

# Proprioceptive Sensing in Soft Robotic Arms Using Soft Strain Sensors

Martina Maselli, Giulia Campinoti, and Matteo Cianchetti, *Member, IEEE*

**Abstract**— Soft robots actively interact with their environment, exhibiting large distributed deformations due to their structural compliance. These features make them ideal for applications in wearable robotics, medical devices, and assistive technologies. However, a major challenge in their development is integrating sensory systems that do not constrain their movements while enabling accurate estimation of the end-effector position. This work focuses on addressing this limitation in the context of a soft robotic arm. Commercial piezoresistive textile Electrolycra was identified as a suitable candidate for strain sensing. Following electromechanical characterization, Electrolycra sensors were integrated into the soft arm. Using a derived calibration curve and the constant curvature approximation, the system's performance in position tracking was evaluated. The sensing system and estimation method successfully tracked the end-effector's position with errors of 13.1 mm, 13.7 mm, and 4.8 mm in the x, y, and z coordinates, respectively, within a global reference frame during workspace operation. These results demonstrate the potential of Electrolycra-based sensing for soft robotic applications and open avenues for further development, particularly in closed-loop control systems.

**Clinical Relevance**— A sensorized soft robot with enhanced closed-loop control can significantly impact the clinical field by enabling precise and adaptive interactions with patients, improving safety, efficacy, and personalization in rehabilitation, assistive technologies, and motor assessment.

## I. INTRODUCTION

The field of soft robotics has formed and evolved in the last two decades; its new paradigm with respect to traditional robotics paves the way to a further integration of robotics device in the society and in those applications where automation and assistance is complex. The advantages of compliance and inherent safety come with the possibility to develop low-cost devices that are accessible and intuitive to use. The many available solutions in terms of actuation and materials enabled the development of many prototypes and in some cases the deployment in real-world scenarios.

To improve the performances of soft robots, sensing and control is needed. Having perception of both the internal state - proprioception - and of the external environment - exteroception - would enable soft robot to leave the laboratory. Solutions used in the case of traditional robotics can no more be implemented and new technologies need to be explored and adapted to the problem at hand. In particular, the need of

measuring the state of the robot is aimed at enabling its control, in particular in terms of closed-loop feedback strategy.

The issue of sensorizing a soft robot is still an open research question although many solutions have been proposed. The field of soft robotics, and all the related fields of applications, demands the development of sensor technology able to withstand and measure high strains and have a compliant behaviour. The need for stretchability and flexibility leads to a wide research field in the study and fabrication of materials able to couple these characteristics with the ability to act as transducers. It is possible to find many proposed solutions in literature for soft robots sensorization [1]. Thuruthel et al. [2] use polydimethylsiloxane (PDMS) with carbon nanotubes (CNTs) to obtain conductive sensors. A novel conductive hydrogel with extremely promising results is described by Munoz et al. in [3]. Truby et al. [4] presented a commercial conductive elastomer applied to a soft robotic arm; whereas in the study of Wall et al. [5] the applied sensors are constituted of EGaIn channels. Conductive textiles have also been used, since they tend to be easy to integrate in a device and there are commercial solutions for both wires and garments. Cianchetti et al. [6] used a smart textile to statically predict the bending of the OCTOPUS arm. Wurdemann et al. presented [7] a conductive yarn used to create a low-profile strain sensor to insert within the STIFF-FLOP manipulator for tracking of the tip's position.

The aim of the present work is to investigate the feasibility of adding a piezoresistive proprioceptive system to a soft robotic arm, in order to estimate the tip position with an appropriate accuracy and without hindering the mobility of the robot. Among the sensing systems previously described, the choice of restricting the field to conductive textile is due to the fact that in this class there is the possibility to investigate commercial low-cost solutions and to keep the overall setup easy to integrate since simple electronics is needed.

In the following study, a piezoresistive conductive textile is evaluated and applied to the soft arm and tested in its ability to track the end-effector position in a reliable and repeatable way.

## II. MATERIALS AND METHODS

### A. Soft Arm and Proprioception system design

This work builds on the I-Support platform [8][9], a soft continuum robotic arm for elderly bathing assistance. The arm is composed of modules hybridally actuated (cables and fluidic

\*This work is part of the SWAG Project that has received funding from the European Union's Horizon Europe programme under Grant Agreement No. 101120408.

