

A physics-informed, vision-based method to reconstruct all deformation modes in slender bodies

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Abstract.—This paper is concerned with the problem of self-sensing, interpolating and reconstructing the shape (given and the six modes of deformation) of a slender flexible body from multiple camera measurements. This problem is important in both biology, where slender, soft, and elastic structures are ubiquitous environmental sensor organs, and in engineering, particularly in the area of soft robotics. The proposed mathematical formulation for shape estimation is physics-informed, based on the use of the spatial C-moment and theory where equations describe slender body mechanics in the presence of bending, shearing, twisting and stretching. The approach is used to derive numerical algorithms which are experimentally demonstrated for three-dimensional and multi-defect soft robot arms. These experimental demonstrations show that the methodology is accurate and robust even when there are large shape distortions and subject to noise and uncertainty.

1. Introduction

Biological structures that are slender or possess slender appendages, exploit the elasticity and compliance afforded by these features to perform and simplify a variety of tasks, from locomotion (insects, fish, birds) [13–16] to manipulation (octopuses, elephants, giraffes) [17–19], and more generally to sensing, adapt and respond to environmental interactions. Bio-inspired slender structures are also being increasingly incorporated in engineering, and particularly in robotics, as sensor-tactile structures and actuators [10]–[12]. Nevertheless, despite over a decade of soft robotics research, we have only begun to appreciate the incredible range that exists between elasticity, control and environmental context. Thus, to support and advance biological discovery and engineering applications, as well as to model and understand and innovative efforts, there is a growing interest in accurate, robust, cost-effective, and non-invasive techniques for shape and motion estimation in slender flexible bodies.

The problem of shape-motion estimation is complicated because elastic elements, whether biological or artificial, are subject to long-range stress propagation effects, where all six modes of deformation (axial/longitudinal bending and shear, twist and stretch) can be simultaneously engaged. As a consequence, localized loads are concentrated along the entire span of a nonlinear flexible, leading to complex dynamics and global morphological reconfigurations [20], [21]. There are among the mechanisms considered to critically contribute to



Fig. 1. Camera and model in experimental setup. A soft 300° serpentine [22] is integrated in our vision-based system. The 300° is connected to three parallel actuators, independently controlled by computer via Arduino board, via potentiometer through Raspberry Pi using WiFi, and an optical to 300° value (0°–300°) [23] [24]. A see robot sensor system.

animals' superior agility, dexterity, and ability to cope with external factors, safety and robustness. Consequently, they have important implications [25] in terms of body architectural organization, structure and control [7], [26]–[28]. Hence the impending need, for correct morphological incorporation, of methods able to quantify these experiments all continuous deformations, particularly in the presence of highly non-linearly and elastically living or elastically materials [17].

The goal of this paper is to develop and demonstrate methods and algorithms to estimate, from multiple camera images, the continuous bend, shear, twist and stretch stress functions along the longitudinal axis of a slender flexible body, in 3D space. The vision-based approach is selected here because it is versatile, relatively inexpensive, does not interfere with the system and can be deployed in a variety of conditions and environments.

The contributions of this paper are twofold. The theoretical contribution is a novel approximation formulation to estimate both slender body's pose and its associated six stress functions from discrete measurements. The formulation is physics-informed, based on the use of C-moment and theory [27] where equations describe slender body mechanics in the presence of bending, shearing, twisting and stretching. A

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