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UNIVERSITY OF CALIFORNIA SAN DIEGO

**Soft-Backboned Screw-Driven Snake Robot: Design, Shape Estimation, and Motion
Control for Challenging, Constrained Environments**

A Thesis submitted in partial satisfaction of the
requirements for the degree
Master of Science

in

Electrical Engineering (Intelligent Systems, Robotics, and Control)

by

Andrew Saad Abd El-Messih

Committee in charge:

Professor Michael Yip, Chair
Professor Nikolay A. Atanasov
Professor Vikash Gilja

2018

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The Thesis of Andrew Saad Abd El-Messih is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California San Diego

2018

DEDICATION

To my family, friends, professors, and mentors for all their support.

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ABSTRACT OF THE THESIS

Soft-Backboned Screw-Driven Snake Robot: Design, Shape Estimation, and Motion Control for Challenging, Constrained Environments

by

Andrew Saad Abd El-Messih

Master of Science in Electrical Engineering (Intelligent Systems, Robotics, and Control)

University of California San Diego, 2018

Professor Michael Yip, Chair

This thesis covers a newly developed design of a snake-like robot that has a flexible backbone, embedded shape estimation, and multi-axis control of pose and shape. Many applications require a soft-backbone snake-like robot that will non-destructively conform to its environment and yet retain active locomotion abilities. To our knowledge, such a solution does not exist as of the time of this publication. We propose a novel model which utilizes a series of discrete propulsion modules which allows us to distribute forces along the body evenly. Each module consists of a screw-like shell which is driven to provide the propulsion as well as an Inertial Measurement Unit (IMU) to obtain the orientation of each module. These segments can then be

individually manipulated to control and visualize the shape of the overall robot.

Chapter 1

Introduction

There has been increasing momentum for the usage of snake-like robots in search and rescue, pipeline inspection and maintenance, space exploration, and endoscopic surgery. This momentum is because of a snake-like robot's ability to adapt mechanically to significantly different environments or terrain. While most snake-like robots in literature feature monolithic designs with individually actuated joints, they tend to be bulky due to the density of actuators, fragile and quick to wear, as well as sensitive to environmental disturbances that require significant on-board sensing of contact. Therefore, there is a strong impetus for soft-backbone snake-like robots that can passively conform to an environment yet retain active locomotion properties.

In this thesis, we present two different sizes of a soft-backboned, screw-driven, snake robot with motion control. The only differences between the two robots are their size and the application. We present a soft-backboned, screw-driven, snake robot with motion control. However, relying on the environment to dictate robot shape between controlled segments requires a new way to derive robot pose. Furthermore, a non-modular snake-like robot can be difficult to adjust to operating in many different environments. The proposed robotic design encompasses this modularity and flexibility. One caveat of this implementation, however, is the lack of motion along the perpendicular to the ground due to the loss of individually actuated joints.

The soft-backbone gives the robot significant flexibility in motion and corners compared to the robot in development of the snake-like rescue robot “Kohga” [1]. The outer shield in the proposed robot increases the traction between the surface and the robot, which makes the robot motion smoother when compared to “Visual Sensing for Developing Autonomous Behavior” in Snake Robots [2]. A novel feature we introduced in this robot is the localization of the whole robot by segment. Since each module houses an IMU (Inertial Measurement Unit), it is possible to determine the pose of each module and infer the entire robot’s orientation. The individuality provided by this modular design allows for the robots use over many surfaces and environments. Flexible segments reduce the complexity of the robotic system by relying on the environments to dictate the shape of the robot. The main contributions of this thesis are:

1. A screw-driven soft-backbone robot design that offers passively compliant shape control and locomotion using screw propulsion.
2. Global, embedded shape estimation with a distribution of embedded, commodity IMUs (generalizable to any snake-like robot).
3. Multi-axis control of pose and shape of a snake-like robot using sequentially distributed screw modules.

1.0.1 Related Work

The research in undulating robots started in 1970. Shigeo Hirose developed a robot that mimicked the movement of a snake: Active Cord Mechanics [3]. The latest design from Hirose’s lab, ACM-R3 can perform a 3-D undulations [4].

The 1990s was the peak of the undulating robots as documented by Dowling in his Doctoral dissertation [5]. Skin serpentine is a type of snake-like robots. The first skin serpentine robot called KR-I was introduced by Hirose and Morshima in 1990 [6]. The issue with this robot was that it was huge and heavy, weighting 350 kg.

Table 1.1: Unified snake robot specifications

Power	6 V, 500 mA (per modules) 4 A (8 modules)
Data	Universal asynchronous receiver-transmitter
Sensors	3-axis Acceleration 3-axis Gyroscope Voltage Motor Current
Torque	0.99 Nm (0.73 ft-lb)
Mass	One module without backbone: 55 g Eight modules without backbone: 440 g One module with the backbone: 160 g Eight modules backbone: 1,280 g
Dimensions	One module without backbone: 44 mm Length x 32 mm Diameter One module without backbone with thread: 44 mm x 37 mm One module with backbone: 298 mm Eight modules: 2,384 mm

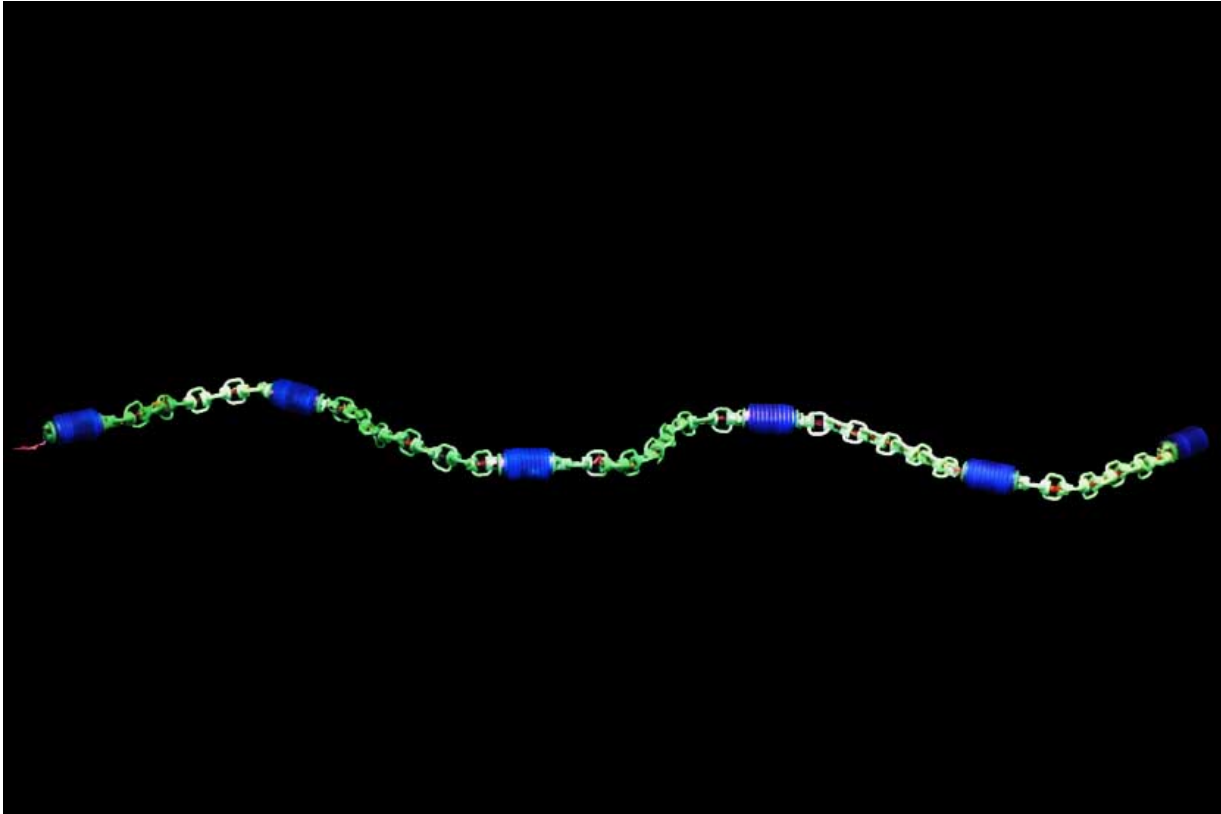


Figure 1.1: Our modular robot using six segments and featuring a soft-backbone with two degrees of freedom. The goal of this experiment is to shape an "S" letter. The length of the six modules is 1,788 mm.

Several snake-like robots have been proposed in the literature in the past several years, due to their unique mechanical design. Masayuki et al. [7] proposed, Souryu III, a connected crawler vehicle robot for inspection inside narrow and winding spaces. They connected their crawler vehicles with active joints capable of posture change. However, this method limits the length of the robot to 120 cm. The front and rear bodies swing symmetrically, with the center body between them in vertical and lateral directions by coupled drive two stable axes at the joints. Souryu III has high mobility even though it only has three degrees of freedom.

Matsuno et al. [8] developed a snake-like robot using a screw-drive unit that is connected by active joints. This design allowed the robot to generate propulsion on any side of the body in contact with the environments. This robot also introduced the idea of omnidirectional mobility by combinations of screws' angular velocity. The team also derived a kinematic model for this robot. The kinematic model helped them in reducing the commands and the control of the robot. The operators are required to command end effector. The commands for the rest of the robot are calculated automatically to track the path of the other units. The concept for this robot was reported in a patent [9].

Wright et al. [10] produced the Unified Snake Robot that typically controls the motion of the robot with gaits, cyclical controls that coordinate a system's internal degrees of freedom to produce net locomotion. Each module houses its motor and gearbox and has a custom donut-shaped connector to pass power and data between the modules. The robot has 16 degrees of freedom where each free joint alternates between vertical and horizontal movement. It has a width of 5.1 cm and a length of 94 cm.

Liljeback et al. [11] presented the snake robot, Kulko. Each module has two degrees of freedom and consists of two links supported by bearings in a steel ring. Each link has a connection point at its center that allows it to be connected to next module by two screws. The locomotion of each module is determined using a magnetic rotary encoder, motor encoder, and a force sensing resistor. Each module is driven by its servo motor that limits the Kulko to only two degrees of

freedom.

Borenstein et al. [12] introduced a variety of snake-like robots. The outside shield of each module is designed to have tracked all around each segment. The OmniTread OT-4 has a fixed length of seven segments. Six of the segments have two degrees of freedom. Each segment contains one motor that controls the traction of the external shield.

In this thesis, we propose a modular design that allows for robots any size between 28 cm to 245 cm long with a diameter of 34 cm. The modularity of the robot also allows for the control of each module separately since each module has its controller, IMU, and motor. Through the use of carefully designed backbone, this robot can also conform to complex environments. The robot tested in this thesis uses up to eight segments that give that robot up to eight degrees of freedom.

1.0.2 Applications of Snake Robots

Snake-like robots have been used in many different application in the past. Some examples include, search and rescue operation in hazardous environments, like victims of earthquakes, and information collection in unknown dangerous environment [13], as well as in pipe inspections. The design of our robot was a proof of concept for the design of our endoscopic robot for colonoscopies.

To avoid the accumulation of forces seen when performing traditional colonoscopies, a series of propulsion modules are used to distribute force. Modules are connected with flexible linkages allowing the robot to conform to its environment. In chapter 2, we will talk more in detail about the design.

1.0.3 Contribution

We have developed a functional sizeable snake-like robot. We also have a prototype of our endoscopic robot, producing a chainable robot which utilizes screw-propulsion for mobility.

As of now, each motor is directly powered, so we are unable to control the motors individually. In the future, we will integrate small circuit boards into each module which would allow more precise control. By doing this, we can begin to apply more advanced control theory to define the shape and movement of a robot comprised of multiple modules. In addition, we will start testing more complex mechanical designs by configuring multiple modules in parallel to each other. Rather than having a line of singular screws, we would test configurations similar to that used in the Screw-propelled vehicle [14]. This would allow each module to be able to easily propel itself forward or turn without the support of the environment or additional modules further down the chain. As our robot becomes more developed, we will begin consulting professionals in the UC San Diego Medical School and nearby hospitals to develop an functional robot which can be beneficial for both the patient and the doctor.

Chapter 2

Design

In our design, each module houses its own IMU, motor controller, and microcontroller. The mechanical system is comprised of an inner housing for the motor, drive gears, and electronics and an outer shell lined with external threads that are driven in order to produce motion. By alternating the direction of the threads, a net forward force propels the robot deeper into the colon. As the scope moves more in-depth, the flexible linkages allow it to naturally conform to the shape of its environment enabling the robot to traverse bends and corners easily. The relatively simple mechanical design of the system also allows the robot to be adapted to its environment easily. The outer shell can easily be replaced with custom-sized threads for different conditions. Since the drive mechanism does not require complex couplings, the limiting factor of the overall diameter of the endoscope is the size of the motor.

