EVALUATING STRAIN SENSOR PERFORMANCE FOR MOTION ANALYSIS

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Keywords: Piezoresistivity, Bend sensor, Motion analysis, Posture recognition.

Abstract: Investigation on the more suitable technologies to register human body movements in 3D space with great spatial accuracy is a very challenging task, because a wide range of applications are concerned, from registration of post-stroke rehabilitation or sports performance, to monitoring of movement of disabled or elderly people, etc. In this paper the possibilities offered by piezoresistive bend sensors applied as wearable devices, integrated on body garments, have been explored. Piezoresistive sensors can be usefully adopted to recover human joint bend angles for body movement tracking. Due to their pliability, sensitivity and cheapness, they could be a valid alternative to movement analysis systems based on optoelectronic devices or inertial electronic sensors. This paper suggests a new approach to model their electrical behavior during bending and extension movements, in order to predict their real-time performance during different kinds of applications.

1 INTRODUCTION

Technology progress in the last decades has provided the opportunity to observe human behavior in 3D space with great spatial accuracy, thanks to image-based methods or virtual reality tools. This is a very challenging task, because a wide range of applications are concerned, from registration of post-stroke rehabilitation and sports performance, to monitoring of movement of disabled and elderly people, only to give some examples.

Optoelectronic techniques, based on infrared cameras with reflective markers, for measurements of human motions and gait analysis, have been developed. However, these methods are conceived for maximum reliability and precision in equipped environments, such as a laboratory, and therefore are usually expensive and/or not readily transportable, complicated to set up, and finally do not guarantee the visibility under all circumstances.

On the other hand, inertial and electromagnetic sensors, such as accelerometers and gyroscopes, and new technologies in the field of strain and bend sensors can lead to the development of wearable devices to solve the relevant outdoor application problems in human posture recognition. Special applications in the field of telerehabilitation are under study (Draicchio F. et al., 2010 - Giorgino T. et. al, 2009 - Dipietro L., 2008). Adoption of wireless technologies allows the removal of wire ties, which hinder the human motion (Saggio G. et al., 2009).

In order to measure human body kinematics it is convenient to adopt sensors, which can measure bending angles with good precision despite a low cost. Piezoresistive sensors can be made of a polyester base material printed on with a special carbon ink. The polyester acts as a support while the ink's resistance increases the more it is bent. The ink is screen printed so it can be applied on virtually any custom shape and size film to fit to each body joint. The substrate film material is usually formed by Kapton and/or Mylar for their properties, stands the fact that substrate must be able to bend repeatedly without failure for the sensor to work. The sensor can be over-molded (for instance with silicon or urethane) and it can work in dirty environments (oil, dust). This kind of sensors are available on the market (Images SI Inc. Staten Island NY, Flexpoint Sensor Systems Inc. South Draper UT, USA). They can be applied to body joints as electronic goniometers, to realize goniometric sock for rotation assessment of body segments in human posture recognition, or to goniometric gloves, which enable multiple finger joint positions to be acquired

Orengo G., Saggio G., Bocchetti S. and Giannini F..
EVALUATING STRAIN SENSOR PERFORMANCE FOR MOTION ANALYSIS.
DOI: 10.5220/0003168402440249
In *Proceedings of the International Conference on Biomedical Electronics and Devices* (BIODEVICES-2011), pages 244-249
ISBN: 978-989-8425-37-9

simultaneously, and allow hand patterns to be recognized (Giorgino T. et al, 2009 - Dipietro L., 2008).

In order to useful exploit sensor's properties, a complete electromechanical characterization is mandatory. For this purpose a fully automated measurement bench was realized and sensors modeled from both mechanical and electrical point of view. We propose and designed the bench ourselves because sensor modeling stands lacks in literature in that sense. Sensor's characteristics were exploited to reproduce their movements inside instrumented garment revealing human motions.

Moreover, a new modeling technique will be developed. Available piezoresistor models, in fact, continue to incorrectly employ a merely variable resistance to model the sensor electrical properties under a bending stress. Little experimental study and theoretical analysis has been undertaken on the effect of a range of bend angles and rates on sensor response. One perceived problem is to calibrate sensor performance in terms of prediction error in the foreseen applications. As a result, in order to use piezoresistive sensors in high precision and/or high speed applications, an electrical model is required that not only models the static piezoresistive effect, but also characterizes the electrical behavior during bending transitions. A logical choice seems to investigate on sensor behavioral models, as a consequence of the most important manufacturers of commercial bend sensors do not provide any description of their own technological process.

