Final Report

Team Sprocket

ENGS 146, Spring 2016

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Abstract

This design challenge, which culminated in a jousting tournament to test speed and maneuverability, called for a pedal powered walking vehicle that fit within a 4x6x3 foot box. The design met these criteria by using two sets of driven legs (with four legs in each set) and a skid steer drive mechanism actuated using disk brakes and a differential. The Jansen linkage was used for the legs, proven to be effective in the Strandbeast project[1] by artist Theo Jansen. The brakes were activated using bike caliper brakes, and the legs were powered with a chain and sprocket that attached to the drive shaft, which was driven via another sprocket chain combination going out to the pedals. Design choices were driven by the accelerated timeline of the project, with most details chosen because they had been proven to be effective, such as the Jansen linkage, the differential, and the use of only driven legs. The major design consideration was to create something that would work well with minimal redesign and debugging required. The machine walked smoothly and turned well, with very little re-machining of parts required, and no redesign of the overall components. The only major flaw in the design was an oversight of the strength required in the bottom linkage of the leg to withstand the torque created by turning. Overall the design was effective, performed well, and requires very little tweaking to bring it to peak performance.

Introduction

This semester we built a pedal-powered walking machine, dubbed Penelope, which was to compete in a jousting tournament. In the tournament points were rewarded for being robust, quick, polished, and having a tight turning radius. Therefore, we decided that Penelope would be smaller than the maximum dimensions (4x6x3'), light, and well made.

With that in mind, we made design decisions such as making the legs only 2' tall, shortening the width of the chassis and spacing the legs closer, opting for ½" thick plywood instead of ¾", and super gluing each hole that a bushing pushed into it to enforce the vision of having a light, well made, fast walking machine. Available to us were the Thayer machine shop, Allyn large frame lab, bike kit tools, and 2 old bicycles. Since Penelope had to be pedal powered we used chains, pedals, brakes, brake handles, frame members, and sprockets from the bicycles. With these resources and this vision, we embarked on designing Penelope from the ground up. We had group meetings nearly every other day leading up to competition and for the final week we met every day. Each meeting we had design reviews of our parts, talked about the week ahead, set goals for each team member, and took notes to hold people accountable. We developed a "punchlist" with tasks needed to complete the robot as part of our organization scheme, and that helped us be more organized, work effectively as a team, and communicate. When designing we always kept the vision in mind, kept an open mind to comments, and

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[1] Theo Janson's Strandbeest. Theo Janson, n.d. Web. 6 June 2016. <http://www.strandbeest.com/>

frequently checked designs with others. In this report you will find a discussion of our design procedure and implementation, analyses done on our designs, troubles we ran into, and finally a reflection of the project as a whole. In the appendices we include mechanical drawings, renderings, a Bill of Materials, and analysis results of critical components and complete assemblies for your reference.

Discussion

Overview

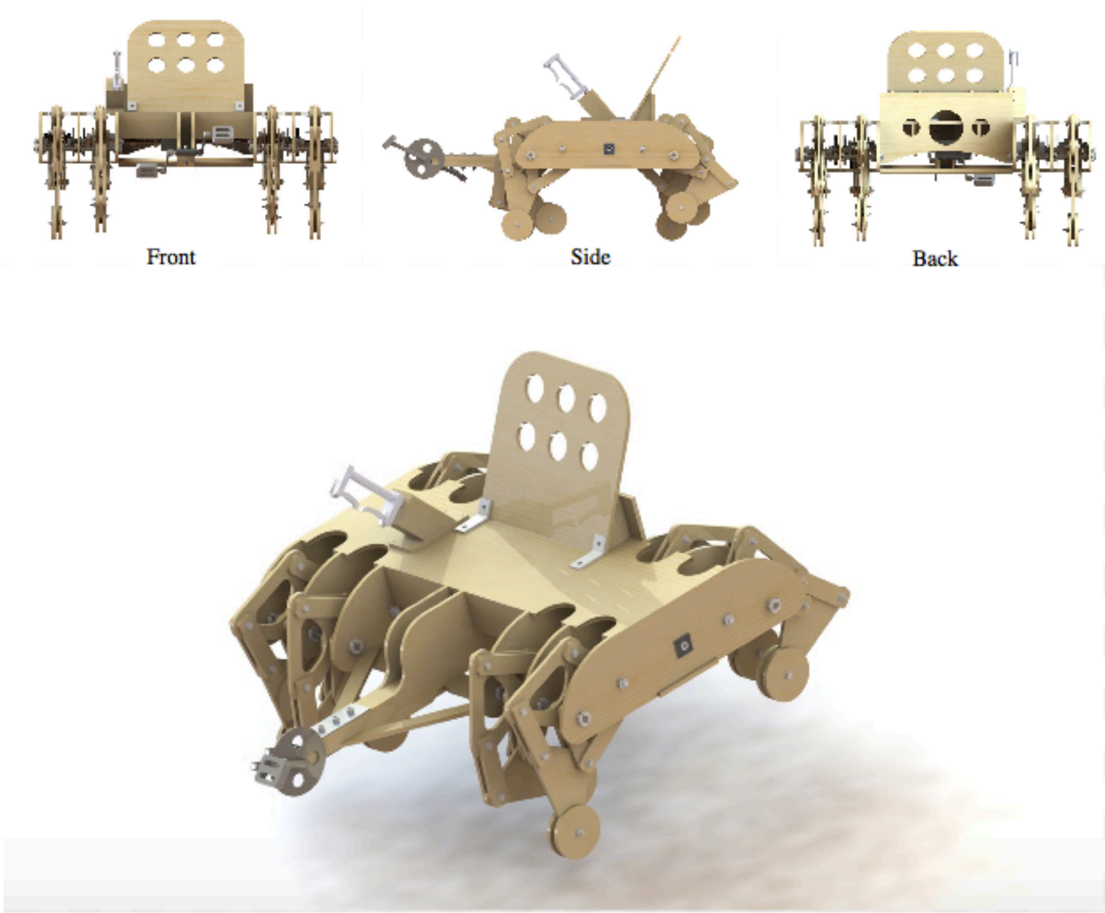

Figure 1: Penelope from all sides.

The design used in competition originated in a brainstorming session that compared top-level functionality ideas, such as using skid steering vs. passive leg steering, and positioning driven legs in front or behind. From this meeting, the team decided to pursue a system with all driven legs, as a passive leg system may be too light and not get enough friction on the ground to provide effective steering. The design would use skid steering, braking one of the sets of legs in order to turn. The center of mass should generally be stable and close to the ground, precluding work on any sort of two-legged stilt design, as center of mass would vary too much. In theory, this would create a stable machine able to get high friction on rough surfaces, like the gravel of the Dartmouth green.

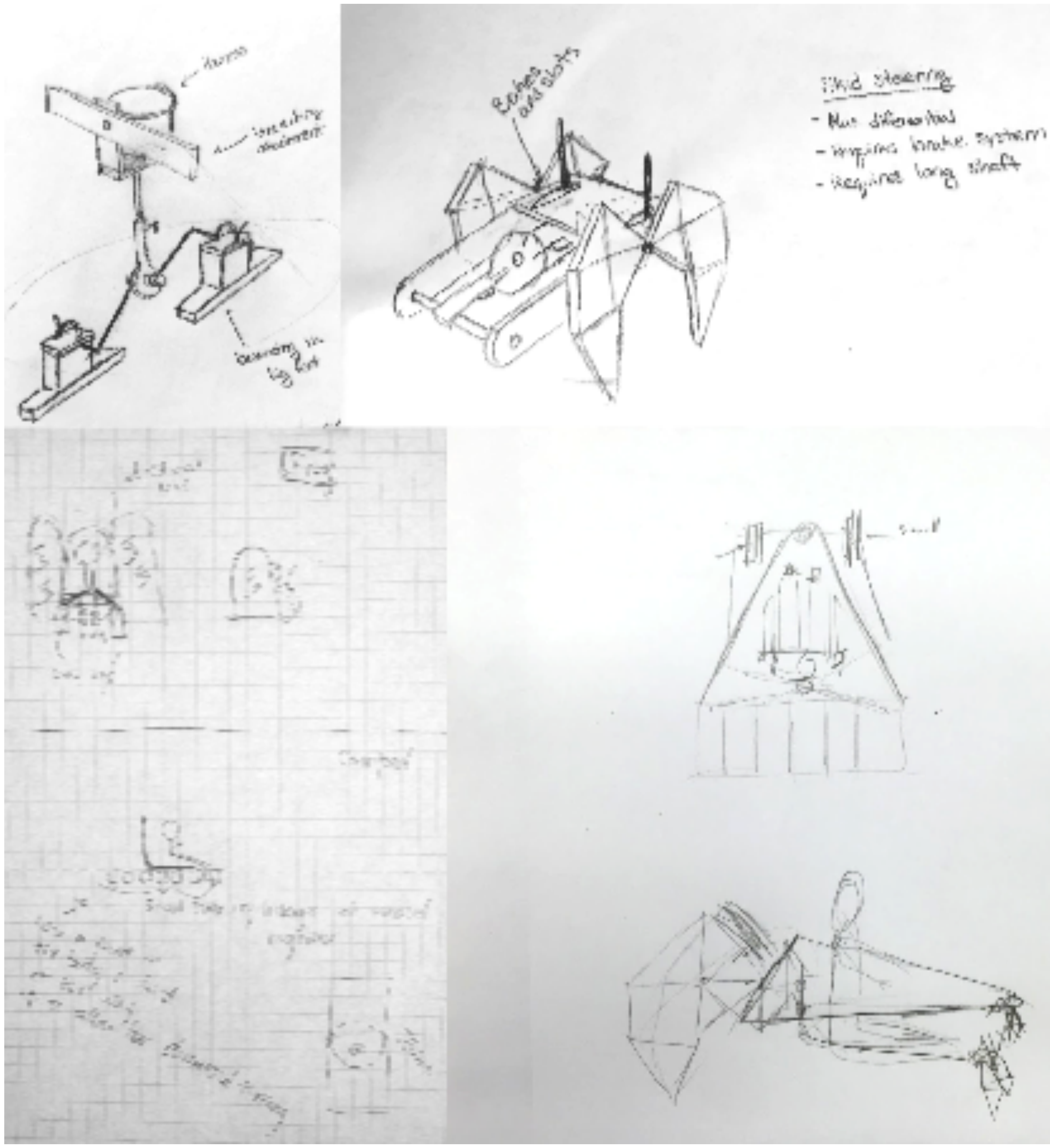

Figure 2: Some initial design concepts

Pursuing a simple skid steer vehicle, the design can be broken into modules of leg sets, brakes, differential, pedals, and chassis and supports. A single leg set included four legs, two crankshafts, the driveshaft, three walls, two support shafts, a cross support piece, and sprockets and chains to connect the crankshafts and driveshaft. Legs in a single set were aligned so that the legs diagonal to each other would rotate in phase, while the legs in line with each other would be 180˚ out of phase. This alignment allowed more chassis stability than if two legs on the same side were in sync. It was not possible to align leg phases between the two leg sets because of the differential.

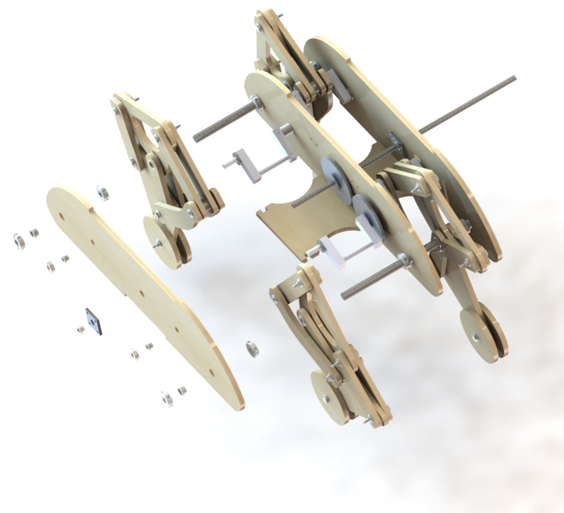

Figure 3: Partially exploded leg set

The brake system used two aluminum circles attached directly to the keyed drive shaft, and the brake calipers and handles appropriated from a bicycle. The calipers were mounted in a wooden frame attached to a leg set and the chassis, and could squeeze the aluminum circle to restrict the rotation of the drive shaft. The calipers were controlled by wires that connected to the brake handle system on the top of the chassis. The brake system, in combination with the differential, allowed the vehicle to turn.

The differential is made of four bevel gears, a support shaft, bearings, and six aluminum walls: two base plates with four cross support walls. The two additional cross support walls were added to help ensure that the driveshaft was extremely straight approaching the differential (shaft bending was a problem noted in the teaching assistant prototype vehicle). The two pieces of the drive shaft are linked in the differential, so that they may rotate independently. The large sprocket of a bicycle crankset was attached to one side of the differential to connect it to the pedals using a chain.

The pedal assembly used the existing bike crankset and a wooden mount to attach the pedals to the chassis. Multiple bolt holes were set into the shaft extending from the crankset to secure the crankset to the mount, and also to provide some sizing adjustability for the riders.

The chassis and supports were simply designed, connecting the two leg sets and providing support in the space between them. A seat back was added to support the rider's ability to push against the pedals.

More information on these modules is included in Appendix 4.

Design Challenges

Leg Linkage Interference

The prototype leg built in the demonstration jig had some issue with clearance. At one point in its cycle, the lower and upper fixed triangles would collide, and considerable force was needed to push past this position. At the time the cause was uncertain; the holes in the jig for the shafts were not able to be reamed to the proper size, and the shafts were floating in the holes rather than within bushings pressed into the holes. With this uncertainty, there was the fear that removing any material would make it more likely for the leg to lock out in an unrecoverable way in actual fabrication.

Upon construction and integration of the final legs, it was proved that there was a real clearance issue between the upper and lower triangles. This interference was both a function of the way the legs were designed, with upper and lower triangles moving within the same plane, and the scaling of the legs. In the mathematical version of the Jansen Linkage, all linkages are lines, and all joints are points. For there to be interference, two lines would have to cross each other, which does not happen. In our physical version, those linkages are made wider, and the joints must include the shafts, bushings, and necessary material around the bushings to hold them without breaking. Because the linkages were then wider, they collided where the idealized version of the leg did not.

The remedy to this issue was to sand down the upper fixed triangle where the collision occurred. It was determined that of the two parts, the upper and lower fixed triangles, it was the upper triangle that would be least degraded by the removal of material. Material was removed until it was easy to cycle the leg through the collision, but not to the point at which the collision no longer occurred. This was done to minimize the material needing to be removed, and because it was the difficulty in powering the leg rather than the collision itself that was the problem needing to be resolved.

Brakes

The cost for the initial bespoke brake lever design came in close to $200, which was deemed excessive and a redesign was initiated. The new design utilized material removed from the provided bicycles and scrap from the machine shop. The brake mechanism itself remained unchanged.

