Advancing Soft Robot Proprioception Through 6D Strain Sensors Embedding

Daniel Feliu Talegón[1], Yusuf Abdullahi Adamu[1], Anup Teejo Mathew[1,2], Abdulaziz Y Alkayas[1], and Federico Renda[1,2]

[1]Department of Mechanical and Nuclear Engineering, Khalifa University of Science and Technology
[2]Khalifa University Center for Autonomous Robotic Systems (KUCARS), Khalifa University of Science and Technology

March 19, 2025

Abstract

Soft robots and bioinspired systems have revolutionized robot design by incorporating flexibility and deformable materials inspired by nature's ingenious designs. Similar to many robotic applications, sensing and perception are paramount to enable soft robots to adeptly navigate the unpredictable real world, ensuring safe interactions with both humans and the environment. Despite recent progress, soft robot sensorization still faces significant challenges due to the virtual infinite degrees of freedom of the system and the need for efficient computational models capable of estimating valuable information from sensor data. In this paper, we present a new model-based proprioceptive system for slender soft robots based on strain sensing and a strain-based modeling approach called Geometric Variable-Strain (GVS). We develop a flexible 2-Plate 6D strain sensor (Flex-2P6D) capable of measuring the 6 dimensions (6D) strain at specific points of the soft robot with an accuracy higher than 95 %. Coupled with the GVS approach, the proposed methodology is able to directly measure the configuration variables and reconstruct complex robot shapes with very high accuracy, even in very challenging conditions. The sensors are embedded inside the soft-body, which makes them also suitable for underwater operation and physical interaction with the environment. Something that we also demonstrate experimentally. We believe that our approach has the potential to be applied across a wide variety of applications, including observation and exploration missions, as well as human-robot interaction, where the states of the system are required for implementing precise closed-loop control and estimation methods.

Advancing Soft Robot Proprioception Through 6D Strain Sensors Embedding

Daniel Feliu-Talegon,[1*] Yusuf Abdullahi Adamu,[1*] Anup Teejo Mathew[1,2]
Abdulaziz Y. Alkayas,[1] Federico Renda[1,2]

[1]Department of Mechanical and Nuclear Engineering,

Khalifa University of Science and Technology, Abu Dhabi, UAE

[2] Khalifa University Center for Autonomous Robotic Systems (KUCARS),

Khalifa University of Science and Technology, Abu Dhabi, UAE.

Corresponding author: daniel.talegon@ku.ac.ae

March 14, 2025

Keywords: soft robot proprioception, capacitive sensing, 6D strain sensor, shape reconstruction, embedded sensors.

Abstract: Soft robots and bioinspired systems have revolutionized robot design by incorporating flexibility and deformable materials inspired by nature's ingenious designs. Similar to many robotic applications, sensing and perception are paramount to enable soft robots to adeptly navigate the unpredictable real world, ensuring safe interactions with both humans and the environment. Despite recent progress, soft robot sensorization still faces significant challenges due to the virtual infinite degrees of freedom of the system and the need for efficient computational models capable of estimating valuable information from sensor data. In this paper, we present a new model-based proprioceptive system for slender soft robots based on strain sensing and a strain-based modeling approach called Geometric Variable-Strain (GVS). We develop a flexible 2-Plate 6D strain sensor (Flex-2P6D) capable of measuring the 6 dimensions (6D) strain at specific points of the soft robot with an accuracy higher than 95 %. Coupled with the GVS approach, the proposed methodology is able to directly measure the configuration variables and reconstruct complex robot shapes with

This is the original submission version (pre-peer review) of the following article: Feliu-Talegon, D., Abdullahi Adamu, Y., Mathew, A. T., Alkayas, A. Y., & Renda, F. (2025). Advancing Soft Robot Proprioception Through 6D Strain Sensors Embedding. Soft Robotics., which has now been formally published in final form at Soft Robotics at https://doi.org/10.1089/soro.2024.0017.

very high accuracy, even in very challenging conditions. The sensors are embedded inside the soft-body, which makes them also suitable for underwater operation and physical interaction with the environment. Something that we also demonstrate experimentally. We believe that our approach has the potential to be applied across a wide variety of applications, including observation and exploration missions, as well as human-robot interaction, where the states of the system are required for implementing precise closed-loop control and estimation methods.

