WORM LIKE LOCOMOTIVE AND FLEXIBLE MESH ROBOT

Project Reference No.: 49S_BE_2087

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Keywords:

Bio-inspired Robotics, Mesh based architecture, Hyper-redundant systems, Peristaltic motion, Kinematics model, Soft robotics.

Introduction:

This project involves the design of a low-cost, soft worm-like robot that mimics peristaltic crawling motion using a flexible mesh structure and an actuator. Inspired by earthworm locomotion, the robot is capable of crawling with rhythmic contraction and relaxation, powered by a motor-driven Bowden cable system. The mesh body is capable of stretching, compressing, and curving without damage, allowing the robot to fit through tight spaces. Its simplicity, modularity, and plug-and-play architecture make it suitable for applications like pipeline inspection, subsurface exploration, and education—an alternative that is both affordable and scalable to rigid robotic systems.

Objectives:

1. Design and build a soft robotic system that integrates worm-like locomotion with a flexible mesh structure model
2. Implement peristaltic motion to enable movement in confined spaces
3. Evaluate the robot's performance and energy efficiency
4. Enhance adaptability and safety for real-world applications such as pipeline inspection, movement in the pipeline with known distance (testing prototype)

Methodology

1. Design and Modeling

- Objective: To create and digitally model a flexible, worm-inspired robot.
- Tools Used: CAD software like SolidWorks or Fusion 360.
- Structure: The robot is made up of rhombus-shaped mesh segments crafted from medical-grade nylon pipes. These segments connect through X-shaped 3D-printed joints.
- Actuation Integration: Cable routing paths and attachment points were added to the CAD model to support tendon-based motion.

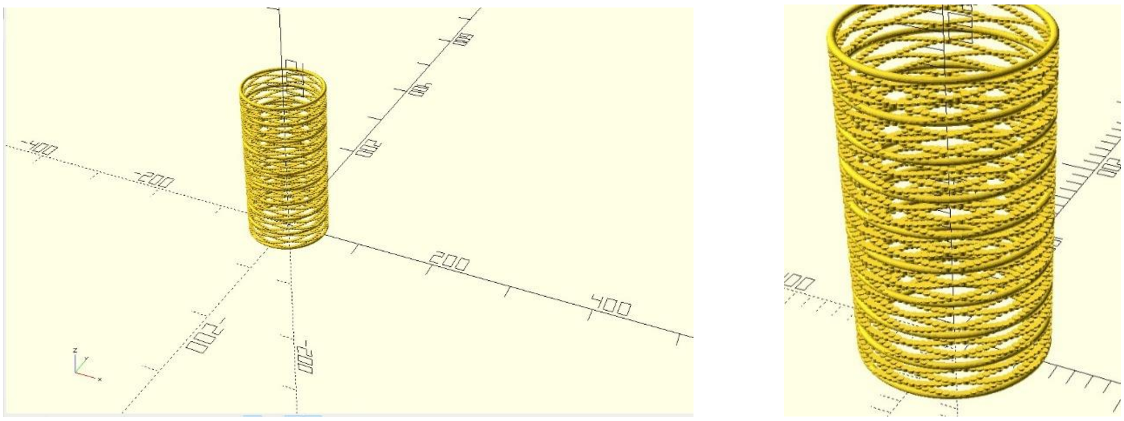


Figure 1: Design Parameters – Helical Rhombus Mesh

Feature	Updated Dimension / Value
Wire / Strand Thickness	4mm((→ wire radius = 2 mm)
Outer Diameter	100mm
Radius (from centre)	50mm
Total Length of Mesh	200mm
Number of Helices 6 Right-handed + 6 Left-handed	12 total.
Number of Horizontal Rings	10
Pitch of Helices	60mm
Rhombus Height (approx.)	35-40mm
Ring Spacing Evenly spaced along	200mm

2. Fabrication of Structural Components

- Materials: Medical-grade nylon pipes and 3D-printed joints.
- Assembly: Nylon pipes were cut to the same lengths and arranged in a crisscross pattern. Then, they were inserted into 3D-printed connectors to create the mesh structure.
- Output: A lightweight, flexible skeleton that supports actuation.