The following sections describe:

1. A generalized model for pose estimation of a set of sequentially chained locomotion modules with passive, soft-backbone connections,
2. A novel locomotion mechanism using external screw propulsion that is effective in unknown, constrained environments with limited sensing, and

3. Control strategies that can independently control movement and shaping.

Each propulsion module contains a motor controller and IMU, allowing for individual control and sensing. Using sensor fusion, an accurate heading of each module can be derived. These headings are then modeled as the tangents to a circle, producing an arc representing the shape formed from two modules. Chaining this model for each additional module produces an approximate shape for the entire robot. Then, by rotating propulsion modules at varying speeds, the form of the robot can be manipulated as well. By sensing the shape of the environment

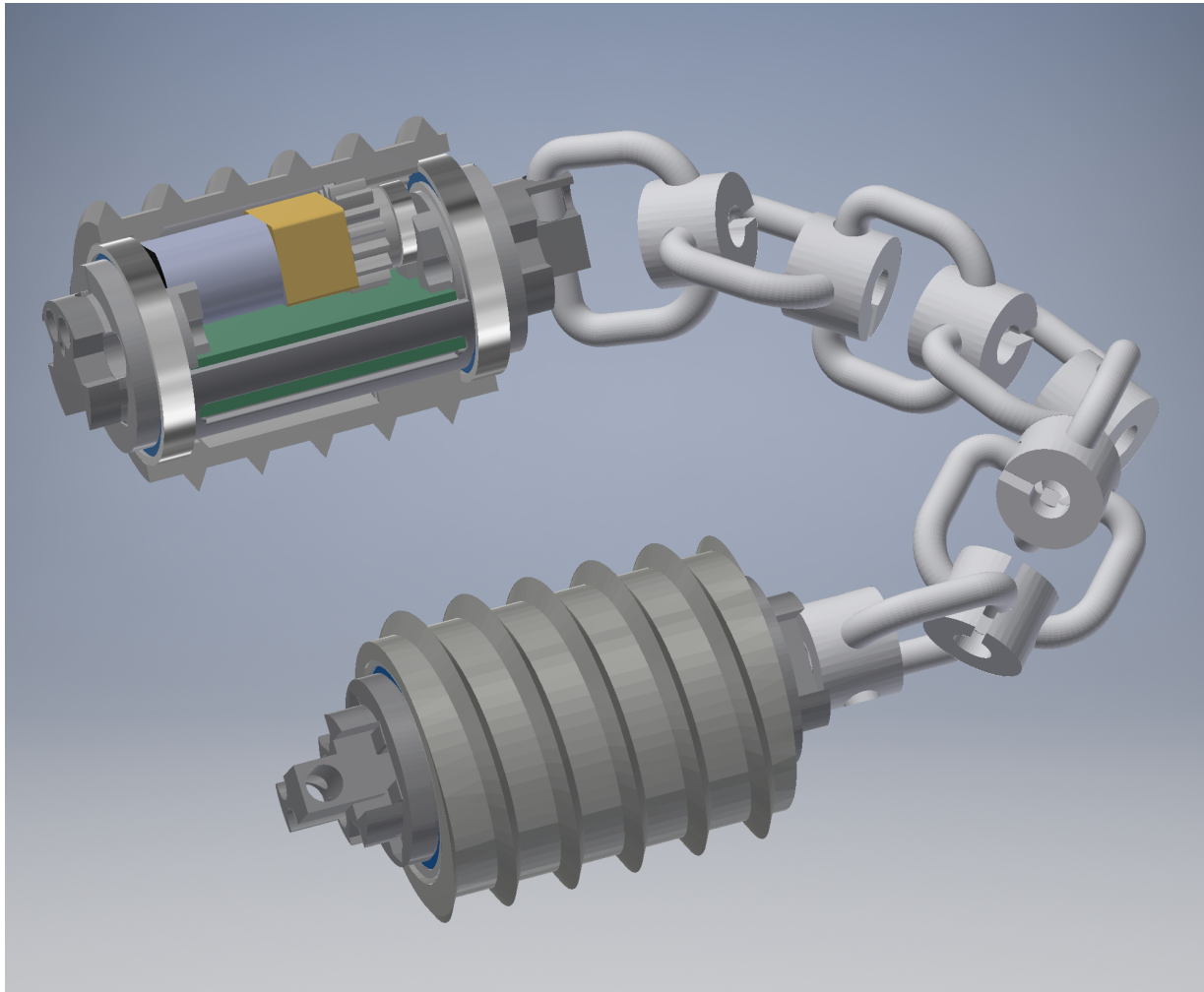


Figure 2.1: Two screw-drive unit with a cross section module (left) and a fully assembled module (right) with the backbone. The "U" shape link between the modules are designed so that the robot would have a soft-backbone.

through the robot, it becomes possible to actively manipulate the robots configuration so that it is able to progress through the test environment smoothly.

2.1 Embedded Software

Arduino was used to control each module, since the main point of this project is to have modulation and the ability to have each module fully operate separately. Using Arduino IDE, we were able to load each module with all the code needed to perform by itself fully. One of the reasons that Arduino IDE was chosen is its support, since a lot of the component used had a lot of support from the Arduino community. The library that was used for the IMU is developed by Sebastian Madgwick [15] based on a paper by T. Hamel's "A complementary filter for attitude estimation of a fixed-wing UAV" [16]. Mike Hord developed the motor drive library from SparkFun Electronics. The communication library was developed by Bill Porter's research at Naval Surface Warfare Center Panama City Division. Finding all these libraries and integrating them was not easy. These libraries were made for general use. We had to rewrite a lot of parts of these libraries to fit our requirements.

Figure 2.2 shows the maximum number of messages that we were able to send and receive per module. As expected, the number of messages decreases due to increasing parasitic capacitance. This decrease in the number of messages is anticipated as the bus state is not reset until the diode depletes its charge. As a result, this technique should not be used in large robot chains without some form of signal integrity verification or buffering. Since all of the modules are self-contained, they all execute their own PID (Proportional Integral Derivative) control loops simultaneously.

The communication scheme between the devices and the master is set up in the same way as inter-device communication as shown in Figure 2.3. To reduce the number of messages sent between devices, the devices send their heading to the master only when the last signal received

came from the last device. While this means that the update rate takes a hit as more modules are chained, it ensures that the PID loop runs at roughly the same speed with any number of modules in use. Since the master is only used for sending the desired pose to the devices and evaluating performance, there was no need to place a delay in communications to ensure stability.

The code was designed to be robust, and the same code runs on all the modules except master. The only differences between the modules are the module number defined at the beginning of the code and the IMU training. To ensure the robustness of the code, the modular programming method was used. Each part of the code was thoroughly tested with the corresponded hardware using breakup boards.

Once all the code is uploaded to the module with the module number an LED blink two

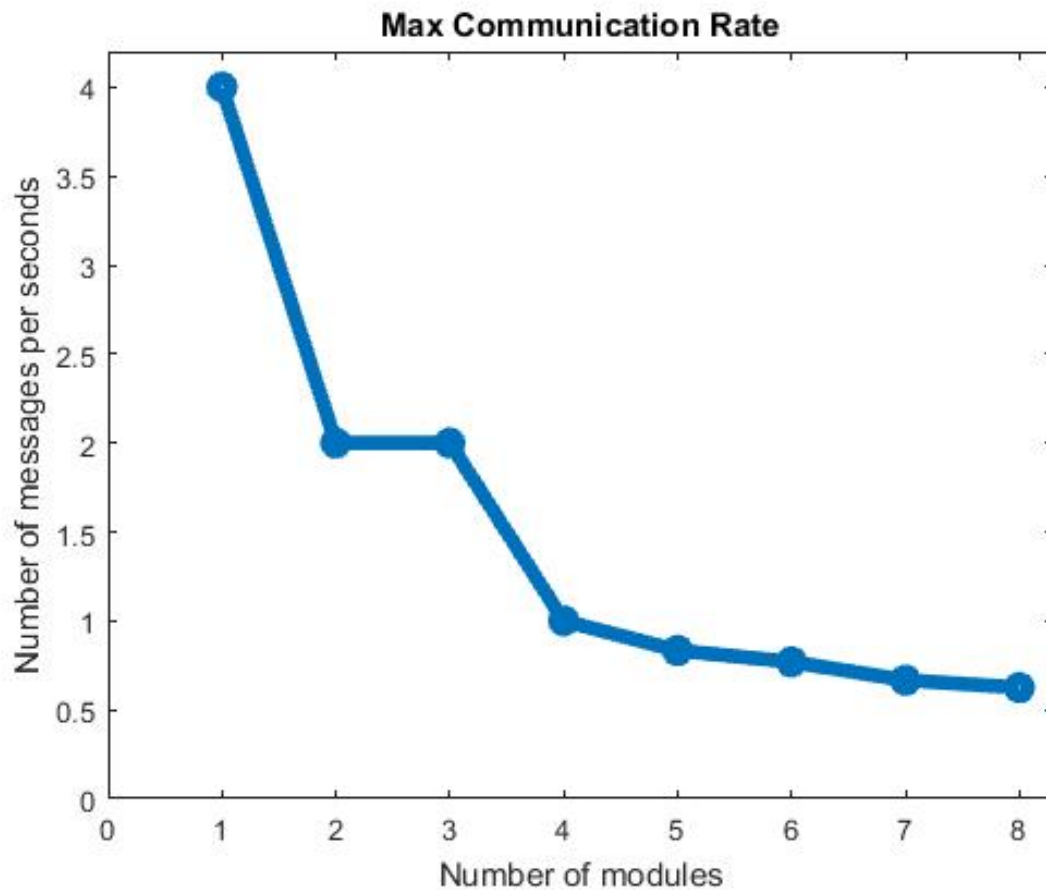


Figure 2.2: Maximum Communication rate between computer (master) and the modules (slaves)

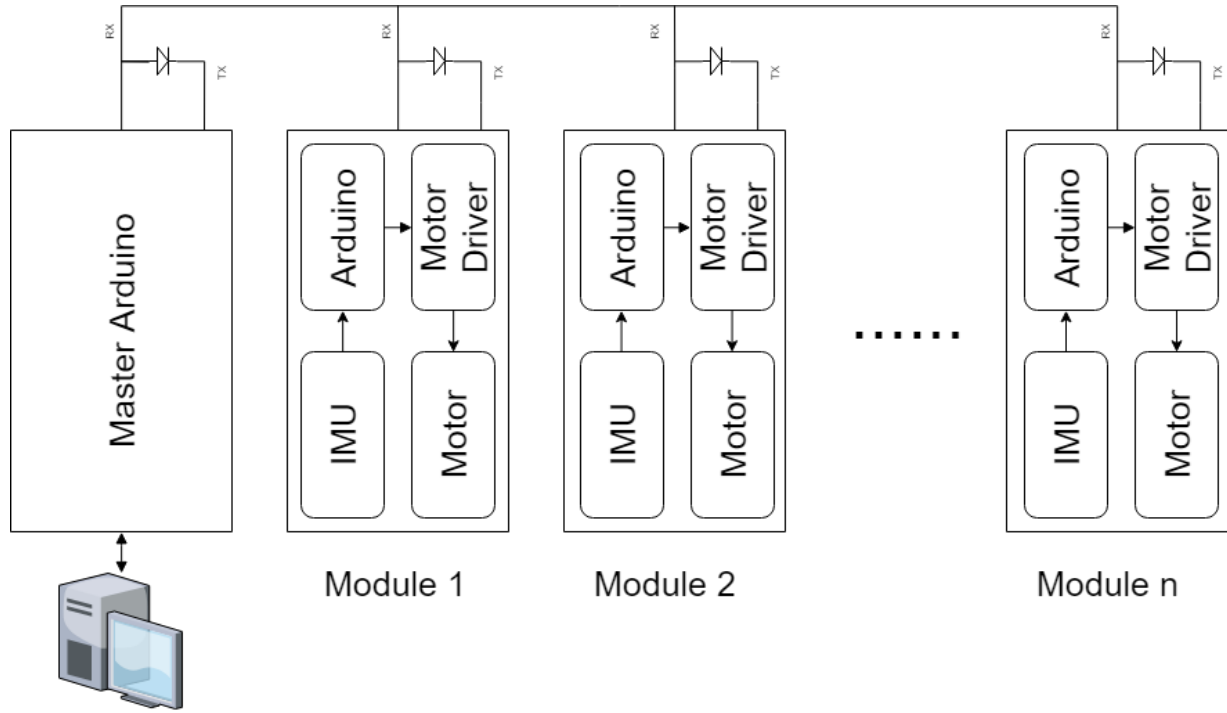


Figure 2.3: System Block Diagram. This figure shows the electronics components of each module and the method used to communicate with master.

times, which indicate that this module is ready for training. The training of each axis takes around 1-2 minutes. An LED will blink to note that this axis finished training.

