Final Report

Team 10

Development of a Helical Path Tree Climbing Snake Robot

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ABSTRACT

The removal of trees is a hazardous task for those involved. Human interaction can be reduced by using a remotely-operated tree-cutting robot. Due to time constraints, this project will focus solely on the climbing aspect. To climb trees a snake inspired model was chosen, since it has high mobility and variable length due to its modularity. Research has shown the existence of other snake robots as well as climbing robots that can be used for inspiration, demonstrating the feasibility of this project. A three degree of freedom, modular design was developed by the team. The degrees of freedom decoupled the main aspects of climbing helically, which are: clamping, helix generation and driving. Early testing showed promise, with the wooden prototype holding 11 lbs. of distributed weight with 18lbs of force being used to tension the cable for clamping. Similarly, the helical generation and motorized driving tests proved that with enough clamping force and wheel speed, the robot can curl up the tree. Once all the aspects were decoupled and proven in theory, they were implemented into the final design. The final prototype is still in development and requires further testing and refinement.

1. Introduction

1.1 Problem Statement

Fallen trees cause over $1,000,000,000 worth of damage every year. To prevent damage from trees, professionals are hired to remove them before the trees fall on property. But even with all their technical skill and equipment, there are still over 200 tree related deaths yearly. There is a need for the removal of trees, and it is not safe to do so. The aim of this project is to build a robot that will be remotely controlled that would aid in the safe removal of trees. A snake-like robot that climbs in a helical manner was chosen by the sponsor and verified to be a valid solution by the team. However, removal of trees is a complex process as it requires the climbing of the tree first. Due to time constraints, this is the sole focus of the team. A payload will represent a cutting arm, which would be replaced in future iterations.

1.2 Scope

The original scope was to create a robotic snake that will climb a tree in a helical manner and cut it down via the method of 'topping.' However, due to time constraints and limited resources the scope was altered to focus on the climbing aspect of the robot. The revised scope is to create a robotic snake that will climb a branchless tree, in a helical manner, carrying a payload for future iterations. The reason for the tree being branchless is because branch avoidance is not part of the focus for this year's project. The payload will represent the cutting mechanism that will be implemented in the future.

1.3 Goal Statement

To build a remotely operated snake-like robot that will safely climb trees in a helical path, carrying a payload for future iterations.

1.4 Objectives

The robotic snake must be able to ascend and descend a tree while satisfying the following:

- Tree must have a diameter of 10-30 inches
- Robot must climb in a helical manner
- Ascend with a speed of at least 1 foot per minute (60ft per hour)
- Hold a payload of at least 10 pounds
- Have a camera attached to provide feedback

Originally the team stated that the payload would be 20lb. Since it is a concentrated payload, the team believes that 10lb is achievable. If the team has enough time, they would like to increase the payload to 20lb.

2. Background Research

The main objective is to develop a snake robot that can climb and cut down trees. The use of a snake robot is mostly due to customer desire. There are many types of climbing robots and some robots have been developed to prune trees. These robots were investigated as well as snake robots to see if a snake robot is the right tool for the objective. It is important to analyze if the different robots that have been developed for the task being asked may be a better option and if some redesign or an alteration of the project may be needed.

2.1 Problem Overview

When trees get old they begin to rot, making them highly unstable. These trees poses a great threat to their surroundings and should be removed before causing significant damage. But removing trees should be done by professionals, especially the tall ones. Chopping down trees requires specific skills, precision and a good understanding of safety precautions. There is a specific process on the removal of trees. The worker will remove the branches as he or she climbs up to the top of the tree. Once at the top, worker will cut the top segment of the tree. They will then descend and cut off the top segment. They will repeat this step until the tree reaches a height of around 10 feet. Once at this height, they complete the job by simply cutting the tree at the base. However even with all these professionals, tree removing is still considered one of the most dangerous occupations. There are on average 200 [1] tree-related fatal injuries every year in the United States. We would like to minimize this number by replacing the climbing workers with a robotic snake.

2.2 Types of Climbing Robots

There are many methods and types of wall climbing robots. A popular way to navigate trees is using a wheeled robot [2]. These kinds of robots use two platforms each having two wheels that clamp around the trunk of the tree. The wheels can have spikes known as spines which increase the traction for climbing up the tree [2]. With the added spines the robot is able to climb trees and rough surfaces unlike some type of climbers that are more suitable for smooth surfaces. Other climbing robots consist of legged robots, such as bipedal and hexapod robots [2][3]. The ‘mini bipedal climber’ uses small claws to adhere to a surface [3]. Another robot, ‘Rise’, utilizes suction as a means of adherence to a surface [2]. Another method that was developed to climb walls was using a swarm type crawling, or anchor climbing [4]. It enables large payloads to be transported up and down walls. This is done so using parent and child units. The parent climber is attached to multiple child units that pull and assist the parent unit, all of which stay on a surface using magnetic adhesion [5]. This method is similar to a group of ants carrying large items. Other types of robots can climb up rounded surfaces using an inch worm technique of climbing [5]. The top and bottom of the device are clamps. As the bottom is clamped down on the surface the top can reach out and clamp down. This method of locomotion is extremely slow [5]. Many of the robots mentioned above typically climb on straight, even walls, aside from the wheeled robots and the pole-like climber mentioned. Some of these types of climbing are not practical for climbing trees. For instance, magnetic adhesion or suction are not useful when climbing trees. The speed at which the robot needs to traverse the tree needs to at least be moderate, meaning the inch-worm technique is not a useful climbing method for the purpose of the objective. Something to consider towards the design is that it could have the ability to both, to be able to climb and move on flat ground. The wheeled robots need to be attached to the tree directly by the user, as it is unable to move from the ground to the tree on its own. A snake robot has the ability to shift from crawling on the ground to climbing up a tree at a reasonable speed. For these reasons, a snake-like robot is a viable option for becoming a tree cutting robot.

2.3 Snake Robots

2.3.1 Gaits

A main focus for the project is for the robot to be able to climb trees and crawl on the ground. This is because the customer desires a remote controlled robot. This can be more easily done using the snake robot because different gaits for both of those motions have already been developed [6]. Gaits are the different way the robot can move and typically change based on the type of surface it is traversing. Crawling on a horizontal surface is much different than a climbing motion. Some of the more common type of horizontal gaits include: sidewinding, rolling and slithering [6]. By sending different sine waves to the robot it is able to alter its motions to the aforementioned gaits. For climbing, the rolling gait tends to be used by having the robotic snake wrap its body around the object tightly, clamping itself to the object and using its segments as wheels to roll upward. On the ground the rolling gait makes the body in a c shape and rolls individual links to allow for motion [6].

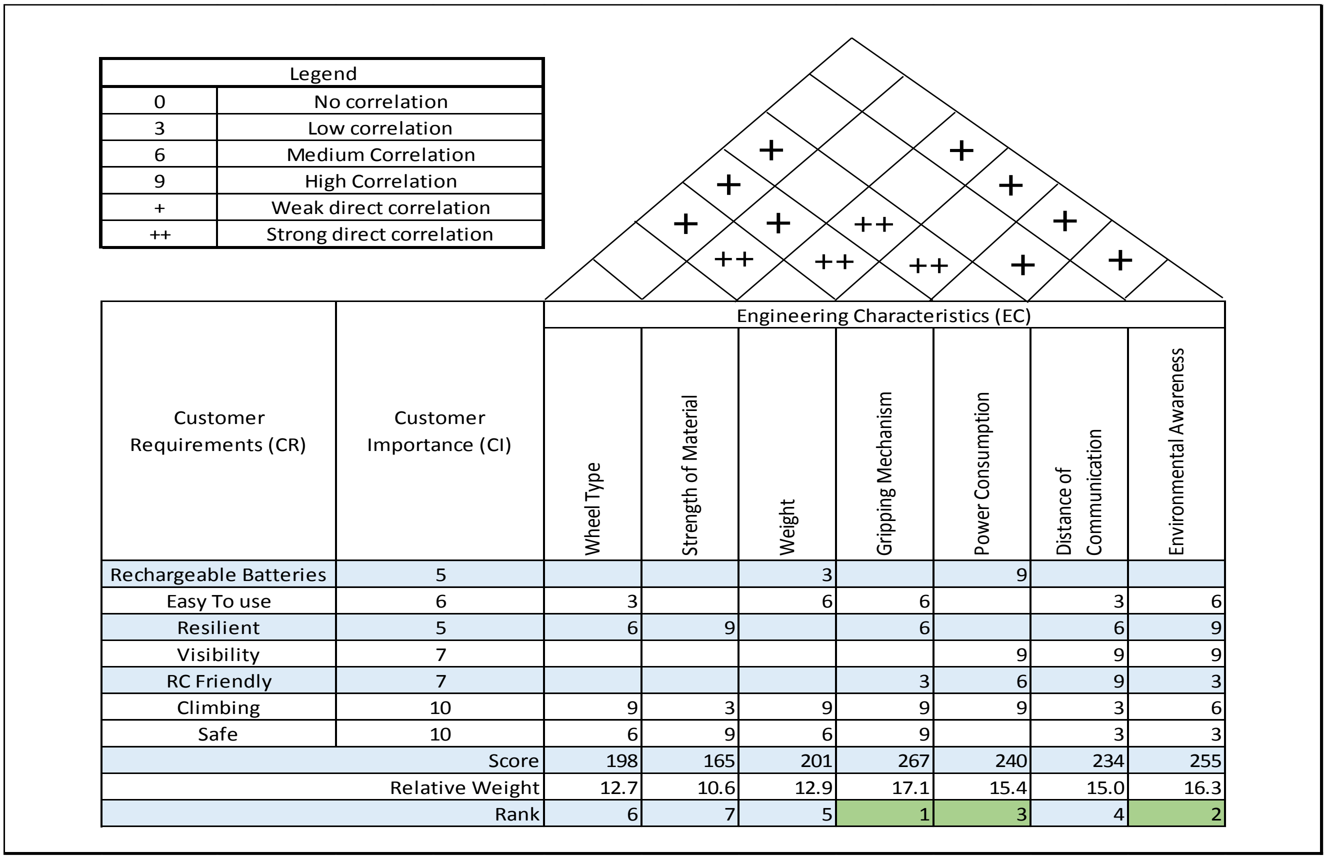
2.3.2 Designs

The motion of a physical snake is very fluid and smooth, in order to achieve motion similar to this, the snake robot needs many segments or modules that can move independently from one another. A few different designs that use modules are reconfigurable robots such as ‘PolyBots’ [7]. These types of robots can be reconfigured by adding or taking away modules to create new designs. They are not limited to just snake-like designs, but making them attachable and finding ways for the modules to communicate with one another can be difficult [7]. Another type of modular robot is a string type robot, these are the typical snake robots that are built [7]. They cannot be taken apart during operation. Instead, they are a series of modules connected together. To allow for more variety of motion (allowing the use of multiple gaits), these modules can be oriented offset to each other by 90 degrees. Each module needs to have at least one degree of freedom, while powered by motors individually [7]. More research on the different designs of snake like robots need to be done, but it is worth noting that the ones research have proven to be successful in their tasks.

