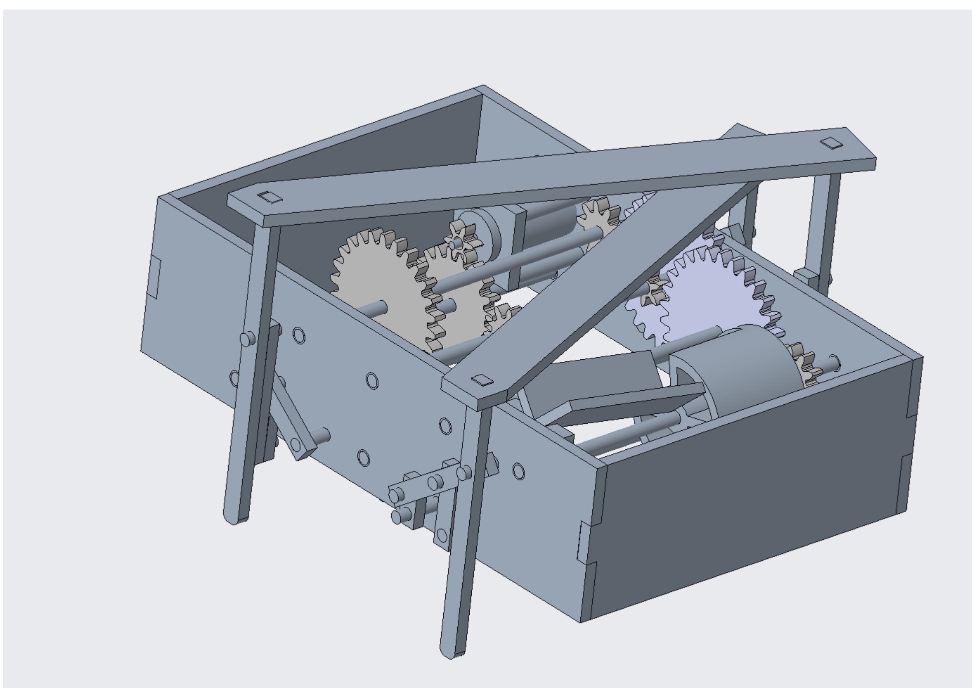
Final Report

Snack Delivery Robot



Team 14, Section BB3

Jessica Nicholson, Peter Figura, Jasmine Lee, Lauren Mah

Design Process and Theme

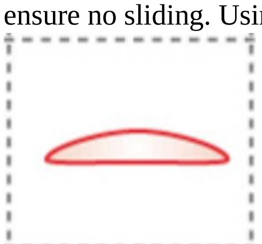
For this Project, we were given the task of designing a snack robot which would be used in campus dorms to deliver snacks in replacement of social gatherings for snack breaks due to this year's COVID-19 pandemic. Our goal for the robot's functions were for it to be a fully autonomous robot with its mechanical actions running off a single motor. In addition to this, it would be moving in a straight line at a speed of at least 0.1 m/s, delivering snacks every 2 m. Dimensionally, the overall robot would fit in a standard shoe box of size 35(L)x25(W)x12(H) cm^3 and the snack mechanism. The snack mechanism should hold 5 snacks that weigh 25 g or less, each snack individually packaged. Snacks should also be fed from the storage bin to the snack mechanism. As for the walking mechanism it should use legs or feet to move with only the addition of wheels as support. It should also have at least three points of contact with the ground, two of which being mechanical legs. Also, considering the cost of the robot is important in its manufacturing and should not be more than $200 beyond the provided kit.

Through this project, we were able to translate the specific requirements into a detailed design for a functional prototype, as well as create a detailed design including moving elements, motors, gear trains, cams, bearings, fasteners, and chassis. All of which were done while practicing staying within a modest budget range. With the use of analysis principles such as instant centers, position-velocity-acceleration (PVA) analysis, dynamic force analysis (DFA), and finally virtual work, we were able to optimize the behavior of the mechanism. Most importantly, when figuring out the design and analysis of the robot, communicating the design effectively to the user/stakeholders and each other as a team was key.

Our robot's theme was the carnival, this was mainly decided based on our snack mechanism's similar shape to a Ferris wheel. During the time we were deciding on a theme, in the Midwest carnivals and pumpkins patches were a seasonal commodity so we decided it would be an interesting and relatable theme to have. To further emphasize the fall carnival theme, we also decided to use candy corn as our snack that would be delivered at the dorms to each resident. Delivering small packets of candy corn, this robot will embody the spirit of fall. While students are stuck in their dorm, hopefully this allows them some semblance of what this festive season should be like.