M. Maselli\*\*, G. Campinoti, and M. Cianchetti are with The BioRobotics Institute and Department of Excellence of Robotics & AI, Scuola Superiore

Sant'Anna, Viale Rinaldo Piaggio 34, 56025 Pontedera, Italy (e-mail: [martina.maselli@santannapisa.it](mailto:martina.maselli@santannapisa.it); [giulia.campinoti97@gmail.com](mailto:giulia.campinoti97@gmail.com); [matteo.cianchetti@santannapisa.it](mailto:matteo.cianchetti@santannapisa.it)).

\*\*Corresponding author (phone: +39 050 883489; e-mail: [martina.maselli@santannapisa.it](mailto:martina.maselli@santannapisa.it)).

actuation). Each module is 205 mm long with a 60 mm diameter, featuring three longitudinal slots for McKibben pneumatic actuators (spaced 120° apart) and three for cable actuation (shifted 60° from the pneumatic ones).

For the scope of this work, only the pneumatic actuation was used. The setup includes:

- Three proportional micro regulator valves (Camozzi S.p.a.) that are used to modulate the pressurization of the three pneumatic actuators.
- Air compressor able to provide up to 4 bar pressure.
- Arduino Uno board to receive the control signals for the valves via serial port.
- A PC running a Matlab script to communicate with the Arduino.

### 1) Proprioceptive Sensor Requirements

The proprioception system was designed with the following goals:

1. Minimal interference with arm motion and workspace [8].
2. Accurate tip position estimation (mm-level), without complex calibration.
3. High mechanical flexibility and low invasiveness.
4. Minimal electronics for low cost and easy deployment in unstructured environments.

In order to satisfy these requirements, we selected Electrolycra (Mindsets Ltd, UK) for its unique properties, including high conductivity due to its 76% silver-plated nylon and 24% elastic fiber composition [6]. Its knitted structure features strands with non-conductive cores coated in silver, enabling resistance to vary with stretching. Electrolycra performs optimally after 200% pre-stretching and exhibits a preferential direction for resistance changes, allowing accurate strain detection within a 0–50% elongation range [10].

The primary objective is to determine the position of the module’s end-effector using electrical signals measured from Electrolycra strips integrated directly onto the module. These strips serve as proprioceptive sensors, enabling position estimation without relying on external position or force measurements. The strips were strategically placed on the module. To determine the number and placement of sensors, we rely on techniques from the literature that model the kinematics of soft arms [11], such as the I-Support arm. A simplified kinematic model, specifically the constant curvature approximation, is used. The I-Support arm can extend, shorten, and bend through non-uniform actuation strategies involving pneumatic and cable actuators. These actuators generate forces at the arm’s extremities, resulting in a bending moment. The deformed shape can be approximated using the Euler-Bernoulli beam theory with an acceptable margin of error, attributed to the relaxation of certain assumptions of the model. This approximation requires measuring three longitudinal lengths to compute the arc parameters (curvature, plane angle, and arc length) and determine the position of the end effector.

Electrolycra sensors were positioned longitudinally along the module and cover its whole length in order to estimate the total deformation. For symmetry arguments, it is chosen to dispose three sensors with 120° angle in between, in correspondence with the actuators of the module. Moreover, Electrolycra is unable to sustain compressive loads, exhibiting a piezoresistive behavior: when bent, the sensor becomes slack, and its resistance remains unchanged, as it operates exclusively under tensile strain. For this reason, the choice is to apply three more sensors in a 25% pre-stretched configuration. This leads the total number of sensors to six. The tested configuration is shown in Fig.1.

Sensors were connected via conductive copper tape to a voltage divider (12 Ω, 3.2 V input) and fed into a DAQ board (USB-6009, National Instruments)..

