Project 2: Inverted Walker

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ABSTRACT

Our group aimed to create a 2 legged inverted walker robot, referenced from a possum, which would hang from a rope upside down and climb along the rope as fast as possible. As critical constraints for the robot, we wanted it to be stable as it climbed along the rope, climb as quickly as possible which would involve reducing friction, finding a fitting gear ratio, optimizing the linkage kinematics, ensuring proper grip with the rope, and more.

The robot we designed features two articulating legs which are powered by a small gear-train with a 5:4 velocity ratio and synced up by a shaft running across the side of the robot. The legs themselves are based on the Hoeken straight line linkage which follows a dome-shaped path with a flat bottom.

From our work in the design process, we gained insight on a preliminary gear ratio through the PVA process, and made significant progress in figuring out details of our design such as shaft diameters, mounting hardware, link connection hardware, and more. Furthermore, while the tested prototype successfully displayed our working mechanism, several problems, including colliding legs and swaying, reduced the mechanism performance. To optimize the robot's motion, chamfers were applied to the legs to allow smooth transitions, rubber bands were added on the feet to increase grip on the rope, and the carabiner tail was replaced by a bearing-roller tail to reduce friction. As a result for the changes made after the design review, our robot swiftly crossed the Boneyard Creek within 26 seconds.

DISCUSSION

The final overall design is a 2 legged robot with a stabilizing tail. In order to increase speed and stability, we aimed for a balanced center of mass as well as a compact overall shape. Other design goals included continuous (without starting and stopping) forward motion that eliminates as much vertical motion as possible, maintaining consistent grip with the rope, and finding a good gear ratio that makes use of the motor's maximum power output.

For the legs, we wanted to minimize any unnecessary vertical motion of the mechanism, so we investigated a straight line four-bar linkage mechanism. By looking at the trace curve we can find the four-bar linkage mechanism mainly contains two parts in a working period (See PVA Section). The main part of motion is a linear motion on the rope which pulls the robot forward, other part of motion is a quick return trace slightly above the linear trace to let another leg as well as the rope go below it during the quick return part. The crank links of each side are fixed in the opposite direction to provide alternatively motion of two legs. The links that touch the rope are slightly inclined inwards to reach the rope from the outside of the robot. The inline surface on that leg also has the function to redirect the robot to the desired direction in case it has some rotation on the horizontal plane. Chamfers were also added near the feet, where collisions between the two legs were observed on the prototype. For better stability, counter balancing cranks were also implemented as well as wider feet surface area to lay in contact with the rope. Adding rubber bands to the feet was also seen to improve the robot's motion as there is greater grip on the rope.

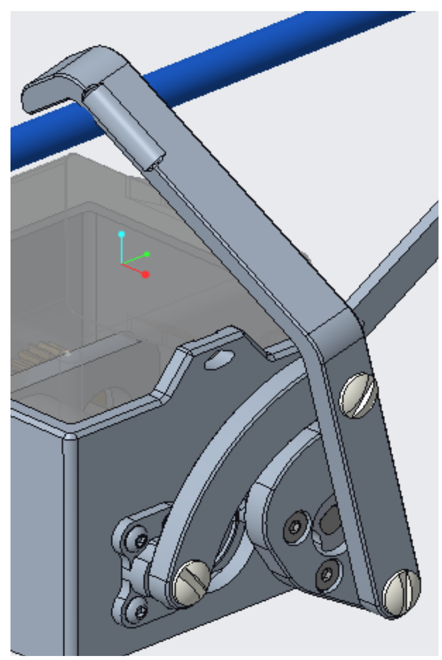


Figure 1: Leg CAD

For the frame, we wanted to balance the weight of the whole robot and make its width as small as possible. To accomplish this we designed a very compact frame which puts the battery and motor together. Basically, we put the motor and power transmission system in the bottom part of the frame and used the motor's mounting to separate and support the battery. To fasten the battery, we designed two holes on the top of the frame and will use a nylon cable tie to keep the battery in its position. The center of mass is nearly centered below the grippers of the

To increase stability, we also designed a tail behind the main body of the robot. From the consideration of only having one of the legs touching the rope, it is very easy to have the robot rotate in an undesirable way and lose balance. Since we designed our legs to perform a linear movement, we can place a tail which rides on this same line as shown in Figure 2. This design makes sure our robot is always facing forwards in the moving direction. Consisting of two rollers fitted with bearings, the tail allows smooth motion between the rope, not hindering the robot's motion with much friction. We have also tried to make the end of the tail to be assembled as quickly as possible because we have to assemble the tail on the rope in actual use.

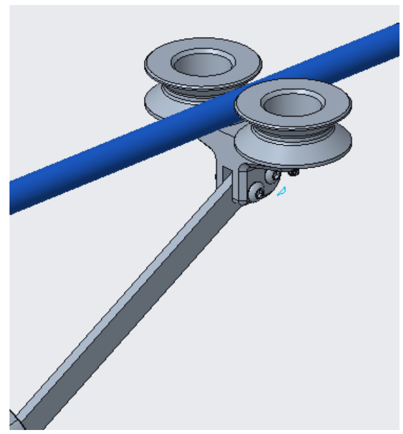


Figure 2: Tail Design

For the power transmission system, we wanted to minimize the energy/torque loss by using a simple and robust design. If the transmission system is complex, there are many disadvantages such as higher cost, difficulty with assembly and maintenance, higher energy loss and greater space usage. In order to make the crank links move at the same angular speed we put them on the same shaft, as shown in figure 3. Because the output shaft of the motor is only on one side and we want to change the output torque and speed, we are using one set of gears to transmit the force from the motor the shaft connects to two legs. It is a simple but efficient design because the output of the motor is relatively strong enough for a two-leg design (see PVA), so we are not using a big gear ratio and only have two small gears that fit in the frame easily.

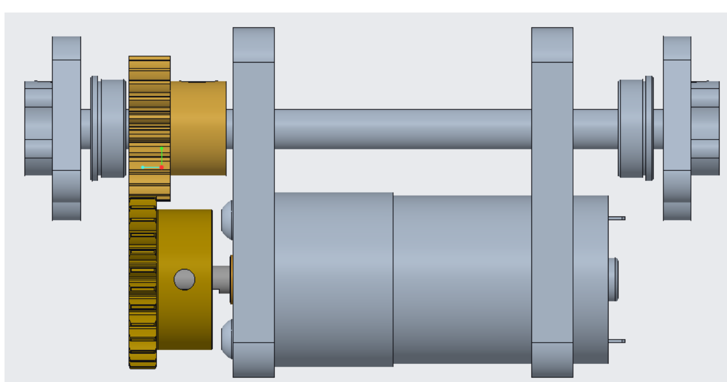


Figure 3: Power Transmission Assembly

At the early stages of our design, we were discussing whether to build a four-leg robot or a two-leg robot with a tail to balance itself. We saw a lot of advantages to using the four-leg robot such as easily keeping the body horizontal by always having two legs on the rope without the need for a sliding tail which would add friction. Furthermore, a 4 legged design would have better overall traction with the rope.