Once all the modules are ready, we start chaining the modules together. The master Arduino is programmed to blink every-time a new device is connected. The number of blinking indicates the number of modules connected to master. For example, if there are four modules connected to the master, once you connect the 5th module, the LED on master should blink five times.

2.2 Mechanical Design

The robot is designed as an assortment of modular blocks which can be serially assembled to create a customized snake-like robot which can be configured and adapted to the specific environment it is exploring. In this thesis, we investigate the design, modeling, and controls of a

soft-backed, screw-driven, snake-like robot. The robot is assembled by alternating propulsion modules which define the movement of the robot, and shape-control modules which define the shape of the robot.

2.2.1 Propulsion Module

The propulsion module consists of two main areas: an inner shell and an outer shell. The inner shell houses the PCBA (Printed Circuit Board Assembly), motor, drive gear, and transitional segments. Since the drive acts similar to a planetary gear driving a ring gear, the gears are designed as such. On smaller systems where the ratio between the planetary and ring gear becomes too large and teeth cannot easily mesh correctly, we have successfully replaced the

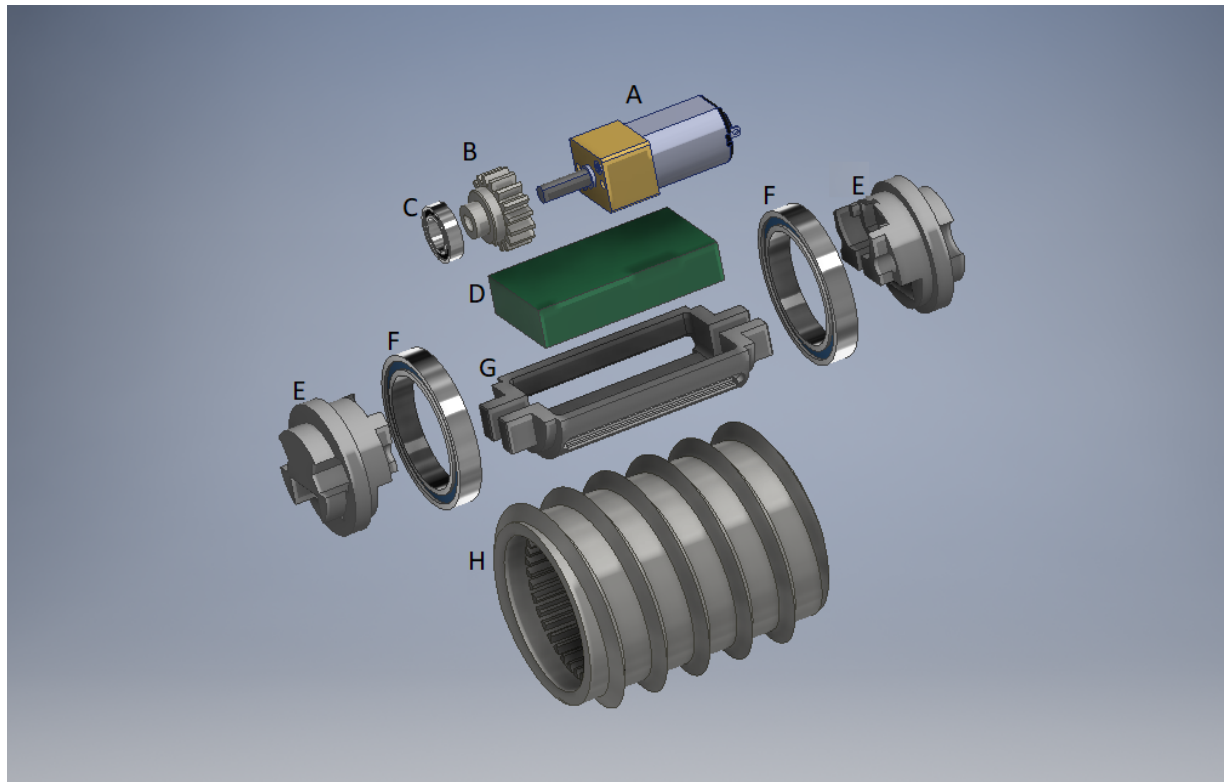


Figure 2.4: Internal Components A: DC Motor, B: Gear to connect the DC motor with the shield, C: Bearing to decrease the friction, D: PCBA, E: Transitional Segments, F: Bearing to decrease the friction with the shield, G: PCBA Housing , H: Outer shield

planetary gear with a friction drive instead. By having each propulsion module self-contained with its controller, sensors, and drive motor, we are able to reconfigure the robot as needed for the environment quickly. The only restricting factors are the initial motor and diameter selections which define the size and power of each module. The transitional segments (Figure 2.4E) of each module provide an input and an output port which are used to connect different modules serially.

2.2.2 Outer Shell Customization

The outer shells are designed to house the contents (Figure 2.4). The outer shells (Figure 2.4G) are intended to both house the contents of the inner shell (Figure 2.4A-G) and propel the robot forward. The inner face of the shell is embedded with a ring gear which the motor and drive gear mesh while the shell itself rides on a set of bearings (Figure 2.4F) to rotate. This also provides the ability to fully waterproof the propulsion module by selecting appropriate bearings and transitional segments. By using 3D printing, we can easily define the three primary design characteristics of the outer shell.

2.2.3 Diameter, Thread Pitch, and Thread Design

By using the Formlabs printer, we can print multi-material shells that have solid bodies, but can also have softer, more rubber-like threads, if needed. The diameter of the outer shell can be optimized for the environment the robot is trying to traverse. A larger diameter will increase surface area against the environment aiding movement but may make it challenging to navigate turns or tighter spaces.

Thread pitch determines the speed of movement. Since the threading is used for movement, assuming no slippage, one rotation of the outer shell will move the module forward the pitch of

the thread. Thread pitch affects [17] movement speed according to the following equation:

$$\delta = l \times d \frac{\alpha}{360^\circ} \quad (2.1)$$

where δ is the distance traveled when it is rotated with an angle α and a thread lead of l . d is the diameter of the module.

Finally, the thread design can be selected to optimize for the environment. For example, a massive, solid thread would be useful in compliant environments such as sand as it improves surface area to push against while a small, soft or rubbery-like thread would be helpful to in delicate situations.

2.3 PCB Design

Each module contains one of our designed Printed Circuit Boards, and an Arduino mini as shown in Figure 2.4 D. A PCB was designed with the size of 700 x 1700 mils to control each segment individually. The designed PCB goes on top of an Arduino Mini Pro (3.3V - 8 Mhz) that was designed by SparkFun [18]. The PCBs were designed using Altium Designer. Each PCB contains 16 passive components, a motor driver (DRV 8830 [19]), IMU (LSM9DS1 [20]). Each module has internal communication and external communication. I2C is used to communicate internally between the IMU, motor driver, and the micro-controller. A universal asynchronous receiver/transmitter (UART) is used to communicate with the other modules as shown in Figure 2.3. To reduce the wires between the modules, the EasyTransfer communication method [21] is used. Each module has three wire connection between the modules: 5V, RX (from the UART connection), and ground. Since each Arduino Mini Pro has its own voltage regular with a maximum input voltage of 16V [22]; we don't add an external component to regulate the voltage to 5V. Each PCB has five connections the to Arduino Mini Pro (3.3V, Ground, 5V, and the two I2C lines) as shown in Figure 2.6.

2.4 Embedded Control

In other designs, 2 DOF u-joints are used as shape-control segments to create a fully actuated snake-like robot. Our approach utilizes a passive soft backbone which allows the robot to change shapes according to its environment naturally. In a scenario such as a pipe inspection, the robot is well constrained by its environment, allowing more straightforward controls than a fully actuated robot. Alternatively, in a delicate environment such as navigating through the intestines without damaging any tissues, the soft backbone allows the snake-like robot to reshape itself through the complicated twists naturally and turns it may encounter without risk of exerting significant forces. The flexible backbone acts as a connection between the propulsion modules that help define the overall shape of the robot while leaving it flexible and adaptable to the environment without additional controls.

The most important property of the backbone is that it needs to be torsionally stiff. Since the movement of the robot is produced by rotating the outer shells, the center line of inner shells and backbones must remain torsionally rigid so that the robot does not twist itself. Since movements in three dimensions are not required and may impede robot movement, the backbone should be designed such that it prevents rotation of the connected modules and allows for enough movement in the desired axes. For the robot examined in this thesis, the backbone was designed with two degrees of freedom in mind. While this robot is designed to travel only using a single degree of freedom, by leaving some slack in the direction perpendicular to the main direction of motion, the robot would be less likely to lock up under a situation where there is a small change along the y-axis in the environment while the robot was moving.

Each propulsion module contains a motor controller and a 9 DOF IMU to allow for individual control and sensing. For notation purposes, let α_i and β_i be the estimated roll and pitch of the device as shown in Figure 2.5, $\mathbf{a} = [a_x, a_y, a_z]$ be the accelerometer readings vector and $\mathbf{g} = [g_x, g_y, g_z]$ be the gyroscope readings vector given at time t . The fusion scheme used for each

module uses accelerometer and gyroscope readings from the IMU to derive the initial orientation of the robot using Eq. 2.2 and Eq. 2.3 [23] .

$$\alpha_i = \arctan \frac{a_x}{a_z}, \quad \alpha \in [-\pi, \pi] \quad (2.2)$$

$$\beta_i = \arctan \frac{-a_x}{a_y \sin \alpha_i + a_z \cos \alpha_i}, \quad \beta \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right] \quad (2.3)$$

In order to increase robustness, the gyroscope readings are filtered using a running average to generate $\bar{\mathbf{g}} = [\bar{g}_x, \bar{g}_y, \bar{g}_z]$ and fused together with the initial pose estimate using a complementary filter with averaging parameter κ of form Eq. 2.4 [24].

$$\beta_{c,t} = (1 - \kappa)(\beta_{c,t-1} + \bar{g}_y \Delta_t) + \kappa \beta_{i,t} \quad (2.4)$$

This generates a much more accurate value for the pose that is resistant to gyroscope drift and accelerometer noise provided the time between samples Δ_t is sufficiently small. As a rule of thumb,

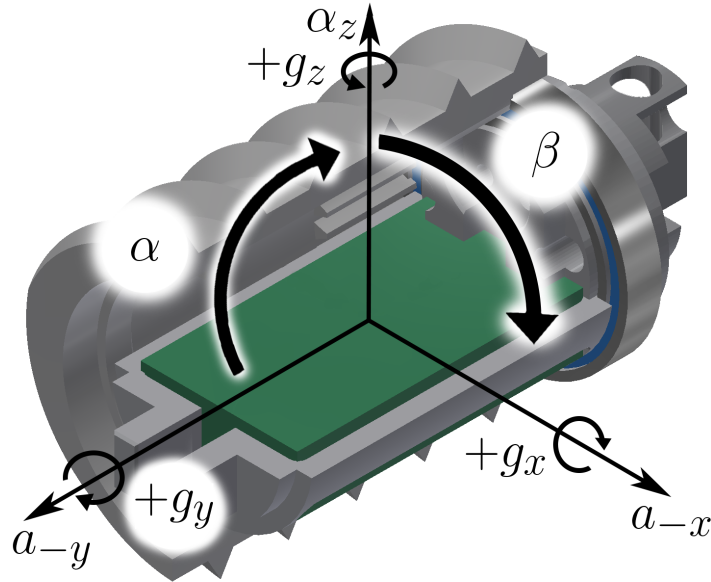


Figure 2.5: The reference roll and pitch angles defined with respect to the robot's accelerometer axes. Directions of positive angular change are also indicated.

the averaging parameter, κ , can be approximated using Eq. 2.5 by finding a reasonable time constant, τ , for which higher frequencies will be smoothed and adjusting as needed thereafter [23].

$$\kappa = \frac{1}{1 + \frac{\tau}{\Delta t}} \quad (2.5)$$

Given the initial pose of the device, these filtered gyroscope readings ($\bar{\mathbf{g}}$) are then integrated over time to calculate the current posture of the device. Since there is no motion along the z-axis of the device, the rate of rotation for the device is equal to the sum of the filtered x- and z-axis angular velocities. Given this, the total change for the heading of the device is the integral of these angular velocities over time with a significant change that depends on the orientation of the device. Since this method's initial reference is produced as a Euler angle constrained between $-\frac{\pi}{2}$ and $\frac{\pi}{2}$, care must be taken for situations where the device may flip. To address this, there is an additional integration loop for the filtered y-axis angular velocity under conditions where there may be uncertainty in the position of the device.

