Modeling and Comparing the Linear Performance of Non-uniform Geometry Bend Sensors

Giancarlo Orengo, Antonino Lagati, Giovanni Saggio
Department of Electronics Engineering
Tor Vergata University
Rome – Italy
orengo@ing.uniroma2.it, antonino.lagati@istruzione.it, saggio@ing.uniroma2.it

***Abstract*— Resistive bend sensors have been increasingly used in different areas for their interesting property to change their resistance when bent. They can be employed in those systems where a joint rotation has to be measured, such as in biomedical systems to measure human joint static and dynamic postures. In spite of their interesting properties the commercial bend sensors have a resistance vs. bent angle characteristic which is not actually ideal as a linear function, to measure bend angles, would be. In this work, we have developed a way to calculate the sensor resistance for different bending angles with a generalized strip contour, in order to predict how shaping it with different non-uniform geometries changes the resistance dependence on bending angles, and investigate what kind of strip geometry can lead to a more linear behavior.**

***Keywords*– bend sensor; gesture recognition.**

I. Introduction

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.

Commercial bend sensors are usually made of a few micrometer tick resistive material deposited onto a thicker plastic insulating substrate. The resistive strip is screen printed with a special carbon ink, to be applied on virtually any custom shape and size film [1]. Normally, however, as well as the overall sensor, it has a rectangular geometry, with one side somewhat larger than the other. The ink's resistance value changes with bending due to an applied external force. The overall thickness is anyway negligible compared to the total largeness and lengthiness. All sensor materials, however, must be able to bend repeatedly without failure for the sensor to work. This kind of sensors are available on the market (Images SI Inc. [2], Flexpoint Sensor Systems Inc. [3]).

These devices can be adopted as sensors when placed on different kind of joints with the larger side bent according to the joints. They can be applied to body joint as electronic goniometers, to realize goniometric sock for rotation assessment of body segments in human posture recognition [4,5,6].

From a characterization point of view, the model which takes into account the mechanical aspect of the sensor predicts a linear behavior of the electric resistive variation with the bending angle [7]. Nevertheless the sensor resistance has increasing derivatives, especially for small angles, which result in non linear characteristics, as provided by the electrical characterization of the sensors.

The idea developed in this paper is to change the regular (rectangular) geometry of the sensor, cutting some part of it, in order to increase or decrease its resistance value, obtaining a linearization of its intrinsic non linear behavior. To this aim, the change of sensor resistance with bending angle has been modeled for a generalized resistive strip contour.

II. Experimental Apparatus

The apparatus employed for this analysis was designed to emulate, in a controlled environment, the behavior of commercial bend sensors, when applied to body joints to track segment rotations. Figure 1 provides a photo of a sensor strip sample.

Fig. 1. Photograph of a resistor sensor sample (Flexpoint Sensor Systems Inc. South Draper UT, USA) in 1:1 scale.

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 +90 degrees, 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 was put in a sliding clamp to avoid the sample stretching. For this kind of sensors the resistive material must be external with respect to the rotation. 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. The sensor resistance measurement against different bending angles was obtained connecting a digital multimeter to the Labview setup [8].

We measured the characteristic of several commercial bend sensors. In particular, we investigated the behavior of 2 inches long Flexpoint non encapsulated sensors, polyester encapsulated sensors and polyimide encapsulated sensors, when bent on a 8 mm hinge.

Measurements results, reported in Fig. 3, demonstrated the non linear mentioned characteristic. In particular the resistance variation is greater for non encapsulated sensors stands their higher flexibility, whereas the polyester one

 ISBN: 978-1-61208-208-0

exhibits better linearity. These imply that the resistive material must be non isotropic and must present non-uniform variation when bent.

The idea developed in this paper is to investigate how the change of a regular (rectangular) sensor geometry, cutting some part of it, increases its resistance value, obtaining a linearization of its intrinsic non linear behavior. In order to predict how shaping sensor resistive strip with different non-uniform geometries changes the resistance dependence on bending angles, this dependence has been calculated for a generalized resistive strip contour in the next section [9].

