Bend Sensors Modeling for Fast Signal Recovering in Human Motion Analysis

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***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, only to give some examples. In this paper, the possibilities offered by resistive bend sensors to register joint bend angles, for human posture recognition and motion analysis, have been explored. This paper suggests to extract an electrical model either to simulate their electrical behavior during bending and extension movements, and to recover the true bending angles from model simulation. To give an example, the proposed model was applied to track human joint movements, and it was demonstrated that it can lead to recover the original signal waveform, which represents the true joint rotation, also for the fastest human speed.**

Keywords– bend sensor; sensor modeling; motion analysis; posture recognition.

I. INTRODUCTION

Technology progress in the last decades have 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 [1].

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. Resistive bend 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 decreases 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 [2]. 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 (e.g., Images SI Inc. [3], Flexpoint Sensor Systems Inc. [4]). Figure 1 provides a photo of a sensor strip sample.

Resistive bend sensors can be applied to body joint 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 simultaneously, and allow hand patterns to be recognized [5,6,7,8]. However, in order to useful exploit sensor's properties, a complete electromechanical characterization is mandatory [9]. Moreover, a new modeling technique will be developed. Available resistive bend sensor models, in fact, continue to incorrectly employ a merely variable resistance to model the sensor electrical properties under a bending strength. Little experimental study and theoretical analysis has been undertaken on the effect of a range of bend angles and rates on sensor response, as well as investigation on repeatability testing under static and dynamic bending strength [7]. One perceived problem is to calibrate sensor performance in terms of prediction error in high precision and/or high speed applications. As a result, an electrical model is required that not only models the static resistive response, but also characterizes the electrical behavior during bending transitions [10]. 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.

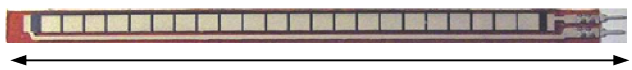

Fig. 1. Photograph of a unidirectional bend sensor, length 4.5”, width .25”, thickness .020” (Images SI Inc. Staten Island NY USA, http://www.imagesco.com/sensors/bend-sensor.html).

In Section II, the experimental apparatus for static and dynamic measurements is described, and the static performance of bend sensors to different bend angles, is provided. In Section III, a new approach to extract electrical behavioral models is described. In Section IV, the behavioral model was applied either to predict sensor performance in tracking slow and fast rotations, and to recover the true sensor rotation angles. Finally, some conclusions are drawn in Section V.

II. 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. Figure 2 shows a schematic of the experimental set-up. The sensor sample was laid as a cantilever beam on a metal hinge. In order to bend the sensor from 0 to 150 degrees (for set-up mechanical constraints) with different bending rates, the sample side connected to the

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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 with one degree resolution from a Labview interface serial 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 [11].

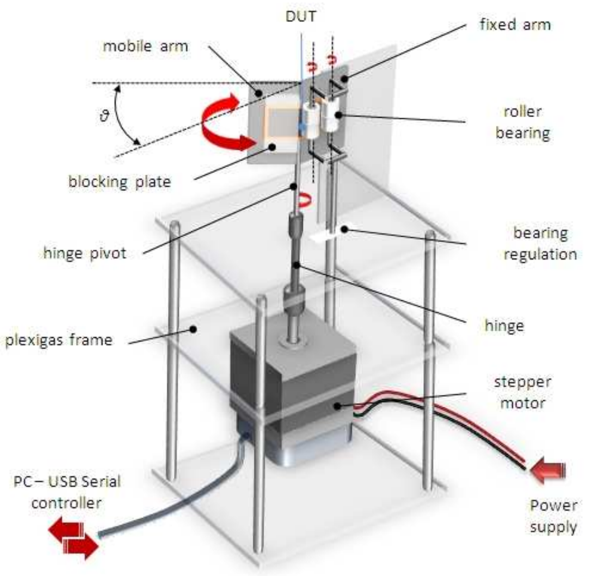

Fig. 2. Schematic of the experimental set-up.