3. Concept Generation

3.1 HOQ

In order to tackle the multi-variable problem set forth by our sponsor the team implemented a House of Quality, see Figure 1. By design, the House of Quality is a methodological tool that consolidates the need of the customer and the need of the product. The customer requirements were obtained through consultations with the sponsor. Engineering characteristics were then developed by the team to provide specifications for the product. From the House of Quality it may be seen that the highest ranking Engineering Characteristics were in order of importance: gripping mechanism, environmental awareness and power consumption.



Legend	
0	No correlation
3	Low correlation
6	Medium Correlation
9	High Correlation
+	Weak direct correlation
++	Strong direct correlation

		Engineering Characteristics (EC)						
Customer Requirements (CR)	Customer Importance (CI)	Wheel Type	Strength of Material	Weight	Gripping Mechanism	Power Consumption	Distance of Communication	Environmental Awareness
Rechargeable Batteries	5			3		9		
Easy To use	6	3		6	6		3	6
Resilient	5	6	9		6		6	9
Visibility	7					9	9	9
RC Friendly	7				3	6	9	3
Climbing	10	9	3	9	9	9	3	6
Safe	10	6	9	6	9		3	3
	Score	198	165	201	267	240	234	255
	Relative Weight	12.7	10.6	12.9	17.1	15.4	15.0	16.3
	Rank	6	7	5	1	3	4	2

Figure 1. House of Quality for Project.

By looking at the ‘roof’ of the house of quality, the correlations between the ECs can be analyzed. Since the gripping mechanism will be an important part of the final design, it will be wise to look at how it affects the weight and power consumption. Since the gripping mechanism holds the robot against the tree, a strong compressive force act on the robotic snake, so a stronger material will be required as this force increases as well.

3.2 Design Considerations

3.2.1 Wheels

The robot is going to need some mechanism to move, as the design calls for a helical climbing motion. Wheels were one of the simplest solution devised by the team. Attaching wheels to the robot allow for mobility with the attachment of a motor on the axle or rotation. The wheel system, although simple, can have a couple of variations.

Single Wheel

A single wheel is mounted with its axis or rotation planar to the center of gravity. This is done to prevent tilting of the system, similar to a motorcycle. It supports the structure on a single pivot point, applying great pressure on the point of contact with the surface. If a thin wheel is used, the system pivots easier than if a paint-roller-like wheel was used. The benefits of having a single wheel is that it is more lightweight and cost efficient that having more. But, as explained before, rocking and tilting of the system is an issue, especially if the robotic snake is to be clamped with great force to the tree's surface.

Dual-Parallel Wheels

Two wheels are mounted parallel to each other, equidistant from the center of gravity. By having the wheels set up this way, the system is constrained from rolling. That is, unless there was some external force that would cause the robotic snake to lose balance. Even though it provides better stability, it increases the torque requirements to overcome the inertial moment of the wheels, as well as the overall weight of the structure.

Placement

The wheels, regardless of shape can be placed at several locations. The further away the wheel is placed, with reference to the ground, the larger it becomes. A larger wheel is harder to spin, since it has a larger moment of inertia. To achieve faster motion, a smaller wheel is desired. So ideally, the wheel would be placed in an axle close to the ground, somewhere in the 'bottom' of the module.

3.2.2 Gripping Mechanisms

There were three main types of gripping mechanisms that were considered; electric actuators applied to each module, a wire actuated so when it is pulled the robotic snake would curl in a tensioned configuration, and the soft actuator relying on pneumatic actuation and a compliant body to form a curled configuration. The first type of clamping mechanism uses electric actuators on a modular design. Each module would be controlled by a motor at the joint. The joints would alternate between pitch movements (up and down) and yaw movements (left and right). The motors would power the joints keeping the segments tightly wrapped. The second idea also relied on a modular design and features a strong wire inside the modules that runs along the length of the snake robot. The wire would be rigidly attached to the head of the robot and the end near the tail would be pulled in tension. The tension would be supplied by a motor or spring or a combination of the two to tighten the wire. As the wire is tightened the robot will want to curl around. The more tension that is supplied the tighter the robot will become around the tree. The third idea is to use a soft actuator. This design utilizes pneumatic actuation to clamp on the tree. The soft actuator is one segment that when pressurized will make a helical shape. The air compressor would be at the tail of the robot and would pressurize the entire segment. The segment would then form to the tree in the set helical shape.

3.2.3 Helical Generation

Once the robot has gripped to the surface of the tree, it needs to generate a helix either before or during motion. Similar methods than those used for the gripping are to be implemented to generate the helical configuration of the robot.

4. Prototyping

Team 10 spent most of their time prototyping and testing. Figure 2 shows the “funky” prototype that the team built. The purpose of this prototype was to obtain a general idea of the motions of a robotic snake. The prototype had alternating joints between each module. One joint allowed the robot to bend up and down, while the other joint allowed the robot to bend left and right. Thus giving the robot 2 degrees of freedom (DOF). The team figured out that the triangular cut out of the modules limited the range of motion between the modules.

Figure 2. Version 1 - "Funky" prototype

The team then created their first working prototype using square cut outs for the modules, to improve the flexibility between each module. A strap ran through the inside of the prototype and was used to generate the clamping force. Below, Figure 3 shows an image of the first prototype successfully clamping on the tree. Although the wheels are not attached in the image, one can see the modules in contact with the tree are not perpendicular. The wheels must be perpendicular to the tree in order to maximize the clamping ability of the robot. Therefore the team decided to add a third DOF, which would allow the modules to twist. This modification can be seen on the prototype in Figure 4.

Figure 3. Version 2 - First working prototype

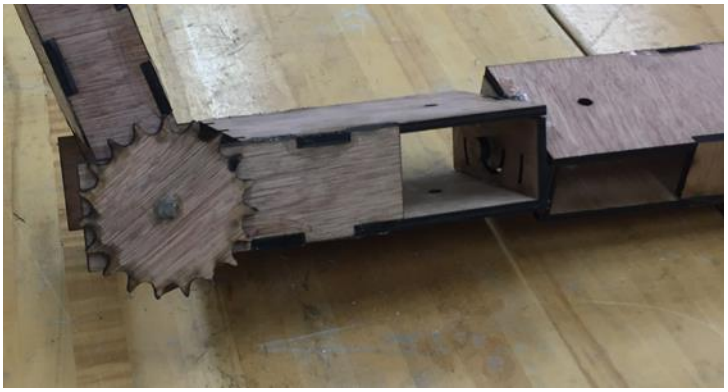


Figure 4. Version 5 - It includes a third DOF for rotation between modules

After testing this prototype, the team noticed that the modules were too long. A later prototype was created with all three DOFs combined at the joints, in the hopes of solving this problem. Figure 5 shows the next version successfully curling up, improving the robot's ability to wrap around the tree. After showcasing this prototype to the sponsor, some slight modifications were made to establish the next design for the body of the robot. Figure 6 shows a wooden model of the robot successfully clamping on the tree.

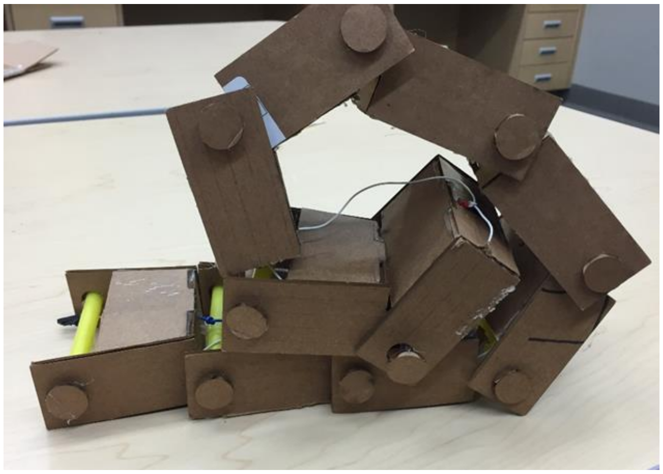


Figure 5. Version 6 - No robust testing was done as it was mostly made for showcasing

Figure 6. Version 7 – Prototype designed with the aid of the sponsor

Although successful in clamping, this prototype was unable to move nor generate a helix. The reason being for this was that the wheels were in contact with the modules. Through testing and consultation with professors, it was found that a pivot point was needed with the team's clamping mechanism. The wheels – and later the modules – force this 'hard stop' when pulling the wire. Figure 7 shows a prototype with controlled pivot points, which is able to successfully clamp and move simultaneously.

