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Fall 2014

### Wind Walking Machine

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# MEMS 411 Final Report

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Machine That Walks  
2

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Will Nocka

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## 1 Introduction

### 1.1 Project problem statement

This machine walks using leg-like linkages and is only powered by “wind” (e.g. an indoor fan). The wind speed is equivalent to 10 mph winds powering a Strandbeest by Theo Jansen. This machine walks a minimum of 4 meters without rolling, proving that it is capable of walking and at least half of the materials used are recyclable or reusable. It does not exceed 10kg and fits in the volume of 30cm x 60cm x 40cm (e.g. fits on top of a desk). The machine is not required to steer, but can walk against the wind. It moves at an observable speed and walks over various terrains, including concrete and carpeting. The budget is not a concern, though chosen materials such as bass wood and Lego gears will be lower in price than heavier alternatives. The design keeps in mind the resources available, and takes advantage of laser cutting to minimize manufacturing time.

### 1.2 List of team members

Team members for this design project are: Taylor Justman, Sam Lazeckko, Isaac Goldenthal, Will Nocka. All members contributed equally to this project, including design, documentation, fabrication, and testing.

## 2 Background Information Study

### 2.1 A short design brief description that defines and describes the design problem

This design problem requires the production of a machine that walks without rolling using leg-like linkages and is powered using only wind generated by an indoor fan. The design solution is environmentally-friendly where resources are renewable (i.e. wind power) and materials are recyclable and reusable (i.e. wood, aluminum). The design problem requires that the machine is lightweight (less than 10kg) and small (fits on a desk).

### 2.2 Summary of relevant background information (such as similar existing devices or patents, patent numbers, URL's, et cetera)

Relevant background information for this project was found using several sources, including the Washington University Library resources, online research, and existing patents. First, we used WUSTL library resources to find “Advances in Wind Turbine Blade Design and Materials” by Povl Brondsted. We used this book to understand blade design for our turbine, keeping in mind aerodynamic design features. A large part of this source was dedicated to the fatigue behavior of composite wind turbine blades, which was more than we needed for this design project, but it was helpful to have this source to understand the design and functionality of wind turbine blades and the challenges in using certain materials. Another source we used from the WUSTL Library was “Wind Turbine Technology” by A.R. Jha. This resource was useful in giving an introduction to wind turbine technology in order to understand structural requirements for wind turbines using experimental data.

Next, our design was influenced by an animation found on Reddit, created by user “qwibble”. The animation is included below in Figure 1. We were inspired by the use of slotted legs rotating in sync, and used a similar concept for our final design. Similar gifs were provided on the image sharing website, Imgur, in various views: [Robot Walker](#).



Figure 1. Reddit Animation

Finally, existing patents for walking devices used for inspiration include the following: US 6260862 B1 and EP 0399720 A1. The first patent was designed to simulate the gait of a walking animal. It includes rocker arms and cranking links axially mounted to provide suitable power for the walking motion. The second patent is more depictive of a robot spider with orthogonal legs. The device has legs which overlap during movement, each leg with a rotatable shoulder. From these existing patents, we chose to incorporate several ideas: first, the concept of having 3 legs on the ground at once for stability; and second, moving the legs and then moving the body forward to resituate itself.

The following citations account for our Works Cited:

Bares, John E., and William Whittaker. "Patent EP0399720A1 - Orthogonal Legged Walking Robot." *Google Books*. 28 Nov. 1990. Web. 22 Nov. 2014. <<http://www.google.com/patents/EP0399720A1?cl=en>>.

Brondsted, Povl. *Advances in Wind Turbine Blade Design and Materials*. Vol. 47. Oxford: Woodhead, 2013. Print.

Jha, A. R. *Wind Turbine Technology*. Boca Raton, Fla.: CRC, 2011. Print.

Klann, Joseph C. "Patent US6364040 - Walking Device." *Google Books*. 2 Apr. 2002. Web. 22 Nov. 2014. <<http://www.google.com/patents/US6364040>>.

"Robot Walker." *Imgur*. 1 Aug. 2014. Web. 22 Nov. 2014. <<http://imgur.com/gallery/lbjcn>>.

"Robot Walker (OC) • /r/perfectloops." *Reddit*. 1 Aug. 2014. Web. 22 Nov. 2014. <[http://www.reddit.com/r/perfectloops/comments/2dgj2b/robot\\_walker\\_oc/](http://www.reddit.com/r/perfectloops/comments/2dgj2b/robot_walker_oc/)>.

### **3 Concept Design and Specification**

#### **3.1 User needs, metrics, and quantified needs equations. This will include three main parts:**

##### **3.1.1 Record of the a-user needs interview**

The following table, Table 1, shows our User Needs interview with Professor Jakiela.

Table 1. User Needs Interview

Customer Data: Wind Walking Machine (WWM)			
Customer: Dr. Jakiela			
Address: Washington University		Date: 10 September 2014	
Question	Customer Statement	Interpreted Need	Importance
How far does it need to walk?	4 meters	WWM walks 4 meters on wind power	5
Powered by real wind or fan (indoor)?	Indoor fan, see "vornado" fan.	WWM powered by Indoor fan	5
What is the budget?	Not a concern	WWM has no hard budget	1
Does it need to be able to steer?	No	WWM does not need steering considerations	1
Does it need to be able to go against the wind?	It would be really nice if it could	WWM ability to go against wind is preferred if possible, but not mandatory.	4
How fast should the WWM go?	Movement should be easily detectable.	WWM needs to move so motion is observable	5
What kind of terrain does it need to maneuver?	We can dictate terrain, at least 2 different terrains ideal.	WWM needs to be able to maneuver hard and carpeted floors	5
What kind of windspeed does WWM need to be able to work with?	Winds that translate to "common" winds on real life scale.	WWM needs to be able to move with equivalent of minimum of 10 mph winds	4
What are size constraints?	Fit on top of a desk	WWM needs to fit inside 3'x3'x3' box	4
What are material constraints?	100% recyclable	WWM needs to be made from only recyclable materials	5
What are weight constraints?	None	WWM does not have any weight constraints, as long as it moves.	1
What is defined as "walking"?	Leave as intuitive notion.	WWM needs to move without "rolling".	5
What path does it need to take?	Straight line is fine, circle/closed loop is preferable	WWM needs to be able to move in a straight line	3
How many parts does it need to be made of?	As few as possible	WWM needs to be made from as few parts as possible	3

### 3.1.2 List of identified metrics

Table 2 shows our identified metrics determined after our user needs interview.

Table 2. List of Identified Metrics

Need Number	Need	Importance
1	WWM walks 4 meters	5
2	WWM powered by indoor fan	5
3	WWM can go against wind	3
4	WWM moves at an observable speed	5
5	WWM maneuvers hard and carpeted floors	5
6	WWM operates in equivalent of 10 mph winds	4
7	WWM needs to fit inside 3'x3'x3' box	4
8	WWM built from only recyclable materials	5
9	WWM moves without "rolling"	5
10	WWM moves in a straight line	3
11	WWM made from as few parts as possible	3

### 3.1.3 Table/list of quantified needs equations

Table 3 shows our quantified needs with minimum and maximum values for each metric determined in Table 2.

Table 3. Quantified Needs

Design Metrics: Wind Walking Machine (WWM)					
Metric Number	Associated Needs	Metric	Units	Min Value	Max Value
1	7	Length	ft	0.5	3
2	7	Width	ft	0.5	3
3	7	Height	ft	0.5	3
4	4,9	Walking Speed	m/s	0.01	1
5	2,6	Fan Speed	mph	1	10
6	1,10	Distance Walked	m	4	100
7	11,8	Number of parts	integer	10	1000
8	5	Number of floor types maneuverable	integer	2	10
9	3	Wind Orientation	Degrees	0	360

### 3.2 Four (4) concept drawings



Figures 2 through 5 are our concept drawings created after reviewing the metrics.

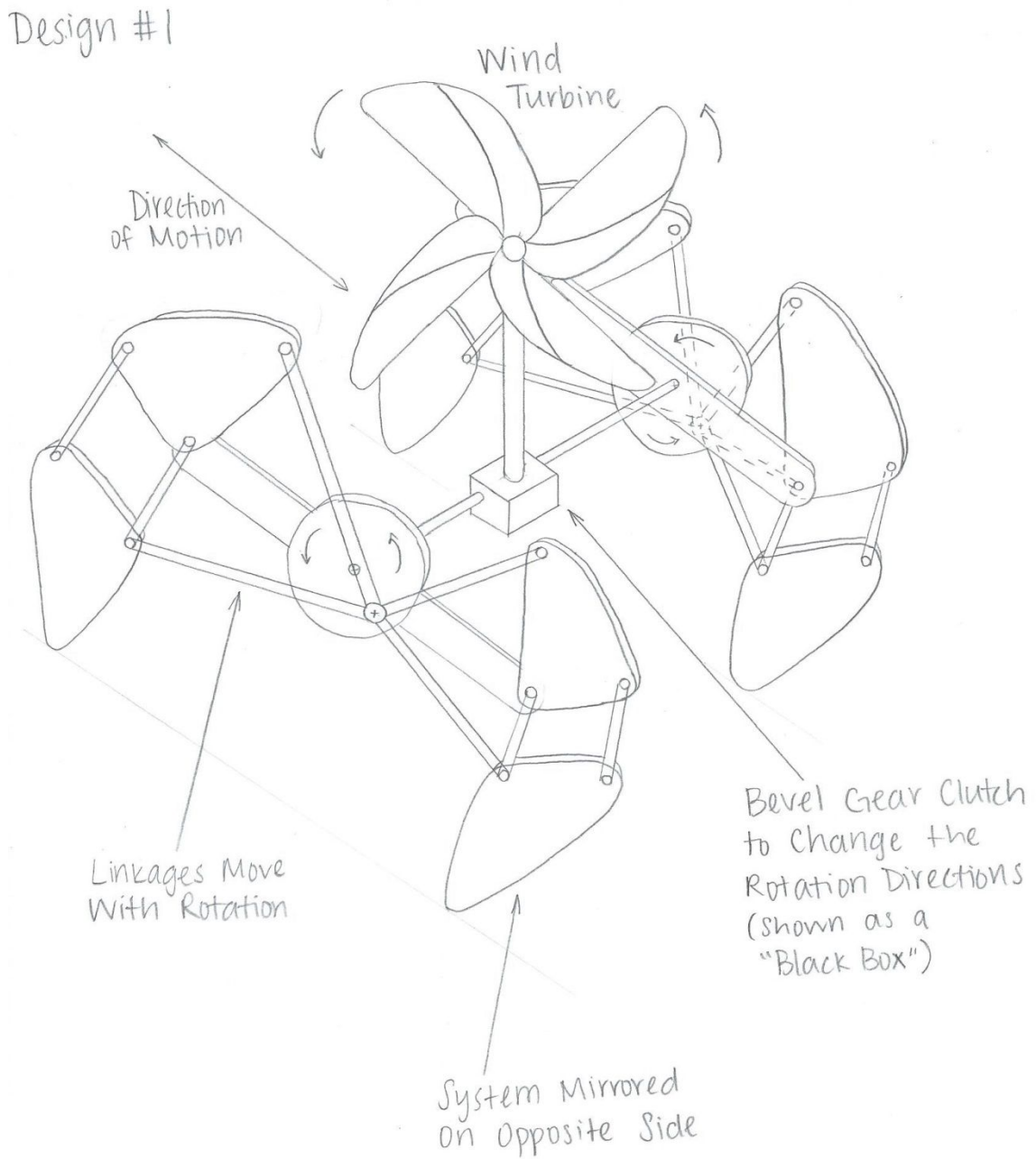


Figure 2. Concept Drawing Design #1



Design #2

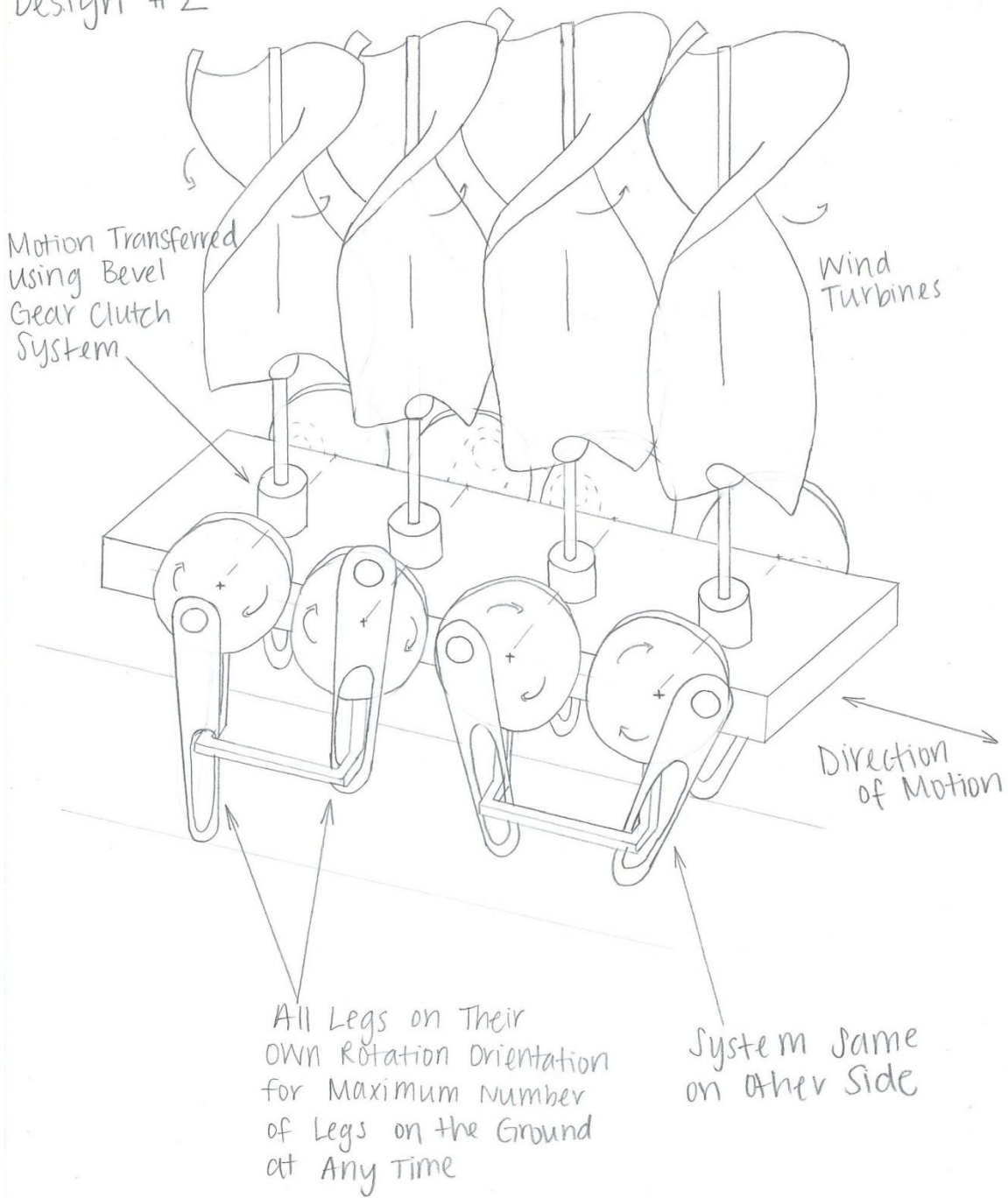


Figure 3. Concept Drawing Design #2

Design #3

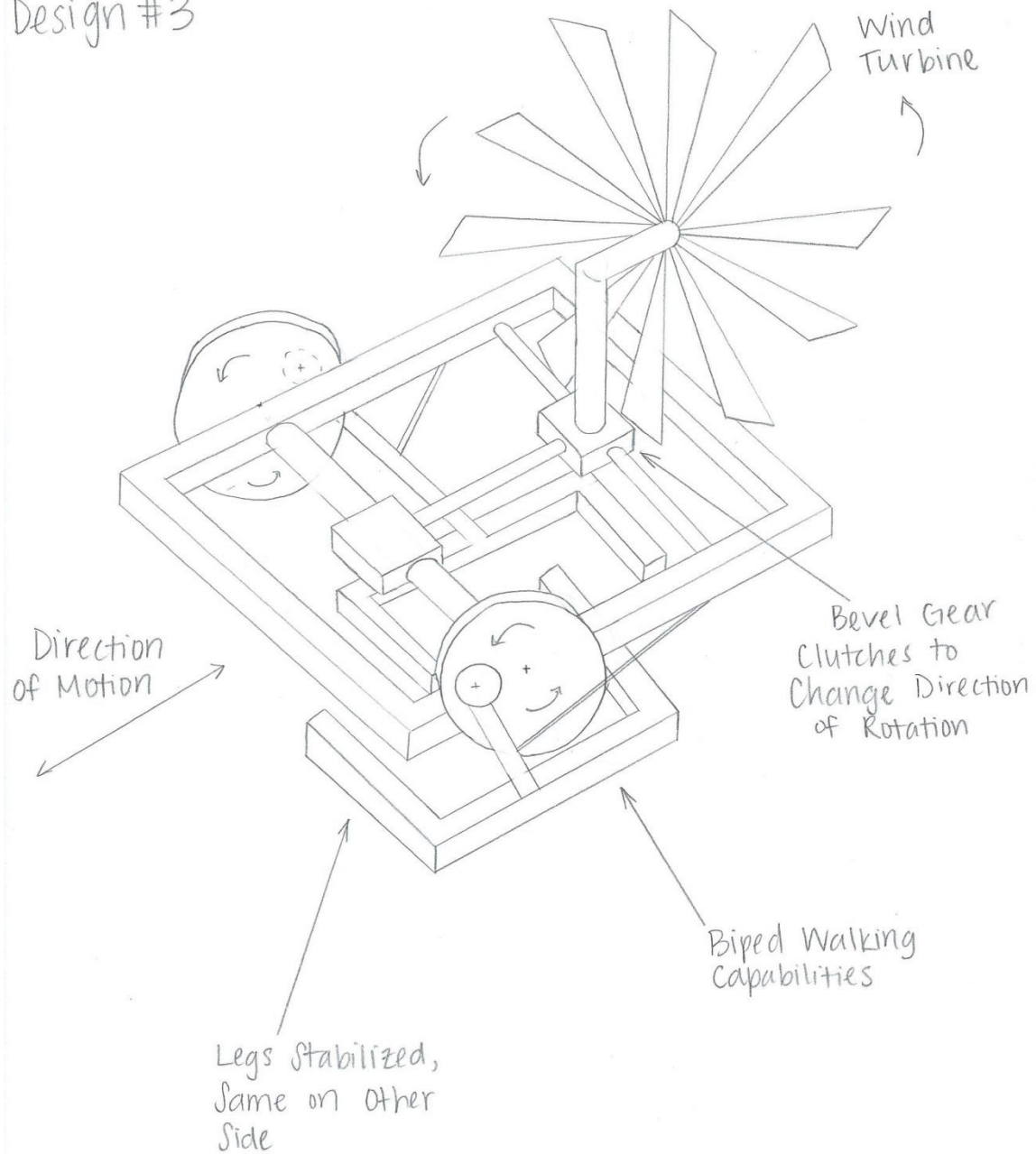


Figure 4. Concept Drawing Design #3

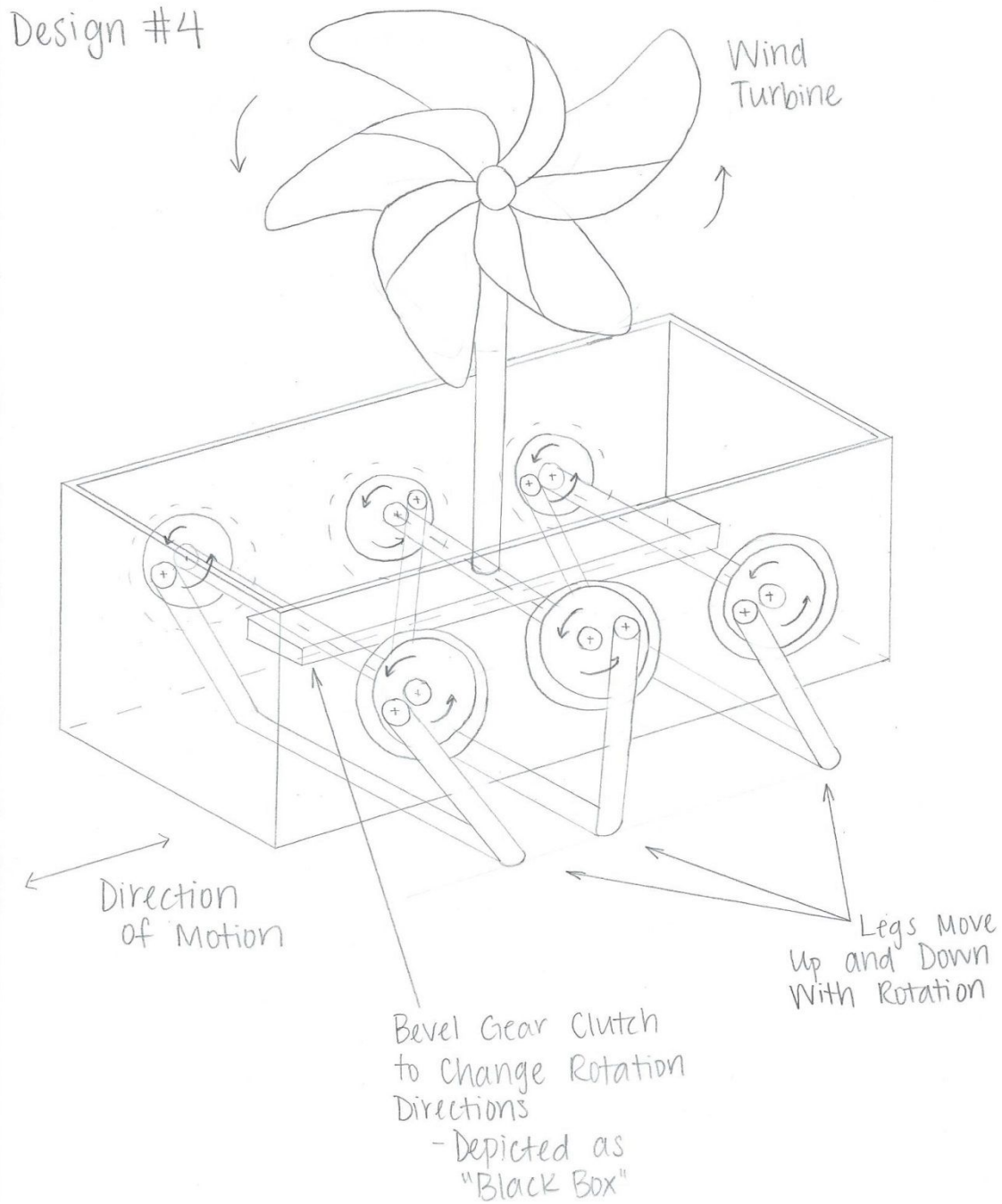


Figure 5. Concept Drawing Design #4

**3.3 A concept selection process. This will have three parts:**

### **3.3.1 Concept scoring (not screening)**

Tables 4 through 7 indicate the concept scoring for each design.

