DESIGN REVIEW II

THE BEASTS

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FEBRUARY 25, 2014

EXECUTIVE SUMMARY

This report details the concept, research, design, and analysis of the project to create a *Strandbeest* pedal-powered walking vehicle. Beginning with inspiration from Dutch artist and kinetic sculptor Theo Jansen's large *Strandbeest* moving mechanisms, we want to design and construct our own walking vehicle that can support the weight of a human rider. After understanding and analyzing the motion and range of Jansen's leg mechanism, a system of eleven rods of specific lengths attached to each other by a series of revolute joints, we were able to design a four-legged walking mechanism. The main assembly of this device is comprised of three systems: the frame system, the leg system, and the drive system. The rigid central frame will be constructed from 1-inch outer diameter easy-to-weld 4130 alloy steel round tube attached to two sets of three fiberglass-coated plywood plates, which will interface with four legs, two on each side of the rider, made out of a series of 5/16-inch stainless steel rods and fiberglass-coated plywood plates. These legs will be constructed to be lightweight with nylon slide bearings at each clevis joint to reduce friction and allow for smooth movement. Attached to the central frame will be a seat, similar to that of a recumbent bicycle, with two transmission systems on either side. Each transmission system will have a gear stick to shift either side of legs to forward- or reverse-mode, allowing the vehicle to turn. After performing a rough engineering and cost analysis to see if our design was feasible, we continued working toward finalizing our design and refining our calculations to obtain results detailing overall dimensions, weight, materials, power, torque, and motion of this vehicle. The results of these calculations, analyses, and design decisions will be presented in this report in the hopes that our reviewers will assist us in determining the best possible design moving forward.

INTRODUCTION

Using eleven small rods, Dutch kinetic sculptor Theo Jansen has created a planar mechanism that, when used in tandem with many others identical to it, can walk in a smooth forward motion. The resulting device has a very organic look, much like a creeping animal. His "beasts" have been made to be wind powered, using a combination of wind sails and empty plastic bottles that can be pumped up to high pressures (see Figure 1 below).

Figure 1: Theo Jansen with one of his Strandbeest *beach walkers*

Using inspiration from Jansen's *Strandbeest* kinetic sculptures, this project aims to create a pedal-powered walking vehicle that can support a human rider. The person riding the vehicle will pedal a custom frame attached to a small array of *Strandbeest* legs to move forward in a smooth motion. Ideally, we would like to modify the traditional linkage so that a rider would be able to control the height of the mechanism step, so as to be able walk up stairs or step over small obstacles. Additionally, we hope to implement the mechanism to enable the device to turn.

CONCEPT GENERATION

With the inspiration from Jansen's walking mechanisms, we began searching for various applications of the Jansen leg mechanism. We found several images and videos on the Internet showing different applications of this design—large and small—that helped us identify what we wanted our design to look like. The appropriation of the Jansen mechanism has ranged from tiny motorized robots to large multi-legged two-seater vehicles, such as the *Panterragaffe,* pictured in Figures 2 and 3. Further research from patents, academic papers, and articles show that no one has yet to create a pedal-powered walker such as the one that we aim to design and build.

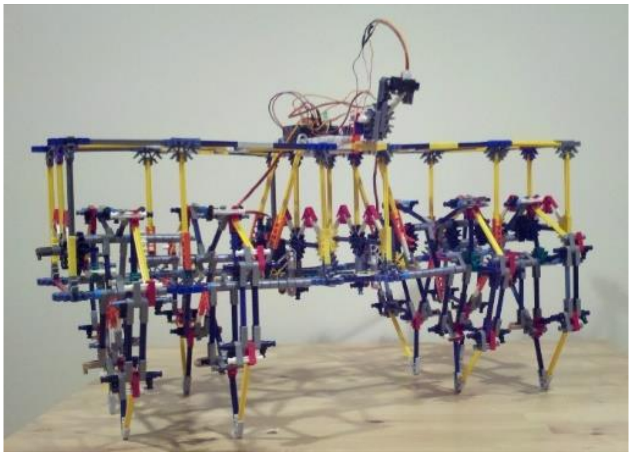


Figure 2: Strandbeest *motorized robot*

Figure 3: Panterragaffe

CONCEPT SELECTION

Beginning with the idea of a modified bicycle frame attached to sets of legs on either side, we started making various sketches of different prototypes of the design (see Figure 4). One of the first considerations was how many sets of legs to include in our design. We ultimately decided on two sets per side to make the entire vehicle smaller and more maneuverable. This choice, however, did come with some trade-offs, which we encountered later in our analysis, such as smoothness of motion and increased force on each leg.

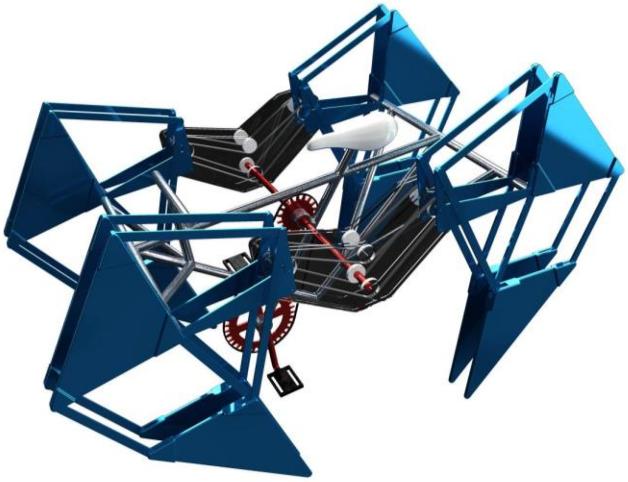


Figure 4: Original prototype

We also had to determine what kind of seat we were going to have on the frame. Although we initially thought it would look like a bicycle seat with two handlebars, the design evolved over time. It occurred to us that having the center of mass lower to the ground would be more desirable in terms of stability, so we moved toward a recumbent seat so that the pedaling could take place on the same axis as the drive shaft.

During the design phase of this project, we also had to decide how each leg would look—whether they would be comprised solely of struts, plates, or a combination. The benefit of using struts would be the decrease in weight of the overall vehicle, however we were concerned with the buckling that might be introduced with a load applied to the walker. After some load analysis using HyperWorks, we were able to optimize the shape of the plates. In addition, we used Creo to determine which parts of the legs would ultimately bear the most load and were able to design an appropriate leg system made out of a combination of plates and struts (see Figure 6).