Figure 7. Version 9 – Pivot points designed into the module connectors

5. Final Design

The final design implements all the best parts of each of the previous designs in order to produce a prototype that should work. The major change associated with the final design is the implementation of a differential in order to generate a helix. The previous prototype required a cable, similar to the one used to generate clamping, offset from the center of mass to produce a moment. In theory, this would produce a helical shape for the snake robot. However, it was found that the helix generation and clamping generation were mutually exclusive. This may be seen by analyzing how the helix and clamping were generated in the previous prototype. For both clamping and helix generation, "hard stops" or points of contact between modules allowed modules to pivot, and as a result the snake robot would respond by clamping or by generating a helix, depending on the cable being tensioned. From experimentation, it was found that these "hard stops" were mutually exclusive. This may be seen in Figure 8.

Figure 8. Prototype Testing Shows Pivot points between Modules are the same for both Clamping and Helical Generation

As one may see in the figure above, once clamped there is an interference between the pivot points due to clamping and helix generation. As a result, there is a limited pitch angle that may be generated. Furthermore, as seen in the first module, the pivot uses the wheels to push off, which when driving will become extremely problematic. From this the team eliminated the cable used for helix generation, and replaced it with a differential.

The final design incorporates a differential to implement helix generation, and the same method of clamping. The differential utilizes different speeds in each wheel to generate a torque that allows the snake robot to pivot about an instantaneous center off the body. A schematic of this may be seen in Figure 9.

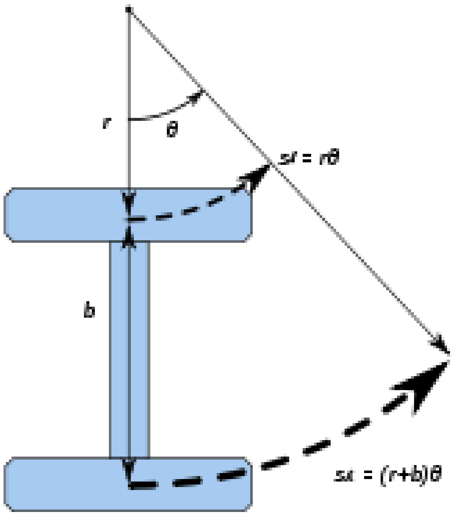


Figure 9. Differential Wheeled Robot [9]

The above image shows a schematic of the kinematics of a differential wheeled robot. One may see that the path of each wheel depends on the distance to the instantaneous center. The path of the furthest wheel may be controlled by changing the wheel axel length and the speed of each wheel. In order to achieve different wheel speeds, the differential mechanism requires one motor per each wheel in the system. As a result, the motion of the snake robot and the helical generation are now coupled.

The use of a differential was verified in testing in order to ensure that it would produce a helix in order to provide enough traction for motion up the tree. The test proved to be successful in generation of a helix but required a pushing force directed tree to replicate clamping in order to provide sufficient clamping in order to prevent slip. This may be seen in Figure 10.

Figure 10. Verification of Helix Generation Coupled with Clamping and Motion

The picture above shows a proof of concept of the snake robot generating a helix while being clamped to the tree by a pre-tensioned rope. The differential was operated using one motor and a gear train used to drive both wheels. The gear train ensured that both wheels were operating at different speeds. The snake robot successfully moved up the tree, but required a force perpendicular to the tree to produce sufficient clamping as the wheels tended to slip. This was done by hand (literally), as seen in the image, and proved as a useful solution to the issue. From this, we were able to see the snake robot move up the tree helically. As a proof concept, the next step was to implement the prototyped design into a final design that could be used to achieve the project scope.

The final design based on the prototype was set to be made of aluminum 6061. This was due to its high strength weight ratio and low cost. The design was made to be modular, as this would allow one to add and remove links of the snake robot. By allowing one to make this change, they could add links to provide more grip for larger diameter trees, and remove links in order to better adhere to smaller diameter trees. The design was also made to be nearly symmetric. The symmetry was such that the operating physics of the snake robot were nearly identical for when it moved up and down the tree. Each module was also minimized in order to remove mass in order to minimize torque requirements for driving. This was achieved by separating the design into 3 modules: motor, body, and clamping.

The motor module was designed to contain motors used to operate the differential. The motor module will be placed directly behind the clamping modules. This was done in order to ensure the maximum clamping force for traction was obtained. Experimentally in earlier prototypes, as shown above, it was shown that the maximum clamping was found directly behind the head module, where the tensioned rope was fixed. Figure 11 shows the motor module for the final design.

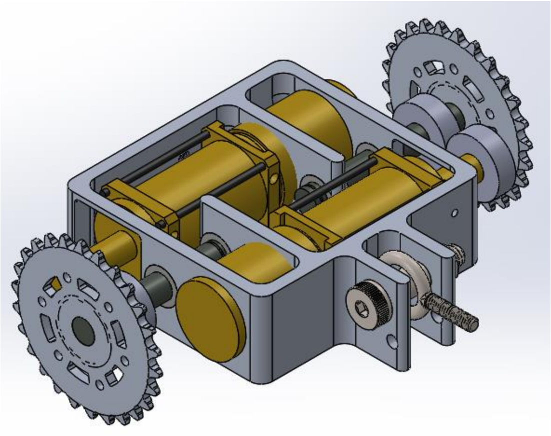


Figure 11. The Motor Module

The body modules were made to be identical as the clamping module. The team chose to do this as this lead to cheaper machining cost. The body modules operates on passive wheels and will contain the electronics of the entire snake robot. The body modules will be situated in between the motor module in the front and the motor module in the back. The body module for the final design may be seen below in Figure 12.

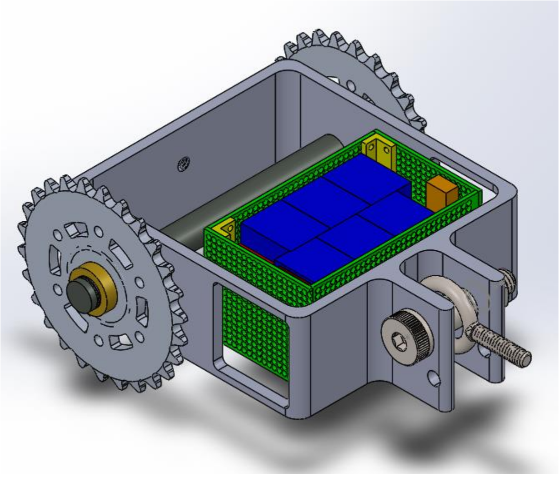


Figure 12. The Body Module

The clamping module was designed to contain the clamping motor. The clamping module will be located at the head and tail of the snake robot. This was to ensure that any losses propagated throughout the snake robot were re-inserted into the system to avoid any chance of slip. The clamping module may be seen below in Figure 13.

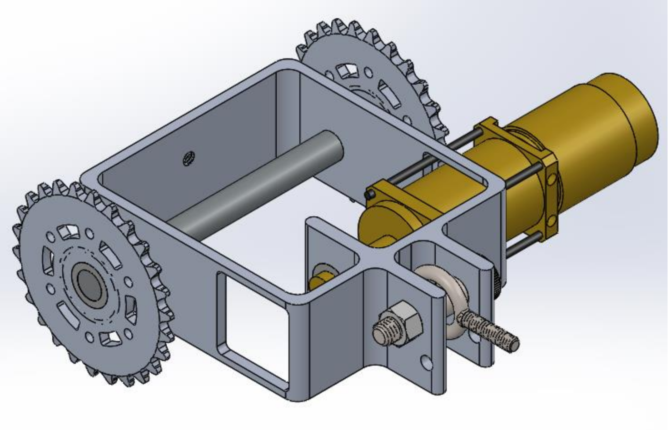


Figure 13. Clamping Module

6. Operations Manual

6.1 Functional Analysis

Due to the complexity of the project, the team separated the functionality into sub-systems of motions. To simplify the analysis, the forces were broken down as a combination of 2D problems that, when put together, they add up to complex 3D motion. The two main aspects that were deemed necessary to create the desired helical motion were a clamping (Figure 14), which would keep the snake robot bound to the tree’s surface, and a differential (Figure 15), which forces a helix by pivoting about an instant center.

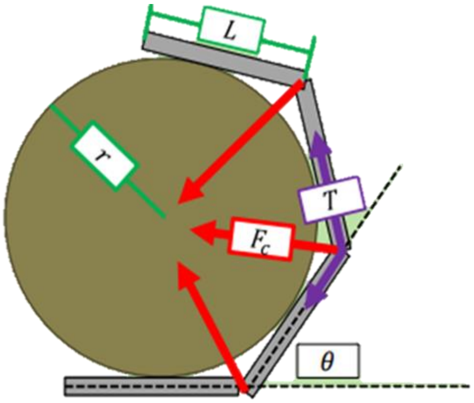


Figure 14. Clamping Analysis.

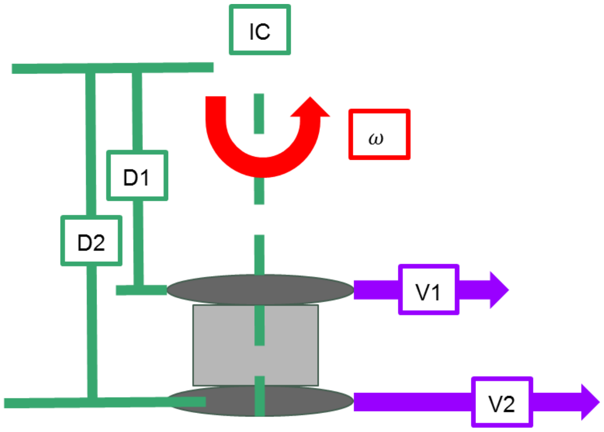


Figure 15. Differential / Helix Analysis.

