Inchworm Robot
Senior Design Final Report
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Executive Summary

Design Challenge

This goal of this project was to create an inchworm style robot capable of moving in a straight line as well as turn with a locomotion mimicking that of an inchworm. The motivation of the project was purely research based and as such the primary goal was the creation of a novel mechanism that would produce the desired motion. Inchworms move using a form of locomotion known as the two-anchor crawl gait which involves the inchworm beginning with its front and back legs close together such that its body is above them forming a "loop", then lifting its front legs and fully extending its body before lowering them back to the ground. A full cycle of the motion is completed when the rear legs of the inchworm are brought close to the front legs once again forming a "loop" with its body. Other typical design considerations outside of the mimicry of the motion, such as scale or speed, were considered significantly less important that the primary goal, and thus did not have any notable impact on the design process.

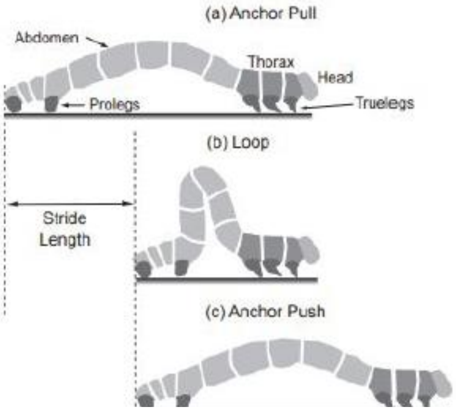

Diagram Depicting the Two-Anchor Crawl Gait of an Inchworm

Design Process

In order to accurately recreate the two-anchor crawl gait, the team identified the lifting of the front legs, the formation of the "loop" with the body, and the dragging of the back legs as the most important aspects of the motion cycle. To do this, the team split the design process into three sections, one for each component of the motion. The front foot section would need to be able to anchor itself to pull the rear forward while also being lightweight enough to be lifted, the rear foot section would need to be able to lift the front section of the robot without slipping backwards and be able to be dragged forward via the arching of the body, and the body section would need to be able to create a "loop" or arch that would drag the rear foot and be able to straighten out when the front section is lifted. Each section was treated as its own design challenge in which several design alternatives were generated, and once a design concept had been selected for each section, the overall robot design was created.

Final Design

The final design of the robot utilizes two different methods of anchoring, one for the front foot and one for the rear foot, and the motion is generated via two stepper motors pulling on tendons through a multi-linkage body section. The body segment consists of 3D printed PLA plastic disks through which four tendons run from the front foot to the rear foot where the controlling stepper motors are housed. A rubber tubing through the center of the body acts as a spring, allowing the body to bend as the tendons are pulled and released by the motors while also forcing the body to straighten when there is no tension on the tendons. The rear foot houses the motors as well as the motor drivers and Arduino Uno microcontroller used to control the motors via analog joystick. Its anchoring system is two rubber wheels mounted on one-way clutch bearings that only allow the wheels to turn in one direction. The front foot consists of a body segment disk with a hinged plate mounted below it. The underside of the plate has a special type of friction pad called Gecko Tape that resists lateral forces but can be lifted up with hardly any force. This allows the front foot to anchor itself and pull the rear foot when the body arches without slipping.

Final Inchworm Robot Prototype

Results

The inchworm robot created by the team successfully re-created the two-anchor crawl gait of an inchworm caterpillar by designing a robot capable of mimicking three of the main characteristics of the motion. With both the front and rear feet of the robot capable of anchoring themselves to the ground surface they are both able to move the other foot in a controlled direction through use of the body segment and its flexibility. Improvements to the robot, such as a smaller rear foot design, a motor change for more torque, or a more refined front foot mechanism to allow for smoother motion, would all allow the robot to mimic the two-anchor crawl gait more accurately and effectively.

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Nomenclature

n = *number of links in body disk stack*

r = *distance from center of disk to outer tendon connection*

r_1 = *radius of arc through center connection of all body disks when contracted*

r_2 = *radius of arc through bottom connection of all body disks when contracted*

S = *arc through center connection of all body disks when contracted*

s = *arc through bottom connection of all body disks when contracted*

T = *center thickness of body disk*

t = *minimum thickness of body disk*

x = *chord length*

X_{step} = *step length per body contraction*

Z = *body length in contracted state*

$Z_{neutral}$ = *body length in uncontracted/neutral state*

ΔZ = *overall change in body length from contracted state to uncontracted state*

θ = *angle of body disk bevel*

ϕ = *overall arc angle of contracted body segment*

Abstract

Nature has evolved numerous methods of movement, allowing for animals to better use their bodies to navigate the world around them. In light of this, some animals are better equipped to navigate different environments and terrains. Studying the locomotion of different creatures has made the creation of robots that mimic their movements possible. The goal of this project was to create an inchworm caterpillar robot capable of utilizing the two-anchor crawl gait of an inchworm caterpillar in both forward movement and turning. The underlying motive for the project was to develop a mechanism that would allow a robot to move in this fashion and discover what might be learned from attempting to mimic nature in this way. Upon completion of the project, the team successfully recorded a video of the functional prototype robot they designed that was capable of the desired motion.

1. Introduction

This goal of this project is to create an inchworm style robot which is able to move in a straight line as well as turn, in a very research minded way. Because of this, the team is interested more in the creation of a novel form of inchworm-type locomotion which can then be refined to serve a specific purpose than in creating a robot which serves a specified purpose at its creation. The process for defining the design challenge presented, gathering relevant information, generating possible solutions to the design challenge, selecting a final design, and the details of such design are all outlined in this report. Through this process the team consulted with their project sponsor Professor Pranav Bhounsule and their project advisor Matthew Alonso, conducted research into several areas relevant to the design challenge, and utilized various tools for generating, organizing, and selecting design options. Additionally, the team utilized tools and processes such as CAD software, geometric analysis, and rapid prototyping to develop a preliminary design and make adjustments to the design as issues emerged. The result of this process was a prototype robot that had been through multiple design modifications and ultimately achieved the desired motion.

2. Problem Statement

The overall goal of this project is to design and build an inchworm robot that is capable of forward motion and turning in the same manner as an inchworm caterpillar. The locomotion of an inchworm can be split into four steps that repeat in order to move the inchworm forward. The inchworm will begin in a “loop” with its front and back legs very close together thus causing its middle section to loop above its feet. Next it will lift its front legs up, using its rear legs as an anchoring point about which to pivot. It will then put its front legs down in such a way that its body is fully extended in the direction it is traveling. Finally, to complete the cycle of motion the inchworm will pull its rear legs forward to the location of its front legs, once again forming a “loop” shape with its body. It is this cycle of motion, called the two-anchor crawl gait that the team design will need to be able to utilize to move forward, and to turn.

Many existing inchworm robots have successfully recreated the forward motion of an inchworm caterpillar, however very few of these have been able to recreate the two-anchor crawl gait locomotion when turning. As such the main focus of this project is finding a way to successfully recreate this turning motion. A robot that is capable of this turning motion may have a broad impact within the study of robotics, as the design may be refined in order to make it suitable for traversing rough terrain or search and rescue missions or miniaturized such that it may be applicable to the medical field to improve accessibility for doctors when performing minimally invasive procedures.

3. Sponsor Background

This project is motivated by the previous research of the project’s sponsor Professor Pranav Bhounsule, a mechanical engineering professor and head of the Robotics and Motion Laboratory at the University of Illinois at Chicago. His research focuses primarily on legged locomotion of robots as well as control optimization. While a professor at the University of Texas San Antonio he worked with undergraduate students on the design of an inchworm robot [1]. This project will largely serve as a continuation of that research, defining constraint metrics such as speed and scale based on the final specifications of the robot from it. Due to this previous research, Professor Bhounsule is less concerned with how the inchworm robot designed by the team will move in a straight line and is more focused on how the team will get the robot to turn. Additionally, because of his interest in optimal control Professor Bhounsule wants the team to focus on finding a simple, easy to control method for each of the functions of the robot. Based on the interests of the project's sponsor, the team's main focus for the project will be finding an easy to control method of turning a robot utilizing the two-anchor crawl gait locomotion.

4. Literature Survey

The literature gathered throughout the team's research process can be broken down into four categories: biological inspiration, theoretical modeling, existing inchworm designs, and non-inchworm robot technologies. The first step the team took was to study and break down the motion of an inchworm to gain biological inspiration for how their robot should move. The theoretical modeling section outlines the physics and mathematical equations the team considered when creating their design for the robot. The team also considered existing inchworm robot designs that could be considered solutions to the design problem as well as designs that utilize mechanisms that could be considered a partial solution. Additionally, the team gathered information on existing technology that could potentially be implemented into the design of an inchworm robot. All of the research gathered was used by the team to generate design alternatives for the various functions of their robot and to decide on the best design choice to pursue further.

