Characterization of piezoresistive sensors for goniometric glove in hand prostheses

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***Abstract*—Piezoresistive sensors can be successfully adopted in many field where bend angles need to be measured. In particular, attention must be paid for increase the sensor numbers, applied to body-sample, which give parallel information on the movement activity. The possibility to capture information from the sensors adopting wireless technology can allow the increasing of sensor number, and the removing of wire ties between sensors and the central processor unit in normal human motion. We utilized these sensors to develop an instrumented glove to measure human joint fingers. The great advantage in applications of piezoresistive sensors rely on their pliability, sensitivity and cheapness. In any case, for effective results, it is mandatory a complete electrical sensor characterization, which lacks in literature and therefore it is the aim of this work.**

***Index Terms*— Piezoresistive sensor, strain gauge, electronic goniometer, wireless sensor network.**

I. Introduction

THE investigation of the new possibilities offered by new technologies in the field of strain and bend sensors can lead to improve sensibility and accuracy, the fundamental topics to understand, as in deep as possible, the human locomotion control and the motion-neuronal activity.

In particular, attention must be paid for increase the sensor numbers, applied to body-sample, which give parallel information on the locomotion activity. So more detailed maps can be obtained, in definition and cross-correlation, among the several elements of the sensor/detector matrix, with the further possibility to capture information from the sensors adopting wireless technology. So wire ties can be removed between sensors and the central processor unit. Wireless technology can allow the increasing of sensor number (otherwise impossible to obtain), and the removing of wire ties in normal human motion.

Wireless feasibility study must be investigated, with the adoption of circuital solutions electromagnetic based rather than optics as in the past (the optic has the drawback of not guarantee the visibility under all circumstances).

Investigation must be focused on which can be an ad-hoc functional wireless communication system (band, protocol, etc) between the sensors and a receiving base station.

In the same field, special attention must be paid for a feasibility study involving actuator sensors for a cybernetic glove suitable for revealing, controlling and measuring movements and/or capture actions of human hands in a three-dimensional space. In such a view cinematic and dynamic can be studied registering flesso/extension and adduction/ abduction movements of fingers.

So called "cybernetic gloves" have been adopted in analyzing of intrinsic and extrinsic hand movements, thanks to sensors on back-hands, palm and fingers. So, a study must be carried out for understanding which kind of sensors must be utilized and how they must be characterized.

Sensors realized with piezoresistive materials change their electrical resistivity when deformed. The piezoresistive coefficient, π, is defined by the ratio of the change of the relative resistivity caused by the change of the relative length of resistor.

$$\frac{\Delta \mathrm{R}}{\mathrm{R}} = \pi \frac{\Delta l}{l}$$

For many metals, the coefficient's value is $\pi = 2$, whereas for semiconductors the deformation changes the band structure and, as a consequence, the coefficient. It ranges from $\pi = -120$ to $+120$ depending on the doping, the temperature, and the crystal orientations [1], [2].

The piezoresistive property has been widely used in many sensor applications, such as strain gauges. In particular, piezoresistive sensor strips, which increase their resistance with degrees in the bending magnitude, can be applied as electronic goniometers. This property, opportunally applied to goniometric gloves, could be useful in the measure of hand function's assessment. A goniometric glove would enable multiple finger joint positions to be acquired simultaneously, and allow hand movement patterns to be recorded.

Exploration of piezoresistive sensors for hand prostheses, where large deformation bending is expected, is therefore a logical step and will be detailed in the following sections where we will demonstrate the high potential of piezoresistive sensors and their ease of implementation.

This paper describes the characterization of bend sensors applied for realization of goniometric gloves, but taking into account that the sensor application potentialities are even much larger, such as personal computer mouses, pointers, human body activities, etc.

The devices under study are commercial carbon ink bend sensors, chosen because of their pliability, very high bending sensitivity, different lengths to adapt to different finger joints, and cheapness.

The objective of this work is to evaluate the behaviour of a bend sensor for a range of bending rates and angles, in order to calibrate their performance in terms of prediction errors in the foreseen applications. To this purpose, the material response was characterized under quasi-static and dynamic bending, using the experimental apparatus described in the following section.

In the first part of the work, after the experimental apparatus description, a sensor characterization, aimed to evaluate the static performance of bending sensor to different bending angles, is described.