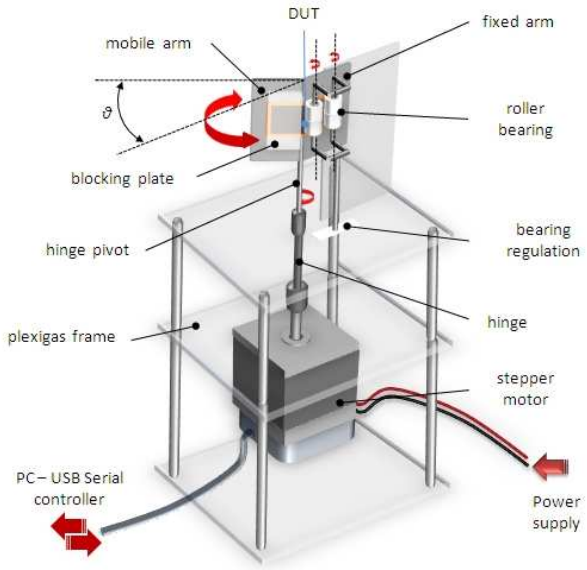

Fig. 2. Schematic of the experimental set-up.

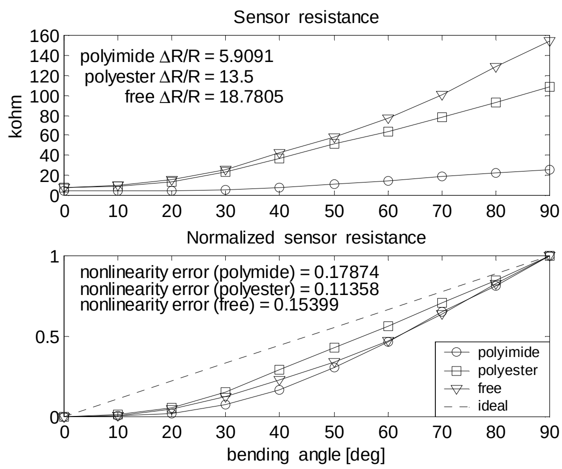

Fig. 3. Resistance variation vs bending angle for three different Flexpoint sensors

III. Sensor resistance modeling

For a flat rectangular sensor of size $L \times W$, where L is the length and W the width of the resistive strip, its constant sheet resistance or resistance per square $R_{sheet}^{0°}$ and its total resistance $R_S^{0°}$ are linked by the equation

$$R_S^{0°} = R_{sheet}^{0°} \frac{L}{W} \tag{1}$$

If the resistive strip has not a rectangular contour, say not a constant width given by the function $w(x)$, the total resistance can be numerically calculated from the equation

$$R_S^{0°} = R_{sheet}^{0°} \sum_{i=1}^{N} \frac{\Delta x_i}{w(x_i)} \tag{2}$$

where the strip length have been divided into N uniform or non-uniform segments of length Δx_i for numerical integration.

As previously affirmed, when the polyester or polyimide substrate is bent, the material of its resistive strip is stretched, and the sheet resistance increases around the bending rotation axis. Although it is rather difficult to physically model this phenomenon, an abstract model can be still attempted with a general Gaussian function centered on the rotation axis, supposed at a known distance L_R from the strip longitudinal edge at $x=0$. Assuming then

$$G(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x)^2}{2\sigma^2}} \tag{3}$$

the sheet resistance results from

$$R_{sheet}(x,\phi) = R_{sheet}^{0°} + K(\phi) G(x - L_R) \tag{4}$$

where the unknown parameters are the calibration factor $K(\phi)$, scaling the sheet resistance with the bending angle, and the variance σ which determines the longitudinal extension of the region around the bending axis where resistivity increases. To this parameter, it has been arbitrarily assigned a starting value $\sigma = d/2$, where d is the hinge diameter. However, by comparison of model simulation and experimental measurements this value can be adjusted, although a constant value seems to fit better than one changing with the bending angle.

As a consequence, the resistance variation of a rectangular sensor with the bending angle can be calculated as

$$\begin{aligned} R_S(\phi) &= \frac{1}{W} \sum_{i=1}^{N} R_{sheet}(x_i,\phi) \Delta x_i = \\ &= R_S^{0°} + \frac{K(\phi)}{W} \sum_{i=1}^{N} G(x_i - L_R) \Delta x_i \end{aligned} \tag{5}$$

from which results

$$R_S(\phi) = R_S^{0°} + \frac{K(\phi)}{W} \tag{6}$$

standing that, if the Gaussian function is almost comprised inside the strip length, results

$$\sum_{i=1}^{N} G(x_i - L_R) \Delta x_i \simeq 1 \tag{7}$$

Equation (6) allows to determine the calibration factor $K(\phi)$ from measurements of the sensor resistance variation with bending angle for a rectangular sensor.