### 2) Mounting System

A dedicated mounting system was designed to securely apply the sensors to the module. The sensors were positioned on the outermost part of the module to facilitate easy installation. To enable mechanical coupling with the plates, a custom 3D-printed component was designed, as shown in Fig. 2a. For the application of six sensors, three of these components were attached to the proximal plate and three to the distal plate of the robot (proximal and distal relative to the robot’s frame). Each component—which host two sensors—is in direct contact with one of the module’s plastic plates and remains securely attached due to a slight interference fit between the component’s slot and the plate’s thickness, generating sufficient friction to prevent slippage during movement. The quasi-cylindrical external section of the component houses the conductive tape, wiring, and sensor. The sensor is clamped to this part using a lid, which was also designed and 3D-printed (Fig. 2b). One end of the sensor is sandwiched between the conductive tape—applied to the cylindrical section of the component—and the inner surface of the lid. The primary design parameter for the lid was the aperture angle: after testing, a 140° lid aperture provided optimal attachment. Fig. 3 shows the complete sensorized module.

### B. Calibration tests

To evaluate the electromechanical behavior of Electrolycra sensors, a calibration tests were performed by using a universal testing machine (Instron 4464; Instron Corp., High Wycombe, UK), while to acquire the electrical signal the acquisition circuit mentioned above was used.

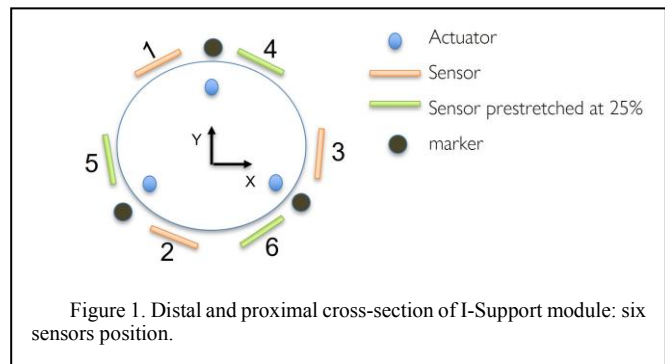


Figure 1. Distal and proximal cross-section of I-Support module: six sensors position.

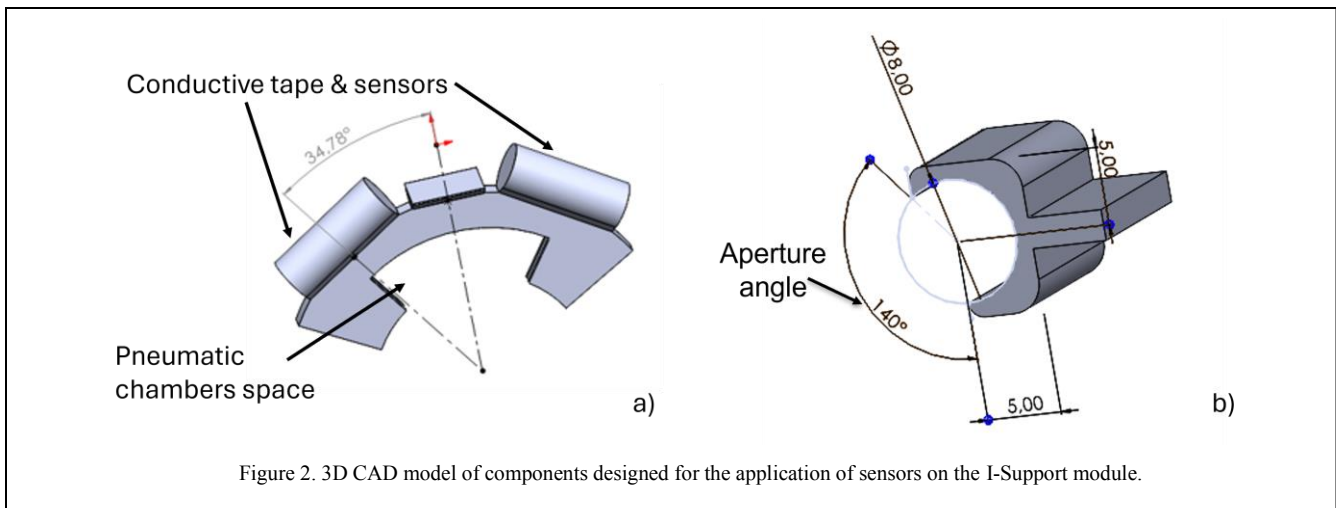


Figure 2. 3D CAD model of components designed for the application of sensors on the I-Support module.