Constraining the drive shaft

The initial design called for each of the half shafts to be fixed twice in the differential, then three more times through the walls containing the legs. Upon consultation with Professor Diamond, it was learned that constraining a precision shaft more than twice would lead to binding and difficult motion. It was therefore decided to keep the two constraints in the differential (which had already been manufactured and worked well), and instead add adjustability within the chassis.

This was to be done by replacing bearings with bushings pressed into aluminum plates that could be moved relative to the chassis walls, then locked in place once everything was aligned. These aluminum mount plates were built, but were never fixed to the wall. In practice, it was seen that Penelope ran very well with the shafts floating in the holes in the chassis side walls. This could in part be a result of the forces acting on the half-shafts. They were being pulled in opposite directions by the two different chains mounted on two different sprockets.

Jigsawing all the chassis pieces

Because the chassis pieces were cut on the ShopBot, internal corners were filleted with the radius of the tool used for cutting. In some cases this provided no issue; multiple pieces could be wedged together, and extra material helped hold things together well once assembled. For other pieces it provided an obstacle to assembly, a combination of a jigsaw and wood file was used to remove the fillet and create a true corner.

Hole spacing on sidewalls

Upon initial assembly of the chassis sidewalls with the legs, it was clear that something was very wrong, as the legs would not rotate through a full cycle. However, the cause was not the leg linkage collision discussed earlier. By looking through the drawings for the side walls, it was determined that the spacing of the holes for the two shafts that held and powered the leg were incorrect. Since the leg itself was a scaled version of Jansen's original numbers, it was easy to see that the dimensions were incorrect.

The holes were moved and the chassis walls were recut, fixing the problem. It is unclear when these incorrect dimensions were introduced into the drawings. It could be that the original values simply put in as placeholders and never replaced. The more likely scenario is that during other modifications to the chassis side walls, the critical spacing was inadvertently changed. If this is what happened, then it makes a good case for using clearly named global variables to define critical dimensions like these, even if the dimension only appears in one place.

Length of pedal assembly

The initial location of the pedal assembly was approximated from the 3D human model provided to the group, and from measuring different group members' legs while in different seated positions. The fear was that the final design would put the pedal assembly too close to the seat, so it was intentionally placed further away than expected. The assembly was designed in a way that allowed easy modification to the length, and adjustability once a narrower range was decided on.

Once Penelope was constructed, it was clear that the pedal assembly was further forward than necessary, causing riders to fully extend their knees and lose power. The assembly was then shortened to provide a good middle ground for riders of different heights (though all group members were between 5'8" and 6'1", making adjustability less necessary).

The issue of loss of power when legs are extended is a common issue in recumbent bikes, which lack the ability to provide high torque at low rpm. Upright bicycles do not have this problem, since the rider is able to stand on the pedals. These issues with the recumbent position were known during the design stage, so the final design called for the addition of toe baskets to help pull on the pedals rather than just push.

Foot rotation

The initial foot design was roughly bell shaped, and relied on gravity to spin the foot into the proper orientation (with the longer, curved bottom on the ground). This worked most of the time, but would occasionally result in a "rolled ankle" where the foot would not be in the proper orientation when it made ground contact, causing it to roll sideways. This meant that the legs had different effective lengths, and the chassis did not maintain a constant height above the ground.

To remedy this issue it was decided that the feet would be redesigned as circles fastened to the legs in the center. To remain rules compliant, these circles were fixed to the legs via wood screw to prevent full rotation.

Leg Fracture

During testing on the gravel surface behind Thayer, a significant deflection in the leg's lower fixed triangle was observed. This deflection was greatest during turning, and when traveling over uneven terrain. While no remedy was made, 4 extra parts were made in case of failures during the competition. This proved fruitful when two of those parts broke in competition, were replaced, and Penelope was able to re-enter the tournament. Scraps from the broken parts were wood-screwed onto the new legs to provide additional support, and none of the braced legs failed again.

An obvious improvement that should have been made was to get rid of the triangular hole in the center of the leg. This bending was greatest where this material was removed, and the eventual failures occurred in this area. Were these replaced with solid versions, it is possible the failures in the competition would have been avoided. Another idea is to attach more material around the area of greatest deflection, a strategy that was implemented on-the-fly in the competition, and one that was implemented before the competition by team #LearningtoWalk.

Bending of the chassis

The top plate of the chassis is a single piece of ½" plywood which spans the full width of the chassis and uses interlocking features to hold other parts in their proper positions. There is no equivalent single part on the bottom of the chassis.

Because of this, upon initial assembly, the bottom of the chassis bowed outward while the top was held firmly in place. As this issue was identified, and more material was added to fix the bottom of the chassis in place, the bowing was at first locked in rather than fixed. To remedy this, this extra support material was removed, the chassis was bent back to true, then the support material was added in a way that held the chassis true. The final assembly had a small amount of downward bowing, but without a more major redesign it was difficult to make the chassis more rigid than it was. The chassis bowing that was present caused no known problems beyond the cosmetic.

SolidWorks Simulation and Motion Analysis

The SolidWorks simulation and motion analysis offered tools for analysis beyond the scope of hand calculations. We used these tools to investigate dynamic motion of the machine and stress propagating through members, details which were critical for the effectiveness of the machine but too complicated to solve by hand.

Motion Analysis

We used the motion analysis tools to design the leg mechanism based on speed, torque, and stress parameters. We focused on investigating the leg mechanism because it was the biggest unknown in the design and because we had little experience dealing with mechanical linkages. Other components of the system also depended on the legs: for instance, the power data from the motion analysis allowed us to predict a gear ratio between the foot pedals and crankshaft. The motion study was also used to predict forces propagating from the leg shafts into the chassis wall through the leg cycle.

To model the leg system, we first determined the forces acting on the legs. These forces were considered in four parts:

1. Vertical force from weight of the machine
2. Horizontal acceleration from rest (full speed in 2 seconds)
3. Uphill movement against an 8 degree hill
4. Vertical acceleration from rest up the 8 degree hill (full speed in 2 seconds)

The forces applied to the legs in the solid works motion analysis below considered the worst case scenario: a machine accelerating from rest uphill against an 8 degree hill, which we estimate would create a vertical force of 381 Newton's and a horizontal force of 48 Newton's. Results and calculations for this analysis can be found in Appendix 1.

After designing a Jansen linkage of appropriate size, we used the motion analysis tools to record displacement values for the Jansen linkage foot trace path. Based on these values we determined that a set of two legs would lead to only 0.333 inch vertical displacement of the walking machine. Additionally, we determined how long each foot was engaged for to be able to apply forces on the foot in the motion study analysis.

This data was then applied to a dynamic motion study. The leg motion analysis identified estimated torque and power requirements to operate the machine at the desired speed of 1.5 feet per second. The following steps were performed:

1. Identify trace path of walking mechanism.
2. Determine angular velocity of drive shaft based on trace path length and desired walking speed (1.5 feet per second) adjust motor speed to the angular velocity.
3. Apply the determined forces to the bottom section of each foot.
4. Collect torque data and identify peaks in torque.
5. Compare this power with the estimated pedaling power of the rider.

Results were as follows:

Power Requirements	
Total theoretical maximum Power (watts)	**Average Power (Watts)**
195.60	103.07

Based on literature research, we anticipated that a rider could output about 175- 200 watts of power[2] so we estimated a one-to-one gear ratio would be a good starting point. One limitation of this analysis is that it doesn't accurately account for friction and resistance in the walking mechanism.

See Appendix 1 for more information on the motion analysis.

Simulation Stress Analysis

We also used the simulation to identify stresses through three critical elements in the design: leg assembly, side wall, and the top piece of the chassis. These components were too complicated to analyze effectively by hand. See Appendix 2 for results. For other components, we relied on past experience and intuition to design them.

The leg assembly stress was evaluated at three points when the trace path is on the ground. The results indicated maximum stress in the lower triangle of the linkage assembly, close to where the linkage broke during testing. Results can be found in Appendix 2.

When calculating stress through the chassis walls we simplified forces as follows:

1. Force from the seat panel
2. Force from the leg crankshaft
3. Force from the leg shaft support

Motion analysis of the leg assembly was used to determine x and y force components propagated from the leg to the chassis wall through the crankshaft and support shaft during one cycle of the leg rotation. The resulting .csv data was exported from SolidWorks and four scenarios were identified when each force component reached its maximum value. Each of these four scenarios was tested in a force simulation and the stress did not exceed the yield stress in any case. The cases and testing are summarized in Appendix 2.

As the top piece of the chassis functioned both as a connector for the two sides of the machine, and as the sole support for the seated driver, it needed to be able to withstand a significant load. To simulate the most accurate results possible an elastic modulus of 1.105×10^{10} N/m^2 was used which is the reported value for plywood according to the Canadian Plywood

[2] "Thread: Whats a Reasonable Wattage Output for a Recreational Rider?" Bike Forums RSS. N.p., n.d. Web. 06 June 2016. <http://www.bikeforums.net/road-cycling/262188-whats-reasonable-wattage-output-recreational-rider.html>.

association.[3] Fixtures were then applied to best reproduce the effect of the most minimal support system we designed for. As seen in Appendix 2, they were included where the top plate was attached to each sidewall, as well as where it was attached to the pedal support system.

To replicate the weight of the driver sitting on the plate, a 250 lbs. equivalent of force (1112.0554 Newton's) was placed on the middle section of the top plate, spanning from the front of the part to the back of the farthest slots (about where the seat back would begin) with a width of 18 inches. It's important to note that this weight is more than fifty pounds heavier than any of the members of the team. The results were promising and very indicative of what was observed during the actual use of the machine. The maximum stress and strain in the piece was 1.274×10^4 and 3.249×10^6 N/m^2 respectively, both occurring at the edge of the pedal fixture. The displacement information was most encouraging to see, with a maximum displacement of .000405104 meters occurring near the back of the part. This is an insignificant amount and did not affect the fit or function of the piece in any way.

Innovations

Penelope was designed to be a reliable machine created in a very short period of time: design was focused on incorporating proven components (like the Jansen linkage) rather than innovation. Nevertheless, there are a few features that are quite creative, such as the brake assembly, inner support structure, leg braces, circular feet, differential braking to turn, and adjustable pedals. The brake handle assembly was designed so that we could turn left and right with only one hand while the other one wields the lance. Skid steering using a differential had not been employed by the TA prototype or the machine created at Columbia[4]. Our braking system performed well at competition, and helped us to focus our attention on working the lance. We noticed bowing in our structure once we started driving, so we added multiple pieces of 2x4" in addition to the original cross pieces. The support structure also served as a seat support, flag holder, handle, and sound resonator for our stereo. To make Penelope drivable by multiple users we had the ability to adjust the pedals to different lengths, and we made sure the pedals could be supported properly by adding bracing to the pedal column.

Conclusions

Penelope is a beautiful example of how the Jansen linkage may be combined with skid steering, in a simple design that is adjustable and easy to modify. The design is focused on

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"Engineered Values." (n.d.): n. pag. Canada Wood. Web. 6 June 2016.
<http://www.canply.org/pdf/main/engineered%20values.pdf>.

4 Theo Janson's Strandbeest. Theo Janson, n.d. Web. 6 June 2016.
<http://www.strandbeest.com/>eest.com/>

simplicity, by using a minimum number of legs for stable motion (four points of contact with the ground) and designing for multi-functionality (using the chassis connector as the seat). The design was created with the intent of keeping machining and parts to a minimum, to intentionally decrease assembly time. Additionally, chassis components included tabs to help with alignment, stabilizing the chassis and tangentially decreasing assembly time. This was a tremendous advantage, allowing the team to be the first to have a walking machine and providing time for debugging. SolidWorks motion studies and leg prototyping revealed where the linkage erroneously contacted itself, which was then rectified.

While the majority of the project work was invested in conceptual design, additional development occurred during manufacturing and debugging. Certain components necessarily changed during fabrication (for example, changing 4-40 screws to 6-32 in the differential) to promote easy machining and design stability. During debugging additional chassis supports were added, chain lengths were adjusted, and sanding/perfecting of components occurred.

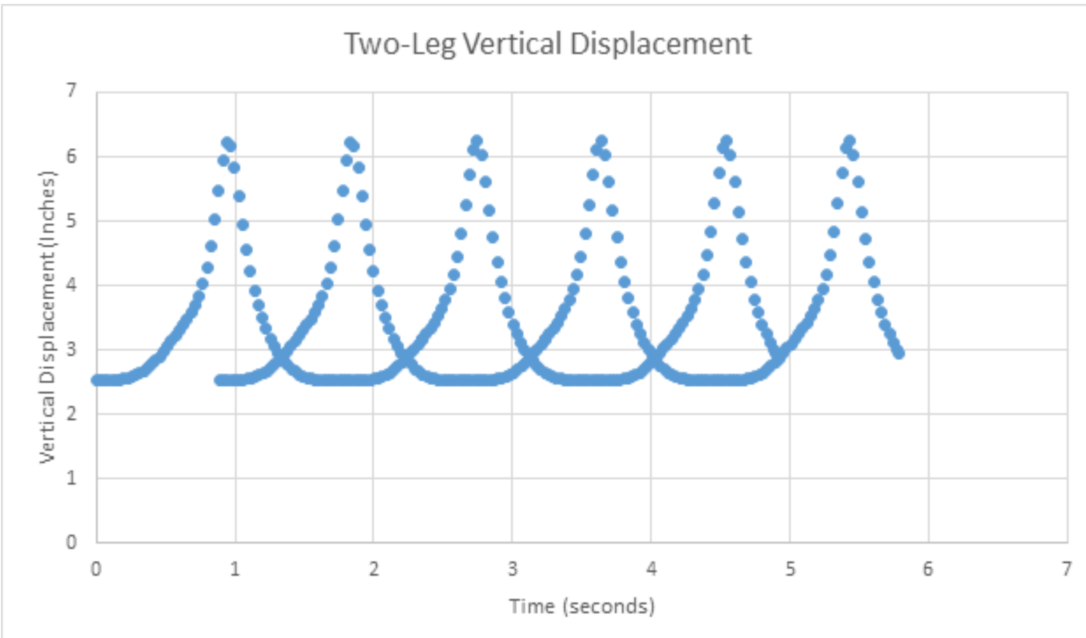
The design spectacularly meets its objective of being a walking machine able to move forward, in reverse, and turn. It was successful in its attempt for simplicity and fast assembly. While legs did fracture during competition, adding wood supports to the outside of the legs prevented the same legs from fracturing--perhaps demonstrating that using thicker wood, or adding permanent support components, would solve this issue.