4.1. Biological Inspiration

An inchworm is, in fact, not a worm at all, rather it is technically a caterpillar since it has legs on the front and rear portions of its body, despite not having legs through its middle section. This leads to the inchworm having a rather unique method of locomotion known as the two-anchor crawl gait. This type of motion involves the inchworm using its front or rear legs as an anchoring point from which to lift and move the rest of its body. Another critical component of the inchworm's locomotion is its arching body that forms a "loop" when its front and rear legs are close together. This "loop" is the driving force that allows the inchworm to propel its front half forward while utilizing its rear legs as an anchoring point. In order to move forward, an inchworm will anchor its rear legs, lift and extend its body until nearly flat, and then place its front legs back down. From there, it switches from anchoring with its rear legs to anchoring with its front legs and arches its back pulling its rear legs forward and once again forming the “loop” shape.

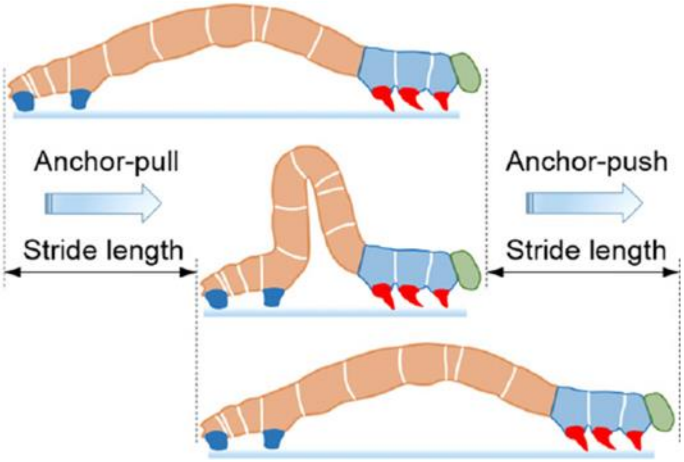


Figure 4.1.1: Locomotion of an inchworm for a single stride [2]

This process, illustrated in Figure 4.1.1, is one full stride of the two-anchor crawl gait, and is virtually the same whether the inchworm is moving in a straight line, or is turning. The only difference being that when its body is in the air, the inchworm will swing its front portion in the direction it is going and place its front legs down toward that direction. It is able to do this because their rear legs make such a strong anchor and can grip the surface they are moving along so easily. In order for the inchworm to successfully turn it must have a strong enough anchor to keep itself steady, but it must also be strong enough to fully lift the majority of its body quite high relative to its feet. All of these mechanics and mechanisms of locomotion need to be taken into consideration by the team when determining how their robot will move, and how it will achieve such motio

4.2. Existing Inchworm Robots

There are many different ways the design problem of this project can be solved. The designs discussed in this section, though they do not cover every existing design, cover the most common and potentially useful design choices. Therefore, the primary goal of this section is not to list every inchworm robot design ever created, but rather to provide a general picture of what kinds of mechanisms and systems are used in these types of robots.

As previously mentioned, Professor Bhounsule previously worked with a group of undergraduate students to design an inchworm robot. The design of this robot can be considered a more traditional robot design compared to many other inchworm robot designs, which would be classified as soft robots. The main focus of their design was their method of anchoring and de-anchoring the robot to the ground in order to facilitate movement. A gripping pad on an actuator in the front and back of the robot would either lift up or be in contact with the ground based on whether the robot needed to move its front or back section. In between this design and some soft robotic designs is the “Loco-Sheet” designed by Chang et al. [4]. The paper discussing this robot talks about a flexible sheet-based inchworm robot that employs a novel locomotion mode made by morphing to overcome discrete high terrains such as steps. In this type of motion, the robot changes its body shape from the standard inchworm “omega” shape to an “S” shape to lift itself up. It is able to do this by exploiting the stiffness of the flexible sheet that comprises the body.

While the previously mentioned inchworm robots use components such as motors and actuators, and have generally rigid bodies, some inchworm robot designs have bodies constructed out of much more flexible materials. These types of robots are generally called soft robots. A specific example of this type of robot comes would be the pneumatic soft robot designed by Zhang et al. [5]. This particular design uses changes in air pressure of a balloon to change the step length of the robot’s locomotion. Another example of a soft inchworm robot comes from Umedachi and Y. Kawahara [6] who proposed a designing scheme to achieve an all 3D-printed wriggle soft bodied robot. Many other soft bodied inchworm robot designs exist; however, it is important to note that because of the nature of these types of robots, they are generally more difficult to control than traditional robots.

4.3. Existing Technology

While researching the team gathered some information on a few technologies that might be useful when designing a mechanism capable of achieving the inchworm’s two-anchor crawl gait. The first of these technologies was shape memory alloy (SMA) which Jani et al. [7] summaries. SMA is a material that, when an electrical voltage is applied to it, will contract to a specific shape. This could potentially be useful in an inchworm robot as it could be used to mimic the contraction and expansion of an inchworm when it moves. Another technology that could be used for the same purpose is Y. Kim and Y. Cha’s [8] tendon-drive soft origami pump. The pump expands and contracts as air is pumped through it and it always returns to the same shape because of the accordion style folds in it. Both of these technologies, or potentially both together, could be used to create the mid-section of the inchworm robot which would enable the two-anchor crawl gait locomotion required by the problem statement.

4.4. Codes and Standards

As this project is primarily research based, there are few industrial standards which are applicable to its design. However, there is one important standard, IEEE 1872-2015[9] which lays out axioms of robotics, and definitions of terms relating to robotics and automation. This document is used as a knowledge reference, and a sort of “style guide”, or dictionary, for writing about the team’s findings and design.

5. Design Criteria

The basic requirements for the team’s robot design are all derived from the motion of an inchworm caterpillar. When analyzing the motion of real-life inchworms, the team identified three main requirements or constraints that their robot would need to comply with in order for its motion to properly mimic the two-anchor crawl gait. First, the configuration of the legs and their ability to act as an anchor for the rest of the body was noted. This led the team to its first design constraint: anchoring. In order to replicate the two-anchor crawl gait, a system needed to be designed that allowed for either the head or rear of the robot to be fixed in order to push or pull the other end, and in the rear’s case, lift the front segments as well. Closely related to this constraint is the team’s second requirement for their robot, being the “looping” motion. The team decided that in order for their robot to properly recreate the two-anchor crawl gait, the stride of their robot would need to include a point at which the front and rear legs of the robot are close together with the middle section being in a loop shape, similar to the shape an inchworm makes.

The final component critical to the movement of an inchworm, and also the primary interest of the project’s sponsor, is the inchworm’s ability to turn. Observing videos of inchworms in motion showed that the inchworms tend to bend the entirety of their arching segment of the body to turn. In order to simplify this motion, the team decided that the bulk of the turning could be captured by simplifying the design so that the pivoting motion of the body originates from the rear leg segment. This simplification of the turning is necessary because doing otherwise would require the body segment to have articulating joints throughout its entirety, which would not be practical. This method of turning and the other two requirements the team has outlined for their design are the basic building blocks of the two-anchor crawl gait locomotion that their robot needs to mimic and serve as the main qualifiers of whether or not their design is successful.

Since this project is more research oriented, the only deliverable required by the sponsor is video evidence of the robot performing both the two-anchor crawl gait and turning accurately once. The qualifier for “accurate turning” will be an obstacle course for the robot to maneuver through. The team also decided that in addition to a video of the robot working, a prototype which can replicate the results from the video would also be delivered. Operation conditions for the robot have been left entirely up to the team and so it was decided as a tertiary objective that the robot should be able to traverse over as many surface conditions as possible. Finally, the project sponsor specified that the robot does not have to be autonomous and so the team decided that the robot will be remotely controlled.

6. Assumptions and Metrics

Based on the end goal provided by the sponsor, as well as the design criteria laid out by the team, a few basic assumptions can be made. First, it can be assumed that the final prototype will resemble the linear motion and turning ability of an inchworm. Additionally, it can be assumed that the robot will be capable of operating multiple types of surfaces, though a smooth surface such as hardwood flooring will likely be more ideal that a rough surface like carpeting. In addition to these assumptions, some target metrics can be defined based on the robot designed by Professor Bhounsule’s students. The robot from their research was roughly two feet in length, so the team will aim for their design to be about the same length, as it does not need to be the size of an actual inchworm. This robot weighed about four kilograms which may prove to be too heavy if the robot is to be able to turn while lifting portions of itself up. In terms of movement speed, the robot was only able to move at a rate of 1 inch per second, which the team will aim to increase. Finally, the turning radius of the team’s robot does not need to meet a specific value, as the goal is to achieve some turning motion, not matter how small.

7. Design Selection

When generating design alternatives and possible solutions to the presented design challenge the team took a multi-step approach. This approach began with general brainstorming and the initial organization of their project's requirements and constraints in the form of a fishbone diagram. It then moved on to the generation of design alternatives that could be a solution to their design challenge. Finally, the team underwent the process of determining a final design upon which to perform more in-depth analysis by generating several concepts for both the body section of the robot, as well as for the leg segments that will be used for anchoring. For each of these major components, a design matrix was created in order to organize, categorize, and quantify the strengths of the various design options more easily.