Table 4. Concept Scoring for Design #1

Need#	Need	Metric									Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
		Length	Width	Height	Walking Speed	Fan Speed	Distance Walked	Number of Parts	Number of Floor Types Maneuverable	Wind Orientation			
1	WWWI Walks far enough	1	2	3	4	5	6	7	8	9	0.5	0.12	0.06
2	WWWI Powered by fan					0.5					0.9	0.05	0.045
3	WWWI travels against wind										1	0.05	0.05
4	WWWI moves at observable speed				1						0.3	0.12	0.036
5	WWWI maneuvers multiple terrains								1		0.5	0.1	0.05
6	WWWI operates in "calm" winds					1					0.8	0.12	0.096
7	WWWI fits inside 3'x3'x3' cube	0.333333	0.333333	0.333333							0.333333	0.12	0.04
8	WWWI 100% recyclable							1			0.6	0.1	0.06
9	WWWI moves without rolling				1						0.3	0.12	0.036
10	WWWI moves in straight line						1				0.5	0.05	0.025
11	WWWI made from small number of parts							1			0.6	0.05	0.03
Units		ft	ft	ft	m/s	mph	m	integer	integer	degrees	Total Happiness		
Best Value		0.5	0.5	0.5	1	1	100	10	10	360			
Worst Value		3	3	3	0.01	10	4	100	2	1			
Actual Value		2	2	2	0.3	2	50	40	5	360			
Normalized Metric Happiness		0.333333	0.333333	0.333333	0.3	0.8	0.5	0.6	0.5	1	0.528		

Table 5. Concept Scoring for Design #2

Need#	Need	Metric									Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
		Length	Width	Height	Walking Speed	Fan Speed	Distance Walked	Number of Parts	Number of Floor Types Maneuverable	Wind Orientation			
1	WWMM Walks far enough	1	2	3	4	5	6	7	8	9	0.5	0.12	0.06
2	WWMM Powered by fan					0.5				0.5	0.85	0.05	0.0425
3	WWMM travels against wind									1	1	0.05	0.05
4	WWMM moves at observable speed				1				1		0.4	0.12	0.048
5	WWMM maneuvers multiple terrains								1		0.7	0.1	0.07
6	WWMM operates in "calm" winds					1					0.7	0.12	0.084
7	WWMM fits inside 3'x3'x3' cube	0.333333	0.333333	0.333333							0.138889	0.12	0.016667
8	WWMM 100% recyclable								1		0.65	0.1	0.065
9	WWMM moves without rolling				1						0.4	0.12	0.048
10	WWMM moves in straight line								1		0.5	0.05	0.025
11	WWMM made from small number of parts								1		0.65	0.05	0.0325
Units		ft	ft	ft	m/s	mph	m	integer	integer	degrees	Total Happiness		
Best Value		0.5	0.5	0.5	1	1	100	10	10	360	0.541667		
Worst Value		3	3	3	0.01	10	4	100	2	1			
Actual Value		2.75	2.5	2.5	0.4	3	50	35	7	360			
Normalized Metric Happiness		0.083333	0.166667	0.166667	0.4	0.7	0.5	0.65	0.7	1			



Table 6. Concept Scoring for Design #3

Wind Walking Machine #3		Metric									Need Happiness		
Need#	Need	Length	Width	Height	Walking Speed	Fan Speed	Distance Walked	Number of Parts	Number of Floor Types Maneuverable	Wind Orientation	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
1	WWMI Walks far enough	1	2	3	4	5	6	7	8	9	0.5	0.12	0.06
2	WWMI Powered by fan					0.5		1			0.65	0.05	0.0325
3	WWMI travels against wind									1	1	0.05	0.05
4	WWMI moves at observable speed				1						0.4	0.12	0.048
5	WWMI maneuvers multiple terrains								1		0.2	0.1	0.02
6	WWMI operates in "calm" winds					1					0.3	0.12	0.036
7	WWMI fits inside 3'x3'x3' cube	0.333333	0.333333	0.333333							0.166667	0.12	0.02
8	WWMI 100% recyclable							1			0.75	0.1	0.075
9	WWMI moves without rolling				1						0.4	0.12	0.048
10	WWMI moves in straight line						1				0.5	0.05	0.025
11	WWMI made from small number of parts							1			0.75	0.05	0.0375
	Units	ft	ft	ft	m/s	mph	m	integer	integer	degrees	Total Happiness		
	Best Value	0.5	0.5	0.5	1	1	100	10	10	360	0.452		
	Worst Value	3	3	3	0.01	10	4	100	2	1			
	Actual Value	2.5	2.5	2.5	0.4	7	50	25	2	360			
	Normalized Metric Happiness	0.166667	0.166667	0.166667	0.4	0.3	0.5	0.75	0.2	1			

Table 7. Concept Scoring for Design #4

Need#	Need	Metric									Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
		Length	Width	Height	Walking Speed	Fan Speed	Distance Walked	Number of Parts	Number of Floor Types Maneuverable	Wind Orientation			
1	WWMM Walks far enough	1	2	3	4	5	6	7	8	9	0.5	0.12	0.06
2	WWMM Powered by fan					0.5				0.5	0.75	0.05	0.0375
3	WWMM travels against wind									1	1	0.05	0.05
4	WWMM moves at observable speed				1				1		0.4	0.12	0.048
5	WWMM maneuvers multiple terrains								1		0.5	0.1	0.05
6	WWMM operates in "calm" winds					1					0.5	0.12	0.06
7	WWMM fits inside 3'x3' cube	0.333333	0.333333	0.333333							0.333333	0.12	0.04
8	WWMM 100% recyclable							1			0.75	0.1	0.075
9	WWMM moves without rolling				1						0.4	0.12	0.048
10	WWMM moves in straight line						1				0.5	0.05	0.025
11	WWMM made from small number of parts							1			0.75	0.05	0.0375
Units		ft	ft	ft	m/s	mph	m	integer	integer	degrees	Total Happiness		
Best Value		0.5	0.5	0.5	1	1	100	10	10	360	0.531		
Worst Value		3	3	3	0.01	10	4	100	2	1			
Actual Value		2	2	2	0.4	5	50	25	5	360			
Normalized Metric Happiness		0.333333	0.333333	0.333333	0.4	0.5	0.5	0.75	0.5	1			



### 3.3.2 Preliminary analysis of each concept's physical feasibility

Our first design has several potential issues that arise from the complexity of the leg systems. The large number and size of the linkages limits the space that can be used for the wind turbine. The multilink system also appears to require a large amount of force to operate. Also, with 4 feet and likely fewer points of contact at any one time the mechanism runs the risk of tipping over in high wind conditions. This design would require very light material for the linkage system, an efficient turbine and a bevel gear clutch to transfer the power to the legs.

The second design would require the bevel gear clutch system, low friction bearings and a high efficiency vertical axis wind turbine. The small feet would require high grip strength to successfully "step." The multiple turbine system allows for lower torque on the wind turbine transmissions because they operate separately. Also, if the wind was aligned with the wind turbines the farthest one would generate less power than the first. This would cause the legs to step out of sync. This problem could be avoided with a gear syncing system or a modified turbine set up. This design appears to have the best balance out of the four. The vertical axis wind turbines allow the walker to move independent of wind direction.

The third design would require a very high torque to operate due to the large feet. Also, the power distribution system would require multiple bevel gear systems which would hurt efficiency. The design appears to be unstable compared to the other three. Also, the walker could only move in the same direction as the wind.

Design 4 relies on one turbine supporting 3 drive shafts. This would require a very high torque and a bevel gear system as well as ultralow friction bearings to transmit the power to the legs. The complicated transmission would hurt efficiency. Also, the legs would require additional linkages or guides to achieve the appropriate trace paths for the feet.

### 3.3.3 Final summary

Design 2 stands apart from the rest for several reasons. First of all, the drive system is simple and requires low torque compared to the others. The strain on each windmill and transmission system is lessened by compartmentalizing each leg pair. In addition, using the vertical axis wind turbines allows the walker to move regardless of the wind direction. The legs themselves have a simple elegant design. They only require one moving linkage. Fewer linkages means less power lost to friction and power transfer between parts. We need to address the issue of the turbines stealing power from each other, but flow analysis and prototyping will allow us to maximize power output from the windmill array. We also need to find a way to sync the legs together so that they operate at maximum efficiency. All in all, this design allows us to capture the maximum amount of power and distribute it to the legs in a simple, efficient manner. The other designs also had several promising elements that will influence our design going forward. Our happiness equations also showed Design 2 as the winner.

### 3.4 Proposed performance measures for the design

Our proposed performance measures for the design are as follows:

1. Travels 4m in 1 minute
2. Moves regardless of wind direction
3. Walks on multiple types of tile and carpet
4. Operates in air speeds equivalent to 10-25 mph full scale wind speeds
5. Made from recyclable materials and as few parts as possible
6. Travels in a straight line
7. Fits inside 3'x3'x3' box

## 4 Embodiment and fabrication plan

### 4.1 Embodiment drawing

Figure 6 depicts the embodiment drawing plan for the wind-walking machine.

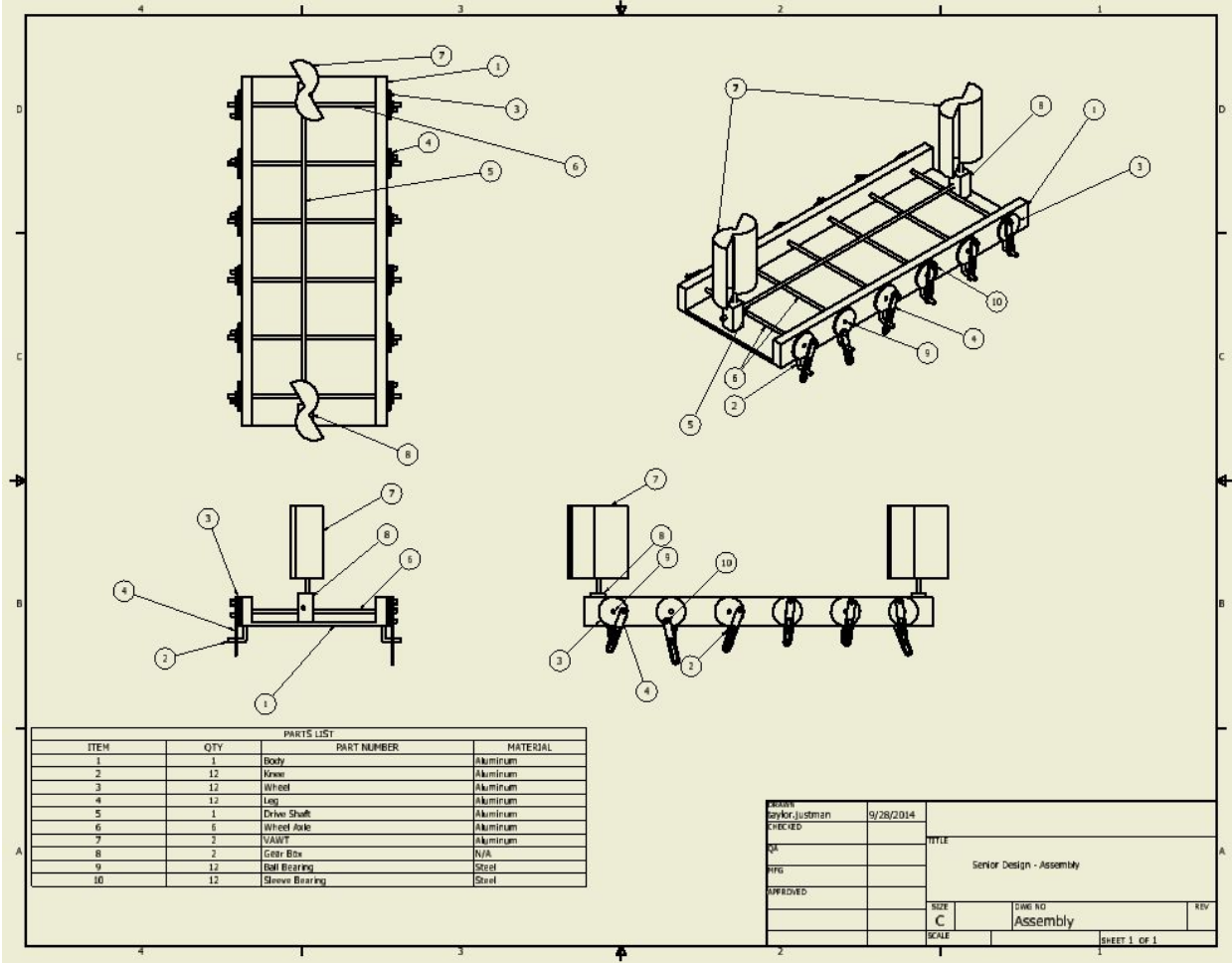


Figure 6. Embodiment Drawing

Figures 7 through 10 are zoomed-in images from Figure 6.

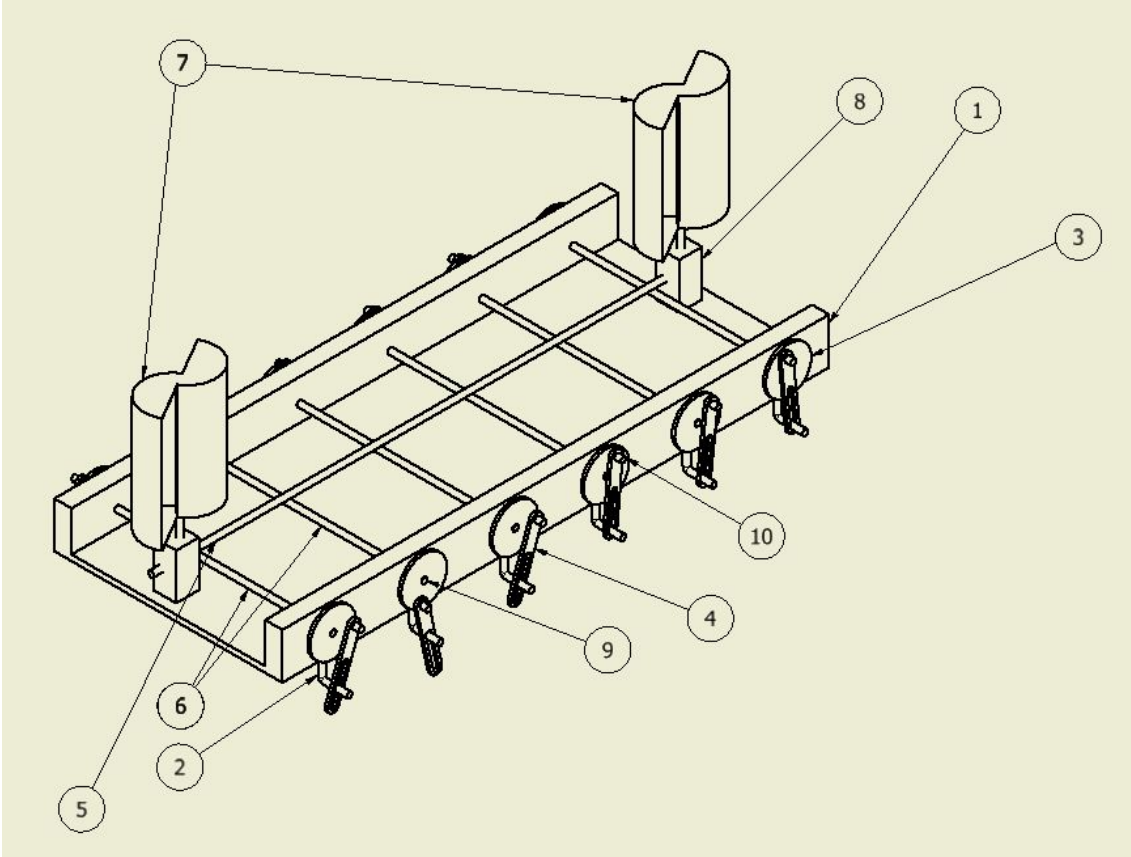


Figure 7. Isometric View Embodiment Drawing

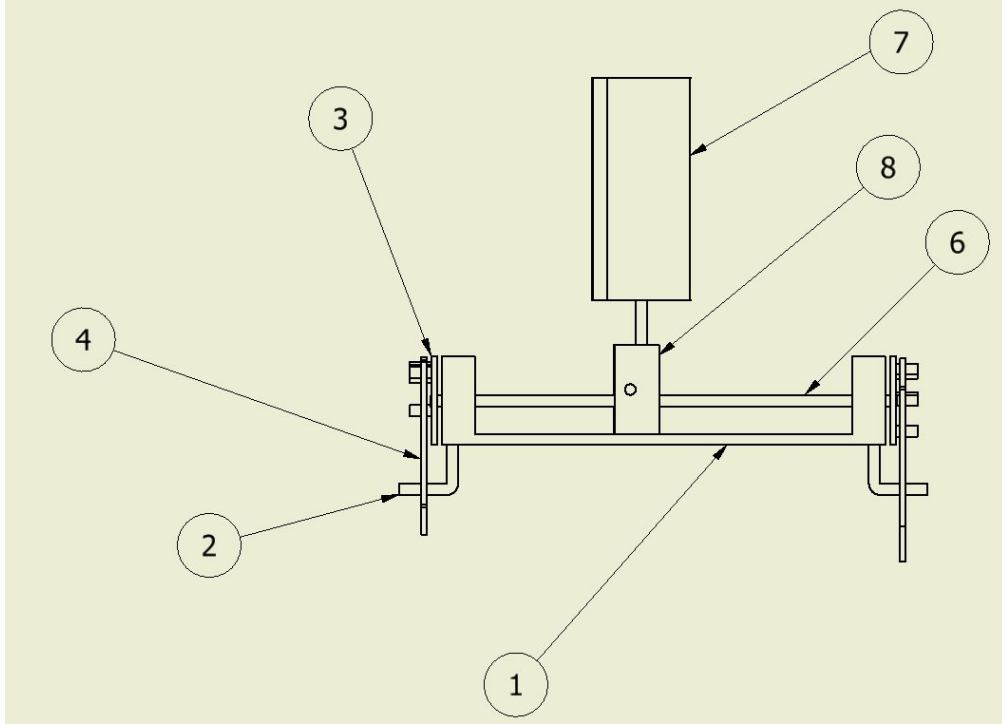


Figure 8. Front View Embodiment Drawing

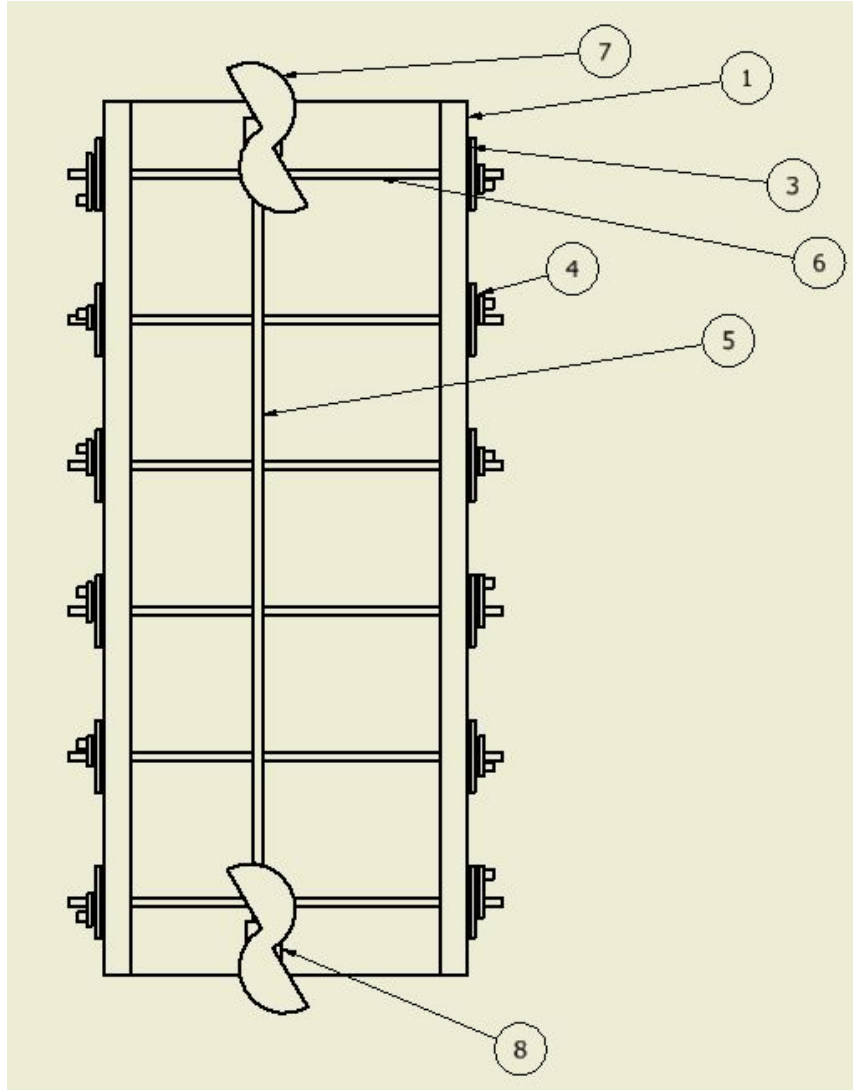


Figure 9. Top View Embodiment Drawing

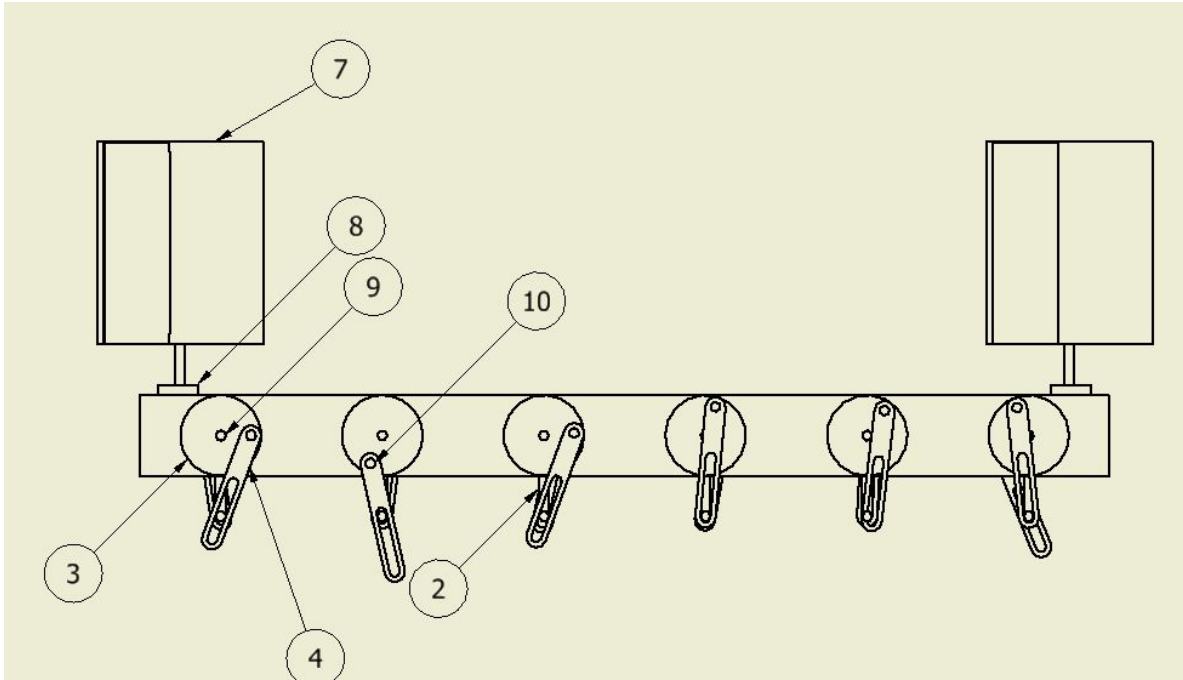


Figure 10. Side View Embodiment Drawing

## 4.2 Parts List

Tables 8 and 9 outline the parts as shown in the embodiment drawings and the raw materials and costs.

Table 8. Parts List

	Part Name	Source	Part #	Quantity	Unit Price	Price
1	Body	Custom	WWM2_001	1	~	~
2	Knee	Custom	WWM2_002	12	~	~
3	Wheel	Custom	WWM2_003	12	~	~
4	Leg	Custom	WWM2_004	12	~	~
5	Drive Shaft	Custom	WWM2_005	1	~	~
6	Wheel Axle	Custom	WWM2_006	6	~	~
7	VAWT	Custom	WWM2_007	2	~	~
8	Gear Box	Custom	WWM2_008	8	~	~
9	Ball Bearing	McMaster-Carr	6383K12	12	5.30	63.60
10	Sleeve Bearing	McMaster-Carr	6391K401	12	.69	8.28

Table 9. Raw Materials

	Material Name	Source/Part #	Use	Quantity	Unit Price	Price
1	Multipurpose 6061 Aluminum Rod 1/4" Diameter, 6 ft length	McMaster-Carr 8974K22	WWM2_002, WWM2_005, WWM2_006, WWM2_007	2	6.08	12.16
2	Hard High-Strength 7075 Aluminum, Short Rod, 2" Diameter, 1/4" length	McMaster-Carr 9035K41	WWM2_003	12	5.05	60.60
3	Used aluminum cans	Recycling	WWM2_007	2	~	~
4	Steel Plain Bore 14-1/2 Degree Spur Gear, 32 Pitch, 16 Teeth, 0.5" Pitch Diameter, 3/16" Bore	McMaster-Carr 6325K89	WWM2_008	8	15.30	122.40
5	Multipurpose 6061 Aluminum, 1/4" Thick, 4" x 48"	McMaster-Carr 9346K422	WWM2_004	1	31.24	31.24
6	Multipurpose 6061 Aluminum, U-Channel, 10" Base x 3-1/2" Legs 3 ft	McMaster-Carr 1630T45	WWM2_001	1	111.78	111.78
					TOTAL COST	410.06

### 4.3 Draft detail drawings for each manufactured part



Figures 11 through 16 are draft detail drawings for the drive shaft, wheels, legs, knees, body, and wind turbine.

