Fall Final Report

Team 10

Development of a 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. A snake inspired model was chosen since it has high mobility and required little interaction when setting up. Research has shown the existence of other snake robots that can be used for inspiration, also demonstrating the feasibility of this project. The research includes other types of robots to be able to compare and examine them with the snake-like model. After deciding for the snake robot, research was done about the different types of movement that can be achieved with this model, to allow for grounded and climbing movement. Research was done as well on the design to successfully build the robot. Part of this research includes different concepts that are necessary to the gripping and mobility of the robot. Some things to keep in mind during development will be the gripping mechanism, the environmental awareness and the power consumption of the robot. This report contains the analysis of the needs of the customer, and research on: other climbing robots, some snake robots and the types of movements that can be achieved with such robots. This report details several prototype iterations and describes the plans for the future to successfully finish the project.

1. Introduction

Currently it is very dangerous and expensive to remove trees that are on the verge of falling. If these trees are not taken care of, they can cause a great deal of damage to their surroundings, especially to residential and commercial property. This ends up being more expensive than removing the tree initially. These trees need to be professionally removed in order to minimize their potential hazards to their environments. However, the tree removal profession is still considered a very dangerous occupation. This can be fixed by removing people from the equation and replacing them with robots.

After researching tree climbing robots, it was concluded that a snake-like robot will be the most effective. The main reason was because snake robots can climb trees and crawl on the ground without direct human interaction. Many problems could be solved if a remote control tree removing snake robot was created.

Due to time constraints, this project will focus solely on the climbing aspect. Needless to say, this project will set the base for future iterations. To ensure high performance of future iterations, the robot will have to carry a payload to simulate any cutting mechanism that will be attached on any future designs.

2. Project Definition

2.1 Need Statement

The removal of trees is too technical and dangerous for the average person.

2.2 Background and Literature Review

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 really 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 scope may be needed.

2.2.1 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.

2.2.2 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. An important aspect of the design is that it needs 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.

2.2.3 Snake Robots

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].

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. 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 one degree of freedom, rotation about the z axis, and it has to be powered by motor individually [7]. More research on the different designs of snake like robots need to be done, but it is worth noting that the ones described have proven to be successful.

2.3 Goal Statement

The goal is to build a remotely operated snake-like-robot that will safely climb trees.

2.4 Objectives

The objectives for this project are detailed under Table 1. Objectives for the Design.

Table 1. Objectives for the Design.

Characteristic	Description
Good Grip	Length of snake robot must be at least 1.5 times the circumference of the tree
Good Range of Communication	Remote must be able to communicate with robotic snake at least 60 ft
Climbing Speed	Robotic snake must be able to climb tree at a reasonable speed (goal is 1 ft/min)
Durability	Must be made of a material strong enough to withstand damage
Climbing Power	Must be able to climb the tree with a 20 lb payload

2.5 Constraints

The constraints for this project are written under Table 2. Constraints for the Design with Descriptions

Table 2. Constraints for the Design with Descriptions

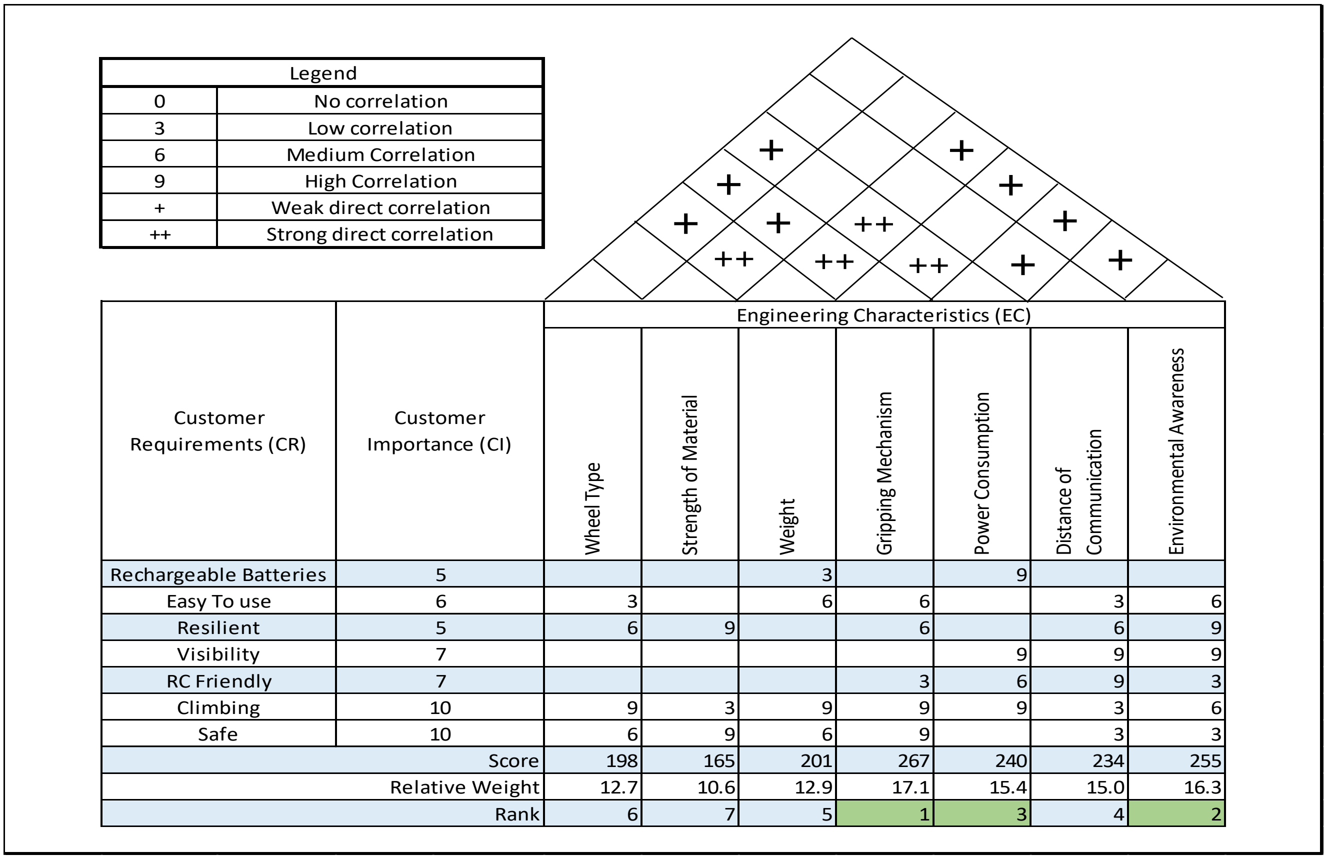
Constraint	Description
Remote Controlled	Snake robot is controlled by user on ground via a remote
Camera	Camera must give user feedback of the snake robot’s environment
Power Source	It must operate on a rechargeable battery
Lightweight	Robot is light enough to overcome dynamic forces
Climbing Method	Robot must climb tree in a helical path

2.6 Project Scope

The purpose of this project is to design a helical climbing snake robot. In future iterations, the robot will be tasked to cut down trees. This is replicated in the design by having it carry a payload of 20lbs representing the cutting mechanism. The robotic snake is to be operated remotely by a user who may visualize the snake’s perspective by utilizing a camera on the snake’s head. The snake needs to obtain a good climbing speed in order to cut trees as quickly as possible. In literature, the maximum found was 3 feet per minute and the average was 1.5 feet per minute [8]. The robotic snake has to be durable in order to handle the stresses induced with climbing and gripping. The snake must be able to climb the tree and descend the tree for the extent of its battery life.

2.7 House of Quality

In order to tackle the multi-variable problem set forth by our sponsor the team implemented a House of Quality, see Figure 1. House of Quality for Project.. 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

Customer Requirements (CR)	Customer Importance (CI)	Wheel Type	Strength of Material	Weight	Gripping Mechanism	Power Consumption	Distance of Communication	Environmental Awareness
		Engineering Characteristics (EC)						
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. Design Contents

In this section, everything regarding the parts used for the designs will be discussed.

3.1 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.

3.1.1 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 gripped with great force to the tree's surface.

3.1.2 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.

3.1.3 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. Some calculations can be found in Appendix A, proving this reasoning mathematically.

3.2 Actuator

There are several ways in which a system can be actuated to produce a desired motion, whether it is climbing or gripping.

3.2.1Pneumatics

Pneumatic actuators are actuators that use air pressure to create different types of motion. The two main types of pneumatics are linear and rotary. The linear pneumatic works like a piston. The air is drawn from outside into a chamber behind the rod at the end. As the pressure in the chamber increases the rod extends outward. Some pros to using pneumatics are their environmentally safe working fluid. Air can be pulled from outside and when it needs to decompress it can be released back into the environment. This also allows it to be lightweight. Because it can pull the working fluid from the environment, it doesn’t need a reservoir to store the working fluid. It has a fast reaction speed, so it can actuate quickly, but because it uses air the movements are also unsteady and jerky. The jerky movements of the pneumatic are because air is a compressible fluid, this makes the motions complicated to understand and the math much more challenging for future work. The other biggest problem with using pneumatics it the seals tend to break or get worn out easily and can be difficult to replace. Once the seal is worn the pneumatic cannot work efficiently or at all.

3.2.2Hydraulics

Hydraulics are very similar to pneumatics but use a different working fluid. Instead of using air hydraulics use some sort of incompressible liquid, most typically oil. The forces that hydraulics can exert are much higher than that of a pneumatic and could ensure strong enough compressive forces to hold the device to the tree. With the use of an incompressible fluid the math becomes much simpler, but the motions that result are smooth and controlled. This is beneficial because it makes it easier for the user to control the robot. Some cons to hydraulics is that it needs a reservoir for the oil to return to when it contracts and expands. This reservoir adds quite a bit of weight and hydraulics themselves are heavier than pneumatics. The other major setback is that hydraulics are much slower than pneumatics. This is an issue that needs to be kept in mind because the robot needs to be able to climb the tree quickly, which will rely on how quickly it can grip the tree.

3.2.3Electric

The electric actuators are actuators that use motors to move. The motors are powered by a voltage source meaning a battery. These type of actuators can be very powerful depending on the motor and are environmentally friendly. The hydraulics uses oil which can leak and cause damage to the sounding area, but the motors run on electricity so there is no oil to be spilt. Electric actuators are very common and are often used in robots, as a result they are easy to acquire and are less expensive than pneumatics and hydraulics. A downside to using electric actuator is that each motor needs its own power source. The pneumatics can be powered by one source and the air line can run to all the actuators. Electric motors cannot be done the same was as efficiently because the after passing through each motor there it going to be a voltage drop and less power to the next.

3.3 Gripping Mechanisms

3.3 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.

4. Design Concepts

The team has constructed two design concepts that are worth pursuing. The design concepts were generated from the Pugh matrix, which was developed from the morphological chart. Both may be found in the contents of this paper. The two designs were: the motorized modular aluminum snake robot and soft actuated fiber snake robot. The two main differences between them were the gripping mechanisms and the modularity, both which will be detailed below.

4.1 Design 1 – Motorized Modular Aluminum Robot Snake

The aluminum modular snake robot was the first design selected from the morphological chart. The aluminum body gives the body high strength as compared to other considered design materials such as the elastic body of the soft actuated robotic snake. The aluminum body is by consequence naturally heavy (compared to wood or fiber), however this may be reduced by hollowing out the material as much as possible. The only drawback from this approach is the reduction in strength by consequence. This design also features spiked wheels. This is due to their incredibly high friction coefficient as well as lack of concern for the residual health of the tree.

