Sensorization of continuum soft robots for reconstructing their spatial configuration

M. Cianchetti, Member, IEEE, F. Renda, Student Member, IEEE, A. Licofonte, and C. Laschi, Member, IEEE

Abstract—This work deals with the sensorization of continuum soft robots for reconstructing their spatial configuration. Since at the present time the proprioceptive perception is prevalently achieved using external 3D optical methods, an embedded system is needed for the improvement of the performances of this promising kind of robots.

The idea is to use stretch sensors to reconstruct the spatial configuration of a robotic structure: differential measurements on strain values can be used to derive local curvatures performed by the arm.

Strain values have been extracted using a conductive textile that presents very high elasticity and lightness. The main feature is that its electrical resistance depends on its mechanical strain and it has been characterized in order to derive this strain-resistance relation. The reconstruction method that allows to obtain spatial configuration from material deformations is then reported.

A practical application on reconstructing the configuration of an octopus-inspired robot arm is finally shown and discussed.

I. INTRODUCTION

The shape control of continuum robots requires means of sensing the curved shape of the robot [1]. Since continuum robots are deformable, they take on shapes that are general curves in space, which are not directly defined by the actuator state variables (as it is in serial hyper-redundant robot). Several methods exist for encoding the shape of curved, flexible devices. One involves embedding strain sensors along the length of the device, as implemented in the robotic cockroach antennae in Lee and Sponberg’s work. In that case the antennae are used to measure the distance between robotic cockroach and walls. When the robot comes closer to a wall, its antennae touch it and are flexed. Measuring the entity of the strain, the robot is able to know which is the distance from the wall [2]. Fiber optic sensors have also been developed for measuring strain in flexible objects. In George’s and Bogen’s work, a strain measurement system has been developed for the mechanical testing of biological soft tissues. The technique creates four spots of light on a tissue sample surface by piercing the tissue sample with two pairs of small light-conducting optical fibers (one pair for each axis of a biaxial stretch), terminated by high intensity infrared emitters. A large-area photodiode, located below the tissue sample, detects the light emitted from the two pairs of lightspots.

Each infrared emitter is sequentially cycled “on” at a rate of 3 kHz, the resulting photodiode signal is proportional to the separation between coaxial light-spots [3].

Dobrzynski et al. have introduced a novel method for deflection sensing where a LED element and a photodiode are placed on two substrates connected physically or virtually at a deflection point. The deflection angle between the two planes can be extracted from the LED light intensity detected at the photodiode due to the bell-shaped angular intensity profile of the emitted light. The main advantage of this system is that the components are not in physical contact with the deflection region as in the case of strain gauges and similar sensing methods [4].

Colobot uses a system of sensor-based motion planning to calculate the safe position of its colonoscopy device. It is based on the measurements of three distance sensors for guidance inside the colon [5].

In other medical continuum devices, such as catheters, the position is tracked thanks to a vision system. Camarillo et al. proposed a «voxel-carving» algorithm to extract the position of their manipulator by projecting segmented pixels from three orthogonal views into a 3D voxel space to determine which voxels are occupied by the manipulator [6].

However, while strain gauges and optical fibers may be options for larger-scale continuum robots, they are prohibitively bulky for integration in medical continuum robots, which are designed to be as thin as possible.

Jayender et al. validated their model of a catheter for left atrial ablation. Three electromagnetic position sensors were placed at three locations on the catheter. Since one sensor was placed at the non-bending section of the catheter, it was considered as the base coordinates of the continuum robot, while another one, placed at the distal tip of the catheter, was considered as the end-effector coordinates of the robot [7].

One efficient and straightforward method of real-time shape-sensing for continuum robots is the use of fiducial markers on the robot. Hannan and Walker employed this approach using a high-speed monocular camera system to observe fiducial bands on an elephant-trunk manipulator [8].

Proof-of-concept endpoint control based on stereo vision has also been accomplished with an active cannula by Webster et al. using a tip-mounted fiducial [9].
Webster et al. used monocular [10] and stereo [11] optical cameras to sense the shape of a steerable needle embedded in transparent phantom tissue by post processing images. The system was subsequently used for closed-loop control by tracking the advancement of the needle tip [12].

Summarizing, the main approach to evaluate continuum robot positions and spatial configuration consists in using external optical methods. As alternative technologies optic fibres and strain gages are sometimes used, but the results still need improvements.

II. BASE CONCEPT

As mentioned in the previous section, at the present time information about the spatial configuration of continuum robots is prevalently achieved using not-on-board optical methods, while others are used to get only the tip position. But it is not always possible to have a structured environment with external cameras, and at the same time information about the tip only could be not sufficient. The aim of this study is to investigate an alternative way to extract a complete knowledge about continuum soft robot shape.

