

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-reading, interpolating and reconstructing the shape (given only 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 easy to use, even when there are large displacements and subject to noise and uncertainties.

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) [23–26] to manipulation (octopuses, elephants, giraffes) [7]–[10], 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 (skin, structure and adaptive) [18]–[22]. 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 (translational 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 [23], [24]. There are among the mechanisms involved in critically contribute to



Fig. 1. Camera and model in experimental setup. A soft 300° serpentine [25] is integrated in our vision-based system. The 300° is connected to three parallel cameras, mutually parallel to components of: (a) skeleton signal, an image from Raspberry Pi using WiFi, and an output to 300° robot (R2-D2) [26]. (b) an robot sensor system.

animals' superior agility, dexterity, and ability to cope with external factors, safety and robustly. Consequently, they have important implications [25] in terms of body architectural organization, structure and control [7], [26]–[28]. Hence the impending need, for correct mechanistic interpretations, of methods able to quantify these experiments all continuous deformations, particularly in the presence of highly stretchable and shapeable living or otherwise 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 strain 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 strain 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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Table of Contents The Informed Vision

1. Understanding the eBook The Informed Vision
 - The Rise of Digital Reading The Informed Vision
 - Advantages of eBooks Over Traditional Books
2. Identifying The Informed Vision
 - Exploring Different Genres
 - Considering Fiction vs. Non-Fiction
 - Determining Your Reading Goals
3. Choosing the Right eBook Platform
 - Popular eBook Platforms
 - Features to Look for in an The Informed Vision
 - User-Friendly Interface
4. Exploring eBook Recommendations from The Informed Vision
 - Personalized Recommendations

- The Informed Vision User Reviews and Ratings
- The Informed Vision and Bestseller Lists
- 5. Accessing The Informed Vision Free and Paid eBooks
 - The Informed Vision Public Domain eBooks
 - The Informed Vision eBook Subscription Services
 - The Informed Vision Budget-Friendly Options
- 6. Navigating The Informed Vision eBook Formats
 - ePub, PDF, MOBI, and More
 - The Informed Vision Compatibility with Devices
 - The Informed Vision Enhanced eBook Features
- 7. Enhancing Your Reading Experience
 - Adjustable Fonts and Text Sizes of The Informed Vision
 - Highlighting and Note-Taking The Informed Vision
 - Interactive Elements The Informed Vision
- 8. Staying Engaged with The Informed Vision
 - Joining Online Reading Communities
 - Participating in Virtual Book Clubs
 - Following Authors and Publishers The Informed Vision
- 9. Balancing eBooks and Physical Books The Informed Vision
 - Benefits of a Digital Library
 - Creating a Diverse Reading Collection The Informed Vision
- 10. Overcoming Reading Challenges
 - Dealing with Digital Eye Strain
 - Minimizing Distractions
 - Managing Screen Time
- 11. Cultivating a Reading Routine The Informed Vision
 - Setting Reading Goals The Informed Vision
 - Carving Out Dedicated Reading Time
- 12. Sourcing Reliable Information of The Informed Vision
 - Fact-Checking eBook Content of The Informed Vision

- Distinguishing Credible Sources
- 13. Promoting Lifelong Learning
 - Utilizing eBooks for Skill Development
 - Exploring Educational eBooks
- 14. Embracing eBook Trends
 - Integration of Multimedia Elements
 - Interactive and Gamified eBooks

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