Penelope is the ideal design for walking machine manufacturers seeking an elegant vehicle for urban exploration. On flat surfaces, the machine can travel forwards, backwards, and turn with stateliness and minimal pedaling effort. Eye-catching flags and designs on the chassis allow the vehicle to stand out from other walking machines, while the undercarriage provides natural amplification for any portable speakers that may be attached, enabling the enjoyment of music during your amble or jousting tournament. Penelope has commercial potential as a children's toy and at a larger scale could be used for hauling heavy loads. The Seuss theme inspired a playful atmosphere, as we believe this walking machine embodies and that will sell well to children and families. In either use Penelope provides a platform in which locomotion becomes fun and interesting, as well as slow and steady, for whoever is operating the machine.

Appendices

Appendix 1: Results from Motion Analysis

Trace Path Analysis: Demonstrates how long each leg is engaged with the ground.



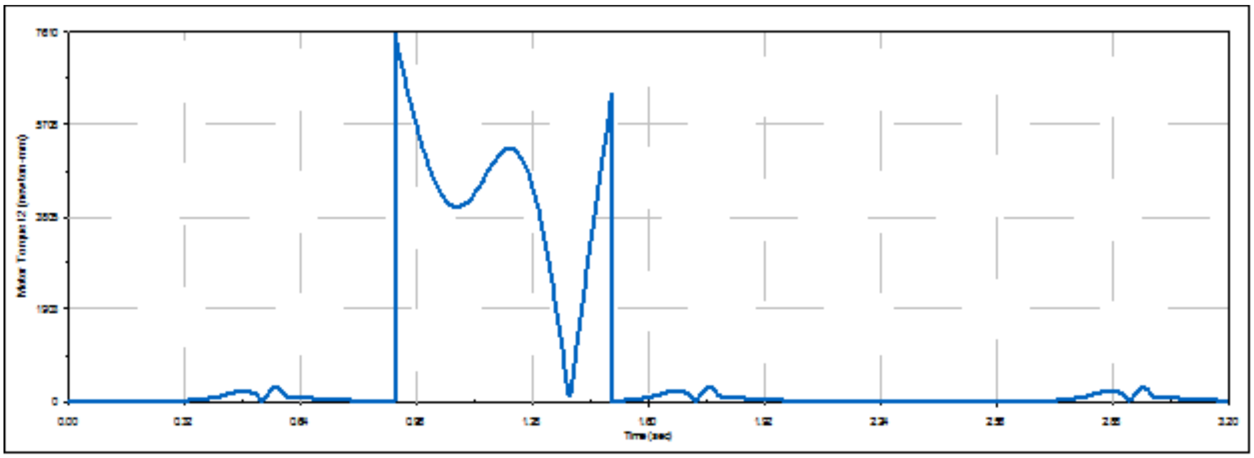
Torque Data from Motion Analysis

Testing Scheme	Human Power (Watts, average)	Vertical Force (Newton)	Horizontal Force (Newton)	Approximate Step Length (feet)	Desired Machine Speed (ft/s)	Total steps per second	Per Leg steps per second	Required rotation speed (RPM)	seconds foot is engaged with ground	Required rotation speed (rad/sec)
1	175	416.3	50.5	0.90	1.00	1.12	0.56	33.46	0.90	3.50
2	175			0.90	1.50	1.67	0.84	50.19	0.60	5.26

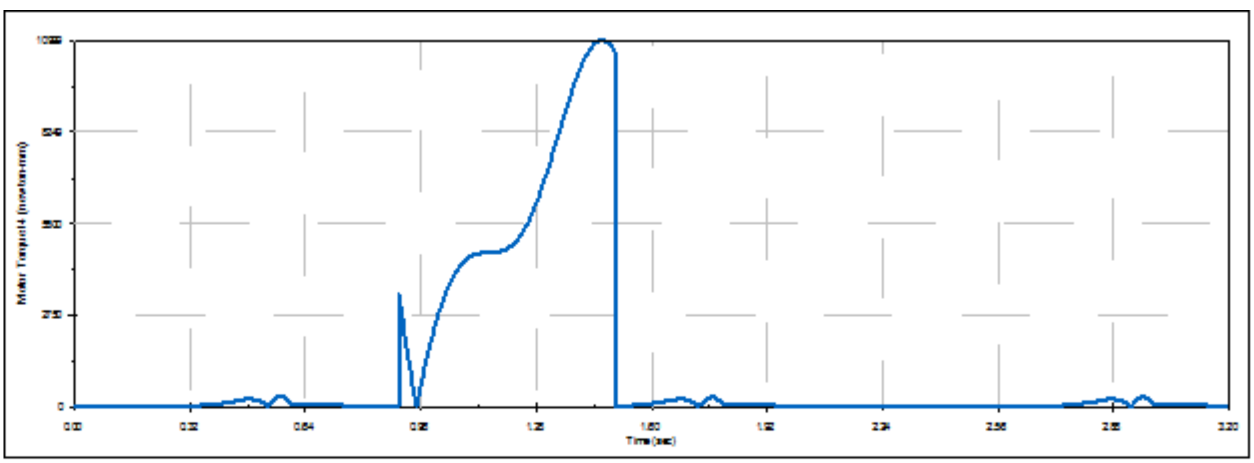
	Outward Horizontal Force		**Inward Horizontal Force**		**Total for leg combination**		**Power Requirements**	
Testing Scheme	Max Measured Torque for movement (N*mm)	Average Torque (from excel document)	Max Measured Torque for movement (N*mm)	Average Torque (from excel document)	Total theoretical maximum (N*mm)	Average Torque sum (N*mm)	Total theoretical maximum Power	Average Power
1	8897	4289	11001	5311.79	39796.00	19201.59		
2	7610	4155	10999	5651.16	37218.00	19612.32	195.60	103.07

Torque Data Graphs: showing torque on the leg crankshaft from the applied forces during Motion Analysis

Scenario 2: Outward Horizontal Force



Scenario 2: Inward Horizontal Force



Appendix 2: Force Simulations

Force Computation for the Legs

Force Computation								
These computations aim to determine the maximum amount of force that will be experienced by each leg assembly, the forces include vertical forces from the weight of the car, horizontal climbing forces, and horizontal and vertical acceleration.								
Vertical Forces							**Data**	
							Step length (feet)	0.896
Assumed Total car weight (ibs)	**User Weight (ibs)**	**Total weight (ibs)**	**Total weight (kgs)**	**Percentage on each foot (assumed to be 25%)**	**Mass on each foot**	**Force on each foot**	Time per step	0.59
120	160	280	127.01	0.25	31.75	311.16	Mass per foot (kg)	31.75
							Force Per foot	311.15
Climbing Force (horizontal and vertical)	**mass per foot**	**31.75**						
Degree angle	**Radian**	**Total mass per foot (kg)**	**Force per each foot**	**Horizontal Force across**				
0	0	31.75	311.15	0			**Final Values**	
2	0.03	31.75	311.15	10.86			Vertical Force	381.31
4	0.07	31.75	311.15	21.70			Horizontal Force	48.13
6	0.10	31.75	311.15	32.52				
8	0.14	31.75	311.15	43.30				
10	0.17	31.75	311.15	54.03				
12	0.21	31.75	311.15	64.69				
14	0.24	31.75	311.15	75.27				
16	0.28	31.75	311.15	85.76				
18	0.31	31.75	311.15	96.15				
20	0.35	31.75	311.15	106.42				

Horizontal Acceleration	mass per foot	31.75						
Desired Speed (ft/s)	Time to get to speed (sec)	Acceleration (ft/s^2)	Acceleration (m/s^2)	Total mass per foot (kg)	Acceleration force (Newtons)			
1.5	1	1.5	0.45612	31.75	14.48181			
1	2	0.5	0.15204	31.75	4.82727			
1.5	3	0.5	0.15204	31.75	4.82727			
Vertical Acceleration								
Desired horizontal Speed (ft/s)	Time to get to speed (sec)		Degree angle	Radian	Desired Vertical Speed	Vertical Acceleration	Vertical Force	
1.5	2		0	0	0	0	0	
1.5	2		2	0.03	0.05	0.83	26.39	
1.5	2		4	0.07	0.10	1.66	52.74	
1.5	2		6	0.10	0.16	2.49	79.03	
1	2		8	0.14	0.14	2.21	70.15	
1.5	2		10	0.17	0.26	4.13	131.29	
1.5	2		12	0.21	0.31	4.95	157.19	
1.5	2		14	0.24	0.36	5.76	182.90	
1.5	2		16	0.28	0.41	6.56	208.39	
1.5	2		18	0.31	0.46	7.36	233.63	
1.5	2		20	0.35	0.51	8.14	258.58	

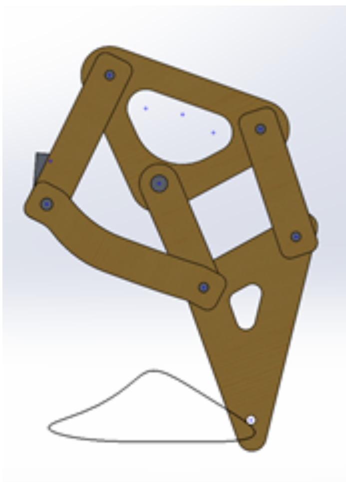
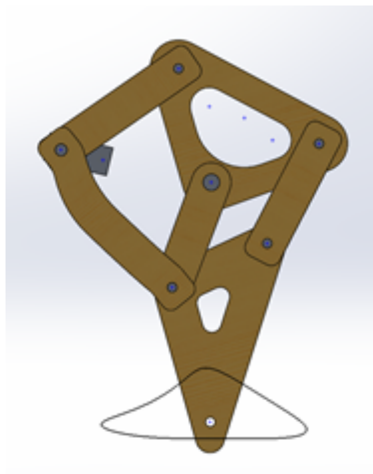
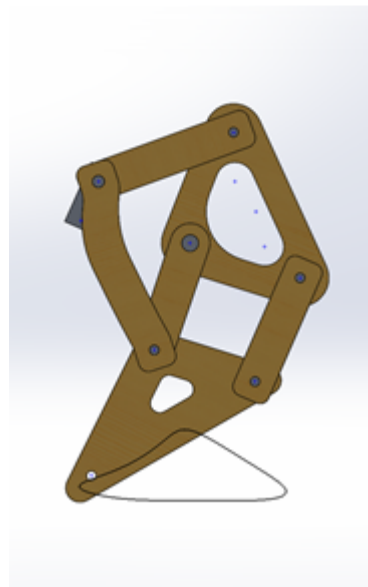
Table 1: Force computations on legs to assess robustness of the design.

Resulting Force Scenarios from the Motion Study Data

Case	Time (seconds into the leg motion cycle)	X Forces: Crankshaft (N)	Y Forces: Crankshaft (N)	X Forces: Support Shaft (N)	Y Forces: Support Shaft (N)
1	0.35	-199.98	311.35	169.59	-805.65
2	0.35	-217.60	424.89	159.00	-804.27
3	0.835	298.90	74.82	-346.49	-451.42
4	0.1	-1628.61	225.95	1.46	-3.84

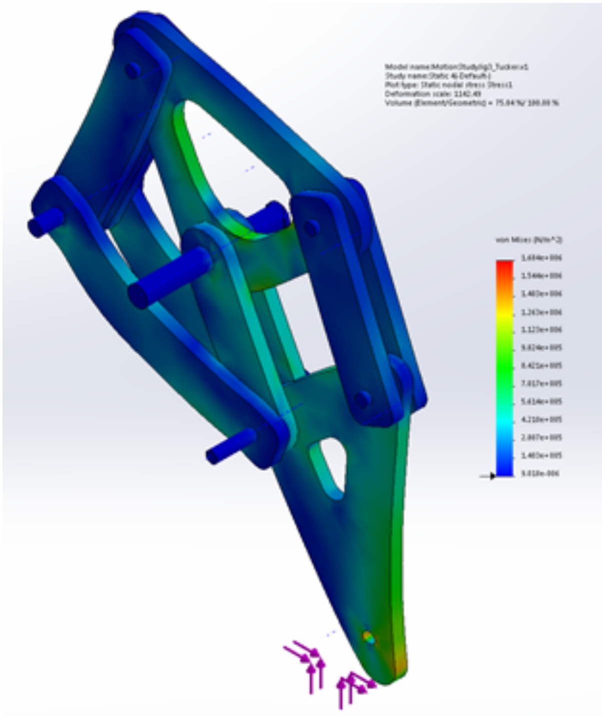
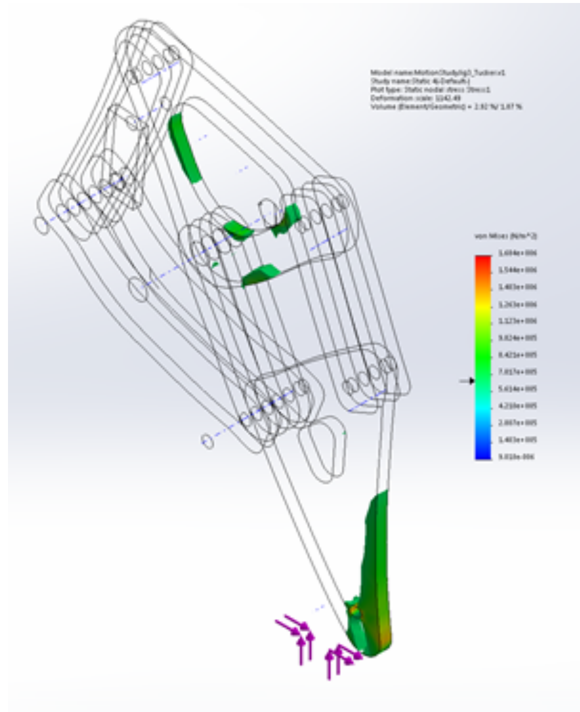
	Max Values	298.8975925	424.8945988	169.5893319	-3.840148262

FEA Analysis 1: Linkages

Position 1	Position 2	Position 3
		

Position 1:

	Showing 650,000 Pa and above

Position 2:

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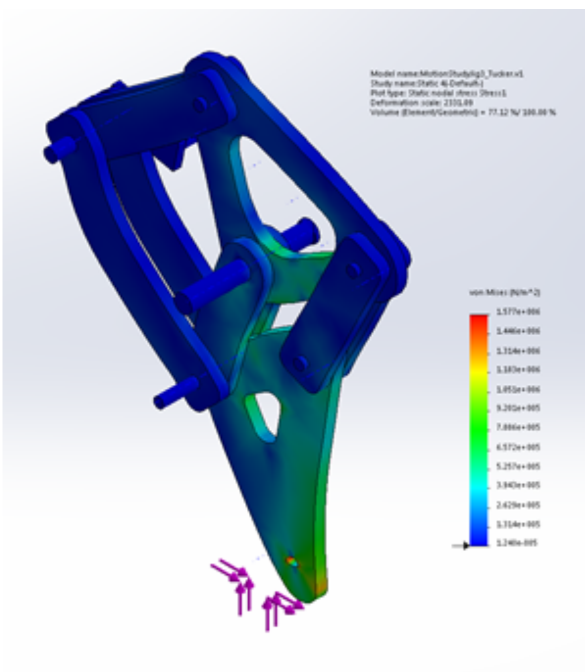
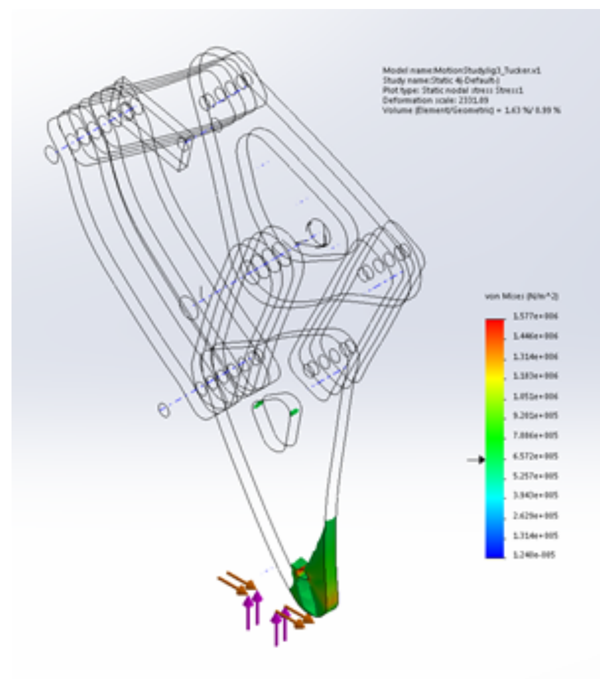
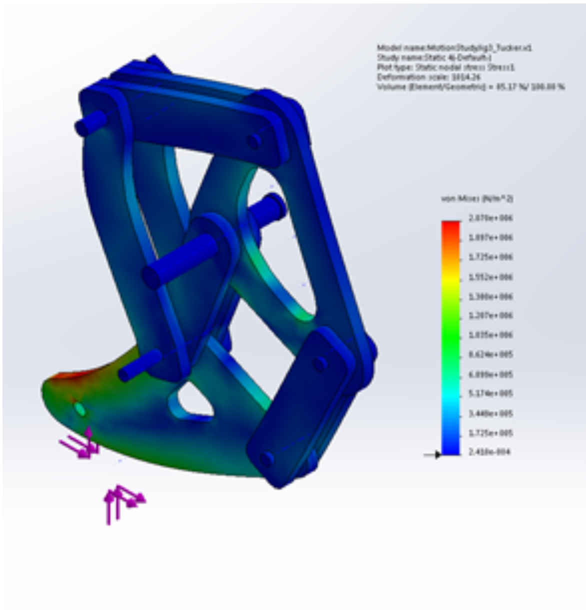
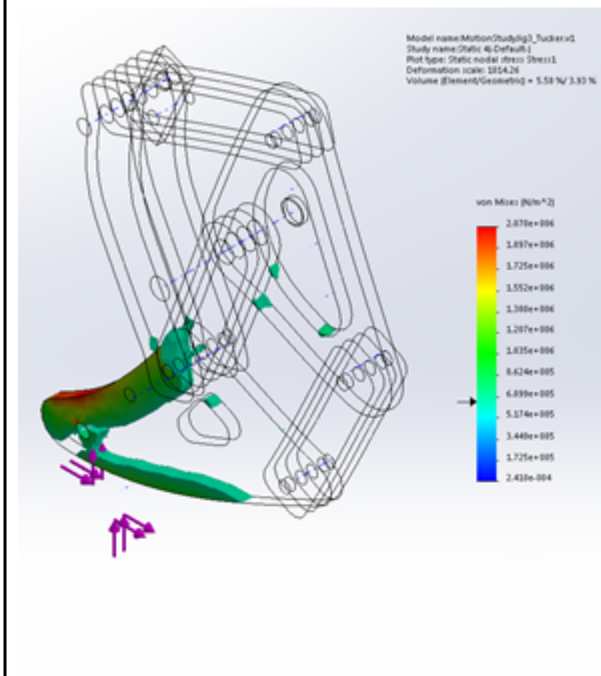
	

Position 3:

	Showing stress 650,000 Pa and above
	

FEA Analysis 2: Chassis wall

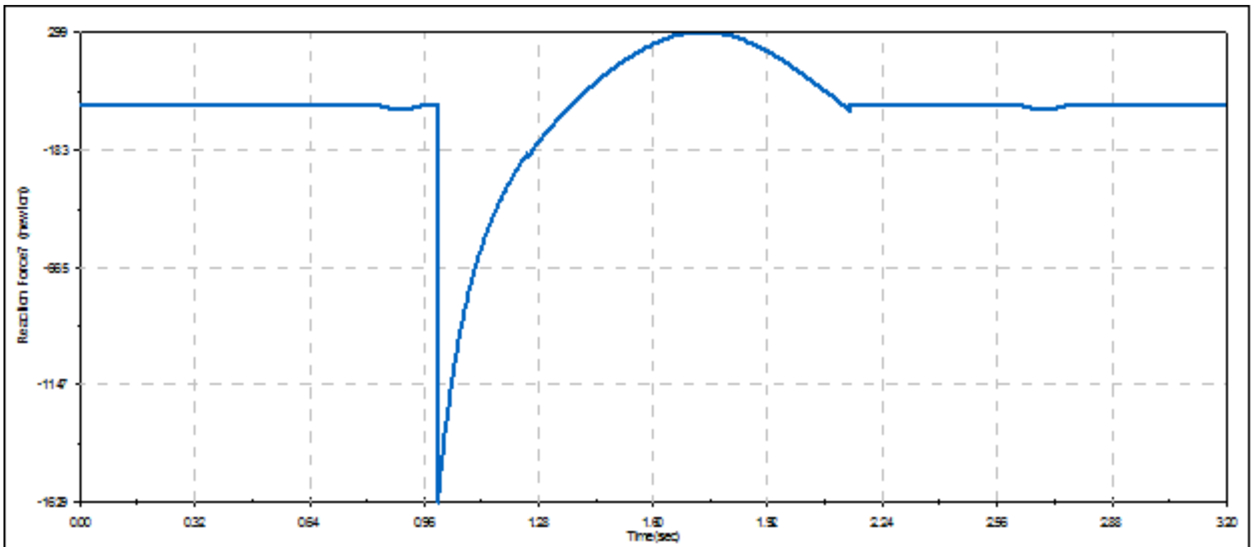


Figure 1: X component on Crank Shaft- This graph represents the x component of force from the leg crankshaft to the wall through one cycle of leg motion.

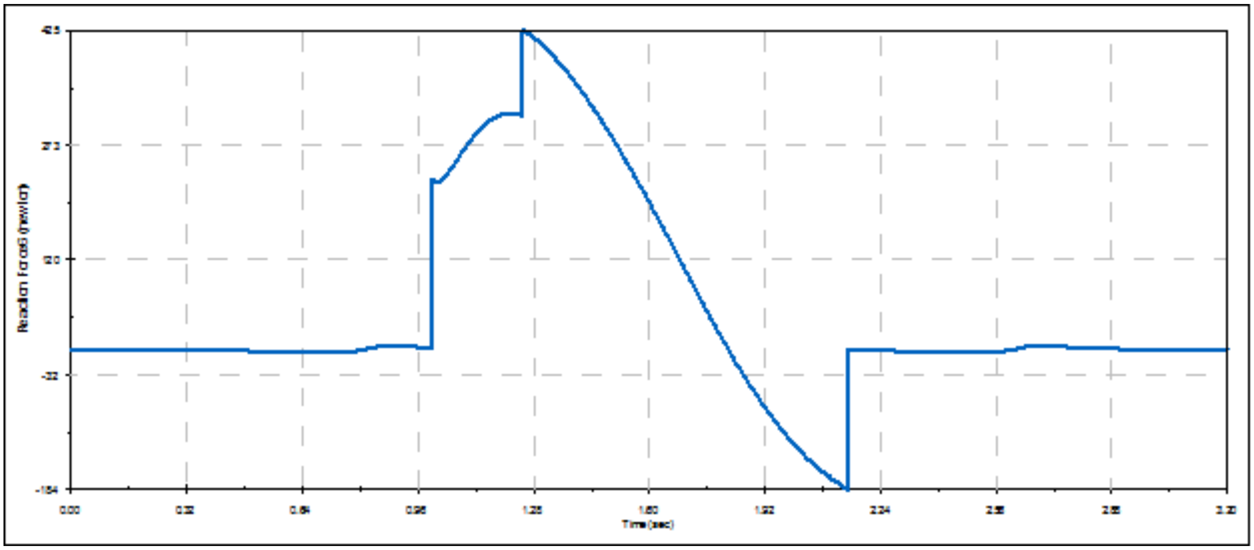


Figure 2: Y component of force from the Crank Shaft to the Chassis wall during one full leg rotation

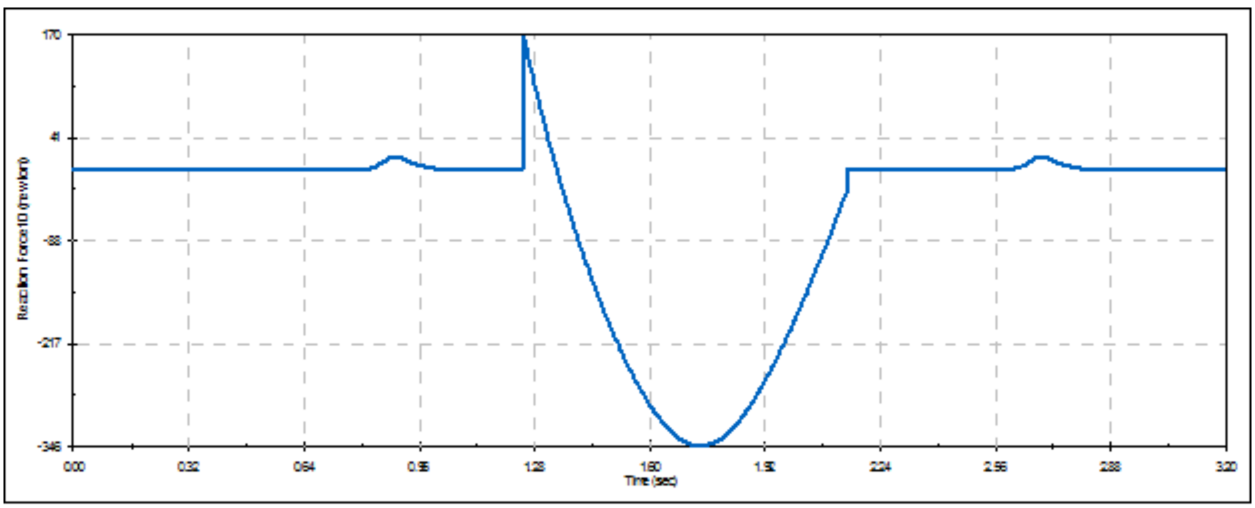


Figure 3: X component from Support Shaft to the Chassis wall during one full leg rotation.

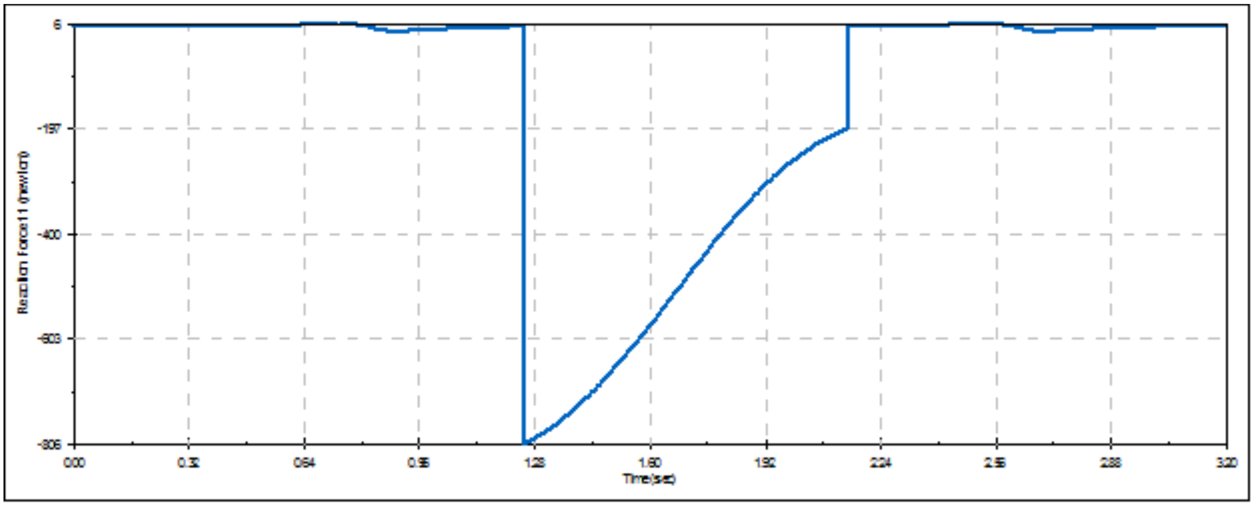


Figure 4: Y component from Support Shaft to the Chassis wall during one full leg rotation