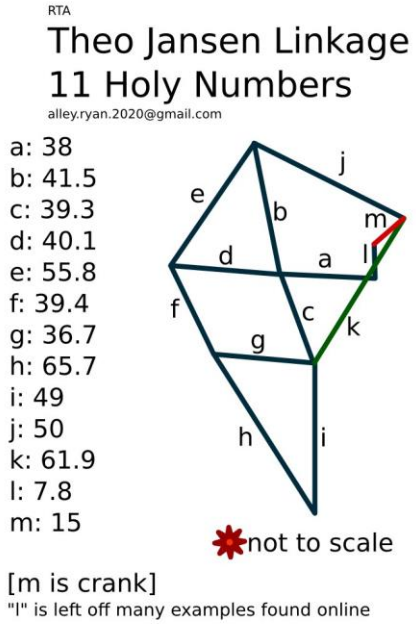


Figure 5: Jansen linkage names and lengths

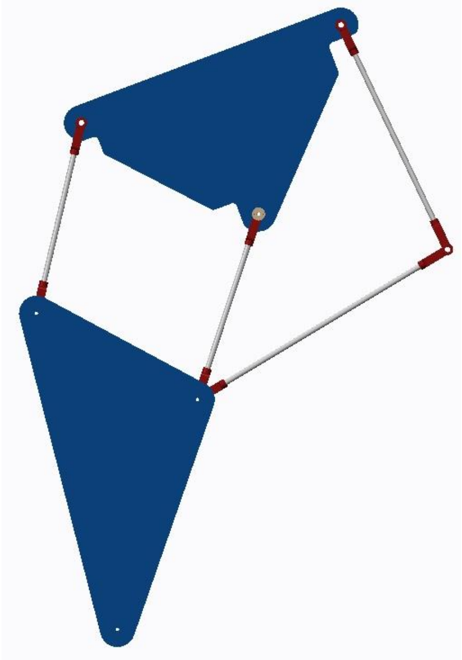


Figure 6: One leg, composed of plates and struts

After some initial calculations, we determined that rods would be more desirable for our vehicle in order to avoid buckling of the struts. Another large consideration was how we would handle the joints in the legs. Because some of the joints had multiple components that needed to be connected, we had to carefully lay out which strut would lay on top of which and place the plates in an orientation that would be well-balanced. Our final design consisted of one top plate (EDB), four tube linkages (C, F, J, and K), and two bottom plates (GHI) (see Figure 5 for reference).

STATIC ANALYSIS

Once our legs were scaled and defined, we could analyze the gait of the walker and gain insight into how the movement would occur. Figure 7 shows the leg in all possible positions throughout one full rotation of the crank shaft, in order to get a better sense of the working envelope of the leg. Figure 8 shows the path of the feet as the crank goes through a full rotation. The color changes from red to yellow as the foot goes through a full cycle, so it is easier to distinguish where each foot will be at any given time. The front and back feet are represented here with a 180° phase shift, which we use to ensure that one foot is always on the ground. However, the transition between feet is not perfectly smooth, and we expect to have a slight dip in elevation as the front foot leaves the ground and the back foot makes contact, or vice versa. This can be seen in Figure 9.

