Characterization and Simulation of a Worm-Inspired Robot*

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***Abstract*— Soft-bodied invertebrates such as earthworms achieve efficient movement through coordinated peristaltic contractions of their body segments. This project explores this unique locomotive paradigm and studies it in its potential as a robotic framework.**

I. PROBLEM STATEMENT

Traditional rigid robots struggle in confined or irregular terrains (e.g., pipelines, soil, rubble). Soft-bodied worms offer a biological blueprint for adaptable motion via peristalsis. Understanding and simulating this mode of movement can inform the design of soft robots capable of traversing restrictive environments (e.g., medical endoscopy, search-and-rescue, pipeline inspection). Although peristaltic motion is effectively one-dimensional, it exhibits remarkable movement economy compared to limb-based locomotion, making it an efficient and robust strategy for soft robotic applications. The movement pattern is predictable yet surprisingly well-adapted to varied surface conditions, permitted friction can be maintained.

We gain insight into this mode of movement through the development of a computational model and simulation of a soft robotic worm. By capturing the coupling between actuation patterns, soft body mechanics and deformation, and frictional interactions with the environment, this model will provide insights into the fundamental physics and control strategies that enable efficient soft-bodied motion.

II. BACKGROUND

A. Peristalsis Mechanics

It is first important to understand the underlying biomechanics that allow worms to move forward. At a high level, peristalsis is perceived as a wave-like propagation of muscle contraction and subsequent relaxation that is practiced repeatedly starting from the head to the toe of a worm's body. One contentious topic of discussion regarding the theory of peristalsis is the role of friction. Some believe friction is not the predominant source of movement, and that momentum transfer inside the body may be the driving mechanism. However, one way friction is believed to propel the worm is by providing a stationary anchor for segments in front of the actuated tissue to lurch forward. Simulation may reveal some of these deeper truths about the mechanics of peristalsis.

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B. Material Construction

The exterior needs to be of pliable but durable/robust construction to accommodate a mode of actuation while being deformable to respond to actuation stimulus. Hydrostatic skeleton

C. Actuation Framework

A class material important to the field of soft robotics are smart materials. They often couple some form of external stimulus to mechanical response. The study of smart materials and their application have proven substantive in the creation of robotic worms. Shape Memory Alloys (SMAs) is one prevalent example of a smart material. They can reset back to a predefined structure when met with ample heat. They have the highest work density compared to other smart materials, meaning a small amount of material can generate a lot of work. They are not fast, but at microscale such as the case of Micro helix SMAs have strain ratios of up to 200% and can be actuated in under a second. The SMA could be wrapped around the robot and actuated by wiring that also constitutes the braided mesh Dielectric Elastomers are another smart material that have a use case in building robotic worms. DEAs consist of a passive elastomer sandwiched between 2 compliant electrodes. Applied voltage acts between the electrodes and inadvertently squeeze the elastomer film through electrostatic pressure, causing expansion of material. DEAs can be shaped around a tube like structure and actuated to mimic the pulsating activation pattern required for peristalsis.

Pneumatics have been applied a system of actuator. However, they require bulky pumps resulting in a unwieldy construction.

Hydrostatic Fluid Actuators - similar to pneumatics in that fluids are used to drive. This method also has size scaling limitations, requiring an effective micro-hydraulic piston.

Ionic polymer–metal composites (IPMCs)

D. Control Strategy

Open loop sin wave controller Stable heteroclinic channels (SHCs) [5].

III. APPROACH

A. Model Progression

The worm is represented as a series of deformable segments actuated by a traveling contraction wave, enabling net forward motion through phase-shifted actuation. By building upon existing soft robotics modeling frameworks such as finite element and Cosserat rod formulations, this work aims to develop a computational foundation for studying efficient, biologically inspired soft locomotion.

One model presents the worm segments as a series of connected four-bar linkages that expand vertically when activated.

B. Contributions

The simulation will explore how actuation frequency, amplitude, and friction anisotropy influence locomotion performance. The results are expected to provide insight into control and design strategies for soft robots operating in constrained or complex environments.

The project will explore the relationship between actuation phase patterns and segment deformation, frictional interactions with the environment, and body compliance and stiffness distribution. Analytical framework surrounding these relationships and gain insight into locomotion efficiency and metabolic activity, maneuverability, stability, and control responsiveness to identify design parameters that optimize performance.

IV. CONCLUSIONS

This project establishes a computational foundation for investigating efficient soft robotic locomotion. The insights gained from modeling actuation and body-environment interactions will guide the design of soft robots capable of adaptive and robust movement in complex settings.

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