7.1. Concept Generation

The first step the team took in their design selection process was to begin with a fishbone diagram outlining their project and design challenge. The fishbone diagram was designed to organize all of the various requirements, constraints, and possibilities for the project into sections that can be focused on individually. Figure 7.1.1 shows the fishbone diagram that the team generated which is organized into six major categories that, when combined together, will meet the customer requirements outlined by the sponsor. This diagram was used by the team to get a better idea of what exactly their robot was going to need to do and what outside factors would need to be taken into consideration when creating more complete design concepts. After creating the fishbone diagram the team formulated more thorough design alternatives for their robot. When doing this the team decided to generate design options for the body section, which would be responsible for the robot's turning, and the anchoring system that would mimic the legs of an inchworm.

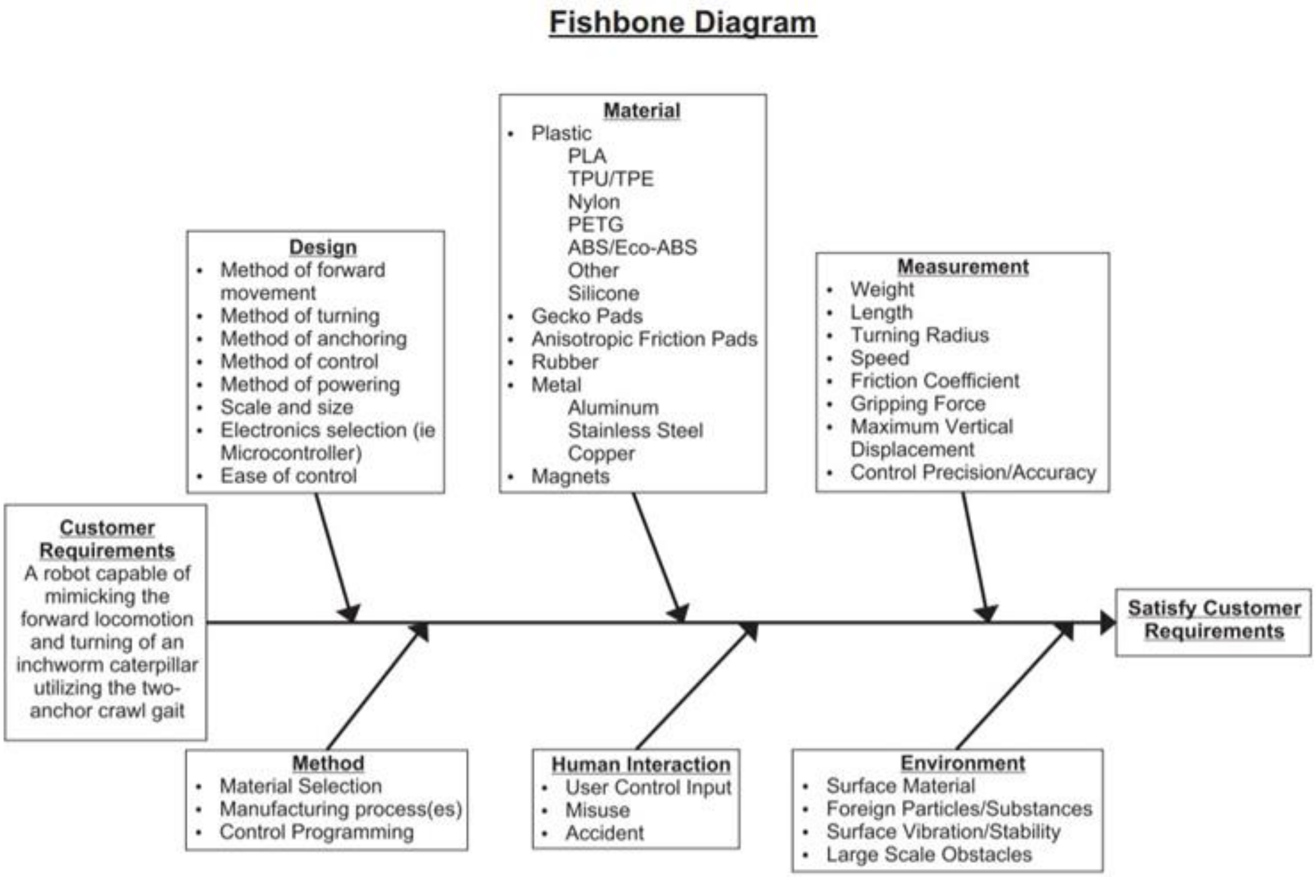


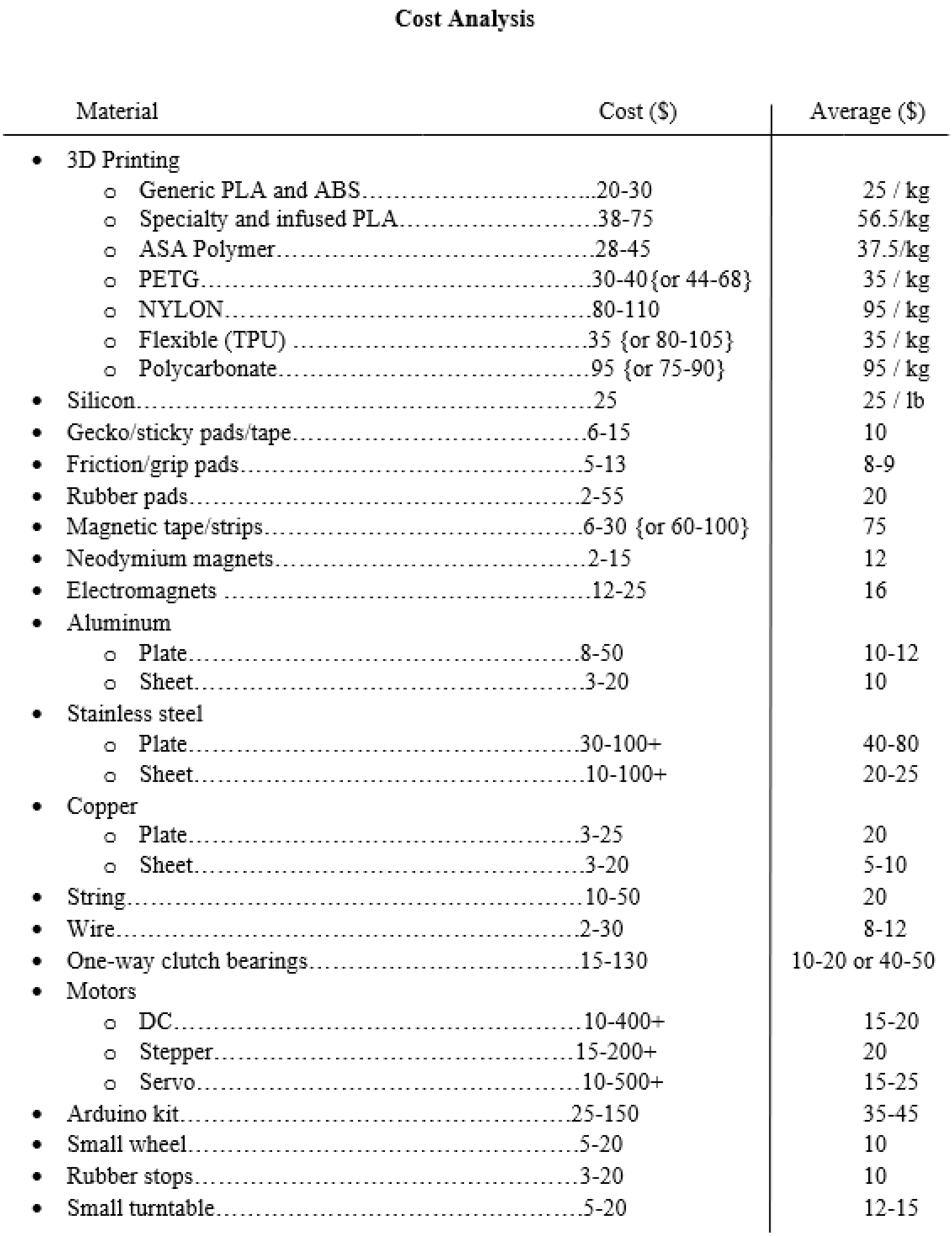
Figure 7.1.1: Fishbone Diagram Outlining the Requirements of the Project

7.2. Design Alternatives

Regarding the articulating body section of the robot, three major design concepts were considered. The first, a traditional robot, made of two feet and two linkage-like body sections with a motor at the joints connecting each segment to the next. The other two designs considered utilize a similar method of motion, in that they consist of flexible, continuous bodies, actuated by motors housed in the rear foot of the robot, along with cables running through the length of the body. One of these designs utilizes a body which is in essence a very loose spring, and the second utilizes a stack of specially shaped plates that allow for a predefined range of motion. In addition to this, four major design concepts were explored as solutions to the problem of anchoring the front and rear feet in order to perform the two-anchor crawl gait most effectively. The major design concepts include using electro-magnets to anchor the feet, a ratcheting wheel mechanism to allow for motion in only one direction, or a roller skate style toe-stop to allow for similar action. For each of these components, the team created a decision matrix in order to analyze the practicality of each design option in a quantifiable way.