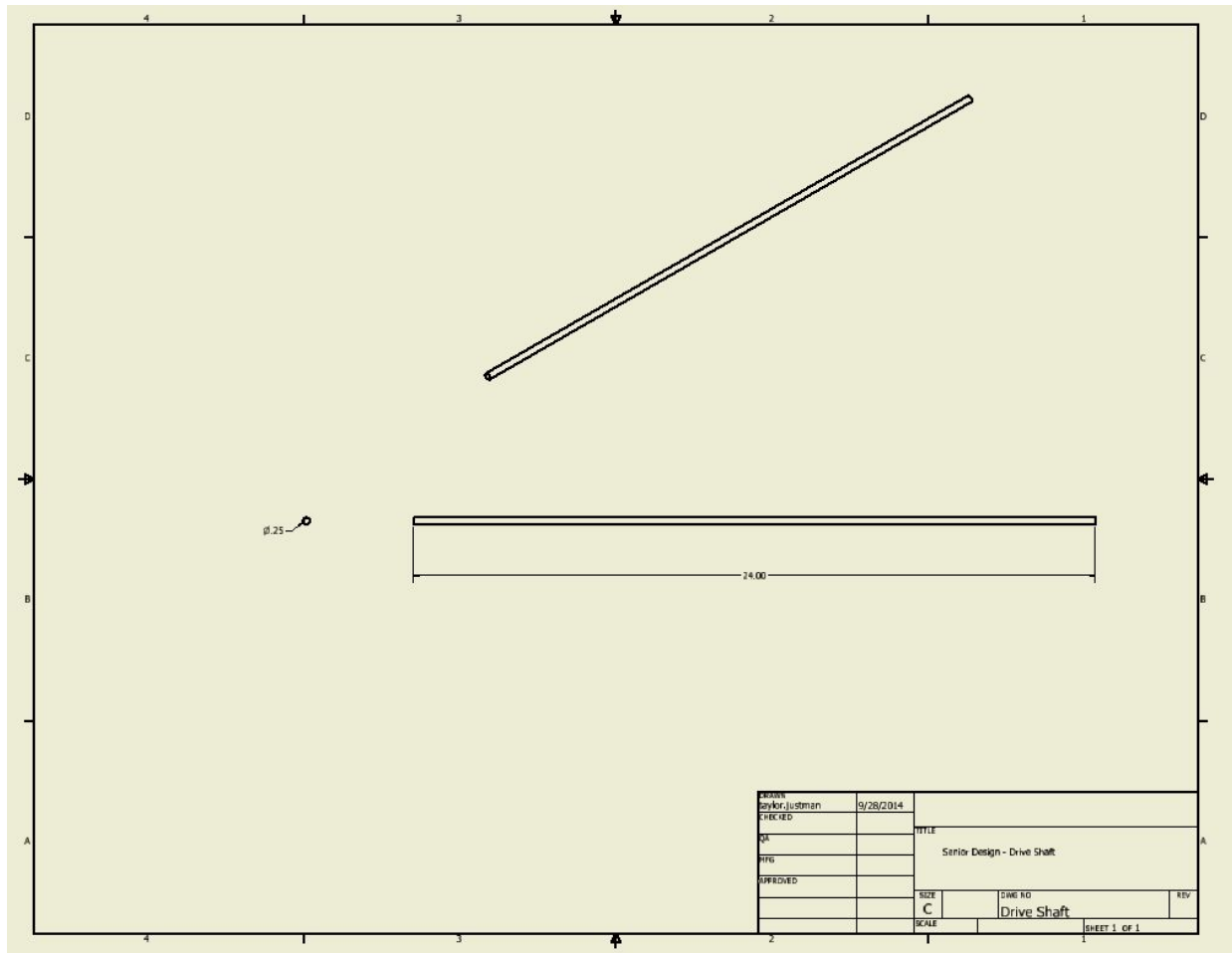


Figure 11. Drive Shaft Detail Drawing

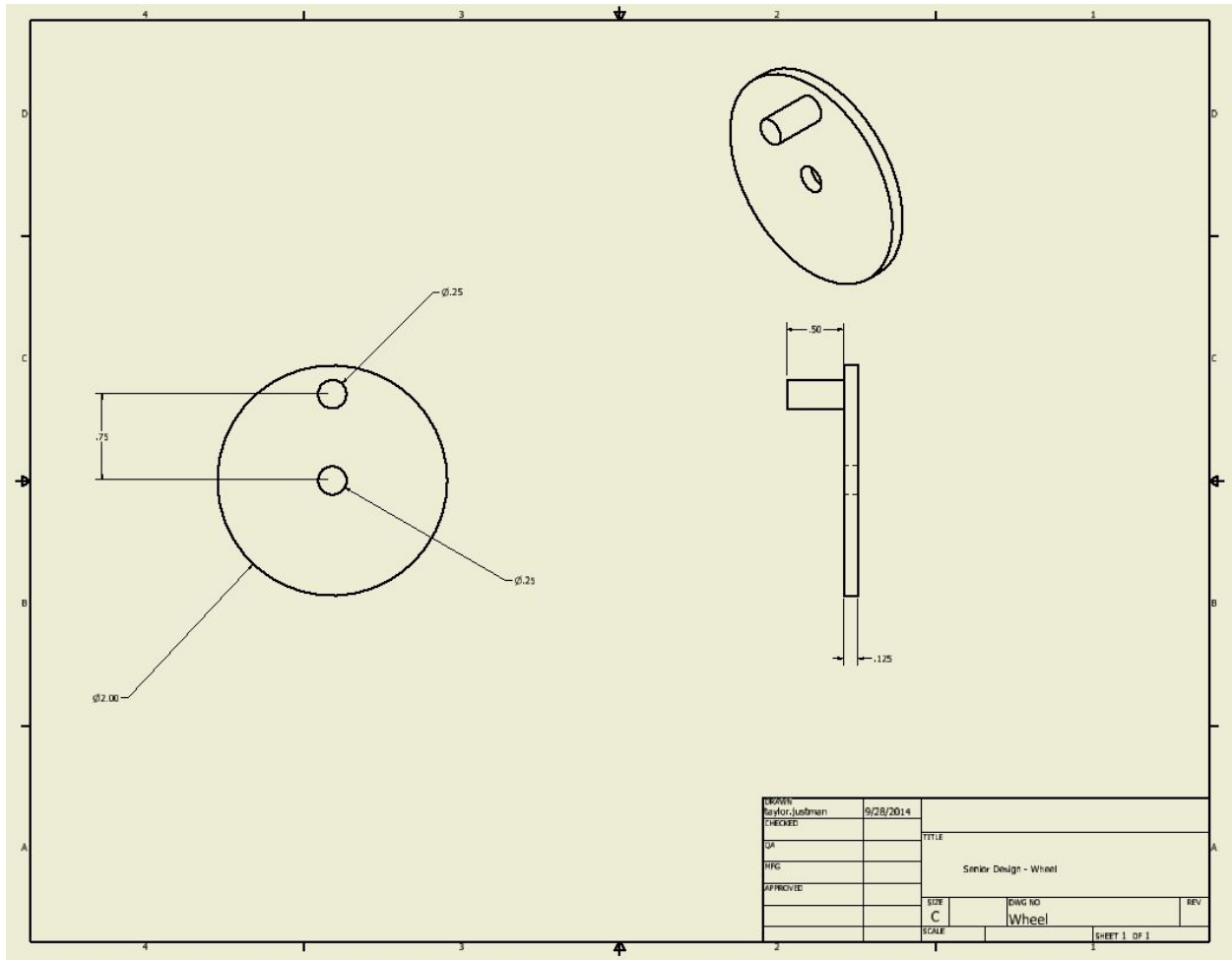


Figure 12. Wheel Detail Drawing

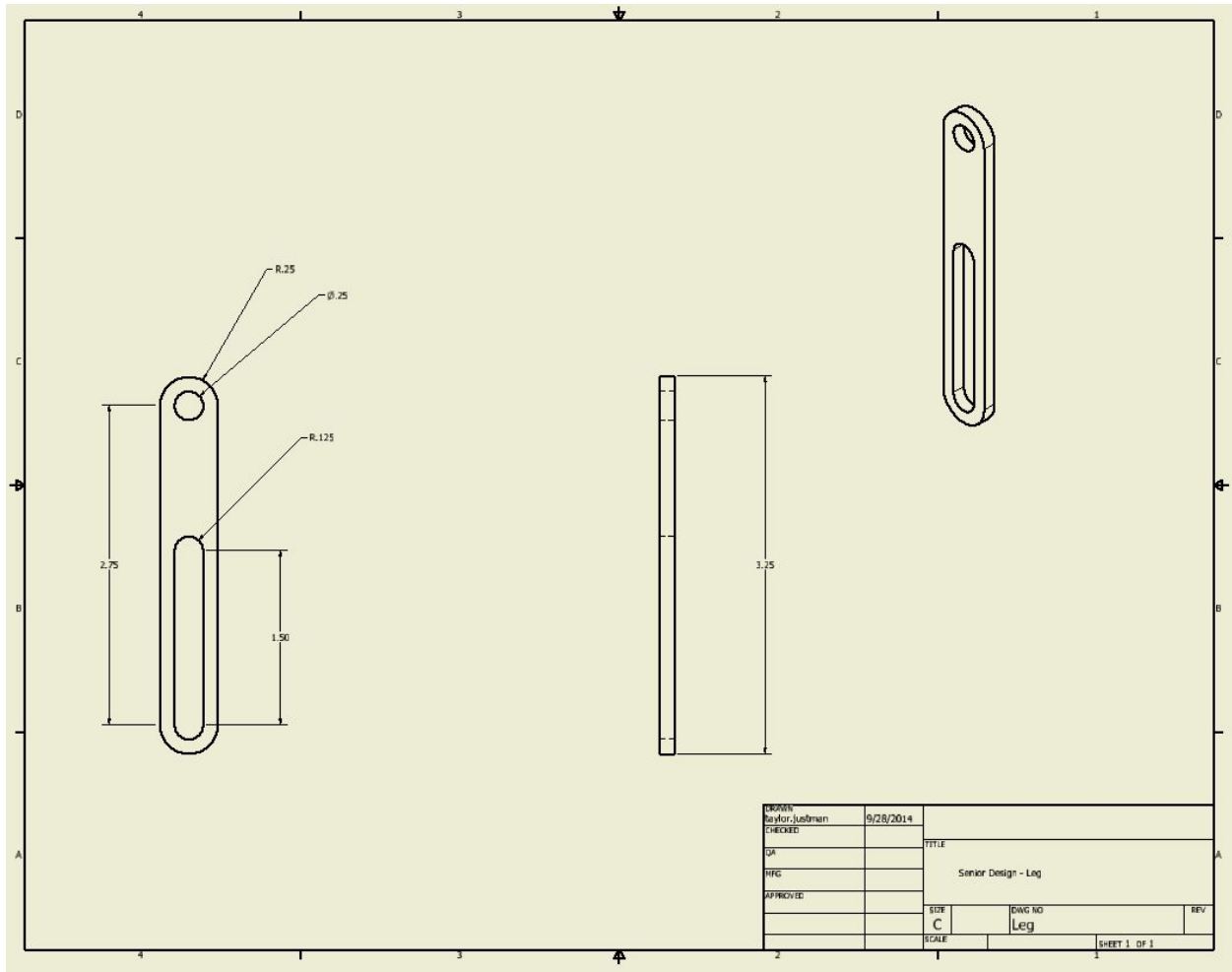


Figure 13. Leg Detail Drawing

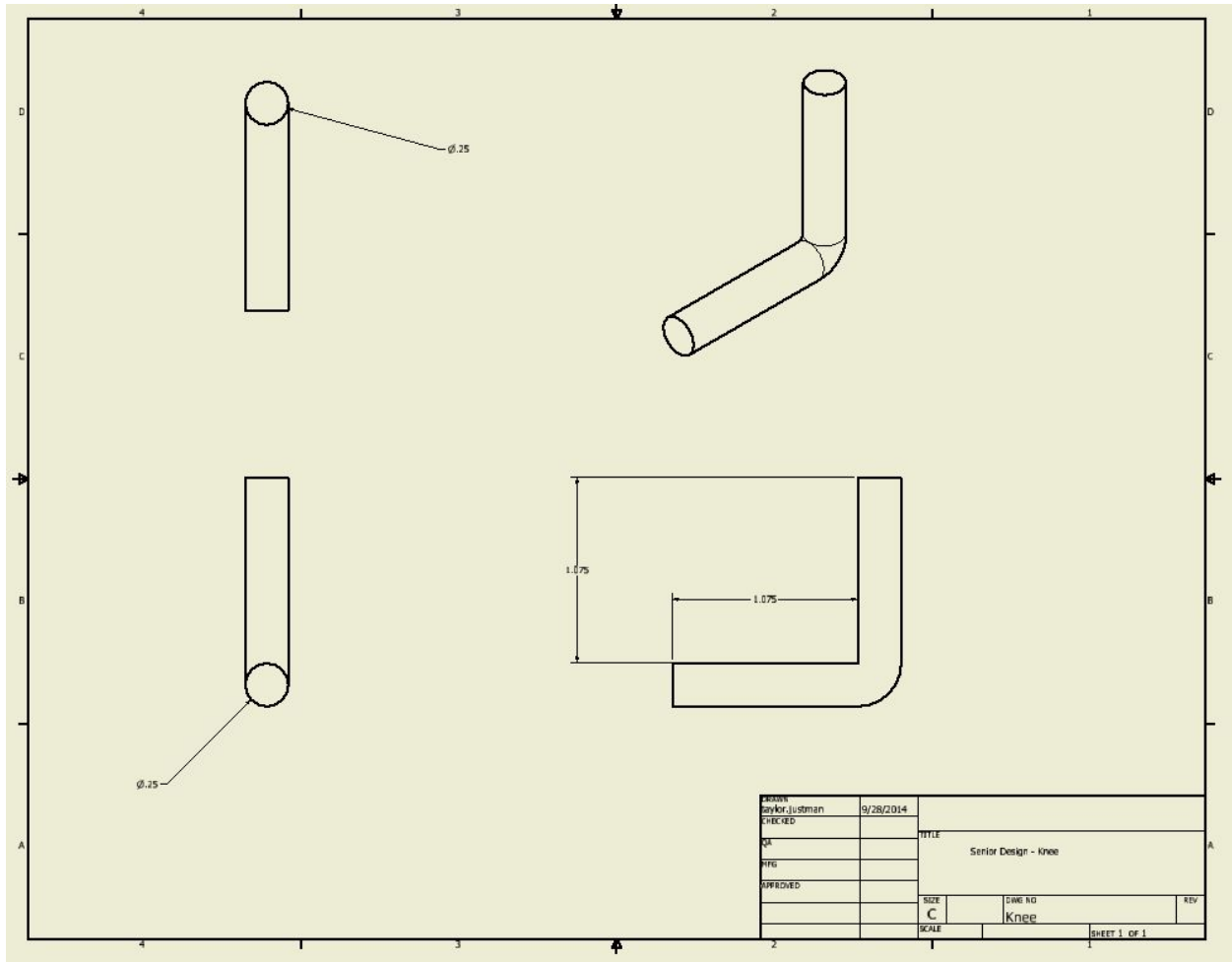


Figure 14. Knee Detail Drawing

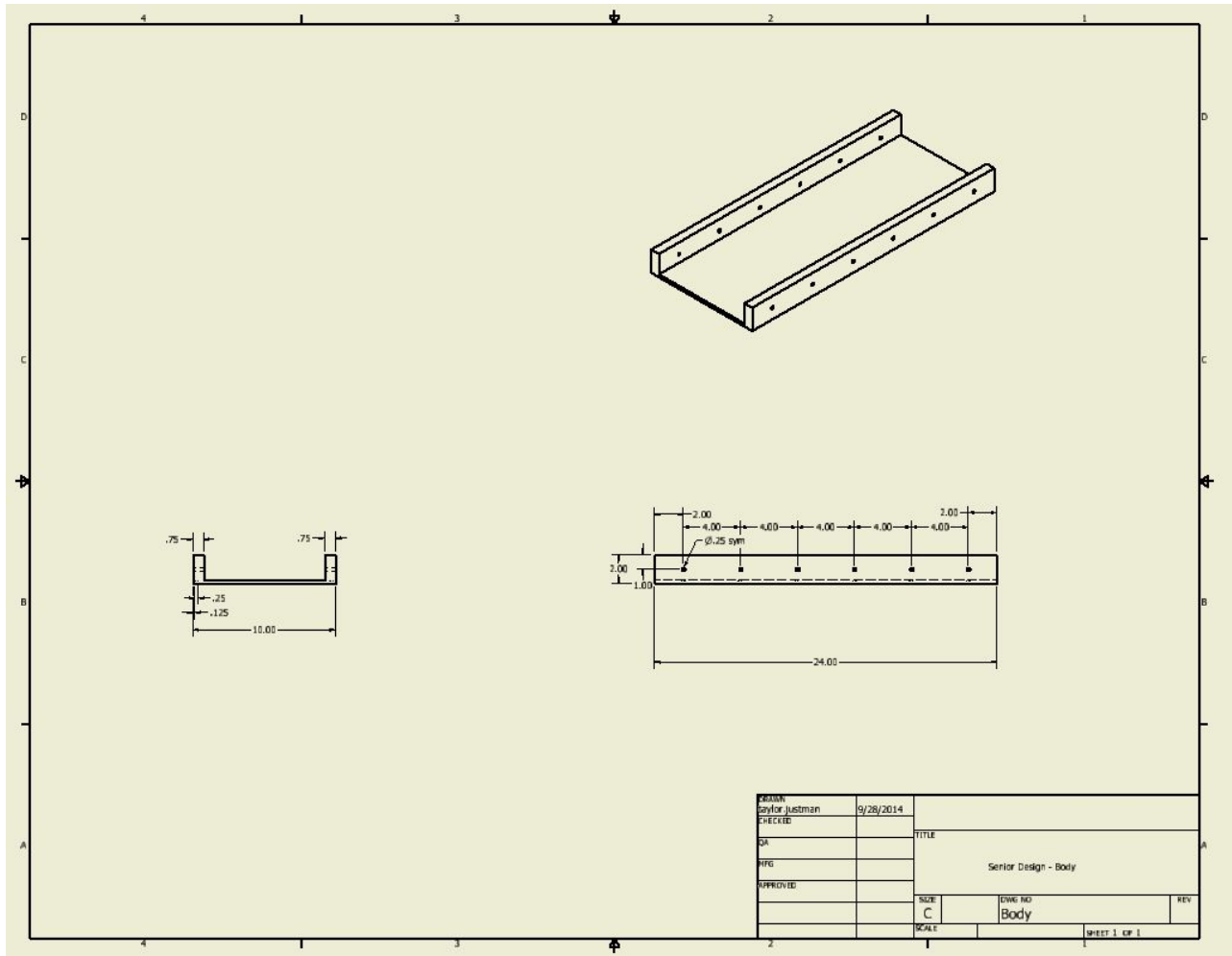


Figure 15. Body Detail Drawing

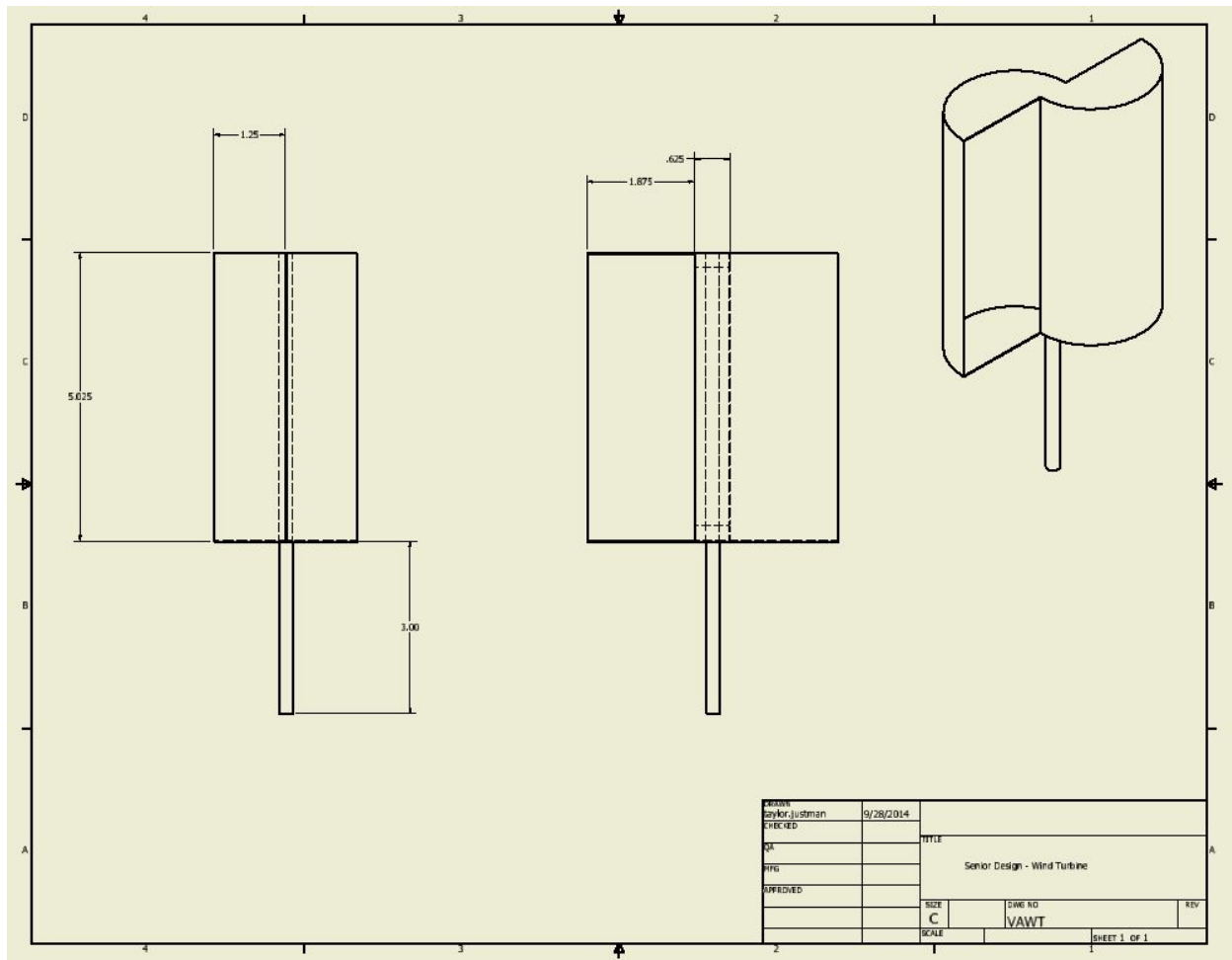


Figure 16. Wind Turbine Detail Drawing

#### 4.4 Description of the design rationale for the choice/size/shape of each part

**Body:** We were constrained by our 3' x 3' x 3' size parameters, so we decided to make the length of the body 2' long. We decided that this would give us the opportunity to add length in the future if need be, but would be a good starting point. Originally, we chose a width of 6", but when we started modeling it, it seemed too thin and when the machine is walking, might not be stable enough. We played around with the width and settled on 10" which will allow for more

stability and space for the bevel gear, drive shaft, and wheel axles. Since the bottom of the body is thin (weight savings), this increase in width should not add too much weight. The body will be aluminum like the U-bars from Machine Elements.

Wheel: From our decision to make the body 24" long, we wanted wheels that were proportional, at 2" diameter. Below, our analysis is shown for the spacing of the wheels, with 4" in between and 2" on each end. This will allow for uninterrupted leg motion, since the legs will be far enough apart to not hit each other, as well as increased stability since the legs are spaced out. Our original design called for 4 legs on each side (8 total), but we determined that there would not be enough legs on the ground at any given time to make sure that our machine will not fall over; therefore we increased the amount of wheels/legs to 6 on each side (12 total). The wheels are each  $\frac{1}{4}$ " thick aluminum to allow for weight savings. Wheels will be attached to the body using ball bearings since they allow for very little friction. Friction would oppose the torque generated by the wind turbine, and we need all the torque available for motion.

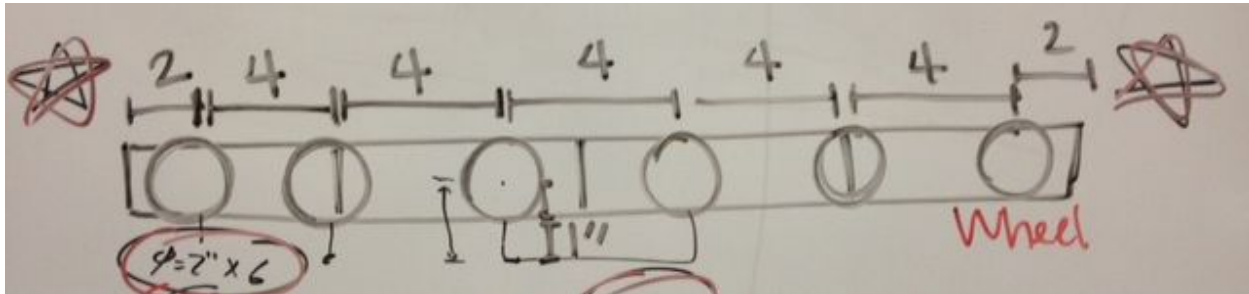


Figure 17. Wheel Design Rationale

Peg: We determined that the diameter of the aluminum peg (the peg holds the leg on) should be  $\frac{1}{4}$ " since that is a common diameter for our machine. The peg is located  $\frac{3}{4}$ " from the center of the wheel. The larger the distance of the peg from the center, the larger travel the leg will make since it is connected to the wheel at the peg. We want a large enough travel so the wind walking machine's motion is noticeable. We will have a sleeve bearing between the peg and the leg to allow for minimal-friction rotation.

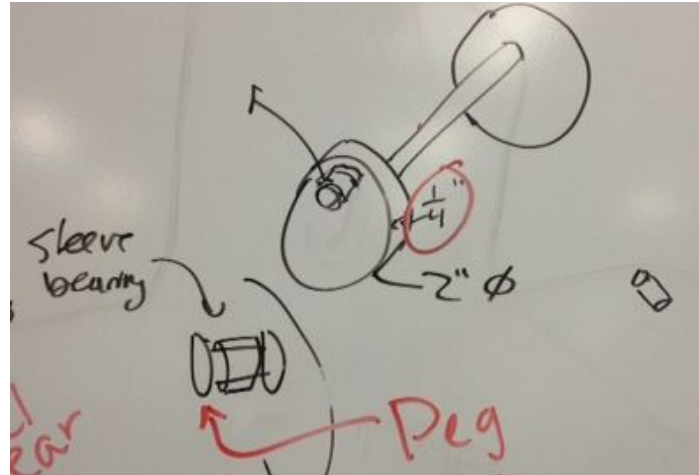


Figure 18. Peg Design Rationale

Leg: Each leg has a slot that we determined needs to be 1.5" long ( $y_2 - y_1$  in the picture). Shown below,  $y_1$  is the distance from the center of the peg to the bottom of the slot, and  $y_2$  is the distance from the center of the peg to the top of the slot. Since the distance from the center of the wheel to the center of the peg is  $\frac{3}{4}$ ", the length of the slot must be twice that. The hole at the top of the leg needs to fit the  $\frac{1}{4}$ " diameter peg, and the leg has a very small amount of other material since we want the legs to be very light. The bottom of the leg, or "foot", is rounded to allow for easy rotation when the leg is taking its step. We do not want the legs to slip against the surface it is walking over, so we will consider coating it or adding some type of rubber if this



problem occurs in the future. We will fabricate the legs from aluminum using the CNC mill. Aluminum is both light and recyclable.