But the disadvantage of the four-leg design is obvious, the power transmission would be much harder to design and build. In addition, the weight of the robot will be much larger if we are having four legs compared to two due to extra components. Furthermore, the power lost is much bigger in a complex power transmission system especially when our prototyping methods have relative low accuracy. In addition, the complex power transmission is going to extend the width of the robot, the increase of the robot's width will cause the larger possibility for the robot to lose balance due to high rotational inertia. Moreover, for the four-leg one we may need to worry about the lack of torque of the motor since the one motor must drive all 4 legs. Lastly, we could save money and time for the two-leg design because we are using less material to build it. Hence, our group settled on a 2 legged design with a stabilizing tail.

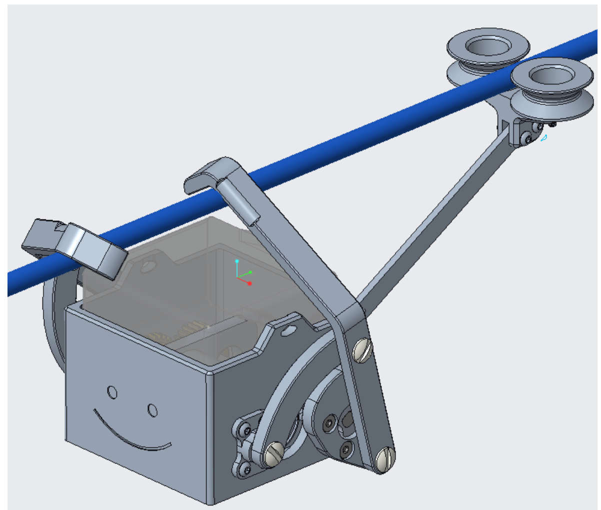


Figure 4: Final 2 legged design

Other iterations included trying our best to shrink the dimensions of the robot as much as possible. By removing shaft collars used in an early design and making use of bearing flanges and the hubs to retain the driveshaft resulted in large size reduction. Small gains in width reduction were also made by making the hubs fit inside the crank link.

For the fabrication of most of the robot, we will utilize 3D printing. This will allow us to create high strength-weight ratio parts with complex geometries, which is ideal for the way we have designed the robot. In order to create a robust and friction free power transmission, our group will purchase D shafting as well as an appropriate gear, bearings, barrel nuts, and hubs to mechanically link the motor and the legs. With an estimated budget of $51.71, fabrication of the robot is possible, especially with a remaining balance of $82.26 from Project 1.

The robot is designed with a simple gear-train which produces a 4:5 torque ratio, making use of a 30t and 24t gear (Figure 5). This was chosen based on our goal for the robot’s legs to move quickly, and some preliminary testing that revealed the gearmotor already produced quite a bit of torque without an additional reduction. Our preliminary PVA also supported our results in absence of a formal dynamical simulation.

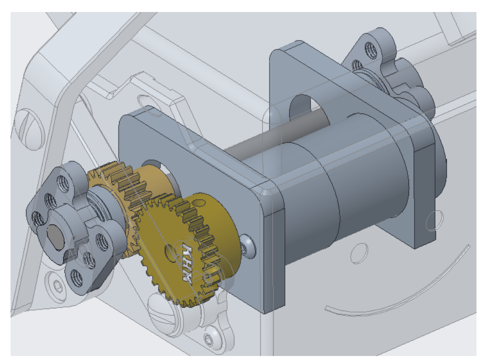


Figure 5: Gear-train Within Robot

As for coordination, we coordinated the legs by having them off set 180 degrees in phase. In order to maintain the exact same angular velocity and to synchronize both legs, we utilized a shaft running through both sides of the robot, as depicted in figure 5, with the crank links mounted at different phases relative to one another.

MECHANISM ANALYSIS

In order to perfect our mechanism, we performed a PVA analysis on our leg linkage. We used MATLAB and edited the given code from a prior lab in order to generate our plots. Figure A.4 in the appendix shows the setup of our Hoeken Straight Line Linkage, with link lengths defined for each link. The original coupler in our linkage was split into two links that are rigidly connected in order to correctly connect link 3 and 4 in Figure 6. The resultant shape of our foot trajectory is as expected, given our choice of mechanism. It has a long flat section and a fast return as indicated by the spacing of plotted dots. This facilitates quick return of the leg linkage, while maintaining mechanical advantage for the motion of the leg in contact with the rope. The graphs of the position, velocity, and acceleration of the foot is shown in the appendix figures A.7-9.

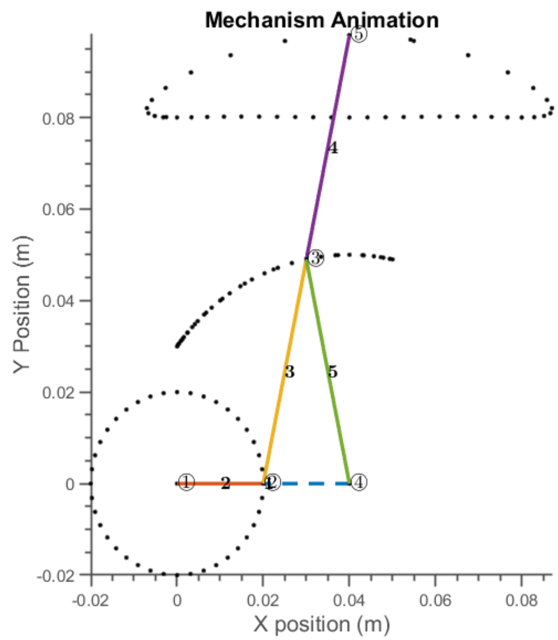


Figure 6: Foot Trajectory for Linkage

The magnitude and shape of these graphs came out as expected. A potential weakness that we noticed at this stage was the fact that the output link rotates a significant amount, and some deviation on the contact distance of the output (green link) due to thickness of the leg link and rotation should be expected.

From looking at the contact and lift phase of our walker, which is shown in appendix figures A.10 and A.11, it can be found that 252 out of 360 degrees of rotation have contact with the rope while the other 108 degrees are in the lift phase. This gives a duty cycle of 70% for a single leg. Given that the walker has two legs, the gait sequence of the walker is shown in figure 7. As a preliminary value, our design used a 180 degree phase difference between the two legs. This ensures constant contact with the rope by at least 1 leg as shown by figure 7, ensuring that the robot will never momentarily lose grip. There is a total of 144 out of 360 degrees of overlapped contact, which will benefit the overall stability of the robot at the sacrifice of some speed;

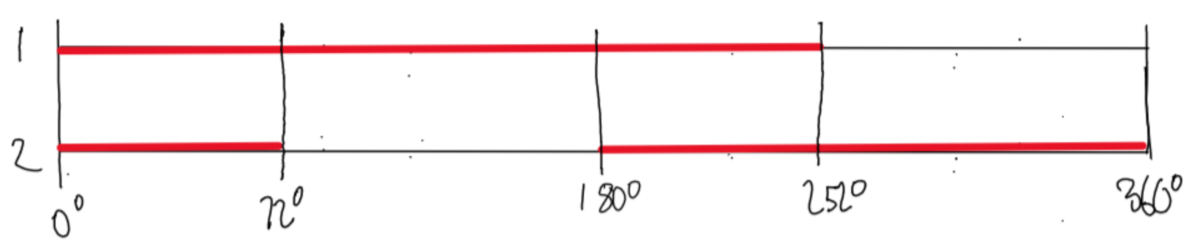


Figure 7: Gait Sequence of our Inverted Walker

The length of a single stride is calculated in appendix figure A.12 to be 94mm. In order to meet the minimum requirement velocity for the robot, the drive shaft on the leg needs to be rotating at 1.55 radians per second. However, we want to be moving much faster than the minimum requirement.