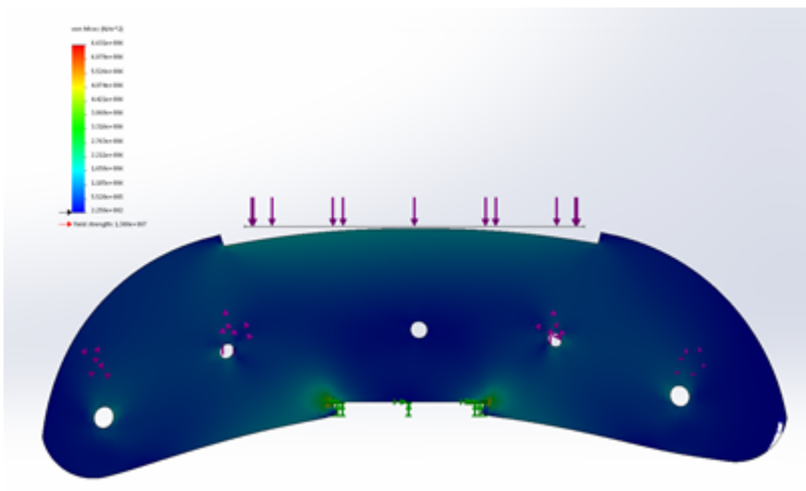


Figure 5: Results from Case 1, Max Von Mises Stress is 6.631E6 N/m^2

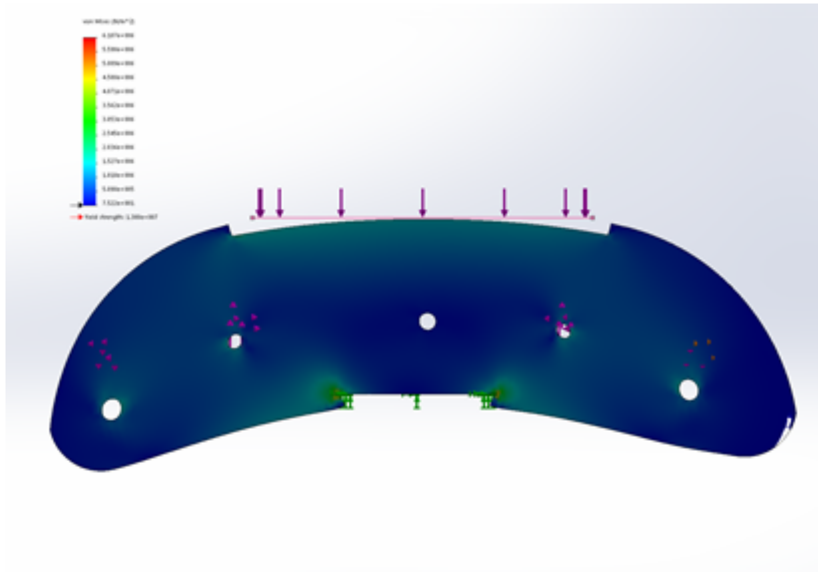


Figure 6: Results from Case 2, Max Von Mises Stress is 6.107E6

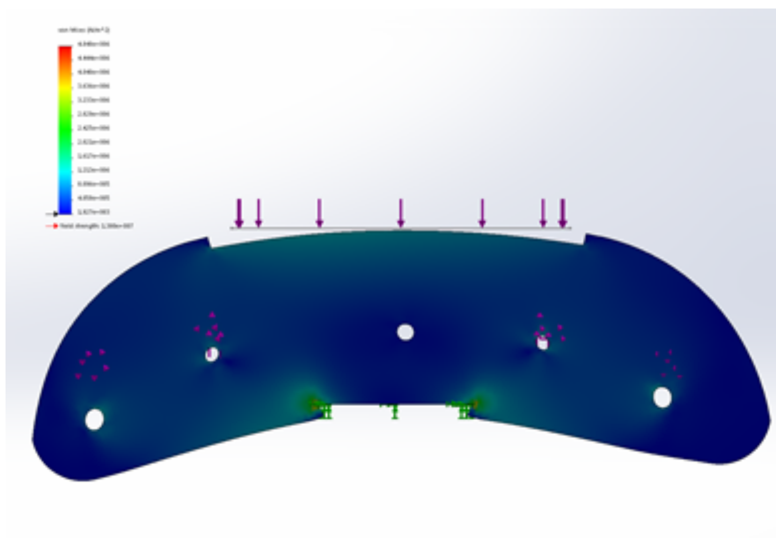


Figure 7: Results from Case 3, Max Von Mises Stress is 4.848E6 N/m^2

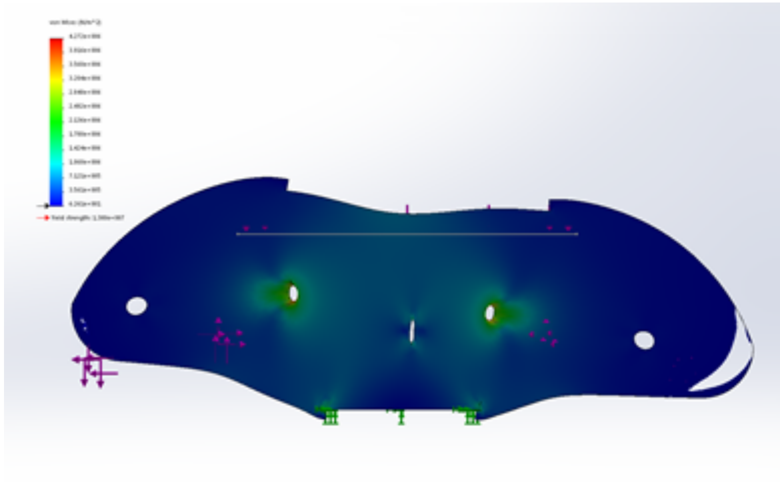
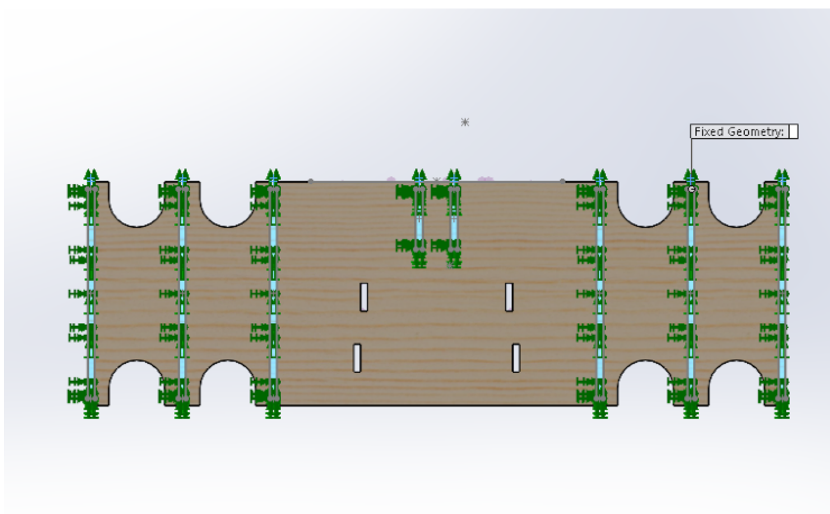


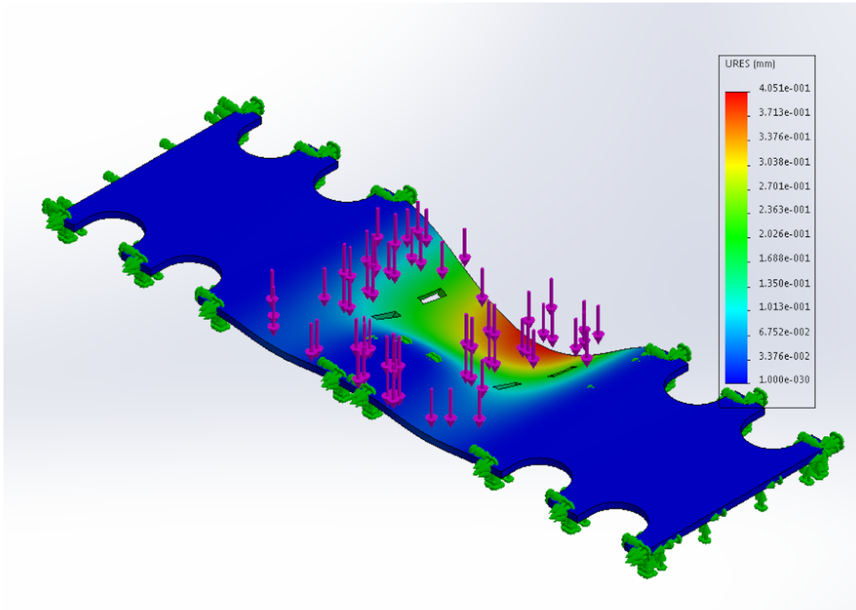
Figure 8: Results from Case 4, Max Von Mises Stress is 4.272E6

FEA Analysis 3: top piece of chassis

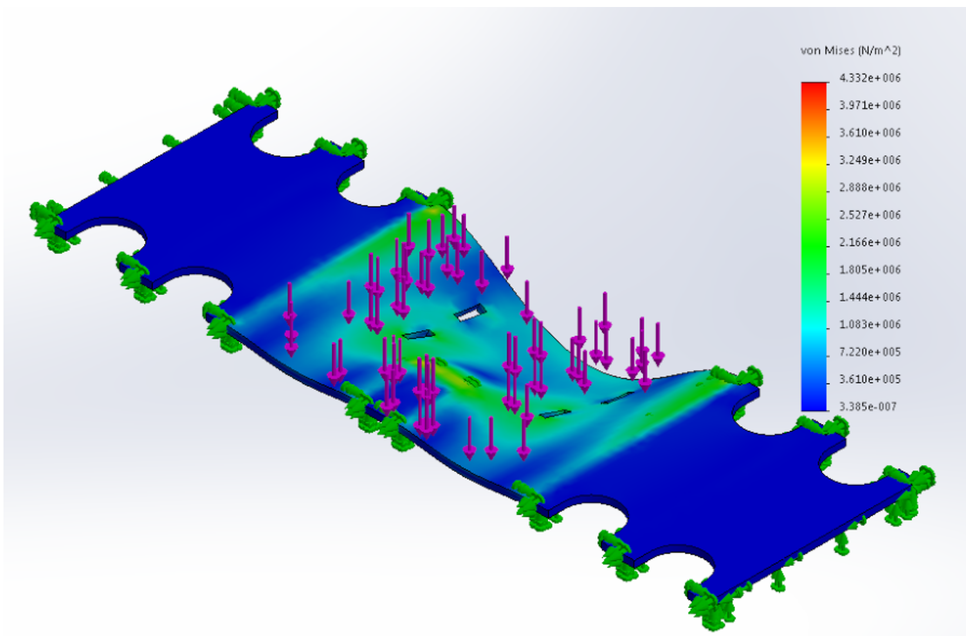
Fixtures:



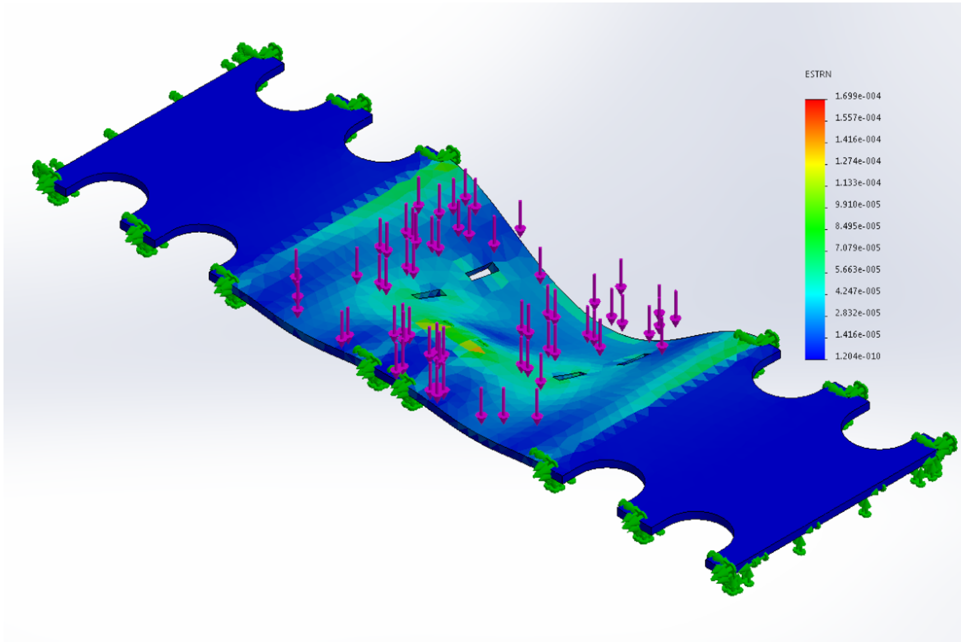
Displacement:



Von Mises Stress:



Strain:



Appendix 3: Bill of Materials

Part Number	Description	QTY.	Price ($)	Pack-Aging Unit	Total Units	Subtotal ($)
Leg					**8**	**$381.45**
6338K415	Oil-Embedded Flanged Sleeve Bearing, for 3/8" Shaft Diameter, 1/2" OD, 1/2" Length, 11/16" Flange OD	14	$0.85	1	112	$95.20
91259A632	Alloy Steel Shoulder Screw, 3/8" Diameter x 2" Long Shoulder, 5/16"-18 Thread Size	3	$1.83	1	24	$43.92
98026A112	Grade 8 Steel Flat Washer, Black-Luster Coated, 5/16" Screw Size, 0.375" ID	12	$12.29	10	10	$122.90
	Alloy Steel Shoulder Screw, 3/8" Diameter x 3" Long Shoulder, 5/16"-18 Thread Size	1	$2.22	1	8	$17.76
92018A320	Nylon-Insert Nonmarring Flange Locknut, Zinc Yellow-Chromate Plated Grade G Steel, 5/16"-18 Thread	1	$5.25	50	1	$5.25
2938T53	High-Load Oil-Embedded Flanged Sleeve Bearing, for 3/4" Diameter, SAE 863 Bronze, 1/2" Length, 1-1/8" Flange OD	3	$0.83	1	24	$19.92

6338K418	Oil-Embedded Flanged Sleeve Bearing for 1/2" Shaft Diameter, 5/8" OD, 1/2" Length	4	$1.15	1	32	$36.80
93852A134	USS Flat Washer, 316 Stainless Steel, 7/16" Screw Size, 0.500" ID, 1.250" OD	6	$7.94	10	5	$39.70
Foot					**8**	**$88.97**
94496A600	Shoulder Screw	1	$8.04	1	8	$64.32
6338K415	Flanged sleeve bearing (ID ⅜ in, OD 1/2)	3	$0.85	1	24	$20.40
90031a179	Wood Screw (Phillips, Zinc-Plated Steel, # 7, 1-1/2" Long)	8	$4.25	100	1	$4.25
Chassis					**1**	**$365.84**
6435k14	one piece 1/2" lock collar	8	$2.17	1	8	$17.36
6435k16	one piece 3/4" lock collar	6	$2.51	1	6	$15.06
98870A310	Steel Machine Key, Oversized with Square Ends, 1/8" Square, 3/4" Length	8	$7.07	10	1	$7.07
1497k31	Fully Keyed 1045 Steel Drive Shaft, 1/2" OD, 1/8" Keyway Width 24" length	1	$29.37	1	1	$29.37
1497k32	Fully Keyed 1045 Steel Drive Shaft, 1/2" OD, 1/8" Keyway Width, 36" Length	1	$37.19	1	1	$37.19
6061k74	Hardened Precision Steel Shaft, 3/4" Diameter, 48" Length	3	$43.55	1	3	$130.65
94639a880	Nylon Unthreaded Spacers, 1" OD, 1" Length, for 1/2" Screw Size	10	$6.26	10	1	$6.26
94639a893	Nylon Unthreaded Spacers, 1-1/2" OD, 1" Length, for 3/4" Screw Size	25	$10.13	10	3	$30.39
1556A63	1.25"x5/8" steel angle bracket	100	$0.73	1	100	$73.00
90031A170	1/2" wood screw, No7	400	$3.30	100	4	$13.20
90252A112	1" No.8 flat head wood screw	10	$6.29	100	1	$6.29
	Bike sprockets	8				
Pedal Package					**1**	**$9.02**
97135A240	7/16-14 nylock nut	4	$3.35	10	1	$3.35
91251A681	7/16-14 bolt, 3" length	4	$5.67	5	1	$5.67
_	Derailer taken from bike	1				
_	Pedals taken from bike	1 set				
_	Sprocket set taken from bike	1				
Crank Shaft					**4**	**$248.03**