Connecting a digital multimeter, a quasi-static resistance characterization against the bending angle of a bend sensor from Images SI Inc. has been accomplished. Since body segment rotations approximately range from 0 to 150 degrees, they will be tracked exploiting only outward rotations. In this case, the sensor resistive strip must be external with respect to the body joint. Sensor resistance behavior is almost linear with bending rotation degrees, as shown in Fig. 3.

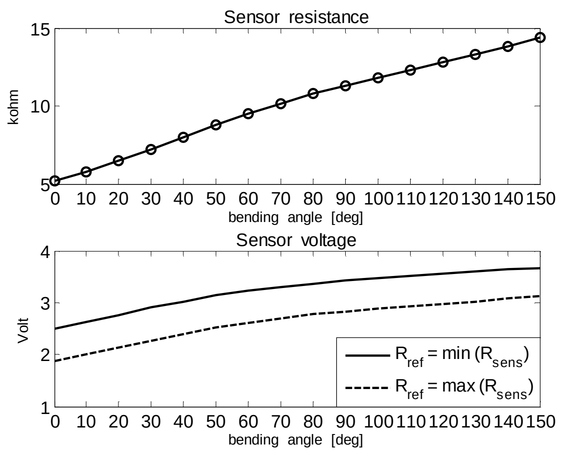

Fig. 3. Static electrical sensor characterization, in terms of resistance and output voltage from a voltage divider.

In most applications, however, the response of the sensor device under test (DUT) is acquired throughout its voltage response in a resistive divider, as shown in Fig. 4. In this case, a linear resistance response does not imply a linear voltage as also reported Fig. 3. As brought out in Fig. 5, the choice of a low or high series reference resistance R_{ref} changes the sensor sensitivity at low or high bending degrees, respectively. To enhance sensor sensitivity at low bending angles, a series resistance equal to the starting value (at 0°) of the sensor resistance is often chosen.

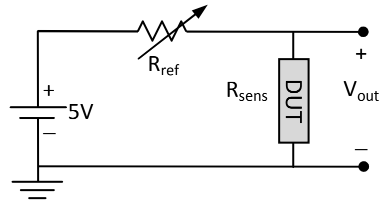

Fig. 4. Resistive divider to read the sensor voltage.

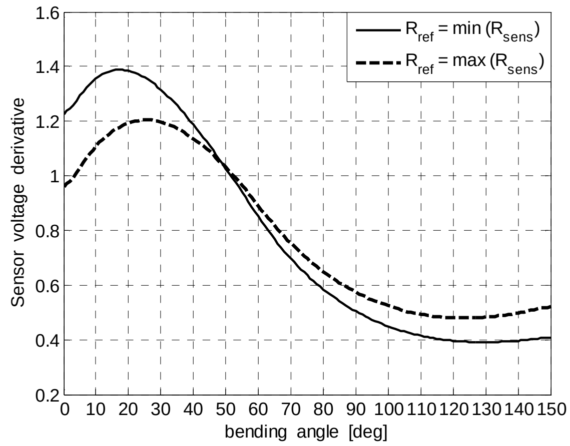

Fig. 5. Derivative of the sensor voltage from a resistive divider shows a sensitivity enhancement at low bending angles for a low value of reference resistance.

Dynamic measurements have been performed at different rotation rates through an LX.1746 impedance meter [12], connected to a PC through its USB interface, where it is controlled by the Visual Analyzer program, a free software of virtual instrumentation [13]. The measurement file data can be saved on a text file. This set-up allows to perform sensor resistance measurements with a great noise immunity. The set-up hardware and software interfaces are described by the block schematic in Fig. 6.