Assuming that our 12V motor is running at around 11V and that the angular velocity of the loaded motor will be a fourth of the unloaded motor, the angular velocity of the motor during operation will be 5 radians per second (Figure A.13). We decided that we want the velocity of the robot to be at least 4 times the minimum requirement for a rather fast moving robot. Using the angular velocity of the motor under load and the bare minimum angular velocity requirement, we found that a gear ratio of 0.806 would achieve this. We are able to have a similar gear ratio using the provided 30t and 24t gears.

Lastly, we constructed a physical prototype of our leg mechanism. We designed this physical prototype using 3D printed components and barrel nuts, and moved the links by hand to get a sense of its motion. We found that the link followed the expected path, and had a noticeable quick return which was very beneficial. Another insight we gained from our prototype was that we had to be careful so that there were no interferences when rotating the limbs, since we had some issues with the prototypes and the barrel nut heads sticking out. We also learned that our gripper shape worked well for gripping the rope. Finally, when testing it with the rope, we noticed that the linkage required very little force for some of the motion, but increased significantly at the moment when the gripper touched the rope, and fell off slightly, which correlates with our results from PVA.

For the DFA analysis, we analyze the torque and energy for our model in matlab and in Figure 8 we can find the contact phase was labeled in orange, the torque reaches maximum when the leg just leaves the rope. The lift phase is a quick return period so the speed of the motor is very large and causes a large vibration in this phase. For the maximum torque calculated in the matlab it is around 1.013125 Nm ($T_{motorpeak}$) when we assume only one leg is on the rope for all the time. However, from the motor lab we know that the maximum torque the motor can provide with a 9 V battery is 0.9696 Nm. However, the maximum voltage of our battery is 9.6 V, by interpolation of the motor lab's data we got maximum motor torque 1.07446 Nm (T_{stall}). In this analysis $T_{motorpeak} < T_{stall}$ which means the mechanism can move but will slow down sufficiently. At motor peak torque, the real angular velocity of the motor will be around 0.9798 rad/s, and the angular velocity of the crank be around 1.225 rad/s. The calculated linear velocity of our robot at the max torque point is around 0.01393 m/s, but the average velocity will be way bigger than this.

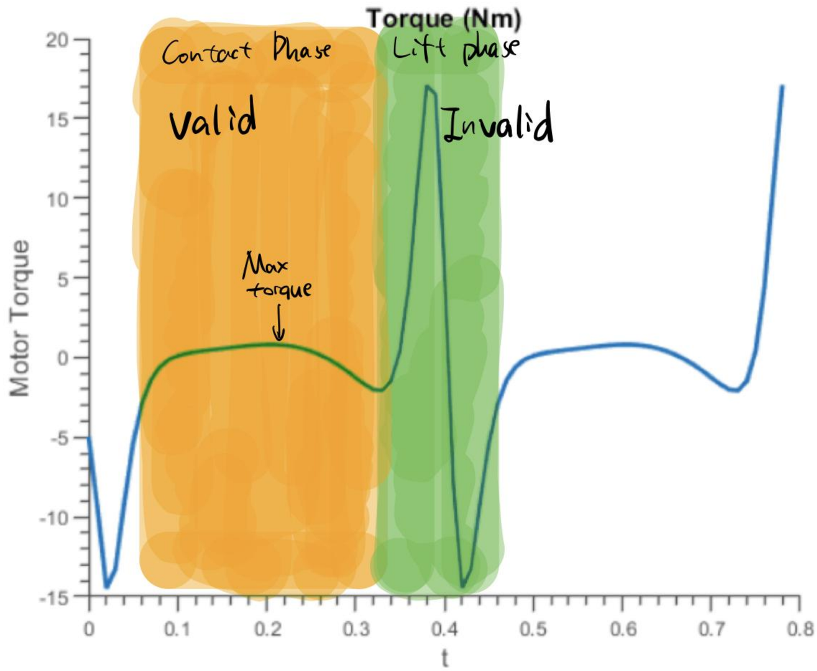


Figure 8: Torque versus time for two cycles

Design Reflection

Our walker crossed the Boneyard Creek river in 26 seconds, which placed us fourth overall in the class. We are really happy about how it performed, but there are certainly changes we could have made to be faster.

The main challenge that we faced was during testing. Only one of our legs was making contact with the rope because we added washers into the system which meant that the legs were further apart and missing the rope. We redesigned the legs to have a wider surface to grab the rope. The other issue we ran into was a high amount of friction at the tail of the robot. We solved this by adding rollers with bearings in them so that the supporting tail would roll along the rope. This allowed for us to center the rope while not having a large amount of friction at the tail.

Looking back at our design, we should've increased our gear ratio from 5:4 to a higher speed such as 3:1 as we did not need as much torque as we did. We also should have tried to design our legs to be longer, as we were well within the size limit and a longer leg length would have let us travel more distance. Our reflection on the design and manufacturing in this project is listed in the table below.

Do’s	Don’ts
Design Process ● Take inspiration from animals ● Find ideal gear ratio ● Delegate work ● Optimize features ● Leave clearance for legs so they do not collide Construction ● Have washers in joints ● Use a grippy material for contact points on the rope	Design Process ● Start late and rush the process ● Forget to ask for feedback ● Leave too little time for testing Construction ● Have unnecessary friction on sliding contacts on the rope ● Start 3D prints late ● Have too much unnecessary space or weight