7.3. Cost Analysis

One of the attributes the design alternatives were rated on in the decision matrices created by the team was cost. In order for the team to ensure that they would be able to construct a prototype of their design, they needed to do an in-depth cost analysis of the different materials and components their different design options might use. A list of the materials and components the team will consider using for their design is shown in Table 7.3.1 including the general range of pricing as well as the average price for the different components.



Cost Analysis

Material	Cost ($)	Average ($)
3D Printing		
Generic PLA and ABS	20-30	25 / kg
Specialty and infused PLA	38-75	56.5/kg
ASA Polymer	28-45	37.5/kg
PETG	30-40{or 44-68}	35 / kg
NYLON	80-110	95 / kg
Flexible (TPU)	35 {or 80-105}	35 / kg
Polycarbonate	95 {or 75-90}	95 / kg
Silicon	25	25 / lb
Gecko/sticky pads/tape	6-15	10
Friction/grip pads	5-13	8-9
Rubber pads	2-55	20
Magnetic tape/strips	6-30 {or 60-100}	75
Neodymium magnets	2-15	12
Electromagnets	12-25	16
Aluminum		
Plate	8-50	10-12
Sheet	3-20	10
Stainless steel		
Plate	30-100+	40-80
Sheet	10-100+	20-25
Copper		
Plate	3-25	20
Sheet	3-20	5-10
String	10-50	20
Wire	2-30	8-12
One-way clutch bearings	15-130	10-20 or 40-50
Motors		
DC	10-400+	15-20
Stepper	15-200+	20
Servo	10-500+	15-25
Arduino kit	25-150	35-45
Small wheel	5-20	10
Rubber stops	3-20	10
Small turntable	5-20	12-15

Table 7.3.1: Cost Analysis Summary of potential materials and components

7.4. Final Design Selection

For the body segment, a decision matrix was created that rated each design option on its resemblance to an inchworm (or, more generally, flexibility), its ease of generating lateral motion, its ease of turning, novelty of the mechanism, and cost. This decision matrix, shown in Table 7.4.1, was informed by very preliminary 3D-printed prototypes of the two flexible body types, and upon completion revealed that the stacked disk body is the most promising of the presented ideas.

Body Segment	Biomimicry	Lateral Motion	Turning Capacity	Novelty	Cost	RANK
Weighting Factor	1	1.5	2	0.75	0.75	1
Linkages	0.8	0.8	0.33	0.05	0.5	
	0.8	1.2	0.66	0.0375	0.375	3.0725
Discs	0.8	0.7	0.9	0.9	0.25	
	0.8	1.05	1.8	0.675	0.1875	**4.5125**
Slinky	0.4	0.7	0.75	0.9	0.25	
	0.4	1.05	1.5	0.675	0.1875	3.8125

Table 7.4.1: Decision Matrix for the Body Segment Design

This concept consists of a stack of octagonal disks, through which four “tendons” run, which will be anchored at the front end of the body, and contracted by motors at the rear, causing a bending of the entire body. By making the disks octagonal and tapered, it provides eight indexed positions into which the body may bend, allowing for more ease of control over a truly continuous body, while the semi-continuous construction will allow the robot to truly mimic the bending motion with which the inchworm moves in nature.

Similar to the process for the body segment selection, the foot segment selection was done through the generation of a decision matrix which is shown in Table 7.4.2. The method that was determined to be the most viable was a material known as Gecko Tape. This tape uses a method similar to that used by Geckos to remain anchored. This means that if a force is applied to the tape parallel to the surface to which it is secured, the tape will not slip, however it takes little to no force to peel the tape from its surface.

Feet Segments	Anchoring	Releasing	Turning Capacity	Novelty	Cost	RANK
Weighting Factor	1.5	1.5	2	0.25	0.5	1
Gecko Pads	0.9	0.45	0.5	0.6	0.8	
	0.9	0.675	1	0.45	0.6	**3.625**
Electro-magnets	0.5	0.5	0.75	0.25	0.9	
	0.5	0.75	1.5	0.1875	0.675	3.6125
One-way Bearings	0.6	0.6	0.33	0.1	0.45	
	0.6	0.9	0.66	0.075	0.3375	2.5725
"Toe Stop"	0.33	0.5	0.5	0.45	0.45	
	0.33	0.75	1	0.3375	0.3375	2.755

Table 7.4.2: Decision Matrix for the Foot Segment Design

By combining these two design concepts, the robot should be able to perform the two-anchor crawl gait by peeling its gecko-like foot off the ground upon complete contraction, and then re-sticking it when placing its front foot back down, and it should be able to lift its front section without falling over due to the presence of all of the actuators and electronics in the rear foot of the robot.

8. Preliminary Design

With an overall design concept selected, the team began the process of developing a more specific design for each section of the robot and fleshing out the details of how these sections would combine to make the robot. The team opted to design the majority of the secondary functions of the robot around what the selected body segment would require to function as intended, and around the capabilities of the selected front foot anchoring system. This approach led the team to develop solutions that utilized the components and designs they knew would be present in the final robot to their advantage. By using this approach the team developed both a front and rear foot design that optimize the motion of the body and take full advantage of the strength of the gecko tape. The final design consists of three main sections, the body segment, the front foot, and the rear foot, and successful execution of the design would result in the desired two-anchor crawl gait using just two stepper motors.

8.1. Body Segment

Since the team wanted to use the selected body design concept as a jumping off point for the rest of the robot, it was the first section the team focused on. Through geometric modeling and the use of 3D printing to rapidly prototype and test different disk designs, the team was able to prove that the selected design would be able to achieve the desired motion. The resulting body segment consists of 13 octagonal disks connected together by string tendons that will later be connected to the front and rear foot segments. The disks consist of two identical 3D printed parts made out of PLA plastic, that were glued together to form a singular body disk. The material and method of manufacturing for the disks were chosen primarily due to PLA being lightweight and 3D printing being the easiest way to quickly and cheaply produce 26 identical, yet rather complex parts.

8.1.1. Design

The body of the robot consists of a series of octagonal disks that are beveled on the largest face so as to provide eight distinct mating surfaces. Four tendons run through the length of the body at the top, bottom, left, and right respectively, and an additional tendon runs through the center of the disk stack. The four outer tendons are secured at the front end of the robot to the front most disk, and at the rear to the gimbal assembly so that they may be contracted, causing the entire disk stack to curve. The inner tendon acts as a return spring for the stack, bringing it back into alignment after curving. Figure 8.1.1.1 shows a small section of body segment disks in both uncontracted and contracted states.

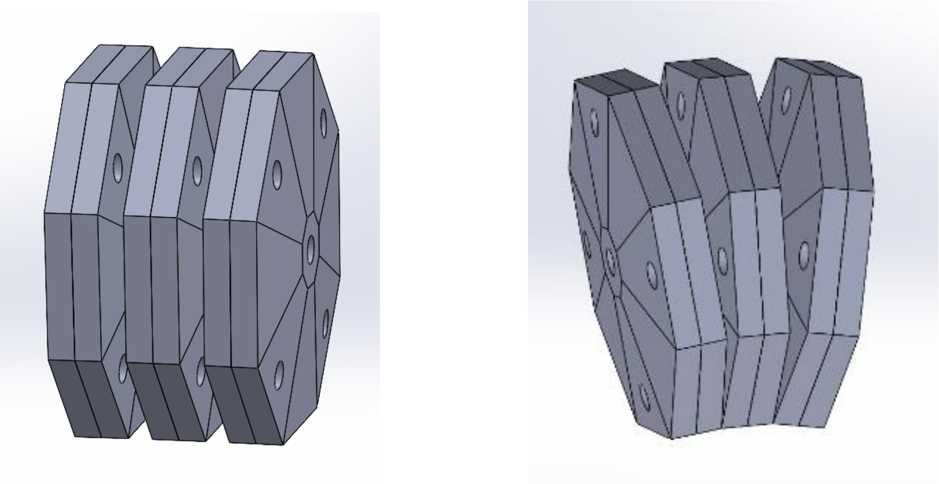


Figure 8.1.1.2: Uncontracted (left) and Contracted (right) Section of Body Segment Disks

8.1.2. Geometric Analysis

An important part of designing the body segment was conducting a geometric analysis of the disk stack to gain a better understanding of how the geometry of the individual disks affects the overall motion of the body. In conducting this study the team was able to determine the amount of contraction required in a tendon to produce the desired motion and the total distance covered in a single stride of the two-anchor crawl gait, both of which informed the design process and helped the team gauge whether or not a design iteration would meet their metrics. It should be noted that several assumptions were made to analyze the body motion. First, the curves created by the contracted disk stack were idealized to be circular, with S being the curve through the points of contact of the disks, and s being the curve at the bottom of the contracted stack.