The clamping works via a tensioned cable, which shortens in length and curls the snake into a circular shape. Once this circular shape is acquired, it can be molded into a helix by adding an additional force. Originally, the team had planned to use another cable, tensioned in a perpendicular direction to that of the clamping. However, it was unfeasible as too many issues arose with that design. As a workaround, the team looked into a differential, which operates by having two wheels rotate at different velocities, causing the object to rotate. This rotating motion showed promise in early testing and the team decided to carry onwards with it. As a benefit, this differential can be equalized to operate as a forward driving motion once in a helical configuration.

6.2 Motors

The selected motors were purchased from BaneBots. Due to the torque requirements for motion, the same motor was used with two different gearboxes. The motor chosen was the RS550-12V and the two gearboxes were the from the P60 series for RS500 motors, with a 326:1 and a 672:1 gear ratio. The resulting specifications can be seen in Table 1.

Table 1. Motor Specifications.

Element	No-load Speed (rpm)	Stall Torque (lb-ft)	Weight (lbs)
Motor (output shaft)	19,300	0.36	0.48
+Gearbox (326:1)	59.2	117.4	1.2
+Gearbox (672:1)	28.7	242.1	1.2

Table 2 has a list of specifications needed to make sure the different components are compatible, as well as making sure nothing exceeds the specified power limits.

Table 2. Electronics Specifications.

Component	**Teensy**	**Wixel**	**Motor Driver**	**5V step-down voltage regulator**	**12V step-down voltage regulator**	**Camera**	**Monitor**	**Transmitter**
Current draw (mA)	60.2	30	17A continuous	600	2.2A	150	250	200
V in (V)	3.6-6.0	2.7-6.5	6.5-30	7-42	13.5-36	12	12	12
Voltage signal (V)	0-3.3, 5v tolerant	0-3.3	1.8,3.3,5v compatible	N/A	N/A	N/A	N/A	N/A
Max output current pin (mA)	10	4	N/A	600	2.2A	N/A	N/A	N/A

6.3 Teensy &Wixel

The Teensy is a microcontroller that sends a Pulse Width Modulation (PWM), which directs signals to the motor drivers to run the motors at specific speeds. The Teensy has multiple digital output pins, which allow each motor driver to be connected to a separate pin to be commanded individually. The Teensy can only handle outputting a max current of 10mA from each pin. By having a separate pin connected to each element on the motor driver, the Teensy is protected from burning out. The Teensy is directly connected to a Wixel to receive serial information that determines the action that the robot should be performing. The Wixel pair is crucial to wireless communication with the Teensy. Two Wixel boards communicate wirelessly with each other, over radio signals. This data is then sent to the Teensy through the serial port, which is then translated into a PWM.

6.4 Motor Driver

The motor driver that was chosen was the Pololu G2 High-Power Motor Driver 18v17. It is a high power, high current motor driver. It can handle a max current of 30A and a continuous current of 17A without a heat sink. The operating current that is intended for our motors is a max of 11A, therefore these motor drivers are more than capable of handling the current. They are very compact, 1.3x0.8 inches, which is needed for the limited space available in the body module.

6.5 Voltage Regulators

Voltage regulators control the input voltage to a value specified by the type of regulator. For the robot, 2 different regulators are needed: a 5V step-down regulator and 12V step-down regulator. The 5V regulator limits the voltage for the Teensy and Wixel. Anything higher than 6.0V could cause permanent damage by shorting out the boards. The 12V step-down regulator is to adjust the power to both, the camera and monitor system, for the same reason. The output current of each regulator is important as well since both the Teensy and Wixel will be powered from the same regulator. The combined consumed current must not exceed the output current of the regulator to prevent damage to the component. In both applications, neither setup exceeds the output current of the regulator.

6.6 Camera system

The camera system sends real-time video wirelessly to the monitor using a transmitter. This gives the user feedback, allowing them to see where the robot is going, while making the control of the snake easier. The camera system is a simple plug-and-play device, meaning set-up is minimal. The set-up should include mounting the camera to the front of the snake and connecting the batteries and transmitter to it. On the receiving side, the user will have a monitor connected to the corresponding receiver and another battery powering the system.

6.7 Assembly

A full assembly of the robotic snake can be seen on Figure 16. This figure depicts the team’s robot assembled with a pattern of clamping and motor modules. The clamping module (Figure 17) also doubles as a body module, when the motor is removed from the assembly. The motor module (Figure 18) is located right after the clamping module to provide extra traction for the wheels.

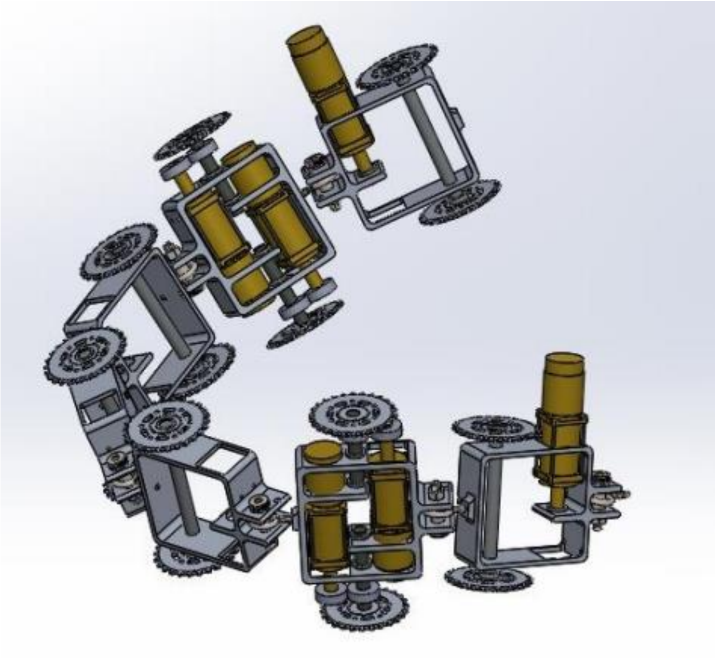


Figure 16. Robotic Snake Full Assembly.

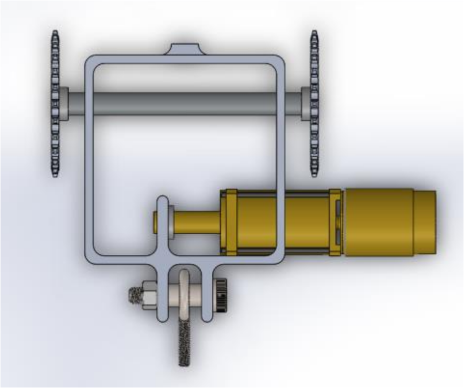


Figure 17. Clamping Module Assembly.

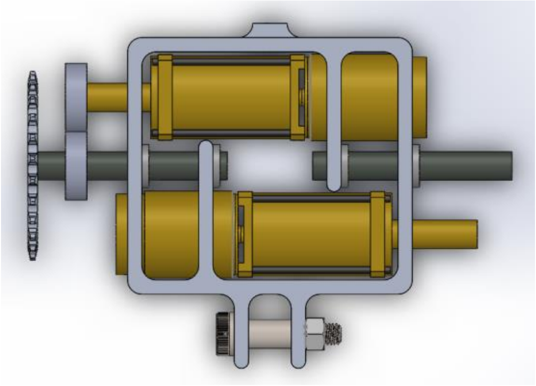


Figure 18. Motor Module Assembly.

To assemble the body module, a bushing will be press fit into the inner wall to provide the clamping motor with extra support. A bushing is also press fit onto the wheel allowing them to rotate freely on the shaft, which is press fit across the module. Since the wheels are free spinning, they are restricted from sliding by the c-clips. The motor is held in place by M3 screws, and the eye hook is detained by the shoulder bolt and nut. The body module is identical, except for the bushing in the wall, and the motor.

To assemble the motor module, bushings are press fit into each wall to provide a smooth surface for the shaft to rotate on. These shafts have a gear and the wheel press fit onto them, and are prevented from sliding by c-clips close to the inner walls. The gearbox shafts also have a gear press fit onto them, which will rotate the gear on the shaft. They are held in place by M3 screws. Again, the eye hook is placed between the ‘bunny ears’ with a shoulder bolt and a nut.

The finalized design for testing will consist of an arrangement of seven modules in the following order:

$$CLAMPING - MOTOR - BODY - BODY* - BODY - MOTOR - CLAMPING$$

Where the motor module provides the driving, the clamping motor helps the robot stay on the tree and the body module is passive. The middle body module will have to be machined to allow placement of electronic components by removing the inner wall. It is important for the design that the motor module have two or more modules around it so that traction is maximized when driving the wheels.

6.8 Operation Instructions

The snake is operated using a controller made of 6 buttons attached to a Wixel board. A Wixel is a wireless communication hub that make the snake operable using a wireless controller. The signals are sent via radio to a corresponding Wixel located on the robot. The on-board (on the robot) Wixel is directly attached to the microcontroller using a physical wire linked to a serial port. The off-board (off the robot) Wixel is able to send 6 commands to the on-board Wixel using the 6 buttons that are attached. The organization of the button placement can be seen in Figure 19. The forward button moves the all the wheels at the same rate in the clockwise direction. The backwards button moves all the wheels at the same rate in the counter-clockwise direction. The left button rotates the wheels on the right side of the robot faster (causing the snake to turn left) and the right button moves the wheels on the left side faster (causing the snake to turn right). Not pressing a button will cause the snake to stop and hold its place. The other two buttons control the clamping and unclamping. The A button clamps the robot while the B button unclamps the robot.