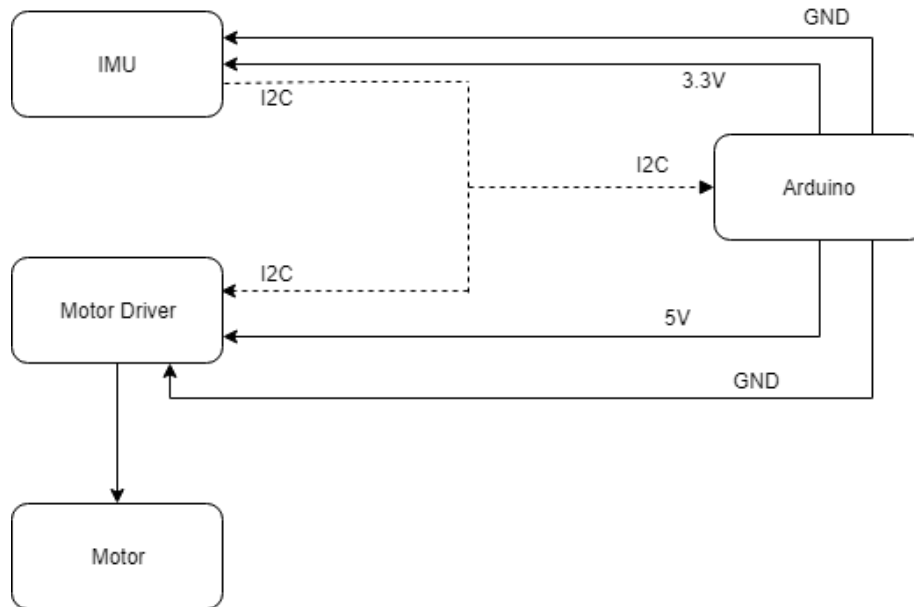


Figure 2.6: PCB Internal Block Diagram. This figure shows the internal connection between electronics components of each module.

These headings are then modeled as the tangents to a circle, producing an arc representing the shape formed from two modules as shown in (Figure 2.8) . Chaining this model for each additional module produces an approximate shape for the entire robot. Then, by rotating propulsion modules at varying speeds, the form of the robot can be readily manipulated. By sensing the form of the environment through the robot, it becomes possible to actively manipulate the robots shape such that it's able to progress through a colon smoothly.

2.5 Kinematic Model

Each propulsion module contains a motor controller and a 9 degrees of freedom IMU allowing for individual control and sensing. Using sensor fusion, an accurate heading of each module can be derived. These headings are then modeled as the tangents to a circle, producing an arc representing the shape formed from two modules. Chaining this model for each additional module produces an approximate shape for the entire robot. Then, by rotating propulsion modules at varying speeds, the shape of the robot can be manipulated as well. By sensing the configuration of the environment through the robot, it becomes possible to actively manipulate the robots shape so that it is able to progress through smoothly.

As seen in Figure 2.8, the robot's overall pose can be estimated using Equation 2.16 - 2.17 with the desired base angle with respect to the origin, x_i , the position of the module the along the x-axis, and y_i , the position of the module in the Y direction, are known for all i devices that make up the robot.

2.5.1 Mathematical Analysis

Let $\Delta\theta$ be the difference in the i -th and $(i - 1)$ -th angle defined from the x-axis.

$$\Delta\theta = \theta_i - \theta_{i-1} \quad (2.6)$$

Where θ_i is the current angle and θ_{i-1} is the previous angle.

Let r be the radius of the circular arc, it is related to the length of the arc l by

$$r = \frac{l}{\Delta\theta} \quad (2.7)$$

where l is the length between the modules.

Let $R(\Delta\theta)$ be the rotation matrix

$$R(\Delta\theta) = \begin{bmatrix} \cos(\Delta\theta) & -\sin(\Delta\theta) \\ \sin(\Delta\theta) & \cos(\Delta\theta) \end{bmatrix} \quad (2.8)$$

Let $\vec{r}_i$ be the position vector of the i -th module. We can easily find the position of the i -th module from the position of the $(i-1)$ -th module by transforming our coordinates by shifting the origin of the original coordinate system to the center of the circular arc, then applying a rotation and shifting back to the original system of coordinates.

$$\vec{r}_i = \vec{r}_c + R(\Delta\theta)(\vec{r}_{i-1} - \vec{r}_c) \quad (2.9)$$

The difference in the positions of the $(i-1)$ -th module and the center of the arc can be related by

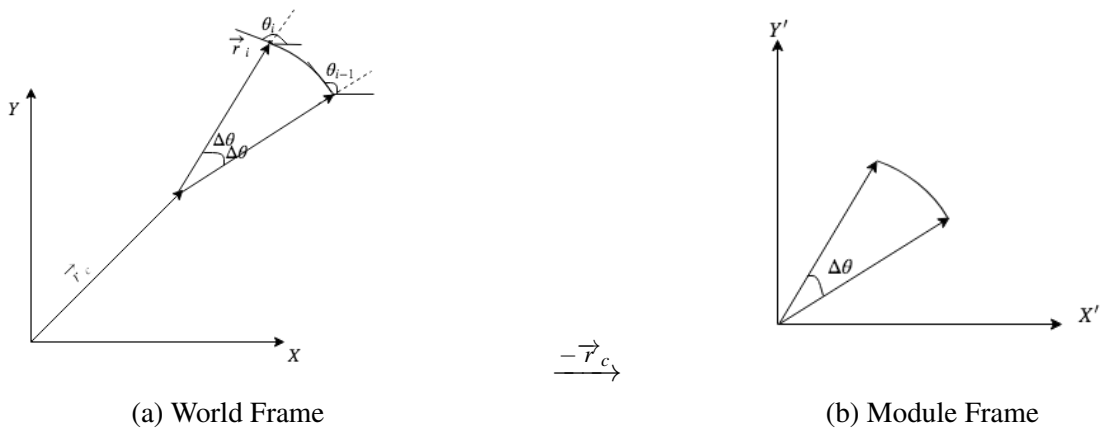


Figure 2.7: Definition of coordinate variables

using elementary trigonometry.

$$\vec{r}_{i-1} - \vec{r}_c = \frac{l}{\theta_i - \theta_{i-1}} \begin{bmatrix} \sin(\theta_{i-1}) \\ -\cos(\theta_{i-1}) \end{bmatrix} \quad (2.10)$$

replacing $\vec{r}_c$ in the first term of the right hand side of Eq. (2.9) using Eq. (2.10)

$$\vec{r}_i = \vec{r}_{i-1} + \frac{l}{\theta_i - \theta_{i-1}} \begin{bmatrix} -\sin(\theta_{i-1}) \\ \cos(\theta_{i-1}) \end{bmatrix} + R(\Delta\theta)(\vec{r}_{i-1} - \vec{r}_c) \quad (2.11)$$

from Eq. (2.8) and Eq. (2.10):

$$R(\Delta\theta)(\vec{r}_{i-1} - \vec{r}_c) = \frac{l}{\Delta\theta} \begin{bmatrix} \cos(\Delta\theta)\sin(\theta_{i-1}) + \sin(\Delta\theta)\cos(\theta_{i-1}) \\ \sin(\Delta\theta)\sin(\theta_{i-1}) - \cos(\Delta\theta)\cos(\theta_{i-1}) \end{bmatrix} \quad (2.12)$$

Using Ptolemys identities

$$R(\Delta\theta)(\vec{r}_{i-1} - \vec{r}_c) = \frac{l}{\Delta\theta} \begin{bmatrix} \sin(\theta_i) \\ -\cos(\theta_i) \end{bmatrix} \quad (2.13)$$

From Eq. (2.11) and Eq. (2.13)

$$\vec{r}_i = \vec{r}_{i-1} + \frac{l}{\theta_i - \theta_{i-1}} \begin{bmatrix} -\sin(\theta_{i-1}) \\ \cos(\theta_{i-1}) \end{bmatrix} + \frac{l}{\theta_i - \theta_{i-1}} \begin{bmatrix} \sin(\theta_i) \\ -\cos(\theta_i) \end{bmatrix} \quad (2.14)$$

$$\begin{bmatrix} x_i \\ y_i \end{bmatrix} = \begin{bmatrix} x_{i-1} \\ y_{i-1} \end{bmatrix} + \frac{l}{\theta_i - \theta_{i-1}} \begin{bmatrix} -\sin(\theta_{i-1}) \\ \cos(\theta_{i-1}) \end{bmatrix} + \frac{l}{\theta_i - \theta_{i-1}} \begin{bmatrix} \sin(\theta_i) \\ -\cos(\theta_i) \end{bmatrix} \quad (2.15)$$

Alternatively, rearranging Eq. (2.15):

$$x_i = x_{i-1} + \frac{l}{\theta_i - \theta_{i-1}} [\sin(\theta_i) - \sin(\theta_{i-1})] \quad (2.16)$$

$$y_i = y_{i-1} + \frac{l}{\theta_i - \theta_{i-1}} [\cos(\theta_{i-1}) - \cos(\theta_i)] \quad (2.17)$$

where x_i is distance traveled in the X direction, y_i is distance traveled in the Y direction, θ_i is the current angle in radian of the current module, θ_{i-1} is the angle in radian of the previous module, r_i is the radius of the circle, and l is the length of the backbone.

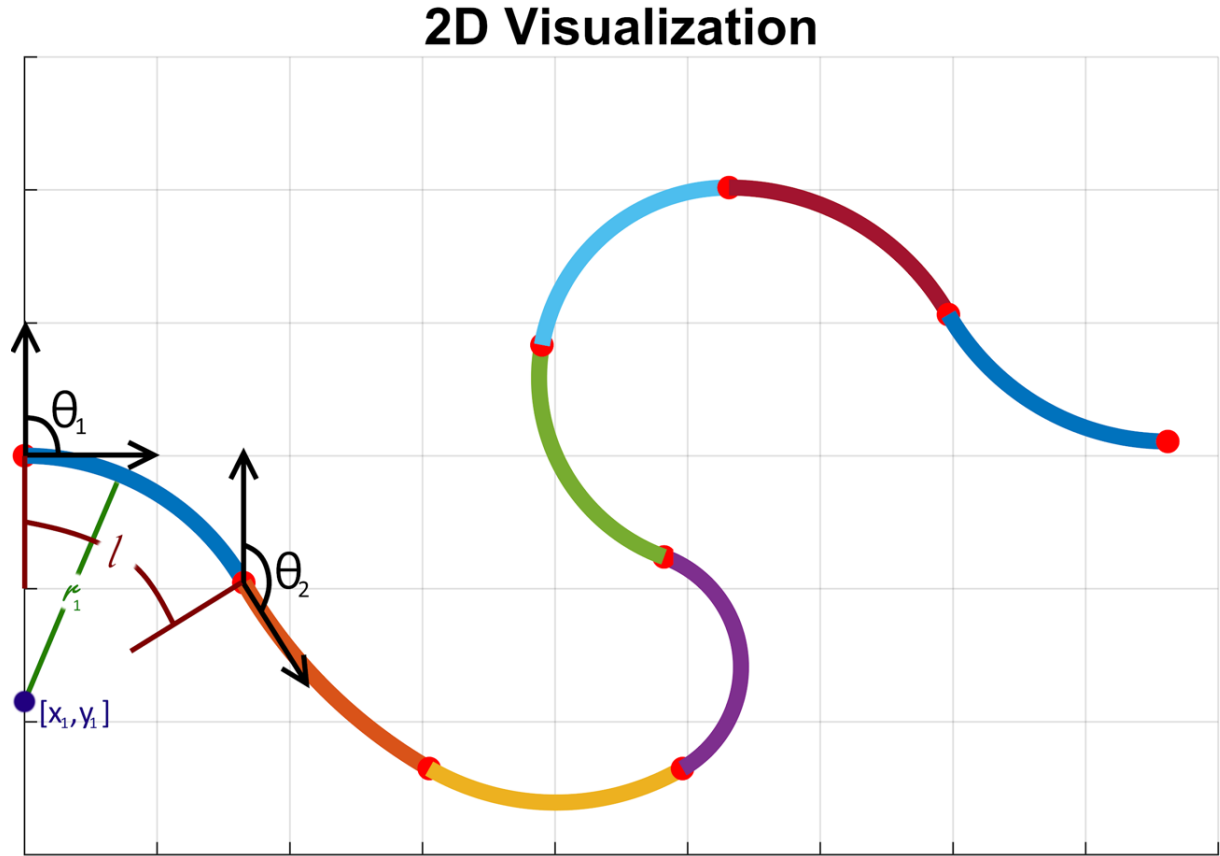


Figure 2.8: Robot 2D Visualization. Each red dot represents a segment and the colored tube between them represents the soft-backbone.