In Section 2 the experimental apparatus is described. In Section 3 the static characterization is accomplished. In Section 4 a dynamic characterization is presented. In Section 5 a RF characterization is attempted to explain the observed delays. In Section 6 a new approach to extract an electrical behavioral model is described. Finally, in Section 7 the behavioral model is applied to predict sensor performance in tracking slow and fast knee rotations, whereas some conclusions are drawn in Section 8.

2 EXPERIMENTAL APPARATUS

The apparatus employed for this analysis was designed to emulate, in a controlled environment, the behavior of commercial carbon-ink bend sensors, printed on pet strip substrates, when applied to body joints to track segment rotations. Figure1 shows a schematic of the experimental set-up. Figure 2 provides a photo of a sensor strip sample. The sensor sample was laid as a cantilever beam on a metal hinge. In order to bend the sensor from -60 to +180 degrees (for setup mechanical constraints) with different bending rates, the sample side connected to the electrodes was locked in a stationary clamp, fixed to a rotating platform operated by a step motor. The other side of the sensor strip was put in a sliding clamp to avoid the sample stretching. Bending angle step amplitude was changed reliably from a Labview serial interface connected to a PC. The step motor is a PD-109-57 sample from Trinamic, connected to the PC through a RS-232 cable. Motor speed rate can be set changing the TMLC (Trinamic Motion Control Language) units (1000 TMCL units correspond to 9.537 RPS or rounds-per-second). In this way, the sensor resistance can be characterized in terms of the expected bending angles at different speed rates.

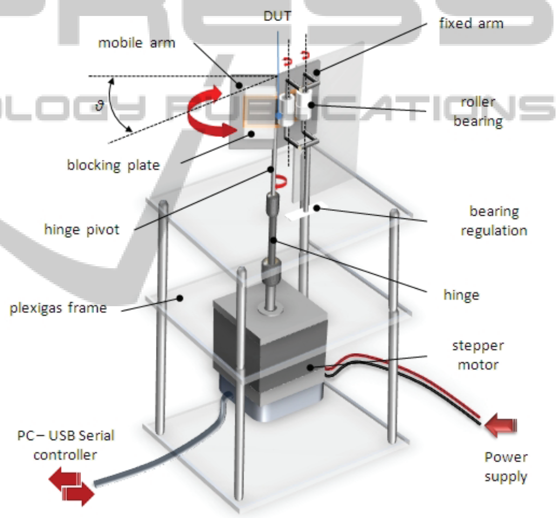

Figure 1: Schematic of the experimental set-up.

Figure 2: Photograph of a piezoresistive sensor strip (Images SI Inc. Staten Island NY USA).

3 QUASI-STATIC BENDING RESPONSE

Using the described test set-up, the sensor resistance value was measured through a digital multimeter, sweeping rotation amplitude of the mobile arm of the hinge, at ten degree steps. For the particular sensor size under test, a quasi-static characterization curve for inward and outward bending angles, corresponding to negative and positive rotation degrees, respectively, was produced. Results are plotted in Figure 3, together with the parasitic capacitance, which will be evaluated in a following section. It can be observed that the sensor resistance changes not linearly with bending rotation degrees, even if efforts were spent to enhance linearity (Gentner R. Classen J., 2009). More sensitivity resulted for outward bending. Since body segment rotations approximately range from 0 to 150 degrees, they will be tracked exploiting only outward rotations. In this case, the piezoresistive material must be external with respect to the body joint.

The repeatability of measurement was evaluated comparing the same bending angles during quasi-static forward and back rotation. Forward and back values succeeded to be superimposed in this case, due to the elasticity of the sensor strip substrate, although temporary memory effects cannot be evaluated under quasi-static stimulation, but they were analyzed in the next section.

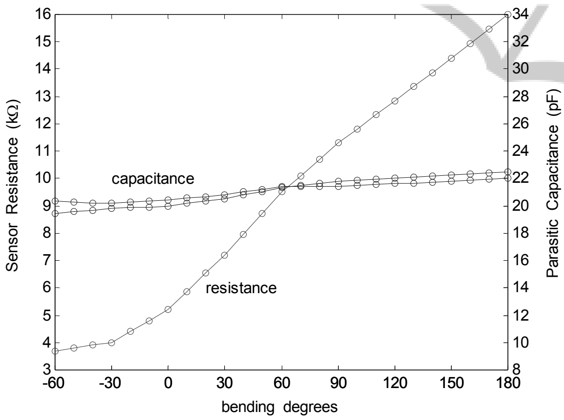

Figure 3: Electrical resistance from quasi-static measurements, and parasitic capacitance from S-parameter measurements, of a piezoresistive sensor, under ten degree stepped bending rotation increments.

