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Curvature Characterization of Flex Sensors for Human Posture Recognition

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Abstract Resistive flex 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, in particular biomedical systems, to measure human joint static and dynamic postures. In spite of their interesting properties, such as robustness, low price and long life, to date commercial flex sensors have been only characterized against the variation of the bend angle with small fixed curvature radius mostly around the device center, so limiting the application to the measure of human joints. Here we aimed to investigate the flex sensor's response when there is a change in curvature radius as it is, for instance, for the measure of the postures of the human torso. So, we designed a novel automated test process to obtain resistances vs. curvature radius pairs. Results demonstrated the usability of flex sensors to other parts of the human body rather than "simply" joints, differently as it is currently done.

Keywords Flex Sensor, Curvature Sensing, Wearable Sensor, Posture Recognition

1. Introduction

In order to measure human body kinematics, it is convenient to adopt sensors, which can measure bending angles with accuracy despite a low cost [1].

Resistive flex sensors can be applied to body joint as electronic goniometers, to realize goniometric sock for rotation assessment of body segments in human posture recognition [2,3]. The device size can be practically fitted to any type of joints.

To date flex sensors have been characterized only against the variation of the bend angle, but considering fixed curvature radius, so without taking into account curvature variations. Human joints have a fixed radius, so to measure them, it is sufficient to evaluate the curvature radius, and to perform measures against the bend angle on a mechanical setup with a constant curvature, as it will be shown in the next section. Indeed this procedure is the most suitable a) when the curvature radius is constant and small, b) when the sensor strip is bend more or less in the medium section, and it is only this region which accounts for the sensor resistance increase. This is especially the case of little body joints as finger, knee and elbow.

Differently, in case of large curvature radii, it can be assumed that all the sensor strip is upon bending, also with a variable curvature radius. For example, it could be when a flex sensor is applied to measure back diseases.

In this case the authors describe here a more general procedure, in which the flex sensor is uniformly subjected, all along its length, to the same curvature, which is varied step by step, and its electrical resistance is measured. This system is, in authors' opinion, the most general way to characterize their static behavior, as it will be demonstrated in the next sections, because it is possible to yield the sheet resistance of sensor samples of different size inside a particular sensor family, measuring only one type.

Authors aim to demonstrate, in fact, that flex sensors of the same type but different size show the same behavior in terms of curvature response. In this way a unique database would be enough to be applied in different cases, when sensor of different size must fit to measure large and variable body curvature, and their resistive behavior can be foreseen integrating their sheet resistance along curvature variations.

2. Materials and Methods

Commercial bend sensor devices consists of a single, thin (less than 0.005" typ.) flexible plastic material that is coated with a resistive film, a proprietary carbon/polymer ink, which can be applied on virtually any custom shape and size [4]. The resistive coating is printed on a plastic film such as polyimide to form a bond that is very strong. The resistive material must be external with respect to the rotation (outward rotation). When the coated film is bent, the ink separates into many micro cracks, which upon movement open/close to the specific bending of the material, determining a decrease/increase of the material conductivity. The ink maintains its integrity in shape and continues to have a very strong bond to the substrate. All sensor materials, however, must be able to bend repeatedly without failure for the sensor to work. Polyimide films are required for wide temperature ranges and extreme durability, even if may be costly depending on the geometry of the sensor. Sensor base (flat state) resistance is adjusted by changing the active geometry, doubling the length will double the resistance or doubling the width halves the base resistance. This type of sensors are available on the market (Flexpoint Sensor Systems Inc. [1]). Figure 1 provides a photo of a 2-inch polyimide sensor sample from Flexpoint.

Figure 1. Photograph of a 2" sensor sample in 1:1 scale, with a resistive film of L×W size (Flexpoint Sensor Systems Inc. [1]).

2.1. Conventional Static Characterization

The apparatus employed for this analysis was designed to emulate, in a controlled environment, the behavior of bend sensors, 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 with different diameters, hence curvature radius decreases mostly in the middle of the sensor for small diameters. 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, paid attention to avoid any stretch force. Bending angle step amplitude was changed reliably with one tenth of 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.

