Design and Actuation of Compliant Modular Worm-like Robot

Akhil Kandhari[1], Andrew D. Horchler[1], Kathryn A. Daltorio[1], Kenneth C. Moses[1], Richard J. Bachmann[1], Hillel J. Chiel[2], and Roger D. Quinn[1]

1) Dept. of Mechanical and Aerospace Engineering and 2) Depts. of Biology, Biomedical Engineering, and Neurosciences, Case Western Reserve University

CASE WESTERN RESERVE UNIVERSITY EST. 1826

BIOLOGICALLY INSPIRED ROBOTICS LABORATORY

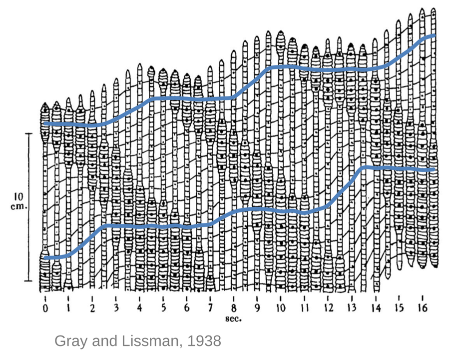
Introduction

Mimicking and better understanding the way an earthworm uses its many segments will help in designing new soft robots for a wide variety of applications. For better understanding of the control and dynamics of such a robot platform we develop a new type of robotic platform: Compliant Modular Mesh Worm (CMMWorm). The robot's body utilizes a compliant mesh that couples decreases in diameter with increases in length. The function of the mesh parallels the hydrostatic skeleton of an earthworm. Because of this diameter-length coupling, as waves of radial contraction travel down the cylindrical body, our robot advances along ground or in pipes with peristaltic locomotion. The mesh consists of rhombuses whose sides are polycarbonate rods or nylon tubes. The vertices of the mesh are 3-D printed and permit pin-joint rotation of the rhombus sides. Each segment of the robot is individually controlled using a smart servo actuator attached to cables for both longitudinal (contraction) and circumferential (extension) motion. The modular mesh enables the robot to achieve a large strain range comparable to that of an earthworm. We measure slip at the contacting surfaces using video analysis and observe the effect of friction on the robot's locomotion.

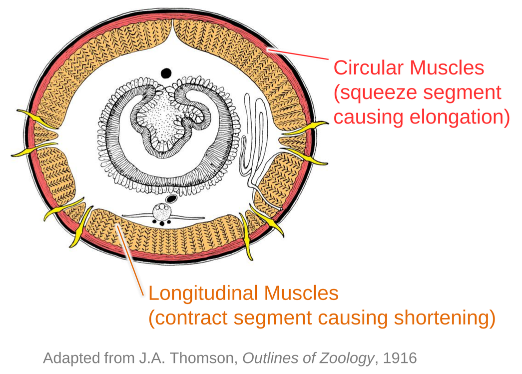
Aim

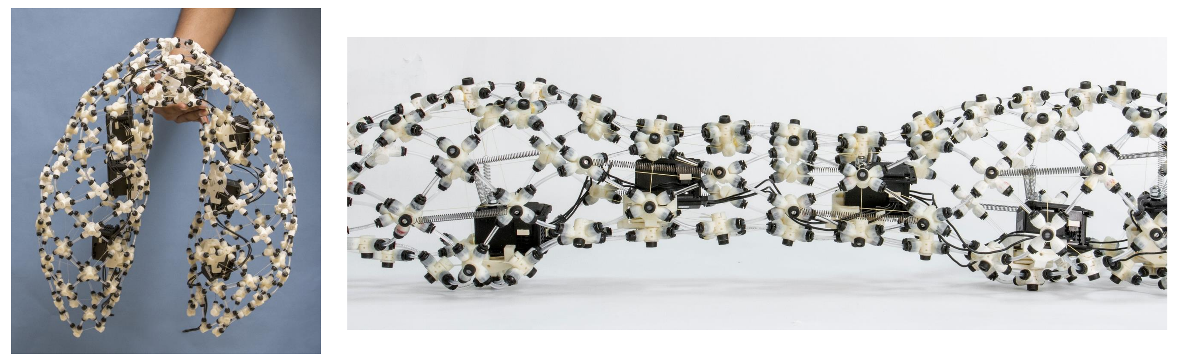
The goal of our research team is to develop a worm-like robot that mimics the motion of an earthworm. The compliant mesh of our robot is capable of creating different waveforms along its body and responding to environmental loads, e.g., from pipe walls. We want to observe how friction, compliance, and control together affect locomotion. Such analyses will be useful for the design and control of future soft-bodied robots for applications such as pipe inspection and medical devices.

