Research on a multi-degree-of-freedom modular soft snake robot

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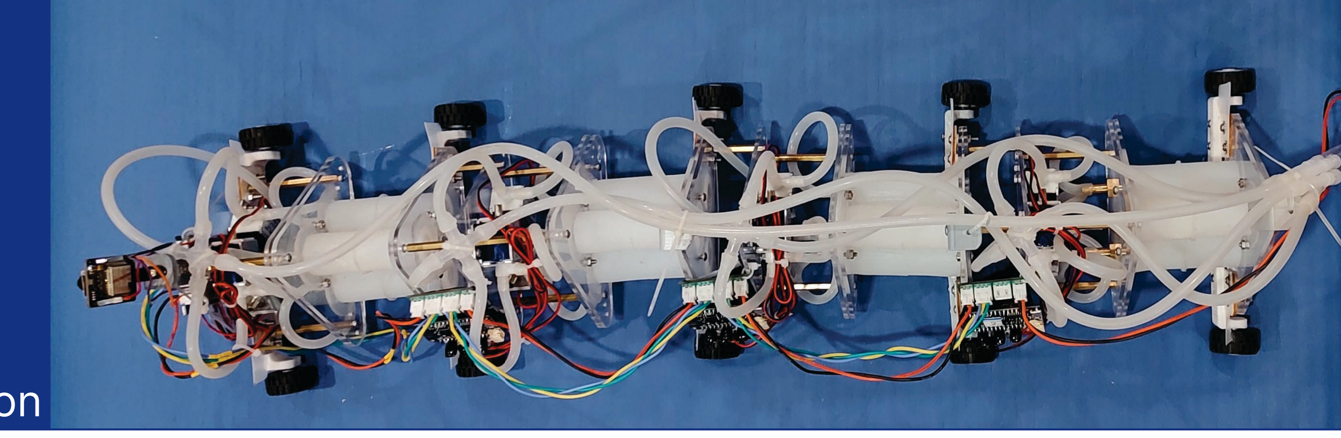


Introduction

Most Robots are made of metal, paint, and plastic, and they are **harmful** to the environment due to the **high energy cost**, **toxicity** to wildlife, and the **difficult recycling process**[3].

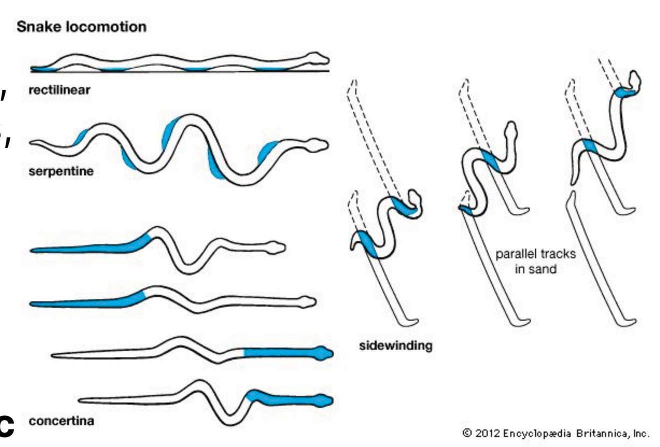
Soft Body Snakes can imitate the locomotion of **biological snakes** [1][4]. Their flexible natures allows for inspection, search-and-rescue, disaster response, medical fields, etc [2][5].

Silicon is also **nontoxic** and more **environmental friendly**.

Snake Overview

Designed with **modularity** in mind. This allows for easy **replacement** of broken parts, **attachment** of different tools, and **adjustment** of length.

The snake is made of four segments though **the length can vary**. Each segment contains a **logic board, air valves**, a **silicon body, acrylic plates**, and **tubing for air**.