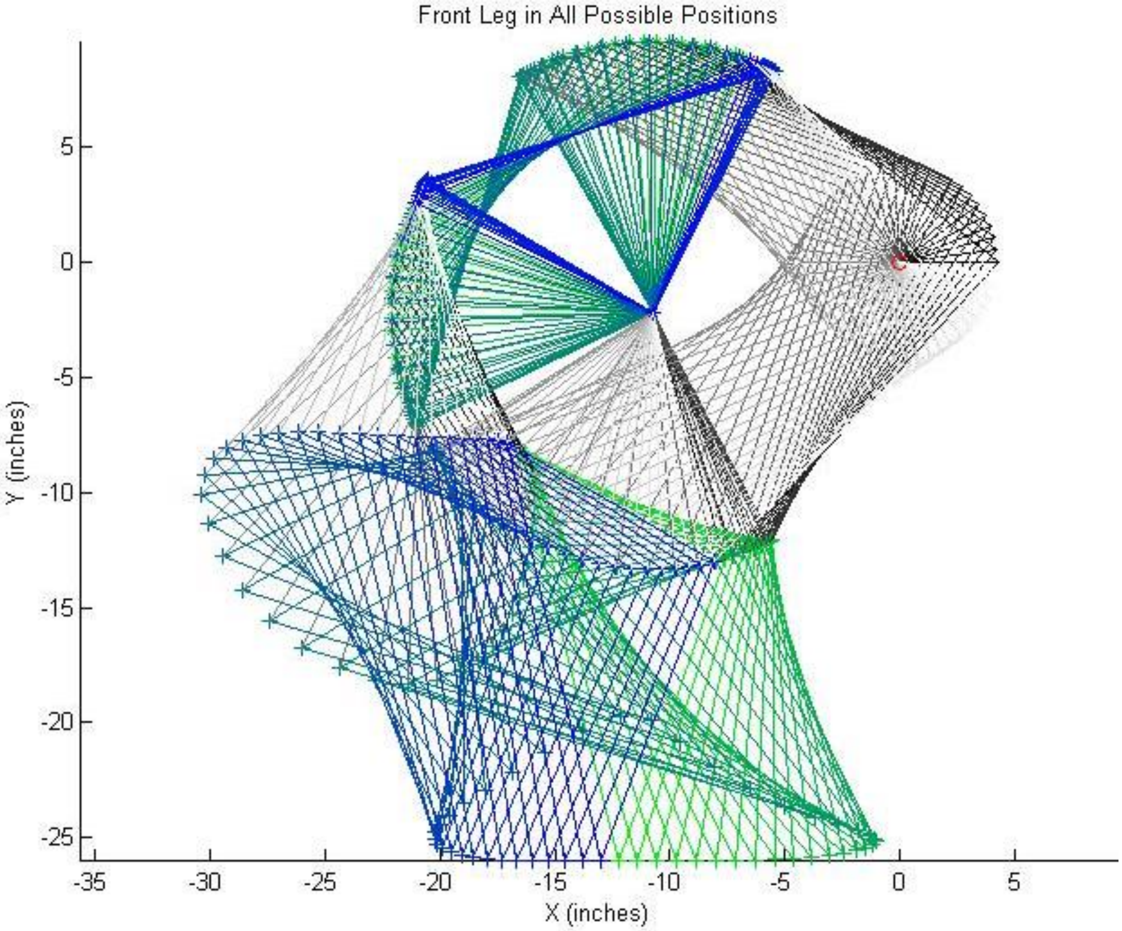


Figure 7: Working envelope of the front leg

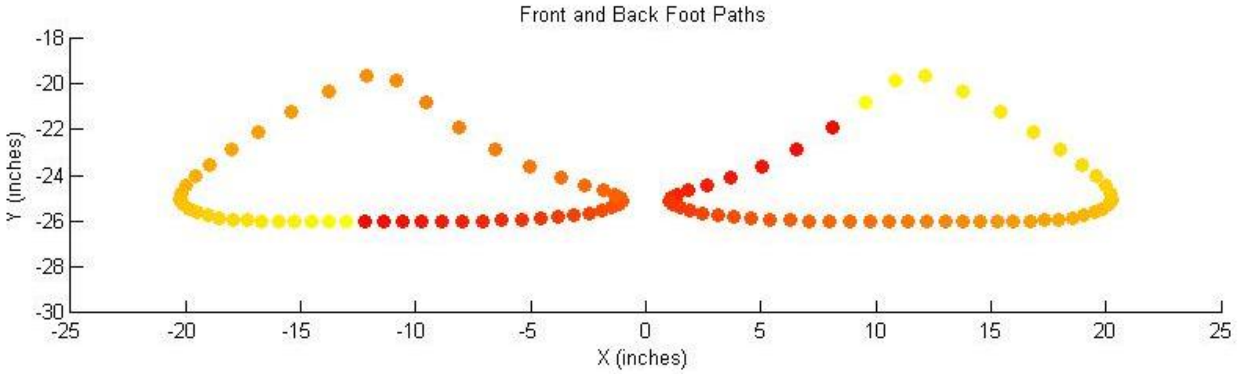
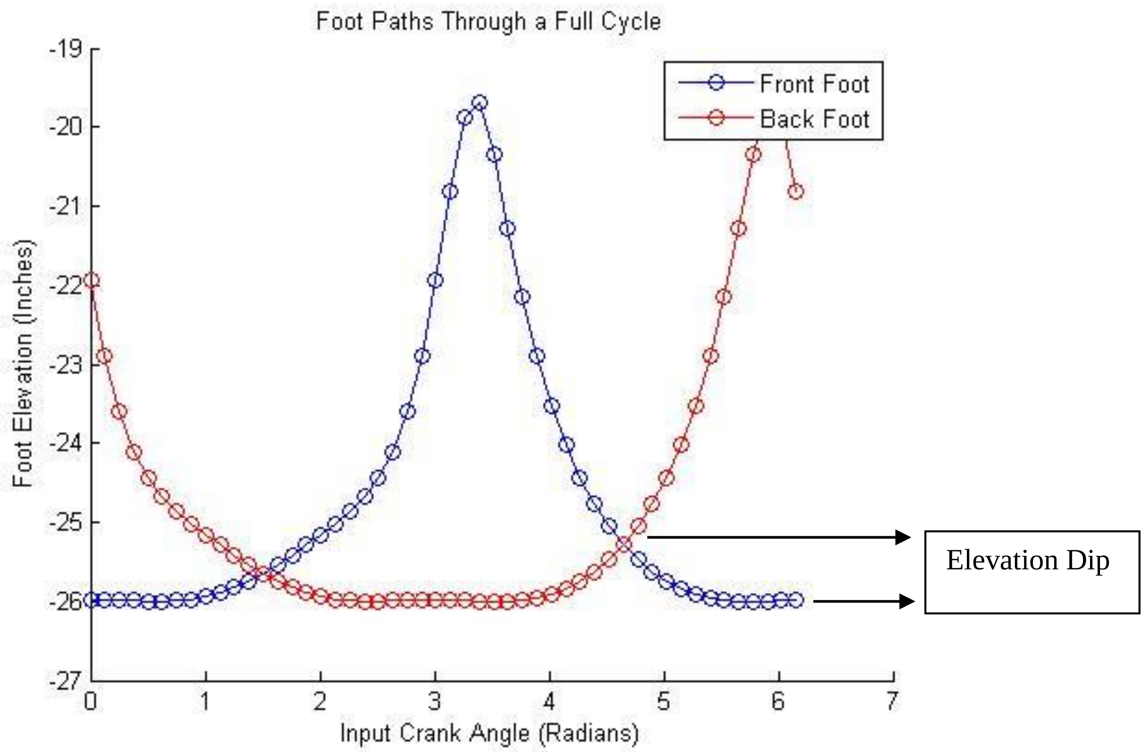


Figure 8: Paths of the front and back legs through one period



Elevation Dip

Figure 9: Foot elevation through one period

MECHANISM ANALYSIS

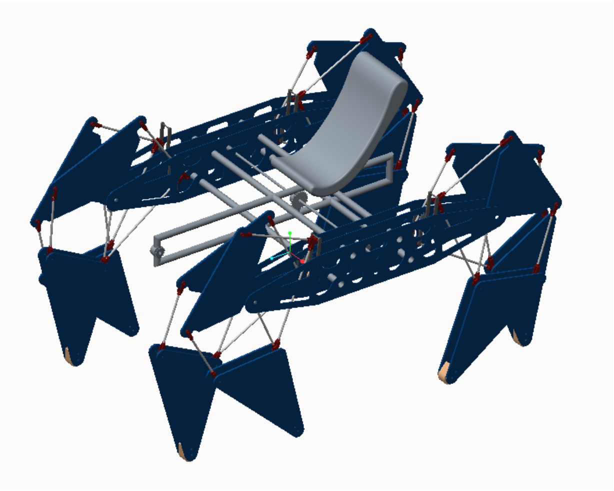
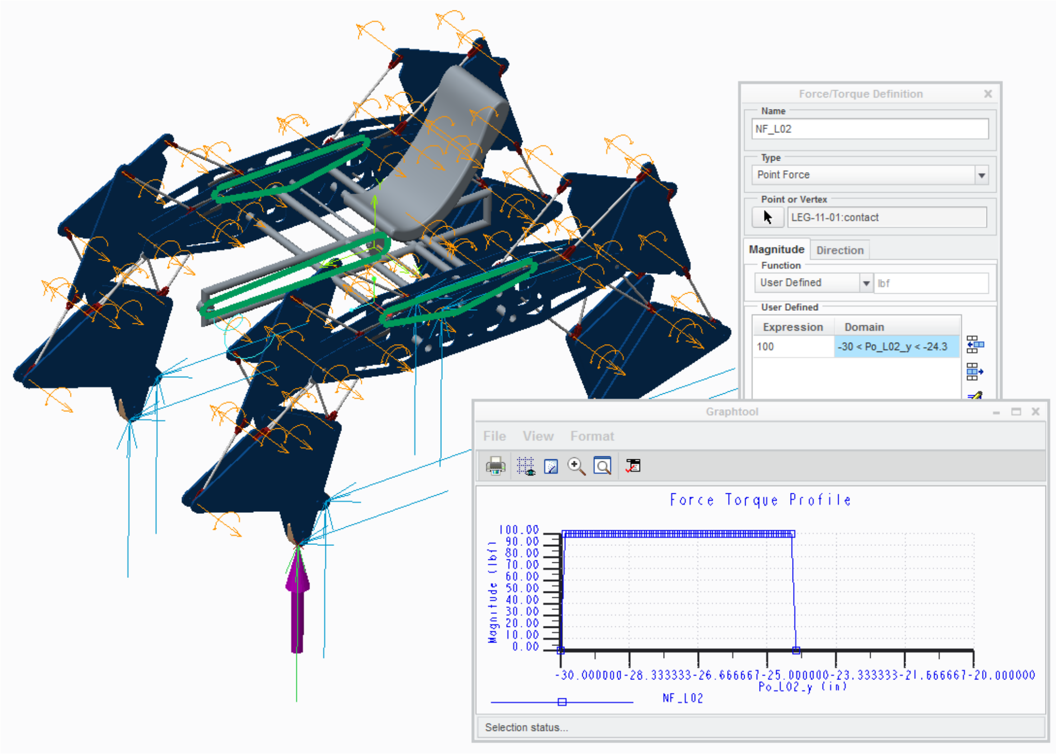