The first phase consisted in cutting Electrolycra for preparing specimens. Since in the previous studies [10] it was demonstrated that a prestretch at 200% strain is needed to increase the repeatability and the linearity of the electromechanical behaviour and it was observed that the prestretch tends to increase the length of the sample of approximately 20% (due to a partial permanent deformation), the sample was cut according to the following equation:

$$l_c = l_d / 1.2 + 20 \quad (1)$$

where  $l_c$  is the length at which the sample should be cut [mm] and  $l_d$  is the final desired length of the active part [mm]. Considering the length of the soft arm module, the dimension of the cut sample is 62 mm.

Two of the non-prestretched sensors that have been applied to the module are used. The samples were subject to a cyclical tensile test (5 cycles) up to 50% strain, at the following velocities: 200 mm/min, 300 mm/min, 400 mm/min and 500 mm/min. These velocities have been chosen as they are considered to cover the expected range of the I-Support module's velocities while it is actuated. The choice of testing up to 50% strain was to respect the known Electrolycra working range, that is monotonic up to a 50% maximum strain [10].

Resistance data have been filtered using a low-pass filter of order 10 and with normalized cut-off frequency of 0.1 (with Matlab functions *fir1* and *filtfilt*). The first of the five cycles was excluded from the mean computation.

### C. Evaluation of proprioception system reliability

The aim of the testing phase is to:

- Evaluate the impact of sensor application on the arm's movements.
- Assess the strain experienced by the sensors under the constant curvature approximation.
- Determine the sensors' ability to estimate the position of the arm's distal end.

To obtain ground truth data for the tip position, a reliable tracking system is required. Commonly used technologies include electromagnetic and optoelectronic tracking systems. In this study, the Vicon optoelectronic system (Vicon Motion

Systems Ltd., UK) was utilized. Additionally, a voltage divider with a known resistance of 12  $\Omega$  measured the electrical signals from the six sensors embedded in the soft arm. Motion and proprioceptive data were recorded at a sampling frequency of 100 Hz.

A Matlab script interfacing with an Arduino board was used to control the activation of the pneumatic chambers according to predefined patterns:

1. **Pattern 1:** Each actuator is activated sequentially to 50%, 100%, and back to 50% of the maximum pressure, maintaining each pressure for two seconds, four seconds, and two seconds, respectively. Subsequently, all actuators are activated simultaneously to achieve maximum elongation following the same pressure steps and durations.
2. **Pattern 2:** Two actuators are activated simultaneously in combinations (actuators 1-2, 2-3, and 1-3), with the same pressure steps and durations as Pattern 1.
3. **Babbling:** Random actuator activations are performed, with commands updated at 10 Hz for approximately 20 minutes, allowing the robot to explore its workspace.

Patterns 1 and 2 were repeated three times for statistical analysis.

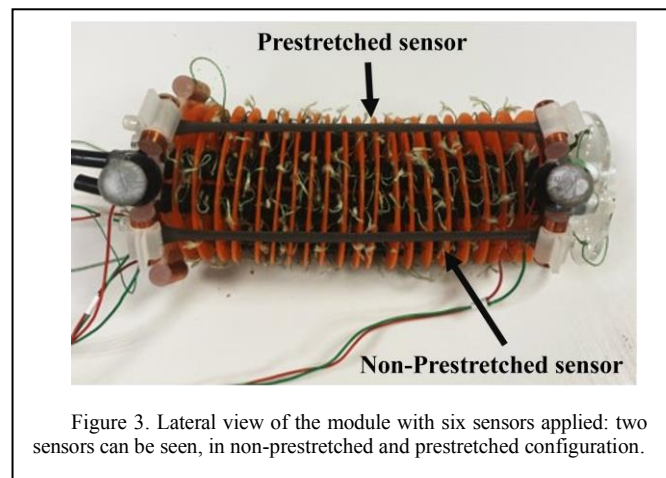


Figure 3. Lateral view of the module with six sensors applied: two sensors can be seen, in non-prestretched and prestretched configuration.