APPENDIX A

Table 1. BOM for Project 1

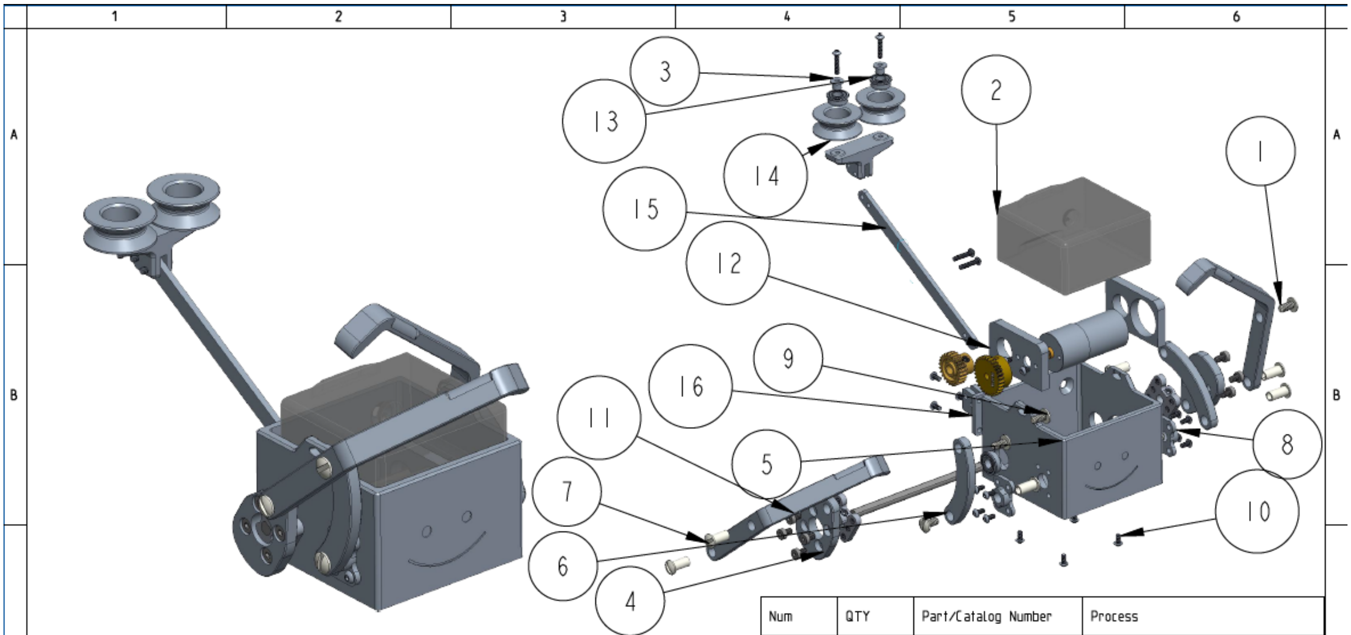
Bill of Materials For Project 1						
Item Name	Description	Source	Link (for external)	Number	Unit Cost	Total Cost
Studio purchases						
Acrylic 1/8" x12" x12"				1	10	$10.00
3D Print				4	0.03	$1.20
Items provided for free/small cost items						
String	String for climber				Free	Free
Colored Paper	Paper for decoration				Free	Free
Sandpaper	Paper for decoration				Free	Free
Rubber Bands	Used for climber				Free	Free
Found /provided by students						
3D Prints	3D prints done by personal printer			58	0.03	$1.74
M3 screws	Small screws used to assemble project			32	0.15	$4.80
External Purchases by students						
Summary of total costs from Project 1						**$17.74**

Table 2. BOM for Project 2

Bill of Materials For Project 2						
Item Name	Description	Source	Link (for external)	Number	Unit Cost	Total Cost
Kit						
30t Mod .8 Gear	Provided gear	Kit		1	Free	Free
DC Brushed Gear Motor	Provided Motor	Kit		1	Free	Free
NiMH Battery	Provided Battery	Kit		8	Free	Free
Battery Holder	Provided battery holder	Kit		1	Free	Free
Items repurposed from project 1						
New Innovation Studio Purchases						
PLA Filament	3D Printing	Innovation Studio		172	0.03	$5.16
Barrel Nuts	Link Connections	Innovation Studio		2	1.00	$2.00
New small items provided for free						
¼" x ½" Bearings	Bearings for roller tail	Found for free in innovation studio		2	Free	Free
External Purchase requests from department						
6mm D Shaft 100mm	Drive Shaft for leg linkages	GoBilda	https://www.gobilda.com/2101-series-stainless-steel-d-shaft-6mm-diameter-100mm-length/	1	2.89	$2.89
6mm D Shaft Hub	Hub to attach legs	GoBilda	https://www.gobilda.com/1308-series-lightweight-set-screw-hub-6mm-d-bore/	2	5.49	$10.98

14x6mm Flanged Bearings	Bearings to facilitate smooth motion	GoBilda	https://www.gobilda.com/1611-series-flanged-ball-bearing-6mm-id-x-14mm-od-5mm-thickness-2-pack/	1	3.49	$3.49
24t Gear	Gear for drive shaft gears train	GoBilda	https://www.gobilda.com/2301-series-brass-mod-0-8-d-bore-set-screw-pinion-gear-6mm-d-bore-24-tooth/	1	7.99	$7.99
M4 6mm Screws	M4 screws for hub	GoBilda	https://www.gobilda.com/2804-series-zinc-plated-steel-low-profile-socket-head-screw-m4-x-0-7mm-6mm-length-25-pack/	1	2.99	$2.99
Button Head M3 4mm Screws	M3 screws for frame	Mcmaster	https://www.mcmaster.com/92095A471/	1	4.40	$4.40
Button Head M3 6mm Screws	M3 screws for frame	Mcmaster	https://www.mcmaster.com/92095A179/	1	5.70	$5.70
Button Head M3 14mm Screws	M3 screws for frame	Mcmaster	https://www.mcmaster.com/92095A168/	1	7.90	$7.90
Any other expenses, found or provided items by students						
Proposed Budget						
Remaining budget after costs from Project 1						$82.26
Total cost of project 2 studio purchases						$6.16
Total cost of project 2 purchases						$46.34
Total cost of any other expenses						-
Total cost of project 2:						**$52.50**

Appendix B



Num	QTY	Part/Catalog Number	Process
1	6	BARRELNUTANDSCREW	Purchase from Innovation Studio
2	1	BATTERYHOLDER	Provided in Kit
3	2	BEARINGSLEEVE	3D Printed PLA
4	2	CRANK	3D Printed PLA
5	1	FRAME	3D Printed PLA
6	2	LINK2	3D Printed PLA
7	2	LINK3	3D Printed PLA
8	2	LINKMOUNTINGBLOCK	3D Printed PLA
9	6	M3-14MM_SCREW	Purchased from McMaster
10	16	M3-6MM_SCREW	Purchased from McMaster
11	8	M4-6MMSCREW	Purchased from McMaster
12	1	POWERTRANSMISSION	Subassembly, see assem drawing
13	2	QUARTERINCHBEARING	Found in Innovation Studio
14	1	ROLLERTAILASM	Subassembly, see assem drawing
15	1	TAIL	3D Printed PLA
16	1	TAILCONNECTION	3D Printed PLA

Mechanical Science and Engineering
University of Illinois: Urbana-Champaign

ME370 05/3/2022	Assembly Name: Full Robot Assembly
Size: A Scale: 0.200	Assembled By: Matthew Zhang
Team BB74	Drawn By: Matthew Zhang
Sheet 1 of 1	Assembly Number: 1