Earthworm Locomotion



Earthworm Body Structure





The compliant actuated mesh structure of CMMWorm permits large deformations.

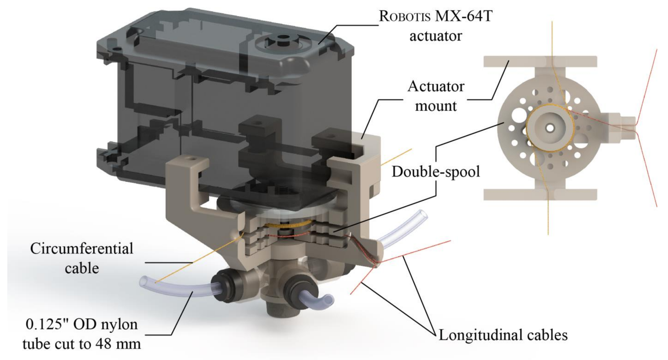
The modularity allows each segment being actuated individually allowing different waveforms.

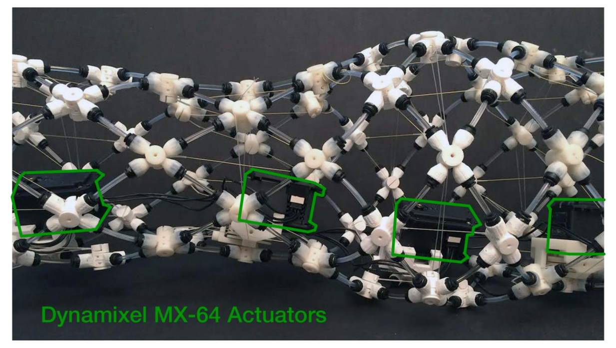
The six segment Compliant Modular Mesh Worm (CMMWorm) in a 15.2 cm inner diameter pipe.

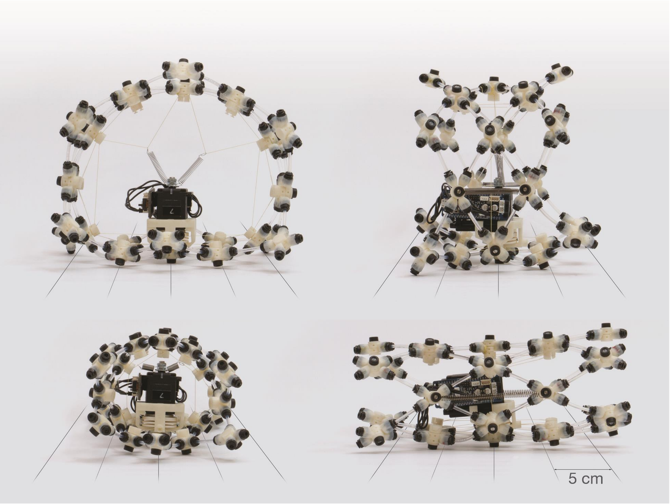
Design of Modular Mesh

Bi-directional Mechanical Coupling

- A bi-directional cable actuation system allows detection of maximum and minimum diameters by sensing cable tension (Horchler, et al. 2015b)
- Robotis Dynamixel MX-64T actuators (right) are used at each segment because of their load, speed, and position feedback capabilities.
- A circumferential cable contracts and elongates the segment while a longitudinal cable expands and shortens the segment.