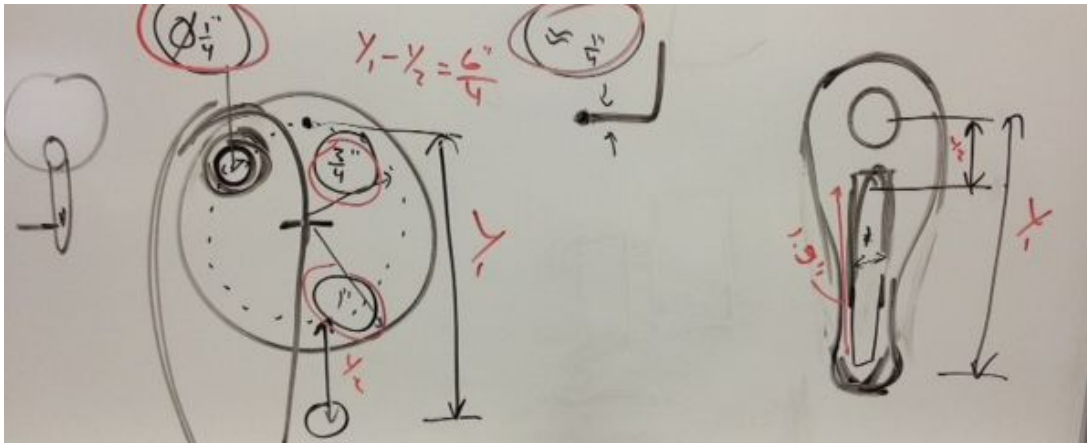


Figure 19. Leg Design Rationale

Knee: For consistency's sake, we made the vertical and horizontal lengths of the knee each 1", and the angle between them is 90°. The thickness/diameter is 1/4" for consistency with other dimensions. The horizontal part of the knee restrains the motion of the leg, and the vertical part connects it to the body. We can have a rubber cap on the end of the knee to make sure the leg does not slide off – it should not slide off since it is restrained by the peg/sleeve-bearing, but we will add a cap for extra safety. The knee will be made of aluminum since it is recyclable and light.

Turbine blade: After doing research, we decided to make a Savonius wind turbine design (shown below). We will use aluminum cans cut in half to make the two semi-circle sections, since our project must be made out of 100% recyclable materials. This will also be cheaper than 3D-printing the wind turbines, which we had planned on originally. In contrast, a helix design would give us constant power, whereas the design we chose might speed up and slow down as the blades turn since they catch air the most when arranged the way in the first picture below. This might make our machine "chug", as it moves fast and then slower, fast, then slower. If this interrupts motion, we plan to create an alternative helix design, which we may be able to 3D-print. For now, we have chosen the simpler, less expensive approach.

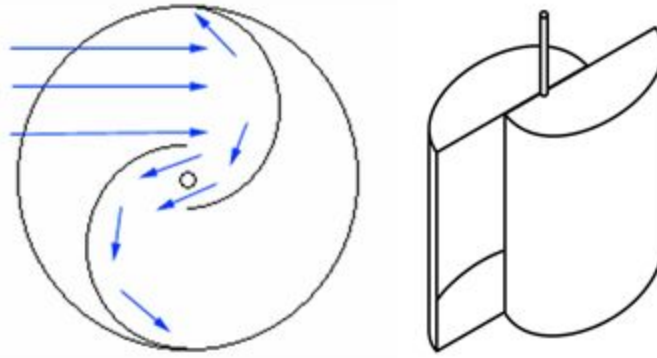


Figure 20. Wind Turbine Design Rationale

Worm gear: We will use a worm gear to transfer the motion from the turbine to the drive shaft, which will act as the worm in the drawing below. We had originally planned to use a bevel gear, but after some research decided a worm gear was more of what we were looking for. We had been trying to make changes to existing bevel gear designs which ended up becoming a worm gear.

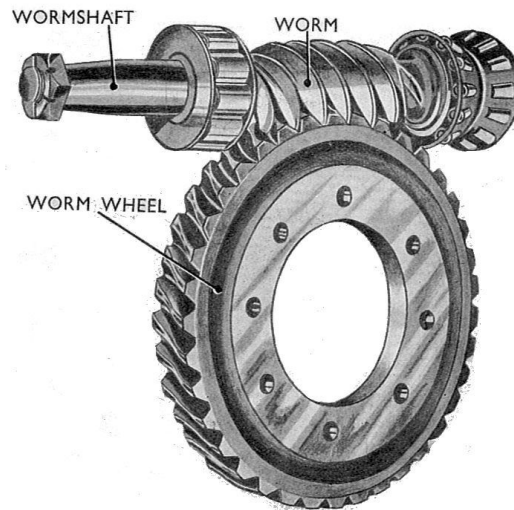


Figure 21. Worm Gear Design Rationale

Drive shaft: The drive shaft will have threads so that the two turbines on each end of the walking machine (front and back) turn the drive shaft. It will essentially be a very long “worm” for the worm gear to turn. It is 24” long, like the machine itself. It will be made of aluminum since it is light and recyclable.

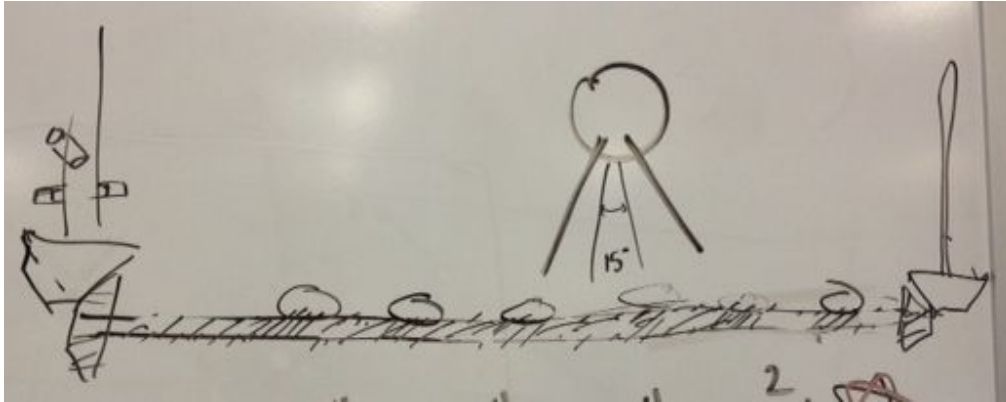


Figure 22. Drive Shaft Design Rationale

Wheel axle: The wheel axles can be seen above, and will also be threaded like the drive shaft. The turning drive shaft from the turbines will turn each wheel axle simultaneously, which then rotates each wheel at the same rotational speed. Therefore, each leg will move in step. Like the drive shaft, it will also be made of aluminum for weight savings and recyclability.

## 5 Engineering analysis

### 5.1 Engineering analysis proposal

### 5.1.1 A form, signed by your section instructor

Figure 23 is the Analysis Tasks Agreement signed by Dr. Mary Malast and all group members.

#### ANALYSIS TASKS AGREEMENT

PROJECT: Wind Walking Machine      INSTRUCTOR: Jakiela

NAMES: Taylor Justman, Sam Lazechko, Isaac Goldenthal, Will Nocka

The following engineering analysis tasks will be performed:

- Analyze torque generated from wind on each turbine, research alternatives
- Determine possible materials (recyclable)
- Make a parts list
- Research 3D printing
- Make a CAD model

The work will be divided among the group members in the following way:

TAYLOR: Determine possible materials (recyclable) TJ

SAM: Research 3D printing SL

ISAAC: Analyze torque generated from wind on each turbine IG

WILL: Analyze torque generated from wind on each turbine WU

ALL: Make a CAD model, make a parts list

Instructor signature: Mary Malast; Print instructor name: Mary Malast

(Group members should initial near their name above.)

Figure 23. Analysis Tasks Agreement

## 5.2 Engineering analysis results

**5.2.1 Motivation. Describe why/how the before analysis is the most important thing to study at this time. How does it facilitate carrying the project forward?**

Our pre-prototype studies depended on our analysis of how torque is generated from wind by the turbine, and researching different types of turbines and materials for the entire machine. After we generated an early version of our working prototype, we tested the physical machine to see how much torque was actually generated. Both analyses facilitated carrying the project forward because our biggest problem with this project is generating power from wind. We need to maximize wind power and minimize the weight of our machine, which is why we also needed to do research on lightweight recyclable materials.



**Figure 24. Early Version of Machine**

Figure 24 shows a very early version of our wind-walking machine, made of Legos. We used this version to determine that our system of legs and wheels would be physically feasible. This version did not help us much with analysis of the torque generated by the wind turbine, since there was so much friction between the parts.

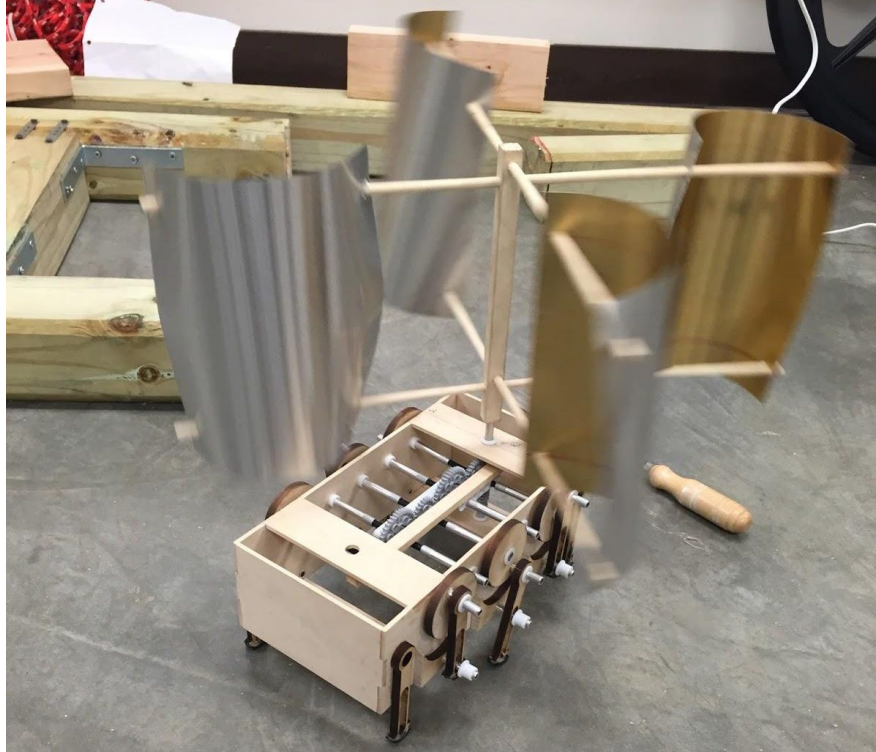


Figure 25. Beginning Working Prototype

Figure 25 shows our beginning working prototype, made of a basswood, aluminum, and Lego gears. We used this model for our engineering analysis, since it is very similar to what our working prototype will be.



### 5.2.2 Summary statement of analysis done. Summarize, with some type of readable graphic, the engineering analysis done and the relevant engineering equations

Our pre-prototype analysis determined the amount of power we could get per unit turbine area. Power from a wind turbine can be determined by the equation:

$$P = C_p \cdot .5 \cdot A \cdot \rho \cdot U^3$$

where  $C_p$  = Coefficient of Power = 0.3

$P$  = Power

$U$  = wind speed = 5 m/s

$\rho$  = Air Density = 1.2922 kg/m<sup>3</sup>

$A$  = Turbine Cross Sectional Area

Using this formula, the power per unit area can be calculated as

$$P/A = .3 \cdot .5 \cdot 1.2922 \cdot 5^3 = 24.2 \text{ W/m}^2 = .00242 \text{ W/cm}^2$$

The second part of the analysis was testing the prototype and modifying the turbine to maximize power. Our initial savonius turbine had several drawbacks. It stalled when it was not perpendicular to the wind and it did not supply a large amount of power. We were able to solve these problems by moving the blades farther from the shaft to increase the torque supplied by the wind, and by adding two blades so that there would always be a blade facing the wind.

### 5.2.3 Methodology. How, exactly, did you get the analysis done? Was any experimentation required? Did you have to build any type of test rig? Was computation used?

We performed the analysis by creating a lego model of our design. We were able to quickly create the model using only lego parts, as gears, axles, and body pieces were pre-fabricated. First, we built a single axle with wheels and legs, connected to a turbine. After this prototype proved successful, we upgraded our lego model to full scale, by adding two additional axle, wheel, and leg sets. We experimented with legos because they were readily available and showed that even with a lot of added friction, our design was feasible.

Next, we built our working prototype. Our first turbine model is shown below in Figure 26.

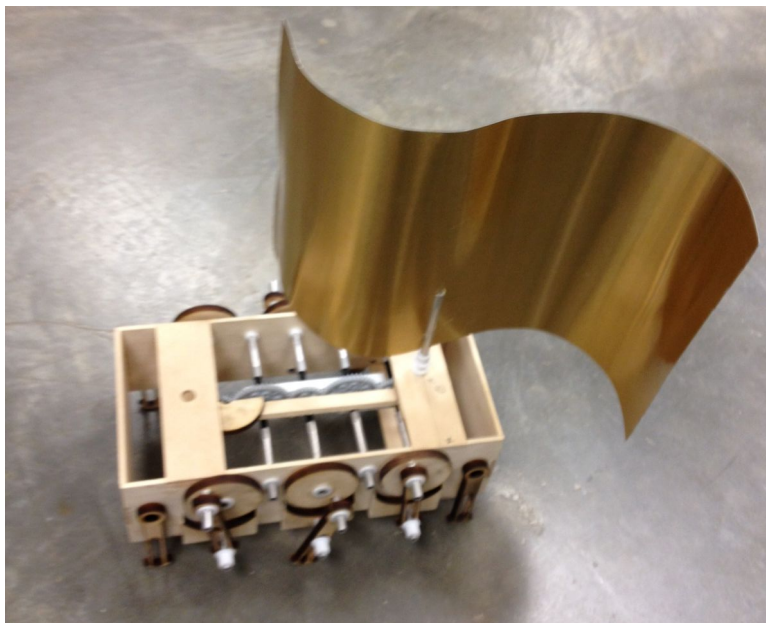


Figure 26. First Turbine Model

From experimenting with this turbine, we realized that the Savonius design was not giving us enough power to get the machine to take a step. After more research, we determined the turbine shown in Figure 2 would give us more power since there would be much more surface area available. Using our power per unit area of  $24.2 \text{ W/m}^2$ , and our new area of  $7\text{in} \times 8\text{in}$  ( $0.036\text{m}^2$ ), the power available is  $24.2\text{W/m}^2(0.036\text{m}^2)=0.8712\text{W}$ .



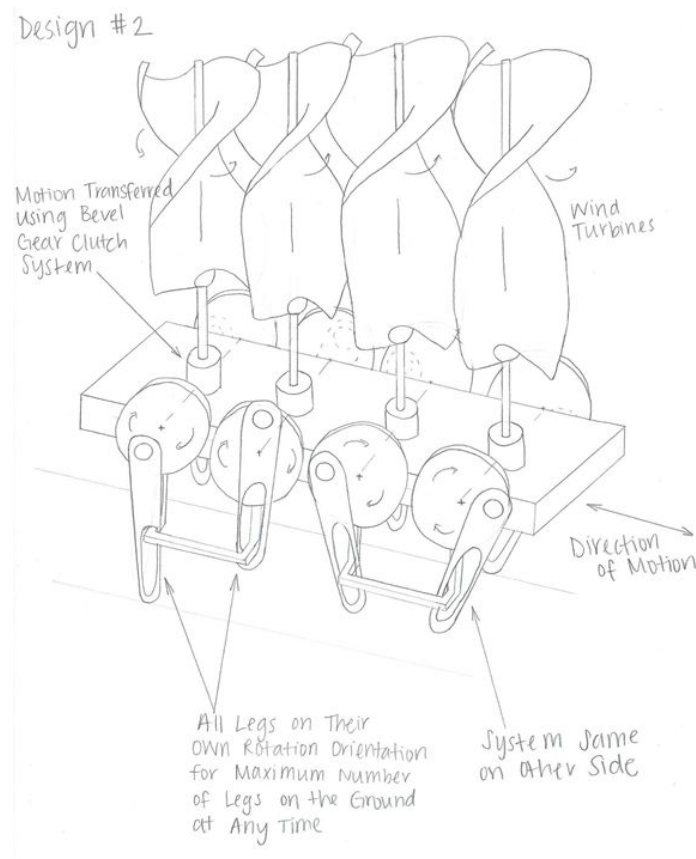
#### 5.2.4 Results. What are the results of your analysis study? Do the results make sense?

The first lego model (with only 2 legs) worked well, as it was easily powered by wind power. Unfortunately, the second lego model did not operate properly. We were able to easily rotate the turbine and power the legs by hand, but not with wind power. However, we determined that this was due to increased friction between the lego parts. With higher quality bearings and axles, we do not believe this will be a problem.

Then we made our prototype. The increased quality of axles and bearings, as predicted, allowed the legs to walk much more easily. However, there are still a few issues with the axles. They flex easily, making a weaker mesh between the gears. This needs to be fixed to ensure that no power from the turbine is lost. Additionally, the first turbine we built proved ineffective. A simple "S" curve, it did not provide enough torque to move the machine. Our second turbine design solved this problem. We increased the number of sails from 2 to 4, and used dowel rods to place them farther away from the wind turbine axis. The increase in the number of sails allows a more consistent power output from the turbine. Placing the sails farther away from the axis created a greater moment arm, and thus more torque to drive the legs. After completing the above changes, our machine successfully walked.

**5.2.5 Significance. How will the results influence the final prototype? What dimensions and material choices will be affected? This should be shown with some type of revised embodiment drawing. Ideally, you would show a “before/after” analysis pair of embodiment drawings.**

The results from our working prototype analysis will influence the final prototype in several ways. First, the dimensions of the turbine have already been changed, and we will make further adjustments to increase the area and distance from the axis to allow for more torque. The material of the turbine is currently thin sheet metal, and we plan to experiment with adding weight to the machine so that the legs do not slip against the ground in strong winds.



**Figure 27. "Before" Embodiment Drawing**

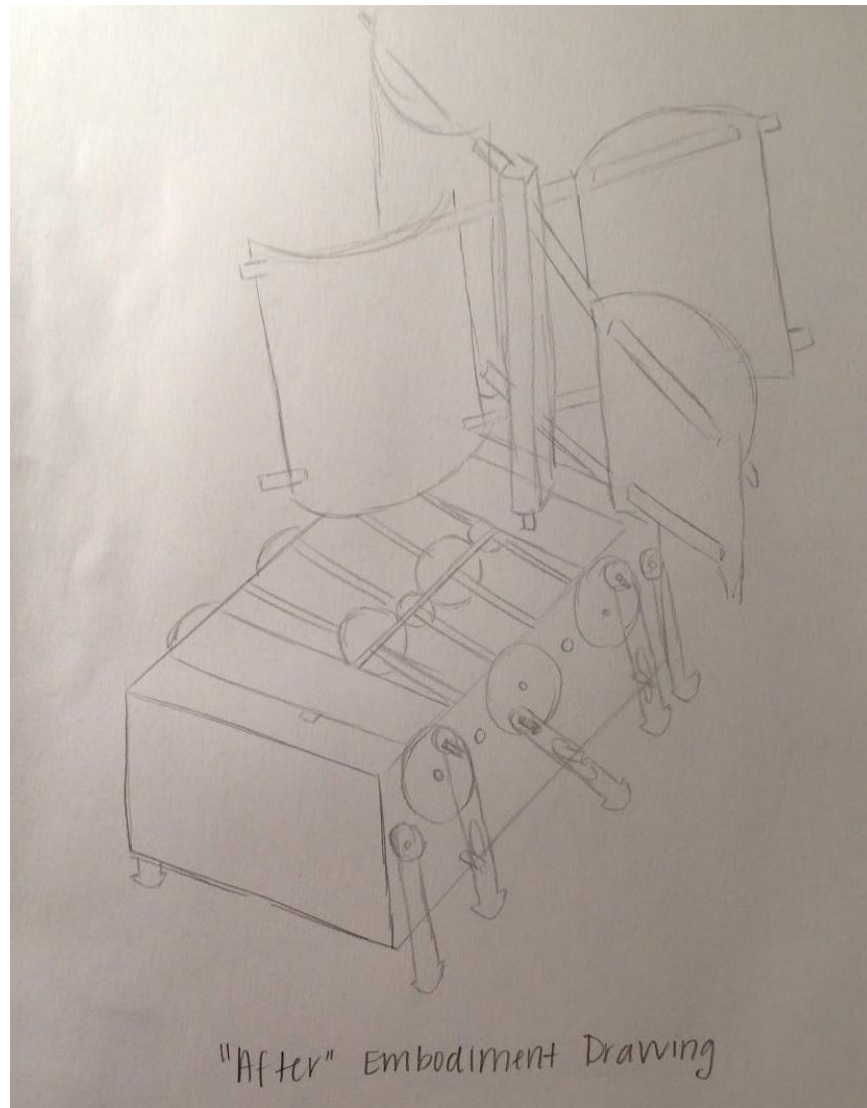


Figure 28. "After" Embodiment Drawing

Figures 27 and 28 show our "before/after" analysis, which includes a box-shape, extra legs for support, and a completely different turbine design. The Savonius design proved inadequate when actually implemented, and we plan to adjust the working prototype turbine we have now to make it sturdier for our final prototype.

### **5.2.6 Summary of code and standards and their influence. Similarly, summarize the relevant codes and standards identified and how they influence revision of the design.**

There are few codes and standards relating to the design of small-scale wind-powered walking machines. However, the topic of wind turbine design has been researched in great depth. We knew we wanted to use a vertical axis wind turbine so that the machine could be powered by wind from any direction. Vertical axis turbines are divided into two main categories: lift and drag type rotors. Lift type rotors use two or three arm vertical airfoils to harness the power of the wind. They are more efficient than drag type rotors but cannot self-start. Drag type turbines, on the other hand, are less efficient but are capable of self-starting.

Building a lift type rotor would require advanced computational fluid flow analysis and high precision manufacturing techniques. In contrast, the drag type turbines are easy to prototype and test. Also, we need the turbine to be self-starting. This made a drag type turbine the clear choice. We began with a simple S-curve of sheet metal, but after reading related literature on drag type turbines, switched to a 4 rotor turbine with the rotors farther away from the axis of rotation. Increasing the moment arm of the rotors increased the torque available to drive the machine. With the decrease in friction throughout the drivetrain and leg linkages, the machine was able to walk. Moving forward, we will continue to research and develop our turbine to achieve maximum efficiency while still being capable of self-starting.

## 6 Working prototype

### 6.1 A preliminary demonstration of the working prototype.

Our preliminary demonstration was performed for Professor Jakiela on November 5.

### 6.2 A final demonstration of the working prototype.

Our final demonstration was performed for Professor Jakiela on November 19.

### 6.3 At least two digital photographs showing the prototype

Figures 29 and 30, below, are digital photographs showing the prototype from side and top views.



Figure 29. Digital Photograph of Prototype - Side View

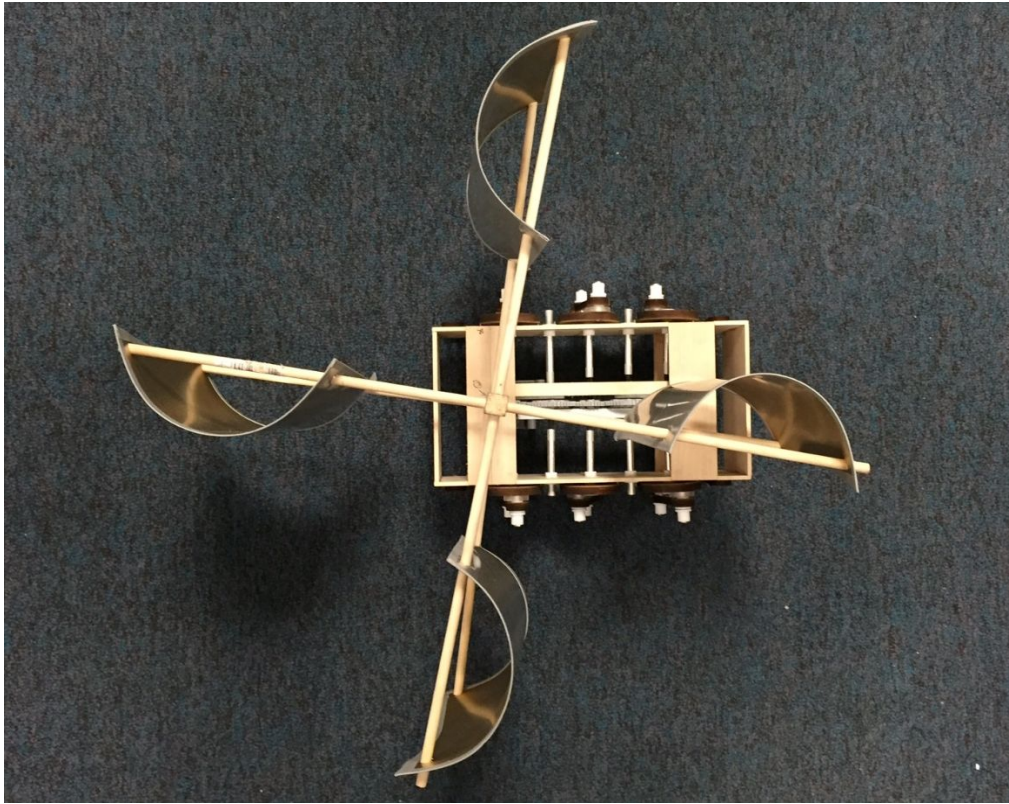


Figure 30. Digital Photograph of Prototype - Top View

## 6.4 A short video clip that shows the final prototype performing

The following video clip, Figure 31, shows the final prototype performing. First in normal time, we see the wind walking machine take a step. The video is sped up to observe more clearly the movement of the legs. This is the Youtube link:

[https://www.youtube.com/watch?v=jU\\_3k8pWjnA](https://www.youtube.com/watch?v=jU_3k8pWjnA).