In order to calculate distance that a tendon must be pulled to fully contract the body, the disks must be examined in both their contracted and uncontracted states, both of which are shown in Figure 8.1.2.1. The length of tendon to be pulled can be calculated on a per disk pair basis by determining the difference in lengths between points at distance *r* from the center line on two disks in both the contracted and uncontracted states. In the uncontracted, neutral state, this distance is

$$Z_{neutral} = 2r\ tan\theta$$

And in the contracted state, the distance is

$$Z = 2r(tan2\theta - tan\theta)$$

From this the overall change in length can be calculated as

$$\Delta Z = 2r(tan2\theta - tan\theta)(n - 1)$$

Where *θ* is the angle of between the vertical axis and the bevels on the disks, and *n* is the number of links in the stack.

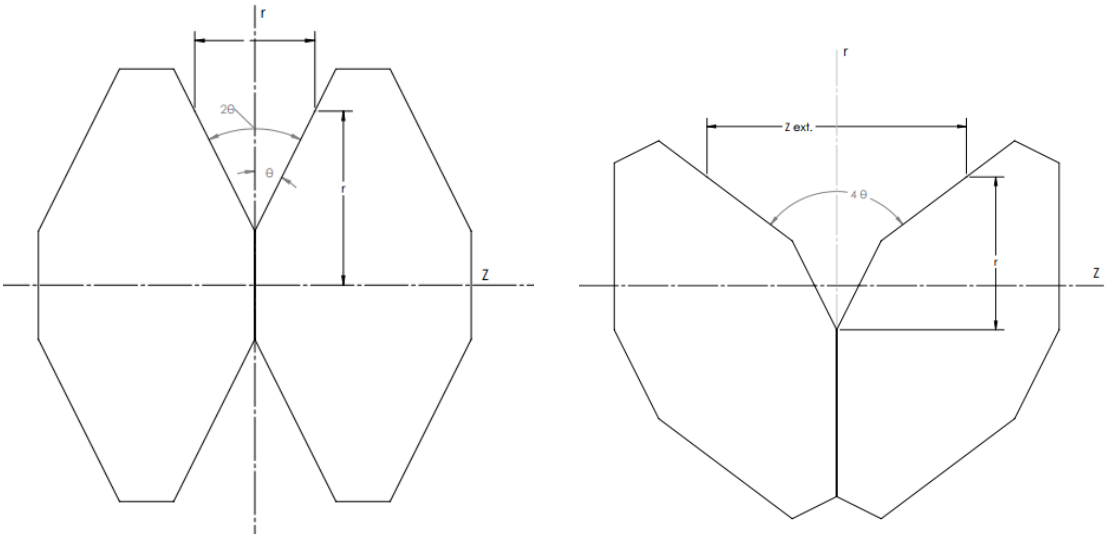


Figure 8.1.2.3: Link Geometry in Uncontracted (left) and Contracted (right) States

In order to calculate the distance covered by a single step of the robot, the difference between the contracted and uncontracted length of the body must be found. Figure 8.1.2.2 shows a model of the overall geometry of the body segment with the disk stack modeled as a singular mass, while Figure 8.1.2.3 shows the geometry of a singular disk.

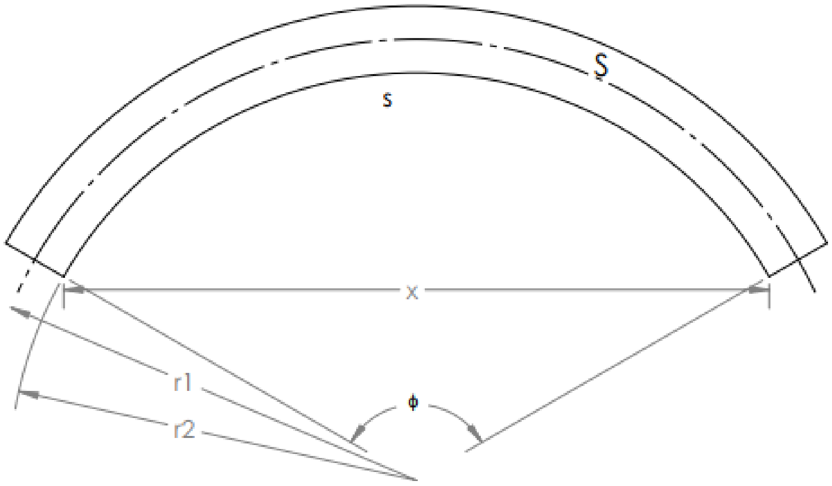


Figure 8.1.2.2: Simplified Model of the Overall Geometry of the Body Segment

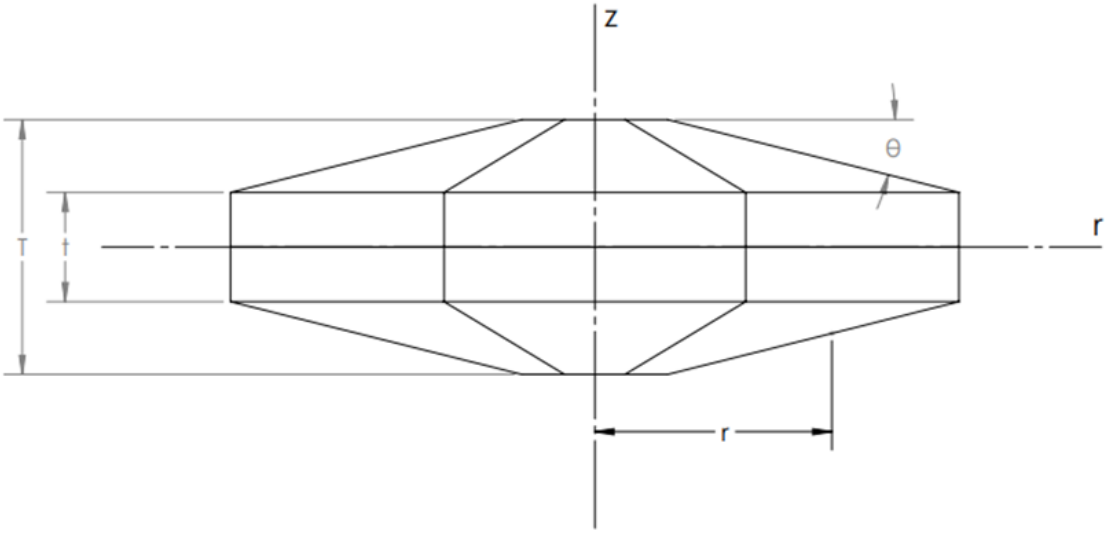


Figure 8.1.2.3: Model of the Geometry of a Single Body Disk

The uncontracted length of the body, with radius r_2, can be calculated as the number of disks present times the thickness T at the center of each disk,

$$S = n * T$$

Similarly, the arc length at the bottom of the body under contraction, with radius r_2, can be calculated as

$$s = n * t$$

Where *t* is the thickness at the edge of each disk. Additionally, the overall arc angle can be found to be

$$\phi = 2\theta n$$

And from this the chord length *x*, that is, the horizontal length of the contracted body, is calculated as

$$x = 2r_2 sin\left(\frac{\phi}{2}\right)$$

Where

$$r_2 = \frac{s}{\phi(\text{rad})}$$

And therefore, the step length per contraction is described as

$$X_{step} = nT - 2r_2 sin\left(\frac{\phi}{2}\right)$$

8.2. Front Foot

The front foot segment of the robot is the section responsible for anchoring the body using the gecko tape, and as a result it needed to provide a way for the gecko tape to be released in order for the foot to be moved. Additionally, the front foot needed to be lightweight to ensure that the motors responsible for moving the body segment would be strong enough to lift it up. It also needed to be able to seamlessly connect to the front of the body segment without restricting its range of motion while also providing a place for the tendons to be connected to. These constraints led to a front foot design, shown in Figure 8.2.1, that was modeled off of the disk segments of the body, allowing the two sections of the robot to work together easily.

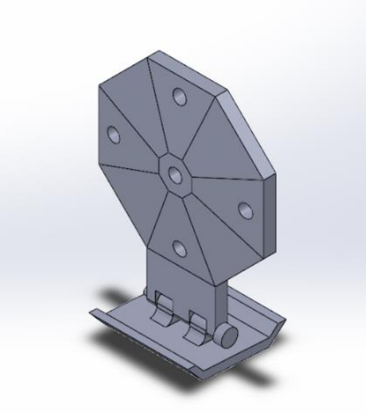


Figure 8.2.1: Model of the Front Foot Design

The front foot is effectively a body disk with a protrusion at its bottom, which is attached to a pivoting flat surface. A large amount of surface area on the bottom of the front foot allows for the gecko tape to create a stronger bond with the surface it is on, making it a more effective anchoring point for the robot. Due to the nature of gecko tape, all that is required to release it is a small amount of upward pulling force, which is provided to the foot by contracting the top tendon, which pulls on the front wall of the foot, causing a slight bend in the bottom and releasing some of the gecko tape from the surface underneath.