98870A310	Steel Machine Key, Oversized with Square Ends, 1/8" Square, 3/4" Length	9	$7.07	10	4	$28.28
92785A116	High Hold Cone Point Set Screw, 18-8 Stainless Steel, 4-40 Thread, 1/4" Long	8	$6.67	50	1	$6.67
1497k31	Fully Keyed 1045 Steel Drive Shaft, 1/2" OD, 1/8" Keyway Width 24" length	1	$29.37	1	4	$117.48
94639A876	Nylon Unthreaded Spacers 1" OD, 1/2" Length, for 1/2" Screw Size	4	$10.60	25	1	$10.60
6545k7	6 foot length of 1045 carbon steel	1	$85.00	1	1	$85.00
Side Wall					**6**	**$244.80**
6384K363	Ball Bearing, Flanged, for 1/2" Shaft Diameter, 1-3/8" OD	3	$12.77	1	18	$229.86
2938T53	High-Load Oil-Embedded Flanged Sleeve Bearing, for 3/4" Diameter, SAE 863 Bronze, 1/2" Length, 1-1/8" Flange OD	3	$0.83	1	18	$14.94
Chains					**1**	**$27.05**
Provided Bike Chain	27.82 in long	3	$4.54	1	3	$13.62
Provided Bike Chain	15.82 in long	2	$4.54	1	2	$9.08
Provided Bike chain master link	#40 chain connecting link	5	$0.87	1	5	$4.35
Brake Handle					**1**	**$21.52**
90031A179	Screw for Wood, Phillips, Zinc-Plated Steel, Number 7, 1-1/2" Long	20	$4.25	100	1	$4.25
90107A029	Type 316 Stainless Steel Flat Washer, 1/4" Screw Size, 0.281" ID, 0.625" OD	8	$8.25	100	1	$8.25
97135A210	Grade 8 1/4-20 Locknut, Zinc Yellow-Chromate Plated, 1/4"-20 Thread Size	8	$3.43	25	1	$3.43
91236A544	Low-Strength Zinc-Plated Steel Cap Screw, 1/4"-20 Fully Threaded, 1.25" Long	2	$5.59	100	1	$5.59
Caliper Brake System					**2**	**$53.28**

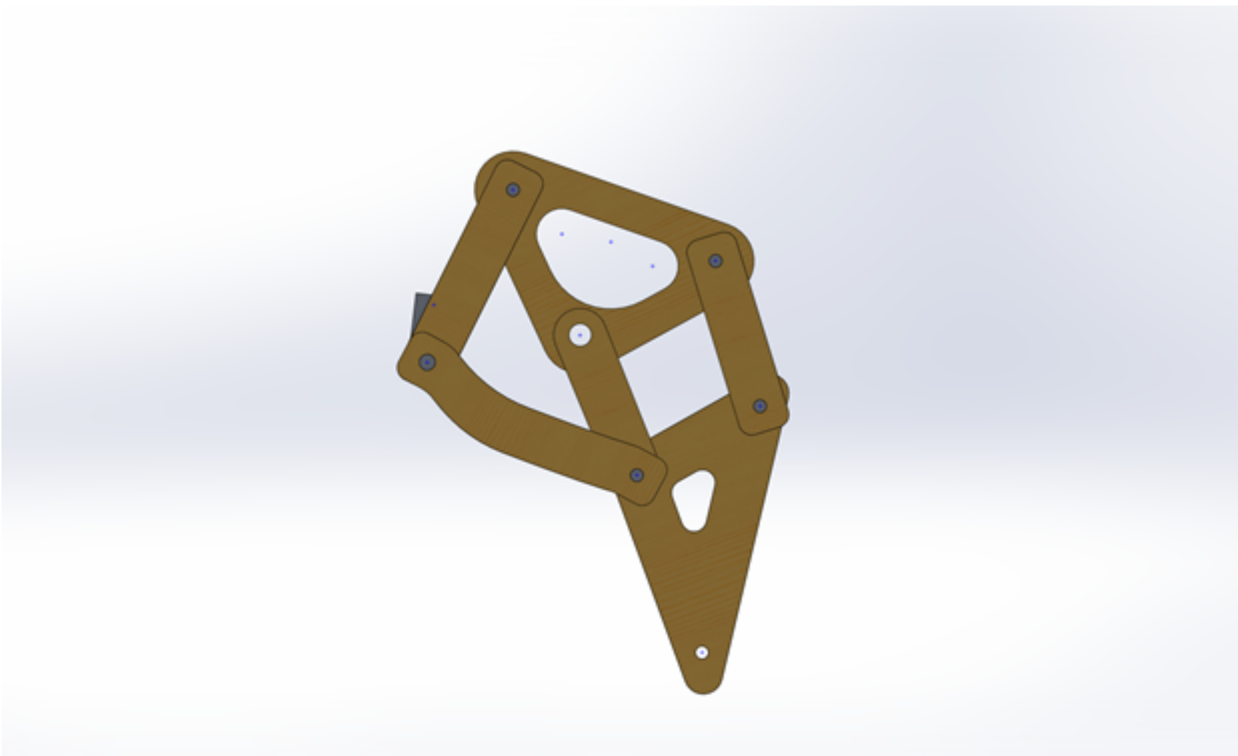
91831A025	Type 18-8 Stainless Steel Nylon-Insert Locknut, 12-24 Thread Size, 7/16" Wide, 5/16" High	4	$6.22	50	1	$6.22
92141A013	Type 18-8 Stainless Steel Flat Washer, Number 12 Screw Size, 0.234" ID, 0.500" OD	8	$3.30	100	1	$3.30
91251A480	Black-Oxide Alloy Steel Socket Head Cap Screw, 12-24 Thread, 1-3/4" Length	4	$7.81	10	1	$7.81
89015K239	Multipurpose 6061 Aluminum, Sheet, .125" Thick, 8" x 8"	7x7	$14.28	8	2	$28.56
90128A110	Zinc-Plated Alloy Steel Socket Head Cap Screw,4-40 Thread, 1/2" Length	4	$8.33	25	2	$16.66
9008K14	Multipurpose 6061 Aluminum, Rectangular Bar, 1" x 1", 6in	3	$4.03	6	2	$8.06
Differential					**1**	**$303.04**
6529K16	Metal Miter Gear --16p, 24t, for 0.5" shaft	2	$28.66	1	2	$57.32
93852A134	USS Flat Washer, 0.5" ID	2	$7.94	10	1	$7.94
6843K12	Keyed Metal Miter Gear--16p, 24t, for 0.5" shaft	2	$52.08	1	2	$104.16
6384K363	Flanged ball bearing, 0.5" ID	4	$12.77	1	4	$51.08
91251A151	Socket Screw, 6-32, 3/4" length	24	$8.63	100	1	$8.63
91102A730	Lock washers for #6 screw	24	$0.62	100	1	$0.62
9397T17	0.25" 6101 Aluminum (3"x36")	25	$68.76	36	1	$68.76
6061K427	0.5" Shaft (Quantity in inches)	3.208	$4.53	4	1	$4.53
	Sprocket taken from bike	1	$1.00			
Wood and Plywood						
	4x4" piece of wood	3 feet				
	Plywood	50 ft^2				
	2"x4" wood	3 ft				
Total Cost						**$1,760.33**

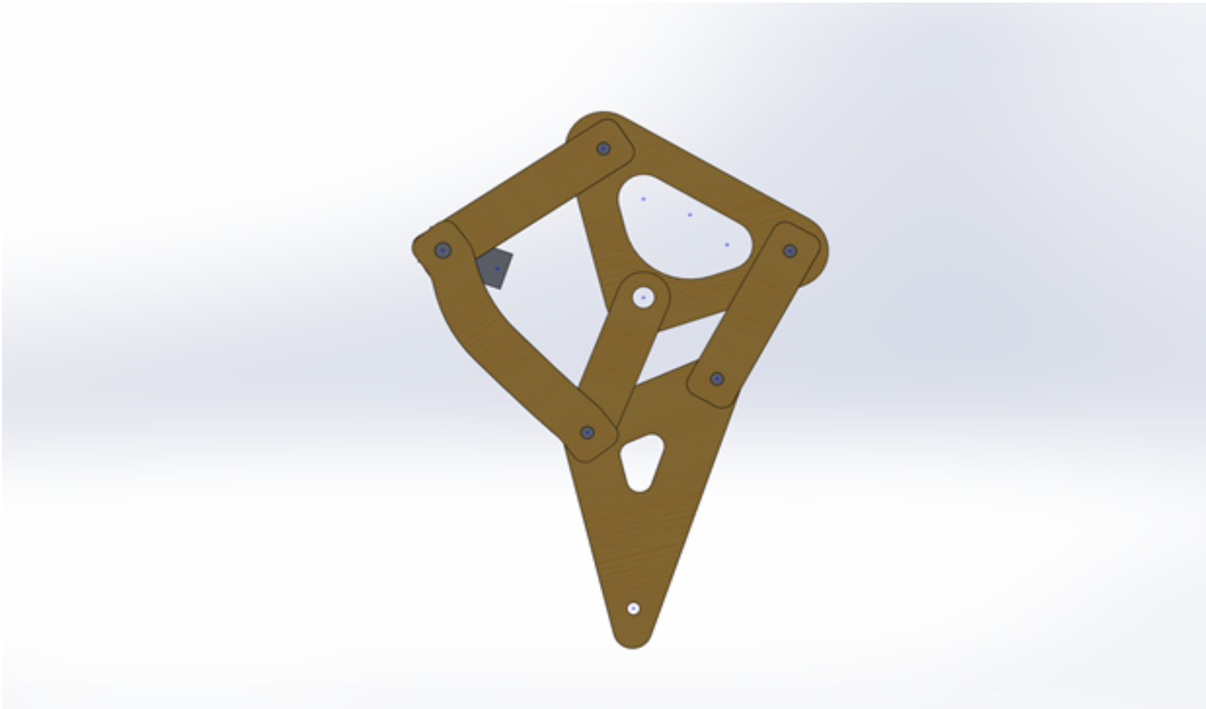
Appendix 4: Module Elaboration

Linkage Choice

To achieve a walking propulsion system, we evaluated mechanical linkages that transformed circular motion into non-circular trace paths conducive for walking. Linkages were evaluated on criteria of: simplicity, trace path shape, and feasibility of implementation. After evaluating qualitatively numerous possibilities, we evaluated the following linkages in SolidWorks: the Klann linkage, Chebyshev's Lambda Mechanism, and Jansen Linkage. Together with evidence demonstrating the feasibility of the Jansen linkage, we decided to use the Jansen Linkage.

The Jansen Linkage Used:



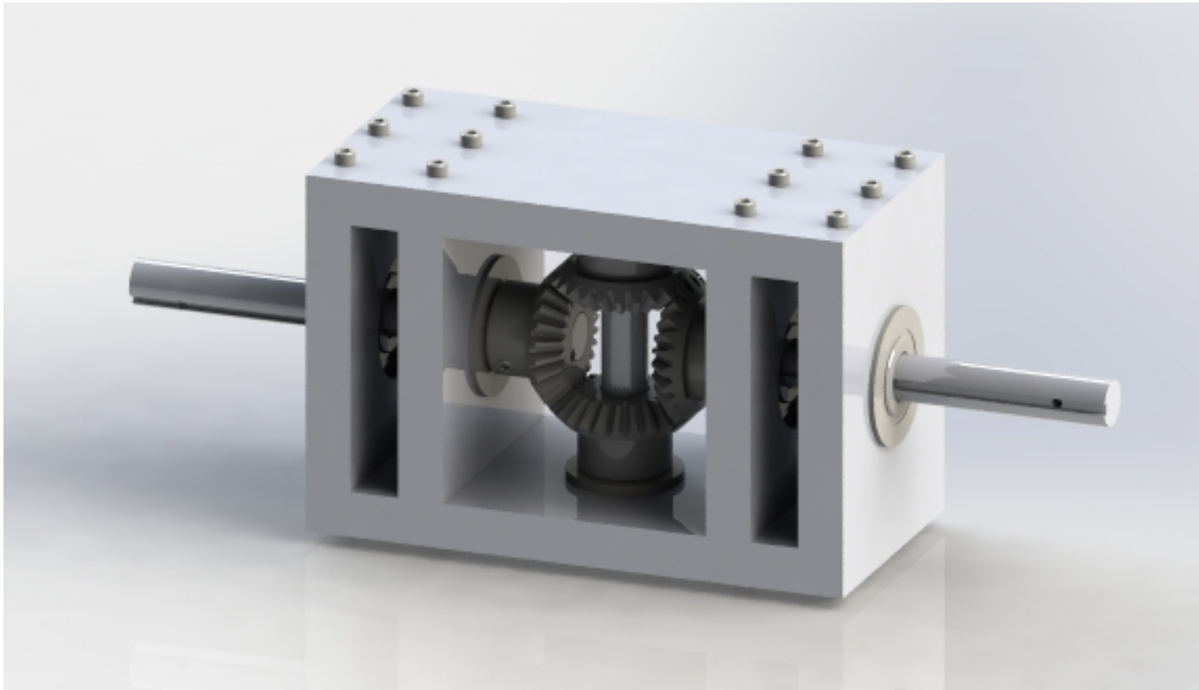


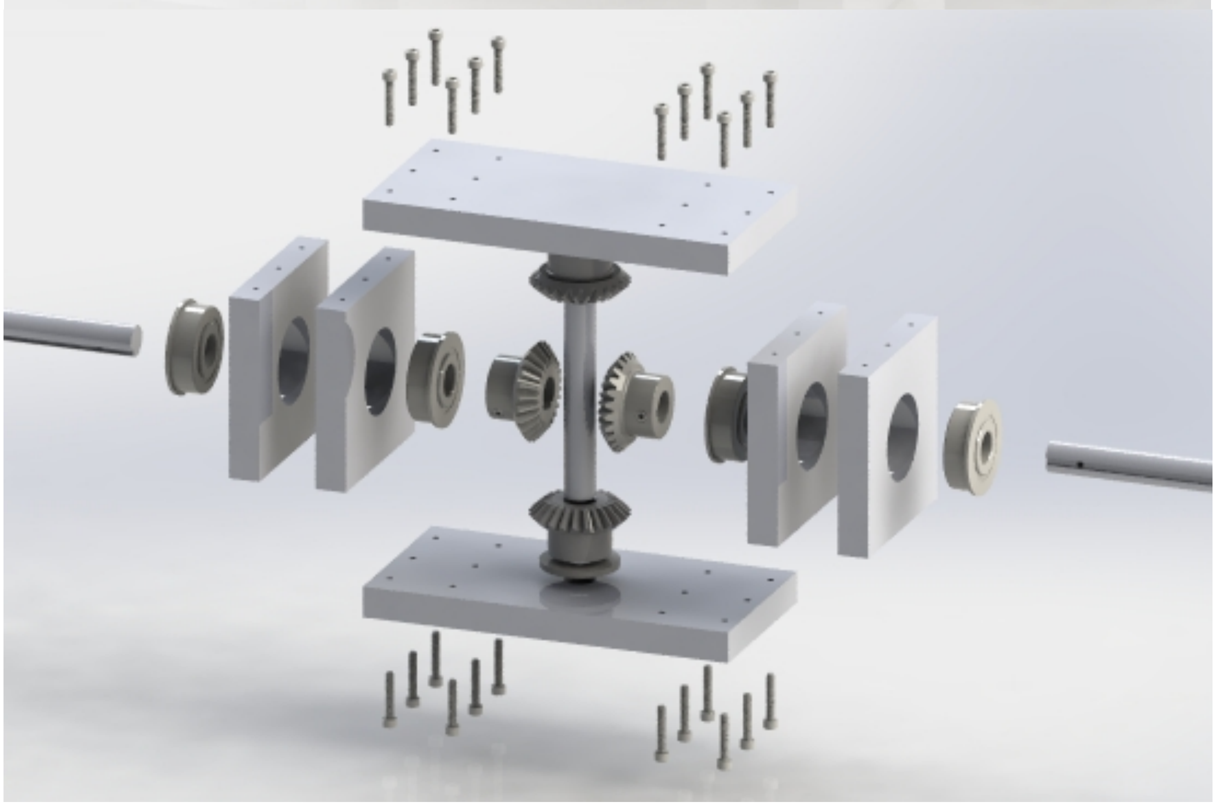
Differential

The differential was modeled after the one built by Alex Rowe for his walking beast. Rowe's design had each of the drive shafts constrained at a single point in a bearing pressed into the side walls. While examining this differential outside of its machine, it was clear that small misalignment in the drive shafts led to difficulty in actuating the differential, it was therefore decided that a second set of bearings held in place by a second set of walls would be added to constrain each half-shaft in two places.