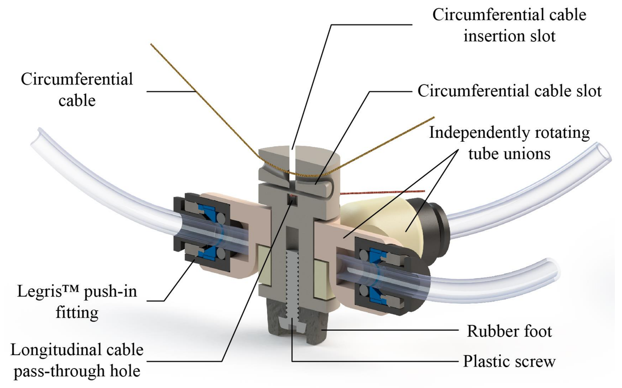




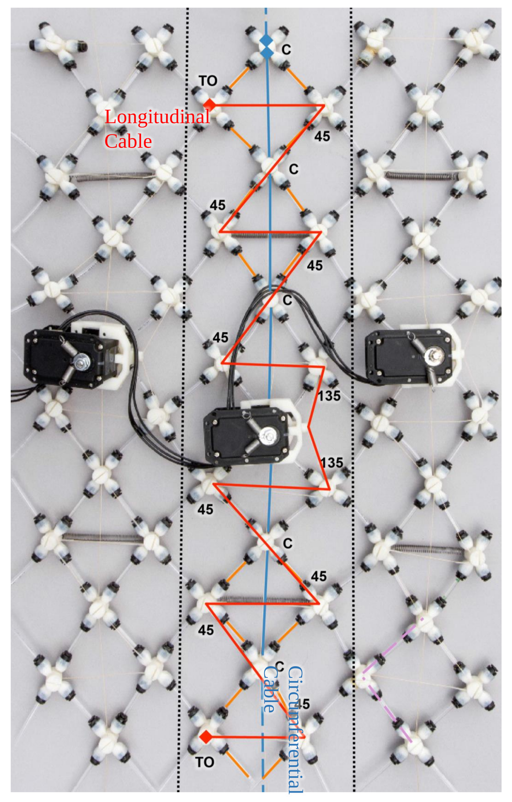
- A single segment of CMMWorm fully expanded (top) and fully contracted (bottom).
- CMMWorm is capable of deforming to 52% of its maximum diameter.

Mesh Structure

- Modular mesh structure fascinates easy assembly and configuration.
- The mesh consists of rigid 3-D printed vertex pieces connected by short pieces of flexible tubing or rod.
- The vertex pieces house four Legris™ push-in air hose fittings that hold the tubing in two independently rotating pieces.



Assembly of Modular Mesh



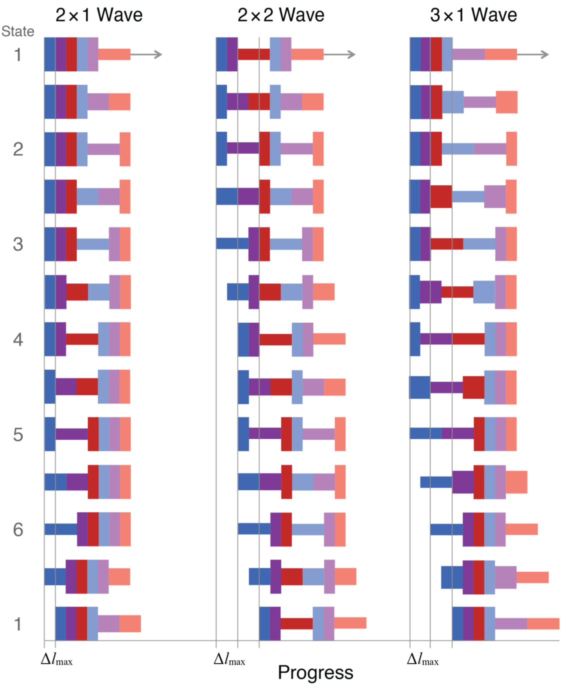
Five different vertex pieces that have unique geometry based on their position and function in the mesh:

C: circumferential vertex,
45: longitudinal 45 vertex,
135: longitudinal 135 vertex,
TO: tie-off vertex,
M: actuator mount.