6.8.1 Button Functionality

Upon startup the default command for the robot is Pause, meaning it does not move; it holds its position. When the forward button is pressed the robot will slowly accelerate to top speed and hold that speed. When the button is released the robot will begin to decelerate to a stop. The backwards button operates the robot in the same fashion but in the reverse direction. The left and right veering can only be operated after the direction of the snake is set by the forward/backward button. The left turn will increase the robot pitch angle on the tree and the right turn will decrease the pitch angle. The clamping and unclamping buttons work in a similar way, although the speed for clamping and unclamping is much slower than the wheel speed and do not need to go through an acceleration process. Sufficient time should be given between commands to let the motors come to a complete stop before changing directions. Sudden change in directions could cause current spikes which will damage the motor controllers.

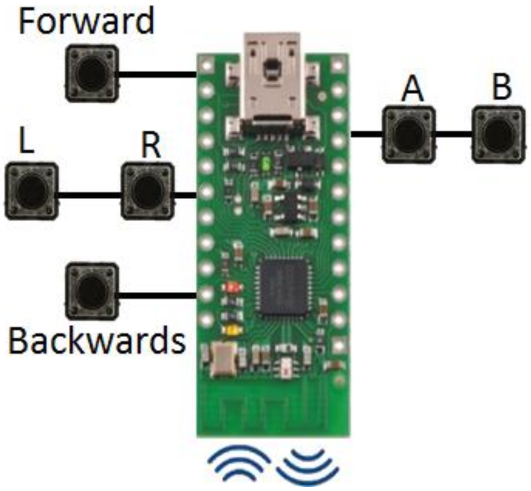


Figure 19. Wixel Button Schematic.

6.9 Troubleshooting

One of the biggest potential problems is for the snake robot to get stuck on the tree. Several factors can cause this problem to occur. Such as the batteries running out of power, motor failures or communication errors. These issues can all be prevented by ensuring all the components are fully functional before operating the robot. If the robot does get stuck on the tree, the user will need to manually unclamp it. Another potential issue is if the robot begins to slip down the tree. In order to prevent this, the user must ensure that the robot has sufficient clamping force before attempting to drive the robot.

6.10 Regular Maintenance

After every climb with the snake robot, the user must check the battery levels. In the current iteration, it is recommended that the user replaces the battery after every use to maximize climbing time. The batteries are rechargeable, therefore the user simply needs to replace the low battery with one that is fully charged. The user should also check the robot to make sure none of the components have been damaged. If a component is severely damaged, it should be replaced before attempting to use the robot again. After several uses, the aluminum spiked wheels will become dull and need to be replaced to maximize the efficiency of climbing.

6.11 Spare Parts / Inventory Requirements

The tree climbing snake robot contains both electrical and mechanical parts that all work in unison to complete helical climbing up a tree. It is therefore important to understand and have spare parts to ensure that the robot may be used effectively after multiple uses. The spare parts that should be kept at a short distance during operation include charged batteries, eye-hooks, e-clips and shafts. The full inventory may be found in the appendix.

7. Design of Project

7.1 Design for Manufacturing

The first step is to assemble each module individually. There are 2 different types of modules, the clamping/body and motor module. In the current iteration, there are 5 clamping/body modules and 2 motor modules. They each mainly consist of a shaft, wheels, and motors (if applicable). Once each module has been assembled, they need to be connected to one another using the eyebolts. After the modules have been fully connected, the electronics will be added and wired. The final step is to make sure all the components are fully functional.

The team expects the assembly to take around 12 hours to complete. The team believes that the assembly of the mechanical components will take 7 hours and the implementation of the electronics will take 5 hours. The majority of time for the mechanical components comes from laser cutting the body, for testing a wooden iteration. It is important to note that the electronics need special care when wiring and soldering to the boards.

The team simplified the overall design because of time and money constraints. However, it can be improved if the design had more components. For example, the clamping is generated by a single metal cable running through the entire snake. If each module had its own clamping motor, it would increase the efficiency and amount of clamping. Also, in the current iteration only two modules have wheels that being actuated, the rest are passive wheels. The motion and the helix generation would be improved if each module had actuated wheels.

To assemble the body module, a bushing will be press fit into the inner wall to provide the clamping motor with extra support. A bushing is also press fit onto the wheel allowing them to rotate freely on the shaft, which is press fit across the module. Since the wheels are free spinning, they are restricted from sliding by the c-clips. The motor is held in place by M3 screws, and the eye hook is detained by the shoulder bolt and nut. The body module is identical, except for the bushing in the wall, and the motor.

To assemble the motor module, bushings are press fit into each wall to provide a smooth surface for the shaft to rotate on. These shafts have a gear and the wheel press fit onto them, and are prevented from sliding by c-clips close to the inner walls. The gearbox shafts also have a gear press fit onto them, which will rotate the gear on the shaft. They are held in place by M3 screws. Again, the eye hook is placed between the ‘bunny ears’ with a shoulder bolt and a nut.

Exploded views for each module can be seen below in Figures 20 and 21.

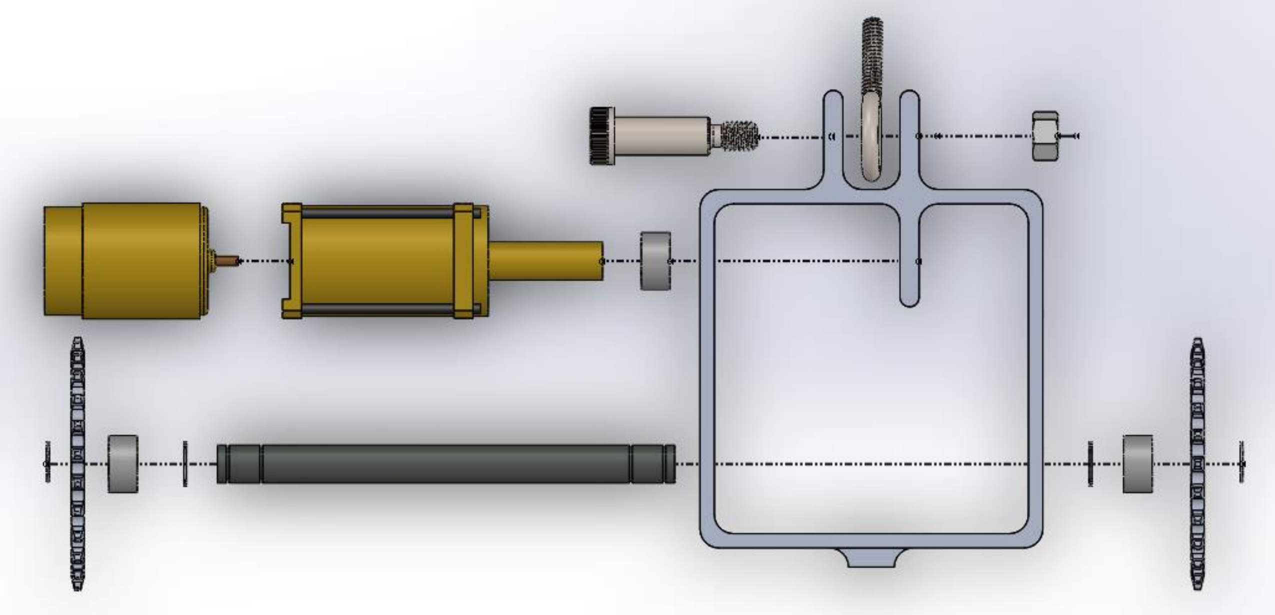


Figure 20. Exploded Clamping Module.

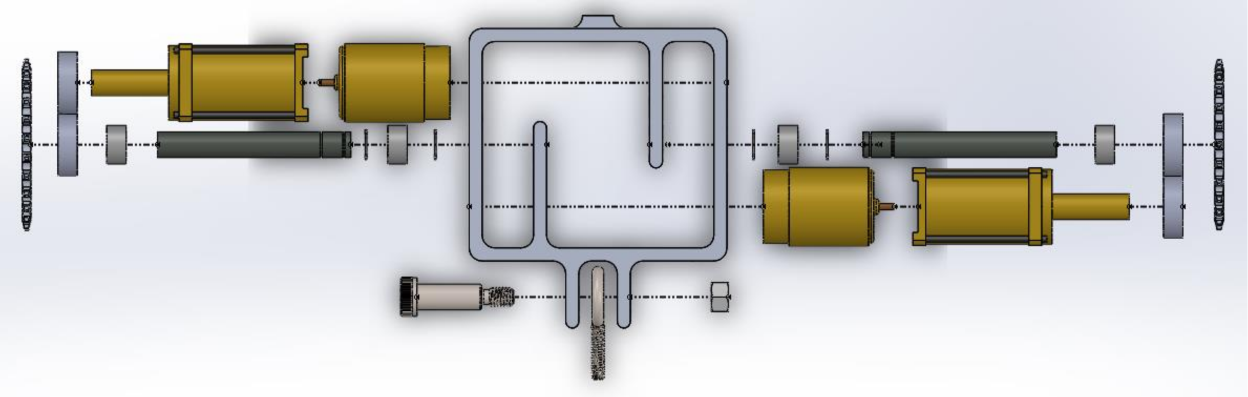


Figure 21. Exploded Motor Module.

7.2 Design for Reliability

The team’s design is not meant to be fragile. Careful consideration was made when choosing components and their interaction with other parts of the design. To better understand how the components behave, a Failure Mode Effects Analysis (FMEA) was developed. Table 3 explains in detail what aspects of the design were scrutinized, while Table 4 inspects each component under these parameters.

It was found that some critical components, such as the motor and the electric boards are the most hazardous during failure. This means that additional measures must be taken to ensure that they will not break during operation. Other components such as the wireless communication are also critical, but the prevention method is simply replacing it with a better option, something that the team's time and budget won't allow.