4 STEP-BENDING TRANSITION ANALYSIS

In order to know the sensor dynamic behavior during flexion and extension, the response to fast rotations was analyzed through time-domain characterization performed with the same experimental apparatus, using this time an Agilent TDS210 digital oscilloscope. The electrical schematic is shown in Figure 4, where a series reference resistor is inserted to measure the current. Probes connected to oscilloscope channel 1 and 2 read node voltages v_{in} and v_{out} , respectively. The aim was to analyze transitions in sensor resistance, when subjected to fast flexions and extensions for different amplitudes of the rotation step.

Stimulating the circuit with a constant DC voltage, the sensor resistance can be easily obtained from

$$i(t) = \frac{v_{in}(t) - v_{out}(t)}{R_p} \quad (1)$$

$$R_{sens}(t) = \frac{v_{out}(t)}{i(t)} = R_p \frac{v_{out}(t)}{v_{in}(t) - v_{out}(t)} \quad (2)$$

To evaluate the resistance transition times, the sensor was subjected to trapezoidal stimulations, each composed of a one-step rotation from 0 to 50, 100 and 150 degrees, respectively, and a one-step back rotation to restore the flat position, delayed of 220 ms.

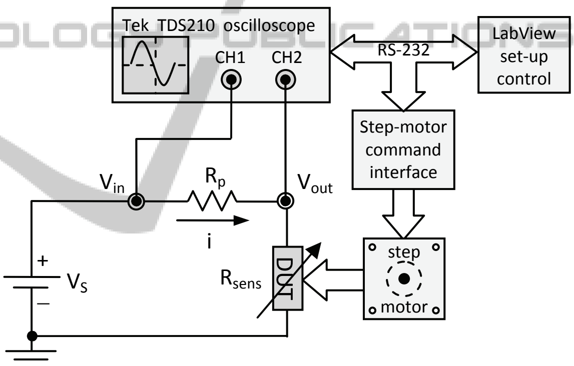

Figure 4: Electrical schematic of the transition characterization set-up.

The rotations were operated setting the maximum allowed motor speed rate, corresponding to 2040 TMCL, which is theoretically close to 20 RPS, that is to say 7 degree/ms. The input and output voltage waveforms were captured in real time from a PC by the Labview interface, setting different delays to the command signal sent to the motor with respect to the trigger signal sent to the oscilloscope to discriminate multiple traces, stopping the acquisition at the end of the selected time-base (0.5 s), and saving the input/output voltage waveforms on a file.

Figure 6 exhibits the resistance waveforms as resulted from (2), together with the ideal response, which would result from the motor rotation, and a model simulation, which will be developed in a following section. It can be observed the rise/fall and relaxation times in the sensor resistance during flexions and extensions. Comparing specified motor and experimental sensor transition times, except for friction delays during sensor strip extension, it can be concluded that the motor rotation speed seems to contribute for less than 20% to transition times in sensor response.

Owing that transition delays cannot be eliminated, authors believe that it is useful to provide a sensor electrical model, which can predict the sensor performance, especially in those applications where high speed movements have to be monitored.

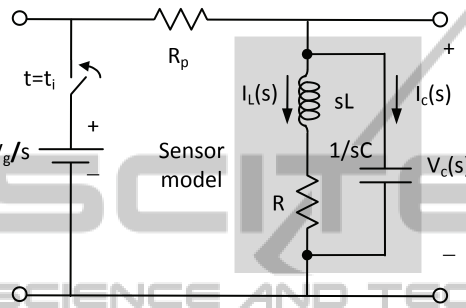

Figure 5: RLC behavioral circuit (t>0).

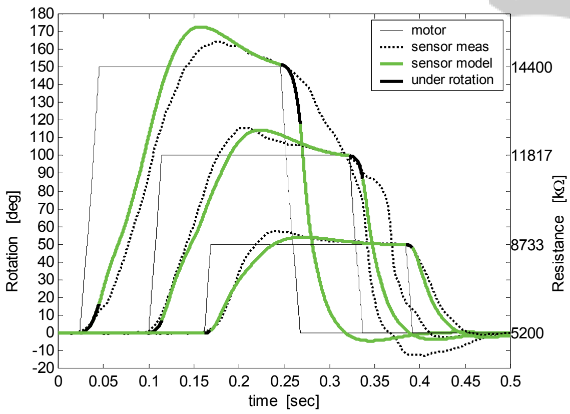

Figure 6: Comparison of measured sensor resistance response with the RLC model simulation, for 50,100 and 150 degrees of bending and extension step amplitudes (darker trace segments correspond to response during motor rotation).