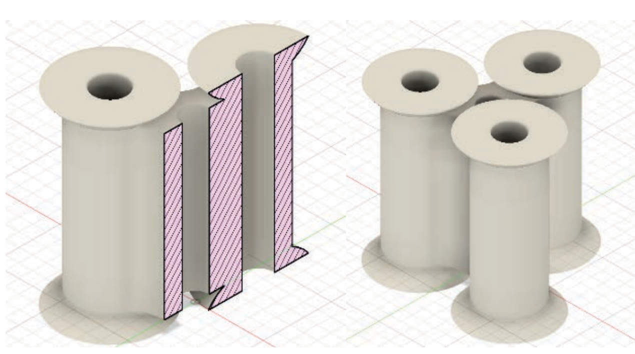


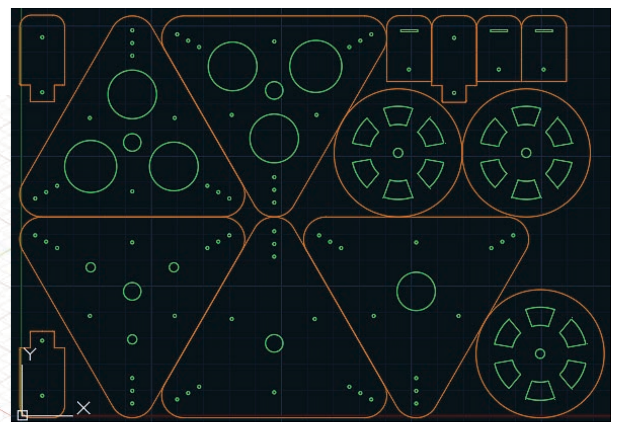
There are four major components to the system: the **physical structure**, the **pneumatic system**, the **electrical system**, and the **software**.

Physical Structure

Rubber silicon is the ideal material for the flexible part as it I **accessible**, **elastic**, and **malleable**. **Shore A-10** was the best as it **retains the shape well without pressure** and **deform easily under high air pressure**. The silicon part has three hollow tubes connected in a **triangular pattern** to allow the segment to tilt left, right, and down.

The rigid structures are mostly made of **acrylic** as it is both a **strong** material and **easy to work with**. They are then secured with M3 screws. There are two pieces of acrylic on each side of the silicon part to secure it in place, and one end houses the air valve and the electronics. This means each silicon part will be **independent** of the others to **ensure modularity**.





References

[1] S. Bittner, G. S. Sawicki, and R. J. Full. "Design Principles for Soft Robotics: Perception, Behavior, and Movement". In: *Annual Review of Biomedical Engineering* 22 (2020), pp. 341–366. url: https://doi.org/10.1146/annurev-bioeng-080119-014129.

[2] M. Luo et al. "Motion Planning and Iterative Learning Control of a Modular Soft Robotic Snake". In: *Frontiers in robotics and AI* 7.59924 (2020), p. 2. url: https://doi.org/10.3389/frobt.2020.599242.

[3] Tina Porwal. "Paint pollution harmful effects on environment". In: *Social Issues and Environmental Problems* 3.9 (2015), pp. 2394–3629.

[4] D. Rus and M. T. Tolley. "Design, fabrication and control of soft robots". In: *Nature* 521.7553 (2015), pp. 467–475. url: https://doi.org/10.1038/nature14543.

[5] Zhenyu Wan et al. "Design, Analysis, and Real-Time Simulation of a 3D Soft Robotic Snake". In: *Soft Robotics* (2022). url: http://doi.org/10.1089/soro.2021.0144.

Mold Design

There are a total of **four** iterations of the mold used to cast the silicon body.

Version 1 Features:

- wooden sticks for chamber
- Three piece design with lid, top and bottom
- Screws for **proper sealing**

Version 1 Flaws:

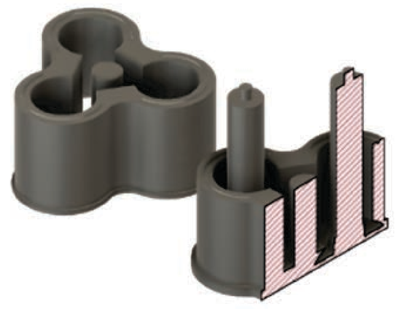
- Size of inner hole is **unchangeable**, which means **can't experiment** with wall thickness.
- Lid **trapped bubbles**, which then created **uneven surfaces**
- Flap around the three tubes are **too small** to be secured by the acrylic plates.
- Stick can easily **misalign** due to lower density than silicon.