The static characteristic of a 2,3-inch Flexpoint polyimide encapsulated sensors, when bent in the middle on a 8 mm hinge (curvature radius 4 mm), was measured for inward and outward rotations, and results are reported in Figure 3. The nonlinearity of the characteristic implies that the resistive material must be non-isotropic and must present non-uniform variation when bent. Inward bending, however, does not shows remarkable variations, not even in log scale.

But these results can be not exhaustive of the sensor behavior, because they have been evaluated for a particular hinge diameter, that is a particular curvature radius, and sensor size. The behavior could be different for different radius of the hinge and different sensor size and shape [5], so that, since these devices can be applied to body joints of different size, the characterization procedure should be repeated for a wide range of hinge diameter values.

The aim of this work is to find a more synthetic procedure, which provide as much as possible complete information of the sensor behavior in each application, in particular for large curvature radii.

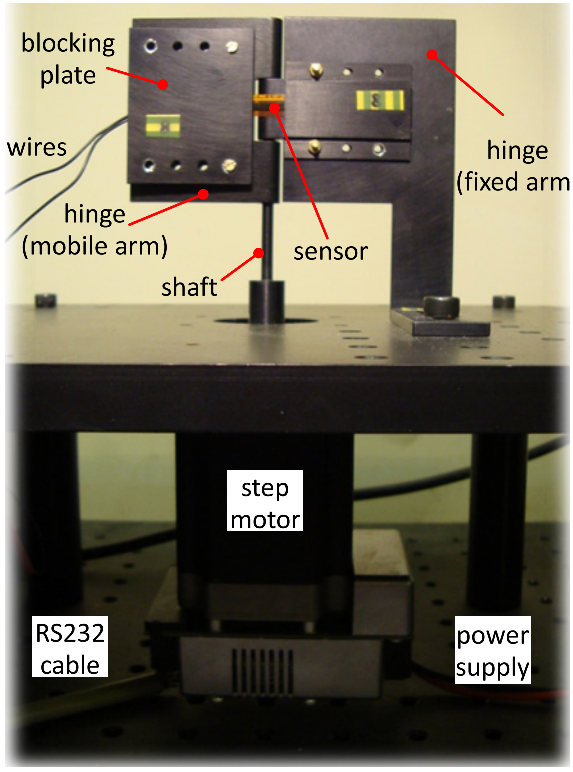

Figure 2. Photograph of the experimental set-up used to characterize the sensor device under test (DUT).

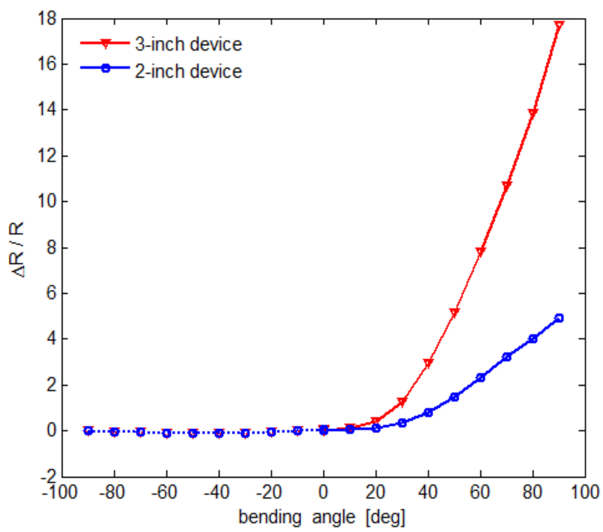

Figure 3. Resistance variation vs bending angle for a 2,3-inch polyimide encapsulated sensor from Flexpoint. Dotted segments refer to inward bending.