5 RF CHARACTERIZATION

To investigate whether electrical parasitic elements could be the source of transient times, parasitic series inductance and shunt capacitance were extracted by mean of RF characterization. Although transient times are too long to be explained only by circuit elements, authors believed that to extract their values and investigate whether they are correlated to bending angle is of some interest to understand the device behavior. To this aim a further experiment was conducted, accomplishing a one-port RF characterization with an HP8150 network analyzer, while the sensor strip was subjected to quasi-static rotations by the step motor using the same test jig, with rotation angles ranging from -60 to 180 degrees. Using the DC resistance values, the parasitic series inductance and shunt capacitance values were obtained from the sensor complex admittance extracted from S-parameter measurements from 50 to 200 MHz. The inductance value resulted too low and was neglected, whereas the parasitic capacitance rated about 20 pF, as also reported in Figure 3. It is clear that the measured transient times cannot be on account of such a low parasitic value.

6 BEHAVIORAL MODELS

As a matter of fact, it can be supposed that piezoresistive material relaxation times should be the source of transition times. Investigation on the physical nature of material relaxation, however, is not the target of this work. The most important manufacturers of commercial sensors, in fact, do not provide any description of their technological process, and, in any case, this kind of investigation does not concern design engineers of sensor cognitive systems.

A behavioral model is here represented by a low-pass RLC circuit, where circuit elements were optimized to fit the model simulation to the electrical behavior shown by measurements, with no account on their physical meaning. The circuit used to simulate the sensor electrical behavior under resistance variation is shown in Figure 5, where the resistance was supposed to change simultaneously with the rotation degrees, while the transition delay was modeled by the LC resonant circuit. The sensor response was analyzed in the Laplace domain, even if, in this case, the voltage source is constant and the stimulus should be represented by the sensor resistance variation itself, in response to a bending stress. Given the Laplace circuit analysis does not allow element variations, the sensor resistance was represented as a piecewise-constant model, where the ramp, whose slope corresponds to the motor rotation speed, was divided into small steps. The sensor response was therefore obtained from an iterative routine, which performs circuit analysis computing successive step solutions, where the initial conditions at each step are the last values of the previous one. The global sensor response is obtained connecting the successive solutions.

Referring to a single step, the system was analyzed solving the following linear system:

$$\begin{cases} I_c = sCV_c - Cv_{ci} \\ V_L = sLI_L - Li_{Li} \\ V_c = I_L R_i + V_L = I_L\left(R_i + sL\right) - Li_{Li} \\ V_c = V_g / s - \left(I_c + I_L\right) R_p \end{cases} \quad (3)$$

where v_{ci} and i_{Li} represent the initial conditions at step i.

The solution is

$$V_c = \frac{1}{LC\,R_p} \frac{\left(V_g + sCR_p v_{ci}\right)\left(R_i + sL\right) - sLR_p i_{Li}}{s\left(s^2 + s\,\omega_{0i}/Q_i + \omega_{0i}^2\right)} \quad (4)$$

$$V_c = \frac{1}{LC\,R_p} \frac{\left(V_g + sCR_p v_{ci}\right)\left(R_i + sL\right) - sLR_p i_{Li}}{s\left(s^2 + s\,\omega_{0i}/Q_i + \omega_{0i}^2\right)} \quad (5)$$

$$\beta = LCR_p = \frac{R_i + R_p}{\omega_{0i}^2} \quad (6)$$

The constant circuit parameters L and C were found from (5) and (6), assigning a reasonable value to the sensor resistance R (*14kΩ*), the resonant frequency f_0 (*10Hz*) and the resonant factor Q (*1.23*), even if they actually change at each step. A reasonable value for the resonant frequency f_0 can be obtained from the equation $f_0 \approx 1/t_{rise} = 10\,Hz$ for a rise time of 100ms. It is worth to note that, for a RLC low-pass circuit, f_0 is close to the 3dB cutoff frequency, which therefore represents an upper limit to the speed of the movements to be tracked by the sensor. The resistance time behavior can be yield from the equation

$$R_{sens\_i}\left(t\right) = \frac{v_{sens}\left(t\right)}{i_{sens}\left(t\right)} = \frac{R_p v_{ci}\left(t\right)}{V_g - v_{ci}\left(t\right)} \quad (7)$$

Transition simulations with the equivalent circuit model were performed and compared with the corresponding measurements, for 50, 100 and 150 degrees of bend step amplitudes, as also plotted in Figure 6. The modeling result is satisfactory.