2.6 Filtering

In our implementation, the magnetometer readings were ignored due to substantial interference from the running motors. Without a metal shielding around the motor, the magnetometer values saturated and contributed nothing to pose estimation. However, even with a mu-metal shielding, the offset would leave only after careful calibration far away from any sources of metal and still change within the same environment.

2.6.1 Filtering Overview

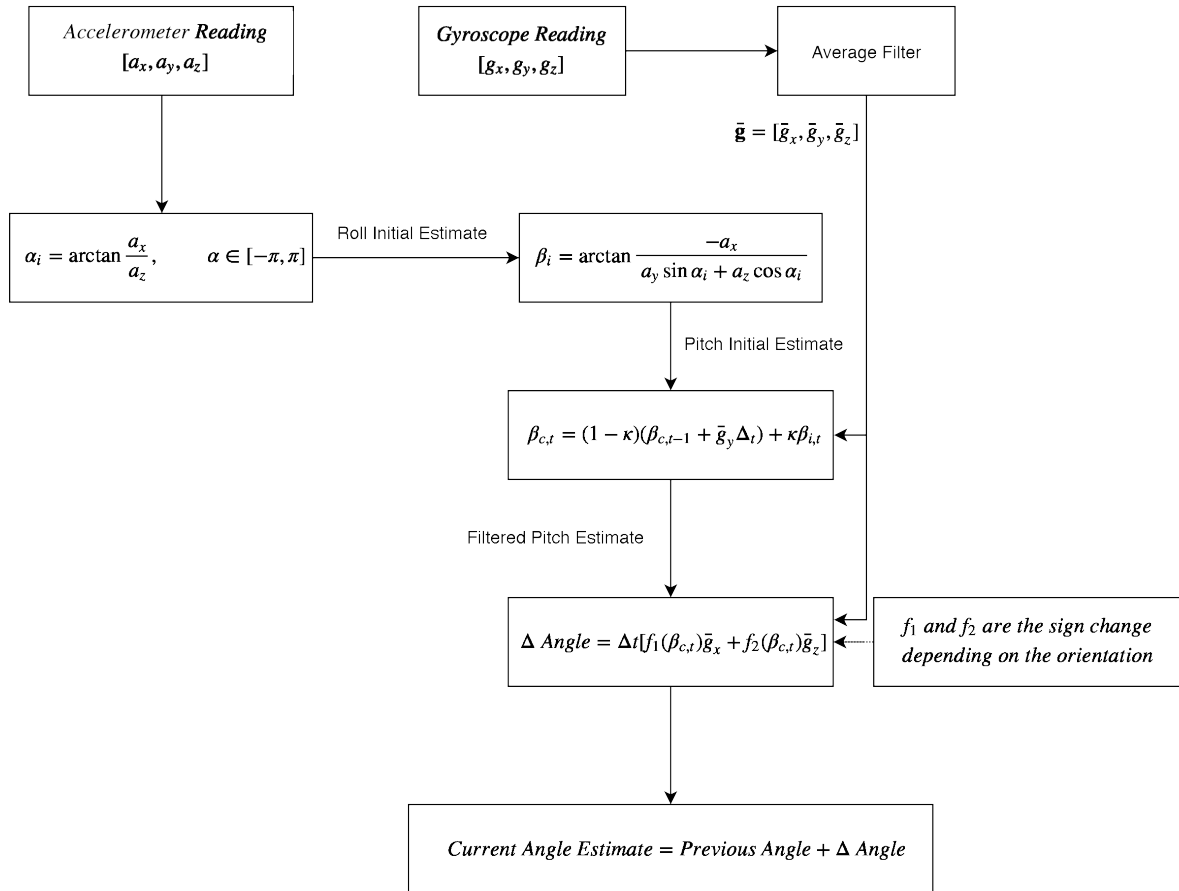


Figure 2.9: This flow diagram represents the filtering steps from raw data to calculate the current angle.

In Figure 2.9, we are representing the method used to calculate the current angle position. In Equation 2.18, the Gyroscope raw data goes into an Average Filter. The filter Gyroscope $\bar{g}$ goes into Equation 2.19, which help us to calculate the roll initial estimate. Using the initial roll estimate and the accelerometer data, we were able to calculate Pitch initial estimate using Equation 2.20. Using the angle complementary filter Equation 2.4, we can calculate the filter pitch estimate. Fusing the filtered pitch estimate with the average filtered, and a function for orientation, we were able to calculate the change in angle. By adding the change in angle to the previous angle, we get the current angle.

2.6.2 Average Filter

As the name implies, the moving average filter operates by averaging many points from the input signal to produce each point in the output signal:

$$y[i] = \frac{1}{M} \sum_{j=0}^{M-1} x[i+j] \quad (2.18)$$

Where x is the input signal, y is the output signal, j is the index, i is the point, and M is the number of points in the average. The derivation of Equation 2.18 is provided by Smith et al. [25] and excluded from this thesis.

2.6.3 Roll Estimation

Roll is the rotation of the robot on the front to back axis. The roll estimation helps us in calculating the Pitch Estimate, which allows us to calculate the rotation angle of the robot. LaValle et. al. [26] explains that every tilt error can be described as a rotation about an axis that lies in the horizontal XZ plane. To calculate the axis, we have to project $\hat{a}$ into X Z plane to obtain $(\hat{a}_x, 0, \hat{a}_z)$. The tilt error α_i is the angle between $\hat{\alpha}$ and the vector $(0,1,0)$ as shown in Figure 2.10.

The Roll Estimation is computed using the following equation [23]:

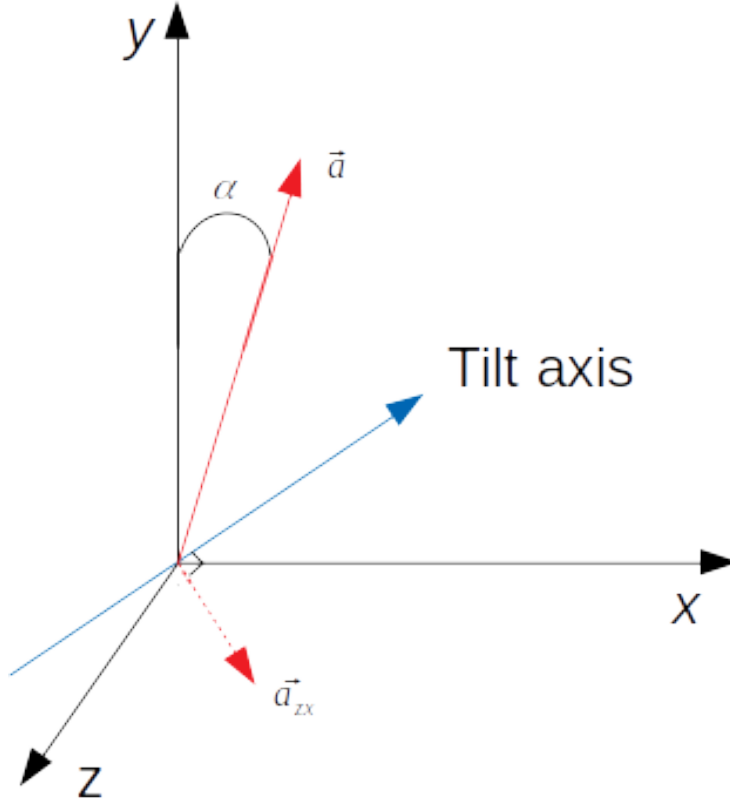


Figure 2.10: Tilt error angle α_i .

$$\alpha_i = \arctan\left(\frac{a_x}{a_z}\right) = \arctan2[a_x, a_z], \quad \alpha \in [-\pi, \pi] \quad (2.19)$$

where a_x is the IMU acceleration reading in the X-direction and a_z is the IMU acceleration reading in the z-direction. The derivation of Equation 2.19 is provided by Pedley et al. [23] and excluded from this

2.6.4 Pitch Estimation

Pitch is the rotation of the robot fixed between the side to side axis. The pitch estimation helps us to estimate the rotation of the robot. Pitch estimation is calculated relating the roll

estimation and the acceleration data using the following equation:

$$\beta_i = \arctan\left(\frac{-a_x}{a_y \sin \alpha_i + a_z \cos \alpha_i}\right) = \arctan2[-a_x, a_y \sin \alpha_i + a_z \cos \alpha_i], \quad \beta \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right] \quad (2.20)$$

where a_x is the IMU acceleration reading in the X-direction, a_y is the IMU acceleration reading in the Y-direction, a_z is the IMU acceleration reading in the z-direction, and α is the roll estimation. The derivation of Equation 2.20 is provided by Pedley et al. [23] and excluded from this thesis.

2.6.5 Filtered Pitch

A Complementary filter was implemented to fusion the accelerometer and the gyroscope data to calculate the pitch. The Complementary filter is composed of a low-pass and a high-pass filter [27]. The low-pass filter allows only the long-term changes go through and filter out the short-term changes. The high-pass filter allows only the short-term changes go through and filter out the long-term changes. The following equation was used to calculate the filtered pitch:

$$\beta_{c,t} = \underbrace{(1 - \kappa) \underbrace{(\beta_{c,t-1} + \bar{g}_y \Delta_t)}_{\text{Integration}}}_{\text{High-pass filter}} + \underbrace{\kappa \beta_{i,t}}_{\text{Low-pass portion}} \quad (2.21)$$

where $\bar{g}_y$ is the gyroscope filtered data, Δ_t is the change in time, κ is the time constant of a filter is the relative duration of signal it will act on, and $\beta_{i,t}$ is the initial pitch estimate. The derivation of Equation 2.21 is provided by Colton, et al. [28] and excluded from this thesis.

2.6.6 Change in Angle

Change in angle is the difference between the previous angle position and the current angle position. The change in angle is calculated using the following equation:

$$\Delta Angle = \Delta t [f_1(\beta_{c,t})\bar{g}_x + f_2(\beta_{c,t})\bar{g}_z] \quad (2.22)$$

Where Δt is the change in time, $\beta_{c,t}$ is the filtered pitch estimate, and f_1 and f_2 are two functions that to determine the significant change in case of the flip of the inner body of the module.

2.7 Graphic User Interface

A graphic user interface (GUI) was developed to control the modules. The GUI was developed using Python. The GUI is divided into two sections “Robot Objective” and “Current Robot Position”. The “Robot Objective” is used to simulate the shape of the robot. Under the simulation box, there are eight boxes. The user enters the value of the angle of each module in these boxes. Once all the values are entered, the user can press “Simulate.” An error message will pop-up if the user enters an invalid value or missed a value. The MATLAB Robotics Toolbox by Peter Corke [29] was used to plot the simulation. Once the shape is ready, the user presses “Submit” and the robots will start to move to format the shape. Under the “Current Robot Position,” the user can read the angle value. The start time, end time, start angle value, desire angle value, end angle value, and module number are saved into a Comma Separate Value (CSV) file. These CSV files were used to calculate the results of each simulation. A serial communication window was made to read all the serial communication with the modules. The serial communication was used to debug any problem or error. The Python TKinter [30] was used to build this GUI. This interface is developed to control the big modules and the small modules since both modules communicate using the same method.