Robot Mechanism and Power Train: Summary of Critical Design

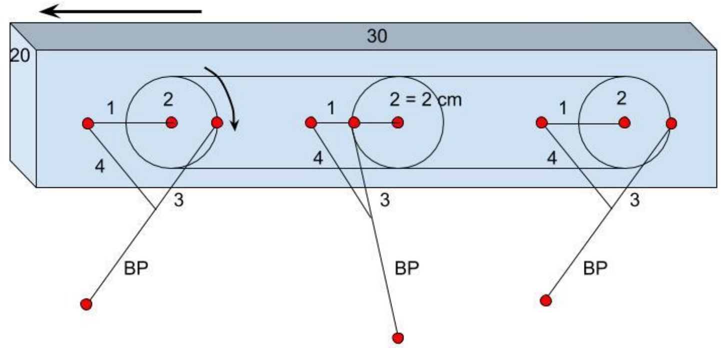
Leg Mechanism Motion Design: To complete our design, we had to create a four-bar linkage to act as our mechanism legs. Using the Coupler Curve Look-up Table, we chose a path that creates adequate walking motion with a flat portion of path and constant velocity while in contact with the ground to ensure no sliding. Using these requirements, we chose this path:



Coupler angle: 180 degrees
L3/L2 = L4/L2 = BP/L2 = 2.5

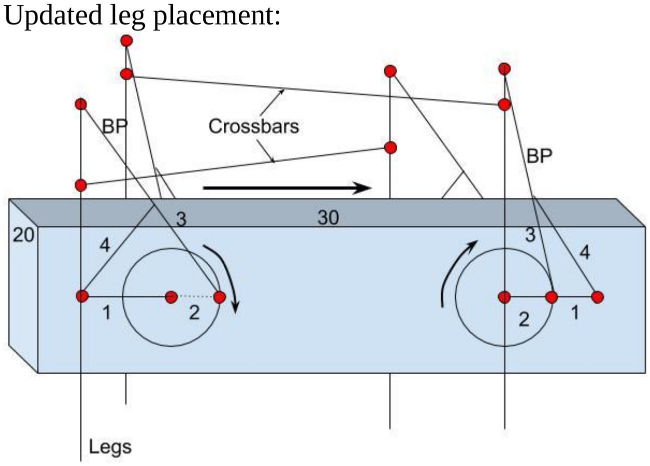
Based on the dimensions of our design, we had to pick appropriate link lengths for the walking mechanism. Our crank link L2 is 1.2 centimeters with the other links following the ratios above.

The diagram below shows our initial leg placement and orientation on one side of the mechanism based on these parameters.