1 Introduction

The observation of creatures in nature has been a profound source of inspiration for numerous researchers, leading to the development of bio-inspired designs. Animals, in particular, exploit their body compliance to navigate complex environments, enabling them to accomplish tasks more efficiently. Soft robotics takes the cue from this research and stands as a growing field, aiming to mimic the physical characteristics of living organisms [1], including physical compliance, and seamless interaction with the environment. The importance and functionality of soft robots have recently driven new advances in modeling, actuator design, and the development of control and sensory systems for this new generation of robots [2, 3]. However, the development of proprioception systems to accurately estimate the state of a soft robot is still a challenging task and requires the development of new technologies and paradigms that can push the boundaries of soft robots' abilities. Sensory systems enable animals to perceive and respond to stimuli, providing crucial information for various essential functions. Similarly, soft robots require sensory systems to navigate unpredictable environments and perform complex tasks in a more human-like or animal-like manner [4].

Soft robot sensorization requires unconventional approaches to detect the robot's large deformations without introducing rigid components into the system [5, 6, 7]. Soft robots are highly susceptible to deformation from external forces or internal actuation, resulting in complex and extensive deformations characterized by nonlinearities, hysteresis, and viscoelastic effects, among other factors. This highlights the crucial need for new technologies capable of detecting complex shapes with localized deformations. Earlier research has presented innovative methods to measure the configuration of soft robots maintaining a constant strain or curvature along the robot's length, restricting the potential to attain complex shape results [8, 9, 10, 11, 12]. While these methods prove to be reliable, they encounter difficulties in accurately reconstructing complex shapes that involve variable deformations along the robot length. The highly deformable nature of soft robots, combined with their inherent infinite degrees of freedom, presents a challenge in accurately reconstructing their 3D morphology solely based on a limited set of measurements. In response to the essential need to capture variable strain along the robot structure, and to enable practical applications of soft robots in real-world scenarios, recent studies have been making notable advancements in the development of soft proprioception systems with an expanded set of sensors. In this direction, recent research has successfully implemented multiple sensors across various sections of the robots combined with machine learning algorithms to capture more intricate shapes [13, 14]. Although these strategies have demonstrated excellent results, they require the segmentation of the soft robot into a number of elements and assume constant strain along these individual elements. Additional methods involve employing a stretch-receptive sensor network [15] inside the soft robot to reconstruct the full deformation of the robot by measuring the elongation of the sensors or the introduction of stretchable shape-sensing sheets that provide orientation and strain measurements from sensor arrays [16].

The current trend in soft robots estimation explores the emerging confluence of developing biologically inspired stretchable electronic skin (e-skin) and machine learning algorithms to process the sensed data [8, 13, 17, 18, 19, 20]. Despite these recent advances, there remain several challenges yet to be addressed in the field of soft robots estimation. Particularly, the methods based on machine learning face a significant limitation arising from the uncertainty regarding how these algorithms will adjust or adapt to shapes that were not included in their training dataset. Regarding skin sensors, numerous challenges persist, including the enhancement of shape-sensing skins' stretchability, improving sensor resolution for detecting small curvatures and optimizing their performance amidst continuous surface contact or external factors like temperature or humidity. Furthermore, extracting valuable information from the large quantity of data provided by e-skin sensors requires algorithms that maintain computational efficiency for real-time implementation, especially for control system implementation [21, 22].

A rising trend in soft robotics involves utilizing the strain field to represent the robot's configuration, encompassing curvature, twist, elongation, and shear. Visualizations of the six strains $\boldsymbol{\epsilon} \in \mathbb{R}^6$ are provided in Fig. 1.

[Figure 1 about here.]

In this article, we propose a model-based proprioception system designed for soft robots. Our proposed system involves embedding 6D strain sensors along the robot's body and utilizes a model-based methodology that correlates the measured strain with the 3D morphology of the system (see Fig. 2). This approach builds upon the recent Geometric Variable-Strain (GVS) model [23, 24, 25], which describes the soft manipulator configuration using a finite set of strain bases. We propose 'FEM-like' local strain bases where the 3D geometry can be reconstructed with the measurements of our sensors acting as the generalized coordinates of the system. This approach resembles the Finite Element Method (FEM); however, it utilizes the values of strain at element nodes. By strategically positioning the sensors at various sections of the robot, our method enables the detection of geometric variations across the entire soft body. The sensor configuration consists of two closely positioned plates embedded in the soft body. By measuring the relative displacement and rotation between these plates, we can compute the 6D strain of the system at that specific point. We refer to this as Flexible 2-Plate 6D strain sensor or Flex-2P6D. While previous works in soft robot proprioception primarily focused on measuring bending, twisting, and stretching, e.g [26, 11, 9, 10, 27, 14, 20, 28, 29, 30, 31, 32, 33], our sensor distinguishes itself by its ability to measure the complete 6D strain, marking a distinctive and innovative feature within this particular field (see Table 1).

[Table 1 about here.]