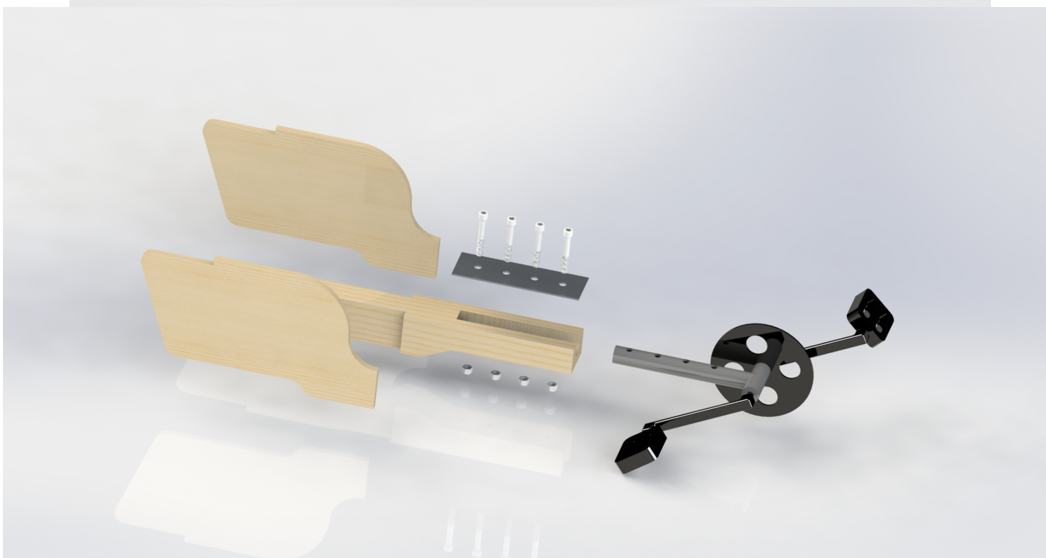
Rowe's design had interlocking features between the four walls to increase rigidity. The manufacturing complexity of this detail was deemed too complex, and it was thought that the four walls bolted to the top and bottom plate would be sufficient. This decision was later deemed the correct one when the differential operated without issue both during testing and in competition.

The design for the differential initially called for ¼" aluminum walls and 4-40 bolts. An error in material ordering required that new material be ordered, and it was decided then to increase to ½" aluminum and 6-32 bolts. It was decided that the thicker material would lead to only a slight increase in manufacturing complexity and weight, but would greatly increase the strength of the final part. Rowe's design used the smaller material, but its lack of testing in a completed beast meant it could not be used as comparison.





Pedal Assembly



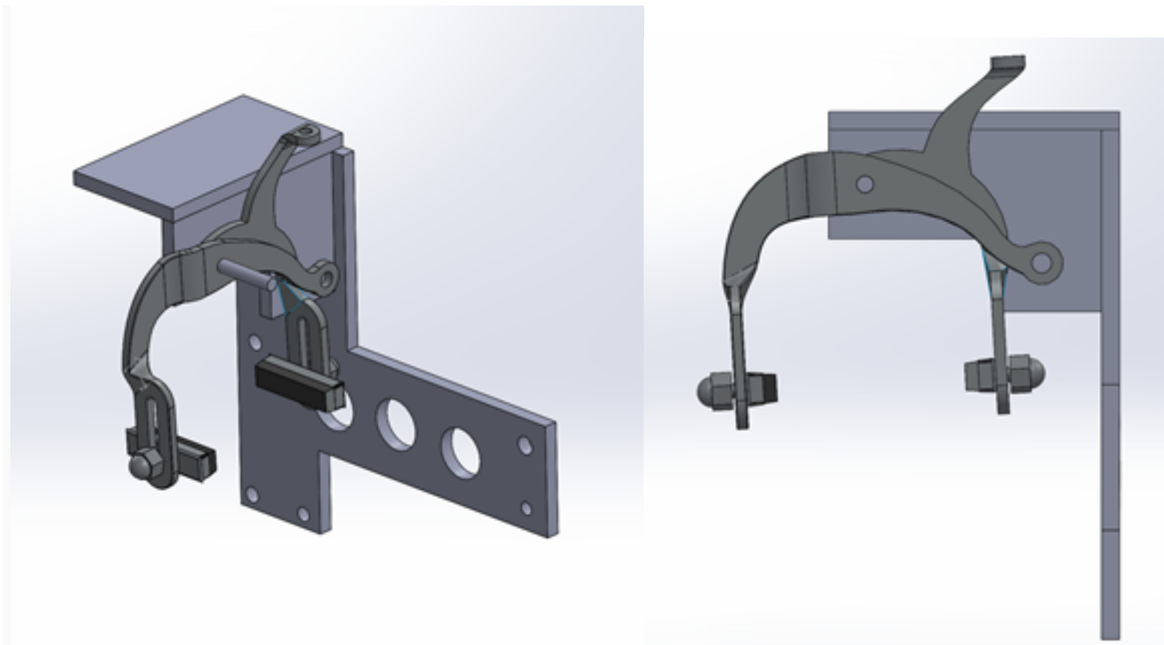
The pedal assembly is made from part of the bike provided (the crankset and part of the frame, a carved 4x4, two aluminum plates fabricated in the Thayer machine shop (one was added during real assembly, between the nuts and the 4x4), two wooden supports, and bolts. The assembly was designed to take advantage of the existing bike crankset, and to provide some size adjustability for each rider by allowing the crankset to be attached at different lengths. All riders were similar enough in height that this adjustability was not used.

Brake System

The brake system has the dual purpose of braking the entire machine and also turning the machine. By braking either side of the differential, the speed of one side of the walking device is reduced causing the entire machine to turn. A brake cable is engaged by the user to activate a caliper brake against a disc attached to the drive shaft. The design was split between the caliper disc brake system and the brake handle.

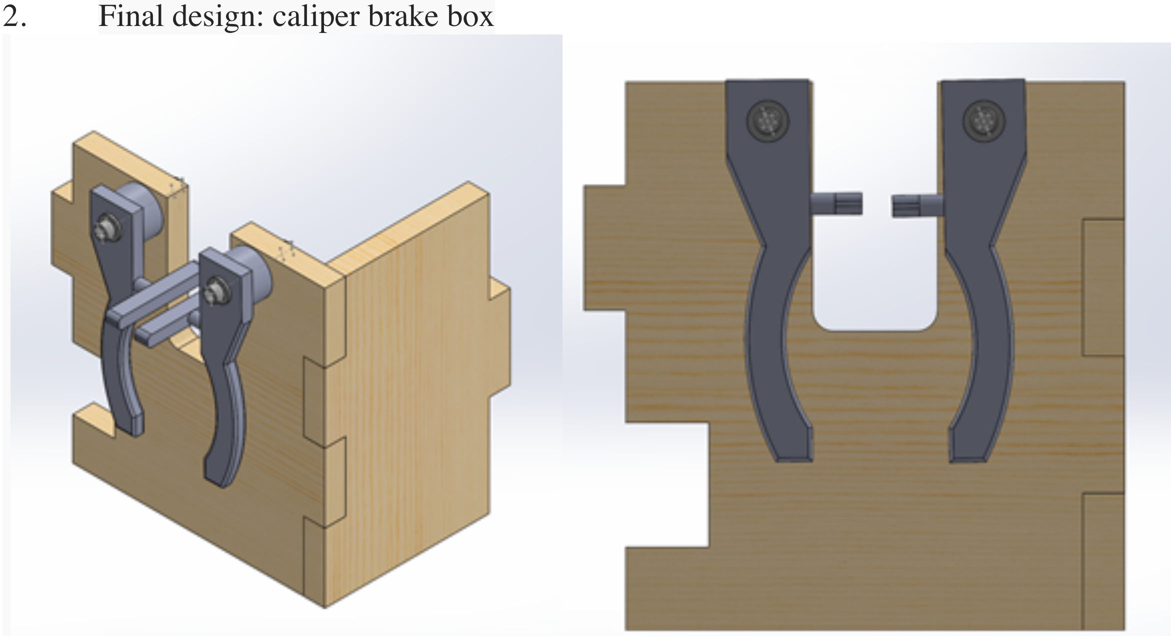
The caliper disc brake underwent two major design iterations:

1. Initial design



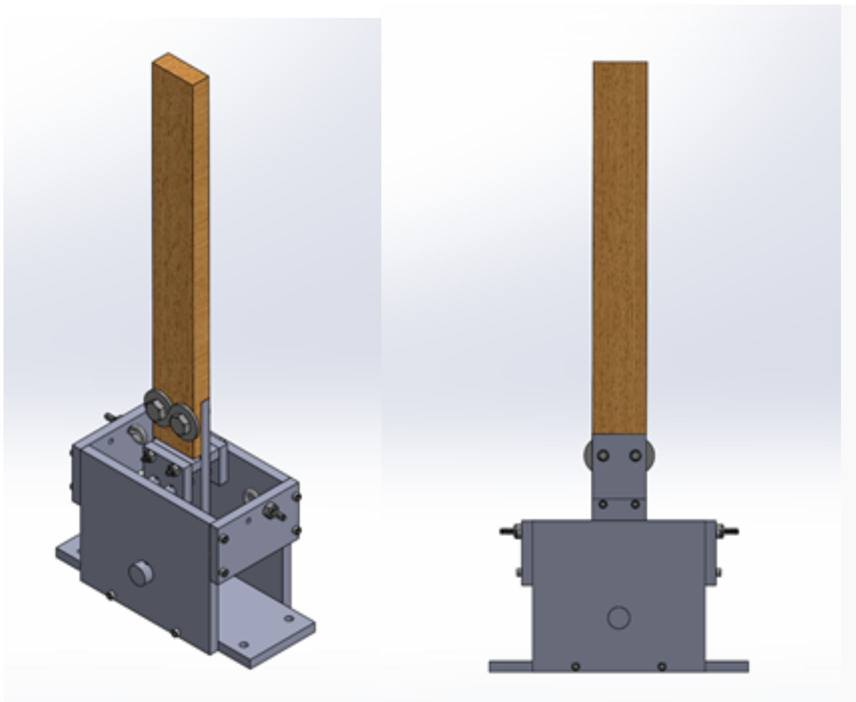
(Caliper brake used from GrabCad)

2. Final design: caliper brake box

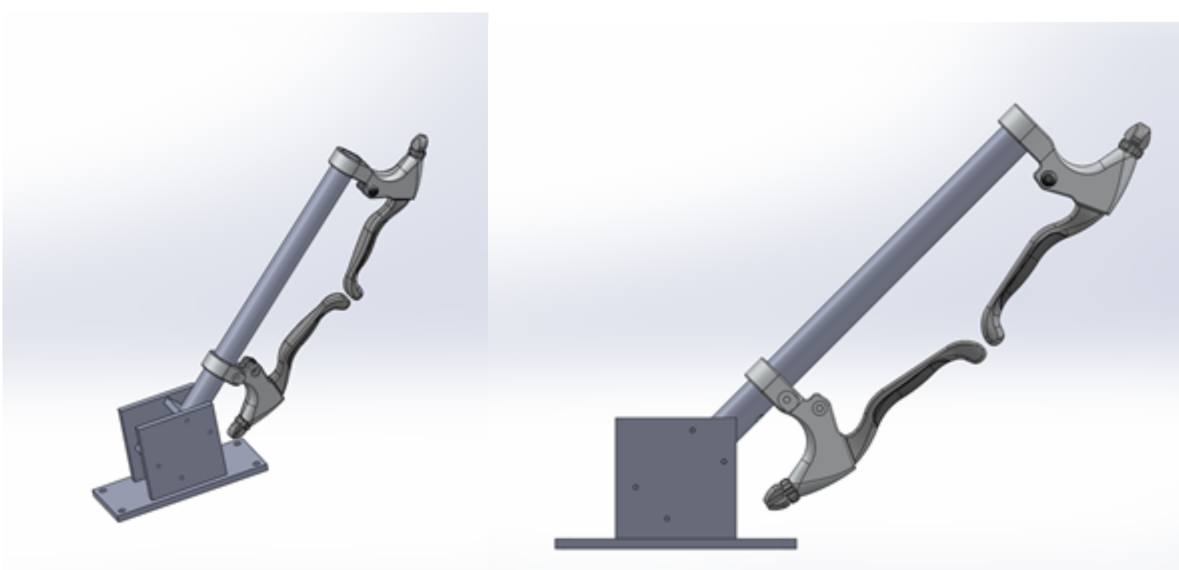


The handle brake system underwent three design iterations:

1. Lever press
    a. Advantages: improved torque for depressing brakes
    b. Disadvantages: very expensive, long machine time, unable to engage both brakes at once