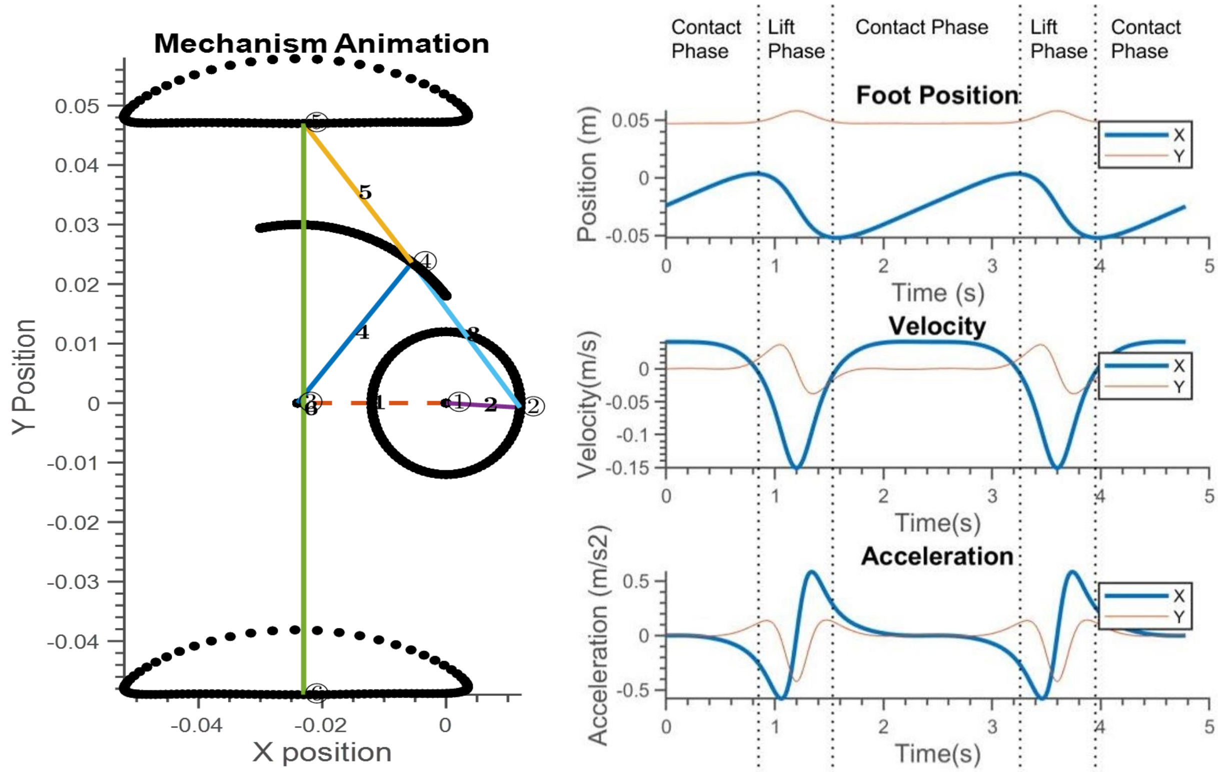


During PVA analysis, we realized that these linkages created the path we needed, but traced upside down. We flipped the orientation of the linkages at each leg to fix this, changed the mechanism gait to quadrupedal rather than hexapedal, and created a vertical leg at each link to translate the motion to the ground. We secured these legs with two crossbars connecting the diagonal legs and at varied heights, so they do not interfere with one another. Each leg is 9.6 centimeters long in order to reach the ground yet not exceed the height requirement for our mechanism.

Updated leg placement:



<u>PVA Analysis Simulation Results</u>:
Our mechanism animation from our PVA analysis traces the path of the end of link 5, and its translated motion at the end of the vertical leg. The vertical leg is constrained not to rotate. The x and y components of the foot position, velocity and acceleration are graphed below.



Period = T = 2.4 seconds Ideal walker velocity = 0.2 m/s

Using these chosen values and our simulation, we were able to find some values important to the analysis of our mechanism.

Stride length = L_s = 0.08 m Duty factor = β = 0.729 Overlap = 23%

We then used a formula for the velocity of our mechanism to find the motor angular velocity we need to achieve our ideal walker velocity.

$V_{robot} = L_s{*}w_i / 2\beta{*}pi$

$\mathbf{w_i} = 2V_{robot}{*}\beta{*}pi / L_s$ = 2*0.2*0.729*pi / 0.08 = **11.45 rad/s**

Motor angular velocity $\mathbf{w_m} = w_i m_v$ = 11.45 * 1.667 = **19.087 rad/s**

Snack Mechanism: Our leg design meets project criteria because its contact phase is flat and has constant velocity. It also has a long stride length which allows the mechanism to reach a high velocity. The foot spends most of its time on the ground during the crank cycle, meaning that there are always two feet on the ground and sometimes four. This is good to ensure stability.

The snack's delivery mechanism is a rotating pinwheel design that has four sectors with only one of the sectors opened for the input of the snack from the snack storage, and the delivery of the snack to the ground. With its rotation the mechanism holds the snack momentarily and delivers by rotating it out of the system every 2 meters. The mechanism rotates by a gear on the shaft of the snack wheel that is then connected to a gear train from the motor.

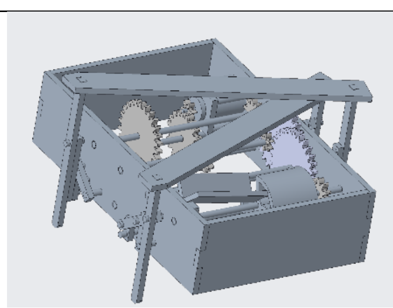
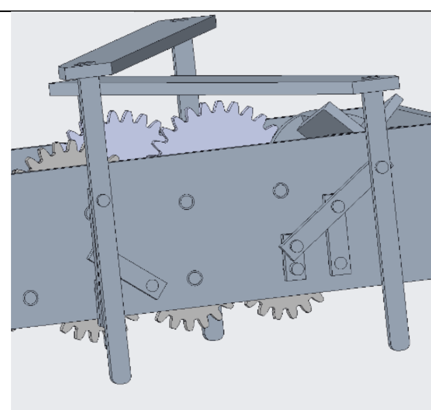
The snack itself is a mini package filled with candy corn with the dimensions of 60.3(L)x20.3(W)x52.5(H) mm^3 with a weight of about 14 grams. The snack storage is an angled ramp with a length of 135 mm and two angled sides that are 25 mm tall, slanted 90 degrees about each other. Considering the width of each snack being 20.32 mm, the total length of 5 snacks lined up would be 101.6 mm. We wanted to make sure there was leeway room for the snack storage to carry the snacks, so and additional 30 mm was added to the length of the snack storage. The height of each slanted wall was not as important as its only necessity was to support the snack from tipping out. With this consideration, our dimensions were set to so that the snack compartment height be about ½ of the snack height.

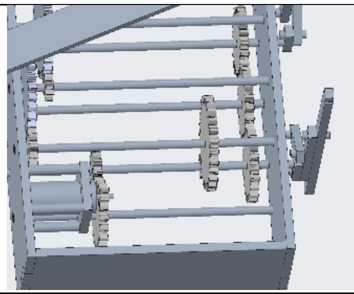
The snack mechanism will be 3-D printed at the Innovation Studio. It comes to the final weight of about 92.4 grams and a price of $12.77 which is made up of the cost for the 3-D printed weight and the additional cost of labor time to design and manufacture the part.