4.2 Design 2 – Soft Actuated Fiber Robot Snake

The soft actuated snake robot was the second design selected from the morphological chart. The soft actuated mechanism allows the robotic snake to take a helical form actuated by pneumatics. The materials implemented are also much lighter than the aluminum material. However, this in turn makes the material more prone to tears and unwanted deformations. This design also features spiked wheels. This for the same reasons as mentioned above. Both designs will be further detailed in the comparison below.

4.3 Design Comparison

In terms of gripping mechanisms the motorized modular aluminum snake robot design implements electrically actuated servo motors to apply a perpendicular force to the surface of the tree. The servo motors will be revolute and be implemented throughout the snake robot’s length to oppose gravity and avoid slipping. The main issue with this design is that the snake robot would require a large amount of motors which tend to be expensive. Furthermore, the motors will consume energy from the same source being used to drive the snake forward. This in turn may require larger or more batteries in series. This consequently will increase cost in batteries and the weight of the system. Figure 2. Helically Wrapped Modular Robotic Snake., shows a modular snake wrapping itself helically around a constant radius pole.

Figure 2. Helically Wrapped Modular Robotic Snake.

The second gripping mechanism is that of the soft actuated snake robot. The soft actuated gripping mechanism comes in a variety of geometries, and by implementing pneumatics it can bend in a variety of ways. It possesses the ability to bend and twist simultaneously. The bending motion tends to form a helical shape which is used to form the robot into the desired position. The twisting tends to turn the robotic snake along an axis that is aligned with the geometry's symmetric axis. To visualize the symmetric axis assume the object was fully stretched and thus appears to be a cylinder. The axis referred to as the symmetric axis is the axis along its height placed directly in the center of its circular cross section. The twisting and bending is formed by a pneumatic cylinder in the geometry of the object to be actuated. This pressure is placed off the center of mass causing the geometry to bend and twist. The gripping mechanism would thus depend on the pressure input by the pneumatic actuator. This means that a compressed air is necessary for operation. Having a compressor will increase the overall weight of the system. On a positive note, this component is completely independent of the electrically actuated driving mechanism. An alternate method would be to use tanks to store pressurized air. The downfall that made the second design less attractive than the previous is the fact that soft actuators are complex to build. Furthermore, they rely on elastic materials to achieve its variance in helical parameters. This in turn means the materials is not as strong as the aluminum design mentioned above. It is crucial that the materials are strong as the cutting of tree will require great force to resist falling from as well as to have a stronger grip for the tree. Given the complexity of the build and the large force being exerted on the robot, the modular aluminum snake was the design chosen to move forward with. Figure 3 shows an example of a soft actuated object undergoing bending and twisting.

Figure 3. Example of Soft Actuated Object Undergoing Bending and Twisting.

A further distinction between the two designs is the modularity of each. The modular aluminum snake robot is inherently modular. The soft actuated snake robot on the other hand is a single segment. The modularity from the aluminum snake robot comes from its links that may be attached with as many as needed to wrap itself around the tree. The soft actuated snake robot is set to a fixed length. This consequently puts a strict limit on the diameter of the trees in which the soft actuated snake robot may climb.

The similarities between them are straight forward. Both rely on electrically actuated servo motors to drive the system. Both also will feature spiked wheels. This becomes an obvious issue to the soft actuated mechanism if it were to puncture a hole in the elastic air-filled material. Both will be remote controlled and will feature rechargeable batteries to power the robotic snake. As seen and described above, the design that produces the least amount of future complications is the modular aluminum snake robot and thus is the design chosen to move forward with.

5. Design Selection

5.1 Morphological Chart

Table 3. Morphological Chart of the Snake Robot.shows the morphological chart used to make the designs above. Every functional parameter has at least two possible ways in which it could be employed. The numbers displayed under the solutions are the rating given to that solution in comparison to each other. A plus 1 means that it would be the most optimal, since it follows the constraints or fulfils the requirement the best. A zero means that, though it is a good solution, a better alternative exists. A -1 means that either the integration of the system will be complicated or it is undesirable to have as part of the design.

Table 3. Morphological Chart of the Snake Robot.

Requirements	**Functional Parameters**	**Concepts or Solutions**		
Climb Trees	Wheels	Spiked Wheels (+1)	Rubber Wheels (0)	Continuous Track (-1)
	Gripping	Soft Actuator (+1)	Cable (+1)	Electric Motor (0)
	Construction Type	Single Segment (0)	Modular (1)	
Durable	Material	Reinforced Fibers (0)	Aluminum (1)	Steel (0)
Ease of use	Communication	Wireless (1)	Wired (0)	
	Transportation	Self-Moving (1)	Carried to tree (0)	
	Power input	Wired (0)	Disposable Battery (-1)	Rechargeable Battery (1)

5.2 Pugh Matrix

To fulfil the requirements stated in the previous section, it was ideal to choose only one solution. This was done for simplicity, since the integration of several solutions would not only be redundant, but also increase the complexity of the system. Table 4. Pugh Matrix for Selection of Design. below shows the Pugh Matrix that was used for design selection.

Table 4. Pugh Matrix for Selection of Design.

Concept	**Base**	**Design 1**	**Design 2**
Wheels	0	1	1
Gripping	0	1	1
Construction Type	0	1	0
Material	0	0	0
Communication	0	1	1
Transportation	0	0	0
Power Input	0	1	1
Score	0	5	4

Design 1, the Motorized Modular Aluminum Robotic Snake, was the one with the highest score. This means, that this design was the most optimal in fulfilling the requirements for this project and will be the one to be developed. It is worth mentioning that design 2 was behind by only one point, so perhaps part of the second design could be meshed with the first one and create a third, better design overall.

5.3 FMEA

After selection, it was important to understand how it could fail and what such failures mean for the overall design. A Failure Mode Effect Analysis was constructed on Table 5. FMEA for Snake Robot. It describes what happens to the robotic snake if a component were to fail. Of course, this process is preliminary and some further failures are yet to be determined. Additionally, if more components were to be added, this table would expand to accommodate.

Table 5. FMEA for Snake Robot.

No.	Functional Parameter	Failure Mode	Cause	Effect on Primary System
1	**Wheels**	Axles breaks or wheel deforms	Wear / Fatigue / Concentrated Stress	Snake robot becomes stranded / mobility severely reduced
2	**Gripping**	Gripping system breaks	Wear / Fatigue / Concentrated Stress	Robotic snake becomes loose and falls
3	**Material**	Material deforms or breaks	Wear / Fatigue / Concentrated Stress	Damage to immediate surrounding / internal systems
4	**Method Of Communication**	Damage on transceiver / interference	Water Damage / Short Circuit / Noise	Robotic snake is unable to be operated manually
5	**Power Input**	Power stops flowing	Battery Leakage / Cable Damage	Snake robot shuts down

6. Prototypes

6.1 Version 1

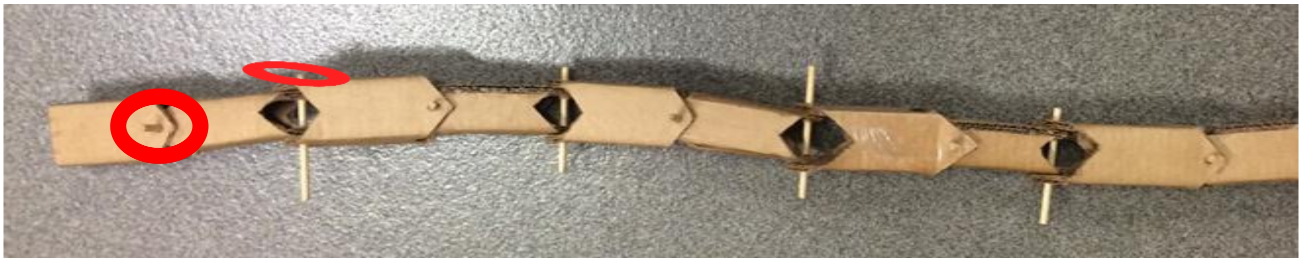


Figure 4. The degrees of freedom of the snake-robot cardboard prototype are demonstrated.

Figure 4 shows the first prototype of the snake robot concept. It was made using cardboard because cardboard is cheap and easy to cut-and-assemble. This prototype was made in order to test concepts and ideas. If the concepts generated work with cardboard, then better prototypes can be made out of sturdier materials. This prototype concentrates on understanding the linkage shape and degrees of freedom needed to acquire the desired motion. The alternating cutouts on each module allow the design to pivot in two directions, one of the pivots allow for gripping while the other allows for directional control to give it a helix shape. This design also allows for the use of repetitive modules, where only two need to be designed and the rest are the same. This aids in making machining and production of the design simpler. This prototype was a rough prototype meaning dimensions of the modules were not taken into consideration. The other aspect of this design that proved to be problematic was the range of motion each module had. The triangular cutout shape shows to have less range of motion for each module to pivot. As a result the design was unable to curl the amount necessary to wrap around a cylindrical object. To resolve these limitations the modules were modified in the first revision.

6.1.1 Revision 1

Figure 5. (a) Shows the original module. (b) Shows the modified module and its cutout.

The first revision to the design included modifying the cutouts to be square instead of triangular which can be seen in Figure 5. The square cutout allows for each module to pivot with more range, while cutting less material from the module. With the triangular design the cutout has to be much deeper and some of the removed space is unsued. The square cutouts allow the modules to push up against each other. The other modification that was perfomed was making the modules to a half-scale size of the actual design. For this revision the module length was based on the size of the smallest tree diameter that is being designed for and the number of effective modules needed to encompass the circumference of the tree. An effective module is the length from one joint that controlls the curling motion to the next joint that controls the curling motion. Figure 6 shows how the design is wrapping around the tree and the effective module. The module length for the half scale was determined to be 3in; the calculations for this can be found in Appendix A.

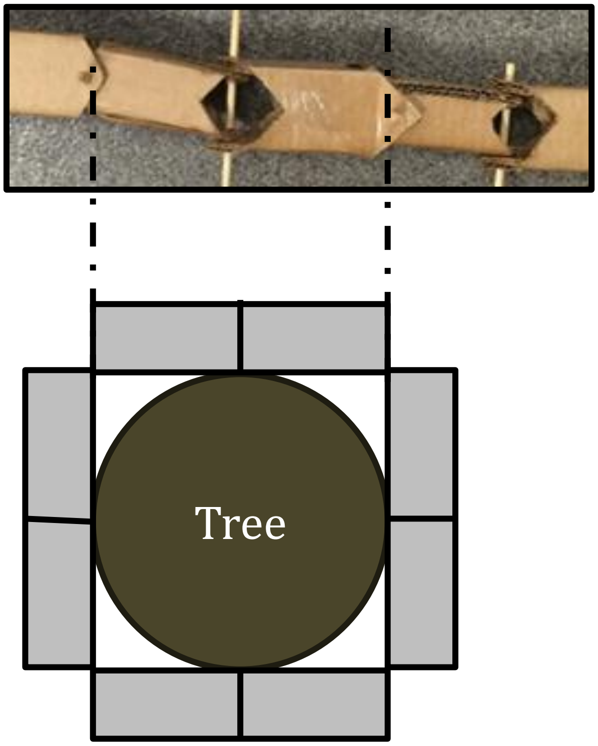


Figure 6. A diagram of how the design wraps around the tree. Note how only half of the joints contribute to the gripping motion.