The two pairs of cables pass through the various vertices for actuation in the two directions.

Control and Sensing

Waveforms for Locomotion

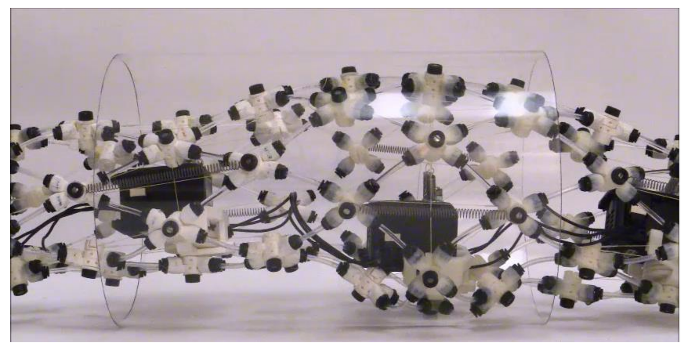


A cyclic state-based control scheme with fixed period is used to generate waves along the six segments. Here, the waves are propagated from right to left as the robot moves from left to right. Each wave consists of a radially expanding segment, a radially contracting segment, as well as inactive anchoring segments.

Sensing Load within the Mesh Structure

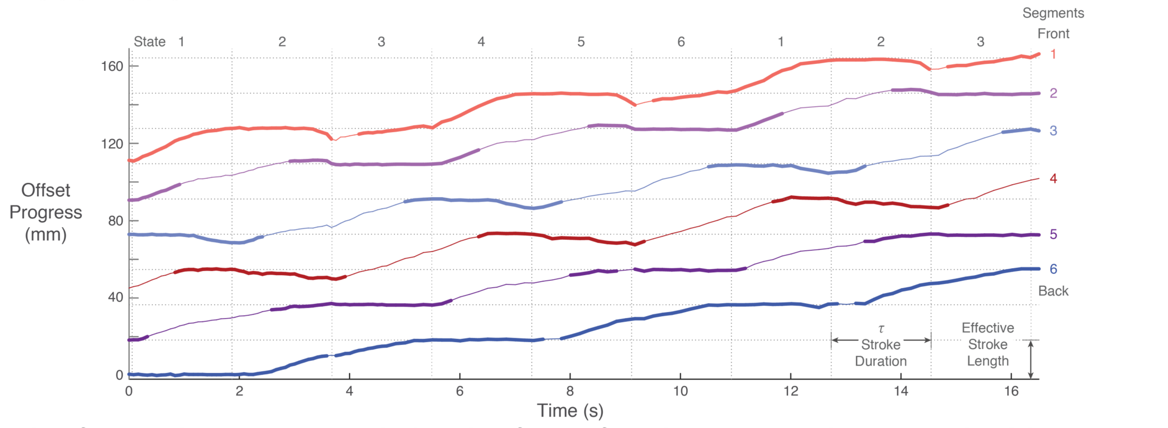
Each segment of the robot is capable of detecting limiting loads in either direction and stopping. The load value of the actuator at the limits crosses a preset threshold value.

A still from video of CMMWorm locomoting in a 15.2 cm inner diameter pipe. The robot detects the inner wall of the pipe using the load detection method and stops expansion and starts contraction.