The metrics used to evaluate the performance of the estimation in each of the activation tests performed are the root mean square error for each coordinate (RMSE<sub>i</sub>, with i = x, y or z) and a normalized RMSE<sub>i</sub>[%]:

$$\text{RMSE}_i[\%] = (\text{RMSE}_i / \text{disp}_{\max}) * 100 \quad (2)$$

where  $\text{disp}_{\max}$  is the maximum displacement along coordinate i (x, y or z) during the overall activation.

### III. RESULTS AND DISCUSSION

#### A. Calibration tests

In order to relate the measured resistance variation to the strain of the sensors and hence their length, a calibration curve is derived. Given the electrical hysteresis of Electrolycra, two curves have been derived: a load curve (LC) and an unload curve (UC). The curves have been obtained averaging first among the different velocities of each of the two samples and then averaging among the two samples. The data acquired have been resized to allow a monotonic behaviour of the mapping between resistance variation and strain. To obtain a calibration curve, the load data are fitted with a fourth order polynomial curve, whereas the unload curve was fit with a linear curve (see Fig. 4a and 4b). In Table 1, curve parameters and  $R^2$  are reported.

#### B. Evaluation of proprioception system reliability

For the purpose of this work, the constant curvature model applied to a cable-actuated continuum robot presented in [12] has been used. To translate the problem described in the paper—estimating the end-effector position and robot shape, assuming the lengths of the three cables running longitudinally along the robot and fixed radially at 120° intervals are known—into the context of this work, the cable lengths have been interpreted as the lengths of the non-prestretched sensors applied to the module, maintaining the same radial arrangement.

In order to estimate the position of the module's end-effector using the sensory system implemented, the signals

TABLE I. RESULTS SENSOR CALIBRATION DATA FITTING

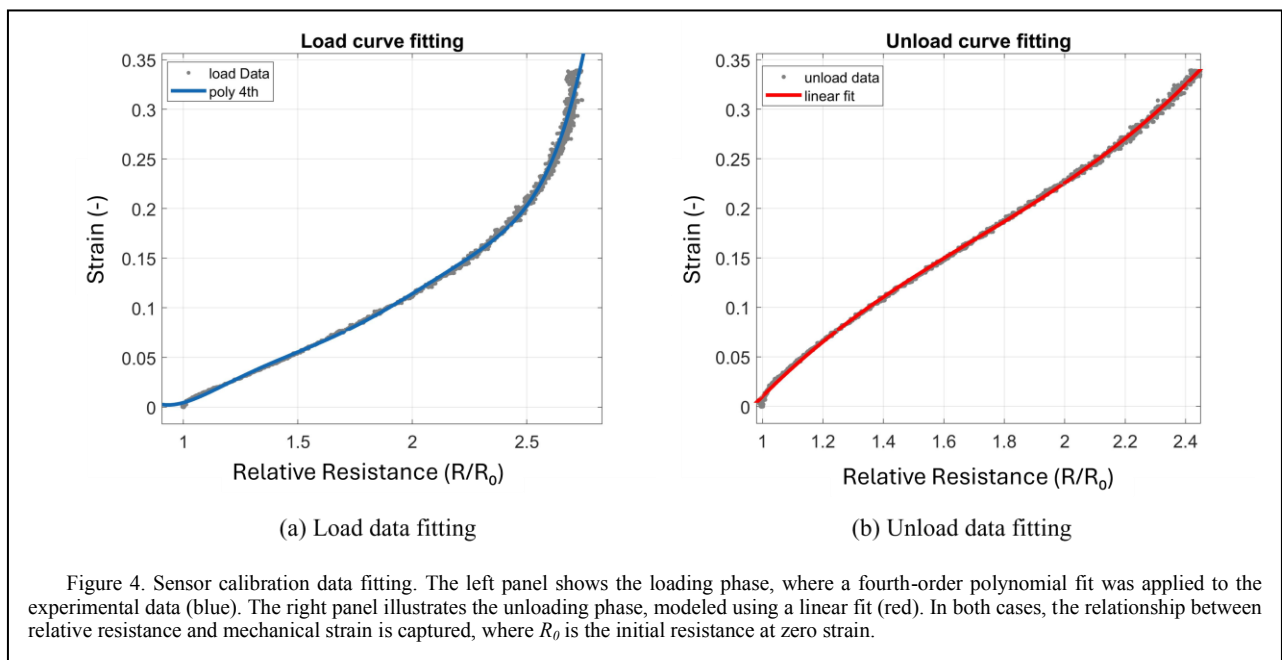
$p_1$	$p_2$	$p_3$	$p_4$	$p_5$	$R^2$
Load curve: $y(x) = p_1x^4 + p_2x^3 + p_3x^2 + p_4x + p_5$					
0.1603	-1.088	2.71	-2.82	1.047	0.991
Unload curve: $y(x) = p_1x + p_2$					
-0.1949	0.2135	-	-	-	0.996

