Advanced characterization of piezoresistive sensors for human body movement tracking

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Abstract—Due to their pliability, sensitivity and cheapness, piezoresistive sensors can be usefully adopted to recover joint bend angles in human body movement tracking. After providing quasi-static and dynamic electrical characterization of piezoresistive sensors, the authors develop a simple and accurate RLC model fitted on sensor electrical response under fast deformation and relaxation movements, which allows to predict the actual device behavior in tracking body fast movements.

I. INTRODUCTION

The investigation of the new possibilities offered by new technologies in the field of strain and flex 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 [1].

Special applications in the field of wearable sensors can be the cybernetic gloves, suitable for revealing, controlling and measuring hand and finger movements, or capture and translate actions of a human hand in a three-dimensional space to drive actuators, pointers, keyboards, joysticks etc. [2]. Other interesting applications are in the field of tele-rehabilitation, where wearable detecting systems are realized with sensorized socks to monitor movements of body joints, such as knee, arm, ankle etc.

As a consequence, a study must be carried out to understand which kind of sensors must be utilized and how they must be characterized. In particular, the piezoresistive sensor strips analyzed in this paper change their resistance with degrees in the bending magnitude, and therefore they can be applied as electronic goniometers to measure body segment’s assessment [3].

In this work, the devices under study are commercial carbon ink flex sensors, chosen because of their pliability, very high bending sensitivity, different lengths to adapt to different finger joints, and cheapness.

Characterization of piezoresistive sensors for wearable device application, where large bending deformation is expected, is therefore a logical step and will be detailed in the following sections, where we will demonstrate the potentialities and limitations of piezoresistive sensors and some modeling techniques. Available piezoresistor models, in fact, continue to incorrectly employ a merely variable resistance that may arise from calibrating the sensor with a metal hinge. In order to bend the sensor from -60° to +90° degrees (as usual adoption) with different bending rates, the end of the sensor sample connected to electrodes was locked in a stationary clamp, fixed to a rotating platform operated by a stepper motor, varying bending angles and rates reliably with a step size of one degree, and controlled by a dedicated software on a serial connected PC. The other end of the sensor strip was put in a sliding clamp, to avoid the device stretching. 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. Fig.1 provides a photo of one sensor sample, whereas Fig.2 shows a schematic of the experimental set-up.

III. QUASI-STATIC BENDING RESPONSE

Using the calibration test jig, the sensor resistance value was measured through a digital multimeter controlled from a PC by a Labview routine through a serial (RS232) link, for each imposed rotation degrees of the mobile arm of the hinge, at ten degree steps. For the particular sensor size under study, 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 Fig. 5. It can be observed that sensor resistance changes almost piecewise linearly with bending deformation degrees, even if better performance resulted for inward bending. 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, although temporary memory effects cannot be evaluated with quasi-static stimulation, but they were analyzed as reported in the next section.

4.1 Mechanical delays

The first idea to explain the observed delays was that they could be originated by friction of one end of the sensor strip inside the sliding clamp. However, friction is not a matter during sensor bending, because sensor is pulled by the motor power, whereas it can be crucial during relaxation, when the strip should be free to slide inside the clamp. In fact, observing the transition response under relaxation (fall), it can be noticed a further delay due to friction of the strip in the sliding clamp. Aside that, the transition times are almost the same during bending and relaxation, which entitle us to believe that friction cannot be the main source of delays.

To evaluate the resistance adaptation and relaxation time, the sensor was subjected to iterative bending and relaxation cycles, each composed of a one-step rotation from zero degrees to a specified angle, ranging from −60° to +90° degrees (as usual adoption), and a one-step opposite rotation to restore the flat position, setting the motor speed rate at 0.1 ms/deg. The input and output voltage waveforms were captured in real time on the scope display, stopping acquisition after each cycle with a given delay. On relaxation the original resistance should be restored, when the original flat displacement was recovered, thanks to the elasticity of the sensor substrate.

Fig.8 exhibits the resistance waveforms as resulted from (1). It can be observed the rise time and overshoot in the sensor resistance when the sensor is abruptly bent, as well as when the original flat position is restored.

The resistance adaptation and relaxation times can be easily computed from upward and downward markers on the measured waveforms, and are reported in Fig.4. It can be noticed that adaptation and relaxation times are very close, whereas those ones for inward and outward rotation are similar.
be simply originated by the motor rotation time. The declared speed rate from motor maker are of the order of 0.1 ms/deg, which correspond to a transition delay of more or less 10 ms for 90 degree rotations. It is clear that the measured transition times are much greater than the motion duration. Hence it can be concluded that the rotation times are not responsible for the transition delays. In the next sections we will look for other possible source of delays, in particularly parasitics and material relaxation.

4.2 Physiological speed rate

Problems with sensor delays, however, could arise when fast physiological movements have to be tracked. The highest physiological rotation speed was estimated to be around 2 degree/msec, whereas the sensor delay is higher than 1 ms/degree. Table I shows a comparison of the minimum body segment rotation times, in particular the keen of a running man at the maximum speed rate of 10 m/sec, against the sensor transition delays. As it can be seen, sensor delays are higher in this case. It can be concluded that piezoresistive sensors are limited in following the fastest body-segment movements.

Table I. Comparison of the minimum knee rotation times against sensor delays.