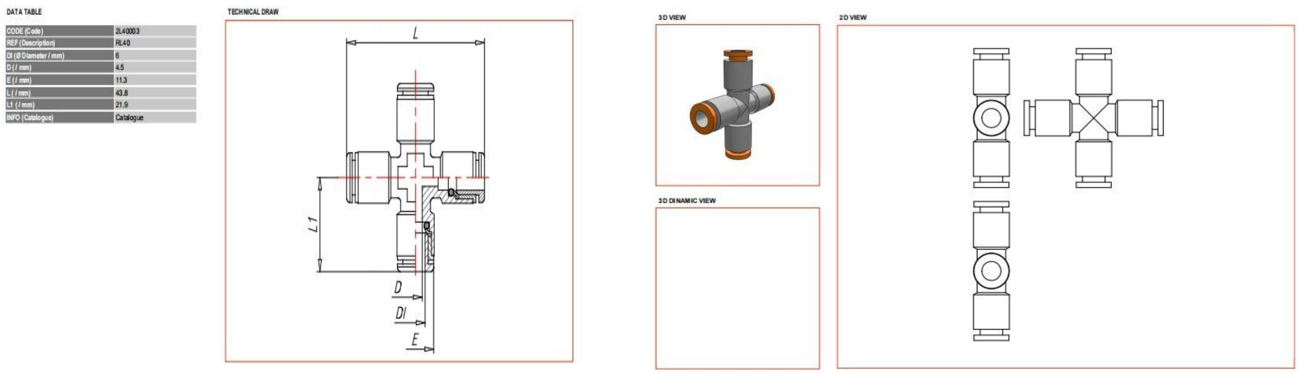


Figure 2: connecter design 1

3. Actuation System Setup

- Actuator: A single high-torque motor (e.g., MG996R or Dynamixel XL-320) is mounted at the base.
- Transmission: Bowden cables (bicycle brake wires) transfer motor motion to different segments.

- Mechanism: A rotating cam mechanism pulls tendons in a phase-offset manner to mimic sinusoidal contraction, replicating peristaltic movement.