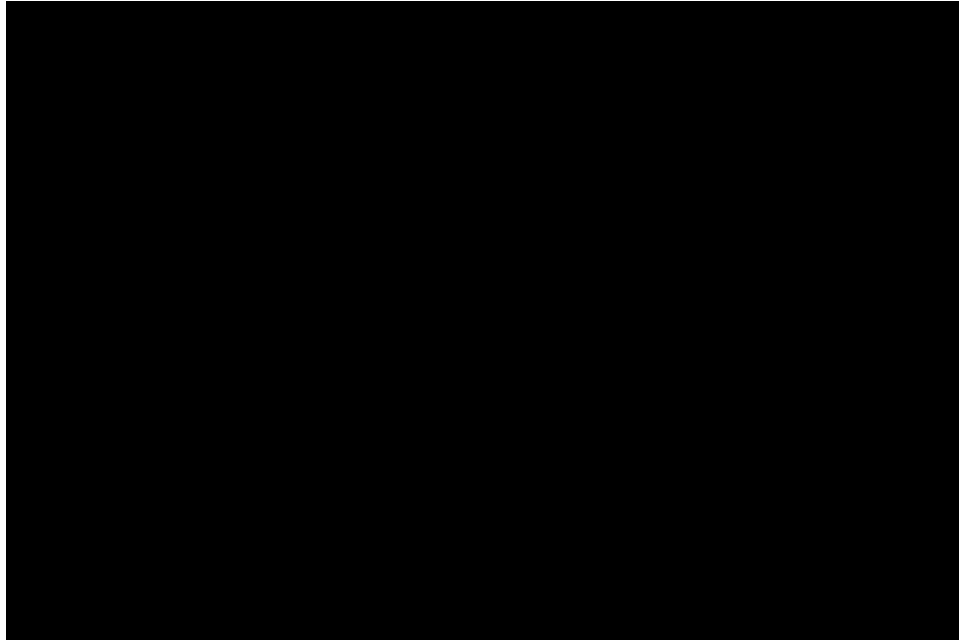


Figure 31. Prototype Performance Video



## 6.5 At least four (4) additional digital photographs and their explanations



Figure 32. Close-Up of Gears and Axles

Figure 32 shows a close-up view of our gears and axles system. The large gears are used to connect rotary motion to the small gears, which turn the legs. The white bar on the close side of the gears is a Lego piece that keeps the axles consistent and straight. Since our axles are made of black Lego axles to fit the gears and aluminum tubes to fit the bearings, we needed to use Loctite to glue them together. The white Lego piece keeps the black Lego axles from bending under high torque, which keeps the gears meshed and eliminates the gears jumping out of place.



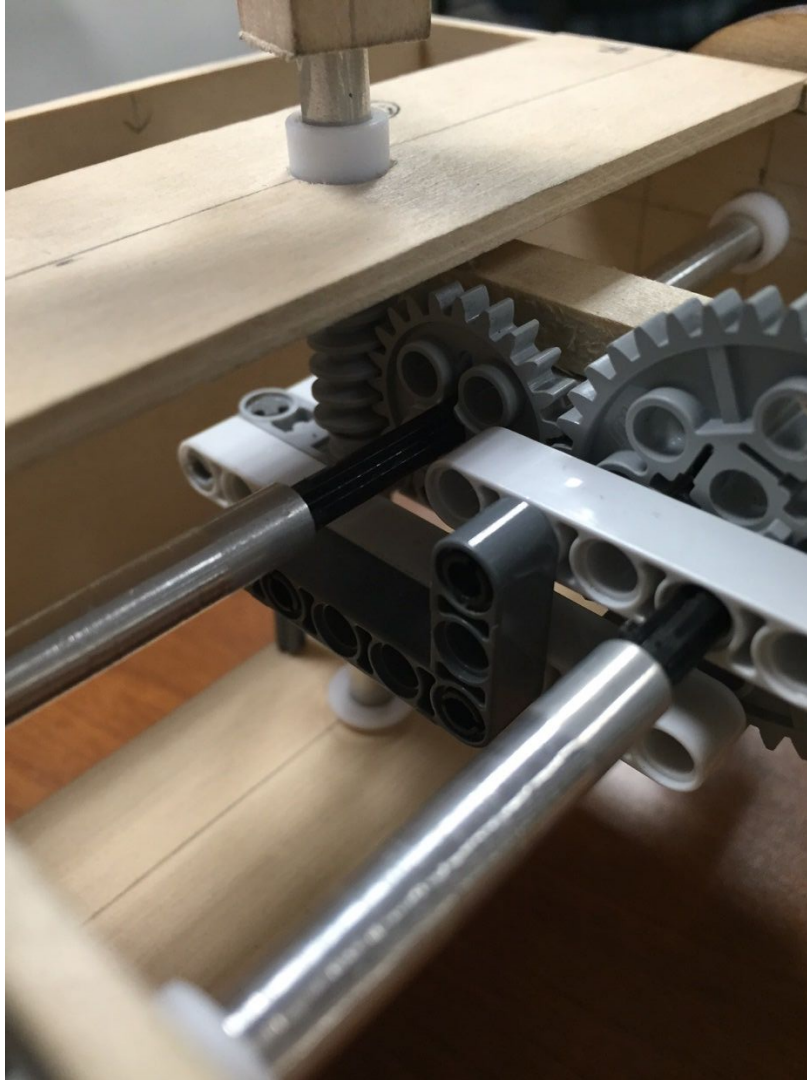


Figure 33. Worm Gear and Support

Figure 33 shows the worm gear on the shaft of the turbine meshed with the first gear. Under high torques, our shaft was bending which was dislocating the worm gear from the first gear. In order to combat this, shown to the left/behind the worm gear in Figure 33, is a Lego support which kept the shaft from bending away from the first gear. This was a major change from our initial prototype, where the high torque on the turbine from the wind bent the shaft and worm gear out of place. With the addition of the worm gear support, we eliminated this issue in our final prototype, making the machine fully capable of walking all 4 meters.

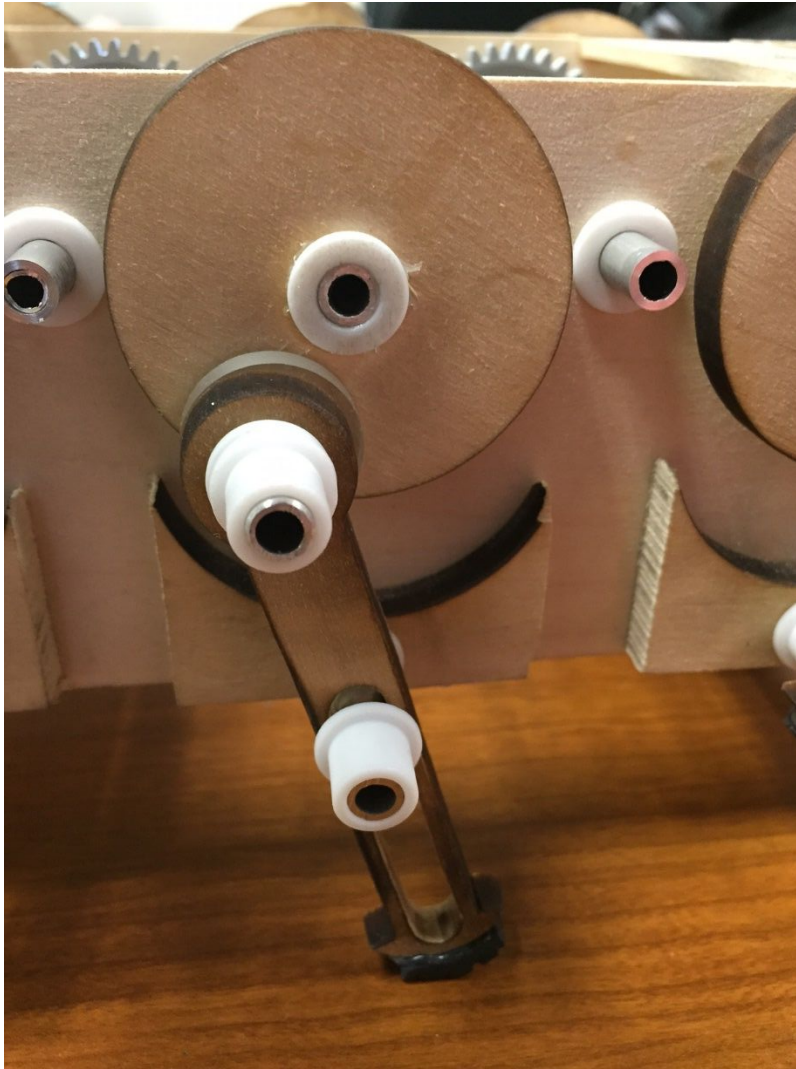


Figure 34. Close-Up of Leg Mechanism

Figure 34 shows a close-up view of the leg mechanism in its low phase in the rotation. Shown above, the “wheel” is rotating counter-clockwise, which will allow the leg to push off the ground, which will allow the machine to take a step to the right. The white flanged bearings were used to provide low friction spacing to allow the leg to rotate perfectly upright. Shown on either side of the wheel are the aluminum tubes in bearings, which allows the second and fourth gears to spin freely in place. These gears are used to keep the first, third, and fifth gears in sync, which allows for three legs to take a step at a time.

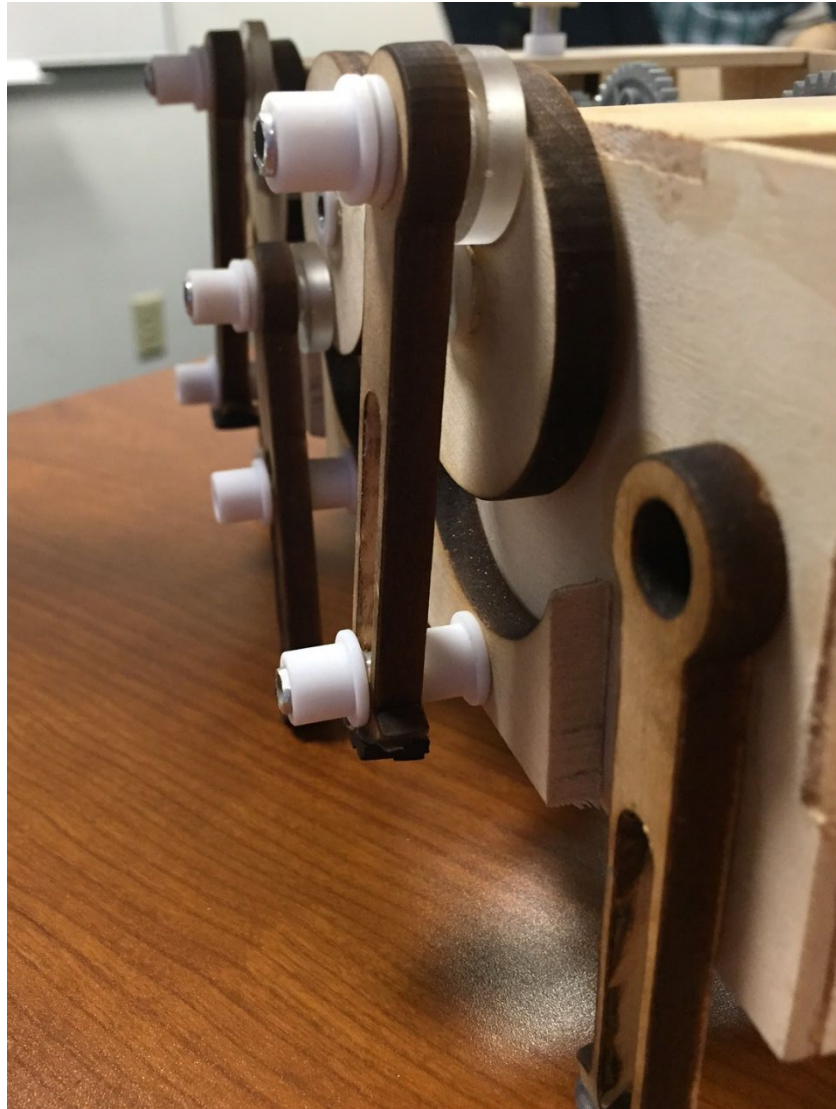


Figure 35. Clear View of Laser Cut Pieces

As shown above in Figure 35, we used laser cutting to precisely cut our wheels and legs. This is much more accurate than we ever could have been by using band saws or hand tools, and we were appreciative to have access to this through the Art School. Unfortunately, due to the angle of the laser, the cuts were not perpendicular to the front face of the bass wood. This can be seen in Figure 35 at the very top of the leg, where the cut is slightly angled from 90 degrees. This ended up not being an issue for us since the perpendicularity was not critical. However, it is quite interesting and is something we had not considered before deciding to use laser cutting for this prototype.

## 7 Design documentation

### 7.1 Final Drawings and Documentation

#### 7.1.1 A set of engineering drawings that includes all CAD model files and all drawings derived from CAD models. See Appendix C for the CAD models.

Figures 36 through 50 show the engineering drawings for all CAD models used in the fabrication of the wind walking machine.