Figure 10: Assembly used in mechanism analysis

STATIC ANALYSIS AND ESTIMATE OF REACTION FORCES ON ASSEMBLY

Due to the complexity of the assembly, with some 60+ pin joins, we were unable to perform a static analysis of the entire structure to estimate the ground reaction force in Creo successfully. This analysis is needed as the ground reaction forces need to be manually added to the dynamic analysis later on. As an assumption, the weight of the structure is assumed to be distributed equally between all four legs that are touching the ground simultaneously. The weight of the three main parts of the assembly (the frame with seat, and each of the two legs sets) were calculated to be 12.2 and 2x19.1 lbs respectively, giving a total weight of 50.4 lbs. Along with a 200 lb. rider this brings the total weight distributed up to 250.4 lbs. As a first approach, this was raised to 400 lbs., a safety factor of 1.6 with a 200 lb. person, which distributed equally at each leg gives 100 lbf of reaction force for each foot. In Creo this was modeled as a discreet force which set in as the position of the tip of the foot was below a certain height. It is not an accurate definition; however, it gives a good estimate of the forces we expect from the ground.

The friction force was modeled on the same principle. If we assume that the max load will be when friction force is max right before slipping, i.e. F = µN. With an estimated 400 lbf as max, and a coefficient of friction of 0.5 (a moderate estimate with rubber against floor), this gives a 50 lbf load on each foot. These forces were also applied discretely, turning on/off as the tip of the foot hit "ground".



Name: NF_L02

Type: Point Force

Point or Vertex: LEG-11-01:contact

Function: User Defined lbf

User Defined

Expression	Domain
100	-30 < Po_L02_y < -24.3

Figure 11: Example of reaction force modeling with a discrete force

Additionally, the current ratio between the pedal sprocket and the sprocket on the crankshaft turning the legs has a ratio of 1.6, where the pedal sprocket is smaller. This ratio may also have to be increased due to the amount of torque required, as is evident later from the results of the analysis. As a second step in the analysis, friction forces were added to the pin joint. The plan is to use nylon sleeve bearings, which have an estimated coefficient of friction 0.2. These are quite inexpensive and are easily replaced. They also have the ability to withstand a 1000 lb radial load.

DYNAMIC ANALYSIS

The dynamic analyses were performed in several steps, increasingly adding more forces and loads. The input parameters were varied to check if the analysis gave the expected results. The final results shown below include outside forces (normal reaction force from ground, friction reaction force from ground and gravity) and internal forces (friction in pin joints with coefficient of friction of 0.2). There was one servo motor rotating the pedal crank with a constant velocity of 180 degree/sec, a quite reasonable pace. Gravity and friction was enabled, and the analysis was run for 12 seconds, i.e. 6 full rotations of the crank and 3.5 of the leg sets. Plots are shown below, and further discussion follows.