Now that the scale and the range of motion was sufficient the next modification was to add the gripping mechanism to the design for testing. However, after further research it was determined that using pneumatics and motors as actuators would prove too complicated and expensive for the project.

6.1.2 Revision 2

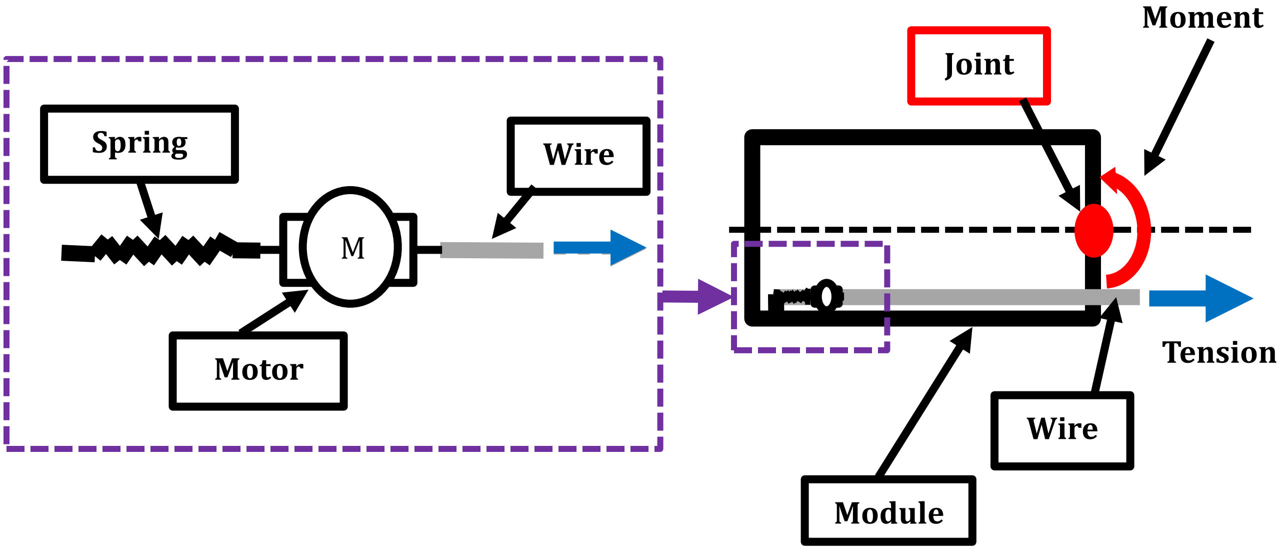


Figure 7. Explanation of how the wire provides tension to the system to aid in the gripping of the tree.

For the second revision of the design the tension wire was added. The goal of the tension wire is to produce significant gripping force to keep the prototype attached to the tree without external influences. Figure 7 is a diagram of how the tension wire works. A wire is attached to a motor and spring in series at one end of the overall design. The motor winds up the wire. Then, as the wire gets shorter, the modules begin to bend due to the moment created about the center of the module. Once the motor tightens the wire to its limit the spring will start to stretch instead. At this point, the motor needs to hold its position to keep the tension in the wire. The spring also allows the system to stretch around imperfections in the tree without losing tension.

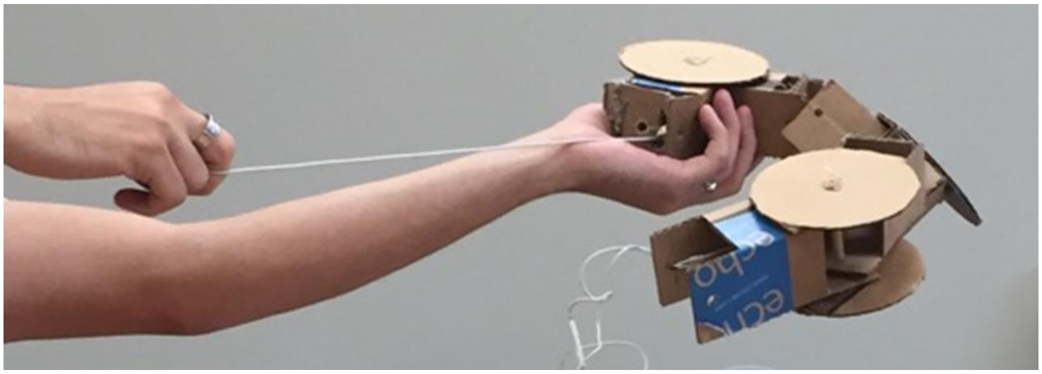


Figure 8. Prototype curling as the string is pulled, proving the concept of the gripping mechanism.

Figure 8 shows the second revision prototype curling when a force was applied to the tension wire. The wire in tension caused the design to curl and hold itself up against gravity. To test for the gripping force, the wire was cut to about 2/3 the length of the design and a spring was attached to one end. This allowed the wire to be pre-tensioned to test if the design could hold itself without outside interference. The first test was on a small tree of about 5in in diameter. It was able to hold its own weight without any problems. Since the final design needs to carry a 20 pound payload up the tree, some extra weight was added to the cardboard prototype. The maximum weight it was able to hold was an additional 500g, which can be seen in Figure 9.

Figure 9. The prototype can be seen holding up 500g of extra weight only using the pretension wire.

As it can be seen in Figure 9 the design is lacking wheels, which the final design must include. The reason for neglecting the wheels was due to their placement and orientation in early testing. The wheels were not in ideal positions when the wire was tensioned. Figure 10 shows how the angle of the wheels relative to the tree slowly increases. At the bottom of the design the wheels are horizontal and perpendicular to the tree's surface. As the design spirals upward, the wheels become more and more slanted and almost vertical. Because of this the wheel were removed for testing grip and a new design proved necessary.

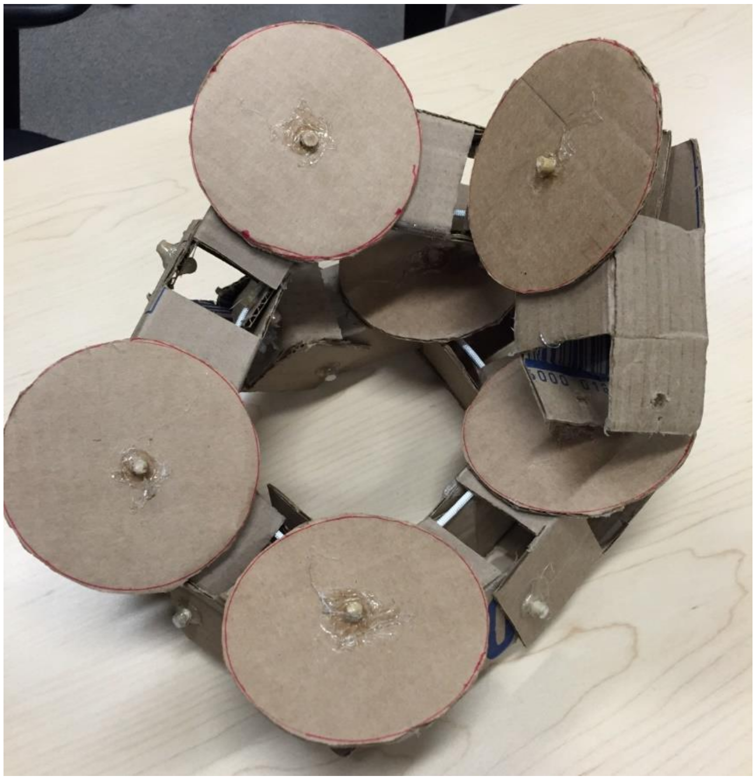


Figure 10. The misalignment of the wheels can be seen when in a curled up configuration.

6.2 Version 2

Figure 11. Version 2 of the snake robot design.

A new prototype was designed to solve the wheel alignment problems the first design had. The joint that created the helix motion, by allowing the modules to pitch up and down, was rotated. The modules now roll about their central axis to allow it to create a helix shape, while aligning the wheels properly to the tree. This new orientation can be seen in Figure 11. This design, in conjunction to the wire, is more complicated. This is because instead of being a hollow tube, it requires a face plate with cutouts at the end of each module.

The tension wire was tested on this prototype to test the new prototype's ability to curl. With the first test, the tension wire failed. The prototype was unable to curl nor hold any tension. Upon closer inspection of the, it was discovered that the assembly of the prototype was done improperly. The wire needs to be located along one side of the design. During the assembly of the prototype, the cutout were alternating instead of being aligned. This can be seen in Figure 12. The top diagram shows what the assembled design looked like, while the bottom diagram shows what it needed to be.

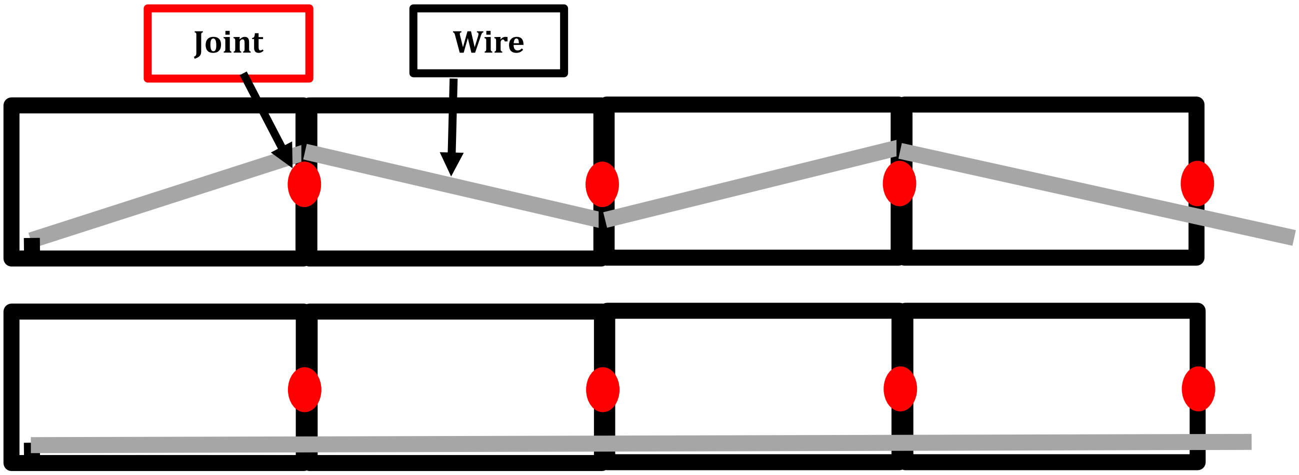


Figure 12. (a) Top: Incorrect way of alignment. (b) Bottom: Corrected alignment of the wire.

After the wire was realigned properly, the curling capabilities were retested. The test proved successful, as the new design was able to curl and hold itself against gravity (Figure 13). It was also able to be rotated to align the wheels without losing tension in the body. The gripping capabilities of the design were not tested on this prototype. After testing the gripping on the previous design, the prototype was rendered useless for any future testing. Figure 14 shows the damage the previous prototype took. The cardboard prototype of version 2 was already weakened by adding the face plates and was worn from assembly errors. To be able to test the gripping capabilities of this design the prototype needs to be made out of a sturdier material. The first revision to this prototype was to make it out of wood and to make it full scale.

