AUTEX Research Journal, Vol. 2, No4, December 2002 © AUTEX

SMART TEXTILES FOR WEARABLE MOTION CAPTURE SYSTEMS

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Abstract

The implementation of truly wearable instrumented garments capable of recording biomechanical variables is crucial to several fields of application, from multi-media to physical rehabilitation, from sporting to artistic fields.
Here we report on wearable devices which are able to read and record the posture and movements of a subject wearing the system. The sensory function of the garments is achieved by fabric strain sensors, based on threads coated with polypyrrole or carbon-loaded rubbers. The presence of conductive elements gives these materials piezoresistive properties, enabling the detection of local strain on the fabric.
Strips of strain fabrics are applied together with conductive tracks at strategic points in a shirt and a glove in order to detect the movements of the principal joints.
The 'smart shirt'-sensing architecture can be divided into two parts: a textile platform, where a wearable device acquires biomechanical signals, and a hardware/software platform, to which a wireless communication system sends the acquired data after electrical conditioning.

1. INTRODUCTION

Textile-oriented systems with different functions and applications have recently become the subject of great interest, mainly because of their versatility and comfort. Several properties, such as thermal regulation, flame resistance and high mechanical strength are being investigated, which requires a dedicated multidisciplinary effort.

Here we report on a new type of textile able to work as a strain sensor, based on conducting polymers (CP) or carbon-filled rubbers (CFR). It can be used to create wearable devices able to read the posture and movements of a subject wearing the system. The basic applications of such a system are in sectors where it is important to know human body actions: rehabilitation, sport and multimedia.

2. MATERIALS AND FABRIC PREPARATION

Sensors were created on the basis of conventional fabrics coated with a thin layer of polypyrrole (PPy, a Π-electron conjugated conducting polymer) or with 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 [1].
Sensors based on carbon filled rubber (CFR) were made either by directly printing the carbon/rubber mixture onto fabrics or by weaving CFR-coated fibres. Threads and fabrics of this type have been obtained as an experimental product (Smartex Srl, Prato Italy).

3. SENSOR CHARACTERISATION

The sensors were characterised in terms of quasistatic and dynamic electromechanical transduction properties. The thermal and aging properties of the sensing fabrics have also been assessed.
Mechanical characterisation of the sensors 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 characterisation was executed by applying small increments of stretching, while dynamic testing was performed with step-wise stretching.
A simple thermal characterisation procedure was carried out 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 also measured to evaluate their aging behaviour.

4. RESULTS AND DATA ANALYSIS

4.1. Ppy-coated fabrics

The characterisation on Ppy-coated fabrics has pointed out a gauge 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.

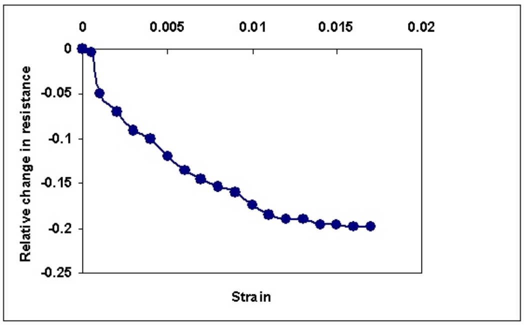

Figure 1. Quasistatic response in terms of percent change in electrical resistance versus uniaxial strain for a PPy based sensor

Despite the fact that a high GF value is suitable for strain gauge implementation, two serious problems affect Ppy-coated fabric sensors. The first problem resides in the drift with time of the sensor resistance. This process is called aging, and is due to the slow oxidation of the polymer deposited on the textile. The second problem is the slow response time of the sensors; in fact, after sudden application of a mechanical stimulus the resistance reaches a steady state only after several minutes (see Figure 2); this makes these fabrics unusable in most applications.

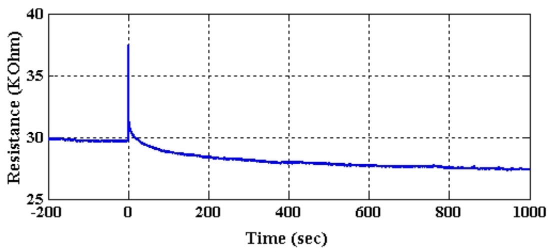

Figure 2. Response in terms of change in electrical resistance under stepwise stretching for a Ppy-based sensor

Both limitations have been partially overcome by the following '*ad hoc*' coding procedure. Analysing the resistance response in the first 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 mid-point between the peak and the final value of such range. It has been demonstrated [2] that the area of this triangle codifies the strain independently of the sensor resistance aging.