Table 3. FMEA Ratings and Explanation

Functional Parameter	**Failure Mode**	**Impact on Overall Product**	**Cause**	**Method of Detection**	**Likelihood of Occurrence**
Rating / Description	How the component fails	1- Minimal Impact, product can still work for short periods of time 3- Moderate. Damage to product is inevitable. Some damage to environment may be present. 5- Catastrophic. Product fails entirely and lives are at stake.	What causes the component failure (i.e. Overloading, Fatigue, etc.)	1- Easy to detect before /during operation 3- Detection is difficult, but achievable through specialized equipment 5- Impossible to detect before/ during operation	1- Unlikely 3- Very likely 5- Almost guaranteed

Table 4. FMEA for Snake Robot.

Functional Parameter	**Failure Mode**	**Impact on Overall Product**	**Cause**	**Method of Detection**	**Likelihood of Occurrence**
Wheels	Wheel deforms or teeth become dull	2. Snake becomes stranded / mobility severely reduced	Wear, fatigue, concentrated stress	2. Inspecting component pre-operation	1. Stress concentration should not reach the point to where this occurs
Wheel Axle	Wheel axle bends or breaks	2. Snake becomes stranded / mobility severely reduced	Wear, fatigue, concentrated stress	2. Inspecting component pre-operation	1. Stress concentration should not reach the point to where this occurs
C-Clips	C-clips bend or break	3. Wheel / axle are free to slide, causing wheel / axle failure	Wear, fatigue, concentrated stress	2. Inspecting component pre-operation	1. Stress concentration should not reach the point to where this occurs
Motor (clamping and driving)	Motor overheats or a gear set breaks	4. Motor catches on fire. 2. Motor stops working	Damaged wire, extended runtime, power spike	5. Impossible to detect until it occurs	2. Careful management of power is necessary, fail-safes can be employed to prevent
Clamping Wire	Clamping wire snaps	3. Robot becomes loose and falls	Wear, fatigue, concentrated stress	2. Inspecting and testing component pre-operation	2. Stress concentration should not reach the point to where this occurs
Main Body	Material deforms or breaks	2-4. Failure to other systems (clamping, wheel axle, etc.)	Wear, fatigue, concentrated stress	2. Inspecting component pre-operation	1. Stress concentration should not reach the point to where this occurs
Wireless Communication	Damage on transceiver / interference	3. Snake is unable to be operated 2. Camera stops broadcasting video	Water damage, short circuit, environmental noise	2. Visual indicator for current functionality (LED)	3. Interference is likely to occur with the branches as robot climbs trees
Power Supply	Battery overheats, runs out of power, leaks	4. Snake robot ignites 2. Snake robot shuts down	Damaged wire, extended runtime, water damage	5. Impossible to detect until it occurs	3. Careful management of power is necessary. Fail-safes can be employed to prevent
Camera	Camera breaks / stops broadcasting video	2. Operator loses visibility	Damaged wire, water damage	2. Visual indicator for current functionality (LED)	2. Careful operation of robot should prevent direct damage to camera
Micro-controller / Motor Driver	Component breaks or catches on fire	3. Snake robot’s motors are inoperable.	Current spike, water damage	5. Impossible to detect until it occurs.	2. Careful management of power is necessary. Fail-safes can be employed to prevent

7.3 Design for Economics

7.3.1 Cost of Design

The total resulting cost of the project was $3,750. The budget allocation of the project may be seen in Figure 22. The cost was mostly due to machining cost and electronics. Therefore, it is important to analyze these aspects of the project when attempting to reduce cost.

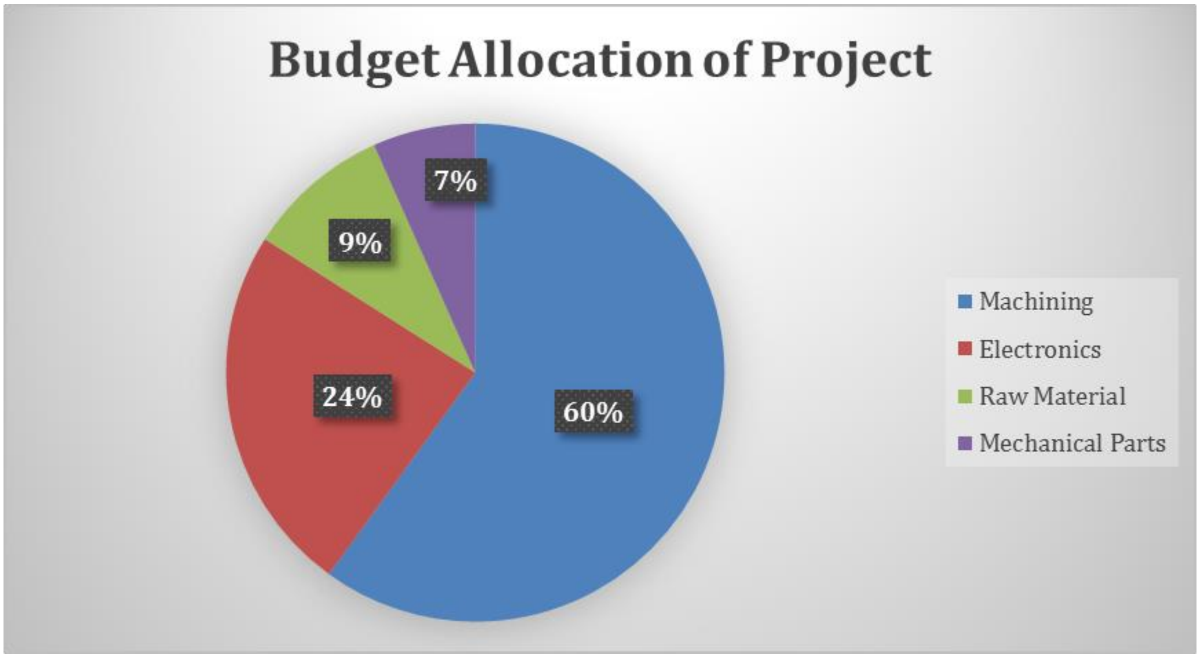


Figure 22. Budget Allocation of the Project.

Machining cost is by far the largest contributor to expenses. The main factors associated with increased cost in machining are the time it takes to cut and the desired time it takes to return. The time it takes to cut may be further broken down into complexity and size of the part. Table 5 shows the quote generated from velocity works where the machining was outsourced.

Table 5. Quote from Velocity Works Machine Shop.

Description	**Price/Unit (dollars/unit)**	**Number of Units**	**Extension (dollars)**
Motor Modules	363	2	726
Clamping Modules	238.35	5	1191.75
Total	-	7	1917.75

As seen in the table above, a total of 7 modules were produced, resulting in a cost of $1917.75. The table also shows that the motor modules cost more per unit to machine. This was due to the difference in complexity of the cuts for the parts. However, this is necessary as each module serves a specific function. Another distinction between the clamping and motor modules is the amount of material in each part. The clamping and motor modules correspond to a volume of 6.5 in^3 and 7.8 in^3, respectively. This also contributes to longer time for machining, increasing the cost associated with it.

What is not shown in the table are two important factors when minimizing cost. First, the time asked to have the parts ready was expedited to two weeks. This, based on discussion with Velocity Machine Works, was by far the largest contributor to cost. It is therefore highly recommended for future engineers working on this project to obtain a quote for a standard return rate for the parts to be machined, which will undoubtedly lower machining cost. Secondly, the senior design team attempted to reduce cost by simplifying the models to be machined. This attempt took a week of reworking the CAD models. This reduced cost by nearly $250. This contributed to a reduction in cost of 13%, which shows that complexity is not nearly as large a factor as the time desired to have the parts returned by. Based on the approach taken by the senior design team to mitigate cost, the best approach would be to allow for standard machining time. It would also be recommended to obtain quotes from various machine shops in order to find the minimum price for machining in the case for standard machining time.

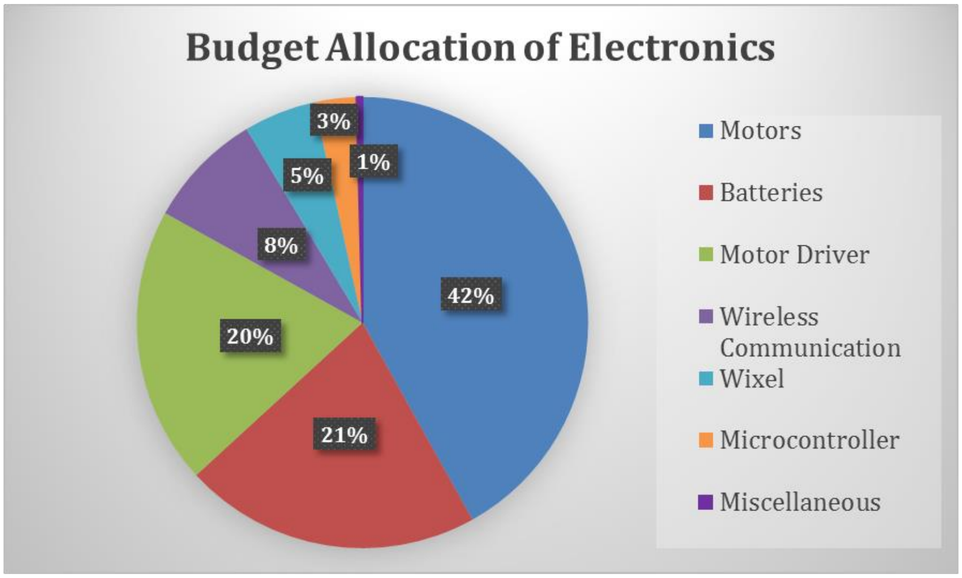


Figure 23. Budget Allocation of Electronics.