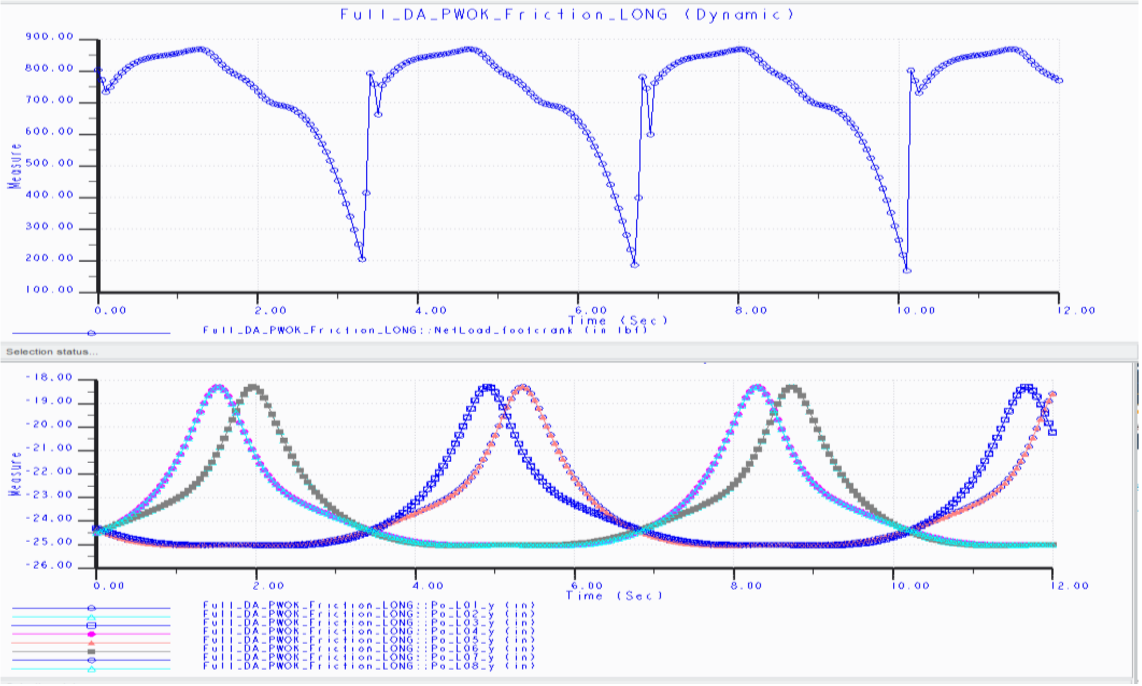


Figure 12: Top: Pedal torque requirement. Bottom: vertical position of the feet

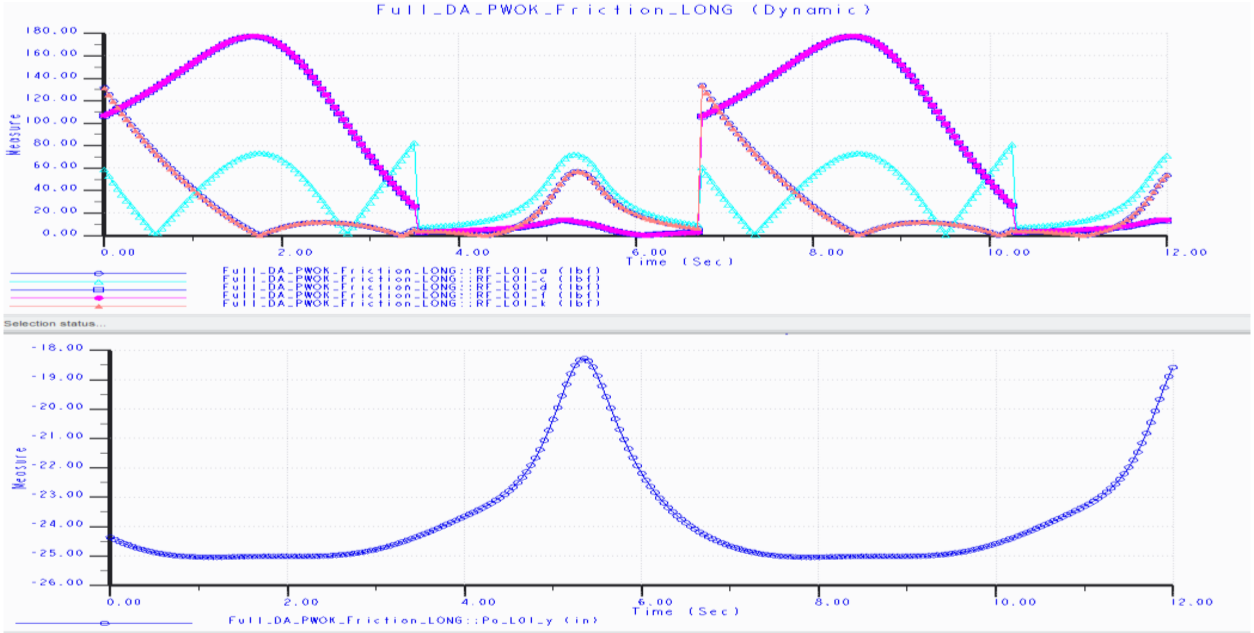


Figure 13: Top: Radial forces on pin joints on leg 01. Bottom: Vertical position of foot of leg 01

As Figure 12 shows, the torque is uneven, and follows the cycle of the legs. When both legs are close to the ground, there is not much torque requirement, as there is no inertia to work against. Large parts of the torque required is to move the inertia of the legs themselves. The discontinuous torque curve is due to the fact that we only have two leg sets, offset by a 180 degrees. As evident from the bottom part of graph 3, this creates an uneven distribution of the vertical position of the feet, and a larger torque requirement in part of the cycle.

Figure 13 show the forces in the pin joints of one leg, with the vertical position of the foot of that leg at the bottom. Ground is defined as anywhere the vertical position of the leg tip is below -24.3 in. As the forces are discreetly defined, so are the results in Creo. The real life scenario will be much more continuous, however, the analysis gives a good estimate on what forces to expect. The highest force, 180lbf, occurs at a pin joint with a diameter of 3/16". This gives a stress of 6500 psi on the pin. With a factor of safety of 2.5, this becomes 16,300 psi which much lower than the yield strength of cold drawn alloy steel E52100 (62,000 psi).

The analysis does not include the extra friction we will experience with the gearbox, something which will need to be further analyzed. The sprocket ratio will become important when it comes to reducing the amount of torque required to power the vehicle.

The graph below shows the forces on the crank that drives the leg. The sharp spikes are believed to be a result of the discreet application of the forces, and the force will most likely be lower than 275 lb as this result implies. The analysis team is currently working on improving the modelling of the forces. However, we will build and test a crank to see how it performs under various loads.

All in all the biggest challenge is the amount of torque we need to apply. As it is now, it seems that the rider would need to produce about 80 ft lb of torque, which is on the higher end for an average biker. However, with a larger sprocket ratio between the pedal and drive shaft sprocket, the torque required will be lowered to a more appropriate torque.

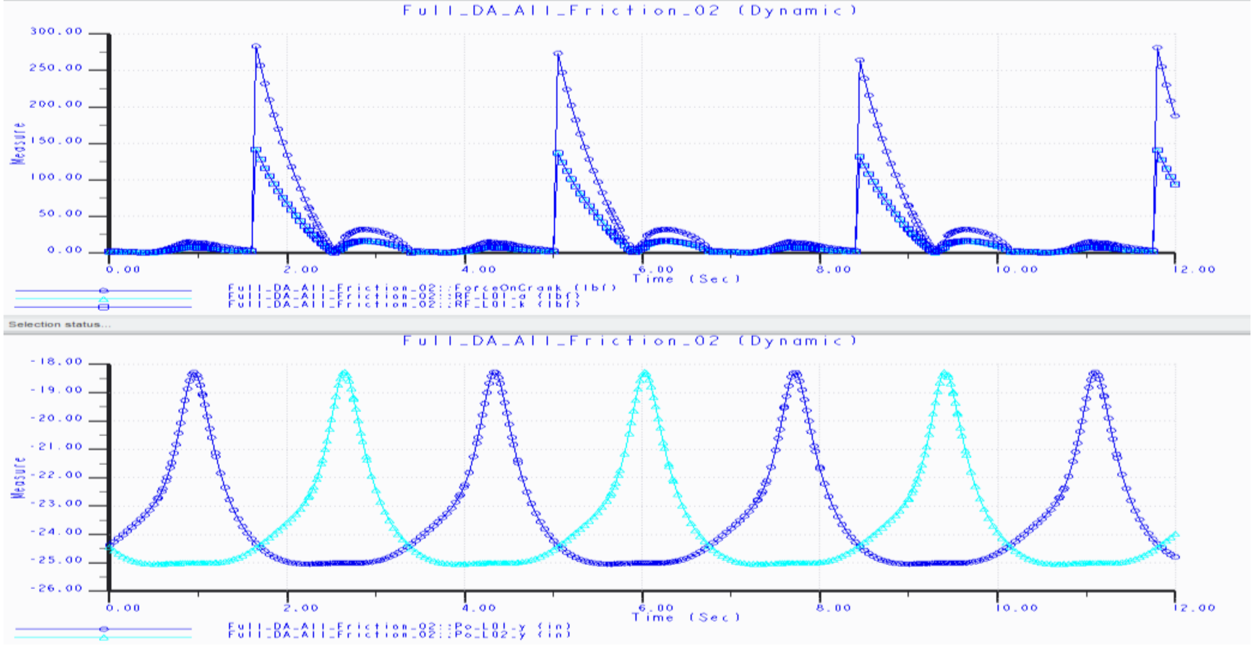


Figure 14: Top: The two forces on the crank driving one leg, as well as the combined force (superposition). Bottom: Position of the two legs.

TRANSMISSION

The transmission was a large consideration as well. We had decided early on to make this vehicle entirely mechanical so that it would move without motors, purely based on how much power the rider was exerting on the pedals. We modeled our transmission roughly after a car transmission, with two modes to shift between—forward and reverse—for each side of legs, enabling the vehicle to turn (see Figure 15).