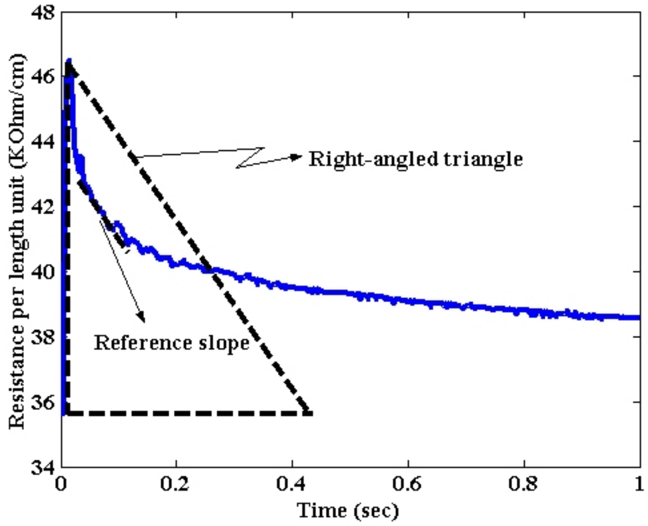

Figure 3. PPy sensor resistance per unit of length vs. time after the application of the mechanical strain. The triangle we consider to be useful in data treatment is also traced.
The reference slope is given by the slope at mid-point between peak and final value.

4.2. Carbon-filled rubber-coated fabrics

The CFR-coated fabrics have 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.

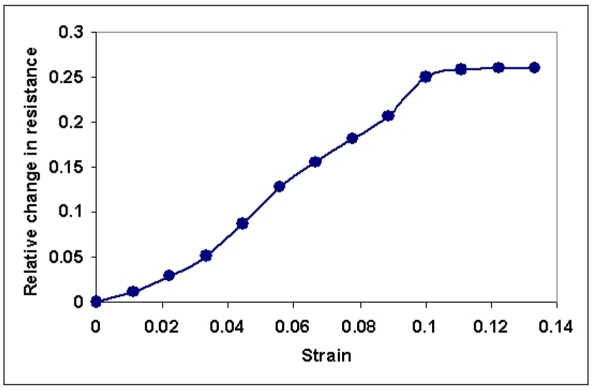

Figure 4. Quasistatic response in terms of percentage change in electrical resistance versus strain for a CFR based sensor

CFR fabrics age very slowly, and behave like low-pass filters with a bandwidth from DC to 8 Hz. In Fig. 5 we report the response of this type of sensors to a step-wise stretch [3].

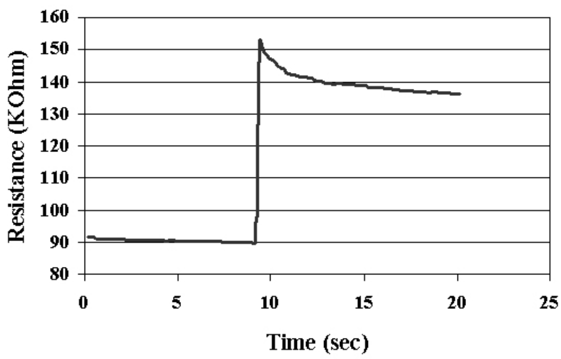

Figure 5. Response in terms of change in electrical resistance under step-wise stretching for a CFR-based sensor

5. PROTOTYPES

A few prototypes which we have already made [4] have shown reasonable capabilities of detecting and monitoring body segment position by reading the mutual angles between the bones. Figure 6 shows a sensorised glove and a sensorised leotard. In particular, the gleno-humeral joint, elbow joints, and the joints of the hand have been investigated. We have attributed three degrees of freedom to the shoulder, two to the elbow, 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 (see the glove of Fig. 6).

Figure 6. Sensorised leotard and sensorised glove

In these early prototypes, sensors were intuitively located in correspondence to each joint in a number equal to the degrees of freedom. In the new generation of prototypes, the strategy of redundant allocation is adopted, and a large set of sensors is distributed over the garment.

6. APPLICATION OF SMART TEXTILES AS KINAESTHETIC AND HAPTIC INTERFACES

The long-term goal of our research is to develop a family of wearable, bi-directional (sensing and display) haptic interfaces to be used in surgery and rehabilitation (Fig. 7). To achieve this distant goal, several methodologies and techniques need to be developed in terms of sensing (tactile and kinesthaetic), actuation and control. In this context, skin-like tactile sensors both for fine-form discrimination [5] and for incipient object slippage detection [6] as well as tactile displays for haptic discrimination of softness [7] have been investigated in our laboratory.