acquired from the six sensors applied to the module are stored and post-processed with the following pipeline:

1. Filter sensors signals (with a 10th order low-pass filter at 0.1 normalized cut-off frequency) to remove noise.
2. Pass the signals through an estimation algorithm to simulate the estimation of the robot's position (x, y, z) at each time step.
3. Filter the estimation to eliminate some high frequency components of the estimation (with a 50th order low-pass filter at 0.01 normalized cut-off frequency).

The estimation algorithm has the aim to:

- Find if each signal from the three non-prestretched sensors is rising or falling in order to apply the proper calibration curve (load or unload).
- Compute the estimated lengths of the three non-prestretched signals, and consequently the arc parameters.
- Increase the curvature parameter if a non-prestretched sensor is estimated as being slack and the associated prestretched sensor shows a decreasing signal.
- Compute the end-effector position (x, y, z).



In Table 2 the results are summarized: for Pattern 1 and Pattern 2 the mean and the standard deviation of the metrics are reported.

The estimation performed with the described method is able to track qualitatively the real position of the end-effector but still the quantitative error is not negligible: this can be mainly attributed to two separate sources:

- Incomplete compensation of the non-linearities of the electrical behaviour of Electrolycra.
- Constant curvature assumption.

As for the 1st source, a more sophisticated model of the hysteresis and relaxation behaviour would be needed to improve the calibration of the sensors (see [13] for a proposed compensation model for Electrolycra). This approach would come at the expense of: i) more time-consuming data acquisition for the training/parameter definition of the model and ii) higher computation complexity. In comparison, the method proposed in this work has the advantage of requiring a fairly short calibration protocol and a low-complexity estimation algorithm.

As for the 2nd source, the constant curvature model is considered a valid approximation for the pneumatic actuation of soft/continuum robots. However, certain real-world conditions challenge the assumptions on which the model is based. Specifically: i) the I-Support module does not fully satisfy the slenderness condition, as its length is not significantly greater than its diameter; ii) the module undergoes deformations that may exceed the small-strain assumption; and iii) external forces, such as gravity, are not accounted for in the model, even though they still affect the module despite its low weight.

Despite the presented limitations of the constant curvature model, for the purpose of this work it is considered acceptable as a first approximation. Overall, the results in terms of error, for the use case of I-Support, can be considered good enough to be used to provide data to a control system.

#### 1) Generalization tests

In order to verify if the method developed can be generalized, another set of tests was performed with a new set of sensors applied to the robot. The new set of sensors, with same dimensions and positioning as for the previous tests, is composed of other Electrolycra sensors, which have been laser-cut from the same original batch and prestretched at 200% before the application to the robot. The same tests have been conducted (Pattern 1, Pattern 2 and Babbling) and the same calibration curves reported in section III.A were used.

TABLE II. RESULTS OF END-EFFECTOR POSITION ESTIMATION

	$RMSE_x$ [mm]	$RMSE_y$ [mm]	$RMSE_z$ [mm]	$RMSE_x$ [%]	$RMSE_y$ [%]	$RMSE_z$ [%]
Pattern 1	9.9 (±2.1)	6.7 (±1.8)	10.6 (±1.5)	9.9 (±2.1)	6.9 (±1.8)	20.7 (±2.9)
Pattern 2	10.0 (±0.3)	11.4 (±3.1)	4.2 (±1.0)	10.0 (±0.3)	11.7 (±3.1)	8.0 (±1.7)
Bubbling	8.6	10.5	5.6	8.6	10.7	11.0

Since there can be variability both in terms of material and in terms of the manual application of sensors, these tests were meant to evaluate how much the method is robust against this kind of errors.