The principal scope of this work is to use embedded sensors on a continuum robot arm and find a way to get enough information to derive its spatial configuration. In order to achieve this result, we chose to use a material that is able to sense the curvature of the manipulator without affecting its performances and use the information obtained to reconstruct the robot arm spatial configuration.

First of all it is important to remember that a continuum manipulator is able to bend at any point. Moreover, a continuum soft robot has also the peculiarity of being able to be stretched out: thus it means that whatever will be put on it must not limit its flexibility or movements. Therefore an ideal sensor should have this important feature and moreover it should be able to measure at the same time bending and stretching. Thus, a possible candidate enabling both the measures is the use of conductive textiles and in particular for this study Electrolycra (Mindsets Ltd, United Kingdom) has been used. This is a material which looks and feels like ordinary Lycra but it is highly conductive because it is weaved with Silver plated 76% Nylon 24% elastic fibers. Its conductivity depends on how tightly it is stretched, so if pulled its resistance increases. Electrolycra is also very compliant, very lightweight and can be cut into strips of whatever dimension.

These features make Electrolycra a perfect candidate for the sensing technology needed. Despite the main characteristics of such a material are well known, there are no data available about their mechanical and electrical behaviour in literature. Thus this study starts with the investigation on the material and then its practical application as a transducer for soft continuum manipulators are faced. For this last phase a validation platform is required: a silicone arm inspired by the octopus has been used, but the results obtained are easily exportable in whatever soft continuous structure.

III. MATERIAL CHARACTERIZATION

A precise characterization was needed to derive the operating characteristic curve of the Electrolycra. Thus mechanical and electrical tests were carried out to know the stress-strain behaviour and the range of strain that the variation resistance is able to detect. Obviously, the two tests were synchronised so that when a stress was applied the sensor was stretched and its resistance value changed accordingly.

The first step in order to characterize our material consisted in preparing specimens and this was done by cutting Electrolycra in pieces of different sizes. Testing samples of different size was required by the unknown behaviour of the material, that could have changed in function of its length or width. So, starting from the fact that the width of the sensor should have been as small as possible, we had to take into consideration that there were some practical limits such as the space needed to connect electrical cables and to anchor the sensor on the robotic structure. Thus, we cut pieces of Electrolycra from 10 to 20 mm in length and from 5 to 20 mm wide. Bigger sizes were considered not useful to our purpose.

After that, we repeated the following procedure for each specimen we had. First of all, we fixed the samples in the tensile-compression tests machine grippers and block it there. Once it was set at its rest length, electrical cables were sewn on its extremities in order to carry voltage. Electrical conduction was assured by sewing the wires on the samples extremities.

A voltage divider is used to measure the voltage on Electrolycra based stretch sensor. An acquisition board (National Instrument DAQ Assistant) has been used to collect data resistance during the deformation of the specimens and they have been used, in turn, to calculate the resistance percentage variation.

Mechanical tensile tests have been carried out to extract stress-strain relation and evaluate the presence of hysteresis. Moreover the samples have been subject to one hundred of cycles in order to study the variation of the response after many times. Each test included different level of velocity in order to evaluate eventual variation of the response time depending on the stress speed. The first test was always done at 30 mm/min, then the followings were incremented at 60 mm/min, 120 mm/min, 180 mm/min up to 360 mm/min. The last corresponds to a cycle time shorter than two seconds (for specimens of 10 mm in length, that are the most interesting for the applications under investigation), that is reasonably higher than the speed of deformation of the final robotic prototype that will be moved by cables in a water environment (introduced later).

In this way we are sure that our material will be able to detect all the robot movements. During preliminary tests we noticed that the material is able to stretch over 100% of its length, but since -as we are going to show- it is capable of
detecting strains under 50% we plotted and used all the results up to 50%.

A. Mechanical characterization

The sensor was tested by applying small displacements up to 50% of the resting length of Electrolycra. Mechanical hysteresis was calculated as the difference between the areas under the up-curve and the return-curve compared to the up-one. This was done by the MATLAB function trapz(Y) which computes an approximation of the integral of Y via the trapezoidal method. The mean hysteresis was always about 16%.

The curves shown in Figure 1 are referred to twenty cycles, but they are superimposed and for this reason not easily noticeable. Every specimen keeps always the same behaviour and gets repetitive results assuring the same response during time. The force needed to stretch a sample up to 50% is 3.5 N.