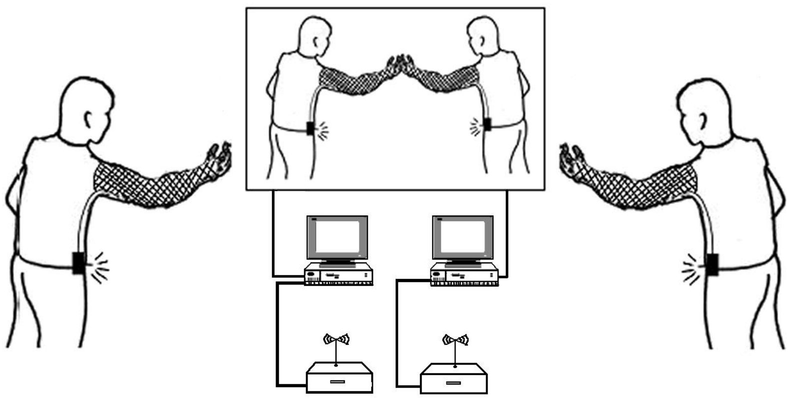

Figure 7. Scheme of telerehabilitation

Figure 6 refers to a scheme of telerehabilitation, where a bilateral active haptic interface is worn by the patient and is telemetrically controlled and monitored by a medical specialist from a remote position. Another domain of interest is telesurgery, where a haptic interface could be worn by the surgeon in a master-slave system to provide better manoeuvrability, dexterity, and an ergonomic coupling: the surgeon could manoeuvre the system as though he were directly manipulating the remote object itself. Finally, a bilateral haptic interface could be used as wearable active orthoses for a paralysed arm. In this case, the impaired subject could perform the physical therapy by himself, and the haptic interface could also provide assistance with arm movements.

7. INVERSION TECHNIQUE

The adopted reconstruction (''inversion') technique is in a certain sense functional: the final aim of our work is to know which gesture a subject holds, and not which individual sensor has modified its status. We have studied a reconstruction '('inversion') technique based on an identification phase, not of the single sensor but of the entire system. Thus we calibrated the sensor network while ignoring the location of the applied deformation. From this point of view, redundant sets of sensing fabric 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 joint variables in the identification phase, it is possible to reconstruct postures and gestures in the data acquisition phase.

8. CONCLUSION

We have shown that fabrics coated with a conducting polymer such as PPy or with a mixture of carbon and rubber have piezoresistive properties. We investigated these properties, showing that they can be used to create strain sensors which may have useful applications 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 to the subject.

AKNOWLEDGMENTS

The support of DARPA through NICOP grant n N000140110280 is gratefully acknowledged.

REFERENCES

[1] De Rossi D., Della Santa A., Mazzoldi A. 1999. ''Dressware: Wearable hardware', Material Science & Eng. C, 7:31-35.

[2] Scilingo E. P., Lorussi F., Mazzoldi A., De Rossi D. 2002. 'Strain sensing fabrics for wearable kinaesthetic systems', IEEE Sensors Journal, in press.

[3] De Rossi D., Ghelarducci B., Paradiso R., et al. (2001), 'Sensing Threads and Fabrics for Monitoring Body Kinematic and Vital Signs', Proceedings of Fibres and textiles for the future, Tampere, Finland.

[4] De Rossi D., Lorussi F., Mazzoldi A., Scilingo E. P, Rocchia W (2001), Strain amplified electroactive conducting polymer actuator, Proceedings of SPIE [4329-07]

[5] Caiti A., Canepa G., De Rossi D., Germagnoli F., Magenes G., Parisini T. (1999), IEEE Trans. Syst, Man, Cybern., vol. 25, p. 533-546.

[6] Canepa G., Petrigliano R., Campanella M, De Rossi D. (1998), Detection of incipient object slippage by skin-like sensing and neural network processing, IEEE Trans. Syst., Man, Cybern., Part B, vol. 20, n.3, p. 348-356.

[7] Bicchi A., Scilingo E.P., De Rossi D. (2000), Haptic discrimination of softness in teleoperation: the role of the contact area spread rate, IEEE Trans. Robotics & Automation, Vol. 16, n.5, p. 496-504.