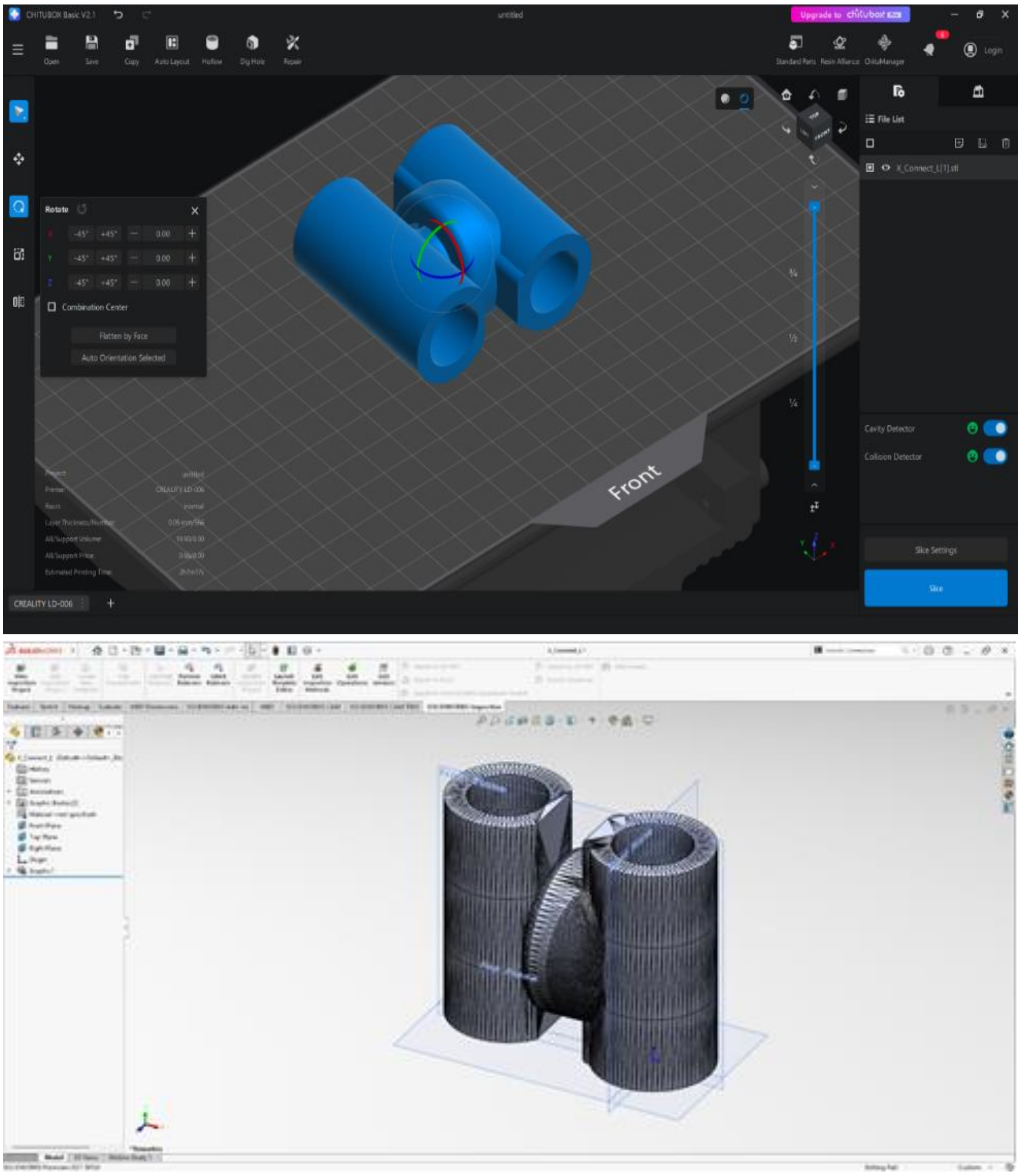


Figure 3: connecter design 2

Connectors Feature	Value
Overall Length (X-axis)	**22.72 mm**
Overall Height (Y-axis)	**21.00 mm**
Overall Depth (Z-axis)	**13.50 mm**
Outer Diameter	**8 mm**
Inner Diameter	**6.1 mm**
Connectors Length	**20 mm**
Wall Thickness	**2= (Outer Ø – Inner Ø) / 2**
Connectors Centre-to-Centre Distance	**9 mm**
Connectors Edge-to-Edge Spacing	**2 mm**

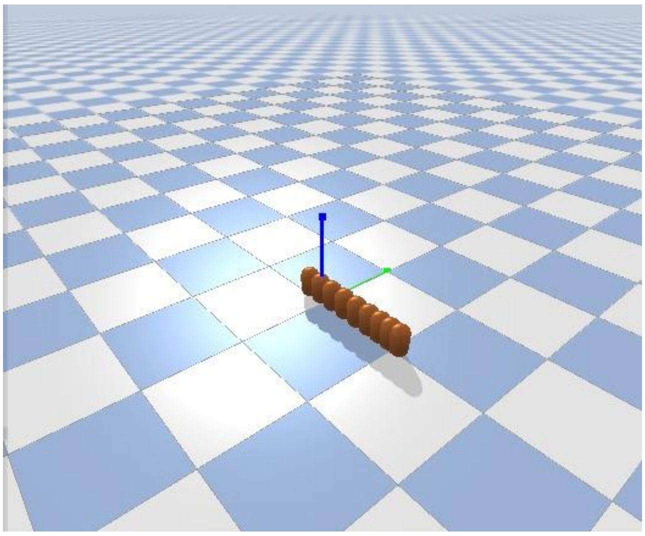


Figure 4: motion simulation

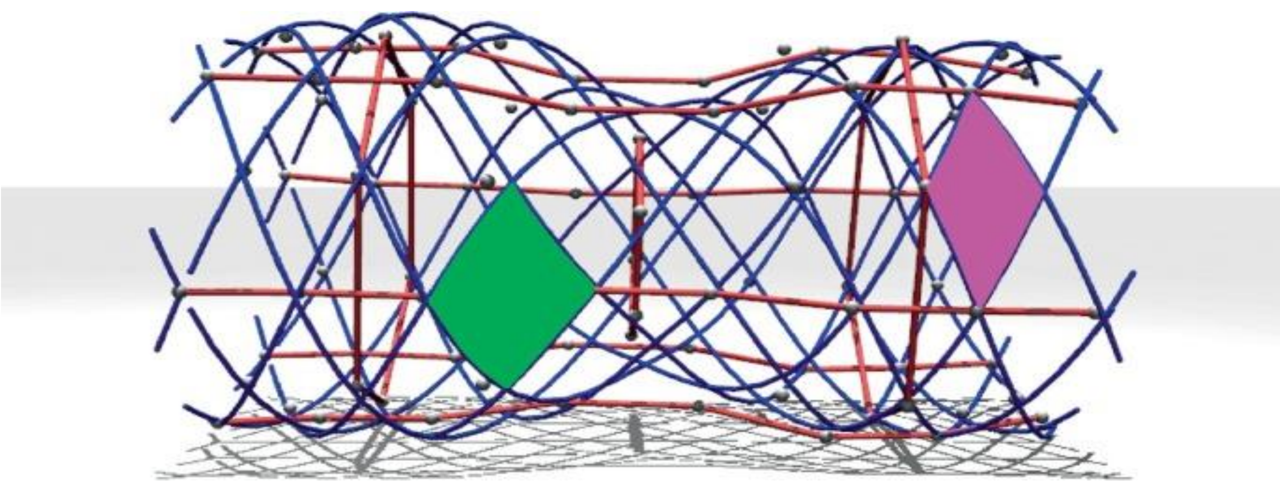
4. Electronics and Control Integration

- Controller: A microcontroller handles actuation cycles.
- Power Supply: It is powered by a 7.4V to 12V LiPo battery or a DC adapter.
- Control Logic: This was developed to provide timed signals for consistent and repeatable motion patterns that mimic a worm's movement.