Figure A.1: Assembly Drawing of Robot

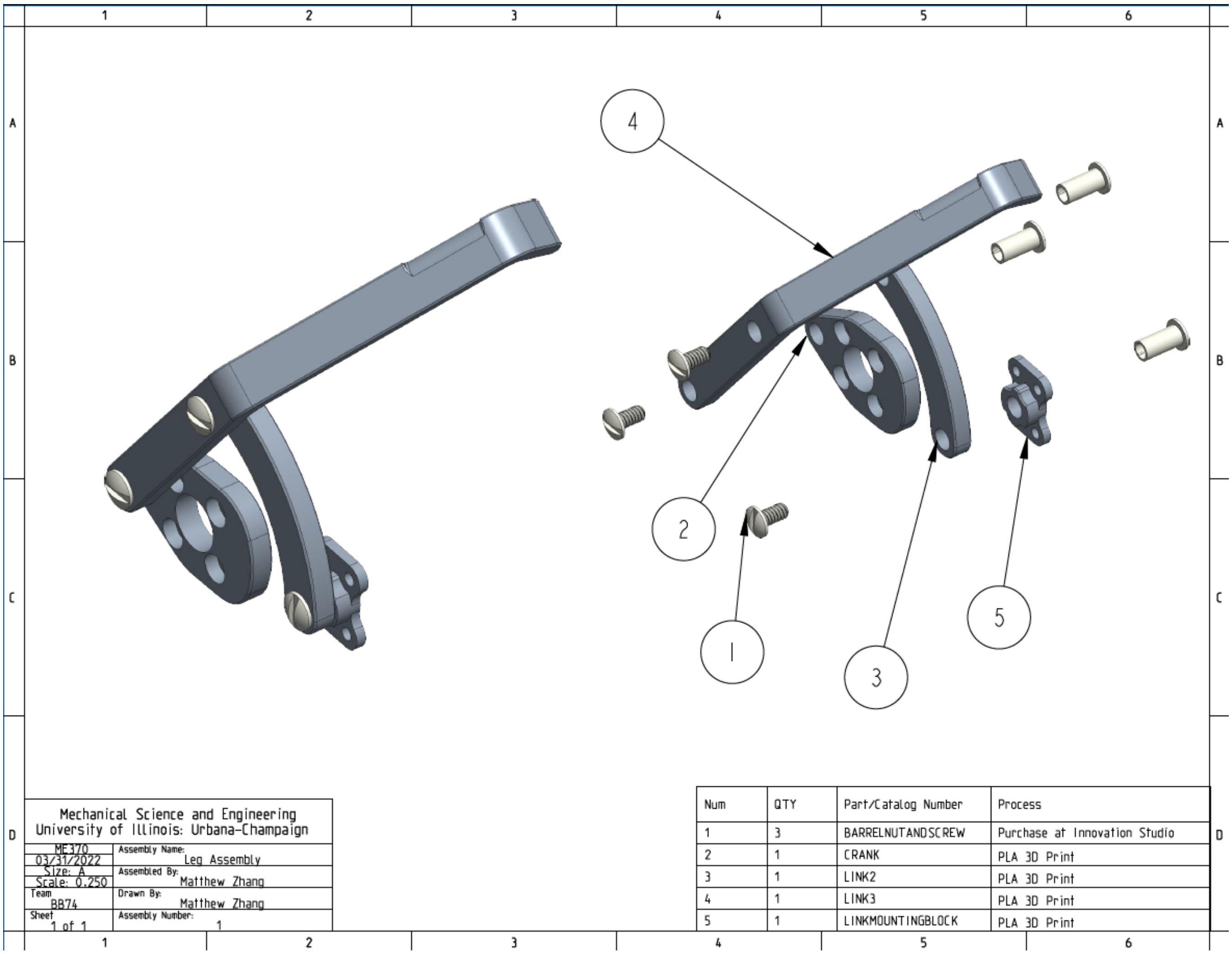
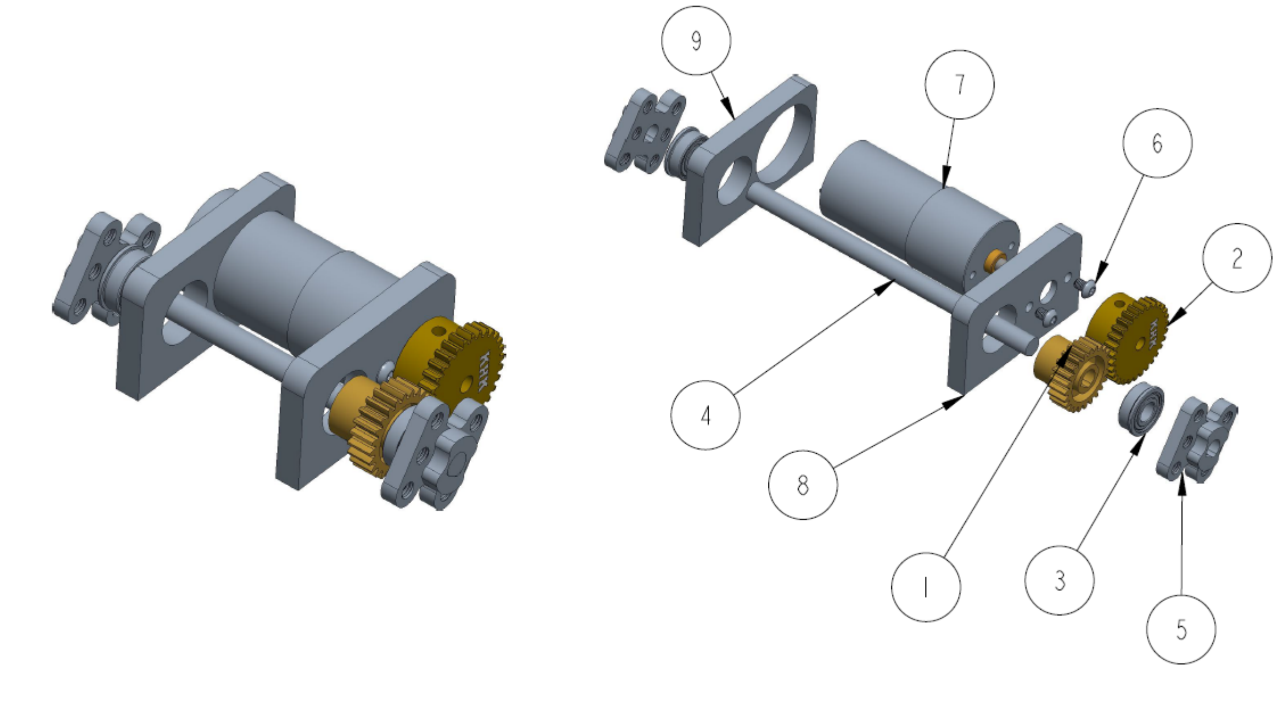


Figure A.2: Assembly Drawing of Leg



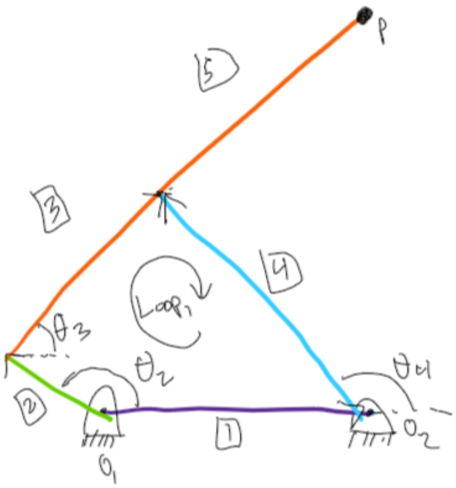
Num	QTY	Part/Catalog Number	Process
1	1	24T6MMBOREGEAR	Purchased From GoBilda
2	1	30T_GEAR_STEP	Provided in Kit
3	2	6MMBEARING	Purchased from GoBilda
4	1	6MMDSHAFT	Purchased From GoBilda
5	2	6MMHUB	Purchased From GoBilda
6	2	M3-4MM_SCREW	Purchased from McMaster
7	1	MOTOR	Provided in Kit
8	1	MOTORMOUNTPANEL	3D Printed PLA
9	1	MOTORMOUNTPANEL2	3D Printed PLA