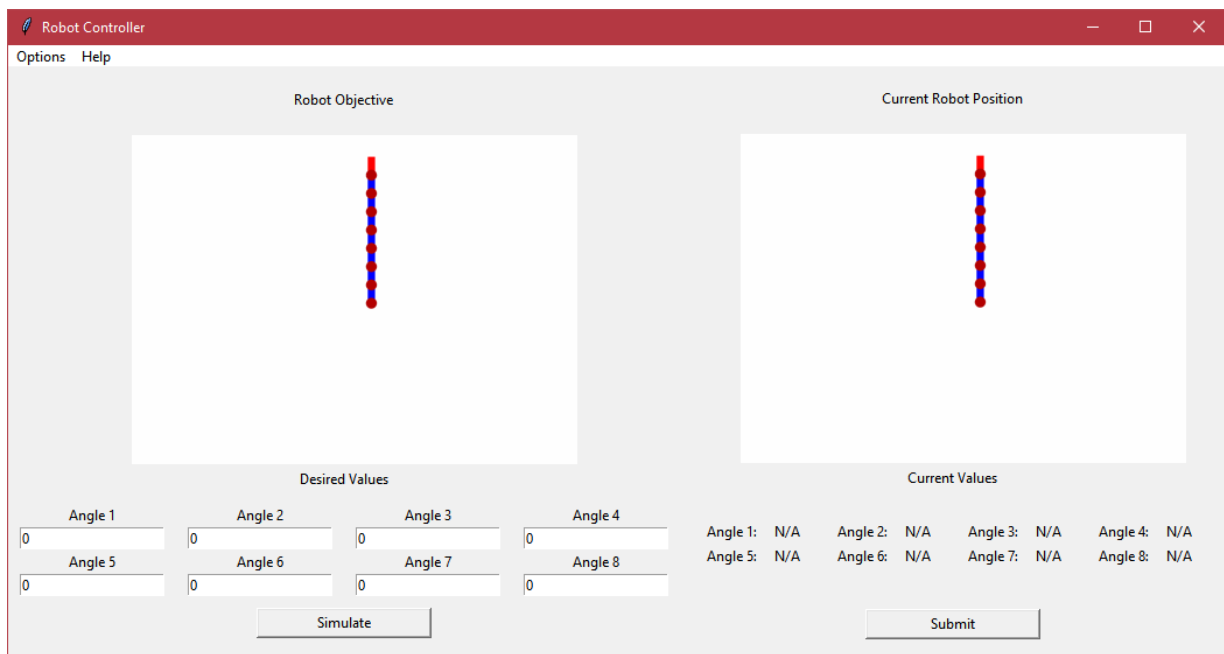


Figure 2.11: In the GUI, the left side represents the simulation of the angles below the graphs. The right side represents the readings from robot.

Chapter 3

Experiments and Results

This section presents the results of data gathered using the proposed robot of chain lengths two, four, six, and eight. In table 3.1, we can see that the robot benefits from a gain value high enough to ensure that the motor throttle speed is higher than the minimum needed for movement around 1 degree. It is important to note, however, that higher equal gain values would lead to slight instability, as shown with the $K_p = 20$. Lower or more upper values were unnecessary to test as they pointed to either significant variability or were unable to converge to the trajectory with a satisfactory rate and duration.

Figure 3.1 two different K_p values with the standard deviation error. For $K_p = 5$, the two modules standard deviation is ± 1.4 ; the four modules standard deviation is ± 1.2 , the six modules standard deviation is ± 1.5 , and the eight modules standard deviation is ± 1.7 . The average standard deviation for ± 1.45 . For $K_p = 20$, the two modules standard deviation is ± 0.2 , the four modules standard deviation is ± 0.15 , the six modules standard deviation is ± 0.3 , and the eight modules standard deviation is ± 0.48 . The average standard deviation for ± 0.306 .

Figure 3.2 shows the settling time of all four different set-ups. Figure 3.2, the two modules have the fastest settling time of 10 seconds since there are only two modules that need to move. The four modules have the highest settling time of 30 seconds. This value is not expected. The

Table 3.1: Results with different PID Values. All tests were performed with 2 modules and desired orientation is 45° and 45° . β_{err} is the difference between the desired angle and goal.

NUMBER OF MODULES	K_p VALUE	SETTLING TIME (SECONDS)	β_{err}
2	5	18	$2.00^\circ \pm 1.41^\circ$
	10	8	$1.125^\circ \pm 0.176^\circ$
	15	15	$0.87^\circ \pm 0.505^\circ$
	20	10	$0.42^\circ \pm 0.254^\circ$
4	5	49	$1.36^\circ \pm 1.24^\circ$
	10	28	$1.07^\circ \pm 0.464^\circ$
	15	15	$0.69^\circ \pm 0.505^\circ$
	20	29.8	$0.40^\circ \pm 0.156^\circ$
6	5	42	$2.23^\circ \pm 1.70^\circ$
	10	22.6	$1.70^\circ \pm 2.21^\circ$
	15	16.91	$0.43^\circ \pm 0.309^\circ$
	20	12.45	$0.463^\circ \pm 0.339^\circ$
8	5	41	$2.57^\circ \pm 1.63^\circ$
	10	23.2	$1.87^\circ \pm 3.12^\circ$
	15	18.7	$0.42^\circ \pm 0.406^\circ$
	20	12.62	$0.45^\circ \pm 0.489^\circ$

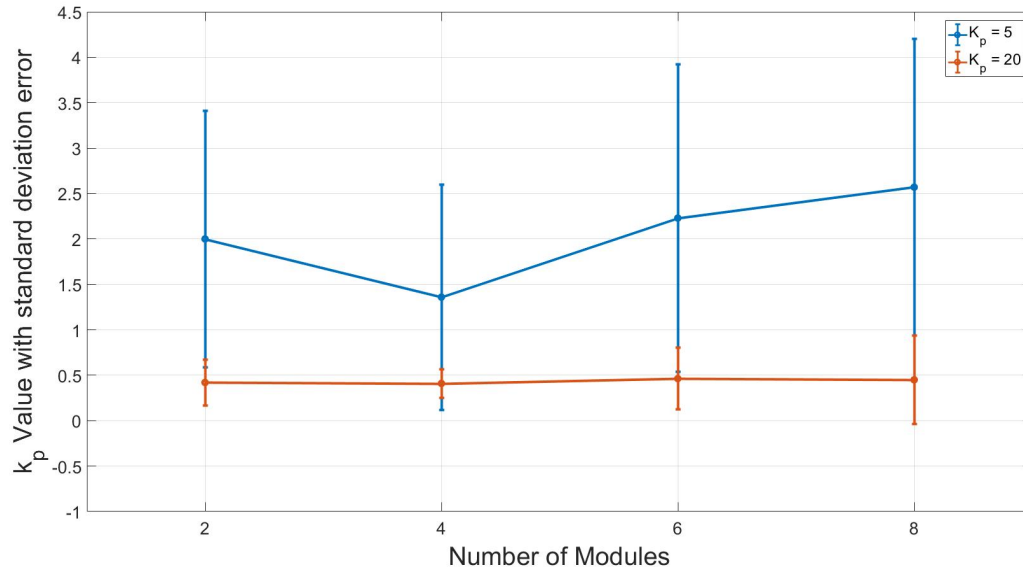


Figure 3.1: This plot represents the different value of K_p . The blue bars are the values for $K_p = 5$ and the red bars values for $K_p = 20$

six modules have the settling time of 12.4 seconds. The eight modules have the settling time of 12.6 seconds. Except for the four modules, we can see that the more modules, the higher the settling time.

From Figure 3.1 and Table 3.1, we can see that k_p value of 20 is the most optimized k_p for our set-up. k_p value of 20 has the lowest settling time of an average of 16 seconds and most accurate with angle standard deviation error of ± 0.306 .

As seen in Figure 3.3 and 3.4, most of the benefit from the filtering came from the filtered gyroscope readings when generating the module heading. Although the fused pitch values benefited slightly from the complementary filter, the filtered pitch values were only used to determine a rough idea of the current orientation (Roughly 8° difference.) This 8° wouldn't make a bit difference due to the rate at which the device traveled. Furthermore, note that when tested with a fixed movement of 90° , there was an additional error due to minor errors from initial filtering that amounted to $4.25 \pm 2.75^\circ$ of error with the motors at max speed. This error was minor on low rates, accounting for only $1.16 \pm 0.854^\circ$ of the final heading estimate.

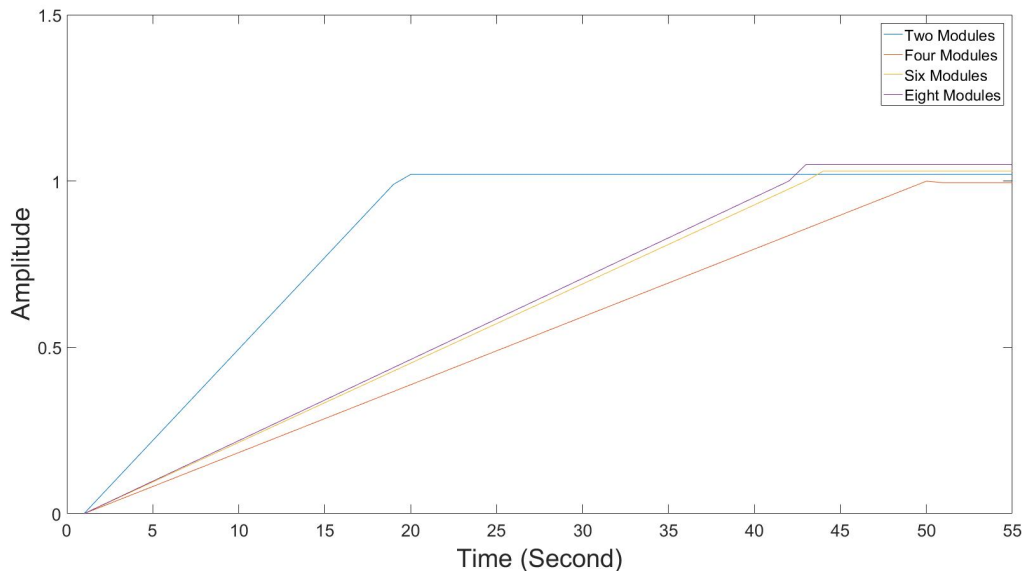


Figure 3.2: This plot represents the settling time of the robots. The data represent four different experiences: Two modules, four modules, six modules, and eight modules.

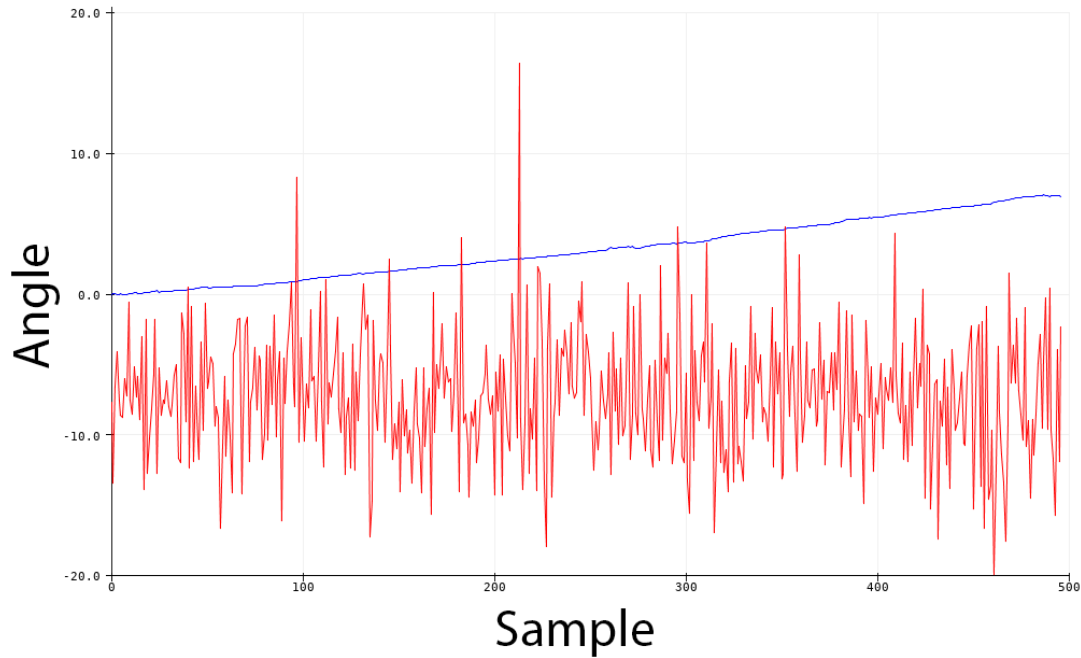


Figure 3.3: Sample of values fused directly from the unfiltered accelerometer and gyroscope readings. The heading can be seen drifting in blue, and the pitch can be seen oscillating in red.

Figures 3.5 to 3.8 show the data comparing the robot simulation and experiment data. On the left (Figures 3.5 - 3.8 a) show the results for our simulation, which is the shape that we are expecting. On the right (Figures 3.5 - 3.8 b) show the results for the robot position. For Figure 3.5, we are comparing two modules. The error difference between the simulation and the experiment is $\pm 1.2^\circ$. For figure 3.6, we are comparing four modules. The error difference between the simulation and the experiment is $\pm 1.4^\circ$. For Figure 3.7, we are comparing six modules. The error difference between the simulation and the experiment is $\pm 1.7^\circ$. For Figure 3.8, we are comparing eight modules. The error difference between the simulation and the experiment is $\pm 1.8^\circ$. Even that the previous data shows a very low angle error. Figures 3.5 - 3.8 b show that the robots have high angle error. We can see that the error is cumulative when we add more modules.