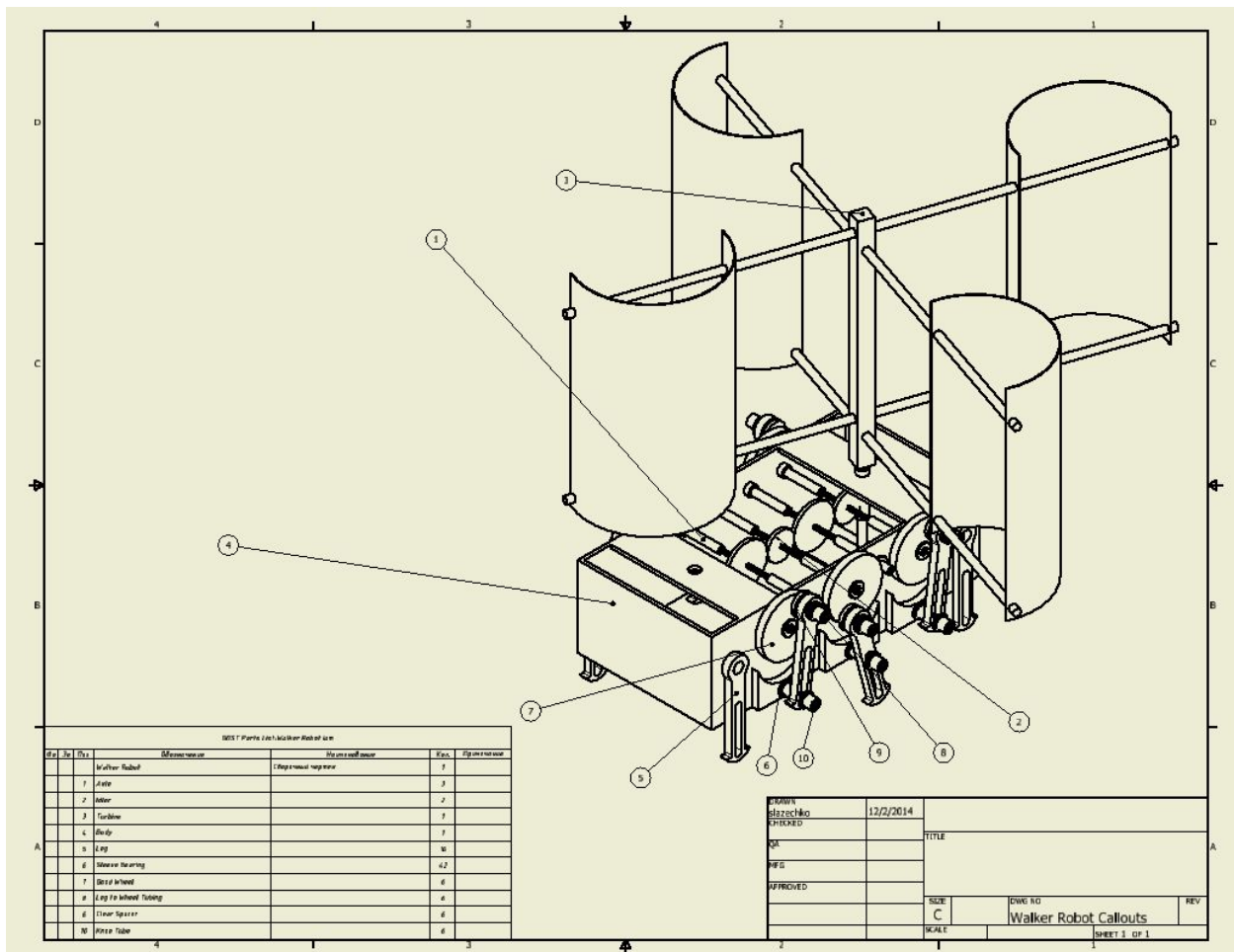


Figure 36. Assembly Drawing with Callouts

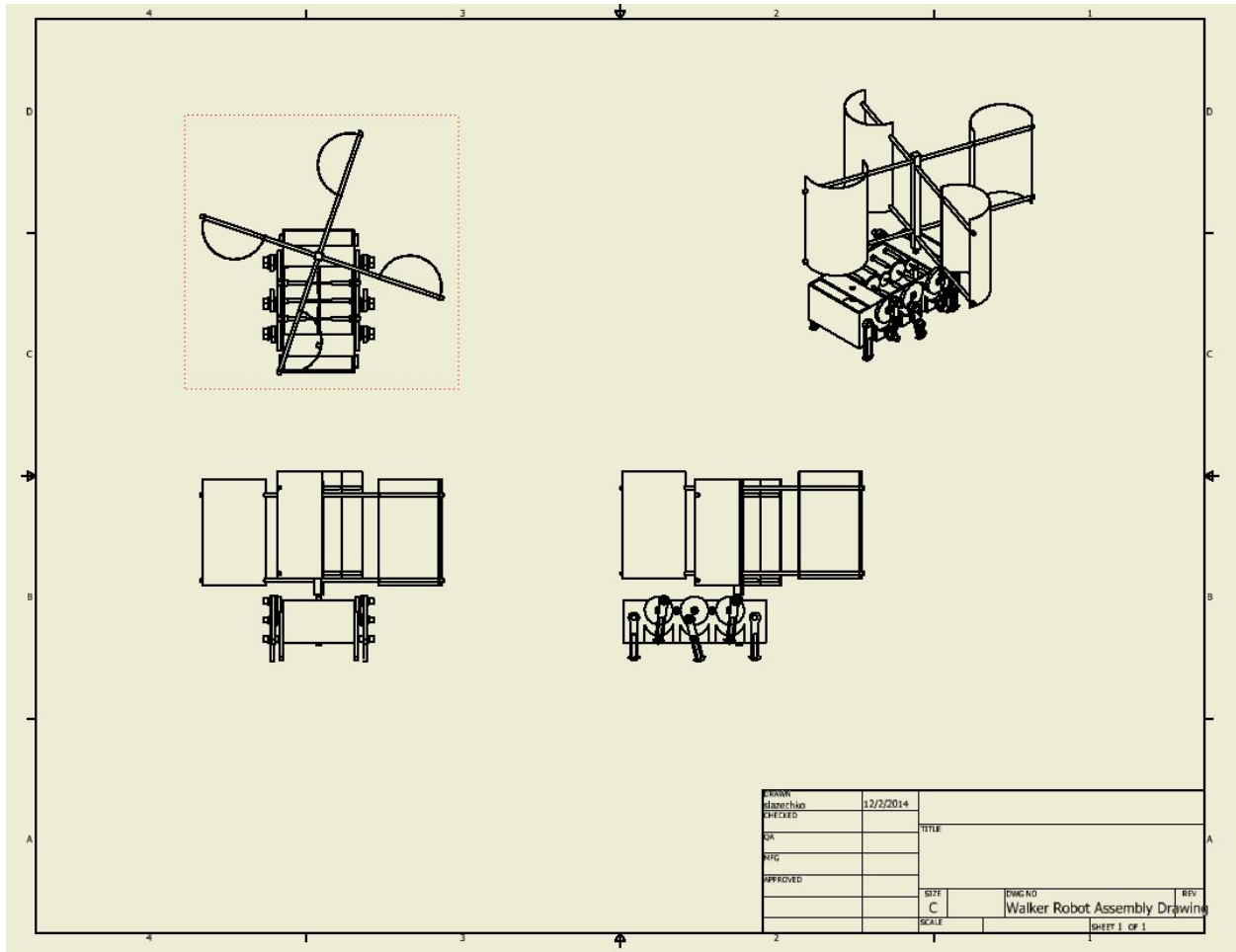


Figure 37. Assembly Drawing All Views



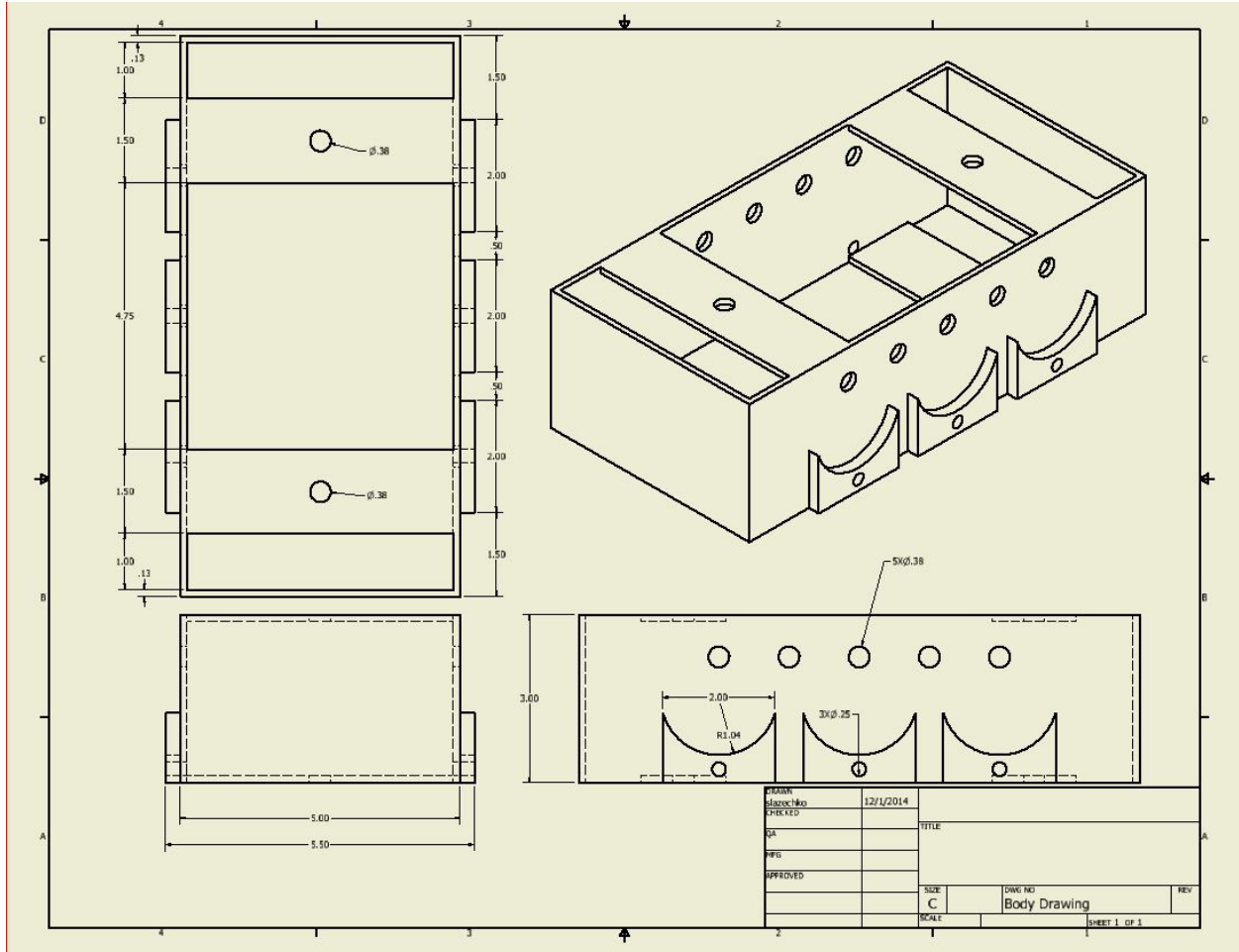


Figure 38. Body Drawing

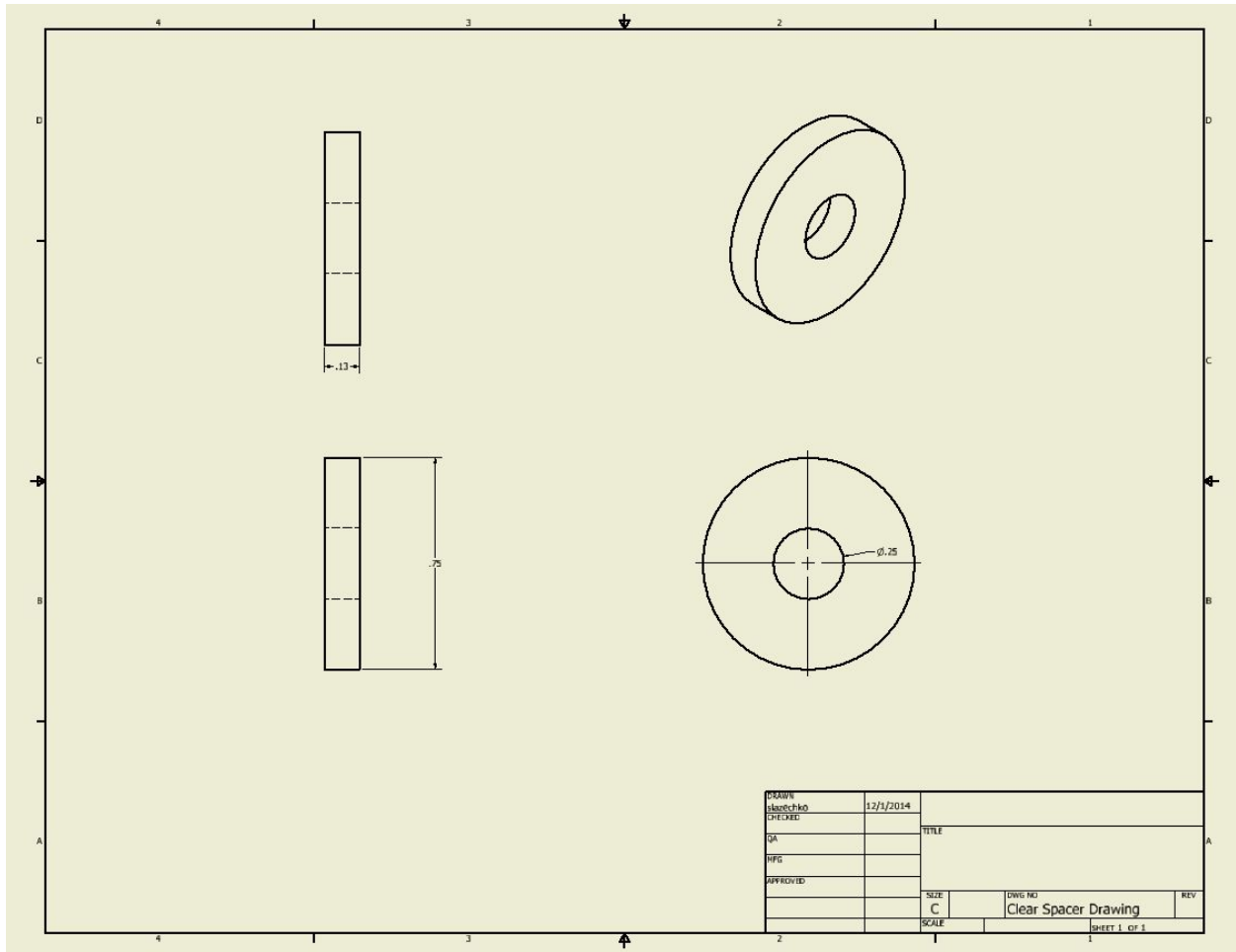


Figure 39. Clear Spacer Drawing

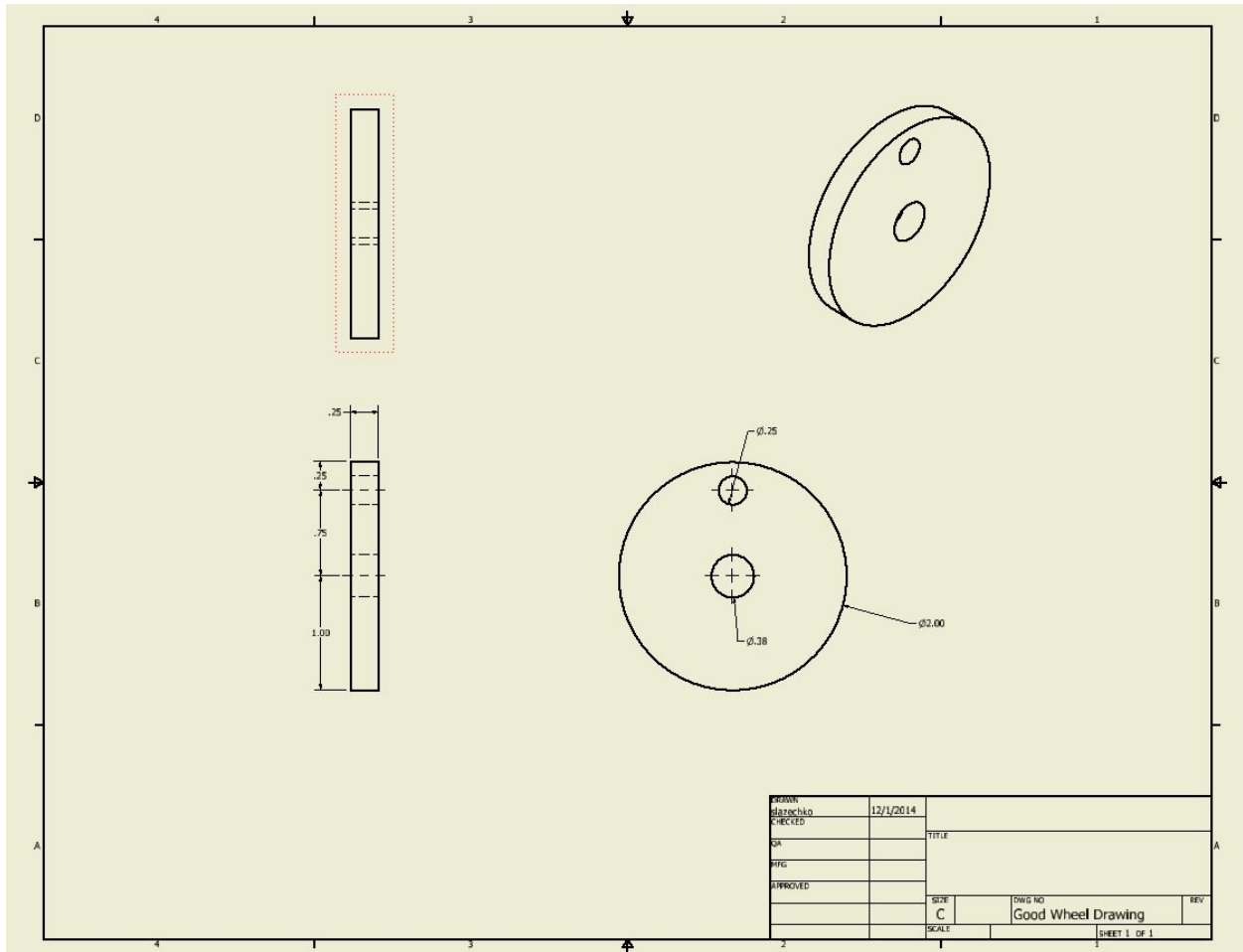


Figure 40. Wheel Drawing



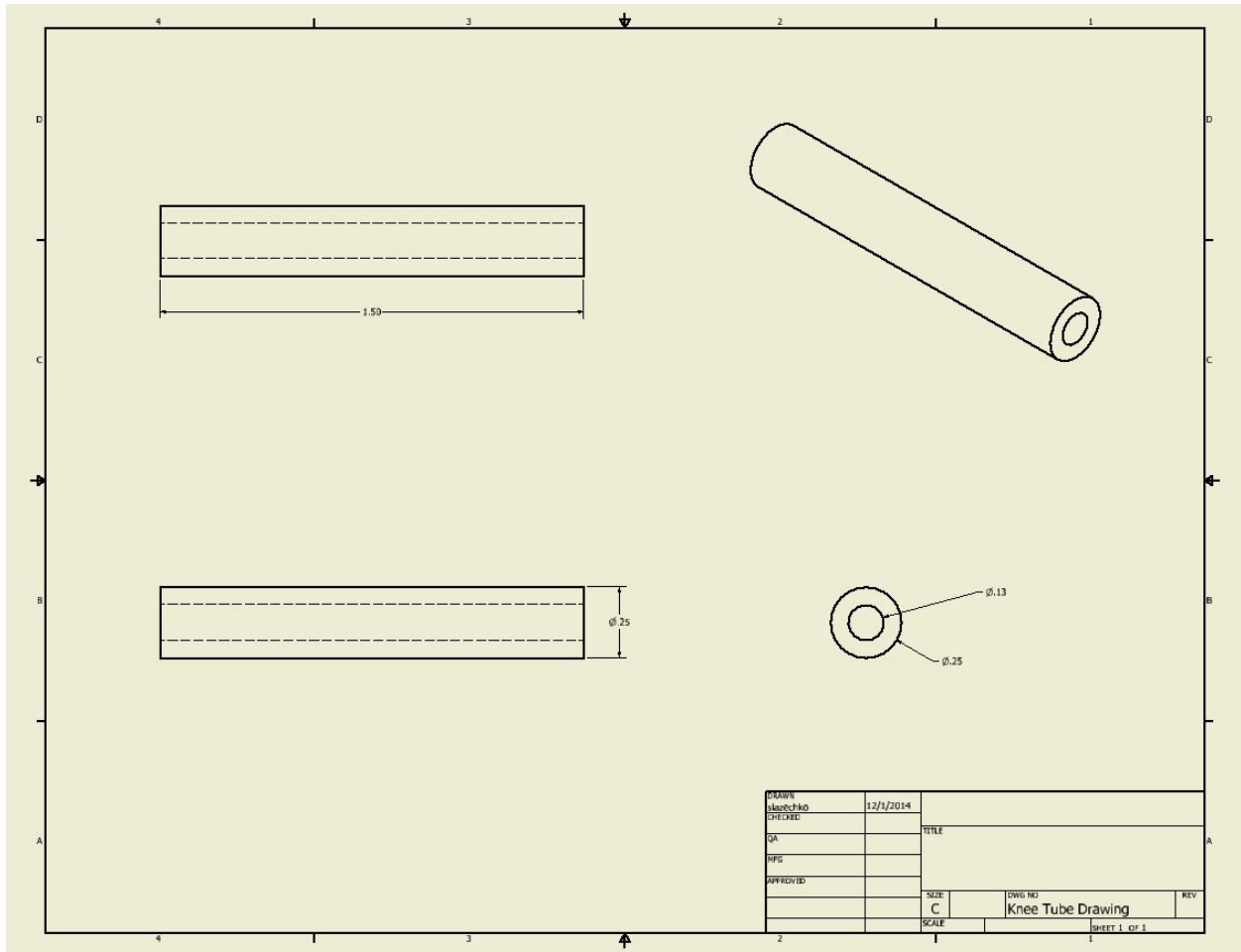


Figure 41. Knee Tube Drawing

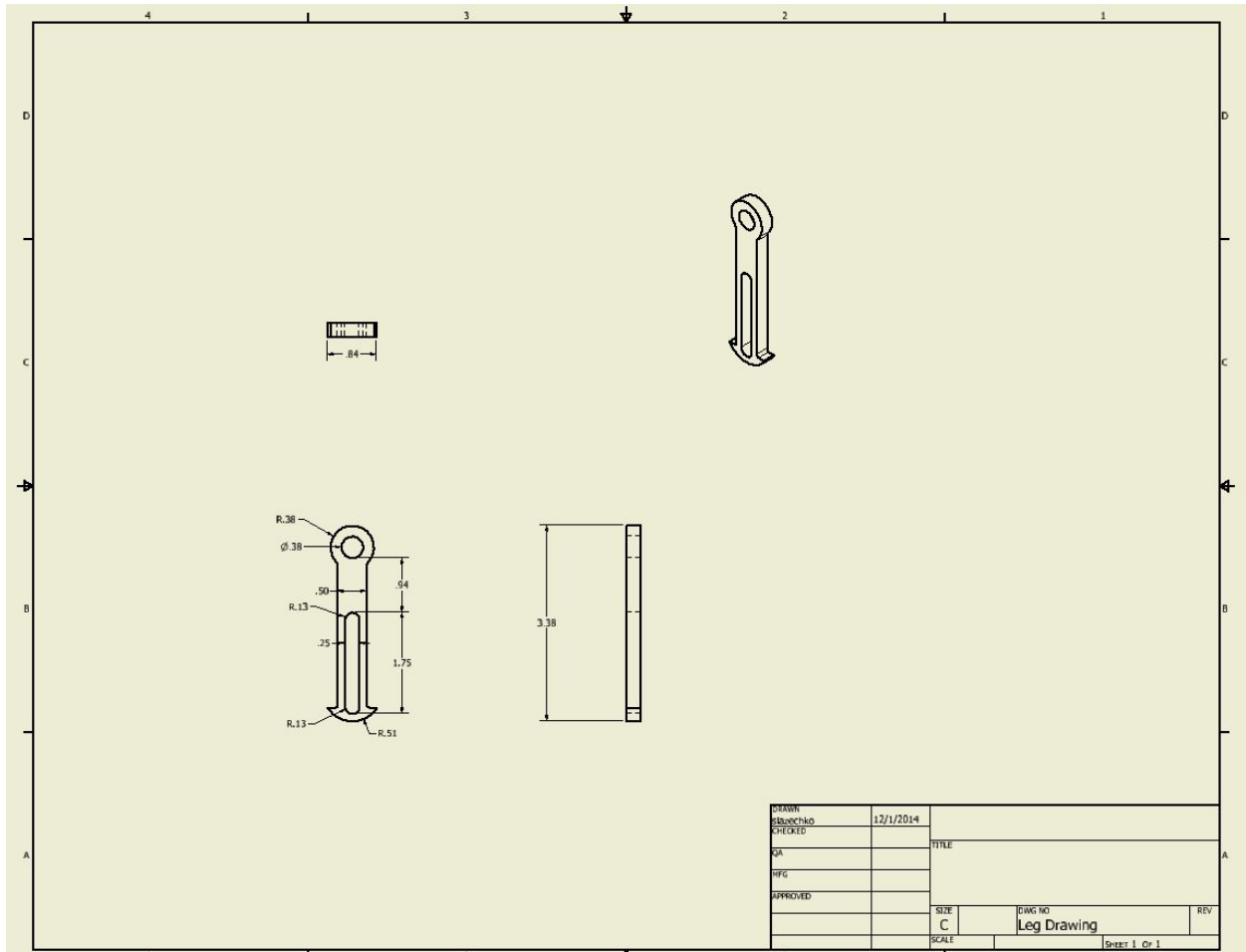


Figure 42. Leg Drawing

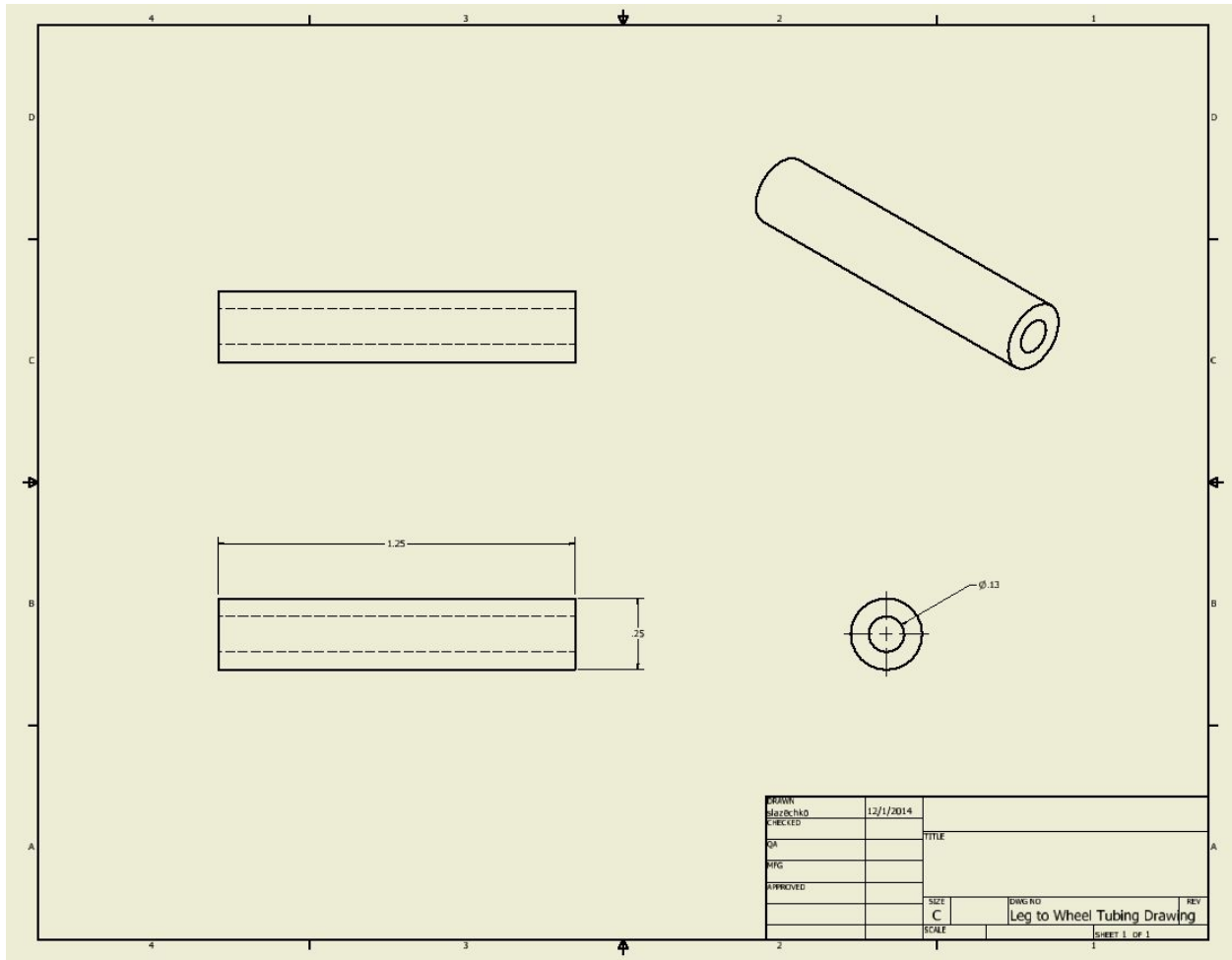


Figure 43. Leg to Wheel Tubing Drawing

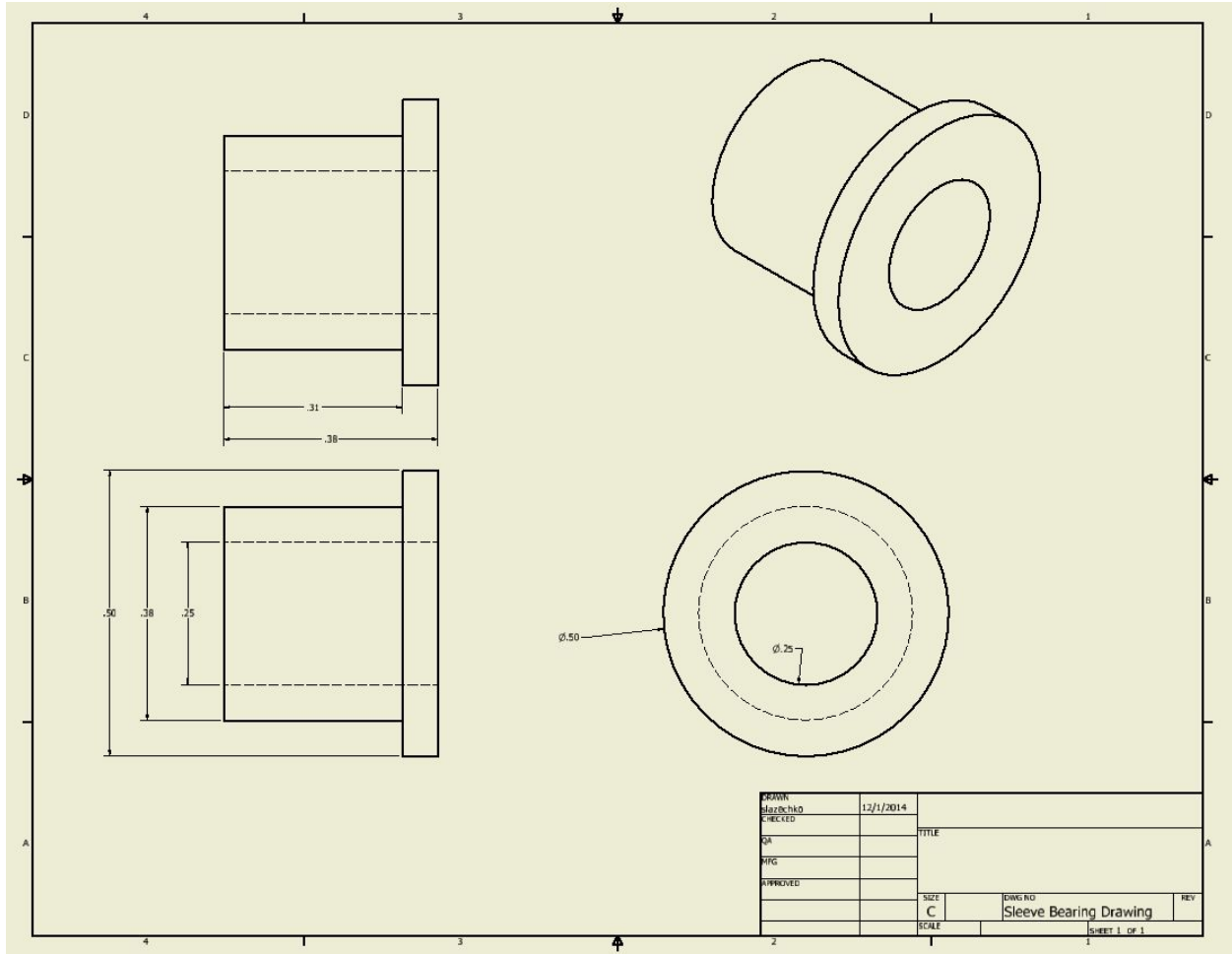


Figure 44. Sleeve Bearing Drawing

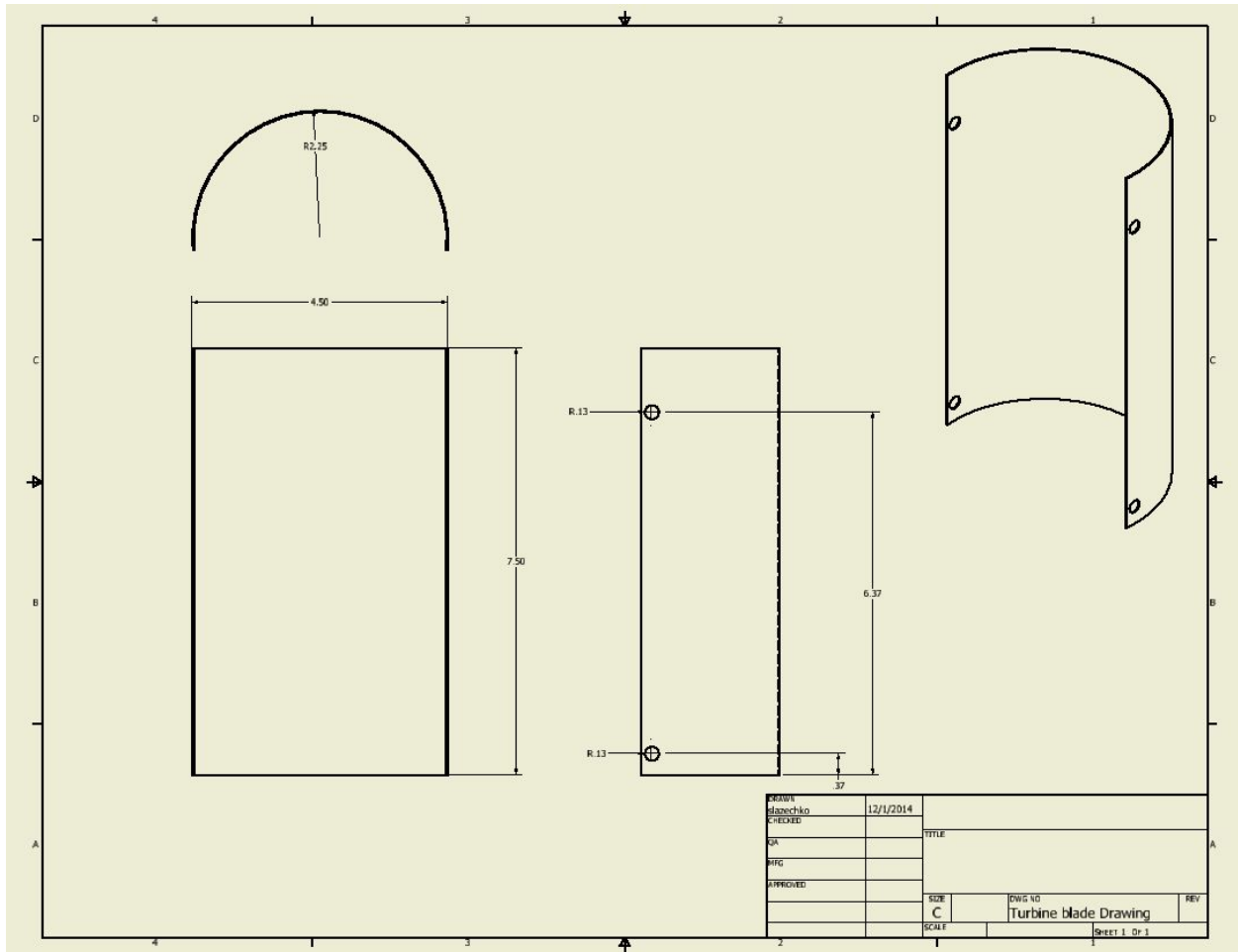


Figure 45. Turbine Blade Drawing

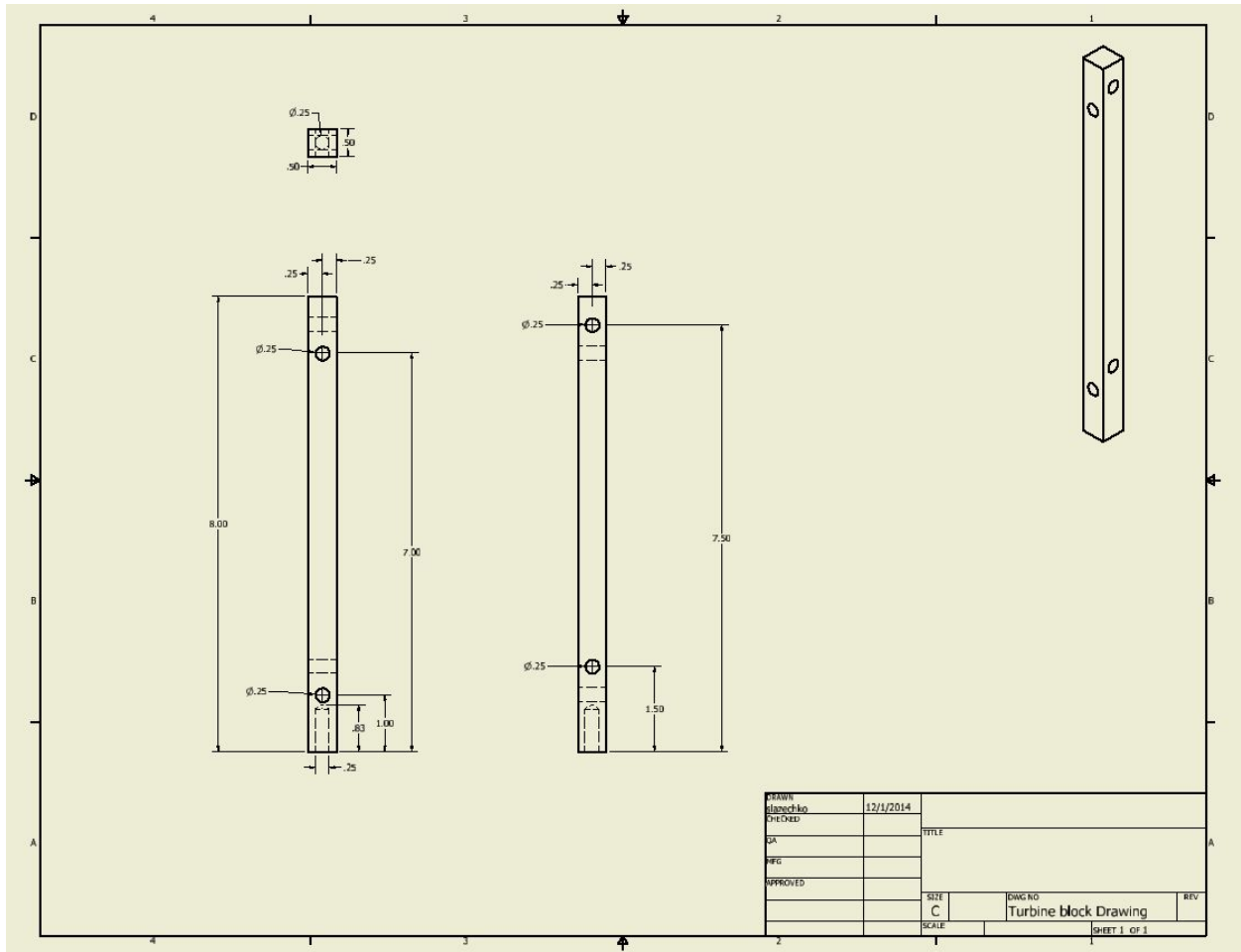


Figure 46. Turbine Block Drawing

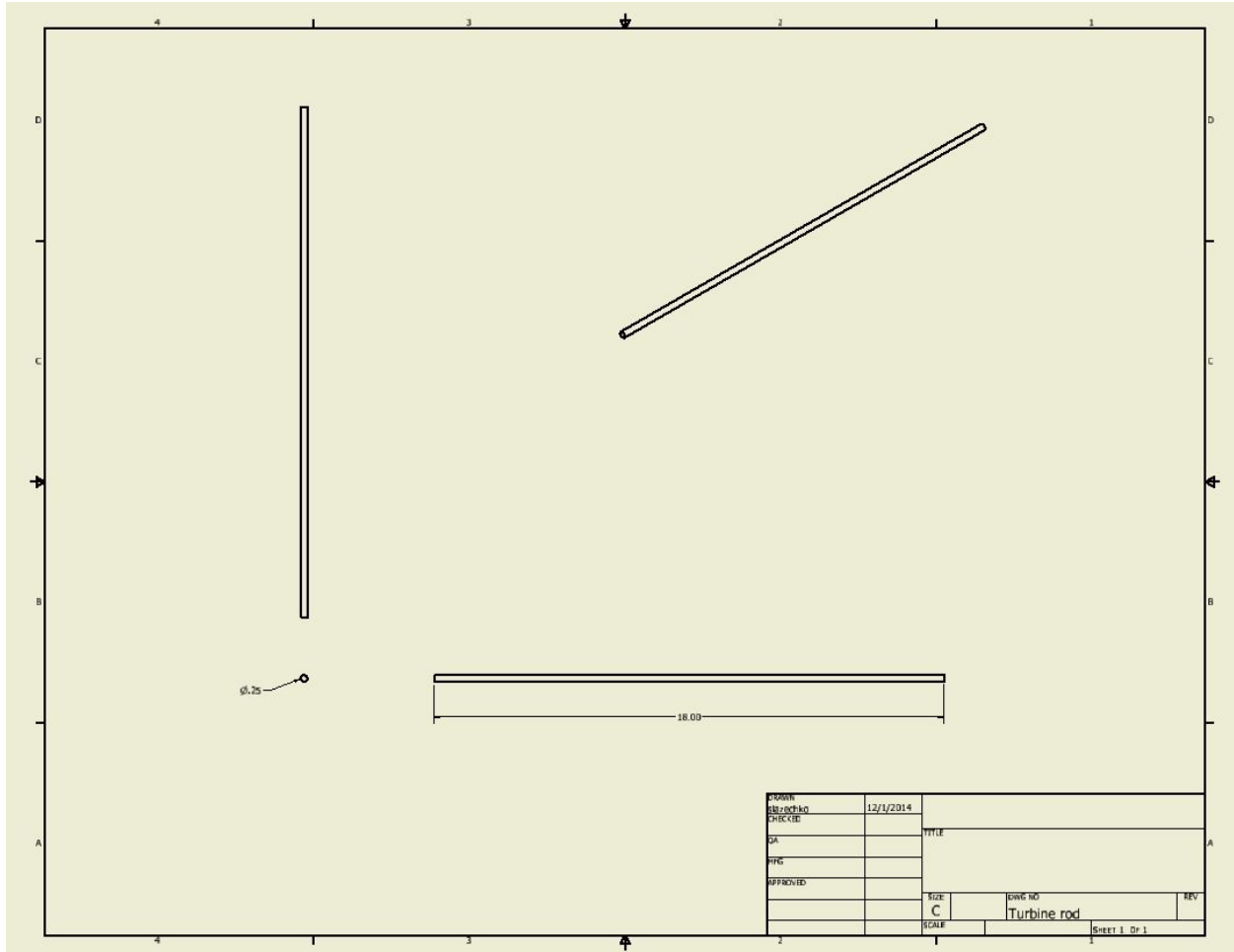


Figure 47. Turbine Dowel Rod Drawing

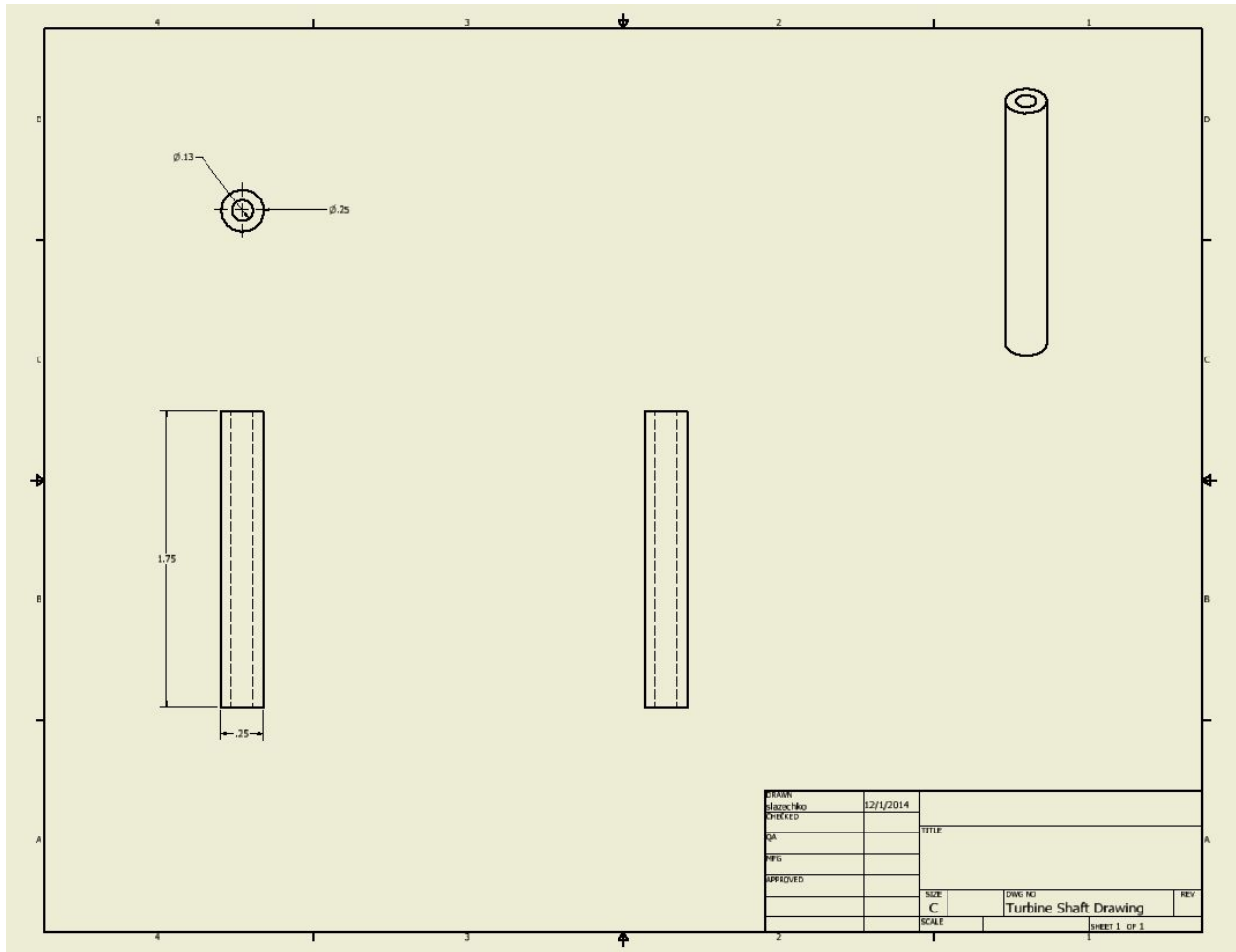


Figure 48. Turbine Shaft Drawing



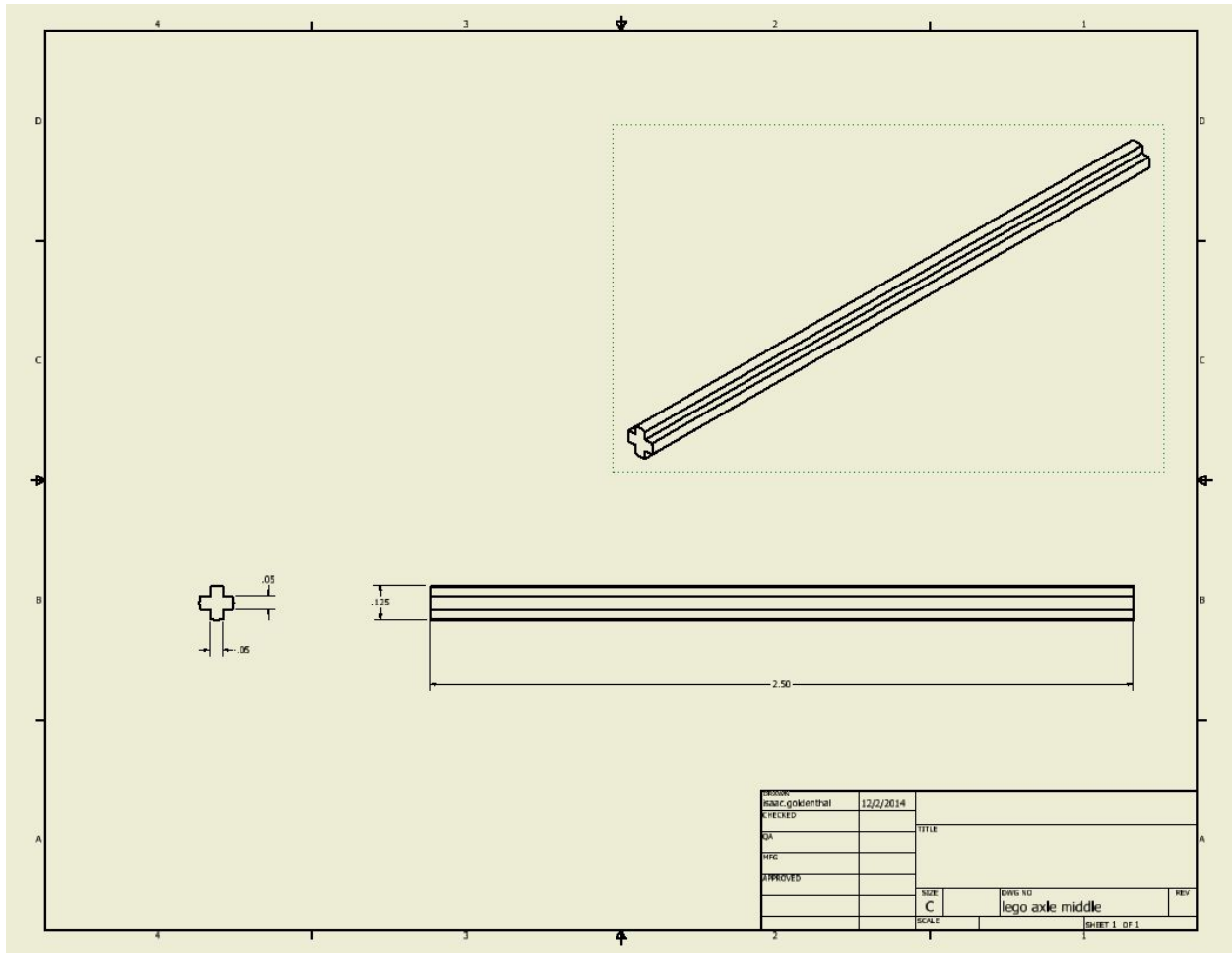


Figure 49. Lego Axle Middle Drawing

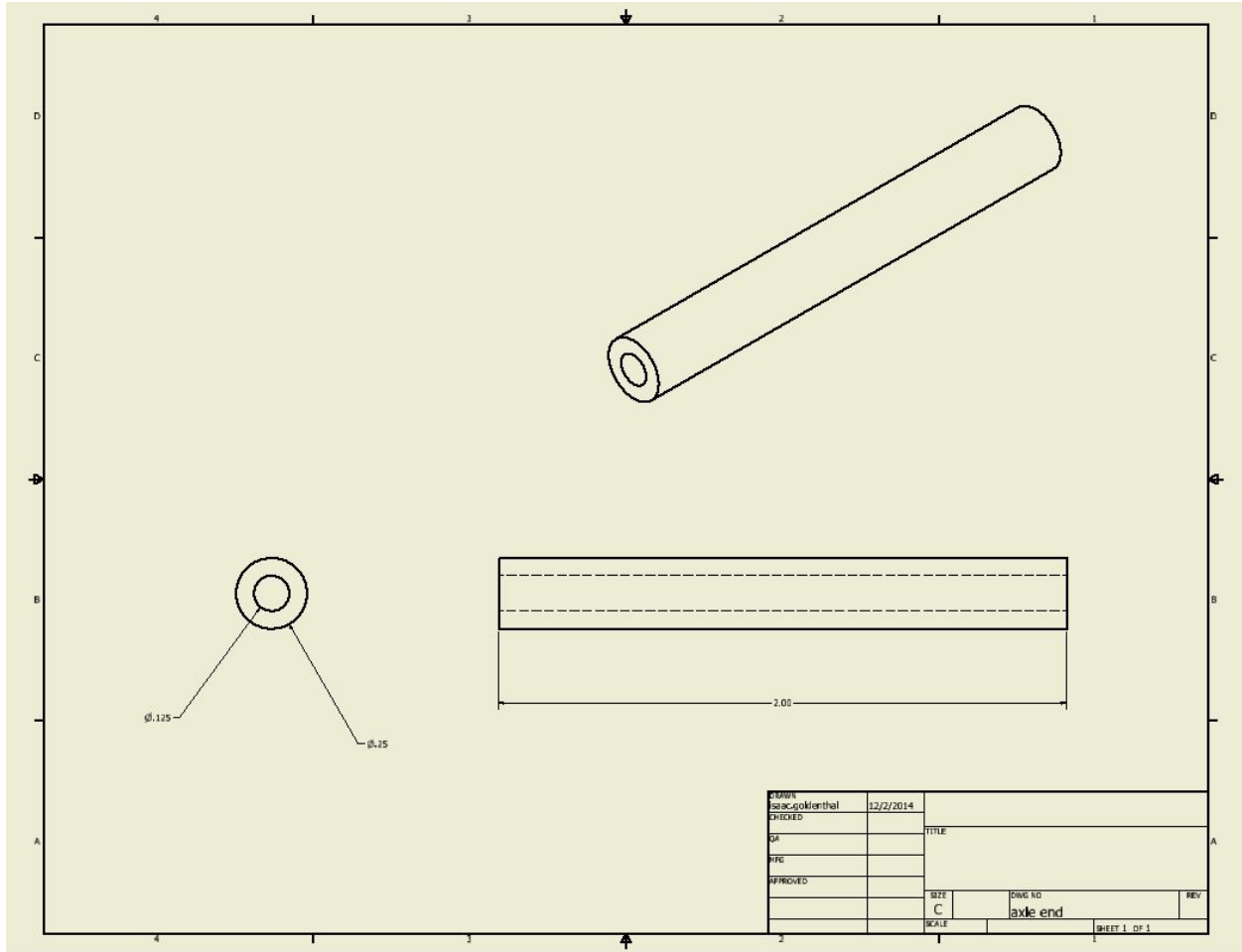


Figure 50. Axle End Drawing

### 7.1.2 Sourcing instructions

All wooden parts are bass wood and can be sourced from local hardware or craft stores.

The sleeve bearings are McMaster-Carr PTFE Flanged Sleeve Bearing for 1/4" Shaft Diameter, 3/8" OD, 3/8" Overall Length item # 2706T13.