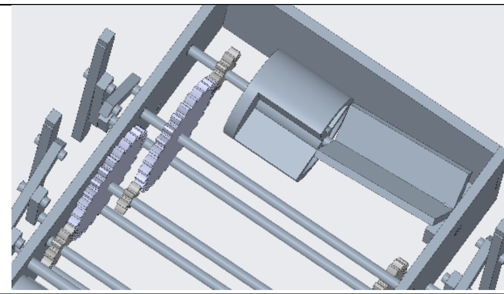
Walker-Snack Mechanism Timing: By looking at the CAD below, our plantigrade leg mechanism can be seen, as well as a drive train connecting from the motor to the leg mechanism and gear train from the leg mechanism to the snack mechanism. Our leg mechanism overall is a four-bar linkage, with a crank of length of 1.2 cm, rocker/BP link of 6 cm, coupler of 3 cm, and a ground “link” of 2.4 cm. Our leg mechanism is connected to a bar that will act as the legs of our mechanism which has a length of 9.9 cm. Two out of the four legs will always be planted, the legs that are in conjunction with one another are the legs that are diagonal from each other. The legs that are acting together will be connected by a rigid bar across the top of the mechanism. For the snack mechanism of our robot, it has a pinwheel and a ramp that will be integrated and run by the same motor using a compound gear train. Within our compound gear train, we found that the required gear ratio between the motor and the walker is 35, and that between the walker and the snack mechanism it should be 20.848. This was found using the ideal velocity of our walker (0.2 m/s) and the rate at which the snacks would be delivered (1 snack every 2 meters). The gear ratio between the snack wheel and its meshed gear on the motor shaft was found based on how many times the crank rotates every 2 meters. By finding the approximate foot position at opposite crank positions, we found that the mechanism travels 8 centimeters during the period a leg is on the ground. This corresponds to half of a crank rotation. The mechanism therefore travels 16 centimeters per one full rotation of our 2-cm-long crank. Since the distance between doors is 2 m or 200 cm, the number of crank rotations between doors is 200 cm / 16 cm = 12.5 rotations. This means the snack wheel must rotate once per 12.5 crank rotations. The gear ratio between the snack wheel and the gear meshed with it is 12.5:1.

Robot Design and Final CAD

Several changes were made to the robot based on the feedback from deliverable two. The most obvious change is the inclusion of a Chebyshev Plantigrade Walker mechanism. This changed the gait from hexapedal gate to a quadrupedal. Additionally, the sprockets and chains that were included in our initial design was replaced with a more robust gearing system.

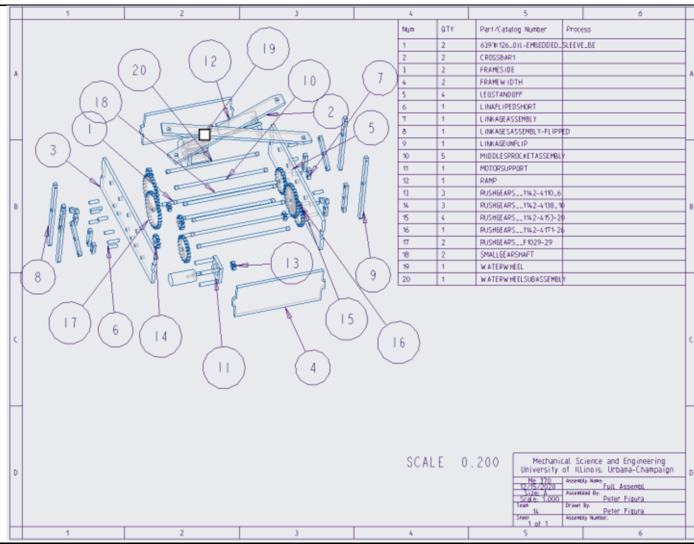
	
Final Robot	Walking Mechanism



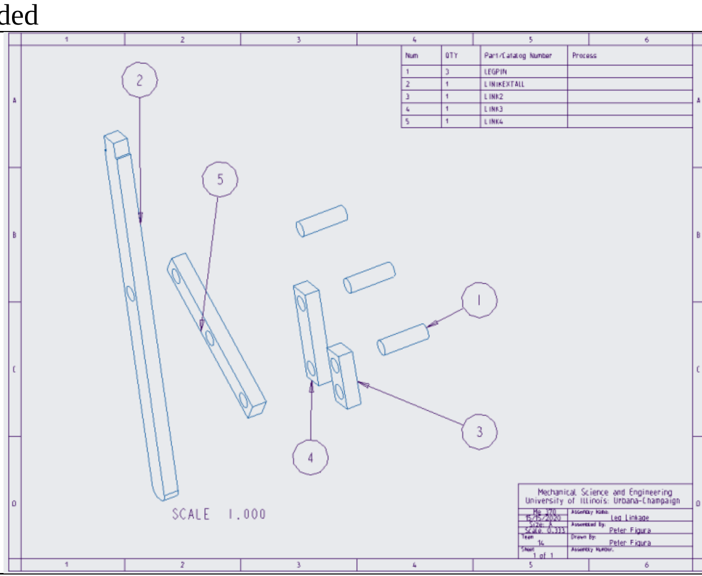


Walker Power Train and Motor	Snack Dispenser and Snack Gear Train
[Link to Animation]()	