$$K(\phi) = W \left[R_{S\_meas}(\phi) - R_S^{0°} \right] \tag{8}$$

It is worth to note that the calibration factor, even if calculated for a rectangular strip, is independent from the strip geometry. Then, the response of a non-uniform geometry can be calculated from the equations

$$R_S(\phi) = \sum_{i=1}^{N} \frac{R_{sheet}(x_i, \phi)}{w(x_i)} \Delta x_i \tag{9}$$

$$\begin{aligned} R_S(\phi) &= R_{sheet}^{0^\circ} + K(\phi) \sum_{i=1}^{N} G(x_i - L_R) \frac{\Delta x_i}{w(x_i)} = \\ &= R_S^{0^\circ} + K(\phi) \cdot H_{geom} \end{aligned} \tag{10}$$

where H_{geom} is a constant factor dependent on sensor geometry, but independent from the bending angle. As a consequence, since $K(\phi)$ is linearly dependent from $R_{S\_rect}(\phi)$ as result from (8), even with non-uniform geometry the normalized sensor resistance is the same of that of a rectangular one given by (5). In other words, no linearity enhancement can be yield from non-uniform geometry in this case.

So far, it has not been taken into account that, when the sensor is bent, the sample side not connected to the electrodes slides in a clamp of an amount equal to the arc of the hinge (diameter d) corresponding to the rotation angle, and the rotation axis moves away from the locked edge ($x=0$) of half this quantity, namely

$$s(\phi) = \frac{1}{2} \frac{\phi}{180^\circ} \frac{\pi d}{2} \tag{11}$$

from which the sheet resistance results

$$R_{sheet}(x,\phi) = R_{sheet}^{0^\circ} + K(\phi) \cdot G\left[x - L_R - s(\phi)\right] \tag{12}$$

To keep the rotation axis in the central region of the strip, a good practice would be to set

$$L_R = 0.5(L - s_{\max}) \tag{13}$$

Calculating the total sensor resistance

$$R_S(\phi) = R_S^{0^\circ} + K(\phi) \sum_{i=1}^{N} G\left[x_i - L_R - s(\phi)\right] \frac{\Delta x_i}{w(x_i)} \tag{14}$$

it can be also expressed as

$$R_S(\phi) = R_S^{0^\circ} + K(\phi) \cdot H_{geom}(\phi) \tag{15}$$

where this time the geometric factor H_{geom} is dependent on the bending angle. In this case, the normalized sensor resistance has a different behavior between uniform and non-uniform geometry. This fact will be exploited in the next section to investigate if particular geometries can lead to a linearization of its intrinsic non linear behavior.

IV. SENSOR PERFORMANCE SIMULATION

The question which now arises, of course, is whether it would be possible to optimize the resistive strip geometry to yield a linear behavior with bending angle. However it is to note that the highest non linearity is observed for small angles, where the sheet resistance has a little increase. As a consequence, the modulation of the sensor width has a little influence on its performance for small angles. Nevertheless, a contour optimization has been attempted investigating different simple geometries, in particular trials have been performed on rectangular, triangular and circular contours, where dimensions have been randomly optimized, on the basis of the rms error between the normalized sensor performance and an ideal linear one (nonlinearity error). This approach has been attempted on the 2 inch polyester sensor from Flexpoint, where the strip size has been set to 36×5.6 mm, with a double width respect to the standard one, to allow safe shrinking of the sensor width do not compromise the sensor capability to bend repeatedly without failure.

Being the squared contour a particular case of the triangular one, results have been presented only for the last one. Random iterations have been tried sweeping three geometry parameters in the following ranges: $W/2 < W_1 < W$, $0 < L_1 < L$, $0 < L_2 < L - L_1$. Fig. 4 plots the results either for sensor resistance and its normalized value, showing difference performance in dynamic ($\Delta R/R$) and linearity (nonlinearity error), either for the rectangular contour and the triangular cut.

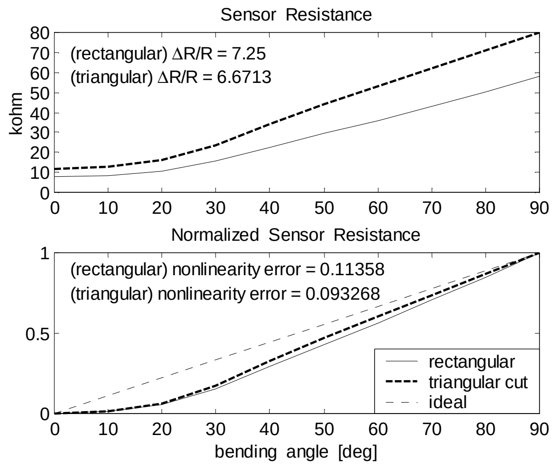

Fig. 4. Resistance and its normalized value variation vs bending angle comparison between rectangular and randomly optimized triangular contours for the most linear sensor resistance.