Mechanical Science and Engineering
University of Illinois: Urbana-Champaign

ME370 3/30/2022	Assembly Name: Power Transmission Assembly
Size: A Scale: 0.250	Assembled By: Matthew Zhang
Team BB74	Drawn By: Matthew Zhang
Sheet 1 of 1	Assembly Number: 1

Figure A.3: Assembly Drawing of Power Transmission

Appendix C



Link 3 and 5 are rigidly connected

Known Link Lengths: $L_1 = 40_{mm}$ $L_4 = 50_{mm}$

$L_2 = 20_{mm}$ $L_5 = 50_{mm}$

$L_3 = 50_{mm}$

* For simplicity and readability, Link lengths will remain a variable.

Vector Loop: $0 = \vec{R}_2 + \vec{R}_3 - \vec{R}_4 - \vec{R}_1 = L_2 e^{j\theta_2} + L_3 e^{j\theta_3} - L_4 e^{j\theta_4} - L_1 e^{j(0)}$ ↑ fixed angle, 0°

Known: θ_2, Unknown: θ_3, θ_4

Figure A.4: Linkage Setup and Position Vector Loop

Position Analysis: $L_2(\cos\theta_2 + j\sin\theta_2) + L_3(\cos\theta_3 + j\sin\theta_3) - L_4(\cos\theta_4 + j\sin\theta_4) - L_1 = 0$

Real: $L_2\cos\theta_2 + L_3\cos\theta_3 - L_4\cos\theta_4 - L_1 = 0$

Imaginary: $L_2 \sin\theta_2 + L_3 \sin\theta_4 - L_4 \sin\theta_4 = 0$

Velocity Analysis: $\vec{V} = \frac{d\vec{R}}{dt}$ Known: ω_2 unknown: ω_3, ω_4

$$\frac{d}{dt}\left(L_2 e^{j\theta_2} + L_3 e^{j\theta_3} - L_4 e^{j\theta_4} - L_1\right) = 0$$

$$j\omega_2 L_2 e^{j\theta_2} + j\omega_3 L_3 e^{j\theta_3} - j\omega_4 L_4 e^{j\theta_4} = 0$$

Real: $-\omega_2 L_2 \sin\theta_2 - \omega_3 L_3 \sin\theta_3 + \omega_4 L_4 \sin\theta_4 = 0$

Imag: $\omega_2 L_2 \cos\theta_2 + \omega_3 L_3 \cos\theta_3 + \omega_4 L_4 \cos\theta_4 = 0$

Acceleration Analysis: known: $\alpha_2 = 0$ unknown: α_3, α_4

$$\frac{d}{dt}\left(j\omega_2 L_2 e^{j\theta_2} + j\omega_3 L_3 e^{j\theta_3} - j\omega_4 L_4 e^{j\theta_4}\right) = 0$$

$$\Downarrow$$

$$\left(j\alpha_2 L_2 e^{j\theta_2} - \omega_2^2 L_2 e^{j\theta_2}\right) + \left(j\alpha_3 L_3 e^{j\theta_3} - \omega_3^2 L_3 e^{j\theta_3}\right)$$
$$+ \left(-j\alpha_4 L_4 e^{j\theta_4} + \omega_4^2 L_4 e^{j\theta_4}\right) = 0$$

Real: $-\omega_2^2 L_2 \cos\theta_2 - \alpha_3 L_3 \sin\theta_3 - \omega_3^2 L_3 \cos\theta_3 + \alpha_4 L_4 \sin\theta_4 + \omega_4^2 L_4 \cos\theta_4$

Imag: $-\omega_2^2 L_2 \sin\theta_2 + \alpha_3 L_3 \cos\theta_3 - \omega_3^2 L_3 \sin\theta_3 - \alpha_4 L_4 \cos\theta_4 + \omega_4^2 L_4 \sin\theta_4$

Figure A.5: Position, Velocity, and Acceleration Analysis

Position of Point P Origin O_2

$$\vec{R}_P = \vec{R}_4 + \vec{R}_5$$

$$\vec{R}_P = -L_4 e^{j\theta_4} + L_5 e^{j\theta_3}$$

Velocity of Point P

$$\vec{V}_P = -j\omega_4 L_4 e^{j\theta_4} + j\omega_3 L_5 e^{j\theta_3}$$

acceleration of point P

$$\vec{A}_P = \left(-j\alpha_4 L_4 e^{j\theta_4} + \omega_4^2 L_4 e^{j\theta_4}\right) + \left(j\alpha_3 L_5 e^{j\theta_3} - \omega_3^2 L_5 e^{j\theta_3}\right)$$

Figure A.6: Position, Velocity, and Acceleration of Point P, the foot.