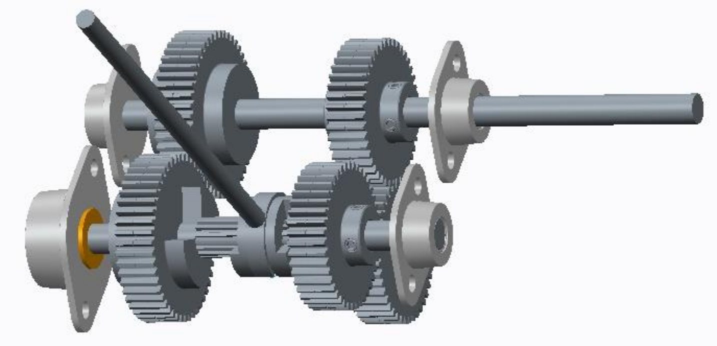


Figure 15: Gears in one transmission box

FINAL CONCEPT DESCRIPTION

The final concept is show in Figure 16. The plates shown are constructed from fiberglass-coated plywood. These plates are profiled to reduce material and overall weight, getting rid of all unnecessary material while maintaining structural integrity. Each leg consists of one upper plate (EDB) made out of fiberglass coated plywood, four tube linkages (C, F, J, and K) constructed from 5/16-diameter stainless steel rods, and two identical bottom plates (GHI) made from plywood coated in fiberglass. In between these plates at the bottom tip will be a foot, constructed from plywood and coated with Plasti Dip to decrease friction and slipping when the vehicle walks.

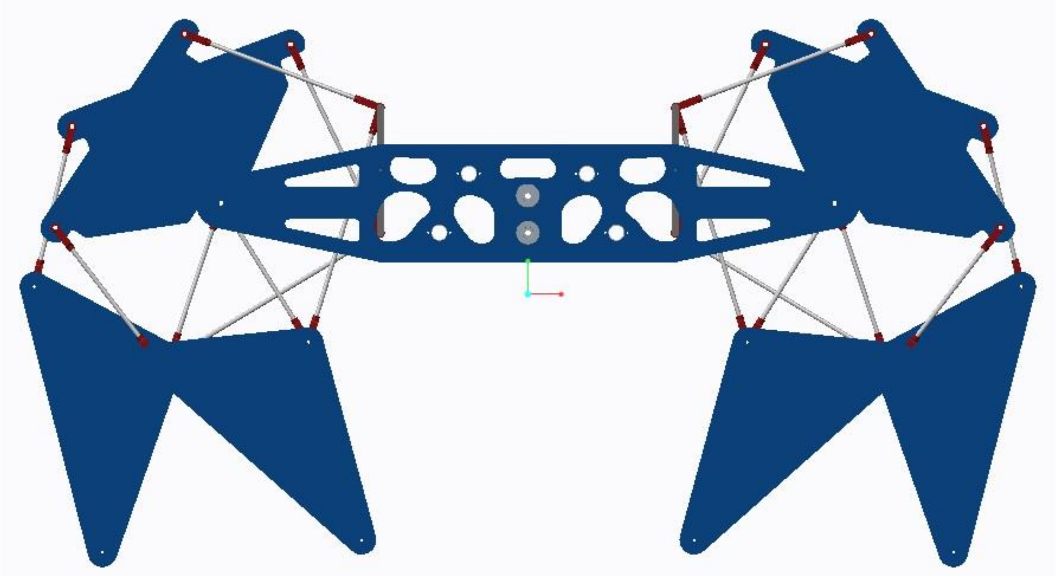


Figure 16: Two sets of legs, connected to the fiberglass-coated plywood plates

The transmission system, pictured in Figure 17, shows the two identical boxes on either side of the recumbent seat. These will be a separate clear plastic transmission box with a shifter. Within the box will be several spur gears that engage in different configurations depending on which position the shifter is in.

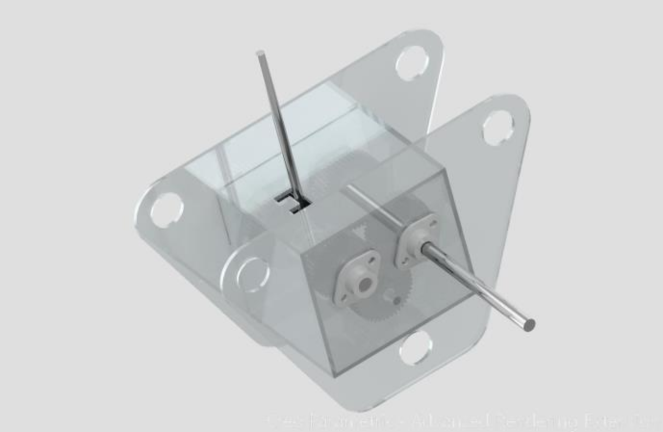


Figure 17: Transmission boxes

LITERATURE SEARCH RESULTS

In performing our literature search, we explored the relatively young field of mechanical robots, specifically walking mechanisms. Along with finding several similar patented walking mechanisms, we found that no one had attempted to create a walking, turning, bicycle using the Jansen linkage.

We found many videos on the internet showing different configurations of actual *Strandbeest* walking mechanisms, as well as several renderings of *Strandbeest* mechanisms implemented in bicycle-like devices, which appear to be most similar to the idea we were conceptualizing. Unfortunately, none of the sources that we found provided anything in terms of technical detail.

We did, however, find many papers detailing kinetic and dynamic analysis of Jansen linkages. Analysis of Jansen walking mechanism using CAD by Moldovan and Dolga discusses the use of ProEngineer and SAM to analyze the mechanism of Theo Jansen's walker linkages, which proved useful when designing the linkages because it allowed us to track the position, velocity, and acceleration of different points on the mechanism. Analysis of Komoda and Wagatsuma's extension of Jansen walking mechanism proposes a solution to extend and retract the leg length by creating a hinged leg, which may help us improve our design to be able to have our design walk up and down hills or even stairs. Using the results detailed in Dynamic Analysis and Modeling of Jansen Mechanism we were able to confirm the results of our force analysis in Creo.

SPECIFICATIONS & PARAMETER ANALYSIS

Although nearly all of the choices in coming to a final design concept were analysis driven, there were other constraints as well that guided us in defining our final design. We had to define several state variables in order to determine the feasibility of the project as well as to determine its predicted performance. Among these state variables, cost is one of the most limiting for this particular project. Working within a $600 budget, we had to select inexpensive, yet sturdy materials that would support the weight of a person riding our *Strandbeest* walking pedal vehicle. Weight is another important variable – we want our design to be as lightweight as possible while still being able to support the weight of a 200 lb person. This is desirable for several reasons, but primarily to ensure that the rider can pedal and move the vehicle comfortably at a reasonable speed. The size of our walker is also a consideration – we want to make sure that the overall device is not so massive that it's inconvenient for us to assemble or difficult for the rider to maneuver. Based on several examples of safety factors for other vehicles and mechanical devices supporting human weight, we chose a safety factor of 2.5 to ensure that a rider could be supported safely while riding our walker.