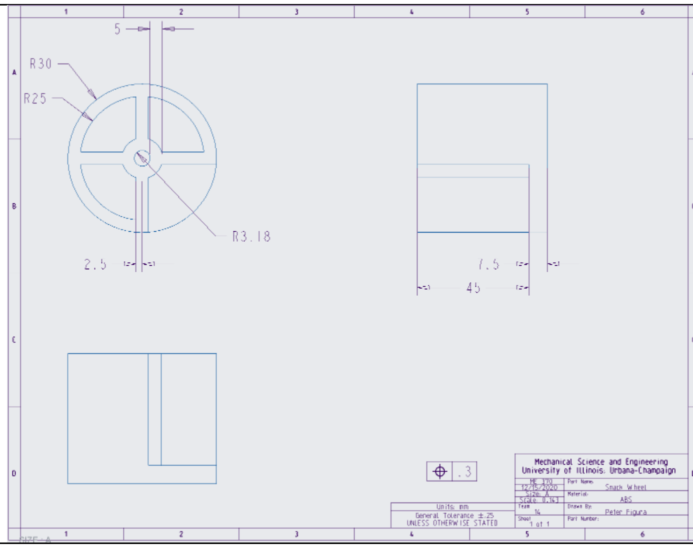
C: Engineering Drawings



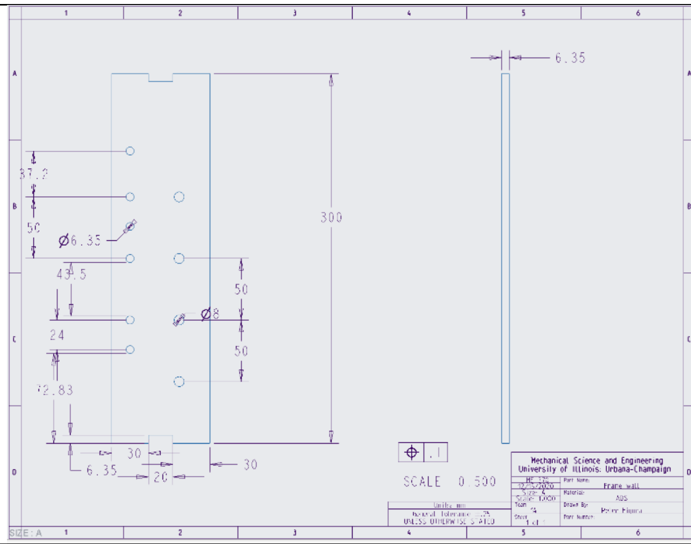
Full Assembly Exploded



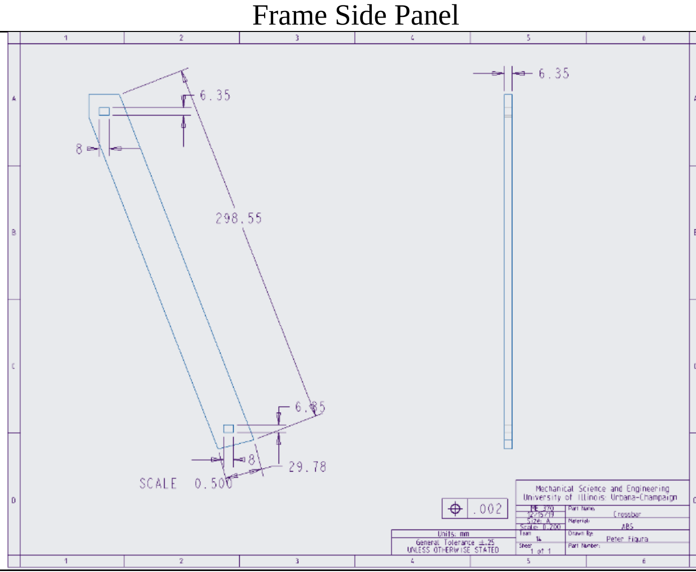
Walker Linkage, Exploded



Water Wheel



Frame Side Panel



Walker Crossbar

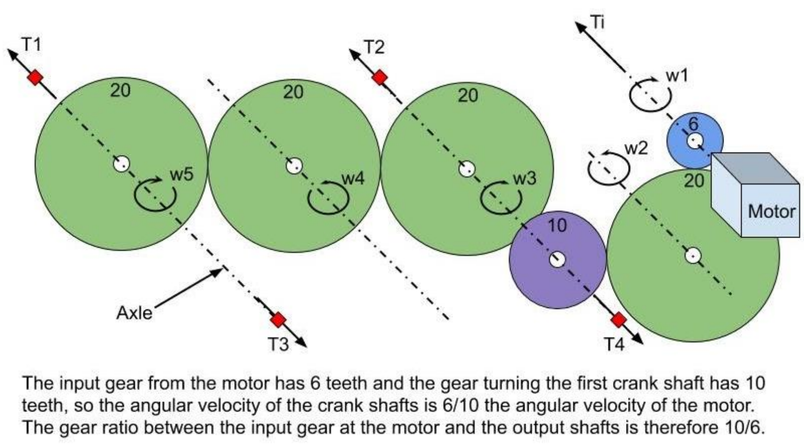
Robot Mechanism and Power Train: Mechanism Analysis

Leg Mechanism Force Analysis: Through our DFA analysis, we were able to figure out whether our design would be able to run smoothly or function at all. The first step in testing our theoretical mechanism was to determine the peak torque on the legs and the torque from the ground reaction forces. This was done using free body diagrams, instant center analysis, and dynamic force balance equations. The next step was to modify the DFA code, previously used in the lab, to meet the specifications of our robot. The resulting code allowed us to plot the x and y position of our robot's foot for two complete cycles. In addition, we plotted the leg crank shaft torque versus time. Through this work we were able to determine the estimated peak motor torque which we found to be approximately 0.08499 N*m. We were also able to find our estimated power which came out to be approximately 0.445 watts. Moreover, we were able to determine the friction and foot slip of our robot. One requirement of our robot is the ability to travel on multiple surfaces. From our calculations we found that our friction force to be 1.006 N, which translated to our robot being able to easily walk on carpet but not linoleum. In order to combat this issue, we decided to add rubber feet onto the bottom of our leg mechanism. This will allow our robot to have a bit more grip which will