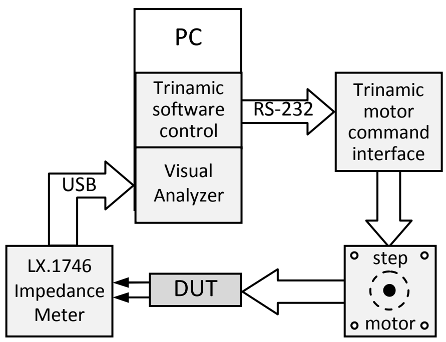

Fig. 6. Block schematic of the electrical characterization set-up.

III. ELECTRICAL MODELS

The most important manufacturers of commercial sensors 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. From observation of sensor resistance response under fast bending rates, that is rotation speed, it has been observed a distortion of measured resistance waveform respect to that which should corresponds to the true forced rotations. If sensor displacement over the hinge has been carefully accomplished, avoiding any obstacle or friction which can hinder the sensor slide inside the hinge guide, this distortion can be accounted only to material relaxation delays. Authors suggest to model this behavior through an electrical model represented by a low-pass *RLC* circuit, shown in Fig. 7.

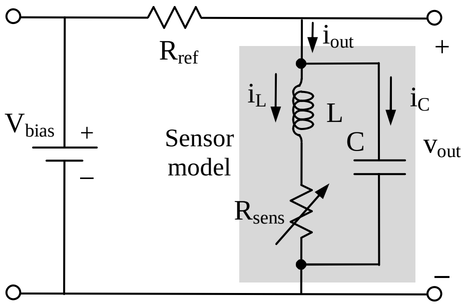

Fig. 7. Schematic representation of a resistive divider containing the sensor equivalent circuit to describe its dynamic behavior.

The resistance *R* corresponds to the static sensor resistance, corresponding to each bending angle. In order to hold linear analysis, *R* was represented as a piecewise-constant model, changing its value for each rotation degree. The sensor response was therefore obtained from an iterative routine, which performs linear 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 as a chain of successive solutions. The other two circuit parameters *L* and *C* can be represented by the resonant factor *Q* and frequency f_0 , which can be tuned in a reasonable range to fit the model simulation to the measured waveform, with no account on their physical meaning [14].

This approach has a twofold advantage: from one hand the model can predict the sensor performance for different bending ranges and rates, especially useful in that applications where high speed movements have to be monitored, from the other hand, a new method to recover the waveform corresponding to the true rotation can be developed.

IV. SIGNAL RECOVERY

Once the RLC electrical model parameters have been fit to the sensor dynamic measurement, the sensor performance can be yield either from sensor measurements with the impedance meter, or circuit model simulation from the equation

$$R_{mod}(t) = \frac{v_{out}(t)}{i_{out}(t)} \tag{1}$$

being

$$v_{out} = \frac{V_{bias} R_{mod}}{R_{ref} + R_{mod}} \tag{2}$$

$$i_{out} = \frac{V_{bias}}{R_{ref} + R_{mod}} \tag{3}$$

The method suggests to recover the ideal sensor resistance R_{sens} from simulation data derivatives, as developed in the following equations

$$i_C = C \frac{d\, v_{out}}{dt} \tag{4}$$

$$i_L = i_{out} - i_C \tag{5}$$

$$v_L = L \frac{d\, i_L}{dt} \tag{6}$$

$$v_{sens} = v_{out} - v_L \tag{7}$$

and finally

$$R_{sens} = \frac{v_{sens}}{i_L} \tag{8}$$

Equation (8) provide the recovered sensor resistance waveform corresponding to the true bending degree of joint rotation. In order to avoid spurious spikes on simulated data derivatives, a twofold strategy has been followed: first of all selecting a model not only on the basis of error minimization but also continuity of second order derivatives, then adopting smoothing techniques based on derivative average and digital lowpass filtering. This approach has been also applied to different circuit topology, which here are not reported for sake of brevity.