In Fig. 5 the Babbling activation pattern is shown, with the blue curve being the estimated trend and the red curve the measured behaviour with the Vicon system. In Table 3 the results are summarized.

The proposed method does not exhibit a significant performance degradation when new sensors are used. This demonstrates its feasibility for real-world deployment, where sensor replacement may be required or when applying the sensory system to a new soft arm with an architecture and dimensions similar to those of the I-Support module.

#### IV. CONCLUSION

In this work, the goal is to investigate the feasibility of the application of a sensory system on a soft arm module and its ability to estimate the position of its terminal part when the soft arm is actuated. In the field of soft robotics, including an efficient and non-obtrusive sensory system within the structure of a soft device is still an open challenge: this is proved by the research efforts aimed at the use of soft sensors for proprioception (sensing of self) and exteroception (sensing of the external world). In particular, the challenge lies in the development of an intrinsic system, that can be deployed on the robot and enable the use of the device out of the laboratory, in real-world scenarios.

For the purpose of this work, the focus is on proprioception, since it can be seen as the first fundamental step to implement a robust control system and, hence, increase the automation and intelligence of the device. Given the architecture of the actuation system, the I-Support module is able to elongate, shorten and bend thanks to deformation of its structure: hence the idea to estimate the position using soft strain sensors.

Electrolycra was selected as the sensing element because it is elastic, highly conductive, low cost, light and not cumbersome. To estimate the end-effector position in space, a calibration protocol was developed to derive a load calibration curve and an unload curve, in such a way to compensate for the electrical hysteresis of the material. A constant curvature kinematic model was used to compute the position. Tests have been performed to evaluate the ability of the sensory system to track the position of the module and the error between the estimated and the measured position have been obtained. The results are encouraging in terms of the ability of the sensors to

TABLE III. RESULTS OF END-EFFECTOR POSITION ESTIMATION - GENERALIZATION TEST

	$RMSE_x$ [mm]	$RMSE_y$ [mm]	$RMSE_z$ [mm]	$RMSE_x$ [%]	$RMSE_y$ [%]	$RMSE_z$ [%]
Pattern 1	9.1 (±1.7)	8.7 (±2.9)	9.3 (±2.1)	9.1 (±1.6)	8.9 (±3.1)	18.1 (±4.5)
Pattern 2	9.9 (±1.1)	16.2 (±1.3)	5.0 (±0.1)	9.9 (±1.1)	16.4 (±1.3)	9.8 (±0.2)
Bubbling	13.1	13.7	4.8	13.1	13.8	9.6

follow the real position, despite the non-linearities in the electrical behaviour.

Future works would be aimed at improving the results presented in this works, by tackling separately or together the identified sources of error, i.e. the material non-linearities and the kinematic modelling of the robot.