![Electrolycra stress-strain response for loading and unloading phase.](image1)

**Figure 1** Electrolycra stress-strain response for loading and unloading phase.

**B. Electrical characterization**

Electrical data tests were obtained by increasing the strain from 0% to 50% (blue dots in Figure 2) and then by decreasing it back to 0% (red dots). The sensor covers the full output range of the resistance for a strain up to 40% of Electrolycra’s resting length. For a larger stretching the response of the sensor reaches a plateau while the resistance starts to decrease again if the sensor is stretched further, (i.e. the response of the sensor is monotonic only up to this point).

![Percentage of resistance change vs strain for Electrolycra stretch sensor.](image2)

**Figure 2** Percentage of resistance change vs strain for Electrolycra stretch sensor.

The detected values of strain are the same for each sample, meaning that the capacity of measuring is not dependent on the material’s dimensions (TABLE I).

Differently, the percentage of resistance variation changes with specimen’s length: Figure 3 shows a logarithmic trend. Width does not significantly influence the response of the material. Typical values of resistance of a 1x1 cm sample are about 5 Ω.

![Maximum variation of percentage resistance vs. length of the specimen.](image3)

**Figure 3** Maximum variation of percentage resistance vs. length of the specimen. (the point x=10, y=400% is taken from the manufacturer’s site)

**TABLE I**

<table>
<thead>
<tr>
<th>Length x Width (mm)</th>
<th>Max. detected Strain (%)</th>
<th>Max. Resistance variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10x10</td>
<td>41.6%</td>
<td>−180%</td>
</tr>
<tr>
<td>15x10</td>
<td>40.9%</td>
<td>−198%</td>
</tr>
<tr>
<td>20x10</td>
<td>41.4%</td>
<td>−220%</td>
</tr>
<tr>
<td>10x5</td>
<td>40.3%</td>
<td>−180%</td>
</tr>
<tr>
<td>10x20</td>
<td>41.5%</td>
<td>−182%</td>
</tr>
</tbody>
</table>

Electrolycra has a preferential direction along which resistance significantly changes and a major strain is possible. The different weaving along the two perpendicular directions could be the cause of this dual behaviour. Figure 4 shows two magnifying of the material when stretched in different directions: in the two cases weaving assumes two dissimilar structures. It is possible to notice that when stretching along the not preferred direction (Figure 4a) the tissue is tighter than in the other case, in which a loose weaving allows a major stretching (Figure 4b).

![Electrolycra stretched along its not-sensible direction (a) and along its sensible direction (b).](image4)

**Figure 4** Electrolycra stretched along its not-sensible direction (a) and along its sensible direction (b). (real measure 4x3 mm)

IV. SPATIAL CONFIGURATION RECONSTRUCTION METHOD

In a previous work [13] Renda et al. described how the robot arm spatial configuration can be reconstructed by mean of information on deformation. Resulting equations are reported in the follow.
\[
\frac{d}{ds}(\vec{r}) = k(1 + q)\vec{y} - \xi(1 + q)\vec{\xi} \\
\frac{d}{ds}(\vec{n}) = -k(1 + q)\vec{y} + \tau(1 + q)\vec{\tau} \\
\frac{d}{ds}(\vec{\xi}) = \xi(1 + q)\vec{\xi} - \tau(1 + q)\vec{\tau} \\
\frac{d}{ds}(\vec{\tau}) = (1 + q)\vec{\tau}.
\]

Where \( k, \xi \) and \( \tau \) are respectively the two component of the bending curvature and the torsion and \( q \) is the longitudinal strain. The two shear strain components are neglected. \( \vec{r}, \vec{n} \) and \( \vec{b} \) are the axis of the local frame of the material element \( s \). \( \vec{u}(s) \) is the position vector that is the final objective of the sensorization system.

Because our focus is to reconstruct the 2D configuration of the arm the only parameters that should be considered to integrate equations (1) are \( k \) and \( q \).

Below the relation between those deformations.

\[
q(s) + k(s)R(s) = \varepsilon_{\text{up}}(s, R) \\
q(s) - k(s)R(s) = \varepsilon_{\text{down}}(s, R)
\]

where \( R(s) \) is the radius of the section, \( \varepsilon_{\text{up}} \) is the longitudinal strain on the upper side of the manipulator and vice versa \( \varepsilon_{\text{down}} \). Remind that conventionally a positive curvature means the robot arm bends in the downward direction.