In addition to state variables, it is important for us to consider design variables such as material, overall dimensions, gear ratios, and manufacturability of our design. Cost was one of the largest influences on what materials were available to us. Although we had originally thought to make all of the plates out of aluminum, we quickly found that the cost of the material would be the majority of our $600 budget. We therefore decided to compromise weight and cost by making the legs out of plywood coated with fiberglass. To ensure that this material would be strong enough for our requirements, we created four dog bone specimens of cross-sectional area of 0.196 square inches to test the material's strength. Using wire to suspend several weights, we aimed to calculate the yield strength of the fiberglass-coated plywood. The contact are between the wires and the dog bone was approximately 0.101 square inches. The highest load measured was 81.2 lbs. The total pressure applied by the weight is 804 psi. We were unable to break the specimen we tested, but after testing we are confident it will be strong enough for the plates in our mechanism.

From the beginning, we wanted our design to be sleek and compact. The main constraint on overall size was the spacing needed between the rider and the legs on each side, as well as the spacing needed between the legs themselves. The overall dimensions of our final design are roughly 37.9 inches wide by 37.9 inches tall by 69.65 inches long. Our gear ratio is 1.6. We knew from the beginning that there would be a lot of machining involved in this project, so we steered away from difficult-to-machine materials or anything that would be hard to assemble. The Easy-to-Weld 4130 Alloy Steel to be used for the frame may be heavier than aluminum, but it will be much easier to work with for our application. Thinking forward towards the manufacturing stage, we plan to fabricate identical parts in parallel to save time.

FINAL DESIGN

Based on the abovementioned parameters, constraints, and design choices, we have come to a final design and have determined the materials to be used. The frame system will be made from 1-inch outer diameter Easy-to-Weld 4130 Alloy Steel round tubes. The leg system will be made from 5/16-inch thick plywood coated with fiberglass and 5/16-inch 304 stainless steel rods. The feet of the legs will be constructed from plywood coated in Plasti Dip for grip. The recumbent seat will be house-made from plywood, foam, and some type of upholstery still to be determined. The gears will be purchased from Stock Drive.

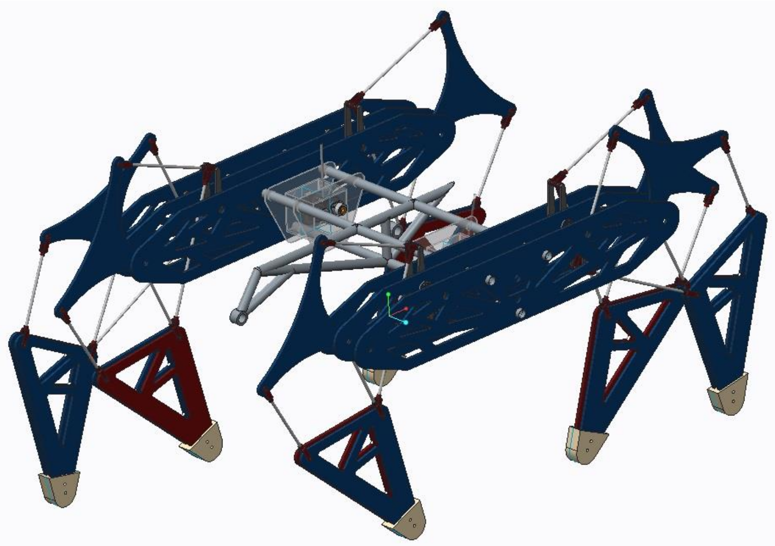


Figure 18: Updated version of final design

PLAN

Because some deadlines have been shifted around and due to the nature of consistently racing with time to try to make deadlines, several revisions to our plan had to be made. Continuing on from Design Review II, we plan on finalizing and freezing our CAD drawings in order to prepare all deliverables necessary for the CAD review and Technical Analysis. We will need to complete a detailed cost analysis and begin ordering all necessary parts. Because of the nature of this project and the large number of machined parts that will have to be completed, it is of utmost importance that we begin the machining and assembling of our device as soon as possible. We want to make sure to leave ample time to address any problems that arise and to test our completed vehicle, making adjustments as necessary (Note: see Appendix 1 and 2 for Gantt Chart and Cost Analysis).

PROBLEM ANALYSIS

Assuming all of our calculations are correct and that we are able to obtain all materials specified in this design, we should be in good shape going forward with his project. It is of utmost importance that we do not fall behind schedule. Because of the amount of machining necessary for the completion of this project, we need to be proactive and begin as soon as possible in creation of parts so that we leave plenty of time for assembly, testing, and troubleshooting. Aside from staying on schedule, we will most certainly run into problems of our machined parts not fitting together exactly as we had expected. This will have to be dealt with on a part-by-part basis to come up with a workable solution.

CONCLUSION

We hope that this report has presented a strong case for the success of the creation of a *Strandbeest* pedal-powered walker. Given our budget and time constraints, we have provided what we see as the best way to proceed with this project. We appreciate our reviewers' time, attention, and consideration with regards to this project, and look forward to hearing any and all feedback, criticism, and comments in Design Review 2. If there are any further questions, comments, or concerns, please feel free to contact any member of our team.