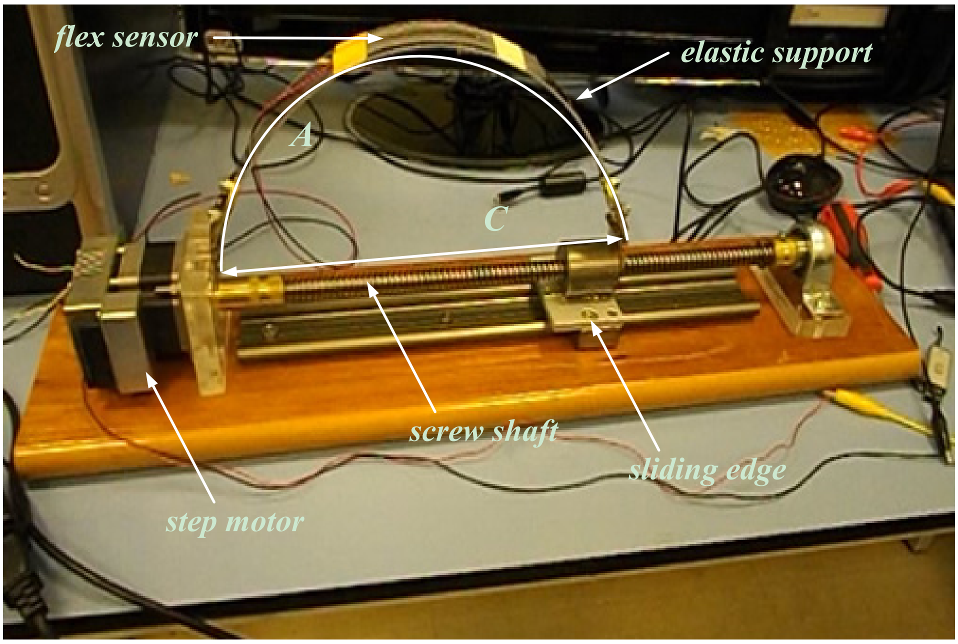

Figure 4. Variable bend-radius setup.

2.2. Curvature sensor Characterization

In order to perform a curvature characterization, a new mechanical setup was designed and built. As shown in Figure 4, now the step motor rotates a screw shaft which, depending on the motor rotation direction, perform a push/pull movement of a sliding trolley on a linear guide.

The sensor under measurement is laid and attached on a rectangular flexible pvc support of 3 mm in thickness. This layer is locked to the sliding trolley, from one side, and to a fixed support from the other one.

A Labview routine operates steps in the linear feed of the sliding trolley, through the correspondent motor rotation degrees, whereas the sensor resistance was measured by a multimeter in the same manner.

3. Curvature Modeling

In order to model the curvature variation against the chord length decrease, operated by the step motor, a geometric model was attempted. Direct curvature measurements were performed with an inelastic flexible support, laid on the plastic sensor support, then graphically analyzed to extract the curvature radius. These experimental results were compared with those ones obtained from geometrical models, obtained imposing the curves pass through the support edges and top, Only two models are analyzed, that is the circular and the elliptic ones. This modeling approximation allows to perform curvature calculation only from the distance of the support edges, that is the chord length, and the support height at the top, without a direct measurement of the support curvature, even changing the length of each step of chord length decrease. This allows to arbitrarily set the motor rotation at each step, and to yield sensor resistance variation against curvature with an arbitrary number of points.

3.1. Support Geometric Models

Trying to model the bent support outline with a circular model, the equation which links the support length (the circumference arc, here named as A), the distance between the support edges (the circumference chord, here named as C) and the curvature radius (here named as R) can be easily yield, being

$$\alpha = \frac{A}{R} \tag{1}$$

$$C = 2R\sin\frac{\alpha}{2} \tag{2}$$

and resulting from (1) and (2)

$$C = 2R\sin\frac{A}{2R} \tag{3}$$

Unfortunately, the implicit form of (3) makes it only possible to iteratively compute the curvature radius R from the arc A and the chord length C. In this way, the distance between the two edges of the plastic support univocally determines the bend curvature radius to which the sensor is subjected.

To further support this assertion, the curvature radius was also directly calculated, by the measure of the chord height H, making the circumference pass through the support edges and top, as

$$R = \frac{C^2}{8H} + \frac{H}{2} \tag{4}$$

obtaining the same numerical results of the previous case. Even if the measurement of the H parameter is easier than the curvature measurement itself, nevertheless it cannot be performed with an automatic procedure without optoelectronic technologies.