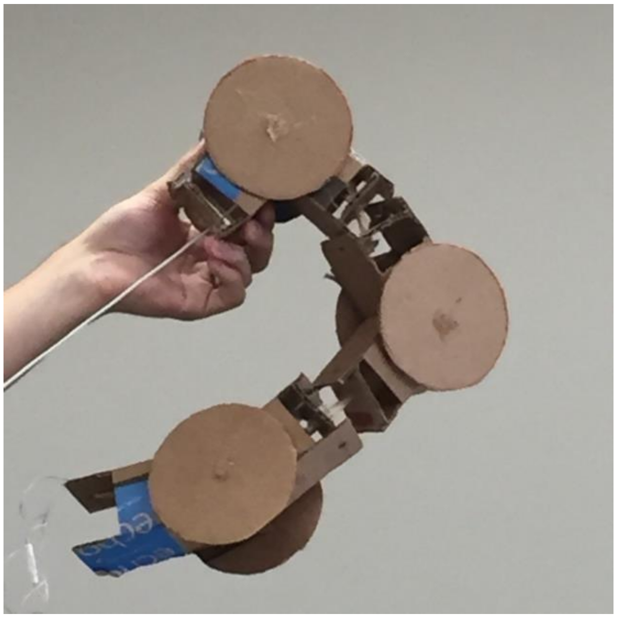


Figure 13. Version 2 of the prototype. Note the curling motion achieved by tensing the wire.

Figure 14. Damaged module of Version 1, Revision 2.

6.2.1 Revision 1

The first revision made to version 2 of the design was to make it out of wood. It needs to be made sturdier since cardboard is not strong enough to handle the amount of tension needed. The first module was cut and assembled at full scale, 6in length 4in wide and 4in tall, which is shown in Figure 15. This was already much larger than anticipated and would cause the wheels to be very large in order to be useful. The width of each module was cut in half, to make it closer to the tree and to reduce the wheel diameter. These two alterations increase the stability and reduce the weight of the design. The altered design was recut and assembled to make sure the pieces could fit together before cutting the full design. Figure 16 shows the altered modules fitting together.

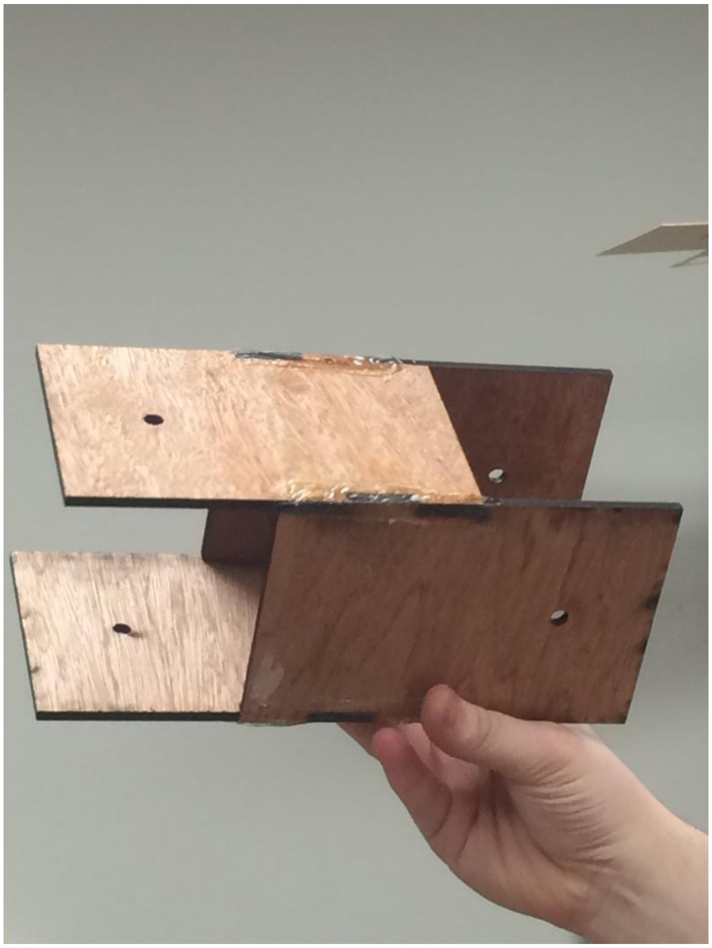


Figure 15. First module made out of wood.

The next modules that were cut for the design were to be tested with the clamping mechanism. Figure 17 shows the design of the modules that will used. The face plate has a hole for the next module to be attached and allows for the rotation between modules. The three other cutouts were made for the wire to be passed through. There are three cutouts to test the best placement for the wire. It is important to know if it can cause enough tension to hold itself to the tree and to see which placement allows the system to curl in a desired and predictable manner. The slots in

Figure 17b show where hooks will be placed to guide the wire. There exist so it doesn't tangle or fall to the wrong side, as well as to reduce friction when pulled. In the near future the wooden prototype will be tested with a cord and a spring to test the clamping power of this design.

Figure 16. Improved modules with half the original width.

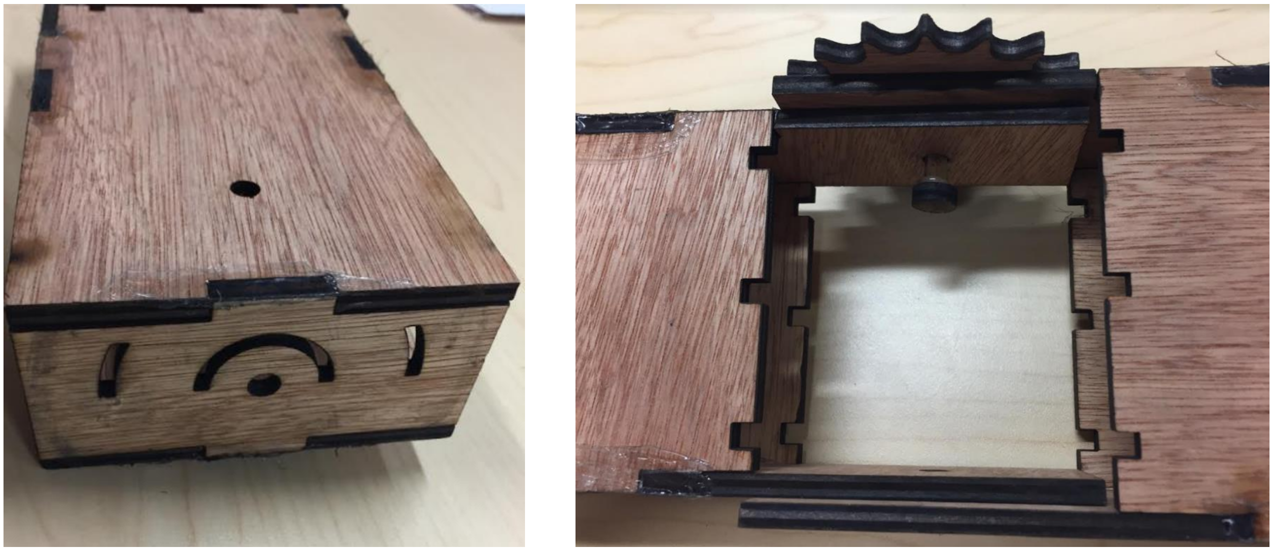


Figure 17. (a) Faceplate. Note the holes for the wire to be guided through. (b) Holes for the guide to be placed on.

6.3 Motor Selection

Motor selection was computed for the gripping mechanism and helical generation. Each mechanism was computed following the same equation (Equation 1).

$$T_m = I\alpha \qquad \text{Equation 1}$$

Where T_m is the motor torque, I is the moment of Inertia of the body to be rotated about its principal axis, and α is the angular acceleration. The moment of inertia was computed using the parallel axis theorem which may be found using Equation 2,

$$I = I_{cm} + md^2 \qquad \text{Equation 2}$$

where I_{cm} was the moment of inertia about the center of mass, m was the mass being rotated, and d is the distance from the center of mass to the location of the motors actuation. Each of these moments were computed using computer aided design of the full scale model snake robot.

The angular acceleration was found by specifying a quintic trajectory that may be modeled as a fifth order polynomial. This was so that one could specify six initial conditions corresponding to: initial angle, final angle, initial angular velocity, final angular velocity, initial angular acceleration, and final angular acceleration. The initial angle was set to 0 rad, final angle was set to $\frac{\pi}{4}$ rad, initial angular velocity was set to $0\,\frac{rad}{s}$, final angular velocity was set to $0\,\frac{rad}{s}$, the initial angular acceleration was set to $0\,\frac{rad}{s^2}$, and the final angular acceleration was set to $0\,\frac{rad}{s^2}$. This was to specify that the angular velocity and angular accelerations were to be zero at the beginning and at the end of the clamping and helical generation. The angular displacement was specified to be $\frac{\pi}{4}$ rad as the helical generation should be no more than $\frac{\pi}{12}$ rad. This was due to analysis from a “Development of a Helical Climbing Modular Snake Robot” [8] that showed the angle providing the maximum climbing speed for helical climbing a constant radius pole was $\frac{\pi}{12}$ rad. The clamping mechanism should provide no more than $\frac{\pi}{4}$ rad as each link will behaves as four effective links in terms of clamping. This may be more easily seen below in Figure 18.

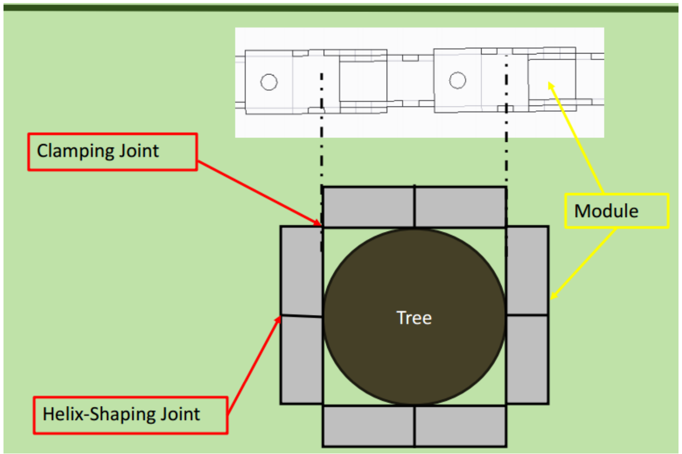


Figure 18. Symbolic Representation of 8 module Snake Robot Gripping a Tree.

As may be seen in Figure 18, the eight module snake robot behaves as four effective links rotating around a circle. Since each provides an equal angle in order to clamp around the circle, the angle in each joint was found to be $\frac{\pi}{4}$ rad. By using the initial conditions specified above, and setting the time elapsed between these values to 1 second, the maximum alpha was used to find the required torque from the motor. The maximum alpha found was to be 4.5 $\frac{rad}{s^2}$.

The final specification required to compute motor selection was the no load angular velocity. This was found by specifying the maximum velocity in order to reach $\frac{\pi}{4}$ rad in one second using the assumptions discussed above in the quintic polynomial model. The maximum velocity was found using MatLab. This value was found to be 84.4 $\frac{rad}{s}$. This value along with the Tm were used to generate graphs that were implemented for motor selection. A sample graph may be seen in Figure 19.