The second largest contributor to the overall budget was found to be electronics. An allocation of the cost due to electronics may be seen in Figure 23.

The largest contributor to the cost of electronics were the motors, while the second and third largest contributor were batteries and motor drivers. These were so large because the batteries and motor driver’s specifications are a dependent of the motors selected. This was due to the large stall current, 80 A, of the motors selected for the project. This lead to the necessity of motor drivers that could handle larger amounts of current. This is in order to protect the micro controller and prevent hazards such as overheating electrical components. The batteries were also a function of the motors, and this was also due to current draw. This may be seen in Equation 1 below.

$$t_{run} = \frac{Q}{i} \tag{1}$$

Where t_{run} is the run time, Q is the capacity of the battery, and i is the current being drawn from the battery to supply the electronic components. Since the motor draws a large amount of current, a large capacity battery was needed to have a long enough run time for the snake robot. Furthermore, the size of the modules had to be redefined with motor size. As a result, the price of machining increased. It is therefore recommended that future engineers optimize the torque requirements. This will lead to less cost in the following: motors, batteries, motor controllers, and machining. Since each of these contribute to a large majority of the budget, it may be declared that in order to reduce cost, one must change the motors of the system.

It is worth mentioning that the initial budget was of $2,000 and the total cost was of $3,750. If machine costs were excluded (using the engineering school’s machine shop), the total cost would drop to approximately 1,800$, which is still within budget. The team’s sponsor was well aware of the increase in cost due to machining and was willing to support the team’s expenses.

7.3.2 Comparison to Competition

To put into perspective how expensive the team’s design is, a comparison to other products in the market can be made. It’s important to note that this topic is mostly research based, so very little was found on the cost of production for snake like robots in general. To show a rough comparison of the cost of our design to another helically climbing snake-like robot, a few key components were totaled and compared. The components that were chosen were based on what was able to be found from the paper "Development of a Helical Climbing Modular Snake Robot". The components mentioned in the paper included motors for the joints and wheels, the microcontroller and the material used to make the body. The total cost of these components for them was approximately $1,900 while the same components for our design totaled to about $700. This is a significant $1,200 reduction from the competitor design, which equates to about a 60% difference of cost.

Figure 24 shows a bar graph comparing the cost of some of the components used in the "Development of the Helical Climbing Snake Robot" paper and the same components that were used for the team's design.

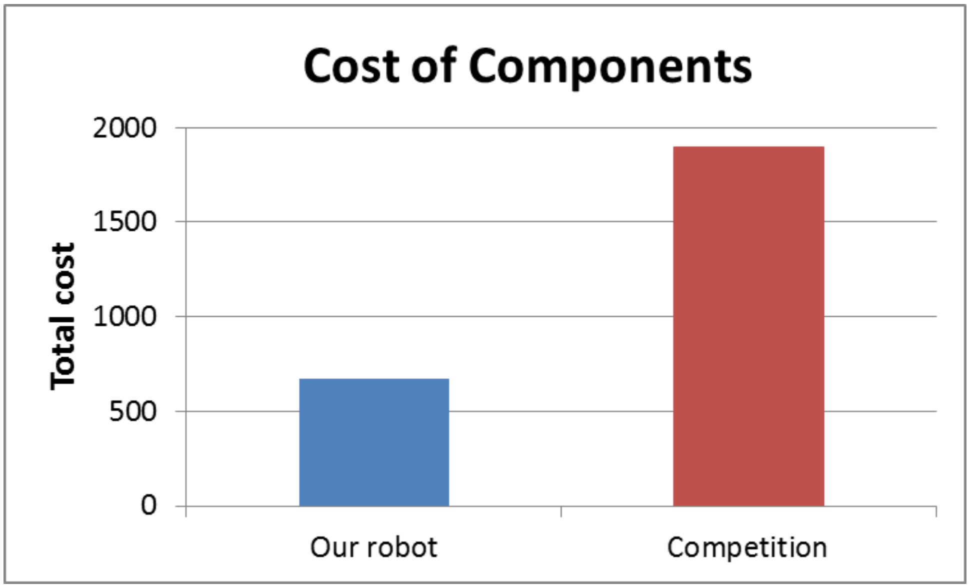
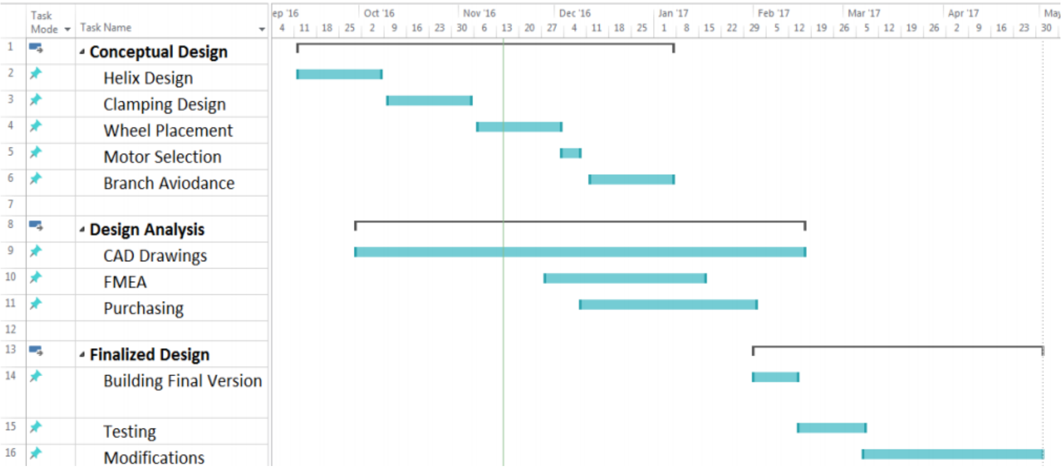


Figure 24. Bar Graph for Cost of Certain Components.

8. Project Management

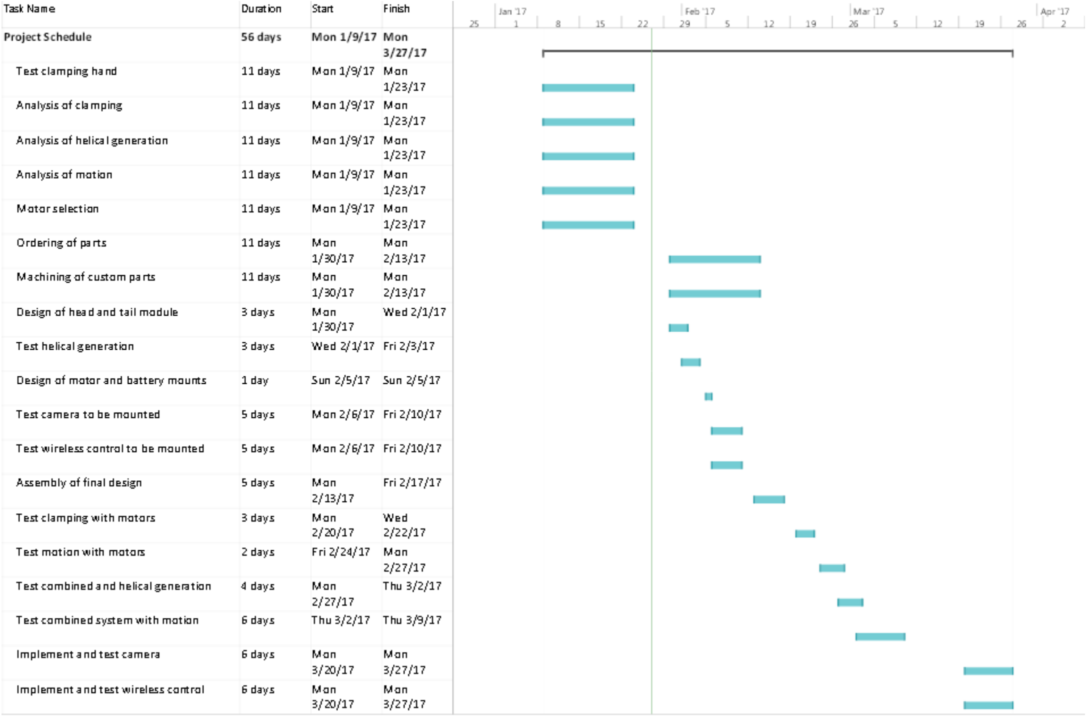
8.1 Scheduling

The Gantt chart on Figure 25 exemplifies the original plan of the team, which got revised as the project developed. The main idea was to have a finalized design purchased and ready by March.



	Task Mode	Task Name
1		**Conceptual Design**
2		Helix Design
3		Clamping Design
4		Wheel Placement
5		Motor Selection
6		Branch Aviodance
7		
8		**Design Analysis**
9		CAD Drawings
10		FMEA
11		Purchasing
12		
13		**Finalized Design**
14		Building Final Version
15		Testing
16		Modifications

Figure 25. Gantt Chart for 2016.



