (responses from sensors which are not influential for the detection of this particular posture degenerate into the entire plane), projected from the entire space of joints variables into the plane of the coordinates of the shoulder. The estimated position is given by the intersection of these solutions.

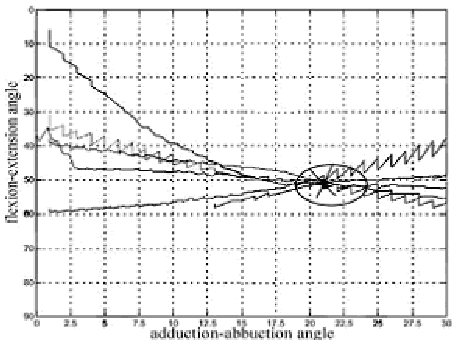

Figure 9. Traces of the value held by different sensors in correspondence of a certain position. The estimated position is given by the intersection of the traces.

In Figure 10 the intersection zone is enlarged.

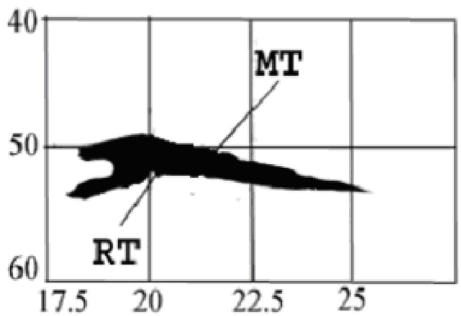

Figura 10. The high-density zone of probability for the estimated position is represented. The measured target (MT) differs from the real target (RT) less than 4%.

Due to the redundant allocation of the sensors, the solution is calculated in the "least square sense", i.e. by considering the entire zone with high density of possible solutions. The position of the target is calculated by the average value of all the points contained on this zone. The distance between the calculated position of the target and the real one in of about 10 cm in a range of about 2.5 meters, that's an error less than 4 per cent. In other cases we have obtained larger errors, always less than 8 per cent.

This technique has shown good capabilities in balancing the irregularities of operation of singles sensors.

APPLICATION

Sensing fabrics described here can be employed in the realization of wearable sensing systems able to record human posture and gesture, which could be worn for a long time with no discomfort. We integrated sets of PPy and CFR sensors into a leotard and a glove linked to an electronic unit which treats the pre-filtered data obtained by the sensors. Prototypes have been already realized in our laboratory [5]; they have shown reasonable capabilities to detect and monitor body segments position by reading the mutual angles between the bones. In particular, gleno-humeral joint, elbow joints, and the joints of the hand have been investigated. We have attributed three degrees of freedom to the shoulder (flexion-extension, adduction-abduction, rotation), two to the elbow (flexion-extension and pronation-supination), one degree of freedom for each interphalangeal joint of the hand, two to each metacarpo-phalangeal joint and two degree of freedom to the trapezium-metacarpal joint. Moreover, relative movements between metacarpal bones have been considered.

In these early prototypes, sensors have been intuitively located in correspondence of each joint in a number equal to the degrees of freedom (Figure 11).

Figure 11. Sensorized glove and sensorized leotard.

In the new generation of prototypes, the strategy of redundant sensors allocation is adopted and a large set of sensors is distributed over the garment. To reconstruct the posture of subject wearing large sets of sensor is used the strategy exposed in the previous section with the encouraging results reported in Figure 10.

CONCLUSION

We have shown that fabrics coated with conducting polymer as PPy or with a mixture of carbon and rubber have piezoresistive properties. We investigated these properties showing that they can be used to realize strain sensors, which may have useful application in the field of man-machine interfaces. In particular, these fabrics are easily integrated into truly wearable, instrumented garments, capable of recording kinaesthetic maps of human motor function with no discomfort for the subject. We also proposed a way to use large sets of sensors without increasing dramatically the number of reading channels.

AKNOWLEDGMENTS

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