8.3. Rear Foot

In contrast to the front foot, the rear foot was designed to be the heaviest section of the robot, as it needed to house the motors, electronics, and mechanical components used to control the body segment, and act as a counterweight when the front foot is lifted. However, the foot also needed to be light enough so that when the body segment arches the anchoring of the gecko tape is strong enough to allow the rear foot to be pulled forward. This led to a design consisting of only two motors, a gimbal joint mechanism used to control the contraction of the tendons, and a few wheels to allow the foot to move forward when pulled. Even this seemingly simple configuration, however, includes multiple subsystems within it in order to achieve the two-anchor crawl gait.

8.3.1. Tendon Control Using A Gimbal Joint

In order to control the contraction and extension of the tendons that drive the arching of the robot's body, two solutions were proposed. The first concept had individual motors connected directly to each tendon, however, this was neither cost effective nor space efficient. The alternative solution proposed was a gimbal joint mechanism. This type of joint consists of two axes perpendicular to one another and an end effector that, when the joint is at its origin, is normal to the plane created by the two axes. The end effector linkage always has one end at the intersection of these two axes, however, rotating one or both of the axes about their center moves its other end in 3-dimensional space above the entire joint. Figure 8.3.1.1 shows the gimbal joint designed specifically for the robot without its frame at its origin, which more effectively shows the two axes and how they manipulate the end effector they control without being affected by the other's rotation.

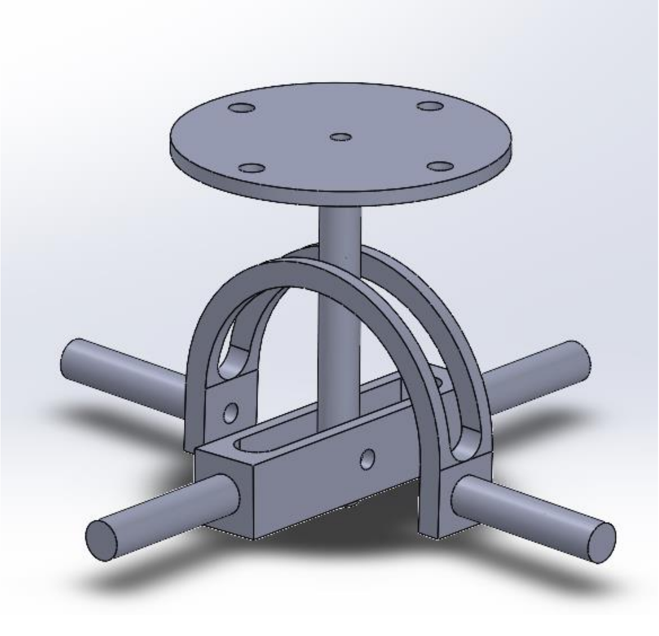


Figure 8.3.1: Unframed Gimbal Joint Mechanism

By connecting a plate matching the hole configuration of a body segment disk to the end effector of the gimbal joint, the tendons of the body can be connected to the gimbal and controlled using just two motors. The joint sits in the rear foot with the end effector plate facing the front and directly in line with the body segment. When the vertical axis of the joint is rotated up, the top of the disk is tilted away from the body segment and the bottom of the disk is tilted toward the body segment. Similarly, when the horizontal axis is rotated counterclockwise, the left side of the disk is tilted away from the body and the right side is tilted toward the body. This allows for a constant relationship between the tensions of the tendons to be maintained, since whenever one tendon is contracted, the opposite tendon is released.

8.3.2. Electronics

The design for the inchworm robot uses two Adafruit stepper motors and two Sparkfun motor drivers to control them simultaneously through an Arduino Uno microcontroller. The motors effectively control the position of the head of the inchworm robot by rotating the axes of the gimbal joint to contract and release the tendons needed to achieve a desired position. Each motor drives one of the two gimbal axes through a short series of gears that allow the motors to control the axes from behind the gimbal which keeps the weight of the rear foot to the back of the segment.

To keep the electronics for the robot both compact and organized, the team designed a custom printed circuit board that would connect the motors, drivers, switches, and power to the microcontroller. Figure 8.3.2.1 shows the schematic for the PCB that was milled. The array of three switches on the top right of the schematic are connected to the microstep selection pins on the motor drivers that can be used to select how much the stepper motors should rotate per step. A DC power adapter on the bottom right allows for both the motor drivers and the microcontroller to be powered via a 12V 5A DC power supply that can be plugged into a wall outlet. The top left of the board has a terminal for an analog joystick that will connect to the microcontroller which can be programmed to use the joystick as an input device to control the motors connected to the board.

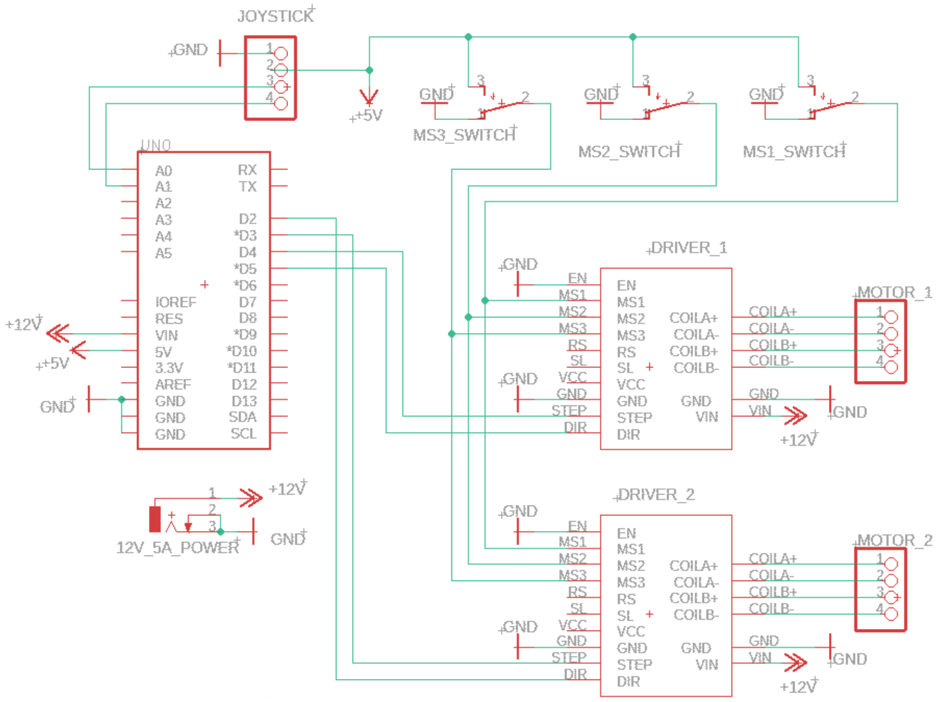


Figure 8.3.2.1: Schematic of the Robot Control Circuit

9. Prototyping and Revisions

After manufacturing and assembling the selected final design, official testing was able to begin. Upon attempting to actuate the gimbal mechanism with the body section and front foot attached, it was immediately apparent that the gimbal mechanism, shown in Figure 9.1, created a lever arm that required a moment larger than the motors were capable of overcoming. This meant that the tendons were not pulled enough for the intended actuation to occur with the mechanism in its current state. Additionally, even without the issue of the lever arm, the difference in the lengths of opposite tendons during contraction was not large enough, meaning a greater range of motion would be required.

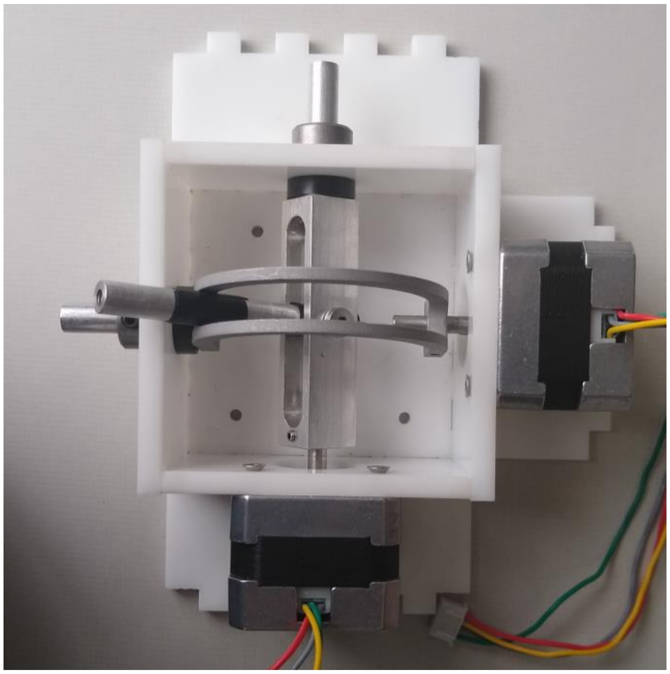


Figure 9.1: Gimbal Tendon Actuation Mechanism

The first attempt to resolve these issues consisted of altering the geometry of the gimbal plate to allow for a longer pull on each tendon. Although this solved the problem of limited motion, it further increased the size of the lever arm, and the increased range of motion was not enough to make up for this. The next step taken to achieve body movement using the gimbal was to explore the option of redesigning the gimbal enclosure to allow for a 4:1 gear reduction between the motors and gimbal input shafts. This solution would have both overcome the mechanical disadvantage, as well as allowed for the fullest range of motion possible with the gimbal (as the motors were no longer constrained to less than one full revolution of movement).