In the second part of the work the repeatability of measurements for an electronic goniometric sensor was investigated using real-time signal analysis. In order to evaluate the sensor ability to distinguish between varying bend angles at different rates of stimuli, the response of the sensor material was evaluated under 2-step rotation cycles between −90° and +60° at the maximum rotation speed rate, which is much greater than the finger one, considering that the maximum bending rate for the human finger is expected to be 6 Hz, corresponding to

$$\omega_{max} = 6\,Hz \times 360° \times 60" = 129600\ degree/min$$

Finally the extraction of an electrical equivalent circuit, also correlating parasitic parameters to bending angles, was performed in the last section.

II. Experimental Apparatus

The apparatus employed for this analysis was designed to emulate, in a controlled environment, the device behaviour as a bending sensor.

The sensor sample was laid as a cantilever beam on a metal hinge. In order to bend the sensor from -90° to +60° degrees (given the hinge constraints) with different bending rates, one end of the sensor sample was locked in a stationary clamp fitted to the sensor isolated electrodes, in order to measure the resistance through a digital multimeter controlled by a Labview routine. Through a sliding clamp, the opposite end of the sensor was fixed without stretching to a rotating platform operated by a stepper motor with a step size of 0.9°, and controlled by the computer via the serial port in order to vary bending angles and rates reliably.

The input as measured by the sensor is therefore the angle of rotation of the stepper motor shaft, henceforth referred to as the bending angle, whilst the shaft angular velocity is subsequently denoted as the bending rate. In this way sensor resistance can be characterized in terms of expected bending angles and speed rates. This was done to reduce the variability that may arise from calibrating the sensor with a manual rotation on a printed goniometer, a practice still utilized in medical rehabilitation treatments. Figure 1 provides a schematic of the experimental set-up.

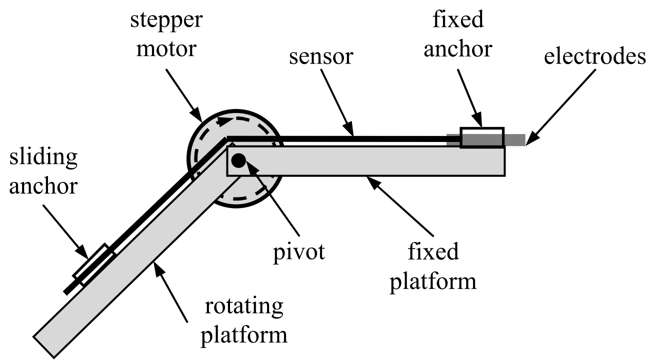

Figure 1. Schematic of the experimental set-up

III. Quasi-static Characterization

Using the calibration test jig, the output resistance value, measured with a digital multimeter, was collected for each imposed bending angles, each set at 10° intervals, and used to produce a static characterization curve for the particular sensor size under study. The repeatability of measurement for the electronic goniometric sensor was evaluated comparing quasi-static forward and back rotation angles for each sensor size. Forward and back values were superimposed in this case. Memory effects cannot be evaluated for quasi-static stimulation.

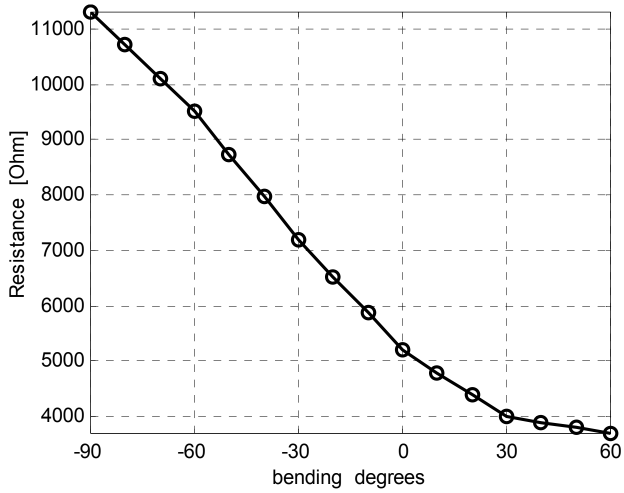

Figure 2. An example of sensor resistance vs quasi-static bending rotation.

IV. Time-domain Dynamic Characterization

Time-domain sensor characterization, performed with a Agilent TDS210 digital oscilloscope controlled from a PC with LaBview through a GPIB link, was based on the auto-balanced bridge. The electrical schematic, including an operational amplifier connected as an inverting amplifier, is shown in Figure 3. This scheme is valid as far as the signal stimulus falls inside the amplifier bandwidth. Probes connected to oscilloscope channel 1 and 2 read node voltages V_{in} and V_{out}.