This method has been applied to distorted sensor measurements, obtained from the test equipment setting the step motor speed for fast sawtooth rotations of the hinge where the sensor is lied, between 0 and 150 degrees, at 5 Hz cycle rate, which are, respectively, the maximum registered human joint rotation amplitude and speed. Look-up tables can map the sensor resistance response in the corresponding bending angles through interpolation of static characterization shown in Fig. 3. Results are plotted in Fig. 8, where it is evident that the suggested method has been succeeded to recover the signal waveform corresponding to the true hinge rotation, because the two traces are almost superimposed.

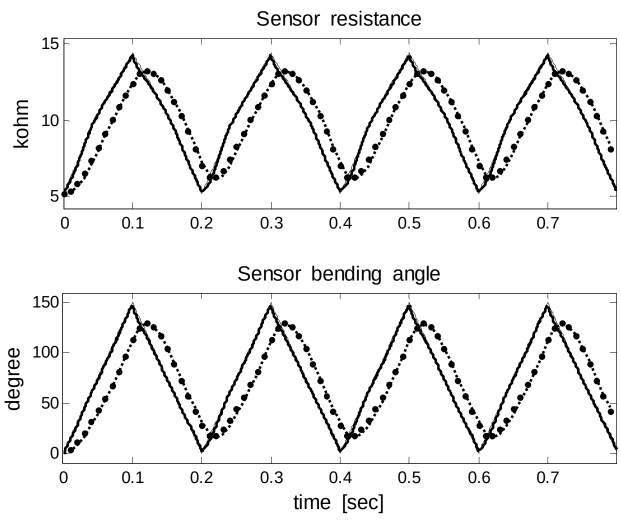

Fig. 8. Recovered sawtooth signal at 5 Hz of true joint rotation extracted from model fitted to dynamic measurements (••• meas, ···· model, — true, ▬ recovered).

In order to validate the method, the same modeling circuit has been used to recover the true hinge rotation from the simulated waveform with less distortion at a lower frequency (2 Hz). Results have been plotted in Fig. 9, which shows a perfect agreement between the true and recovered hinge rotation.

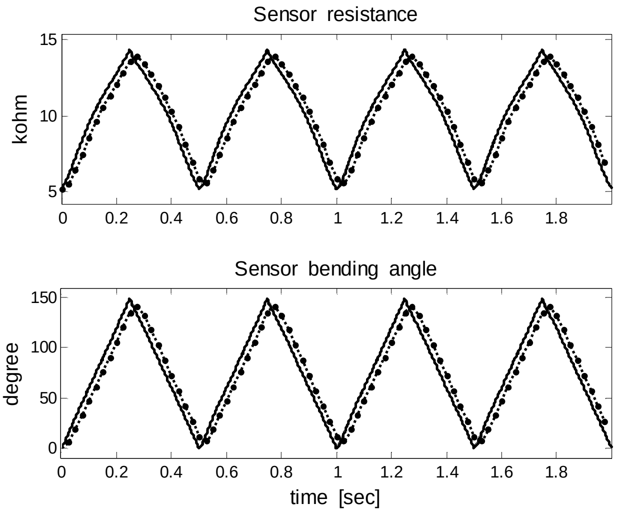

Fig. 9. Recovered sawtooth signal at 2 Hz of true joint rotation extracted from model fitted to dynamic measurements (••• meas, ···· model, — true, ▬ recovered).

Next developments of this method are foreseen where the true signal recovery will be performed in real time by digital signal processing routines, applied on input data stream from one or more bend sensors in a powered microcontroller or digital signal processor [15].

V. Conclusion

This paper aimed to demonstrate that resistive bend sensor can be applied for human posture and motion recognition. Even if static characterization has revealed that bend sensors change their resistance nonlinearly with bending rotation degrees, true bending angles would be correctly detected through corresponding look-up tables, if material relaxation delays would not cause signal distortion. Nevertheless, modeling the sensor behavior with appropriate circuit models, with no mind to the physical meaning of the circuit parameters, can lead to estimate the sensor performance for different rotation speed and amplitude, and to recover the original signal waveform which represents the true joint rotation from sensor measurements. The method has been successfully applied to track the fastest human joint rotation movements.

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