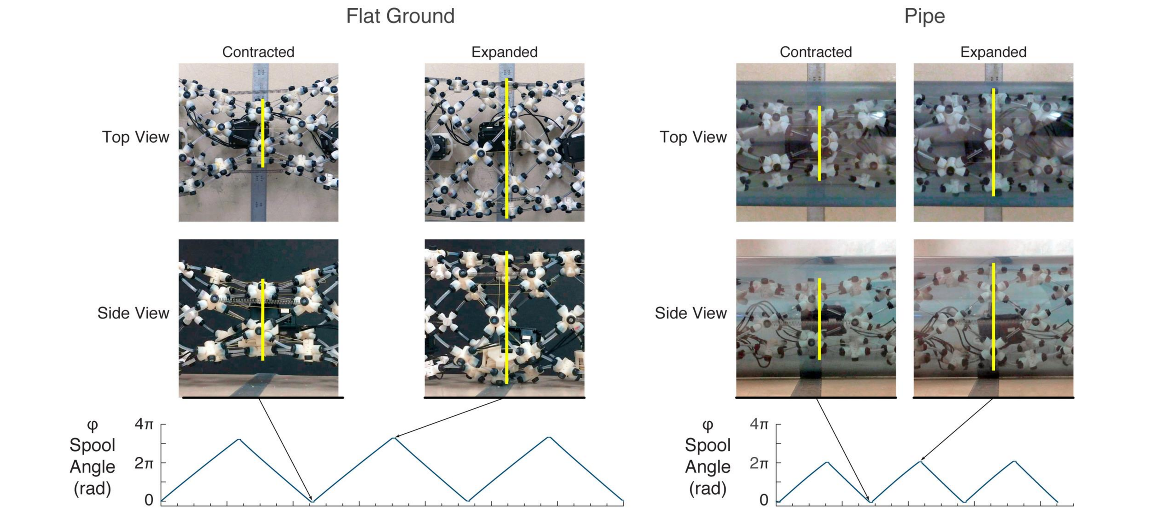
Robot Performance

Locomotion

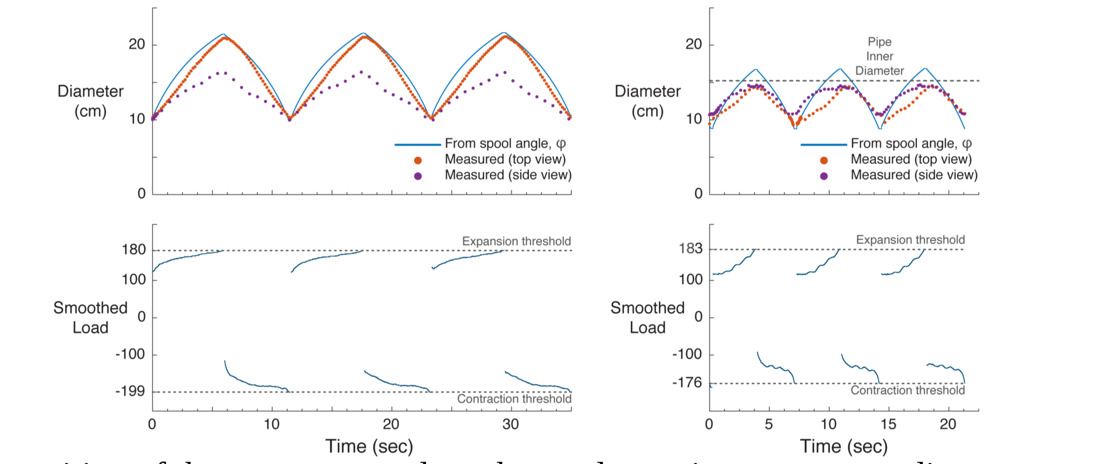


The forward progress made by the foot of each segment during a double two segment (2 × 2) wave. The thicker lines indicate when the segment is on the ground. Observation of tracked position shows slip. The speed of the robot was 3.4 mm/sec on a smooth laminate desk.

Diameter and Load Measurement



Using ImageJ, segment diameter was measured in two dimensions and compared to the estimated segment diameter.



The position of the actuator spool can be used to estimate segment diameter. Diameters measured from the video and using spool angle are compared (top). Load values measured by the actuator, detecting the maximum and minimum diameter of CMMWorm, are shown (bottom).

Conclusion

- We designed and tested a soft structured modular mesh.
- The mesh was compliant and can be controlled to mimic peristaltic like locomotion.
- The mesh can sense load and has a kinematic model which allows us to estimate the diameter.

Continued Work: Use neurobiologically-inspired oscillators (Horchler, et al 799.09/Q6, Wed. 10/21) to design controllers that take advantage of the wall-sensing ability of the robot (Daltorio, et al 637.15/DD42).

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