The elliptic model has been also attempted, imposing to pass through the support edges and top, obtaining for the semi-axes a (horizontal) and b (vertical) the equation

$$a = \frac{C\,b}{2\sqrt{2bH - H^2}} \tag{6}$$

Unfortunately, in this case, a family of ellipses can be yield from the imposed conditions. In order to fit the experimental curvatures, a good compromise between smaller and larger curvature radii could be

$$b = H_{Max} \tag{7}$$

The curvature radius on the top can be calculated as

$$R = \frac{a^2}{b} \tag{8}$$

3.2. Modeling results

Simulation results for a flexible support of 220 mm length were plotted in Figure 5, which shows that the circular model yields the best fitting result, since it still follows the experimental curvature for small radii, whereas the elliptic one returns a smaller radius.

Concluding, the length of the decreasing chord, which can be yielded automatically by the step motor rotation, allows a direct estimation of the sensor support curvature with good accuracy at least in the top of the flexible support. Since the device under measurement is laid on the top, a good accuracy can be yielded only when the sensor length is much smaller than the support one (the arc A).

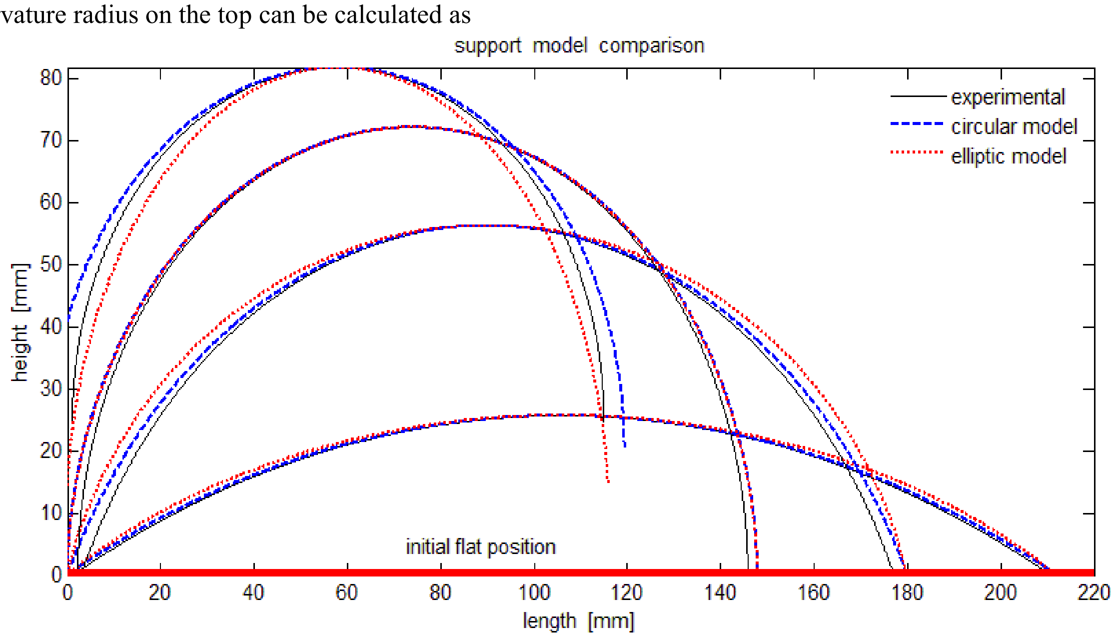

Figure 5. Comparison between experimental curvature meas (dark line) and two modeling results: circular (dashed blue line) and elliptic (dotted red line) curvature approximation, for a flexible support of 220 mm length.

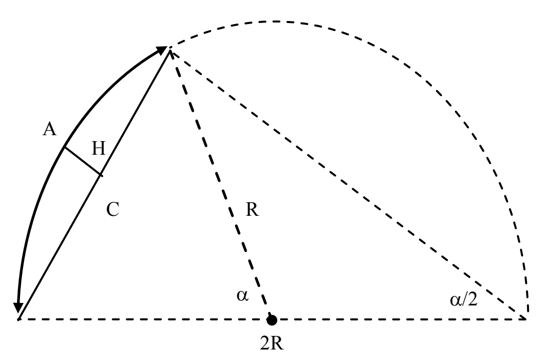

Figure 6. Geometric scheme for direct calculation of curvature radius from chord length.

4. Measurement Results

Measurement were performed rotating the step motor in order to provide a total linear translation of 112 mm, 8 mm each step. Giving a screw pass of 4 mm, the rotation degree has been set to 720 degrees each step, for a total number of 14 steps. The elastic support has been 220 mm long in this case, and the distance between the two edges was reduced to 108 mm after the last step, with a maximum curvature radius of 48 mm.