compensate for the friction of our mechanism. From this analysis we concluded that our robot will be able to walk and deliver snacks. This means that there are no major adjustments that needed to be done to our robot besides the rubber feet. Although our robot will perform to the specifications required from the deliverable, we were able to see that the required velocity and the real velocity are approximately 25% off. This is due to slow down in the motor from torque. In order to solve this issue, we decided to slightly increase our gear ratio. This was done since there is an inverse relationship between the gear ratio and the motor torque.

Power Train: Below is a diagram of the gear train between the motor and the crank shafts that drive the walking mechanism.

◆ = Point where axle drives a leg mechanism
Ti = Input torque from motor
T1, T2, T3, T4 = Crank shaft torques driving each leg mechanism
wi = Input angular velocity from motor
w3, w5 = output angular velocities at leg mechanism cranks

The number on top of each gear indicates the number of teeth it has.



The input gear from the motor has 6 teeth and the gear turning the first crank shaft has 10 teeth, so the angular velocity of the crank shafts is 6/10 the angular velocity of the motor. The gear ratio between the input gear at the motor and the output shafts is therefore 10/6.

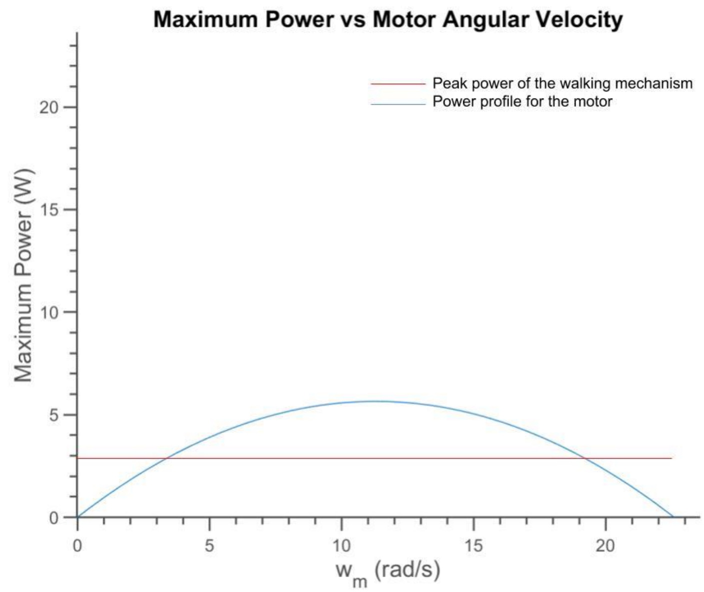
The required motor velocity we found corresponding to our chosen ideal speed, 0.2 m/s, is 19.087 rad/s. This doesn't consider, however, how torque on the legs slows their movement. The motor we use is an 11V motor. For this motor, $T_m = -0.0443w_m + 1.0009$ and $P_{max} = T_m w_m = -0.0443w_m^2 + 1.0009w_m$.