7 SENSOR PERFORMANCE SIMULATION

An interesting application of piezoresistive sensor is the development of wearable devices for tracking and recording physiological movements, such as sensing garments for knee rotation, gloves for hand and finger movement, etc. These devices can be typically applied to telerehabilitation protocols. If associated to virtual reality software, these devices enable to monitor human posture and movements in real time.

The extracted sensor models can be very useful to predict sensor performance in different applications. For example Table 1 shows typical knee rotation parameters for walkers and runners (Saggio G. et al., 2009).

Table 1: Typical knee rotation parameters for walker and runner.

	man speed v_{man}	step length l_{step}	knee rotation amplitude ϕ_{max}	knee rotation frequency f_{knee}
walker	5 km/h	1 m	60 deg	1.4 Hz
runner	10 m/s	2 m	150 deg	5 Hz

Figure 7 shows the model simulation of sensor performance in tracking knee rotation, obtained modeling the knee rotation movements of a walker and a runner, as sinusoidal cycles with the typical amplitude and frequency provided by Table 1, where the knee rotation frequency was yield from the equation

$$f_{knee} = v_{man} / l_{step} \quad (8)$$

The sensor resistance response was mapped in the corresponding bending angles through interpolation of static characterization shown in Figure 3. To perform piecewise-linear simulations, the rotation movement was modeled as one degree successive rotation steps.

To calibrate the sensor response for a sinusoidal stimulus, a constant time delay for a given rotation frequency, which can be yield from the low-pass RLC frequency response as

$$H_{LP}\left(f\right) = \frac{f_0^2}{f_0^2 + j\,f \cdot f_0/Q - f^2} \quad (9)$$

$$t_d = \frac{phase\left(H\right)}{2\pi f} \quad (10)$$

was incorporated into the equations. In this way, running the model simulation, the sensor model is able to reply the knee rotation with good accuracy even for a runner, as it can be seen in Figure 7.

Hence, it can be concluded that, if accurately modeled, the piezoresistive sensors under test can accurately monitor also the fastest body segment rotations.

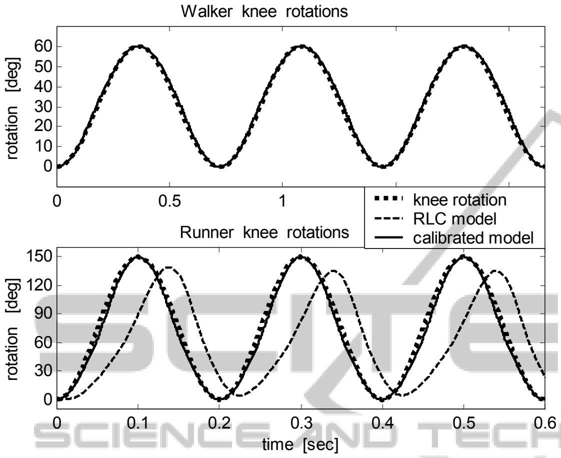

Figure 7: RLC model simulation of sensor performance in tracking the knee rotations of a walker and a runner.

8 CONCLUSIONS

This paper aims to demonstrate that wearable devices instrumented with commercial piezoresistive sensors can be applied for human posture and motion recognition, as a valid alternative to movement analysis systems based on optoelectronic devices or inertial electronic sensors. Static and dynamic characterization revealed that piezoresistive sensors change their resistance with bending rotation degrees, even if transition delays from 50 to 100 ms were measured when monitoring fast bending and extension movements. Given that transition delays were due to piezoresistive material relaxation times, in order to predict the sensor electrical capability to recover rotation angles, the transition behavior under bending and extension movements was simulated by extracted behavioral models based on fictitious RLC equivalent circuits, with no physical meaning associated to the circuit parameters. The device model simulation allowed to evaluate that sensor tracking of the human knee fastest rotation was accurate. To give an example the extracted models were applied to simulate and evaluate the sensor behavior in tracking human knee movements either of a walker and a runner.
This findings represent a sound benchmark, by which others can gauge the accuracy and suitability of bend sensors for different applications.

ACKNOWLEDGEMENTS

This work was mostly supported by the DCMC Project of the Italian Space Agency (ASI).

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