<table>
<thead>
<tr>
<th>Rotation (deg)</th>
<th>Fastest knee rotation times</th>
<th>Sensor transition delays</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°</td>
<td>15 msec</td>
<td>55 msec</td>
</tr>
<tr>
<td>60°</td>
<td>30 msec</td>
<td>70 msec</td>
</tr>
<tr>
<td>90°</td>
<td>45 msec</td>
<td>100 msec</td>
</tr>
</tbody>
</table>

V. RF CHARACTERIZATION

RF characterization was accomplished to extract a linear equivalent circuit of the sensor, including inductive and capacitive parasitics. To this aim a further experiment was conducted measuring parasitic inductance and capacitance with an RLC meter, while the sensor strip was subjected to static bends by the stepper motor using the same test jig, with rotation angles ranging from -60° to +90°. In this way, the plot of parasitic capacitance vs. bending angle degrees can be obtained, as reported in Fig.5. Inductive parasitics are practically negligible, and capacitive parasitics rate around 20 pF. It is clear that such parasitic values cannot be responsible of measured transition delays.

VI. BEHAVIORAL MODELS

As matters stand, piezoresistive material relaxation times should be the source of transition times. Investigation on the physical nature of material relaxation, however, is not the aim 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 is not the concern of the final users.

Owing that transition delays cannot be eliminated, because they do not come from the experimental setup, we believe that it is useful, in some applications, to provide an electrical model of the sensor, which can reply the behavior as it results from time-domain measurements. This would allow 1) to simulate the electrical time response of single sensors or arrays, 2) to accurately predict sensor movements from electrical measurements, 3) to evaluate if the sensor speed performance is suitable for a particular application, for example if it is reliable for human motion monitoring.

We already saw that an equivalent circuit extracted from frequency-domain measurements cannot simulate the sensor response to fast bending and relaxation. A different approach has to be followed in model extraction, if model simulation must return the actual transition behavior. A behavioral model, on the other hand, could be still represented by an RLC circuit, but with fictitious element values, which have no physical meaning, but they are able to reply the same electrical behavior shown by measurements.

The circuit used to simulate the sensor electrical behavior under resistance variation is shown in Fig.6. Its time response was analyzed in the Laplace domain. In this case, however, there is no voltage excitation, but stimulus comes from the sensor resistance variation due to bending deformation. Given that the Laplace analysis does not allow element variations (the system would result non linear with respect to this type of stimulus), the circuit was therefore analyzed calculating initial conditions at t=0 with the voltage supply at \( V=V_g \) and the starting resistance value \( R_{\text{start}} \) before transition, and then supposing a step on the voltage supply from \( V=0 \) to \( V=V_g \), considering this time the final resistance value \( R_{\text{stop}} \) at the end of transition. The circuit used to impose the initial conditions is therefore that shown in Fig.7, where resistance is controlled by two inverted switches.

![Fig.6. RLC behavioral circuit (t=0)](image-url)
The solving system is in this case:

\[
\begin{align*}
I_s &= sC V_c - C v_c \\
V_c &= I_s R_{stop} \\
V_v &= V_f s - (I_c + I_s) \left(R_p + sL\right) + L i_{i0} \\
V_o &= \left(I_c + I_s\right) R_p = \frac{V_f - V_v + L i_{i0}}{R_p} \\
v_c &= V_c(0) = V_f \frac{R_{start}}{R_{start} + R_p} \\
i_{i0} &= i_c(0) = \frac{V_f}{R_{start} + R_p} \\
V_o &= \frac{V_f}{LC} + sC v_{c0} \left(R_p + sL\right) + sL i_{i0}
\end{align*}
\]

Transition simulations with the equivalent circuit model were performed and compared with corresponding measurements, setting parameters as reported in Table II. The best fit to measurements was reached, in this case, tuning the resonant frequency \(\omega_r\) and the resonant factor \(Q\), from which it is possible to calculate circuit parameters \(L\) and \(C\). It is worth to note that in order to achieve a better fit, complex values for \(L\) and \(C\) were chosen in this case. Being a virtual circuit used only for simulations, however, this is not a matter of concern. Comparison of model simulation results against transition measurements are plotted in Fig.8. Only when friction effects introduce a further delay during the relaxation transition, the model cannot follow the measurement data.

Concluding it can be said that behavioral models based on RC or RLC modeling circuits can provide a good fit to time-domain sensor response under bending and relaxation stimuli. The presented models can be quickly extracted using the given equations, tuning only one or two parameters.

Present investigation can be also used for 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.

Here, for sake of simplicity, we assumed that the sensor be subjected to an instantaneous rotation, with no mind to motor rotation times, which, as seen in the previous sections, are negligible respect to sensor response transition times.

\[
\begin{align*}
&\begin{array}{|c|c|c|c|c|c|c|}
\hline
V_f & R_{ref} & R_{cont} & R_{stop} (k\Omega) & \text{time} \text{ [sec]} & \text{friction} & \text{static resistance 0°} \\
\hline
4V & 5.5 & 5.2 & 3.7 & 4.0 & 7.2 & 9.5 & 11.3 & 10Hz & 0.7 & 1.136 \\
\hline
\end{array}
\end{align*}
\]

**CONCLUSIONS**

Wearable devices instrumented with commercial piezoresistive sensors can be applied for human body movement tracking. A static and dynamic characterization of piezoresistive sensors was performed. They show a resistance varying almost linearly with bending deformation and a parasitic capacitance of nearly 20 pF. Measured transition delays of about 50-100 ms, during fast sensor bending, due to piezoresistive material relaxation times, make these sensors unable to follow the fastest body movements. The transition behavior under bending and relaxation stimuli was simulated by a fictitious RLC equivalent circuit, with no mind to the element physical meaning. 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.

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**REFERENCES**