Equations (2) show that in order to obtain \( k \) and \( q \) two sensors able to sense both extension and compression are needed. Anyway in this work we chose to consider only the curvature \( k \) since in practical use the longitudinal strain \( q \) has a lower effect and often it can be neglected. Therefore the following simplified equations are used.

\[
+k(s)R(s) = \varepsilon_{\text{up}}(s, R) \\
-k(s)R(s) = \varepsilon_{\text{down}}(s, R)
\]

By applying two sensors on both sides bending on both directions can be detected. Let us clarify this concept: when bending on one side, the sensor on the other side will register a tensile strain while the sensors on the first side will not detect anything (they sense only strain and not compressions). This allows to reconstruct the direction of the bending and the amount of curvature. Moreover, if the robot arm stretches along its axis, sensors on both sides will measure the same strain that means that the arm is subject to an extension. Thus when the arm is simultaneously bending and extending, the amount of stretch due to extension is subtracted from the one used to calculate curvature. Referring to equation 2, that means that if \( \varepsilon_{\text{up}} \) and \( \varepsilon_{\text{down}} \) are both positive it is possible to know \( q \) too.

It is worth highlighting that in practical conditions it is not possible to sense a punctual curvature: \( k(s) \) represents the mean of the portion of manipulator covered by the piece of Electrolycra and refers to the section \( s \) correspondents to the half of the sensor length.

V. EXPERIMENT ON A REAL PROTOTYPE

In this section the robotic prototype for the validation of the sensing technology will be introduced and the tests carried out will be shown.

The robot arm used for the validation of the proprioceptive sensory system (Figure 5) is composed by a single conical piece of silicone actuated by several cables immersed inside the body and anchored at different distances from the base through a rigid plastic disk built-in the robot arm [14]. There are several cables for each anchorage cross section. By pulling one cable the robot arm bends on the side of the cable in a way that depends on the cable tension and on the arrangement of the tendon inside the robot body [13][15]. In this way the manipulator can be bent and twisted arbitrarily in the 3D space by pulling several cables anchored at different distance from the base. The robot arm is 450 mm length but is not fully actuated along its length because the last anchorage cross section is fixed at \( s \) equal to 310 mm. The radius of the manipulator decrease linearly from a base radius of 15 mm to a tip radius of 2 mm.

![Figure 5 Octopus-inspired arm prototype.](image)

A. Sensorization system

The sensorization system of such a prototype, is composed of Electrolycra sensors, an electric circuit and a DAQ system which interfaces between the signal and a PC.

Electrolycra was cut in ten pieces of 15 mm in length and directly sewn on the silicone arm by mean of a nylon line with a diameter of 0.1 mm. Stitching was done in order to have sensors of 10 mm in length free to move and follow manipulator bending. Thus, each transducer was able to detect deformations along 10 mm of the prototype, but in the remain of the elaboration we will consider the mean value of such data as punctual measurements taken at the centre of the sensor. The distance between the centre of two sensors was 30 mm. This procedure was repeated on the opposite side of the arm, so that we could detect bending on both directions. Electric wires were sewn on sensors’ double-ended, paying attention to make several stitches in order to assure electrical contact (Figure 6). Before and after having sewn Electrolycra, a blanket-stitch on the silicone arm was done to keep wires firm. Those wires carry voltage to the sensors; on the other end, measurements were done acquiring tension from two other wires linked to a constant resistance. In order to read the resistance variation a voltage input is necessary, but no nominal or suggested values have
been supplied by the manufacturer, thus we maintained a voltage of about 1 V to avoid overheating and to read a value from the voltage divider that does not require amplification.

**Figure 6** Octopus inspired arm with two raw of sensors in zero position.

### B. Data acquisition

Before starting tests, we had to calibrate the system in order to be sure of the initial values read when the arm is in its “zero-position”. This last is defined as the position assumed when the arm is relaxed and straight, without any bending or strain as in Figure 6.

The calibration phase requires several acquisitions. It is done by moving the arm, bringing it back to zero and acquiring data; then again: moving, bringing back and acquiring for about twenty times. The mean value of all the measurements of each sensor has been used as reference and considered as zero-value. We were pleased to note that the registered zero-values were all very similar, differing from one movement to another only in the order of a few mV.

To validate the system some interesting configurations have been defined. The choice was based on the criterion of starting from the zero configuration and then progressively bending the arm (Figure 7). For each new arm shape the curvature have been increased, so that we subsequently measured if a major bending introduces a major error. Tests have been conducted for single bends on both sides, but also for double bends on both sides (that means both positive and negative values of curvature).

**Figure 7** Increasing bending: the stretch sensors on the external part of the bend are stretched of an amount that is related to the curvature of the arm.