## REFERENCES

- [1] Wang, H., Totaro, M., & Beccai, L. (2018). Toward perceptive soft robots: Progress and challenges. *Advanced Science*, 5(9), 1800541.
- [2] Thuruthel, T. G., Shih, B., Laschi, C., & Tolley, M. T. (2019). Soft robot perception using embedded soft sensors and recurrent neural networks. *Science Robotics*, 4(26), eaav1488.
- [3] Munoz, J., Piqué, F., A. Monje, C., & Falotico, E. (2021). Robust Fractional-Order Control Using a Decoupled Pitch and Roll Actuation Strategy for the I-Support Soft Robot. *Mathematics*, 9(7), 702.
- [4] Truby, R. L., Della Santina, C., & Rus, D. (2020). Distributed proprioception of 3D configuration in soft, sensorized robots via deep learning. *IEEE Robotics and Automation Letters*, 5(2), 3299-3306.
- [5] Wall, V., Zöller, G., & Brock, O. (2017, May). A method for sensorizing soft actuators and its application to the RBO hand 2. In *2017 IEEE International Conference on Robotics and Automation (ICRA)* (pp. 4965-4970). IEEE.
- [6] Cianchetti, M., Renda, F., Licofonte, A., & Laschi, C. (2012, June). Sensorization of continuum soft robots for reconstructing their spatial configuration. In *2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechanics (BioRob)* (pp. 634-639). IEEE.
- [7] Wurdemann, H. A., Sareh, S., Shafti, A., Noh, Y., Faragasso, A., Chathuranga, D. S., ... & Althoefer, K. (2015, August). Embedded electro-conductive yarn for shape sensing of soft robotic manipulators. In *2015 37th Annual international conference of the IEEE engineering in medicine and biology society (EMBC)* (pp. 8026-8029). IEEE.
- [8] Ansari, Y., Manti, M., Falotico, E., Mollard, Y., Cianchetti, M., & Laschi, C. (2017). Towards the development of a soft manipulator as an assistive robot for personal care of elderly people. *International Journal of Advanced Robotic Systems*, 14(2), 1729881416687132.
- [9] Manti, M., Pratesi, A., Falotico, E., Cianchetti, M., & Laschi, C. (2016, June). Soft assistive robot for personal care of elderly people. In *2016 6th IEEE international conference on biomedical robotics and biomechanics (BioRob)* (pp. 833-838). IEEE.
- [10] Grassi, A., Cecchi, F., Maselli, M., Röling, M., Laschi, C., & Cianchetti, M. (2017). Warp-knitted textile as a strain sensor: Characterization procedure and application in a comfortable wearable goniometer. *IEEE Sensors Journal*, 17(18), 5927-5936.
- [11] Webster III, R. J., & Jones, B. A. (2010). Design and kinematic modeling of constant curvature continuum robots: A review. *The International Journal of Robotics Research*, 29(13), 1661-1683.
- [12] Jones, B. A., & Walker, I. D. (2006). Kinematics for multisection continuum robots. *IEEE Transactions on Robotics*, 22(1), 43-55.
- [13] Oliveri, A., Maselli, M., Lodi, M., Storace, M., & Cianchetti, M. (2018). Model-based compensation of rate-dependent hysteresis in a piezoresistive strain sensor. *IEEE Transactions on Industrial Electronics*, 66(10), 8205-8213.

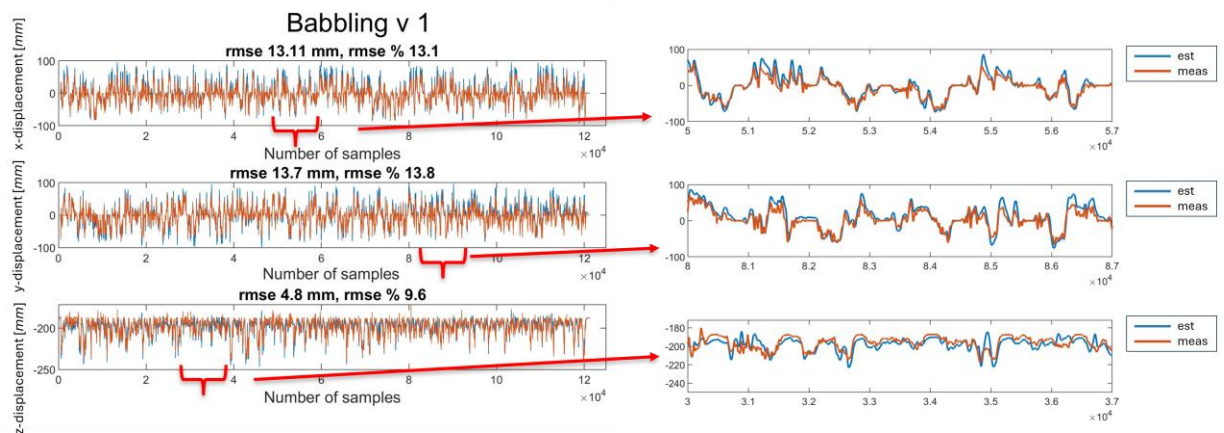


Figure 5. Comparison between estimated and measured displacements along the x-, y-, and z-axes during a free babbling motion of the soft robotic arm. The plots on the left show the full time series of estimated (blue) and measured (orange) displacements across all three axes. Corresponding root mean square errors (RMSE) and relative RMSE percentages are reported for each axis. The insets on the right present zoomed-in views of selected time windows (highlighted in red) to provide a detailed comparison between the estimation and ground truth data. The close alignment in the z-axis estimation highlights improved accuracy in that direction.