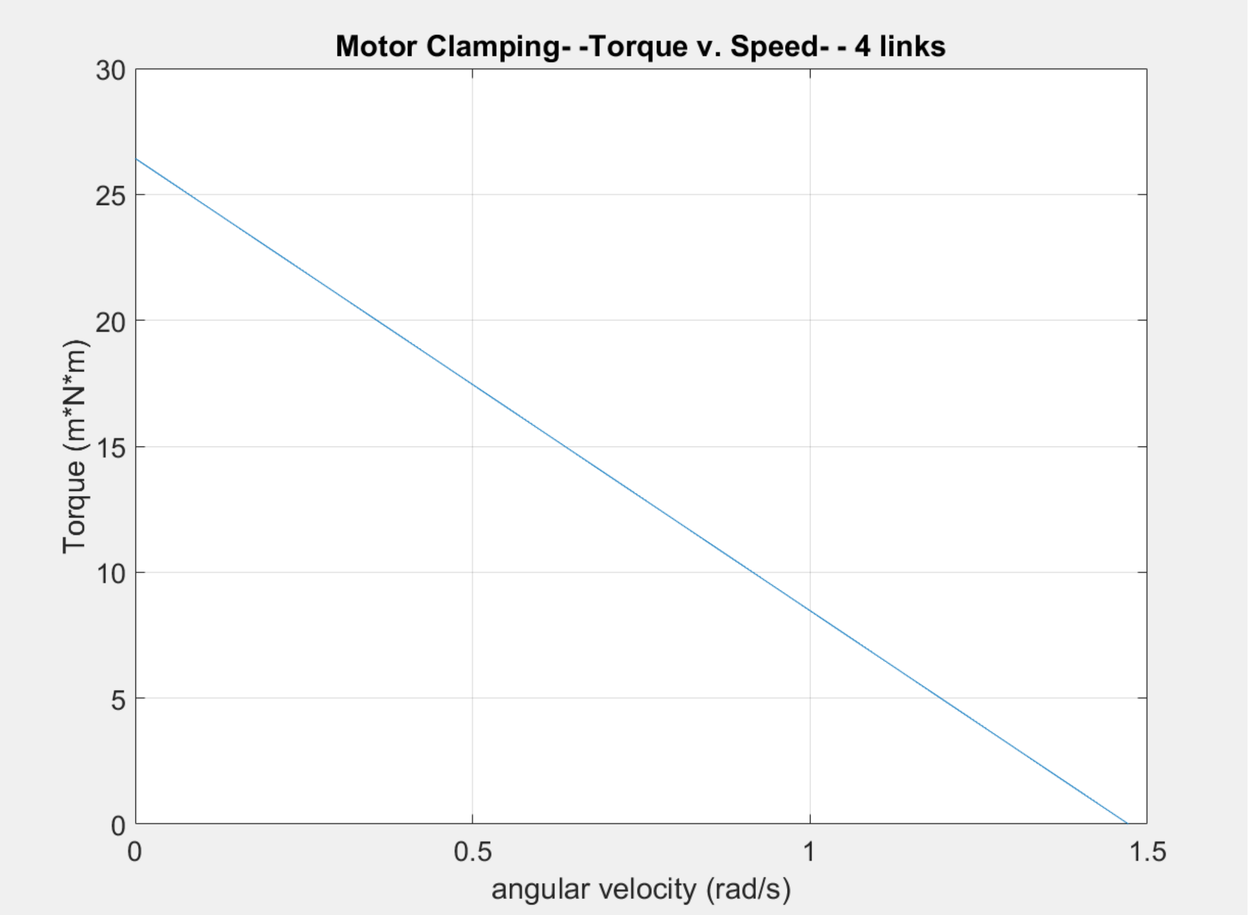


Figure 19. Torque v. Speed Diagram for moving 4 links in order to form helix.

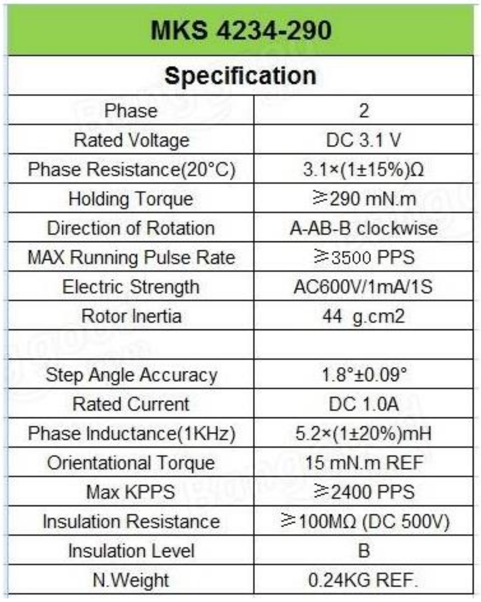
The figure above shows the torque/speed graph implemented to select the motors for the helical generation in order to move four links. This was due to the motor being on the end. The motor on the end has to move all the links before it in order to turn the link in front of which it was rigidly attached to. This causes the required torque to be highest for this link and thus represents the maximum torque requirement in the system in order to achieve an angle of $\frac{\pi}{4}$ rad in 1 second.

The table shown below contains the moment of inertias and the corresponding torque requirements to actuate the helical generation.

Table 6. Moment of inertia and torque requirements for gripping mechanism motors.

Number of Links being Rotated	I (lbf*ft)	Tm (mNm)
1	95.4	0.28
2	659.6	1.9
3	8433.4	24.4
4	9143.3	26.4

From the above values a stepper motor was selected to test the clamping mechanism. The stepper motor was chosen due to its naturally high torque, though low speed. Low speed was not an issue, since the motor's function is to output power, not velocity. The motor selected was a 3d Printer MKS Stepper motor that provides a stall torque of 290 mNm and a step size of 1.8 deg. The stepper motor and its relevant information may be seen below in Figure 20.



MKS 4234-290	
Specification	
Phase	2
Rated Voltage	DC 3.1 V
Phase Resistance(20°C)	3.1×(1±15%)Ω
Holding Torque	≥290 mN.m
Direction of Rotation	A-AB-B clockwise
MAX Running Pulse Rate	≥3500 PPS
Electric Strength	AC600V/1mA/1S
Rotor Inertia	44 g.cm2
Step Angle Accuracy	1.8°±0.09°
Rated Current	DC 1.0A
Phase Inductance(1KHz)	5.2×(1±20%)mH
Orientational Torque	15 mN.m REF
Max KPPS	≥2400 PPS
Insulation Resistance	≥100MΩ (DC 500V)
Insulation Level	B
N.Weight	0.24KG REF.

Figure 20. Picture of the MKS 4234-290 3D printer stepper Motor along with specifications.

The helical shape motor selection followed the same procedure. A table of the values needed may be seen below in Table 7.

Table 7. Moment of inertia and torque requirements for helical generation motors.

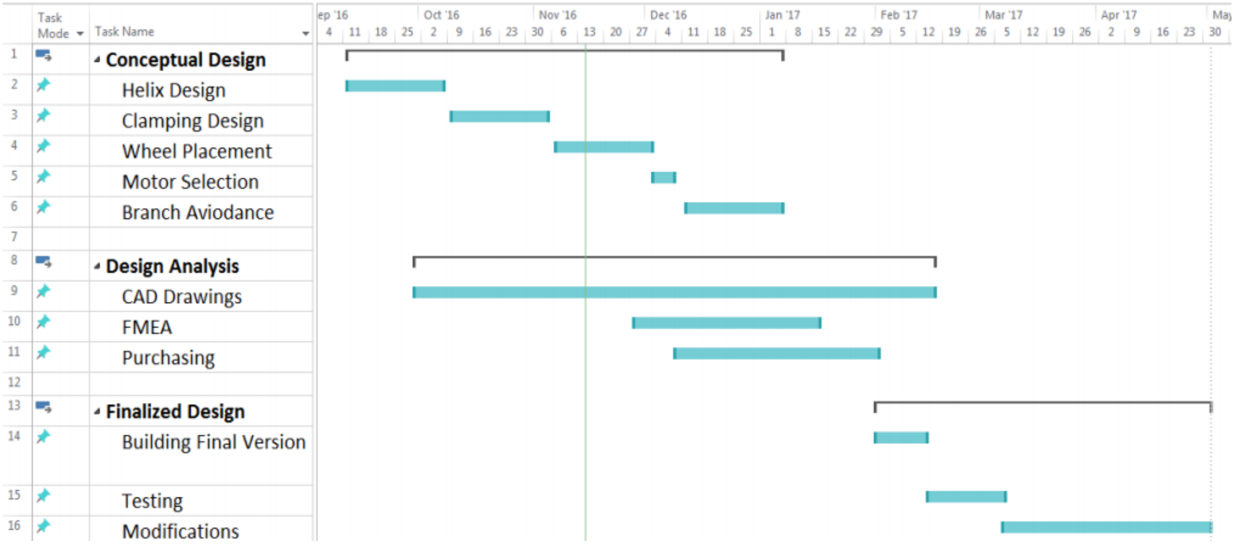
Number of Links being Rotated	I (lbf*ft)	Tm (mNm)
1	70.5	0.20
2	617.6	1.8
3	6645.5	19.2
4	8832.9	25.5
5	9349.2	27

Comparing these values to those above show that the results are similar. For simplicity – and cost reduction – the same type of motor may be used to actuate the helical generation. Since each motor costs $11.05, the full cost for 9 motors was found to be $99.05. This corresponds to just about 5 % of the budget which is accounted for in the cost analysis detailed later in this report.

7. Methodology / Management

7.1 Schedule

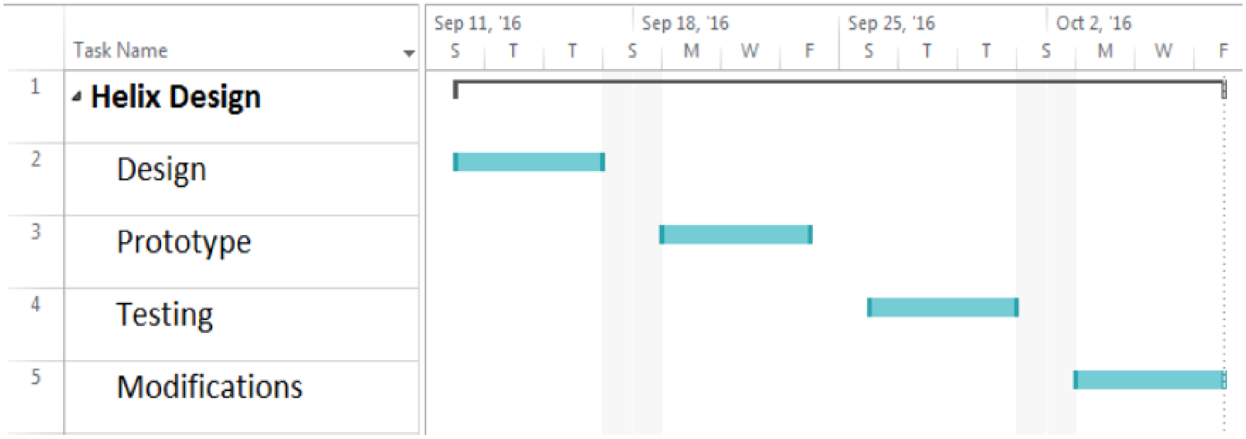
To manage the project development, a Gantt chart was designed. The Gantt chart below (Figure 21) exemplifies the schedule from now till the end of the Spring 2017 semester with the tasks forseen to complete the project shown.



	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 21. Gantt Chart.

Furthermore one could see that dersign will be a large aspect for the completion of this project. In order to have a more detailed understanding of the steps required to complete at least one design iteration, the design aspect of the gannt chart was created in more detail. This may be seen below in Figure 22.



	Task Name
1	Helix Design
2	Design
3	Prototype
4	Testing
5	Modifications

Figure 22. Gantt chart of Helical Generation Design.

This shows that at our pace that each design iteration requires at least a month. Given the lack of time during the spring semester, due to the college of engineering's scheduling issues this year, we may have only two opportunities for iterating design and testing. Based on this it is imperative to use time wisely in order to achieve the best possible design within the time given to complete the project.