To find the maximum power output, we must find the value of w_m for which P_{max} is at maximum.

P'_{max} = -0.0886w_m + 1.0009 = 0, so power is maximum at w_m = 11.2968
P_{max} = -0.0443(11.2968)^2 + 1.0009(11.2968) = **5.6535 W**

From our VW analysis, the required peak torque is 0.121 Nm. At a peak torque T_i of 0.121, $T_m = T_i / m_v$ = 0.121 / 1.667 = **0.07258**. Using this value for T_m in the equation, the motor angular velocity at this torque is 20.955 rad/s. This is slightly higher than the motor velocity we need, 19.087 rad/s. For a motor angular velocity of 20.955 rad/s and a gear ratio of 1.667, we get a crank angular velocity of 12.57 rad/s.

The required velocity of our robot is 0.2 m/s, but the actual velocity of our robot is
V_{robot} = (L_s*w_i) / B(2*pi) = (0.08*12.57) / (2*pi*0.729) = **0.21954 m/s**.
The fraction of the required velocity that our robot will travel at is 0.21954 / 0.2 = **1.0977**.
P_{max} = -0.0443(19.087)^2 + 1.0009(19.087) = **2.965 W**



Based on this graph, the motor will be able to operate between w_m = 3.507 rad/s and w_m = 19.087 rad/s. We want to operate our robot at w_m = 19.087 rad/s, so our robot will be able to operate. With our current design, our robot is slightly faster than our required velocity of 0.2 m/s. In an ideal scenario, our robot would operate at 0.2 m/s, but the motor operates slightly faster than necessary at 11V. Due to this, we calculated the actual robot speed at 0.21954 m/s. In order to get our robot's speed back to 0.2 m/s, we can change the gear ratio for a lower crank angular velocity. The crank angular velocity we need to achieve a speed of 0.2 m/s is 11.45 rad/s, but our actual crank angular velocity is 12.57 rad/s.
This means that for a crank angular velocity of w_i = 11.45 rad/s, our new gear ratio must be:
$w_m = w_i m_{v,new}$ $\qquad$ $m_{v,new} = w_m / w_i$ = 20.955 / 11.45 = **1.83**

Robot Performance: Since an actual robot was not constructed it is impossible to know exactly how it would perform. However, based on our analysis as described in section's IV: A, B and II: C, B. Our robot should in theory be able to travel at a speed of 0.2 m/s. In the time it takes to travel between the two doors the feet will make 25 steps each and the snack wheel will make one full rotation. This should allow a snack to be evenly dispensed once every 2 meters. The robot should not encounter any issues with torque, and as long as the rubber feet are attached it should have no issues with slipping.

Budget and BOM

V: Bill of Materials

Component	Supplier	Catalog Part Number	Link	Quantity	Weight part (g)	Weight Total (g)	Price (USD)	Price Total (USD)
Snack Wheel	Mechse	N/A	https://innovationstudio	1	92.37603	92.37603	$0.03	$12.77
Oil-Embedded	Mechse	N/A	https://www.mcmaster	8	40	320	$0.55	$4.40
Round Shaft 1/4" Dia.	Mechse	N/A	http://www.mcmaster.c	7	45	315	$8.12	$56.84
Motor 4mm D-profile	Mechse	N/A	https://www.pololu.co	1	88	88	$21.95	$21.95
Rechargable battery	Mechse	N/A	https://hobbyking.com/	1	129	129	$17.77	$17.77
Female battery wire	Mechse	N/A	https://hobbyking.com/	1	2	2	$1.33	$1.33
Crank Link (2) 1.2 x 1 x	Laser cut	N/A	Laser cut	4	1.104	4.416	See Acrylic Sheets	
Rocker Link (3) 6 x 1 x	Laser cut	N/A	Laser cut	4	4.59	18.36	See Acrylic Sheets	
Coupler Link (4) 3 x 1 x	Laser cut	N/A	Laser cut	4	2.5	10	See Acrylic Sheets	
Leg 10 x 1 x 0.6 cm	Laser cut	N/A	Laser cut	4	7.21	28.84	See Acrylic Sheets	
Pin, 0.635 cm	Laser cut	N/A	Laser cut	12	1.79	21.48	See Acrylic Sheets	
Rubber foot, Diameter:	Laser cut	N/A	Laser cut	4	21.52	86.08	See Acrylic Sheets	
Top crossbar	Laser cut	N/A	Laser cut	2	9.13	18	See Acrylic Sheets	