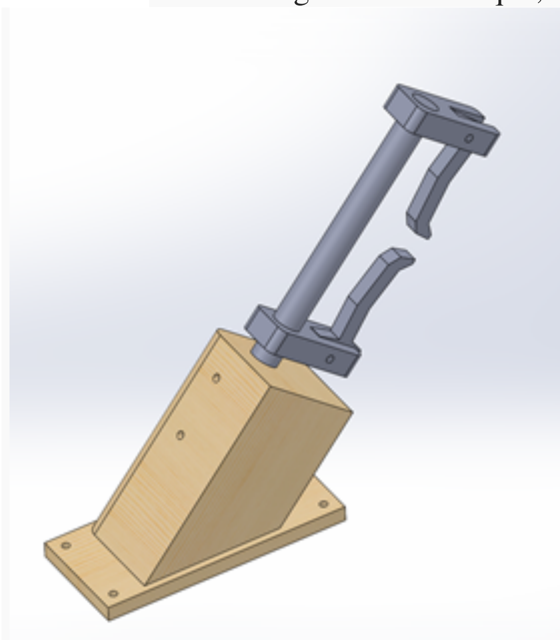
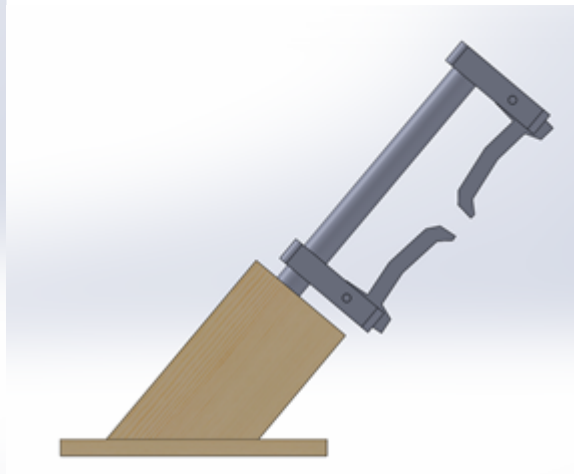


2. Bike brake mounted on aluminum casing
    a. Advantages: can engage both brakes at once
    b. Disadvantages: long machine time

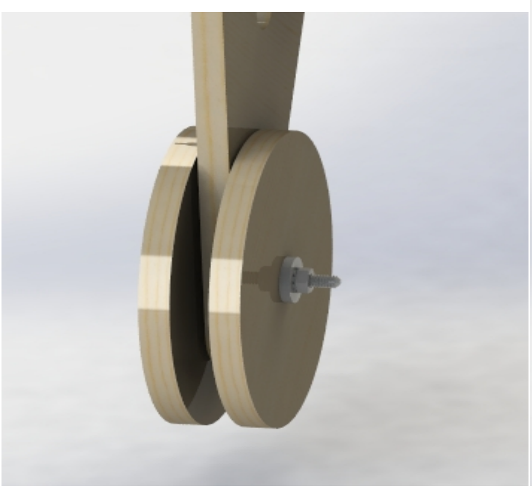
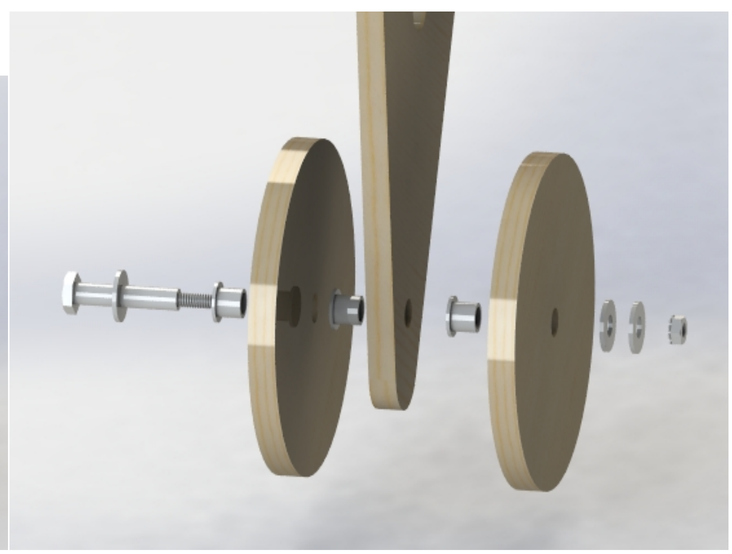


(Brake handle used from GrabCad)

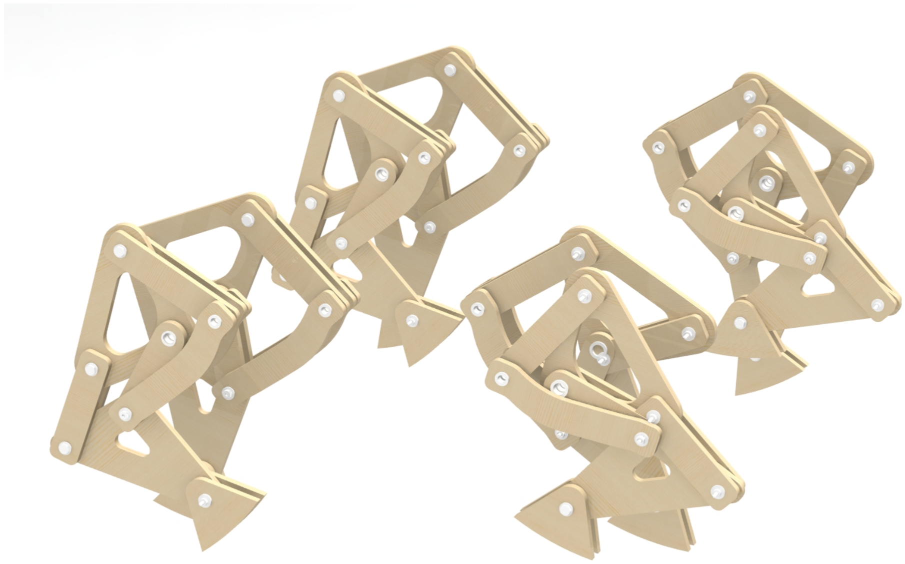
3. Bike brake mounted on wooden casing
    a. Advantages: can engage both brakes at once, very fast machine time
    b. Disadvantages: limited torque, adjustability was challenging

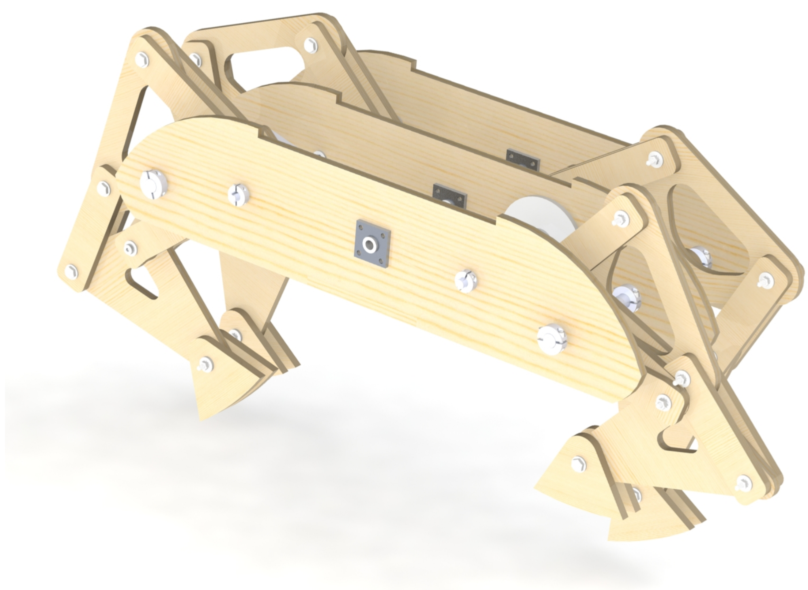



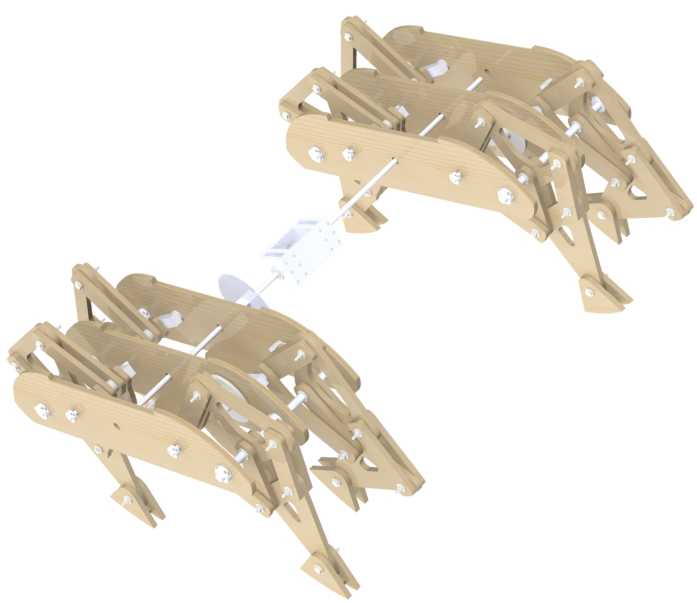
Feet

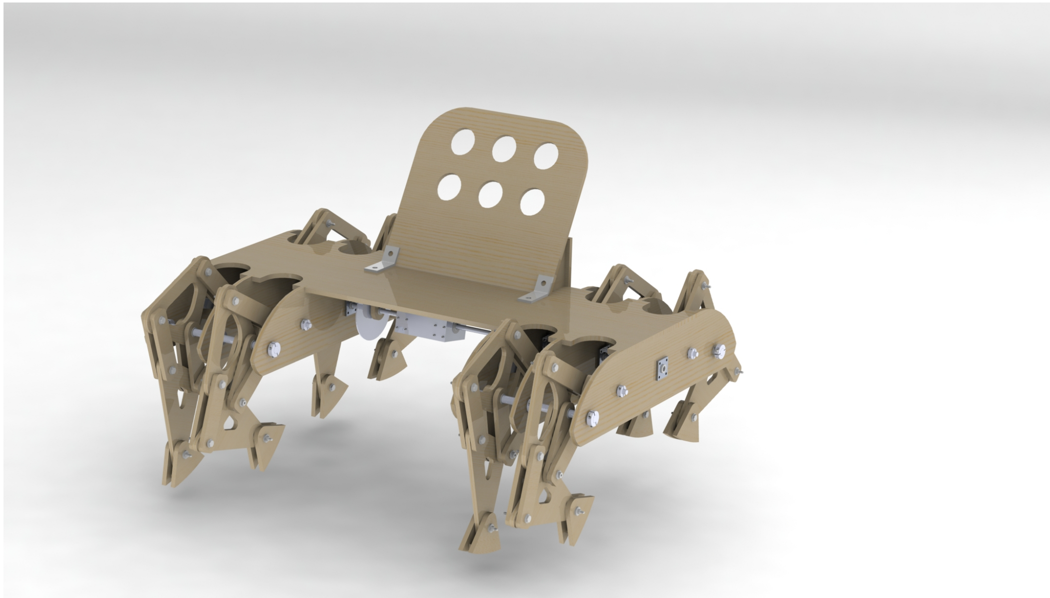



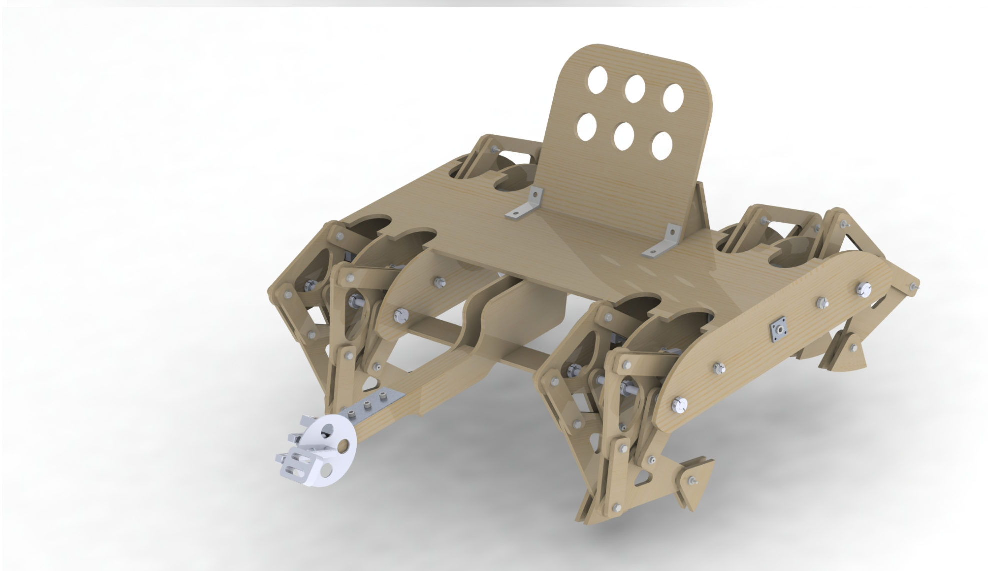
Appendix 5: Assembly Storyboard

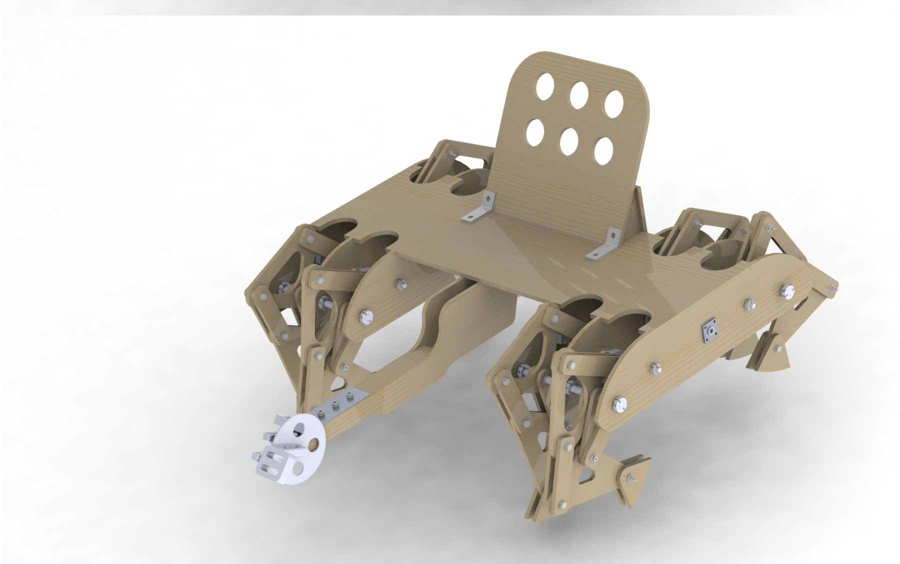












Appendix 6: Unique Part Drawings