7.2 Resource allocation

In order to effectively complete the task at hand, the team must understand how to properly invest their time. Team 10 consist of only mechanical engineers and they are also responsible for the electrical aspect of the project. The team has spent the majority of time prototyping in order to understand the complexity of a robotic snake. The purpose of spending a great amount of time on prototypes is to test and identify problems early in the design process. Also, since team 10 is the first to tackle this type of project, a stable foundation must be created for future iterations. After testing several prototypes, the team has created the final CAD model for the body of the snake. This model has been created and assembled out of wood, with the intention of testing the springs and motors.

7.2.1Budget

The total budget for the development of the snake robot is $2,000 and will be provided be Jeff Phipps, the team sponsor. The budget forecast can be seen in Figure 23. The purpose is for the team to understand what the most expensive aspect of the project is. This will help the team figure out where to invest most of their time for the overall project. The team believes that the majority of the budget (45%) will be spent on the electrical components (EC), 40% on the mechanical components (MC) and 15% for flexible capital (FC).

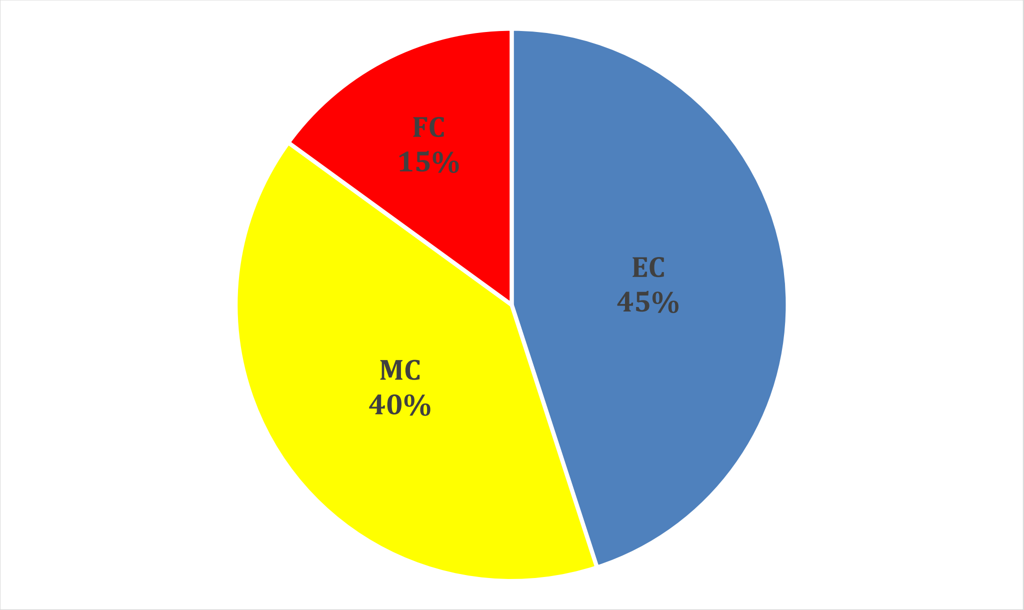


Figure 23. Budget Forecast.

7.3 Challenges

Most of the challenges during development of the snake robot come from the design. Since it will be gripping with onto a tree with great force, the geometry of the design will be crucial to determine the force distribution. Early calculations show that the gripping force, the size adaptability, the stability among other things will vary with how the joint modules are connected. For instance, the closer the joint is to the tree, the greater the stability, but the harder it is to clamp down.

Time is a big challenge to overcome. With only one semester remaining, it is important to efficiently use the limited amount of time. For example, the team needs to identify problems early into the next semester in order to have sufficient time to generate solutions.

7.4 Future Plans

The team is currently working on the addition of wheels and motors. The last step for the design is for the team to complete branch avoidance. The plan is to attach a camera on the head of the snake robot for user feedback. The user will be able to see this feedback via the remote control. With the information of the location of the branches the user will be able to react accordingly. The user will have control of the wheels and have the ability to move the snake robot either above or below the branch.

Once the final design is assembled, the team will be conducting several tests to ensure the design is reliable. Any minor issues regarding the design that may come across during testing will be evaluated. The goal is for the team to ensure the final design is capable of climbing a tree. The success of the design will be measured by the objectives created by the team sponsor.

8. Conclusion

A tree cutting robot is to be designed, with the goal of improving the safety associated with removing trees. Preliminary research suggests that a snake robot is a good choice to handle the task set forth by the sponsor. For snake robots different gaits have already been developed for both, climbing and crawling. While more research was necessary, it was found that the assembly of the snake robot may be handled by attaching the joints modularly with multiple segments connected to one another. In this set-up there is inherently a high amount of redundancies. This will provide flexibility, allowing for more fluid motion. From the information gathered, the main concerns during development will be the gripping mechanism, environmental awareness and power consumption. Preliminary design and testing was done. The design has gone through several iterations, modifying both the module design and the clamping mechanism. The next step is the addition of the motors and the testing that comes associated with it.

References

[1] US Bureau of Labor Statistics.

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[7] C. Wright, A. Johnson, A. Peck, Z. McCord, A. Naaktgeboren, P. Gianfortoni, M. Gonzalez-Rivero, R. Hatton, and H. Choset, “Design of a modular snake robot,” in 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems, Oct 2007, pp. 2609–2614.

[8] Pongsakorn Polchankajorn, Thavida Maneewarn,, 2011, “Development of a Helical Climbing Modular Snake Robot”, IEEE Transactions on Robotics and Automation 11: 790-801.

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.

Appendix I – Sample Calculations

Calculation for length of module at half scale:

$$Diameter\ of\ tree = d$$

$$Circumference\ of\ tree = C = pi * d$$

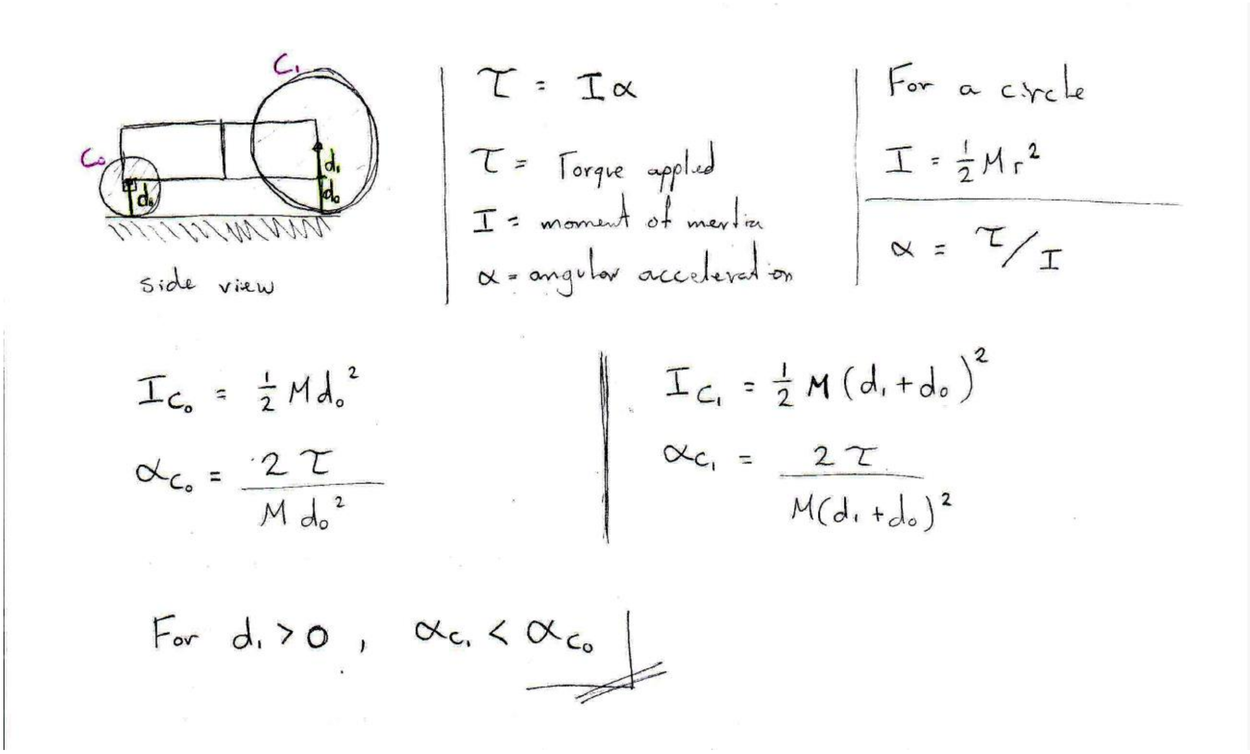
$$Length\ of\ snake = 1.5 * C = 1.5 * pi * d$$

$$Length\ of\ module = \frac{Length\ of\ snake}{\#\ of\ modules\ desired}$$

$$Diameter = 5in; Modules\ Desired = 8\ cnt$$

$$Length\ of\ module\ \approx 3in$$

Calculation for size of wheel and angular acceleration:



$\tau = I\alpha$

τ = Torque applied

I = moment of inertia

α = angular acceleration

For a circle

$I = \frac{1}{2}Mr^2$

$\alpha = \tau / I$

$I_{C_0} = \frac{1}{2}Md_0^2$

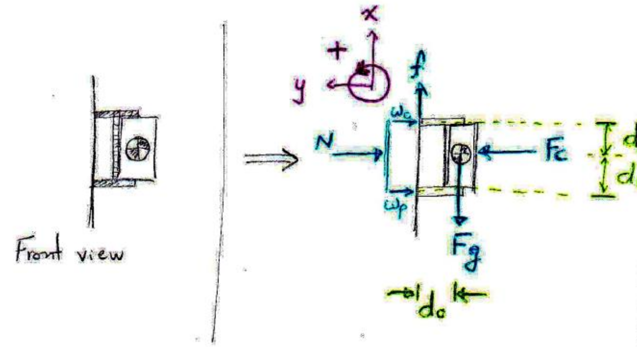
$\alpha_{C_0} = \frac{2\tau}{Md_0^2}$

$I_{C_1} = \frac{1}{2}M(d_1+d_0)^2$

$\alpha_{C_1} = \frac{2\tau}{M(d_1+d_0)^2}$

For $d_1 > 0$, $\alpha_{C_1} < \alpha_{C_0}$

Calculation for clamping force required to stay on tree and to prevent rolling:



F_c : Resultant Clamping force
F_g : Resultant gravitational force
N : Resultant Normal force
↳ ω_o : 'other' wheel component force
↳ ω_p : 'pivot' wheel component force

If we want our robot to be in static equilibrium:

① $\Sigma F_x = 0 = f - F_g$; $f = \mu N$; $N = \omega_o + \omega_p$

② $\Sigma F_y = 0 = \omega_o + \omega_p - F_c$

③ $\Sigma M_p = 0 = F_c d_1 - \omega_o (d_1 + d_2) - F_g d_o$

→ ① $\mu N = mg$
→ ② $N = F_c$

$$\boxed{F_c = \frac{mg}{\mu}}$$

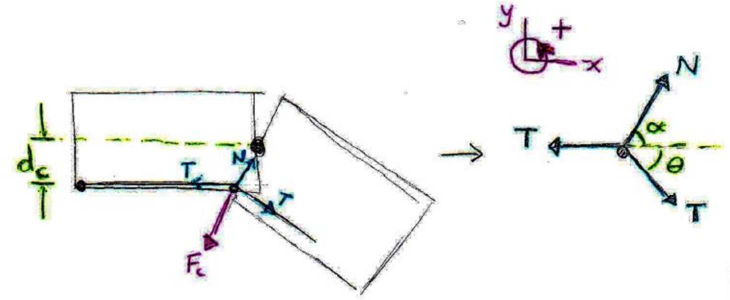
clamping force required to prevent slipping (minimum)