During this stage the voltage data have been acquired from all the 20 sensors. The prototype was imposed to move by pulling its cables and then stopped in a certain configuration we wanted to get data. An acquisition run and data elaboration allows a virtual reconstruction of the arm. In the meantime optical acquisition has been performed, so that we afterwards compared the reconstructed arm configuration with the real one.

### C. Post processing

The post processing phase was performed in MatLab environment where the voltage values measured by the transducers can be processed. Two inputs were provided: a vector containing the zero-values and the vector with the acquired data. Those vectors represented voltage values, so the first step was converting them to resistance ones. Then, referring to the zero values, it has been possible to calculate for each sensor the percentage of resistance variation; this last is associated to the corresponding strain. After that, data from sensors on the two sides of the same portion of arm were compared: if one indicated a strain and the matching one on the opposite side did not detect it, that meant that a bending occurred and only the first value was taken into consideration. Finally the curvature could be calculated by mean of equations (3). From such kind of comparisons, a curve of the backbone curvature (e.g. Figure 8) was obtained by a cubic interpolation of $s$ values from 15 mm to 285 mm, that are the points in which the first and the last sensor were placed.

**Figure 8** Example of curvature $k(s)$ derived from the strain data acquired by the stretch sensors.

### VI. Results and Discussion

Dozens of acquisitions were done in order to have enough data and different configurations to analyse. First of all we noticed that the zero-configuration is always recognized by all the sensors, even after many arm movements. Every test of zero-recognizing has been successful and the reconstructed conformation curves are very close to the real one (Figure 9). The real backbone to refer to was the one manually traced on each photo linking the points situated at half-length of twenty arm’s diameters, matching to the centre of the sensors.
The tests show that the error between the real backbone and the reconstructed one vary from zero (in the zero configuration) up to 3% for the mean one and 5% (respect to the arm length) for the maximum one, strictly depending on the arm shape. In fact, when the arm bends on one side and then on the other one, i.e. when curvatures sign changes from positive to negative or vice versa, the difference between the two curves is major then in other cases. This means that the reconstructed line has some difficulties in following the real backbone curves when the arm performs double bends, even if it regains after that zone and the total configuration is acceptable. This does not happen when bending is only on one side, in fact in such cases both mean and maximum displacement show lower values. For the sake of argument all these things are summed up in TABLE II, TABLE III and TABLE IV. They are the resulting average values from three kind of tests; one can immediately notice that the error values increase with bending: the more the curvature, the more accuracy decreases.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>BENDING ON SIDE ONE.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curvature</td>
<td>Mean Error</td>
</tr>
<tr>
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<td>1.64%</td>
</tr>
<tr>
<td>Medium</td>
<td>1.77%</td>
</tr>
<tr>
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<td>1.91%</td>
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<table>
<thead>
<tr>
<th>TABLE III</th>
<th>BENDING ON SIDE TWO.</th>
</tr>
</thead>
<tbody>
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<td>Curvature</td>
<td>Mean Error</td>
</tr>
<tr>
<td>Small</td>
<td>1.69%</td>
</tr>
<tr>
<td>Medium</td>
<td>1.84%</td>
</tr>
<tr>
<td>High</td>
<td>1.96%</td>
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<table>
<thead>
<tr>
<th>TABLE IV</th>
<th>BENDING ON BOTH SIDE.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curvature</td>
<td>Mean Error</td>
</tr>
<tr>
<td>Small</td>
<td>1.95%</td>
</tr>
<tr>
<td>Medium</td>
<td>2.9%</td>
</tr>
<tr>
<td>High</td>
<td>3.34%</td>
</tr>
</tbody>
</table>

VII. CONCLUSION

In conclusion the obtained results are very impressive compared to the models that simulate continuum robots shape and that are often used to give a position feedback: during the use of the robot they introduce errors between 3% and 6%. Thus it is possible to say that our sensorization system has been successful, especially considering that is not based on traditional optical methods.

With regard to the use of Electrolycra as a sensor, we demonstrated that this kind of material can be useful for continuum and/or soft robots. The results confirmed that the material has a stable behaviour, a mechanical hysteresis of about 16% and that it can be stretched over to 100% of its resting length allowing the robot to do free movements. It is able to detect strains up to 40% when pulled along its preferential direction and its resistance variation changes in function of the resting length.

We have noticed that the length of the specimen influences the variation of resistance: this is a parameter that has to be taken into account when processing the acquired data during a on-board test.

One last remark about the validity of the method: in this work 2D static cases have been treated, but with a different sensors arrangement and more powerful acquisition methods it could be extended naturally to the 3D dynamic cases.

REFERENCES