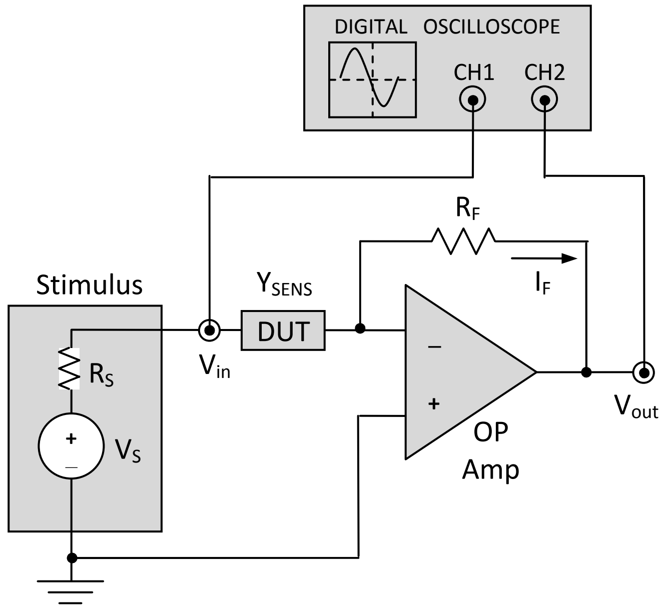

Figure 3. Schematic of DC and RF sensor characterization with a digital oscilloscope trough a auto-balanced bridge.

A. *Transition analysis*

Stimulating the bridge with a DC voltage, it was possible to extract the sensor resistance variation with bending angle.

From the auto-balanced bridge circuit, the sensor resistance can be easily obtained from dc voltage levels

$$I_F = -\frac{V_{out}}{R_F} \qquad R_{SENS} = \frac{V_{in}}{I_F} = -R_F\,\frac{V_{in}}{V_{out}}$$

To evaluate the resistance adaptation and relaxation time, the sensor was bent with a one-step rotation to a specified angle, from −90° to +60° degrees (as allowed by the test jig), and restored to the flat position, with the maximum motor speed rate, while the signal variation was captured in real time on the digital oscilloscope display. In this way, typical motion of both flexion and extension was captured, to measure the resistance adaptation and relaxation times.

On relaxation, however, when the original angular displacement is recovered, given the elasticity of the support substrate, the original resistance is restored. It was noticed that the resistance recovery time with increasing and decreasing rotation is independent on the motor speed rate.

Figure 4 exhibits a little overshoot in the sensor resistance when the sensor is abruptly bent, and a decrease with relaxation, when the original flat position is restored.

Specifically, the peak value of the resistance was measured, along with the time required to reach this voltage peak. This time (~100 ms) is much greater than the motion duration. Using these two values, calibration curves could be generated to predict bending rates and angles.

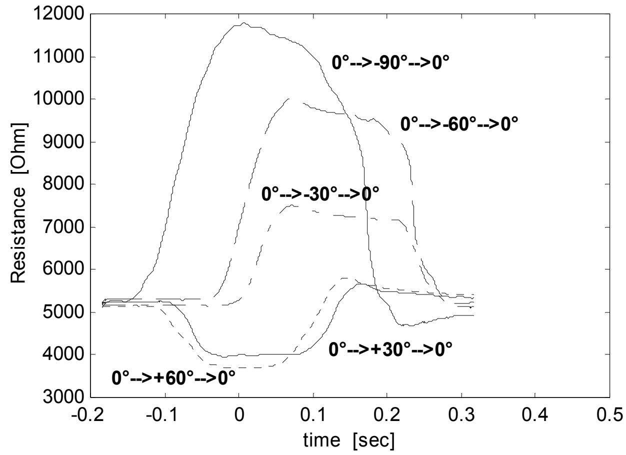

Figure 4. Adaptation and relaxation time for different intensity step rotation.

B. *Steady-state equivalent circuit extraction*

To investigate as parasitic elements are also correlated to bending angle, an RF characterization from 1 kHz to 10 MHz was performed. Stimulating the bridge with a carrier wave (CW), it was possible to yield the magnitude and phase of sensor admittance, from the auto-balanced bridge, as

$$|Y_{SENS}| = \frac{1}{R_F}\frac{|V_{out}|}{|V_{in}|} \qquad \langle Y_{SENS}\rangle = \pi + 2\pi \cdot freq \cdot t_d$$

where t_d is the time delay between the input and output channel voltages.