The metal tubing is McMaster-Carr Multipurpose 6061 Aluminum Tube, 1/4" OD, .035" Wall Thickness, 1/2' Long item # 9056K61.

All Lego parts can be purchased off of Amazon.com. The axles can be found by searching "LEGO Technic Black Cross Axle Size 12 Long Rod Mindstorms NXT Part 3708 Piece (Quantity 28 pcs)." The gears can be found by searching "LEGO Technic 68 pcs GEAR Pack Set Mindstorms NXT Supplemental Lot Robot Motor Parts Pieces Assortment."

The sheet metal for the turbine was found in the machine shop and can be purchased at most hardware supply stores.

The Krazyglue and hot glue used to secure the bearings and axles can be found at most hardware and craft stores.

We scrounged for the following materials: clear plastic spacers, tape, turbine sheet metal, and hot glue. We found them in the machine shop, and returned the extra materials when we were finished.

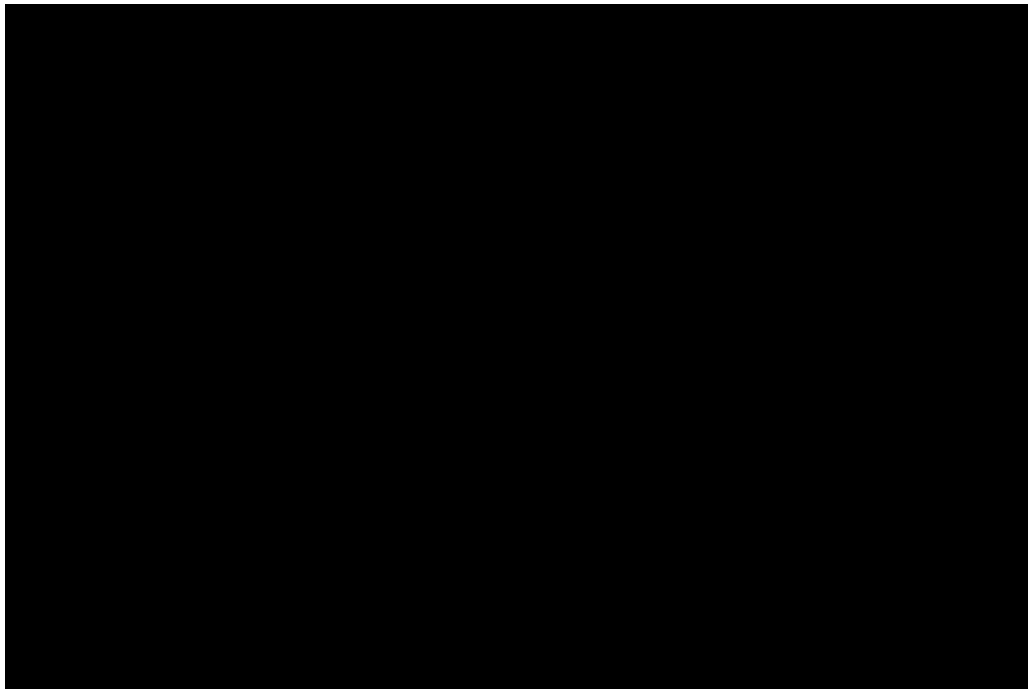
## 7.2 Final Presentation

### 7.2.1 A live presentation in front of the entire class and the instructors.

We presented in front of the class and judges on December 2.

### 7.2.2 A link to a video clip version of 1

Figure 51 shows our video presentation of our final prototype. This is the Youtube link: <http://youtu.be/W3Cb1747Qjc>.



**Figure 51. Video Presentation**


In order to see our slides from our presentation more clearly, we have reproduced them in Figures 52 through 58, below.