Version 2 Features:

- Pillar on the bottom half
- larger flaps
- open top

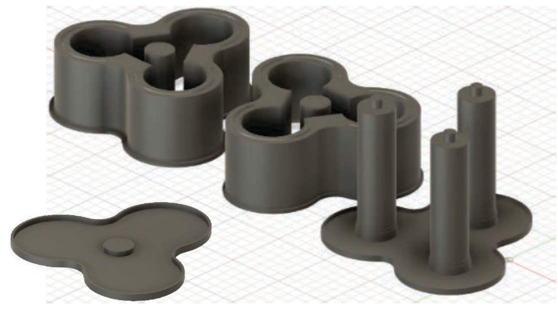
Version 2 Flaws:

- Pillars **must be broken off** to extract silicon.



Version 3 Features:

- The part design with top, bottom, and base with pillar
- pillars can be **removed beforehand**
- new mold for a separate sheet of silicon for **air-tight seal**

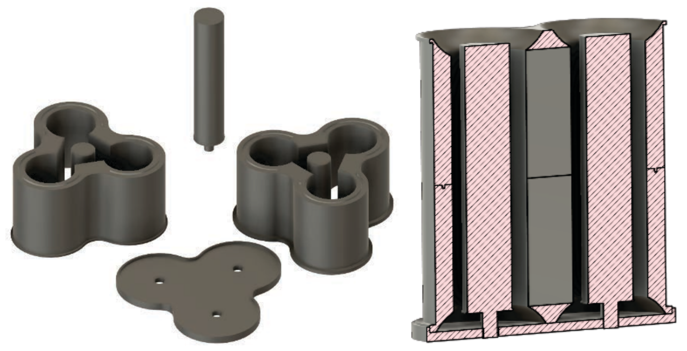


Version 3 Flaws:

- Pillars are still **hard to remove**
- Gluing two pieces of silicon together only creates a **weak seal** and **cannot withstand** the pressure of the pump.

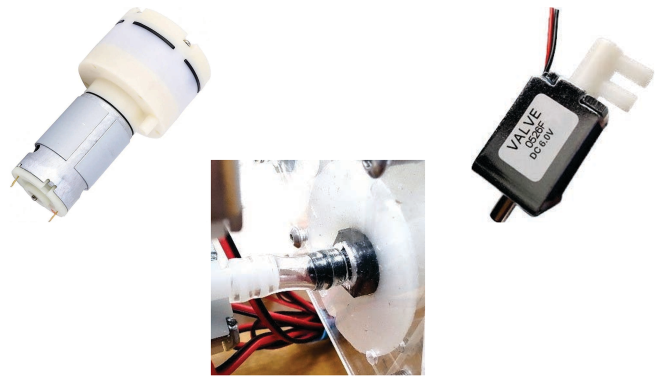
Version 4 Features:

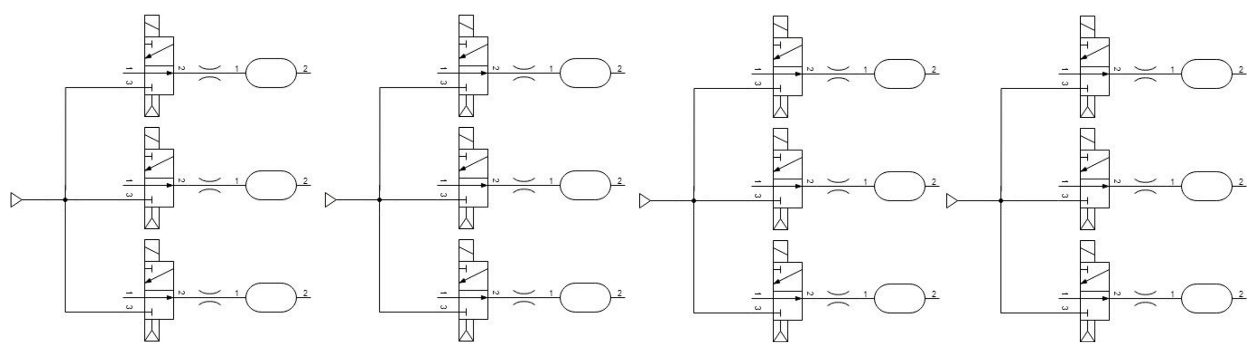
- **Only one small opening** for air valve
- pillars can be **individually removed**



Pneumatic System

A total of **four** pumps are used, each capable of **12kPa**. Four pumps are used so each segment can be **powered individually**. This ensures an **even delivery of air** to each segment **independent of other segments**' inflation states.