Despite the promise of the geared gimbal solution, it was ultimately abandoned due to its need to full redesign the actuation mechanism, as well as due to space restrictions on the gear train. This caused the team to move toward an alternative means of pulling the tendons: levers that controlled the tendons in pairs. This design is very similar to the handle of a marionette in the sense that strings are tied in parallel and when one is drawn taught, the other goes slack. This new driving mechanism can be seen below in Figure 9.2.

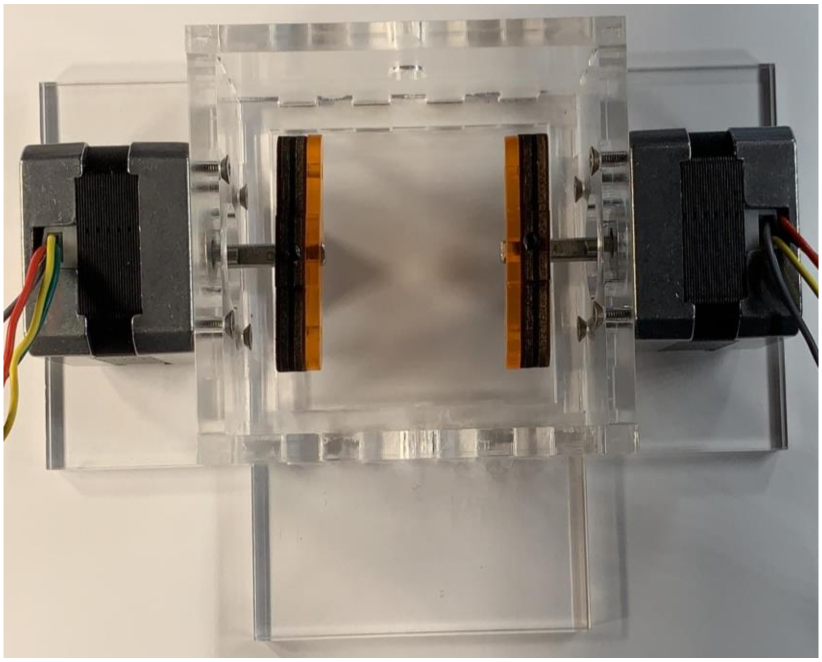


Figure 9.2: Lever Arm Actuation Mechanism

The final modification that the tendon actuator underwent allowed for even more resulting motion from each tendon being pulled by introducing a wheel in the center of the lever arm. The addition of this wheel allowed for more slack to be removed from the pulled tendon; this in turn gave improved resultant motion in the body segments. The final tendon actuator design with the implemented wheels can be seen below in Figure 9.3. By applying this new actuation system to the existing body and foot designs, the robot was able to crawl forward, and to turn about its rear foot. The final prototype design was measured to be able to turn at a rate of 22^{o}/min and was able to perform the two-anchor crawl gait at a rate of 15.6 in/min straight forward. With the modified design, the robot was 14in long, 6.5in wide, and 5in tall and weighed 3.5lbs. These outcomes mean that overall, the inchworm robot can be considered a success, as forward motion and turning were the two major goals of the project.

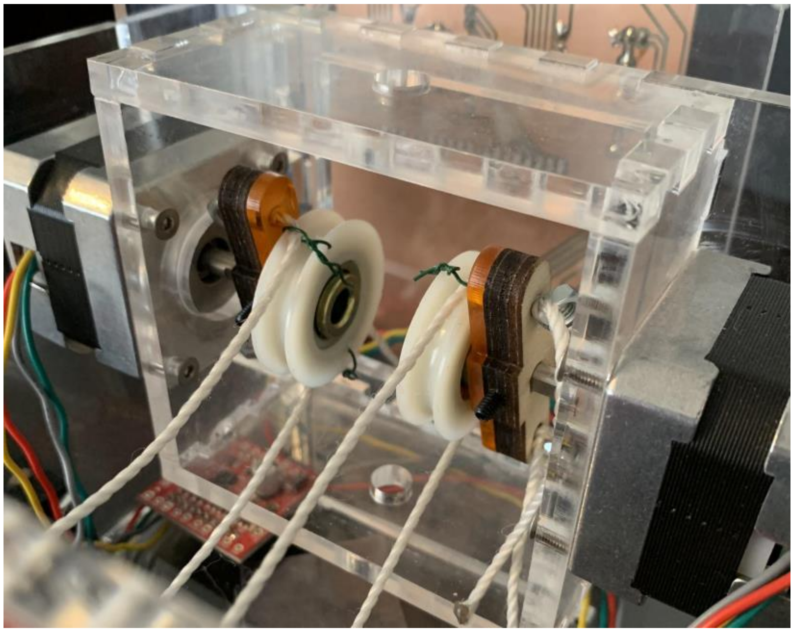


Figure 9.3: Lever Arm Actuation Mechanism Modified with Wheels

10. Conclusion

The team created successfully re-created the two-anchor crawl gait of an inchworm caterpillar by designing a robot capable of mimicking three of the main characteristics of the motion. With both the front and rear feet of the robot capable of anchoring themselves to the ground surface, they are both able to move the other foot in a controlled direction through use of the body segment and its flexibility. Though the initial design of the prototype did not achieve the desired motion, the team was able to make adjustments to the design that achieved the desired motion while also maintaining the large majority of the original design. Improvements to the robot, such as a smaller rear foot design, a motor change for more torque, or a more refined front foot mechanism to allow for smoother motion, would all allow the robot to mimic the two-anchor crawl gait more accurately and effectively.

11. Appendix

11.1. Bill of Materials

Part	Description	Quantity	Unit Price ($)	Total Price ($)
Gecko Tape	4 sheets, 4" x 4"	1	$33.00	$33.00
Stepper Motor	Adafruit Stepper Motor	2	$17.98	$35.96
Motor Shield	Sparkfun Big Easy Steper Driver	2	$19.95	$39.90
Arduino Uno	Elegoo Arduino Uno	1	$13.86	$13.86
Twisted Nylon String	Spool of 350ft of string	1	$4.20	$4.20
PLA Filament	Flashforge 0.5kg Spool	1	$16.99	$16.99
Clutch Bearing	One-Way Bearing, 3/8" OD	2	$28.44	$56.88
Rubber Wheel	3" OD, 1" Width	2	$4.10	$8.20
Rubber Tubing	1/16" ID, 3/16" OD, 10' Length	1	$11.60	$11.60
Shaft Collar	3.8" ID, 5/5" OD, 1/4" Width	2	$1.91	$3.82
Power Adapter	12V, 5A	1	$9.99	$9.99
Balsawood Sheet	1/8" x 3" x 3'	1	$3.99	$3.99
Roller Assmebly	1-1/4" OD x 5/16" Width	1	$6.99	$6.99
Clear Acrylic Sheet	1/8" x 12" x 12"	1	$2.99	$2.99
Clear Acrylic Sheet	1/4" x 6" x 12"	3	$4.39	$13.17
Flat head Screws	M3 x 16 mm flat hex screw	8	$0.01	$0.06
Total				$261.60

11.2. Team Member Contributions

11.2.1. Mikayla Sirovatka

My responsibilities throughout the duration of the project ranged from design, documentation, prototyping, and communication. For each of our four reports written on the project, I was responsible for assigning sections for team to write and the combine them all into a cohesive report with a single, consistent narrative. I was also responsible for the majority of the iterative prototyping and fabrication of the initial robot design. This involved 3D printing various parts, designing and laser cutting housings for the tendon actuation and rear foot, soldering and wiring of the electronics, and other general assembly tasks. Additionally I was responsible for the electronic design of the robot which involved selecting components and designing a circuit for the custom PCB used on the robot. Finally, I was involved in various aspects of the design process, primarily designing the gimbal mechanism from the initial design, as well as working with Alex on the front foot.

11.2.2. Matt Halverson

My biggest individual contribution to this project was conceiving and designing the body section of the robot, as well as performing a geometric study to determine the motion to be generated by a body section made of a given number of links with a known geometry. Along with Omer I created the preliminary designs for the rear foot (four motor, ratcheting wheel design). From this preliminary design is where the final pulley actuator concept was derived, although with substantial change by Alex. Additionally, I, as did everyone else, performed documentation, research, concept generation, and testing.