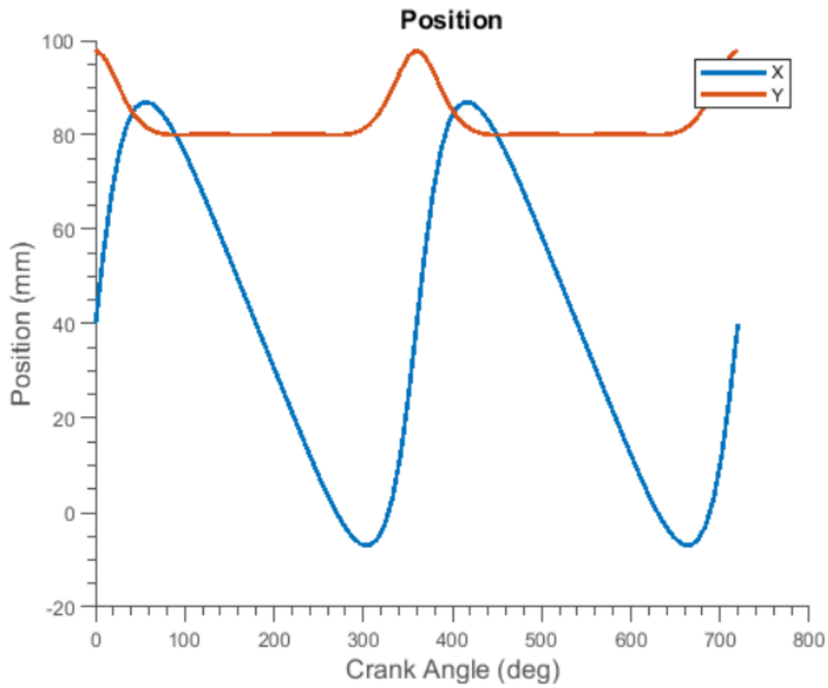


Figure A.7: X and Y Position of Foot v. Crank Angle

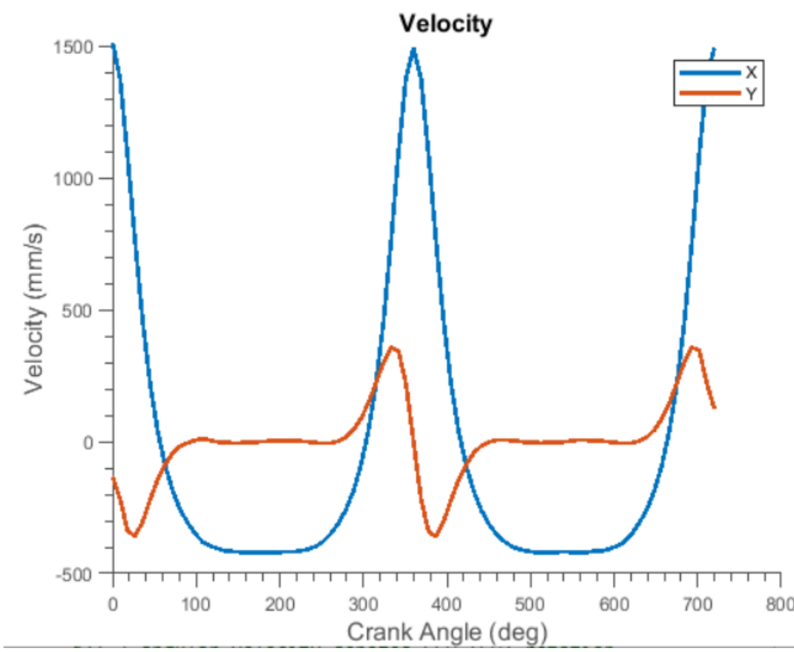


Figure A.8: X and Y Velocity of Foot v. Crank Angle

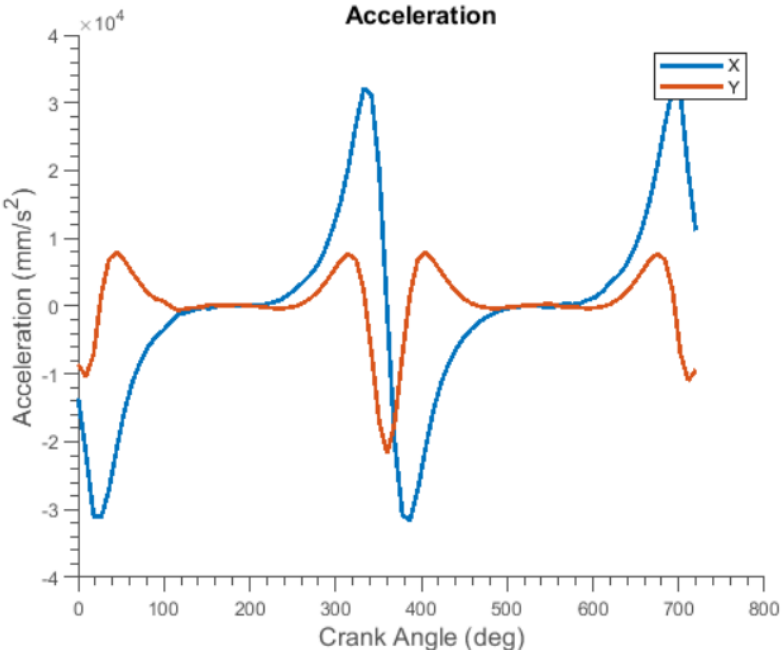


Figure A.9: X and Y Acceleration of Foot v. Crank Angle

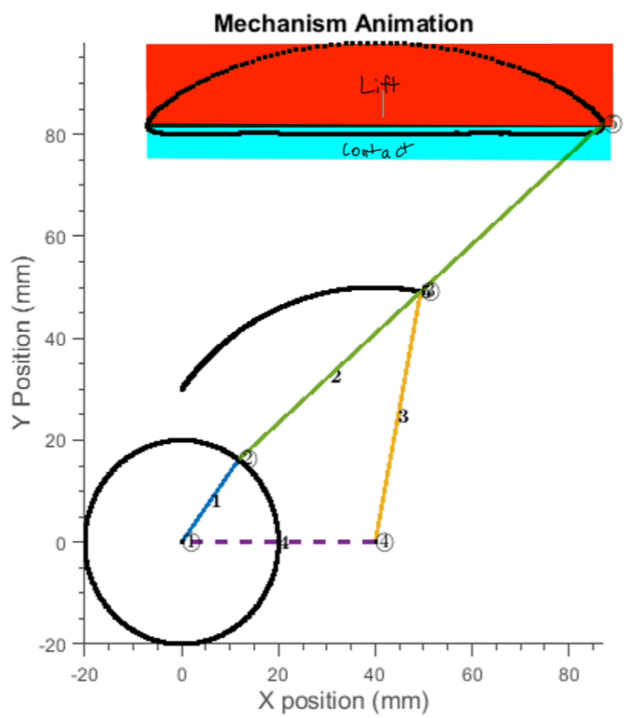


Figure A.10: Identification of Contact and Lift Phases from Mechanism Trajectory

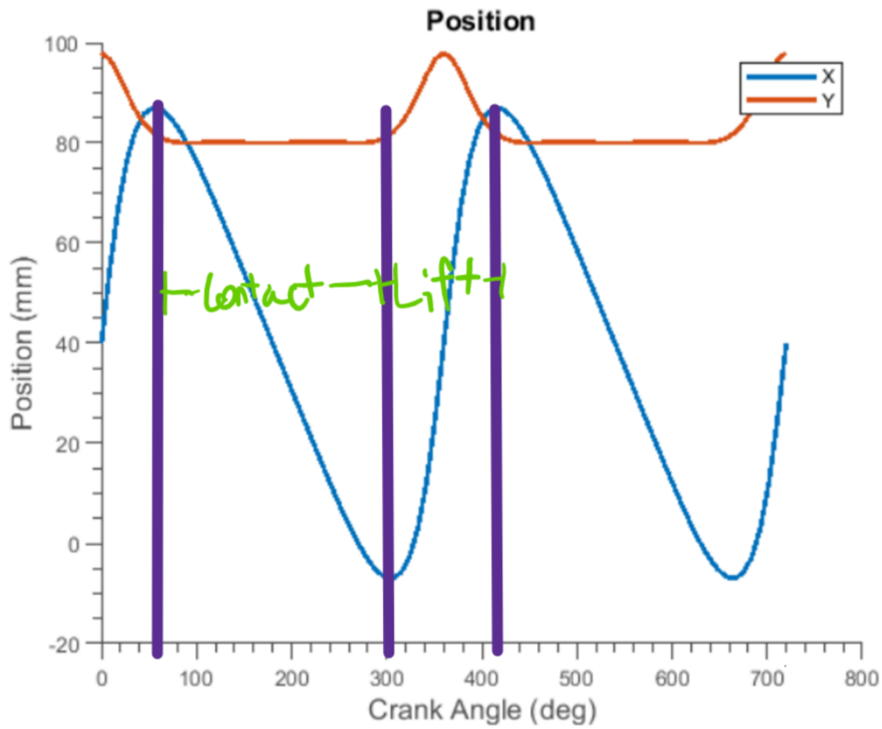


Figure A.11: Identification of Contact and Lift Phases from Position Graph

$$\beta = \frac{252}{360} = .7 \qquad L_s = X_{lift} - X_{contact}$$

$$X(54^\circ) - X(306^\circ) = 87 - -7 \therefore \boxed{L_s = 94\text{mm}}$$

$$V_{Robot} = \frac{L_s}{\beta T} = \frac{(L_s)(W_{crank})}{\beta\,(2\pi)}$$

$$W_{crank_{min}} = V_{Robot\,min} \cdot \frac{\beta(2\pi)}{L_s}$$

$$\left(\frac{2\text{m}}{\text{min}}\right) \cdot \frac{.7(2\pi)}{.094\text{m}} = 93.57\frac{\text{rad}}{\text{min}} = \boxed{W_{crank_{min}} = 1.55\frac{\text{rad}}{\text{s}}}$$

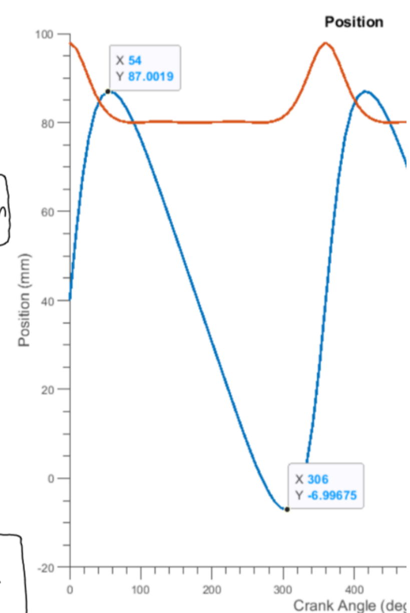
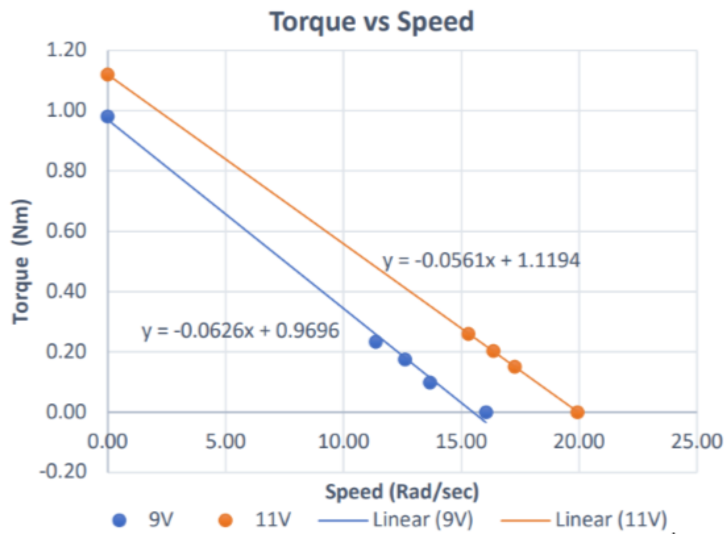


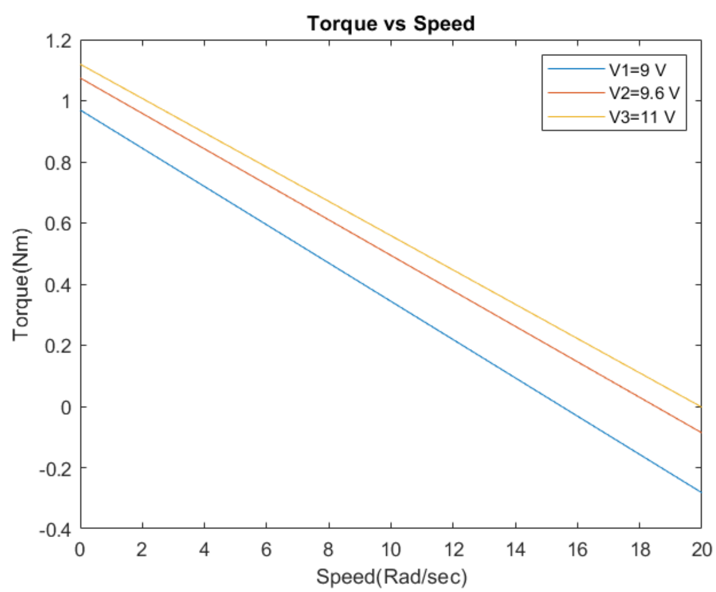
Figure A.12: Stride Length and Angular Velocity of Leg Drive Shaft Calculations



$$W_{motor\ load} \approx \frac{1}{4} \cdot W_{no\ load} \approx \frac{1}{4}(20) = \frac{5\,rad}{s} \quad \text{assuming 11V}$$

$$\text{Gear Ratio} = \frac{W_{motor\ load}}{W_{crank\ desired}} = \frac{5}{4 \cdot 1.55} = \frac{5}{6.2} = .806$$