5. Testing and Performance Evaluation

Multiple tests are conducted to assess functionality:

- **a. Locomotion Test**:
  - Surfaces: Smooth floor, textured board, soft foam.
  - Metrics: Distance per cycle, speed, and motion consistency.
- **b. Confinement Test**:
  - Setup: Simulated tunnels using nylon and foam channels.
  - Observations: Shape adaptability, curvature navigation, and recovery after deformation.
- **c. Energy Consumption Test**:
  - Goal: To measure voltage/current usage and assess energy efficiency for battery-based use.



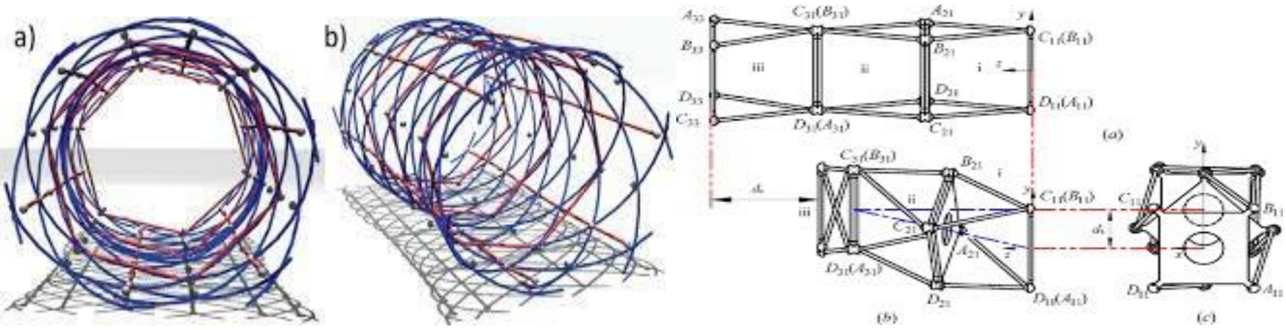


Figure 5: structural design

Skeletal representation of the peristaltic motion:

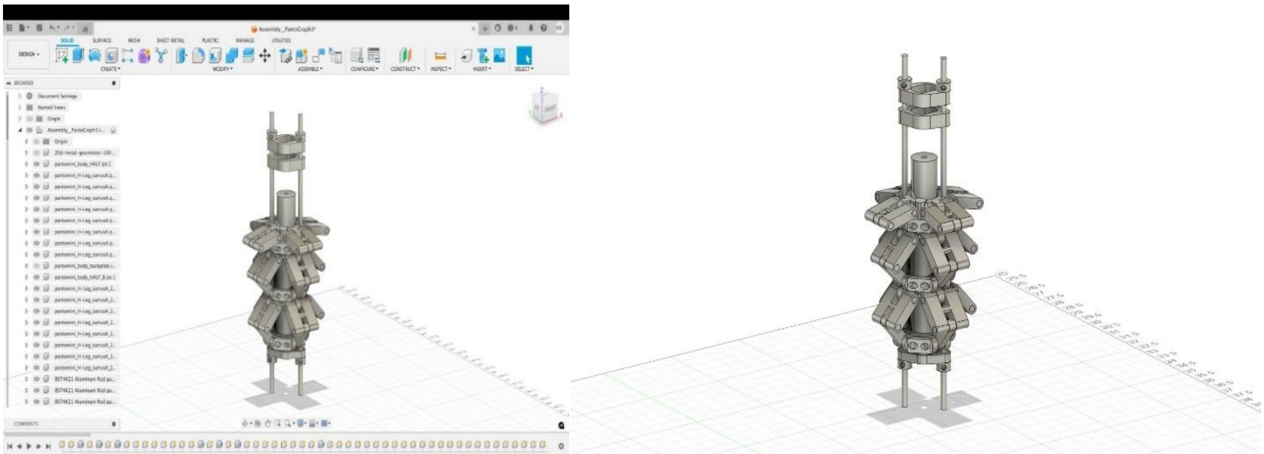


Figure 6: **Skeletal representation of the peristaltic motion:**

Item	Value (mm)
Number of body segments	8
Per-segment axial length	30.0
Segment outer diameter	40.0
Segment inner diameter (cavity)	34.0
Inter-segment free gap (uncompressed)	4.0
Max compression travel per joint	8.0
Overall assembled length (no motor housing)	8×30 + 7×4 = 240 + 28 = 268.0
Motor housing length (external to body)	36.0
Overall assembled length (robot)	268.0 + 36.0 = 304.0
Cam / spool outer diameter	44.0
Cam lobe offset (eccentricity) — produces stroke	4.0
Actuation stroke per pull (radial)	8.0
Bowden cable attachment pitch radius	18.0
Required coupler bore	Ø 3.2
Motor shaft to cam center distance	≈ 12.0
Bowden cable nominal length (per cable)	~380.0
Connector / frame thickness (printed PLA)	3.0
Recommended fasteners	M3 screws
Estimated assembled mass	~420 g
Payload envelope inside body	Ø 30 × L 80 mm

Result and Conclusion:

The soft robot is designed to produce worm-like peristaltic motion by the use of an elastic nylon mesh structure combined with a single-actuator tendon system. It is intended to be low cost, modular, and easy to replicate, so it is appropriate for practical, experimental, and educational purposes.

Key Findings:

- Successful Locomotion: The robot can move rhythmically in expansion and contraction of its segments closely mimicking earthworm movement.

- Flexibility: It freely moves, exhibiting elasticity and recovery when deformed.

- Structural Reliability: The mesh material and 3D-printed joints impart strength and retain shape when loaded.

- Basic Regulation: A single motor with an open-loop setup perfectly regulates all elements, hence simplifying electronic systems and reducing costs.

- Reproducible Performance: The robot is performing under various test environments, showing its robustness and reliability.

Conclusion: The project illustrates the feasibility of realistic, bio-inspired crawling motion with simple, inexpensive materials and one actuator. Although there are issues such as slippage on smooth surfaces and occasional tendon readjustment, these can be improved upon in subsequent designs. The robot as a whole has great promise for use in pipeline crawling, medical devices, and search-and-rescue, where flexibility and compactness are priorities.

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Future Scope:

1. Sensor Integration for Closed-Loop Control

Currently, the robot is performing a pre-programmed open-loop motion cycle and thus experiences a lack of environmental feedback. The addition of sensors like stretch sensors, pressure sensors, or inertial measurement units (IMUs) will allow the robot to perceive its self-motion and the environment in real time. The addition allows for:

- Adjust to terrain resistance or contact.
- Detect slippage or incomplete contraction.
- Automatically adjust its actuation pattern to provide better control.

This transition to a closed-loop control system would greatly enhance both reliability and responsiveness, particularly in circumstances with uncertainty or complexity.

2. Improved Surface Traction and Ground Adaptability

- To enhance efficiency in various terrains, upcoming versions can have features such as:
- Setae-inspired elements (similar to worm bristles) for gripping.
- High-friction pads to prevent slipping backward during contractions.
- Flexible external layers that adjust to different surface textures.

These changes would enhance mobility on uneven surfaces, such as concrete, soil, tile, and the smooth surface of industrial pipes.

3. Multi-Segment Independent Control

The present design has one actuator, and hence complexity in motion is restricted. Future designs can utilize multiple actuators, with each actuator moving a segment. This allows for:

- Advanced locomotion behaviors like pivoting, climbing, or backing.
- The capacity to turn in limited or labyrinthine areas.

Improved precision for specific applications like medical or industrial appraisals. This control would allow the robot to be used increasingly on surgical, pipe-inspection, and scouting missions.

4. Small and Portable Power Systems

Today, tethered power restricts mobility. Future innovations might aim to:

- Employ onboard Li-Po batteries with effective power management.
- Use energy harvesting (i.e., from the environment or vibrations).
- Create light, interchangeable battery packs to enable efficient field deployment.

This would provide more independence, allowing the robot to operate in distant or unpowered locations without power provided from elsewhere.

5. Material Optimization and Durability

Shifting to more robust and advanced materials will improve the robot's longevity and performance. Some enhancements include:

- With TPU, silicone, or fiber-reinforced tubes for enhanced strength and flexibility.
- Using water-resistant or waterproof coatings in wet or underwater environments.
- Utilizing light composite materials to reinforce mechanical toughness while maintaining flexibility.

This ability would enable the robot to perform effectively under harsh environments like underwater pipelines, swampy regions, or factory settings.