11.2.3. Alex Lewandowski

My primary contributions to this project were the design of the lever tendon actuator as well as the front foot. I sketched up the concepts and then modeled them with the assistance of Mikayla. In addition to designing these two components, I also assisted with the written deliverables for the project (as did everyone on the team). I was also responsible for keeping up correspondence with our sponsor, Professor Bhonsoule. This task included setting up team meetings with him and submitting order request forms for any components we needed.

11.2.4. Omer Durrani

Although this was a team project and everyone was working together, to increase the efficiency, the team divided the tasks so that the project was completed on time. I worked on designing the rear foot of the robot which consisted of the mechanical components and all the electronics including the motors. I was helped by Matt on this task and after various ideas, we ended up with the final design of the rear foot which was efficient enough to house all the components. Apart from designing, I also contributed to the initial research of the project, the documentation and the testing of the robot along with the rest of the team.

11.2.5. Daniel Kulach

My primary focus during this project was writing code to control the robot electronics and motors. I wrote three different codes for controlling the robot in varying ways. I also referenced relevant code and commented it to help explain the code to the team. I was also tasked with researching some motors and electronics towards the beginning of the project along with other general research each member was doing. A design contribution I had was my idea of adding circular pulleys, or in this case wheels, to gain a bit more pull on the strings from the same positioning of the motors. I also did a some of the final testing and fine tuning along with Alex.

11.3. Team Member Reflections

11.3.1. Mikayla Sirovatka

For me, the biggest lesson centered around task management and how important it is to not take on responsibility for every portion of a group project. I am very aware that I am a perfectionist, and that this often leads me to taking on more than I am capable of in a group work setting. This was certainly worsened by the pandemic since I was the only one who could regularly prototype for most of the year, so most of that work was done by me on my own, when it would have been more collaborative in a different year. Ultimately, this project taught me more about myself and my own limits and how to better define my boundaries when it comes to the amount of work I am able to do on my own without taking away time from and negatively impacting other aspects of my life, specifically academically.

11.3.2. Matt Halverson

The overall lesson of this project was, for me, one of the importance of team organization. Most of the difficulty we encountered came from having limited access to in person meeting and resources, which greatly complicated the task of organizing tasks, and especially staying on schedule, since so much work ended up getting taken on by Mikayla due to her having the most access to manufacturing resources. Although I do not think this could have been entirely avoided due to the pandemic situation, more effective team organization I believe could have eased the situation a great deal.

11.3.3. Alex Lewandowski

The lessons I learned throughout this project have been invaluable to my transition from school to the workforce. This project was the first time in my education at UIC that I was part of a prolonged group project where I learned the importance of group dynamic. I learned that when working in a design team, it is critical to see proof before making decisions. In our group, we lost a few weeks worth of time because of this. Another lesson that I learned was the importance of task delegation; I feel that this is an area my group excelled in. If we did not distribute tasks in the manner we did, this project would have been far too much work for one person to complete in addition to their normal classes; our collective effort ensured work was distributed evenly and thus was manageable.

11.3.4. Omer Durrani

Overall, this project was a great learning experience for me. I realized after working on this project that having the right people in the team is extremely important. For a project to be successful, it is important for the team members to be on the same page and share the same thought process. I was fortunate enough to have a team who respected each other’s ideas and were there to help each other out. Moreover, working in the middle of the pandemic did have an impact on the project but even then, the team made it possible to complete the project on time by working remotely and dividing the tasks.

11.3.5. Daniel Kulach

Through this project I learned the importance of good communication between a team. We had a few communication problems along the way among team members and from our advisor. I also learned the benefits of working in person. We were a lot more productive when we met as a team in person to discuss and test different theories.

11.4. Project Charter

1. SPONSOR: Pranav Bhounsule

2. PROJECT TITLE: Inchworm Robot

Draft or **Final** (circle one)

Date: 5/6/2021

3. GOAL(s)/ OBJECTIVE(s):
1. A robot that has the ability to move straight and turn
2. The ability to anchor the feet and release the feet of the robot to perform the two-anchor crawl gait.
3. Novel Mechanisms/motors to enable turning
This Project does not include: (if needed to clarify goal)
1. Does not need to be the size of a real inch worm
2. Does not need to be untethered or autonomous

4. DEFINITION(s) OF DONE:
1. Prototype with ability to move straight and turn like an inchworm, or video of working prototype
2. CAD model and simulation
3. Project Binder/Final Report

5.a. KEY METRICS:	
Metric	**Description**
1. Scale	Will be bigger than an inchworm
2. Turning Radius	Maximum angle of turn in a single step
3. Speed	Speed of forward motion
4. Weight	Full weight of robot in motion

5.b. Codes and Industrial Standards:	**Description**
1. IEEE 1872-2015	Reference material for robotics and automation methods, axioms and vocabulary

6. PROJECT TEAM:	**Primary Name/Phone #s:**	**Back-up Name/Phone #s:**
Sponsor	Pranav Bhounsule	
Faculty Advisor	Matthew Alonso	
Engineer	Omer Ashraf Durrani	
Engineer	Matt Halverson	
Engineer	Daniel Kulach	

Engineer	Alex Lewandowski	
Engineer	Mikayla Sirovatka	

7. KEY ASSUMPTIONS and NECESSARY CONDITIONS:

1. Only resemblance to an inchworm is in its style of motion
2. Surface for robot use may be chosen, preferably a common indoor flooring
3. Video evidence of prototype function is acceptable as a submission

8. TIMELINE/SCHEDULE:

Major Project Milestones	Plan date	Latest Best Estimate	Completion date
Design Concept Selection	11/23/2020	12/2/2020	1/8/2021
Preliminary Design CAD/Simulations	2/1/2020	2/22/2020	1/8/2021
Preliminary Design Software	2/21/2020	3/14/2020	2/22/2021
Final Software	3/14/2020	4/17/2020	4/21/2021
Final CAD / Simulations	2/22/2020	4/5/2020	5/6/2021
Final Part and Assembly Drawings	2/22/2020	4/5/2020	5/6/2021
Functional Prototype / Video	4/20/2020	4/24/2020	5/6/2021

9. RISKS:

Risk Description	Risk Owner	Plan to address
1. Electronics Failure	Daniel Kulach	Fire extinguishers will be on hand, care will be taken to properly size components and shield wires
2. Manufacturing safety risks	Mikayla Sirovatka, Alex Lewandowski	Appropriate safety measures will be taken in all spaces when manufacturing is taking place, and experts will be consulted when necessary
3. Battery fires (if applicable to chosen design)	Matt Halverson	Fire extinguishers on hand when working with batteries, checks made for defects
4. Unexpected / unpredicted potentially dangerous motion of robot	Omer Ashraf Durrani	All present will be notified when power is supplied to the robot that unexpected motion may occur

10a. DOCUMENTATION:			
Document #/Name	*	Person(s) Responsible	Description
1. Specifications		Omer Ashraf Durrani	Documentation on the design selection, abilities and components used
2. Quantitative Analysis	Simulations	Matt Halverson	Perform FEA and linkage motion simulations
3. CAD design	Assembly	Mikayla Sirovatka	Maintain current assembly + file structure
4. CAD design	Components	Alex Lewandowski	Modeling of robot components
5. Final Product Drawings		Daniel Kulach	Engineering Drawings of components for manufacturing and final prototype.

10b. DOCUMENTATION: **KEY ASSUMPTIONS**	
1. Only resemblance to an inchworm is in its style of motion	Specified by Prof. Bhounsule
2. Surface for robot use may be chosen, preferably a common indoor flooring	Specified by Prof. Bhounsule
3. Video evidence of prototype function is acceptable as a submission	Specified by Prof. Bhounsule

10c. DOCUMENTATION TIMELINE/SCHEDULE:	
Document #/Name	Key Dates:
1. Fall Midterm Report	11/5/2020
2. Fall Final Report	12/9/2020
3. Spring Midterm Report	3/14/2021
4. Spring Final Report	5/6/2021

10d. DOCUMENTATION RISKS:	Risk description, owner, and plan to address (in order of significance).	
Enter "All" or Document #/Name	Risk Description / Plan to Address	Risk Owner
1. All	Unexpected, potentially personally dangerous robot movement. Extra care will be taken to inform all present of when the robot has the potential to move unexpectedly.	Team
2. All	Battery hazards (ie. Fire) If batteries are used, fire extinguishers will be on hand, and batteries will be checked for defects regularly.	Team

11. PROJECT CHARTER APPROVALS:	
Project Sponsor:	Pranav Bhounsule date:12/4/2020
Team Members	
Omer Ashraf Durrani	Omer Durrani date:11/30/2020
Matt Halverson	Matthew Halverson date:11/30/2020
Daniel Kulach	Daniel Kulach date: 11/30/2020
Alex Lewandowski	Alex Lewandowski date: 11/30/2020
Mikayla Sirovatka	Mikayla Sirovatka date: 11/30/2020

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