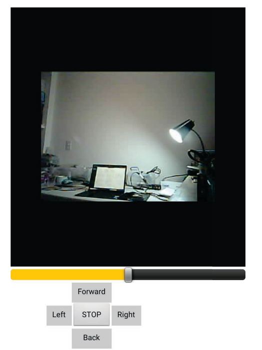




Software Design

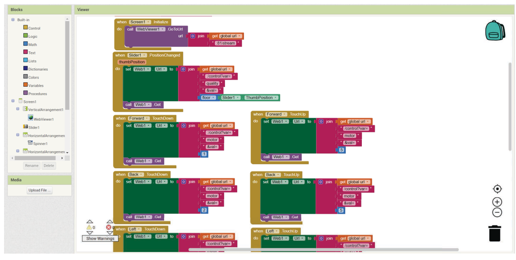
Phone App:

- Made with **AppInventor** from MIT
- Establish a **TCP** connection



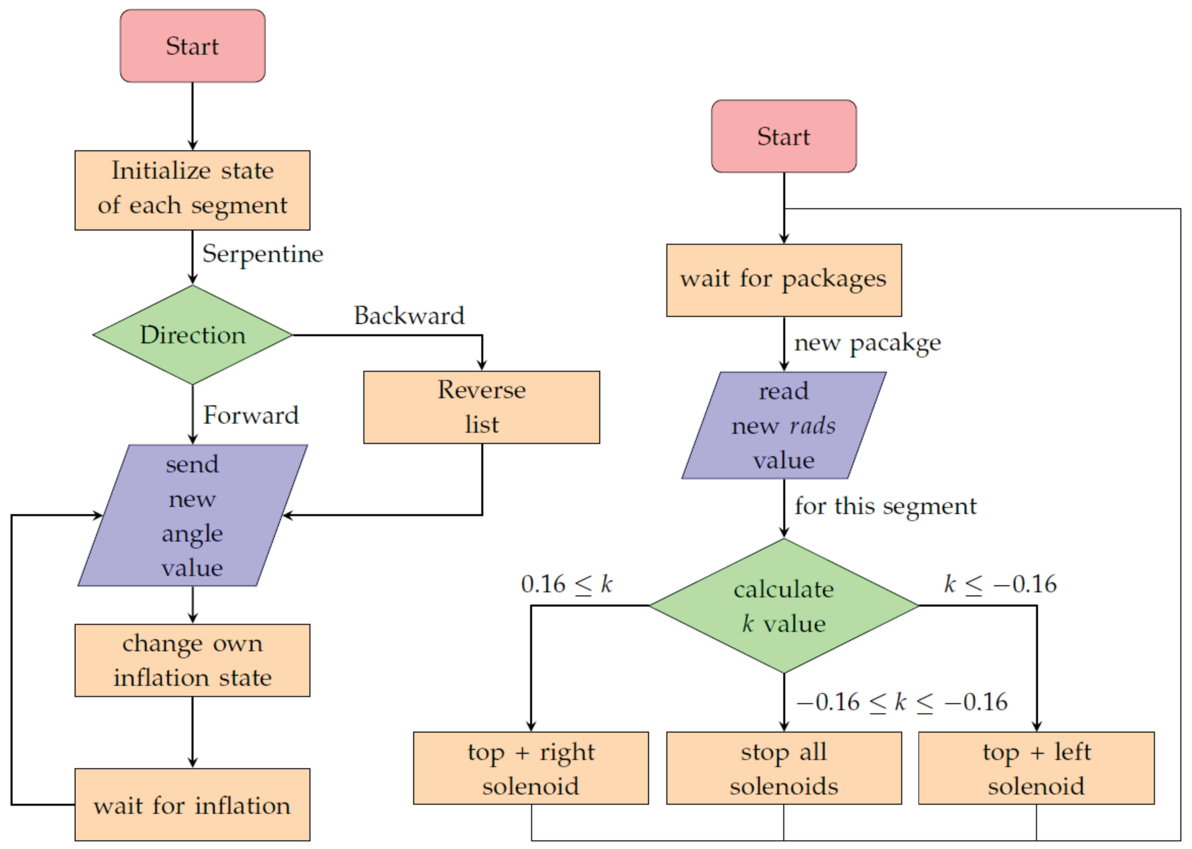
Controller Board:

- **ESP32** Microcontroller Unit
- Coded with **Arduino**
- Communicates with **MQTT** and **HTTP** Protocol
- Snake Follows a **sine function**



Snake Locomotion Function:

- ***k = sin(Speed × rads + id × shift)***
- ***k***: direction. the segment curves right when -0.5 < k < -0.17, the segment curves left when 0.5 < k < 0.17
- ***Speed***: gait frequency
- ***rads***: the time input into the function
- ***id***: the number of segments before this segment
- ***shift***: wave delay between each segment



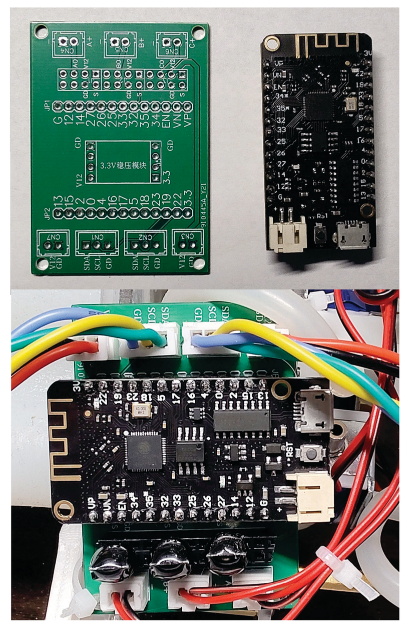
(a) Flow chart how the front ESP32CAM commands each segment *(b) Flow chart of how each segment functions*

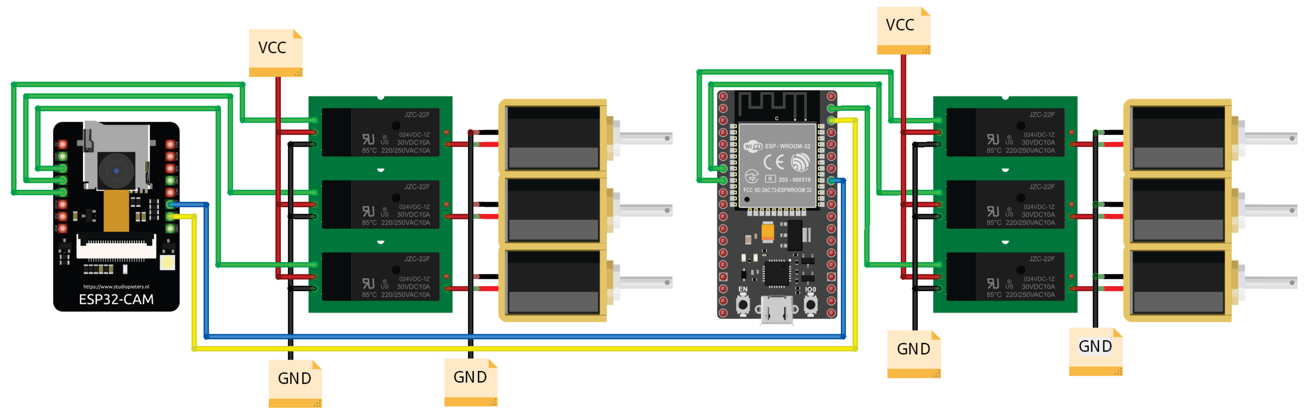
Electrical System

The board chosen for each segment is **ESP32**. The front board is an **ESP32CAM** module used for **sending video stream** back to phone, **receiving controls**, and **sending signals to each segment**. It **controls the movement** of the robot.

Each ESP32 controls three small **relays** connected to three **solenoid valves** which **controls airflow** into the silicon parts.

The boards are communicating through **I2C**, and the on-board WiFi allows the **possibility of communicating wirelessly**.





Silicon Body Parameters

Simulia Abaqus is used to **simulate** the results to ensure that results are **independent from any environmental factors**.