Task Name	Duration	Start	Finish
Project Schedule	**56 days**	**Mon 1/9/17**	**Mon 3/27/17**
Test clamping hand	11 days	Mon 1/9/17	Mon 1/23/17
Analysis of clamping	11 days	Mon 1/9/17	Mon 1/23/17
Analysis of helical generation	11 days	Mon 1/9/17	Mon 1/23/17
Analysis of motion	11 days	Mon 1/9/17	Mon 1/23/17
Motor selection	11 days	Mon 1/9/17	Mon 1/23/17
Ordering of parts	11 days	Mon 1/30/17	Mon 2/13/17
Machining of custom parts	11 days	Mon 1/30/17	Mon 2/13/17
Design of head and tail module	3 days	Mon 1/30/17	Wed 2/1/17
Test helical generation	3 days	Wed 2/1/17	Fri 2/3/17
Design of motor and battery mounts	1 day	Sun 2/5/17	Sun 2/5/17
Test camera to be mounted	5 days	Mon 2/6/17	Fri 2/10/17
Test wireless control to be mounted	5 days	Mon 2/6/17	Fri 2/10/17
Assembly of final design	5 days	Mon 2/13/17	Fri 2/17/17
Test clamping with motors	3 days	Mon 2/20/17	Wed 2/22/17
Test motion with motors	2 days	Fri 2/24/17	Mon 2/27/17
Test combined and helical generation	4 days	Mon 2/27/17	Thu 3/2/17
Test combined system with motion	6 days	Thu 3/2/17	Thu 3/9/17
Implement and test camera	6 days	Mon 3/20/17	Mon 3/27/17
Implement and test wireless control	6 days	Mon 3/20/17	Mon 3/27/17

Figure 26. Gantt chart for 2017.

Figure 26 shows the plan that was developed for 2017. In the original plan, the finalized robot would be assembled by February. As the team progresses with the project, a series of difficulties with the design had to be solved. Every time a problem was solved, a new one would arise. This process, alongside with prototyping took longer than expected, and the purchase of materials was pushed back a couple of months than expected. This caused further delays in the project, to where parts were not finalized and ordered until mid-March.

8.2 Communications

As the project was being developed, it was imperative to maintain proper communication with both, the sponsor and the advisor. Biweekly meetings were scheduled with the sponsor to update on the progress and to increase involvement in the design process. Monthly meetings were set with the advisor to update on the progress and to revise design, if necessary. The team held weekly meetings every Sunday to work on deliverables for the class. During the week, mostly Wednesdays and Fridays, the team would meet to work and develop the project. The team arranged most meetings with the sponsor and advisor through e-mails at least two days prior. The group meetings were scheduled through a phone application (GroupMe).

9. Considerations for Environment, Safety, and Ethics

Several elements were applied in the final design to improve the overall safety when operating the robot. Of the possible hazards, two of the most dangerous for the environment are electrical fires and battery leakage. In order to minimize these potential threats, the team has securely housed the batteries in the body of the robot and ensured the electric wires are properly connected. When designing the spiked wheels, the team decided to round the edges a little since the robot is intended to be manually transported. The current wheels are sharp enough to penetrate the bark of the tree and can be handled without harming the user. The team was also aware that if any components fell from the robot, it could cause serious injuries to the user. Therefore the team implemented c-clips and nuts to ensure all the components were securely attached. Also, as a safety measure, the clamping motors were placed on the top portion of the robot (when clamped on tree) to help prevent it from falling. However, even with all the safety considerations, the team highly recommends the operator use personal protective equipment (PPE). The use of PPE such as gloves, safety glasses, and hard hats will help minimize possible injuries. The robotic snake should only be operated with the intention of safely climbing trees. Operating this robot in any other manner than its primary purpose is considered unethical and dangerous.

10. Closing Remarks

10.1 Challenges / Constraints

There were and will be many challenges as progress is made. A few of the challenges that have been encountered already is the limited literature to use as reference. Currently in research there are only a few groups that build and analyze snake-like robots. Many of these robots do not climb trees and the few that climb do so by rolling their linkages up the tree or pole. This is dissimilar to climbing and more of vertically rolling up the tree. The other setback that comes from analyzing and picking apart these papers for useful information is the actuators that are used for the modules. Most of the links have motors that rotate the module in the necessary 3 degrees of freedom. These research projects are not limited by their budget. As a result, and the robots tend to be very expensive. The solution to limit the cost for this project was to use a single actuator to clamp the robot, rather than multiple motors at each module. The idea to use a cable-mechanism, to clamp the body, is a unique and innovative idea that hasn’t yet been attempted. There has been one paper found on helical climbing [8] but the information is still very limited and much of the work still needs to be developed. As progress continues many unforeseen issues will arise. This was compensated for by allowing some cushion time in the schedule. The necessary tasks were decoupled, so that components could be worked on in parallel. Lastly it was time consuming to learn and put together the electrical components, as no one in the team specialized in electronics. But these issues were to be solved as they arose through perseverance and team work.

10.2 Testing

Testing was decoupled to check each part of the electronics as they were slowly integrated to a whole. This was done to know what the problem was when testing an individual component. All boards were wired using a breadboard for testing. This means components were not soldered, making changes to connections much easier.

The wireless communication was tested with one button to an input pin on the Wixel. When the button was pressed, it was coded that the Wixel sends a specific signal over radio. The other Wixel was plugged into the computer the incoming information was monitored. 2 LEDs were also attached to an output pin to test that the signals were correctly configured. Once a single button worked, a second button was added. Each button would send a different signal that would turn on the LEDs individually, while the other would stay off as a default. After the two buttons were proven to work over wireless with the LEDs and monitor screen, the use of 6 buttons didn’t need to be tested extensively.

The microcontroller was tested in parallel, to make sure code was being uploaded to the chip and running as expected. The instructions for the microcontroller can be found on PJR, the website where the teensy is purchased. These instructions are incredibly helpful to follow to make sure the teensy is working properly. The teensy can be tested by opening the serial monitor on the computer and sending a message to be displayed in code. After the teensy was seen to be working, serial information being sent to the teensy was checked by displaying the incoming information to the serial monitor. A major complication that was noticed was the serial information coming in when the button was pressed always alternated. When the Wixel sent a value of 1, the teensy received 1 or 64; for the value 2, the teensy received 2 or 32. This issue was not resolved but instead compensated for.

Next, the motor drivers and motors were tested. The first part of the test was to wire the driver to the microcontroller, appropriately based on the data sheet. The microcontroller ran code to ramp the motor speed up, then back down, pause, change direction, and perform the same ramp up and down. This made sure the Pulse Width Modulation (PWM) and the direction pin were working with the microcontroller. After each driver and motor was tested, resistors were added between the pins on the microcontroller and motor driver. One more test was performed to make sure the resistors didn’t lower the voltage to prevent the drivers from working. Adding resistors to the microcontroller is not necessary, in most cases, but it protects the microcontroller from overdraw of current.

After each component is tested individually, a consolidated test has to be performed to ensure proper integration of electrical components.

10.3 Future Recommendations

It was discussed earlier that the Wixel was used for wireless control. A remote control needed to be built with a secondary Wixel attached to it to make this communication possible. The main reason for this choice of wireless communication instead of using a raspberry pi, was the size constraint. It is well known that using a raspberry pi from wireless communication is a good option. Code already exists to set the wireless communication with an Xbox controller, which means one less part that needs to be made.

It is highly recommended that a custom Printed Circuit Board (PCB) be made to include motor drivers and a microcontroller. If the current setup is still used that is fine, but it is still recommended that the electronics board be minimized by making a custom PCB.

Another aspect to keep in mind is to look into NBJTs and BJTs, which are transistors that could make driving all the motors much easier and in a much compact area. Transistors are essentially electronic switches that allow for large currents to flow from an outside source using a very small current from a microcontroller.

The most important thing to do for electronics is to start looking into them early. Even if the project is not ready to include electronics, it is of utmost importance to start researching and learning about different electronic elements. It is highly likely that the parts chosen will not be properly specified for what is needed. Reading data sheet is not a trivial task. Data sheets can be very lengthy and have an abundance of information in them but only a very few pieces are usually useful or needed for beginners. It is important to practice these skills early on and to get confirmation from a more experienced source that the parts are being specified out properly.

Lastly when purchasing parts (this goes for all purchasing but especially electronics), it is suggested to buy at least 3 extras. Learning to set up electronics can damage or break them. Throughout the process of testing microcontrollers 3 were destroyed. 2 of them got damaged by attaching a voltage to the 3v3 voltage output pin, and the third by a suspected overload of current by the computer. Keep the microcontrollers protected by setting up switches to be considered on when they are grounded, this prevents accidentally sending voltage to the 3v3 pin. To protect it from the computer do not attach the microcontroller directly to the USB, use a connecter to regulate the current. Another method is to only power the microcontroller to a power supply and cut the trace on the board between powered and the USB, which is what was done on this microcontroller. The other reason it is important to purchase extra boards is so there are boards to test with. One complication that occurred during testing with the motor driver was that they were soldered to the protoboard, as new tests and ideas to control the motor were being thought up. Had there been an extra motor driver and microcontroller these test could had been performed simultaneously to the construction of the protoboards.

11. Conclusion

The team spent the majority of the time prototyping and figuring out the best solution for the project. Due to the complex motion required to make a robot climb helically, the team designed a modular snake robot with three degrees of freedom. The final design is based around the motor size and the modules are as compact as they can be. The team was not able to perform a consolidated test with all the components, however, each aspect has been proven to work when decoupled. The robot holds on to a tree and is able to carry a payload. It is able to drive around, even if in a circular manner around the tree. And the helix is generated with the implementation of the differential. However, it has yet to be seen if these elements maintain functionality when coupled. The team hopes this project is picked up by other Sr Design groups in the future and improved upon.

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Team 10 - Biography

The group leader of this project is Jorge Campa. He is pursuing a career in robotics and control systems. In his time at Florida State University he has been a teaching assistant in Dynamic Systems I and II. He has also served as an undergraduate research assistant at the High Performance Materials Institute.

Justin Morales is currently finishing his Bachelor's degree in mechanical engineering and plans on pursing his Master's after he graduates. He is the WebWizard for his team and is responsible for design and updating the senior design website.

Michelle Maggiore is serving as the lead Mechanical Engineer. She is interested in pursuing the field of robotics and is currently working at Florida State University's STRIDE lab.

Esteban Szalay is a Senior Mechanical Engineer student at Florida State University. By having an interest in teaching and robotics, he aids with the calculations for the design, as well as serving as a source of information whenever possible.