One recurring phenomenon occurring during the robot's movement was a drop in voltage on the power and serial lines. While the serial lines were still capable of adequate throughput

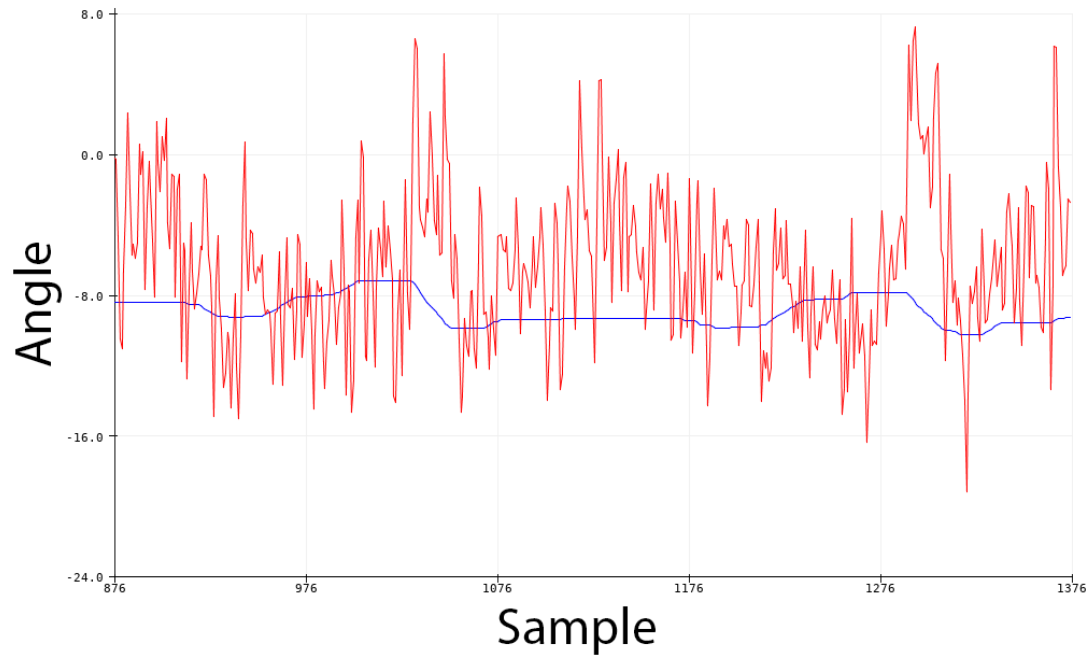


Figure 3.4: After filtering the gyro values using a running average and fusing along with initial estimates using $\kappa \approx 0.5$, the now stabilized heading can be seen in blue and the pitch in red.

up until eight modules, the power line suffered from a transmission line effect especially during sequences of high power draw from motors closer to the power supply. This is sure to become an issue as more modules are chained. Further testing and consideration of extended DC power lines will be needed to identify at which point this will prevent further module chaining.

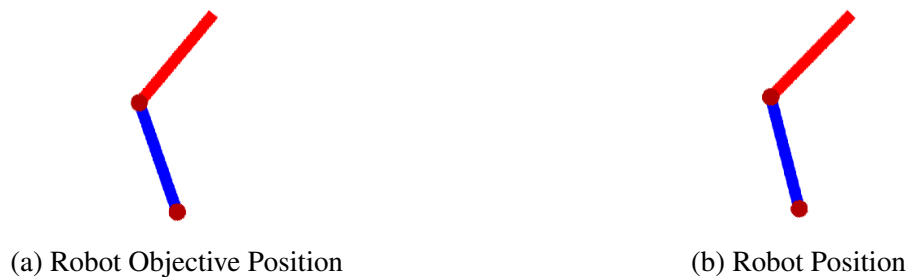


Figure 3.5: Compare among two modules

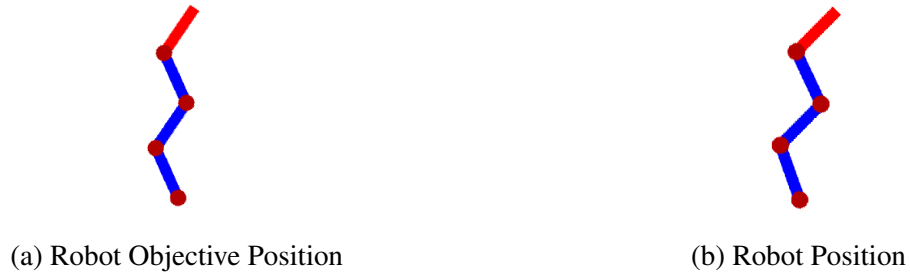


Figure 3.6: Compare among four modules

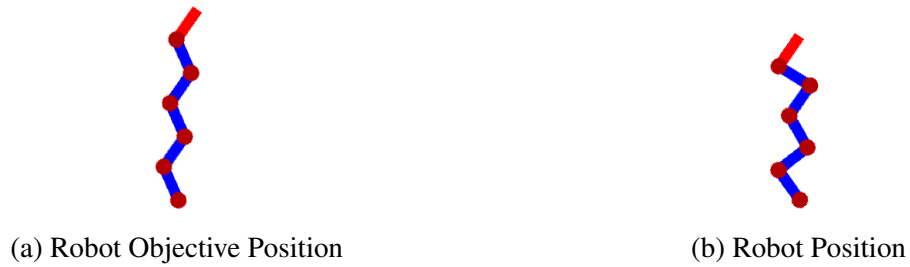


Figure 3.7: Compare among six modules

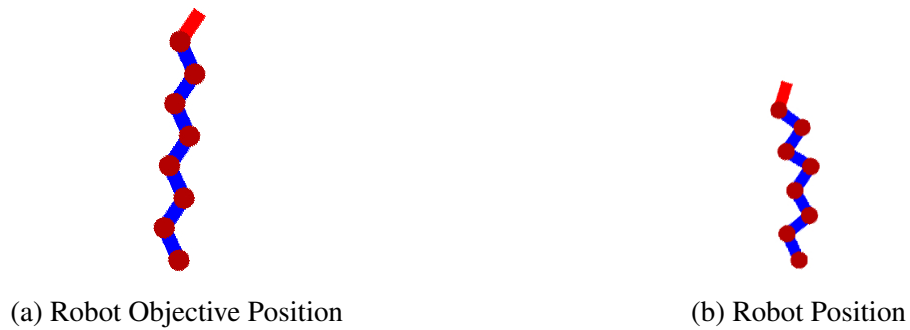


Figure 3.8: Compare among eight modules

Finally, an important consideration was the makeup of the backbone of the device. While the device was able to converge to the desired trajectory without a proper backbone, the more significant number of degrees of freedom present caused the robot to move in undesirable directions during initial testing. A design that restricts movement along the desired axis was chosen for this reason. The following image shows several modules chained together using a

backbone that restricts movement to only two directions.

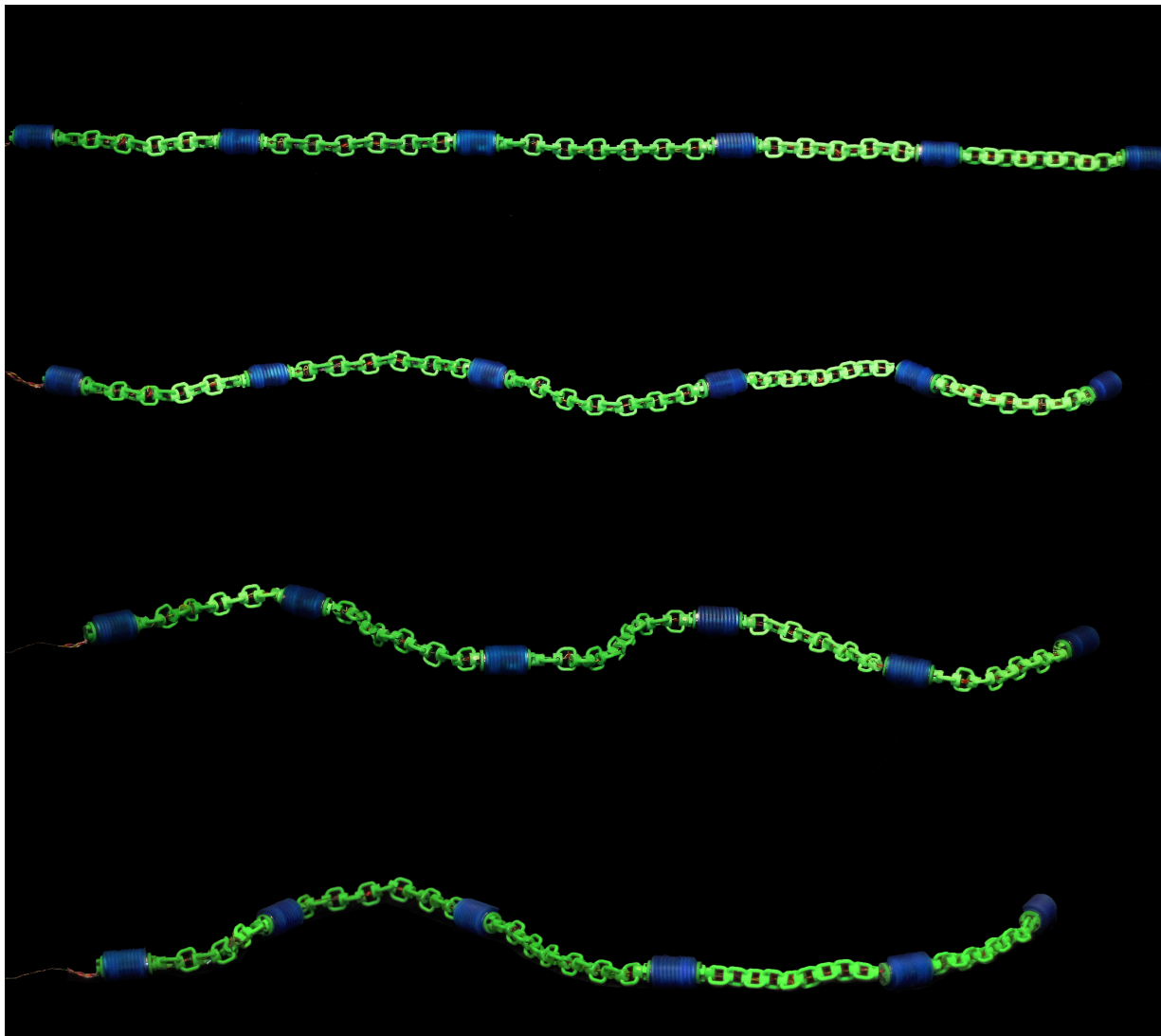


Figure 3.9: The robot can conform into any shape by allowing each segment to bend freely using the soft backbone.

Chapter 4

Medical Application

4.1 Introduction

Modern endoscopes still require high levels of skill and precision to operate as they apply significant forces in small areas to move deeper into their environments. This often results in complications as those forces accumulate and begin to stretch, bruise, or even perforate the body. In this thesis, we propose a novel design which utilizes a series of discrete propulsion modules which evenly distribute forces along the body. Each module is comprised of a screw-like shell that is driven to provide the propulsion as well as an IMU to obtain the orientation of each module. These segments can then be individually manipulated to control and visualize the shape of the overall robot. This allows the surgeon to derive valuable information such as the shape of the environment traversed and accurate localization of problematic areas, increasing the overall safety of the procedure.

Although colorectal cancer is the fourth-leading cause of cancer-related death in the world, stage I detection has a 5-year survival rate of over 90 % [31] [32]. This is why it is vital for prone individuals, people over the age of 50 or with a familial history of colon cancer, to be tested on a regular basis. It is thus vital for the general population to be screened regularly,

and at-risk individuals to be evaluated even more. Traditional colonoscopies are performed using an endoscope which is propelled forward by a somewhat nonspecific manual force applied posteriorly to a 150-180 cm endoscope, accompanied by twisting the endoscope, and pressure on the patients abdomen. These maneuvers increase the risk of patient injury. Getting stuck in the colon quickly leads to complications that include colon tearing, perforation, bleeding, and infection. Progress is estimated by searching for landmarks, which can guide to ending the surgery prematurely if the last milestone is misidentified. We address these traditional endoscope issues with our novel screw-propelled endoscope design, which alleviates painful colonic wall stretching, enables accurate localization and tracking, and increases overall safety.