Let the size of the sensor resistive film be L (length) and W (width). In this case W=2.8 mm for any device size, whereas L=35.8 mm and L=61 for a 2 and 3 -inch size device, respectively. The sensor sheet resistance has been then yield from

$$R_{sheet} = R\frac{W}{L} \tag{9}$$

Results for sensor sheet resistance variation against curvature were plotted on Figure 7 for a 3-inch length device. Comparison has been made between the two method of extracting the curvature radius: experimentally and with the circular model. Plots demonstrate that the circular model is affordable. Sheet resistance has been than compared against curvature in Figure 8 for the two sensor length, demonstrating the independence of this parameter from the device size, even when the device is bent. Differences of few ohms between the two samples are due to fabrication tolerances.

Even if the measurements were performed on available commercial 2,3-inch devices, longer devices will behave in the same way, if the support curvature radius will keep constant along sensor length.

This information can be used to yield the sensor global resistance behavior, when the device is subjected to large but not constant curvature radii, for example when a long device is monitoring the posture of the human torso. From registration of the sensor response, the displacement of curvature variation can be yield.

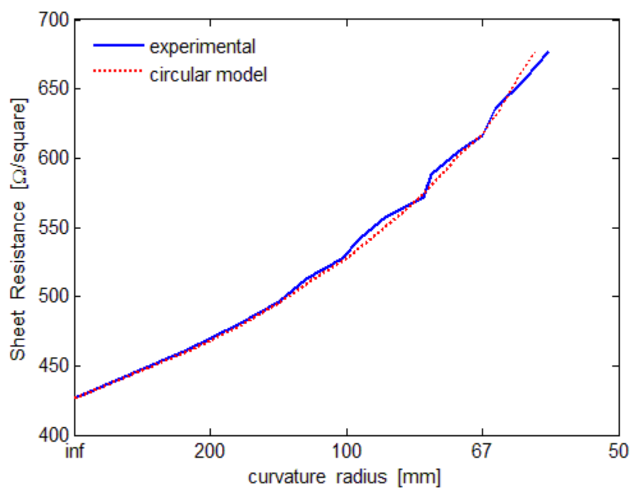

Figure 7. Comparison of the sheet resistance evaluation against the experimental and the circular model curvature radius for a 3” device.

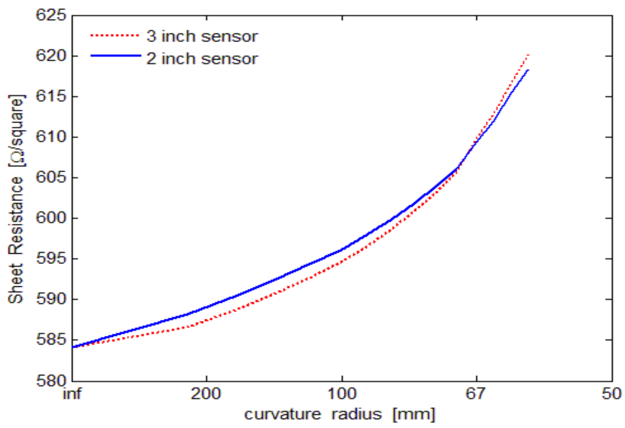

Figure 8. Comparison of the sheet resistance evaluation against the circular model curvature radius for 2” and 3” device size.

5. Conclusion

In this paper two characterization approach were analyzed, a conventional static characterization, where the curvature increases mostly around the point of application, and a new one, based on sensor characterization against curvature variation, uniform along the entire sensor length,. The two approaches were compared from the point of view of the practical utility, the former to apply to small body joints, such as fingers or knees, the latter to register rotations with large and uniform curvature radius, as in back disease monitoring. The accuracy of the two approaches is hard to compare.

For the second approach, two results were obtained: the geometrical approach to curvature modeling, which provides instantaneous curvature radius calculation without geometrical assessments, from one side, and a unique representation of the sensor sheet resistance behavior against curvature, which is independent by the sensor size.

These results allow to fit the sensor device size to different biomedical applications, when body segment curvature registration is required for different curvature radii, without the need of a specific characterization.

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