The result of random optimization of strip contour dimension is reported in Fig. 5, where calibrated sheet resistance Gaussian functions and their shift with bending angle has been superimposed. It can be noted that optimization suggests an almost square and deepest allowed cut as the best performing geometry.

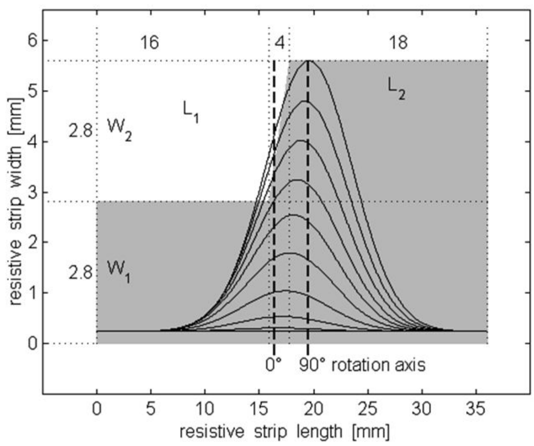

Fig. 5. Randomly optimized resistive strip triangular contour for the most linear sensor resistance.

Finally, the same random optimization can be also tried to enhance the linearity of a resistive divider, shown in Fig. 6, where the sensor is inserted in many applications, when it is the voltage across the sensor rather than its resistance that has to be processed.

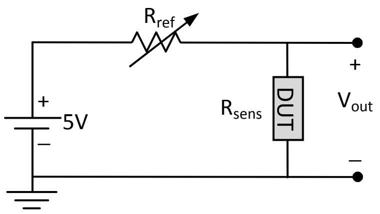

Fig. 6. Resistive divider to read the sensor voltage.

Results have been plotted in Figs. 7 and 8, where the same optimization has been applied this time to a circular contour. Moreover, at each iteration corresponding to a particular contour, the reference resistance R_{ref} has been swept inside the sensor resistance dynamic to yield the most linear behavior. Although not all results have been included in this paper for sake of brevity, it has been demonstrated that a square cut in sensor contour lets to achieve the best linearity performance, especially with a larger sensor width and deeper cuts, either for sensor resistance and voltage.

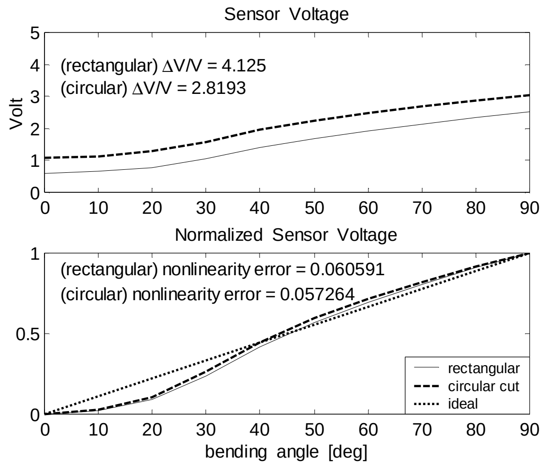

Fig. 7. Resistance and its normalized value variation vs bending angle comparison between rectangular and randomly optimized circular contours for the most linear sensor voltage.

V. CONCLUSION

The linearization of the bend sensor's characteristic leads to undeniable advantages in joint rotation assessment. In this work a method to calculate resistance variation with bending angle for any resistive strip geometry has been proposed, and different contour geometry have been compared from the linearity point of view. Results have demonstrated, from one hand, that the best results can be obtained with a square cut, from the other hand, that the larger is the sensor width and deeper the cut in resistive strip contour, the more relevant is the enhancement in linearity performance, either for sensor resistance and voltage across it when inserted in a resistive divider.

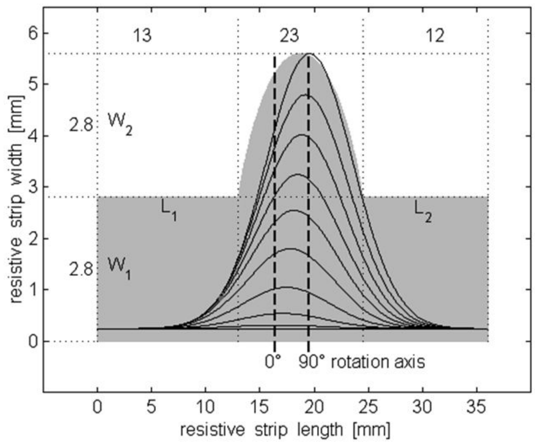

Fig. 8. Randomly optimized resistive strip circular contour for the most linear sensor voltage.

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