Figure A.13: Gear Ratio Calculations



expected peak torque from force analysis $T_i = 0.8105\,Nm$

gear ratio $m_v = \frac{24T}{30T} = 0.8$

$\beta = 0.7$ $\quad N = 1$

stride length $L_s = 0.05m$

$T_m = \frac{N \cdot T_i}{m_v} = \frac{0.8105\,Nm}{0.8} = 1.013125$ (peak torque at the motor)

For motor Lab, $\begin{cases} T_m = (-0.0626\,Nm.s) \cdot W_m + 0.9696\,Nm & (\text{9V batteries}) \\ T_m = (-0.0561\,Nm \cdot s) \cdot W_m + 1.1194\,Nm & (\text{11V batteries}) \end{cases}$

Interpolation

For 9.6 V batteries $T_m = (-0.05805\,Nm.s)\,W_m + 1.07486\,Nm$

$\therefore T_{motorpeak} = 1.013125\,Nm < T_{stall} = 1.07486\,Nm$

$\therefore$ System can work

Motor angular velocity at peak torque : $W_m = \frac{1.013125\,Nm - 1.07486\,Nm}{-0.0626\,Nm \cdot s} = 0.9798\ rad/s$

crank angular velocity $W_i = \frac{W_m}{m_v} = 1.225\ rad/s$

Speed at peak torque : $V_{robot,\,min} = \frac{L_s}{\beta T} = \frac{0.05 \cdot 1.225}{0.7 \cdot 2\pi} = 0.01393\ m/s$

Figure A.14: Velocity calculation using matlab DFA results

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I, Patrick Ottavio Harsono, hereby agree to follow all academic integrity policies while producing this report. In addition to my original contributions, I have read through this entire report and certify that all materials, including the designs, are correct and unplagiarized.

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Date: 5/9/2022

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