⇒ ③ $0 = F_c d_1 - \omega_o (d_1 + d_2) - mg d_o$

→ $$\boxed{F_c = [\omega_o (d_1 + d_2) + mg d_o] \div d_1}$$

clamping force required to prevent tipping (minimum)

Calculation for clamping force related to the spring-wire system:



N - Force from pivot on wire

T - tensile force on wire

Assuming static equilibrium and friction is negligible

$$① \quad \Sigma F_x = 0 = -T + N\cos\alpha + T\cos\theta$$

$$② \quad \Sigma F_y = 0 = N\sin\alpha - T\sin\theta$$

$$\rightarrow ① \quad N\cos\alpha = T(1-\cos\theta)$$

$$\rightarrow ② \quad N\sin\alpha = T\sin\theta$$

$$①^2 + ②^2 \Rightarrow N^2(\cos^2\alpha + \sin^2\alpha) = T^2(1-\cos\theta)^2 + T^2\sin^2\theta$$

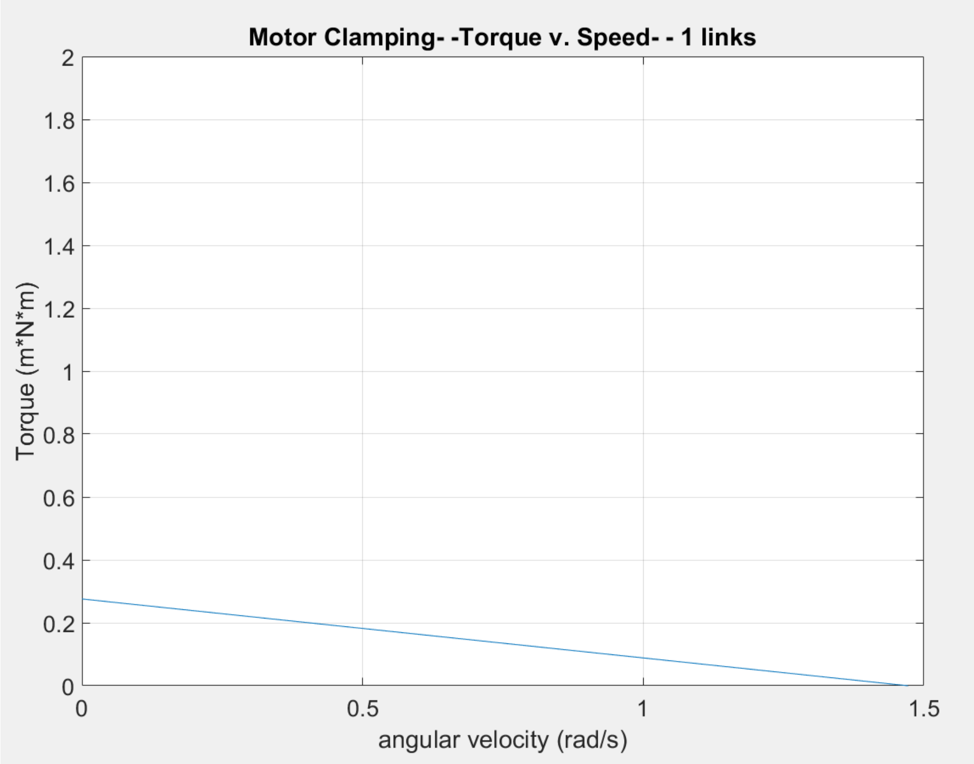
$$N^2 = T^2\left[1 - 2\cos\theta + \cos^2\theta + \sin^2\theta\right]$$

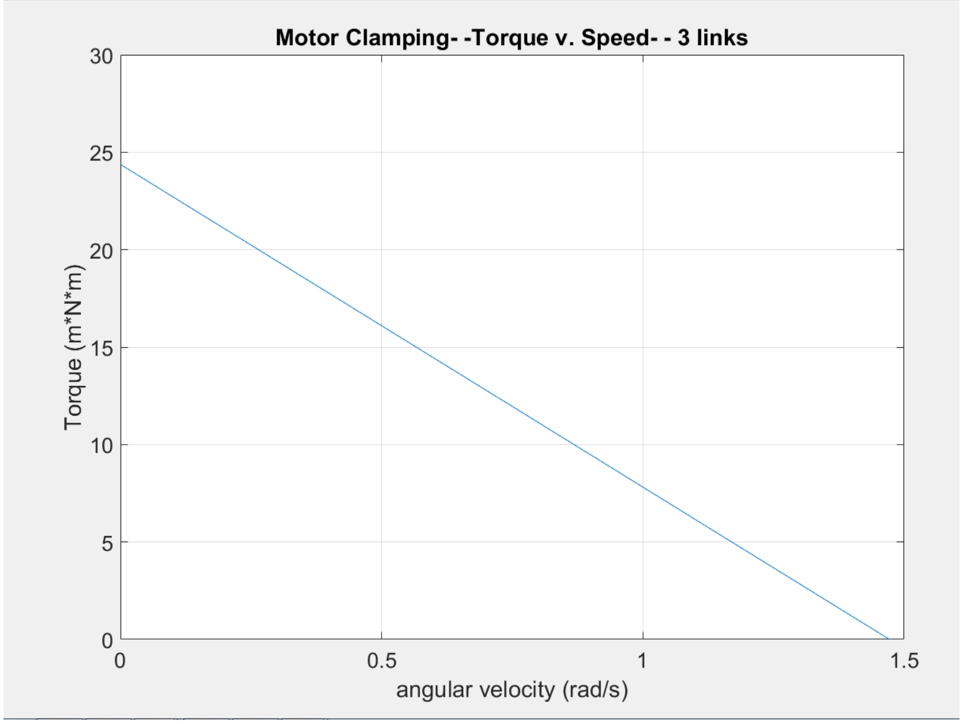
$$\therefore \boxed{N = T\sqrt{2-2\cos\theta}} \longleftarrow$$

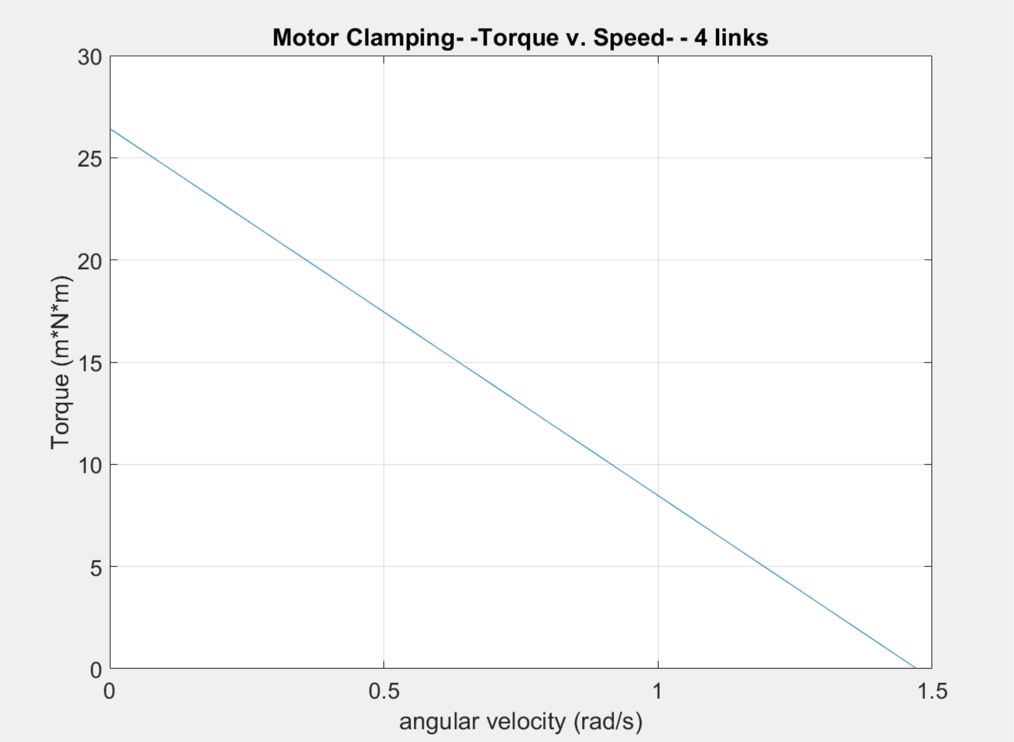
Force from pivot on wire. Will result in clamping force.

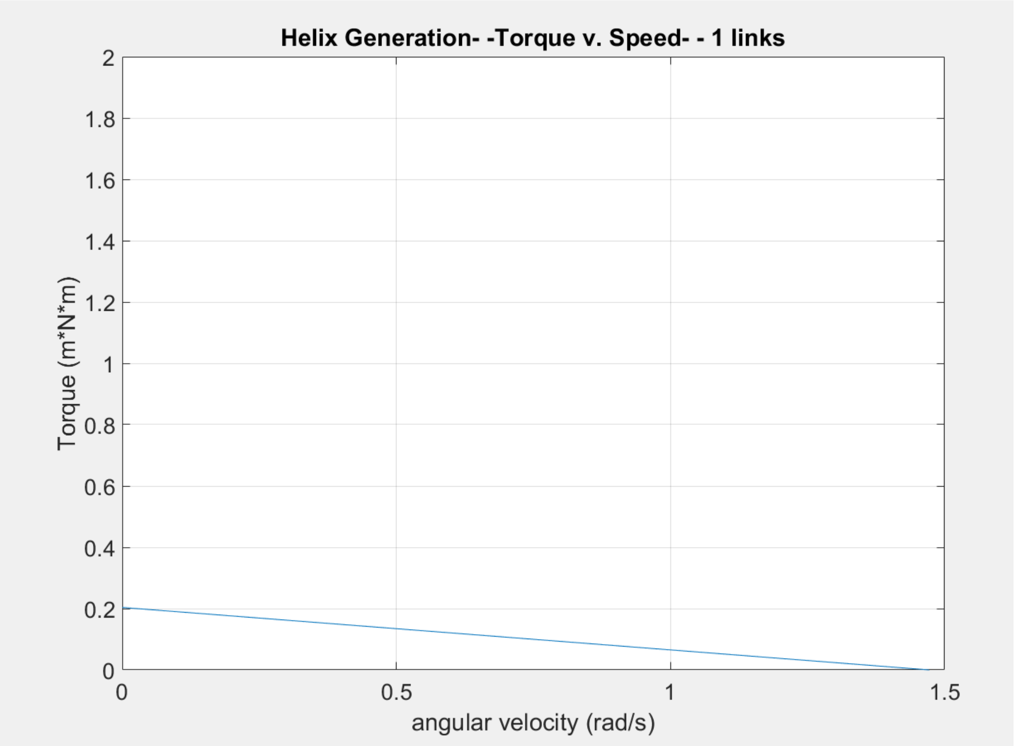
$$\left[\text{Max @ } \theta = 90°\right]$$