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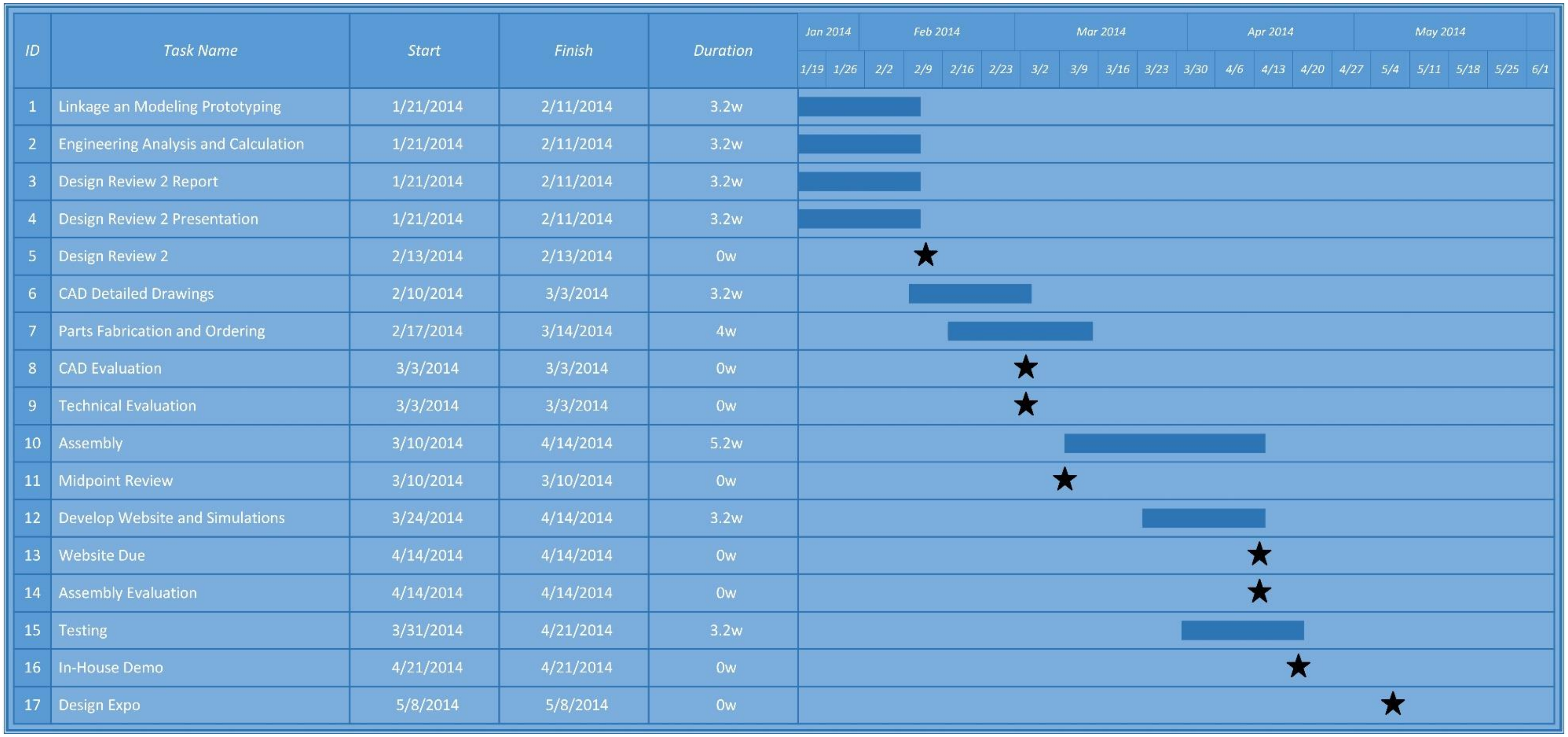
APPENDIX

APPENDIX 1: GANTT CHART



ID	Task Name	Start	Finish	Duration
1	Linkage an Modeling Prototyping	1/21/2014	2/11/2014	3.2w
2	Engineering Analysis and Calculation	1/21/2014	2/11/2014	3.2w
3	Design Review 2 Report	1/21/2014	2/11/2014	3.2w
4	Design Review 2 Presentation	1/21/2014	2/11/2014	3.2w
5	Design Review 2	2/13/2014	2/13/2014	0w
6	CAD Detailed Drawings	2/10/2014	3/3/2014	3.2w
7	Parts Fabrication and Ordering	2/17/2014	3/14/2014	4w
8	CAD Evaluation	3/3/2014	3/3/2014	0w
9	Technical Evaluation	3/3/2014	3/3/2014	0w
10	Assembly	3/10/2014	4/14/2014	5.2w
11	Midpoint Review	3/10/2014	3/10/2014	0w
12	Develop Website and Simulations	3/24/2014	4/14/2014	3.2w
13	Website Due	4/14/2014	4/14/2014	0w
14	Assembly Evaluation	4/14/2014	4/14/2014	0w
15	Testing	3/31/2014	4/21/2014	3.2w
16	In-House Demo	4/21/2014	4/21/2014	0w
17	Design Expo	5/8/2014	5/8/2014	0w

APPENDIX 2: COST ANALYSIS

Internal PN	Description	Key Notes	Unit Price	Unit	Total Price
FRA-01-01	Easy-to-Weld 4130 Alloy Steel Round Tube	Purchase in units of 6'	$ 29.84	3	$ 89.52
FRA-02-01	3/8" metal rod	Find in shop?	$ -		$ -
FRA-03-01	Machinable-Bore Sprockets for ANSI Roller Chain	Bore size?	$ 10.28	2	$ 20.56
FRA-04-01	Seat	We make ourselves!	$ 50.00	1	$ 50.00
LEG-01-01	6061 Multipurpose Aluminm	Already have it	$ -		
LEG-02-01	Crank	We make ourselves!	$ -		$ -
LEG-03-01	EDB plate (1/4" plywood + fiberglass)	1/4"x4'x8' plywood	$ 10.55	1	$ 10.55
LEG-04-01	GHI plate (1/4" plywood + fiberglass)		$ -		$ -
LEG-05C-01	5/16" Multipurpose 304 Stainless Steel		$ 11.44	6	$ 68.64
LEG-06F-01	5/16" Multipurpose 304 Stainless Steel		$ -		$ -
LEG-07J-01	5/16" Multipurpose 304 Stainless Steel		$ -		$ -
LEG-08K-01	5/16" Multipurpose 304 Stainless Steel		$ -		$ -
LEG-09-01	Forged Clevis Rod Ends	5/16"-24	$ 4.98	56	$ 278.88
LEG-10-01	Slide Bearings		$ 8.90	8	$ 71.20
LEG-11-01	Foot - make from 2x4s and Plasti Dip		$ 9.93	1	$ 9.93
LEG-12-01	Frame collars	We make ourselves!	$ -		$ -
LEG-13-01	Pin collars	3D print	$ -		$ -
LEG-14-01	End pin	Find in shop?	$ -		$ -
LEG-15-01	C Clips - Stockdrive ($40 for 50)		$ -		$ -
LEG-16-01	End pin	Find in shop?	$ -		$ -
DRI-01-01	Input shaft		$ -		$ -
DRI-02-01	Transmisison case	Laser cut	$ -		$ -
DRI-03-01	External Spline - Stockdrive		$ -		$ -
DRI-04-01	Internal Spline - Stockdrive		$ -		$ -
DRI-05-01	Small spur gear - Stockdrive		$ -		$ -
DRI-06-01	Small spur gear - Stockdrive		$ -		$ -
DRI-07-01	Plain shaft	Find in shop?	$ -		$ -
DRI-08-01	Shaft coupler - Stockdrive		$ -		$ -
DRI-09-01	Shifter	Find in shop?	$ -		$ -
DRI-10-01	Stockdrive		$ -		$ -
DRI-11-01	Stockdrive		$ -		$ -
DRI-12-01	Stockdrive		$ -		$ -
	DRI-13-01		$ -		$ -

Total Cost Estimate: $605.25 (not including parts from Stockdrive or that are found in the shop).