From the sensor equivalent circuit, shown in Figure 5, where parameters are function of sensor bending angle θ, results:

$$Y_{SENS} = Y_r + jY_i = j\omega C + \frac{1}{R + j\omega L} = j\omega C + \frac{R - j\omega L}{R^2 + \omega^2 L^2}$$

$$Y_r = \frac{R}{R^2 + \omega^2 L^2} \qquad Y_i = \omega C - \frac{\omega L}{R^2 + \omega^2 L^2}$$

$$L = \frac{1}{\omega}\sqrt{\frac{R}{Y_r} - R^2} \qquad C = \frac{1}{\omega}\left(Y_i + \frac{\omega L}{R^2 + \omega^2 L^2}\right)$$

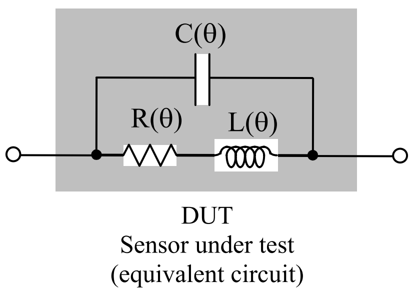

Figure 5. Sensor electrical equivalent circuit (circuit parameters are function of bending angle θ).

In this way, plots of resistance along with parasitic inductance and capacitance vs. bending angle can be obtained, as reported in Figg. 6 and 7, respectively.

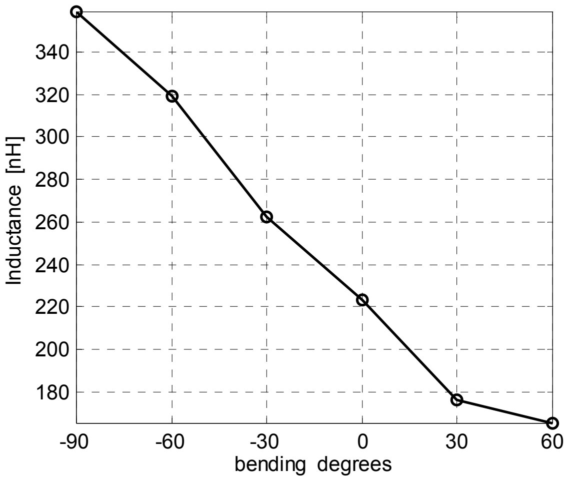

Figure 6. Equivalent series inductance parameter variation for different sensor bending under quasi-static rotation.

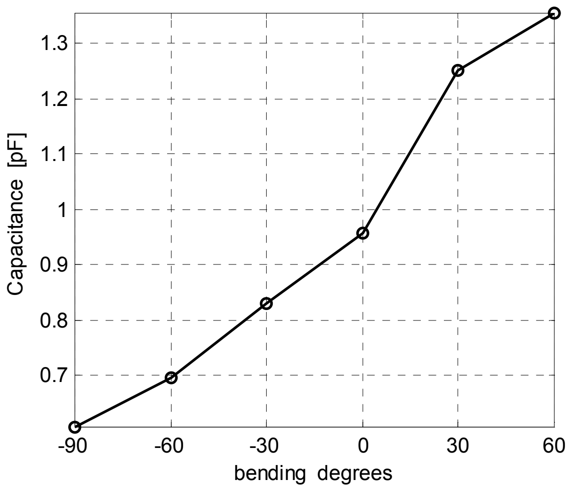

Figure 7. Equivalent shunt capacitance parameter variation for different sensor bending under quasi-static rotation.

V. Going on developments

A. VNA frequency-domain characterization

Further experiments will be conducted to gauge the sensor response under one-port carrier wave stimulation ranging from 300 kHz to 10 MHz from a Agilent E5061A vector network analyzer (VNA). The resulting file containing the Z or S vector versus frequency will be collected to extract the equivalent RLC circuit. Results will be compared with those from time-domain characterization, especially to confirm the high inductance values.

B. Bending rate and angle prediction for sensor calibration

Present investigation regards correlation of the magnitude and timing of the voltage in the adaptation and recovery periods of the sensor response to bending rates and angles.

It is possible to yield a plot of prediction errors for bend angles, during sensor rotation at different speed rate.

This can be very important to calibrate the sensor response for different rates, in order to recover the bending degrees and rates with more accuracy in sensor applications [2].

VI. Conclusions

A static and dynamic characterization on piezoresistive sensors was performed. It is foreseen that results could be utilized to develop and calibrate instrumented glove, in order to predict human joint motion with reduced errors, in wireless sensor network applications such as goniometric gloves in hand prostheses, or, in general, virtual system implementations based on hand motion.

VII. Acknowledgement

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