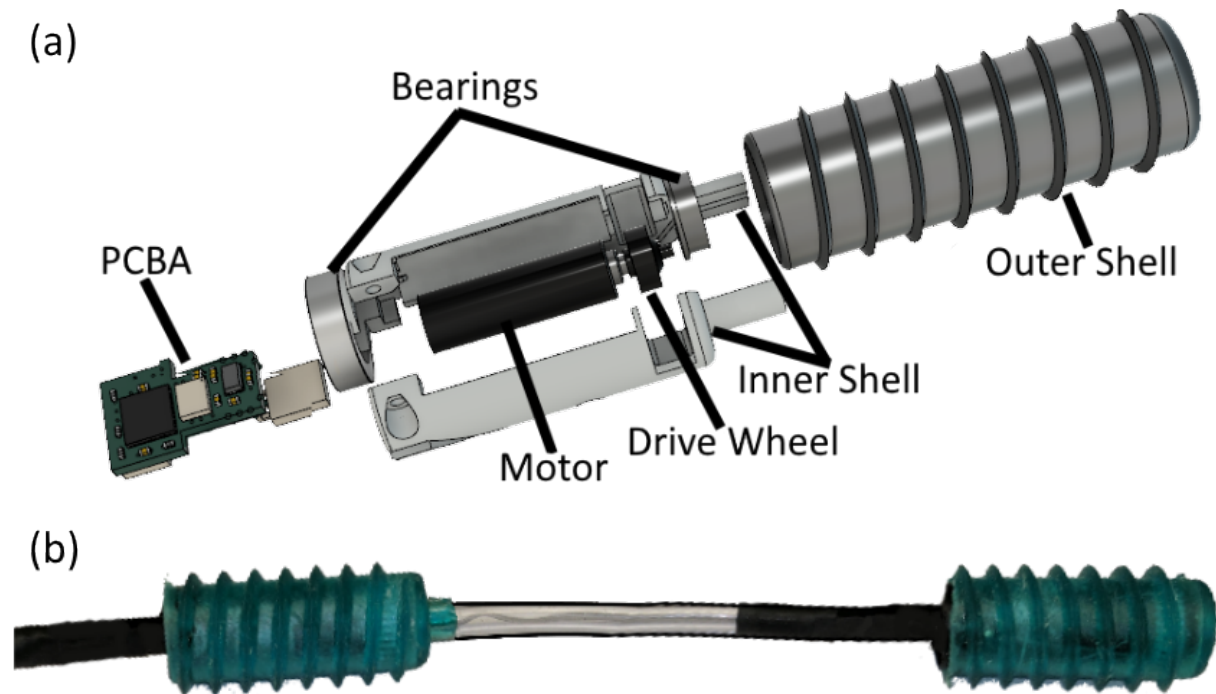


Figure 4.1: (a) Propulsion module assembly in CAD.
(b) Physical prototype

4.2 Related Work

Most colonoscopies are performed using endoscopes that require pushing a 2m long flexible tube through the gastrointestinal tract. In a constrained environment with twists and turns, an endoscope will quickly get stuck (91% of procedures, with a median of 2 events per procedure [33]). Thus, the risk of damaging the environment increases dramatically, leading to colon perforation and bleeding, and a high chance of organ infection [34]. Previously proposed solutions such as self-propelling head nodes [35], [36] share a common problem of friction built up and getting stuck before they get deep into the colon. Techniques that include legs or water-jet propulsion mechanism [37] [38] are either extremely delicate or crude methods to propel forward. Both Invendoscope and Endotics [39] use mechanisms that expand and inch forward using pneumatic or hydraulic mechanisms, which would require a significant change to the equipment and would have limited impact beyond large metropolitan areas.

Medical endoscopy and colonoscopy is a well-established engineering field and market. Most endoscopies are performed using passive endoscopes that require pushing a 2m long flexible tube up the rectum and through the gastrointestinal tract. Proximal control at the rectum are translated to distal insertion/retraction of the endoscope; often a single knob provides a means to articulate the proximal camera head to get a better view of the colon walls. Several practices are currently performed to unstick standard endoscopes [40]. These techniques address looping, where a stuck endoscope will create loops in the colon, both leading to stretch/tearing of the wall, as well as perforation at the head of the endoscope. These techniques are unfortunately addressing the problem too late, where the colonoscope is already stuck and twisted in a configuration painful and dangerous to the patient.

Several groups have attempted to address the challenge of improving colonoscopic navigation [41]. Researchers have developed various techniques that include legs or water-jet propulsion mechanism to aid in pulling the endoscopes forward [42] [43]. However, these are either ex-

tremely delicate or crude methods to propel forward that are insufficiently robust, and could themselves damage the colon walls. Robotic designs of the self-propelling head nodes [44] [45] share a common problem that they still build up friction and will get stuck before they get deep into the colon. Capsule endoscopy (i.e., camera pills [46]) is swallowed and therefore can move through the entire GI tract, but fundamentally do not provide any control of the image, and has no biopsy access to tissues and thus are not favored except for patients with critically sensitive tissues. A few commercial products are being developed for replacing standard colonoscopies. Those that have a high technology readiness level (TRL) are Invendoscope and Endotics [41]. Both use mechanisms that expand and inch forward using pneumatic or hydraulic mechanisms, which would require a significant change to a patient room and equipment. These systems likely will have limited impact on colon screening beyond large metropolitan areas. These devices are not yet FDA approved and are being tested in Europe.

Dr. Junghun Choi led research into a multilink modular robotic system which had expandable length by adding additional modules and easily conformed to its environment due to its natural break between modules [47]. Unfortunately, this system did not provide an active propulsion system so while the robot contained joints to flex around corners naturally, the robot would still push against walls as it was pushed from behind. We propose utilizing a screw-based propulsion system to address this issue. Our propulsion system is comparable to the idea of the Archimedes Screw, a screw-driven system used to transport water held between the threads uphill. Instead of moving water, our environment, the colon, remains stationary while the movement of the threads pulls our robot forwards. This principle was used in the Fordson Snow Machine produced in 1929 in which a screw-propulsion system was used to traverse deep loose snow [48] [49]. We aim to create a modular screw-propulsion based endoscopic robot by combining these two ideas. By combining a modular system with a screw-propulsion system, we can build an adaptable endoscopic robot which can propel itself along turns and loops while under challenging environments such as an unprepared colon.

4.3 PCB Design

For the small module, each module contains one of our designed PCB. Due to the human being anatomy, the PCB had to be 600 by 300 mil to fit in our mechanical design. The design of this board had to be a bit different since we are not using any external boards. The PCB had four layers and 43 active and passive components. Instead of the using an external Arduino Mini Pro, we used the ATmega328P by Atmel [50]. ATmega328P was chosen due to its low voltage. A voltage regulator was required since the motors run on 5V, but the rest of the components run off 3.3V.

4.4 Experiment

For the small modules, we are still working on the electrical part. We were only able to proof-concept from a mechanical perspective. The set-up in Figure 4.2 is to emulate the human being colon. According to MD Grant C. Fowler, Professor and Vice Chair of the Department of Family and Community Medicine at the University of Texas Medical School at Houston [51], colonoscopy takes around 30-60 minutes. In experiment emulates a quarter of a colon, we were able to travel the whole emulation in less than a minute.

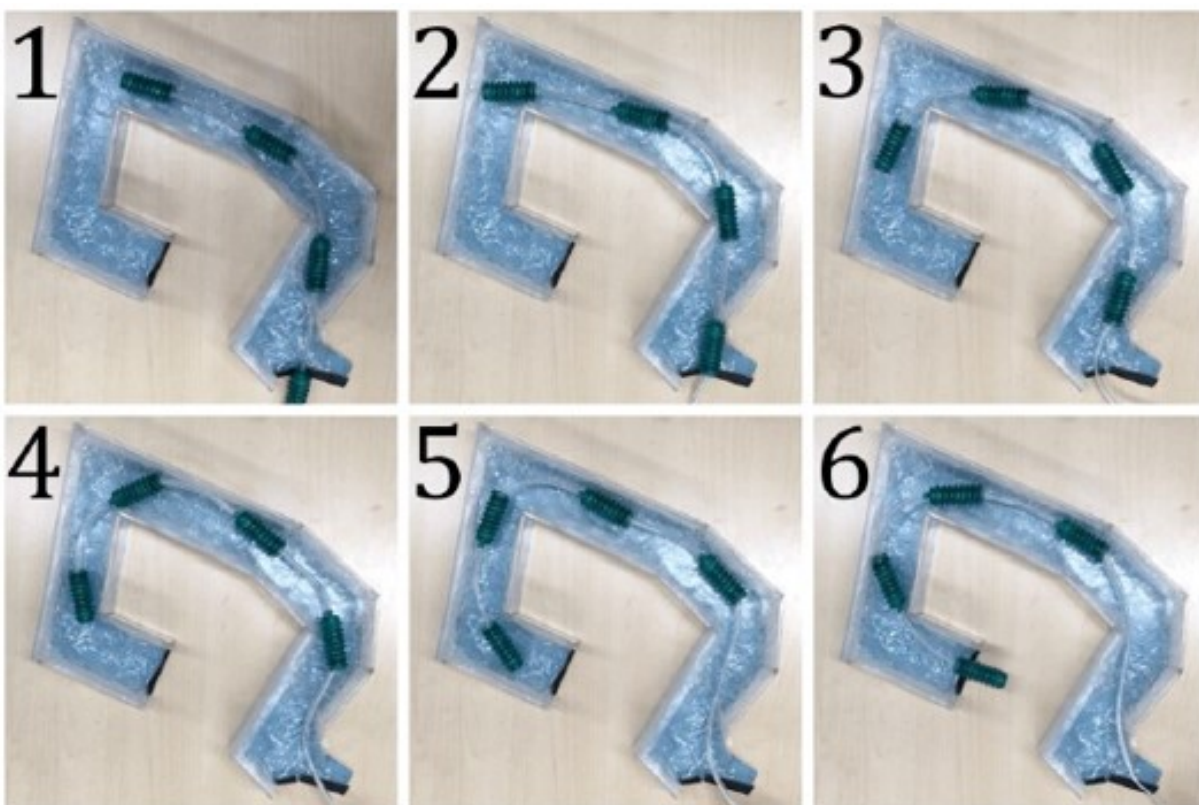


Figure 4.2: Our modular robot using four segments and featuring a soft-backbone with two degrees of freedom. This setup is simulating a hollow organ or cavity of the body.

Chapter 5

Discussion

In this thesis, we introduced a new type of snake-like robot that uses screw-driven modules connected with a flexible backbone. Furthermore, we proposed the ability to individually control each segment and move it to the desired position. Using this snake-like, screw drive actuation gives the robot the ability to be used on many surfaces and in any environment. To adapt to different environments, the gearing on the motor and the outer shell can be changed.

The magnetic noise created by the proximity of the motor to the robot could not be accounted for in the control loop. Although the noise could likely be estimated using a probabilistic model or removed using a notch filter, the microcontroller used was not able to evaluate any non-trivial model at an adequate rate.

Although all the experiments that were presented in this thesis ran with the maximum of eight modules, it is possible to extend these results to use more modules. We might run into issues power issues and communication bandwidth issue. To solve the power issue, we can add some voltage regulator between the modules. To address the communication issue, we can slow down the communication between the modules.

Our lab is also working on the design of a stereo vision system. By modifying the head robot, we were able to fit two Misumi camera (camera size 5.5 mm) into the head. This will be

up to the team in the future to have 3D reconstruction vision in the head of our system.

Chapter 6

Conclusions and Future Work

The experiments have been performed only on a flat floor of indoor environments, as a first set-up. In the future, we would like to run some operations in different situations like grass, road, gravel, and marsh so we can compare our results to other robot [52]. We can also try to replace the outer-shield a rubber outer-shield. This outer-shield will allow us to climb 45° slops and go downstairs like the robot developed by Iqbal [53]. Many problems including improvement of the prototype and enabling the magnetometer reading from the IMU to be tracked so that this robot is applicable outside of the laboratory environments.

We intend in the future to work on an endoscopic robot that uses the same technique for colonoscopy. Applying our design to colonoscopy requires satisfying stricter environmental constraints: a smaller form factor (less than 20 mm in diameter), hermetically sealing the robot to be quickly introduced into the human body and extracted without any damage to the surrounding tissues, and resolving magnetic shielding issues. Since our design does not rely on the usage of individually actuated joints between the modules, the modules can be shrunk down to any size the central motor chosen allows.

The robotic endoscope proposed in this thesis has the potential to address significant issues which exist in colonoscopies today. With early and accurate detection of colorectal

cancer being so essential to the patients survival, surgeons need a tool which can help complete surgeries with minimal risk. Our design proposes a low-cost robotic solution which can help complete more complicated operations while significantly reducing patient risk. Future work in the devices development includes developing a clinically ready model by reducing the robots size, hermetically sealing the device, and completing the user interface which allows shape visualization and video streaming from the device. Once this is done, we would be able to begin in-vitro and ex-vivo testing as well as pre-clinical trials to obtain approval for our new medical equipment.

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