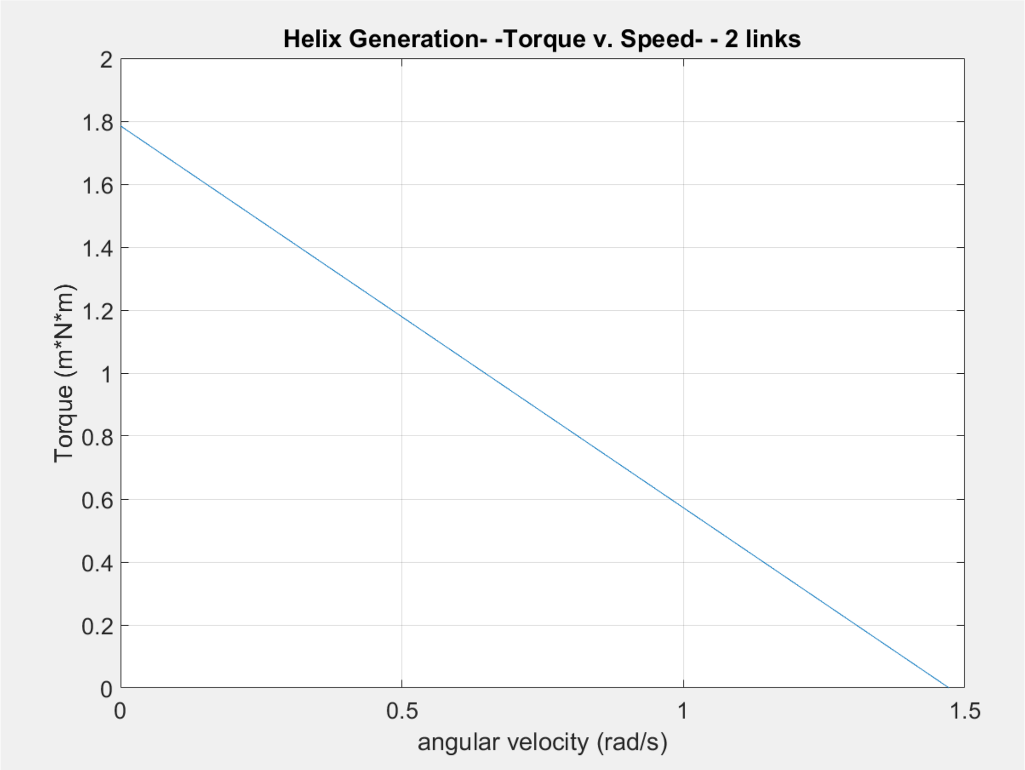
Appendix II – Motor Specs

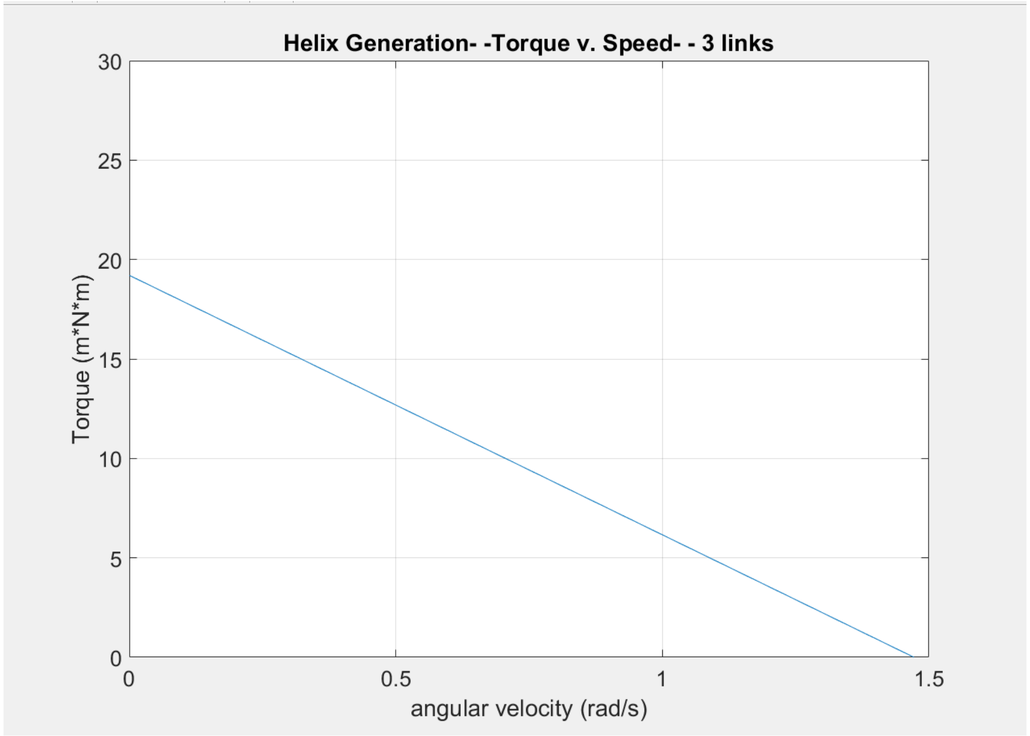


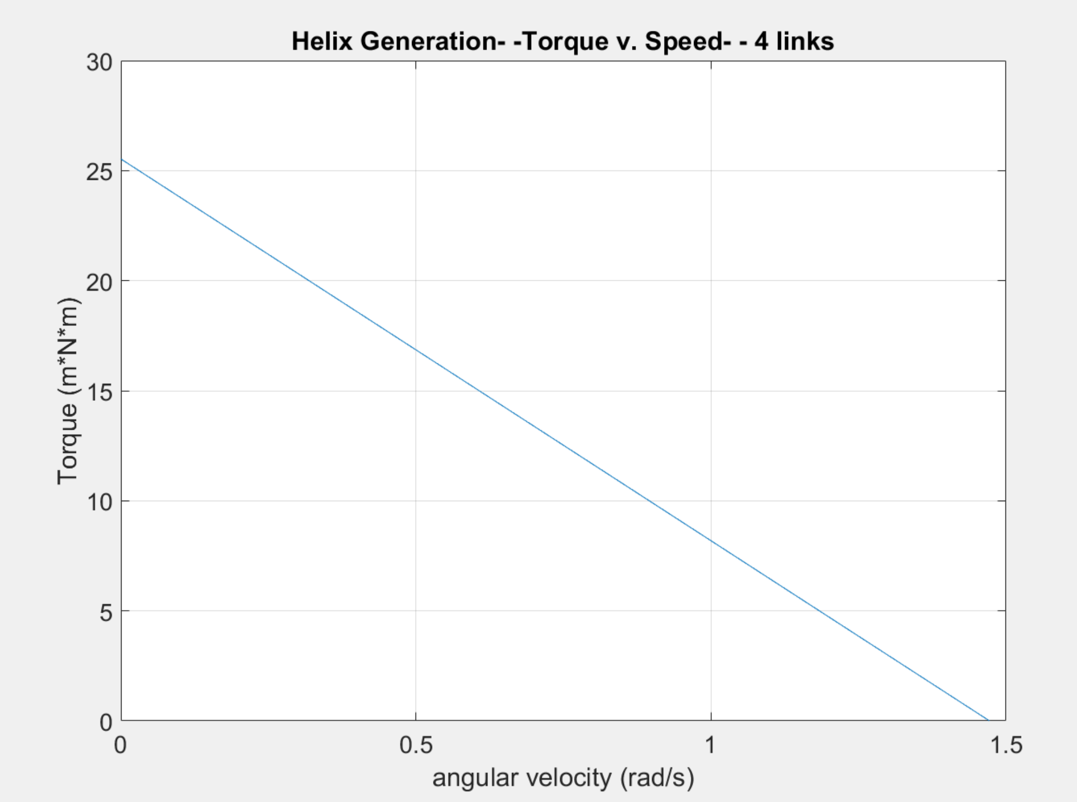


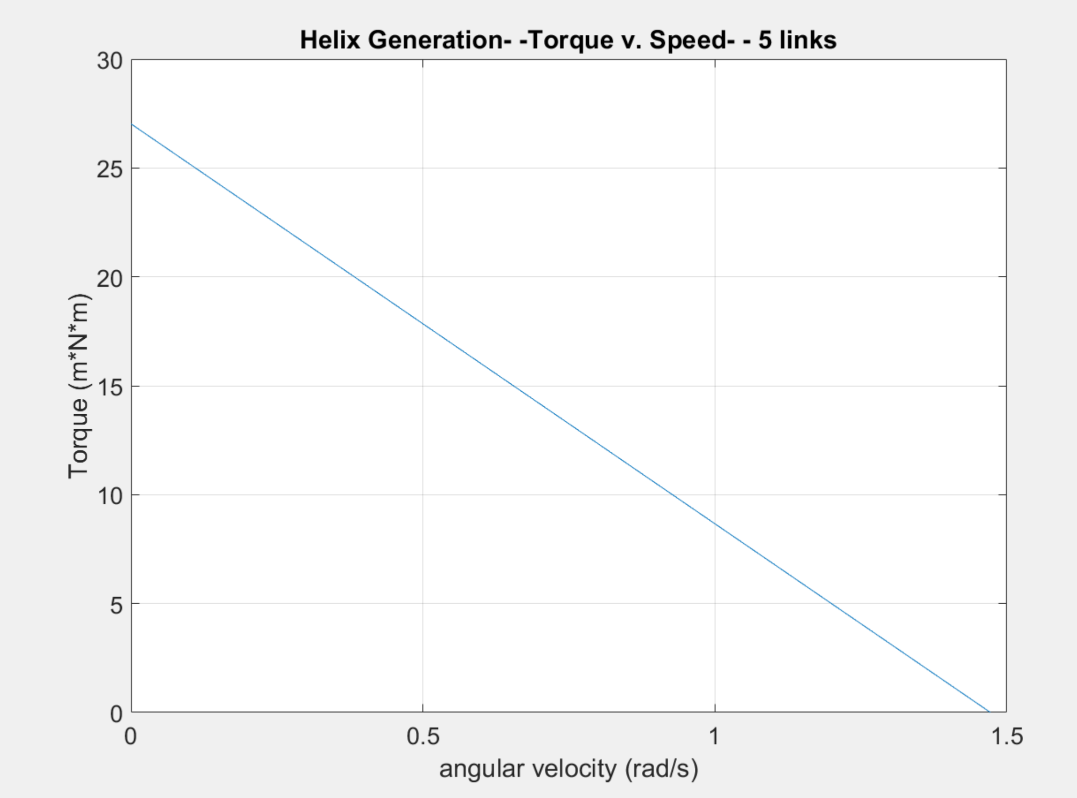

Motor Clamping- -Torque v. Speed- - 4 links
Torque (m*N*m)
angular velocity (rad/s)
0
5
10
15
20
25
30
0
0.5
1
1.5


Helix Generation- -Torque v. Speed- - 1 links
Torque (m*N*m)
angular velocity (rad/s)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
0.5
1
1.5


Helix Generation- -Torque v. Speed- - 2 links
Torque (m*N*m)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
angular velocity (rad/s)


Helix Generation- -Torque v. Speed- - 3 links
Torque (m*N*m)
30
25
20
15
10
5
0
0
0.5
1
1.5
angular velocity (rad/s)


Helix Generation- -Torque v. Speed- - 4 links
Torque (m*N*m)
angular velocity (rad/s)
0
5
10
15
20
25
30
0
0.5
1
1.5


Helix Generation- -Torque v. Speed- - 5 links
Torque (m*N*m)
angular velocity (rad/s)
0
5
10
15
20
25
30
0
0.5
1
1.5