Experiment 1: Wall Thickness

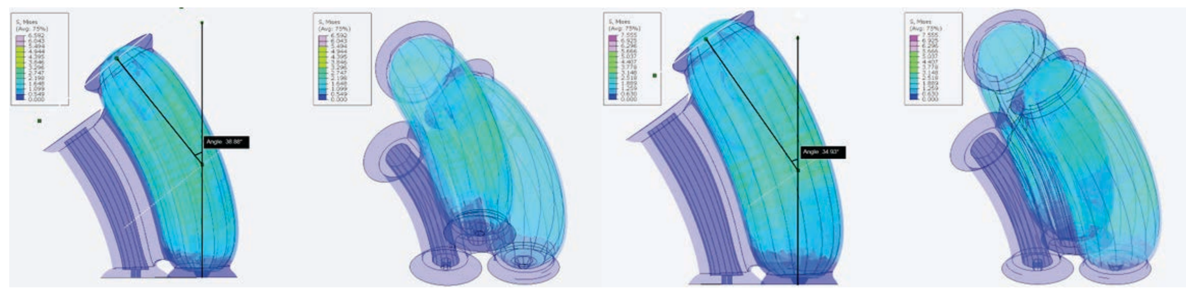
Models with **varying wall thicknesses** of **4mm**, **5mm**, and **6mm** and **uniform diameter of 15mm** were created and simulated. The prediction was that the **wall thickness is inversely proportional to the largest angle of inflation.**

Thickness (mm)	T1 Angle (°)	T2 Angle (°)	T3 Angle (°)	T4 Angle (°)
4	22.50	32.07	41.36	**42.70**
5	18.96	29.80	34.22	36.98
6	4.96	19.85	24.18	29.90

Experiment 2: Tube Diameter

Models with **varying wall tube diameter** of **14mm**, **15mm**, and **16mm** and **uniform diameter of 5mm** were created and simulated. The hypothesis was that **diameter is inversely proportional to angle degree.**

Diameter (mm)	T1 Angle (°)	T2 Angle (°)	T3 Angle (°)	T4 Angle (°)
14	10.55	23.43	33.64	**38.88**
15	18.96	29.80	34.22	36.98
16	21.42	29.31	34.24	34.93

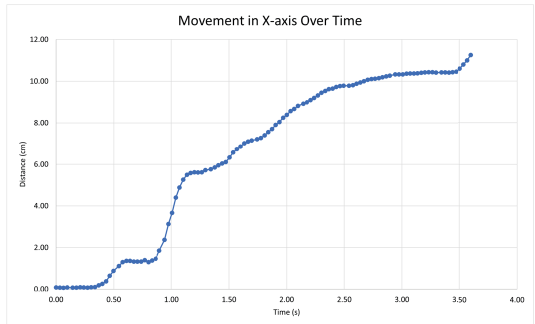


Experiment Results

Tests are ran by taking an **overhead video** of the robot with **marker** and **tracking the movement** of the marker.

One Segment Test:

Time (s)	1	2	3
Δx (cm)	1.57	2.67	3.52

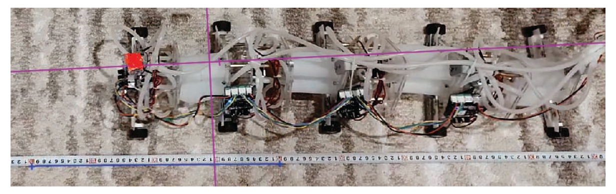


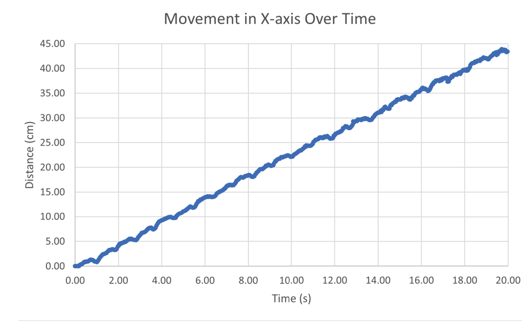
Two Segment Test:

Time (s)	1	2	3
Δx (cm)	3.66	8.49	10.33

Entire Snake Test:

Time (s)	5	10	15
Δx (cm)	11.09	22.18	33.72





Conclusion and Future Plans

Basic functionalities achieved

- **physics simulations**
- high **modularity** with **independent control units** and I2C protocol
- **remote control** with **video**
- three sets **tests** were ran

Future Plans:

- **faster** and more **agile**
- AI **image recognition**
- image-based **mapping**
- **coordinate system** to locate the snake

Without these, the robot cannot achieve its **full potential** as a **life-saving device**.