Figure 52. Final Presentation Slide 1

## Design Brief and Background Info

- The user (Professor Jakiela, WUSTL) seeks a machine made of recyclable/reusable materials that walks, without rolling, using wind power.
- Current Wind Walking Machine - Theo Jansen
  - Big, complicated
- Reddit animation gif



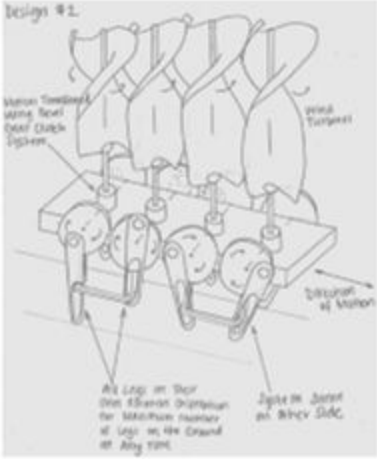
<http://cdn.instructables.com/F14PGKJGGEM/2028N1HPGKJGGEM/2028N1LARGE.jpg>



<http://imgur.com/gallery/lbicn>

Figure 53. Final Presentation Slide 2

## Selected Concept and Rationale



Design #1

Station (indicated) using foot pedal clutch system

Wind Turbine

Displacement of Motion

All legs in their own planes (position for maximum number of legs on the ground at any time)

Legs in series on drive shaft

- **Small:** fits on a desk
- **Simple:** few moving parts, 100% recyclable/reusable
- **Easily fabricated:** laser cut
- **Robust:** materials, high-efficiency turbine design
- **Walks:** 4 meters in a straight line at an observable speed; multiple terrains

Figure 54. Final Presentation Slide 3

## Final Design Choices Made

- **Added stationary support legs on corners**
  - Decreased step size, leg angle, and required torque
  - Increased stability
- **Turbine**
  - Drag based
  - Increased available torque by moving blades farther from axis
  - Reinforced shaft inside body to prevent worm gear dislocation




Figure 55. Final Presentation Slide 4



Figure 56. Final Presentation Slide 5

## Future Actions



- Speed!
  - Test lower gear ratios between turbine and wheels
- More robust
  - Gear interfaces
- Make it smaller
  - Lighter = less torque, lower gear ratio possible
- Increase turbine efficiency
  - Consider lift based addition, increase cross sectional area
  - Improve shape of blades

Figure 57. Final Presentation Slide 6

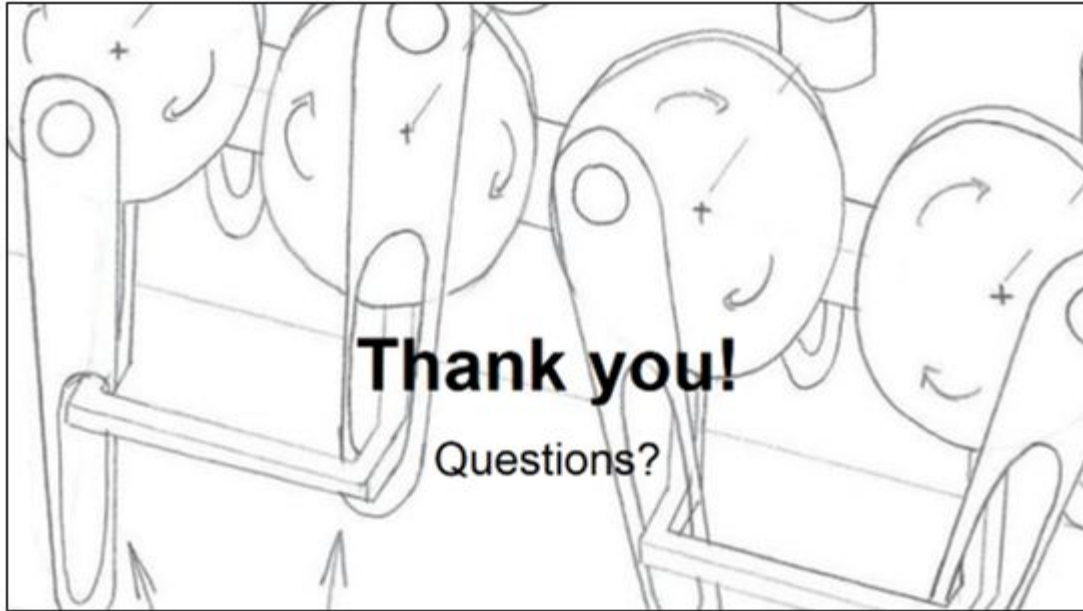


Figure 58. Final Presentation Slide 7

### 7.3 Teardown



We met with Professor Jakiela on December 5<sup>th</sup> to discuss our teardown assignment. Figure 59, below, shows the teardown assignment all group members and Professor signed.

**TEARDOWN TASKS AGREEMENT**

PROJECT: Wind Walker 2 NAMES: Sam Lazechko SL INSTRUCTOR: Jakiela  
Taylor Justman TJ  
Isaac Goldenthal IG  
Will Nocka WN

The following teardown/cleanup tasks will be performed:

We will be keeping our final prototype. For our teardown/cleanup tasks, we will clean up an area in the basement, clear a space, and leave all of our spare parts in a designated area. All unused parts scrounged from the machine shop will be returned.

Instructor comments on completion of teardown/cleanup tasks:

Instructor signature: [Signature]; Print instructor name: JAKIELA.  
Date: 12/5/2014.

(Group members should initial near their name above.)

**Figure 59. Teardown Tasks Agreement**

## 8 Discussion

### **8.1 Using the final prototype produced to obtain values for metrics, evaluate the quantified needs equations for the design. How well were the needs met? Discuss the result.**

The final prototype effectively satisfies the initial design requirements. It fits easily on a desk and within the 30x40x60cm specified in the problem description. The walker was able to operate at all 3 possible fan speeds coming from any direction. As the walker moved away from the fan it slowed, but continued to walk. The machine was able to operate on a wide variety of surfaces provided that the surface was reasonably flat. We used more parts (>100) than we initially expected, but the design was still relatively simple. The walker easily walked the desired 4 meters but we moved the fan several times in the interest of time. The one need we did not successfully meet was for walking speed. Initially, we hoped to walk 4 meters in 1 minute. This proved a difficult challenge as the 4 meter course took approximately 20 minutes to walk.

### **8.2 Discuss any significant parts sourcing issues? Did it make sense to scrounge parts? Did any vendor have an unreasonably long part delivery time? What would be your recommendations for future projects?**

We did not encounter any serious parts sourcing issues. We ordered most of our parts from McMaster-Carr and Lego, both of which came within reasonable time and worked very well for what we intended them to be used for. The only scrounging we did was for the turbine blades and the clear spacers, both of which we acquired from the machine shop. Our turbine design change needed to happen quickly and we did not have much time to try out many materials; luckily, the thin sheet metal we found worked very well. The clear spacers were used to keep the legs vertical to eliminate wobbling in the machine's steps. For all the other parts, it did not make sense to scrounge parts, as many of our parts required strict tolerancing to ensure the gears and axles all aligned properly. The only issue we had was not ordering enough parts with our initial order, so we had to make another order to finish our prototype. In the future, we could do a better job of estimating the number of parts that will be required before making the first order, or even simply ordering extras since our second order was small.

### **8.3 Discuss the overall experience:**

### 8.3.1 Was the project more or less difficult than you had expected?

In some ways the project was easier than we anticipated, but in other ways it was more difficult. For instance, getting the gears and axles to align just right was much more difficult than we had imagined. The connections between the Lego axles and aluminum tubing introduced a lot of unexpected wobble, but we were able to eliminate that by reinforcing the connections with epoxy and adding Lego supports to the worm gear. Despite some unforeseen obstacles, the rest of the assembly of our machine went very smoothly. We did not have to re-fabricate any of the parts we designed since we made extra legs and wheels during the laser cutting stage of our manufacturing process. If we had only made 6 legs to start with, we would have needed to fabricate 4 more since we used our extras as support legs. Luckily we had anticipated some potential roadblocks and we were able to overcome them more easily.

### 8.3.2 Does your final project result align with the project description?

Yes, our final project result mostly aligns with the project description. The only discrepancies are that our machine is slightly larger than specified (though it still “fits on a desk”), and it does not move 4 meters in one minute, as originally specified. The size constraint was given with the original project description, but the “fits on a desk” metric was given to us by Professor Jakiela during our needs interview. Besides this, the speed of the machine is definitely the most limiting factor of our design. We found that our speed was very similar to the other wind-walker group, and this coupled with our own experimental analysis leads us to believe that the original parameter may have been overly optimistic. If we made the machine much larger, with larger legs and powered it with stronger winds, it is very possible that the speed metric could have been satisfied. By aligning with the other metrics in the project description, our machine was not able to walk as quickly as outlined in the description.

### 8.3.3 Did your team function well as a group?

Since we were familiar with each other from previous classes, our team functioned very well as a group. We are proud to say that everyone pulled their weight, with each member committing large amounts of time and effort, as well as contributing critical ideas at various stages of development. The only issue we encountered was scheduling conflicts – due to taking different classes, participating in extracurricular activities, and having out-of-town weekend plans, it was sometimes difficult to coordinate times for all members to meet. In extreme cases of scheduling issues, we divided the work and tried to collaborate online via Google Drive as best we could. This actually worked well for the assignments we used it for, since we were each able to check the other group members' work before we submitted the assignment.

#### **8.3.4 Were your team member's skills complementary?**

Yes, our team members' skills were very complementary since we all came from somewhat different backgrounds with varying levels of experience. For instance, Sam's CAD experience proved invaluable when making the 3D model and drawings of our machine. Similarly, Will's Lego skills were critical in early prototyping and his ability to see the project coming together was very helpful in final stage adjustments. Isaac's laser cutting skills were completely necessary when fabricating the wheels and legs, without which we would have spent a lot more time manufacturing the parts in alternative ways. Finally, Taylor carried the team in the machine shop due to her manufacturing experience from Formula SAE, and kept track of deadlines so we never missed an assignment due date.

#### **8.3.5 Did your team share the workload equally?**

Yes, we shared the workload equally. At times, we had group members out of town and unable to work on certain assignments, but when this happened the other group members stepped up

and picked up extra slack. We made sure that all group members participated in the design, manufacturing, documentation, and presentation of the design project. Even though some people may have worked harder than others on a particular day, by the end of the project everyone had committed equal amounts of work.

### **8.3.6 Was any needed skill missing from the group?**

No necessary skills were missing from the group. As stated above, certain members were more proficient in given areas, but there was not a single area in which we were completely inexperienced. For instance, Taylor was the only group member comfortable using the lathe, so she did all the lathing for the project.

### **8.3.7 Did you have to consult with your customer during the process, or did you work to the original design brief?**

We did consult with our customer (Prof. Jakiela) during the process, but we followed the original design brief pretty consistently. For example, we consulted with him when we were unsure if we were allowed to use Lego gears in our final prototype. We wanted to use them because they were much lighter than any alternative gears we could find online and they were readily available since Will had a large box of Legos. Additionally, we were confused about some of the metrics at the very beginning of the process, which we cleared up with Professor Jakiela during our initial meeting.

### **8.3.8 Did the design brief (as provided by the customer) seem to change during the process?**

The design brief did not seem to change during the process. As stated previously, we cleared up questions and confusion when we ran into issues during the process, but we did not actively change anything from the original design brief. The only metric that was somewhat confusing was the speed; since there was a speed requirement of 4m per minute, but we were also told

that “observable” speed was sufficient, it was confusing as to what was actually expected. Since speed is one of our issues that has persisted throughout the project, there may be room for improvement, but we were satisfied that the speed of our machine was “observable”.

### **8.3.9 Has the project enhanced your design skills?**

The project has definitely enhanced our design skills. This was the first time we were able to start with a design on paper and carry it all the way through to a final prototype. We all gained invaluable experience in the machine shop, and we all learned about the flexibility of designs as they change from the first drawing to the final prototype. There are very strong influences of our initial design on our final design, but there were many changes and variations along the way. We are all more confident in our design skills since our project has proved successful.

### **8.3.10 Would you now feel more comfortable accepting a design project assignment at a job?**

We would definitely feel more comfortable accepting a design project at a job. Having tackled the entire design process, we believe a new task would seem less daunting since we know what to expect. At first, we were unsure that we would be able to get our design to work, but after working together and trying out different ideas, we were able to come to a solution we were all very proud of. This experience has given each of us confidence that will help us in our future design projects.

### **8.3.11 Are there projects that you would attempt now that you would not attempt before?**

There are definitely projects that we would attempt now that would have seemed too intimidating to accept a few months ago. We believe our project required a lot of quick thinking since we had to adjust our project as we went along, and some of the other projects that required similar thinking may not be so hard anymore. In particular, the treadle-driven lathe and drill press seem very interesting, as well as the dog exerciser and toy train. It is amazing to see

that when a number of people contribute ideas, the final project is far greater than any one person could have come up with on their own. Being able to draw from a wide range of talents, we have great confidence in our ability to take on more challenging projects in the future.

## 9 Appendix A - Parts List

Table 10, below, shows our parts list for the machine. The parts numbers correspond to Figure 60 in Appendix C.

Table 10. Parts List

Parts List				
#	Part	Description	Qty.	Explanation
1	Axle	Axle between wheels	3	This keeps wheels across from each other in sync. We used lego gears with lego axles bonded to metal tubes. We chose to use lego axles because they are designed to work with the lego gears we used. The tubing was selected because it was easy to modify to be bonded with the lego axle.
2	Idler	Smaller gear between wheel gears	2	This makes all the wheels have the same direction of rotation. We used lego gears with lego axles bonded to metal tubes. We chose lego gears and axles because they are designed to work together. We used the metal tubing because it was easy to bond to the lego axle.
3	Turbine	Harnesses wind energy	1	This harnesses wind energy and converts it into mechanical energy. We used a basswood shaft, with wooden dowel rods, sheet metal blades, and a worm gear drive. We chose the basswood shaft and wooden dowel rods because they are light weight yet strong enough for our requirements. The sheet metal blades were chosen because they are lightweight and easy to mold into our desired shape. The lego worm gear was selected because it converts vertical rotation into horizontal rotation by meshing with the lego gears in the axles. Sleeve bearings and metal tubing were used to hold the turbine in place. These were selected because we had extra parts from other orders, and they successfully held the turbine in place.
4	Body	Base of assembly	1	For the body bass wood was chosen because of its high strength to weight ratio. It was chosen over balsa wood because although balsa wood is lighter, bass wood is stiffer and more suitable for construction of the body and legs. We chose to use 1/8 inch thick bass wood for the body because thicker bass wood would have been too heavy, and thinner bass wood would have lacked the stiffness required.
5	Leg	Supports robot	10	We used 1/4 inch bass wood for the legs because it was thick enough to provide the stability necessary while being light enough to not require too much power to lift. Additionally, the legs were able to be laser cut out of a blank 3x24x1/4 piece of bass wood, which made manufacturing more simple.
6	Sleeve Bearing	Reduces friction	42	We ordered these sleeve-bearings from McMaster-Carr because they were very lightweight and less expensive than heavier alternatives. We wanted to save weight wherever possible because we wanted as much torque/weight as possible to make our machine take steps. These bearings allowed us to minimize friction between the basswood parts and the aluminum tubing connected to the Lego axles. With minimal friction, the amount of torque generated was maximized.
7	Wheel	Provides rotational motion	6	We used the same 1/4 inch bass wood for the wheels as was used for the legs. To simplify manufacturing of the wind walker, the wheels were laser cut from the same piece of wood as the legs at the same time. The bass wood provided the stiffness that was required for this part at a relatively low weight.
8	Leg to Wheel Tubing	Connects walking leg to wheel	6	We used this aluminum tubing because it had the corresponding inner diameter to the outer diameter of the Lego axles we were using to connect the Lego gears to the wheels and body. Since aluminum is lightweight, it was a good sturdy choice for the axles since we also wanted to minimize as much wobble as possible.
9	Clear Spacer	Provides space between wheel and leg	6	The clear spacer was used to reduce the wobble in the leg mechanism. A plastic spacer was chosen to minimize weight and friction with adjacent parts.
10	Knee Tube	Provides anchor for walking leg	6	The knee tube was used to allow the leg to pivot and step effectively. The aluminum tube was chosen because of its high strength compared to a wooden or plastic piece. The tube was compatible with the bearings which were used to correctly position the leg and improve stepping mechanics.



## 10 Appendix B - Bill of Materials

Table 11, below, shows the Bill of Materials for our wind walking machine. The parts numbers correspond to Figure 60 in Appendix C.

**Table 11. Bill of Materials**

Bill of Materials			
#	Part	Description	Qty
1	Axle	Axle between wheels	3
2	Idler	Smaller gear between wheel gears	2
3	Turbine	Harnesses wind energy	1
4	Body	Base of assembly	1
5	Leg	Supports robot	10
6	Sleeve Bearing	Reduces friction	42
7	Wheel	Provides rotational motion	6
8	Leg to Wheel Tubing	Connects walking leg to wheel	6
9	Clear Spacer	Provides space between wheel and leg	6
10	Knee Tube	Provides anchor for walking leg	6

## 11 Appendix C - CAD Models

Figures 60 and 61 show our isometric views of the CAD models we used for the machine. All individual Inventor CAD models have been submitted along with this report, for reference.

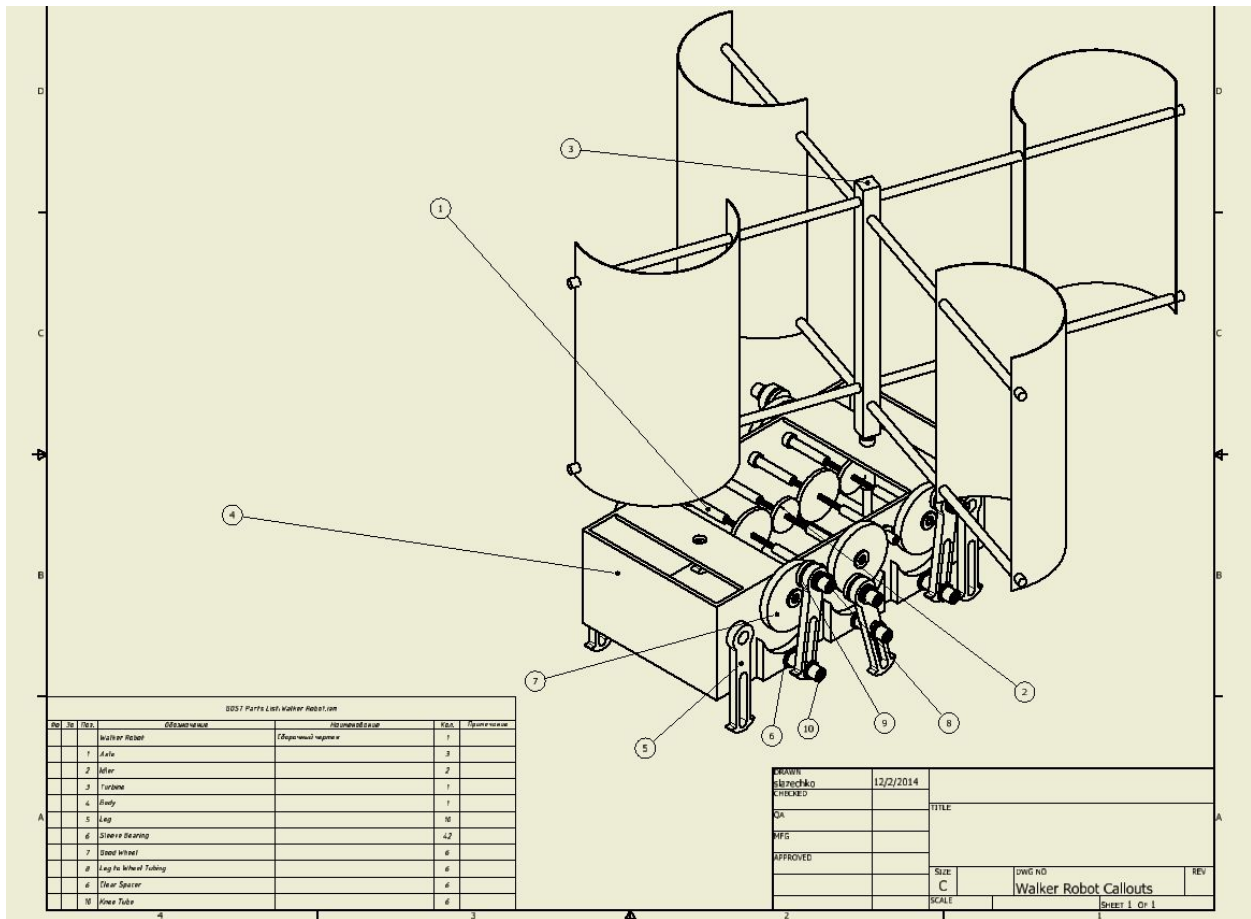


Figure 60. CAD Model Isometric View

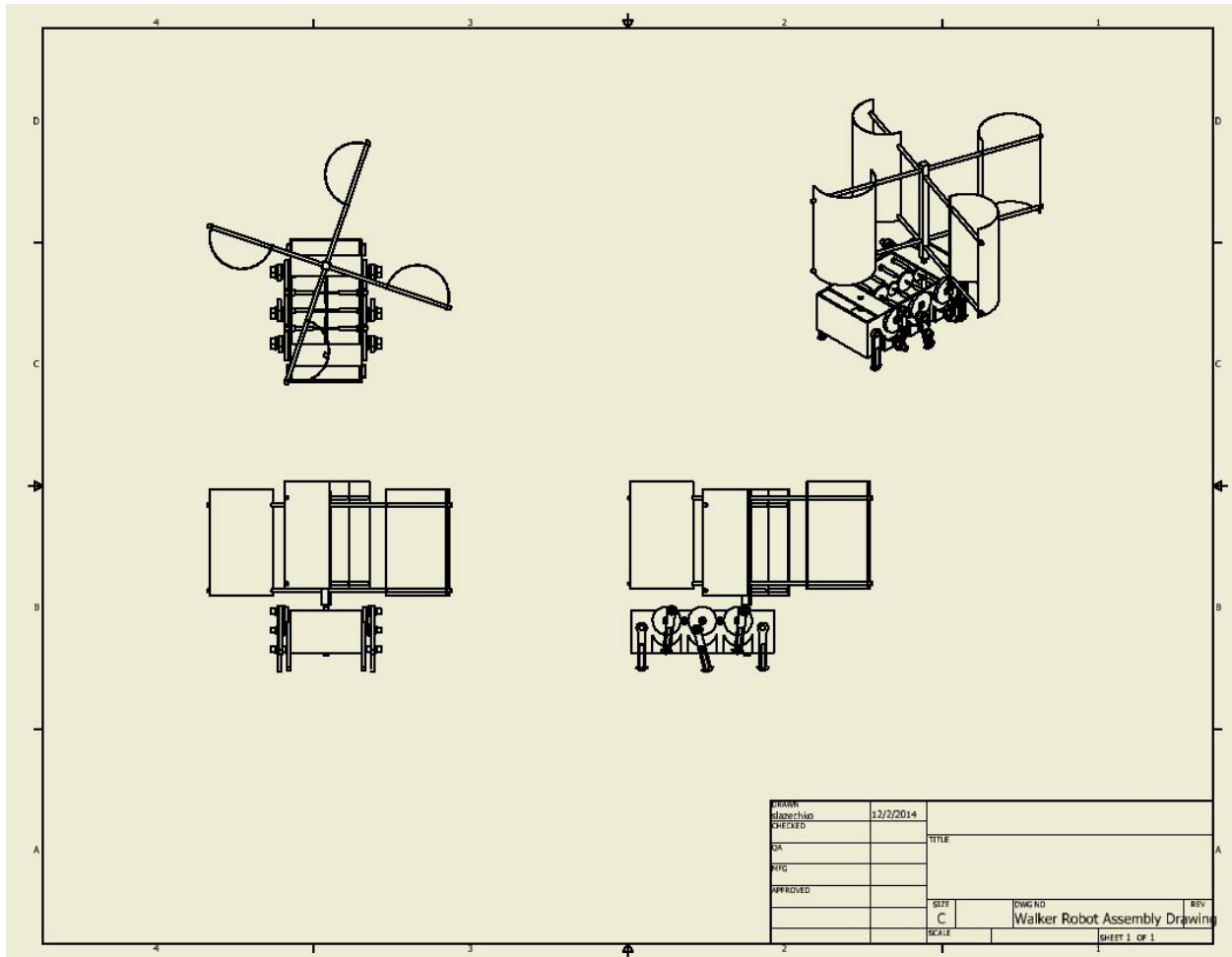


Figure 61. CAD Model All Views

## 12 Annotated Bibliography (limited to 150 words per entry)

Bares, John E., and William Whittaker. "Patent EP0399720A1 - Orthogonal Legged Walking Robot." *Google Books*. 28 Nov. 1990. Web. 22 Nov. 2014. <<http://www.google.com/patents/EP0399720A1?cl=en>>.

We used this patent to study the design of a robot spider with orthogonal legs. The device has legs which overlap during movement, each leg with a rotatable shoulder. During our initial research, we were not sure what kind of walking motion we wanted to work with, and chose to study several different types, including the gait with orthogonal legs. From this design, we used the idea of three legs touching the ground at all times to offer stability. Later on, our addition of support legs offered even more stability to the body.

Brondsted, Povl. *Advances in Wind Turbine Blade Design and Materials*. Vol. 47. Oxford: Woodhead, 2013. Print.

This source helped us understand blade design for our turbine, keeping in mind aerodynamic features. A large part of this source was dedicated to the fatigue behavior of composite wind turbine blades, which was more than we needed for this design project, but it was helpful to have this source to understand the design and functionality of wind turbine blades and the challenges in using certain materials. We used this book to keep in mind already functioning designs for turbines.

Jha, A. R. *Wind Turbine Technology*. Boca Raton, Fla.: CRC, 2011. Print.

This resource was useful in giving an introduction to wind turbine technology in order to understand structural requirements for wind turbines using experimental data. Our initial turbine design was quite wobbly and understanding the structural requirements was important to us during our redesign. Ultimately, we chose a drag-based turbine design, which gave us a lot of torque in light winds.

Klann, Joseph C. "Patent US6364040 - Walking Device." *Google Books*. 2 Apr. 2002. Web. 22 Nov. 2014. <<http://www.google.com/patents/US6364040>>.

This patent was designed to simulate the gait of a walking animal. It includes rocker arms and cranking links axially mounted to provide suitable power for the walking motion. We liked the idea of rocker arms and links and took in this design as well as the orthogonal gait design to come up with our final design of rotating wheels with attached leg linkages that rotate around a stationary knee.

"Robot Walker." *Imgur*. 1 Aug. 2014. Web. 22 Nov. 2014. <<http://imgur.com/gallery/lbjcn>>.

This source shows three images of the Reddit animation walking: one has four legs, one has six legs, and the third view is an underneath view of the animation, where we were easily able to see the legs rotating around the stationary knees. We liked the idea of having stationary knees that slide through the slots in the legs, and modified this design to create a slight variation: our knees do not connect to each other, but are rather pegs that provide the same purpose.

"Robot Walker (OC) • /r/perfectloops." *Reddit*. 1 Aug. 2014. Web. 22 Nov. 2014.

<[http://www.reddit.com/r/perfectloops/comments/2dgj2b/robot\\_walker\\_oc/](http://www.reddit.com/r/perfectloops/comments/2dgj2b/robot_walker_oc/)>.

This animation ultimately provided the greatest inspiration for our group. User "qwibble" posted an animation on /r/perfectloops, which we based our design off of. The animation shows the use of slotted legs rotating in sync, which we altered to have alternating legs off sync. This provided us with extra stability since three legs were on the ground at all times.