Acrylic Side 8 x 30 x 0.6	Mechse	N/A	https://innovationstudio	2	175.428	350.856	See Acrylic Sheets	
Acrylic Front / Back 8 x 20	Mechse	N/A	https://innovationstudio	2	116.875	233.75	See Acrylic Sheets	
Corner Brackets, 6		1088A31	https://www.mcmaster	4	20	80	$2.36	$9.44
Acrylic sheets for	Mechse	N/A	https://innovationstudio	2			$20.00	$40.00
Acrylic-cut gear, 29	Laser cut	N/A	N/A	1	31.41	31.41	See Acrylic Sheets	
Acrylic-cut gear, 6	Laser cut	N/A	N/A	3	0.899	2.697	See Acrylic Sheets	
Acrylic-cut gear, 10	Laser cut	N/A	N/A	3	3.37	10.11	See Acrylic Sheets	
Acrylic-cut gear, 26	Laser cut	N/A	N/A	1	25.09	25.09	See Acrylic Sheets	
Acrylic-cut gear, 20	Laser cut	N/A	N/A	4	14.68	58.72	See Acrylic Sheets	

The robot come in with a final budget of $187.42* and a final weight just over 2 Kg. Several measures were taken to ensure costs and weights stayed low. All gears and links are to be cut out of acrylic, providing cheap and light weight parts that are easy to manufacture.

*Note the final budget is lower than the one reported during the final presentation, this was due to an error of duplicate parts in the BOM. This issues has been corrected for this report.

Conclusion and Reflections

Reflection on Project 2 Experience: Our design process went smoothly, but we had to make a lot of adjustments to our initial designs in order to meet design requirements and ensure our mechanism is functional. For example, our initial design used a walking mechanism that did not trace an ideal path. We therefore changed our leg design to a four-bar coupler linkage. Once we had a proper leg design, we explored a few options to achieve the gear ratio we needed for both the snack mechanism and the walking mechanism. These are two of the major changes we had to make. Although we had to make a lot of design revisions, we were eventually able to create a functional, quality product that meets all design requirements.

Our initial analyses of the mechanism were mostly accurate. We had differing results at some points, however, so we talked over our results once they were complete and were able to come to a consensus on many calculations. We used simple materials and simple components, so none of our design would be particularly difficult to fabricate. Many of our components, including the frame and the gears, are cut from acrylic. Only components such as the motor, battery, and shafts are not. Apart from frequent design revisions during our project and differing initial analysis results, we had a good experience overall and were able to create a successful product.

Advice to Future ME370 Students: This second project was a much more time intensive and rigorous project than the first. It would be wise for future students to introduce themselves to the supplemental documents and the deliverables as soon as possible. It is unlikely that every group member in a group will be able to complete their portion of the work entirely on their own, so we suggest that future students meet with their group at least twice a week in order to ensure that there is no gap in understanding. Our last suggestion is to try and get to know each other in order to create a better work environment.

Reflection on Working in a Design Team: Working in a virtual/remote setting was helpful when sharing systemized information in a centralized manner by sharing screen, however when sharing work on paper it was very difficult to do so. This is because when doing so members had to send a picture to their computer and then upload it to the group and repeat this process when their work had changed. For members who had electronic devices to write on it was easier as they could show their change in work in real time. Additionally, since communication could be done via text it was difficult to reach members if the members were not active on their electric device. If there were in person classes, the alternate manner of talking to a group mate in-person, in-class could have been possible. However, some benefits to working online is digitalizing and centralizing work on an online application such as one-drive. This allowed for work to be more legible and homogenous for the team as well as accessible for members in different time zones.

Appendices

Appendix B: Team contributions

Peter Figura • III: Robot Construction ○ B: CAD Screenshots and Animation (Appendix) ○ C: Engineering Drawings (Appendix) • IV: Mechanism Analysis ○ D: Robot Performance • V: Bill of Materials	Jasmine Lee • I: Project Goals and Theme ○ A: Discussion of Project Goals ○ B: Robot Theme • II: Summary of Critical Design ○ B: Snack Mechanism ○ C: Walker-Snack Mechanism Mechanical Timing • VI: Conclusion and Reflections ○ C: Reflection on Working in a Design Team
Lauren Mah • IV: Mechanism Analysis ○ A: Leg Mechanism Force Analysis ○ Design Optimization • VI: Conclusion and Reflections ○ B: Advice to Future ME370 Students	Jessica Nicholson • II: Summary of Critical Design ○ A: Leg Mechanism: Motion Design • IV: Mechanism Analysis ○ B: Power Train • VI: Conclusion and Reflections ○ A: Reflection on Project 2 Experience

We, Jessica Nicholson, Lauren Mah, Peter Figura, Jasmine Lee, hereby agree to follow all academic integrity policies while producing this report. In addition to my original contributions, we have read through this entire report and certify that all materials are correct and unplagiarized.

Signature: Jessica Nicholson, Lauren Mah, Peter Figura, Jasmine Lee

Date: 12-19-20