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MEMS 411 Senior Design: Wind Powered Walking Robot

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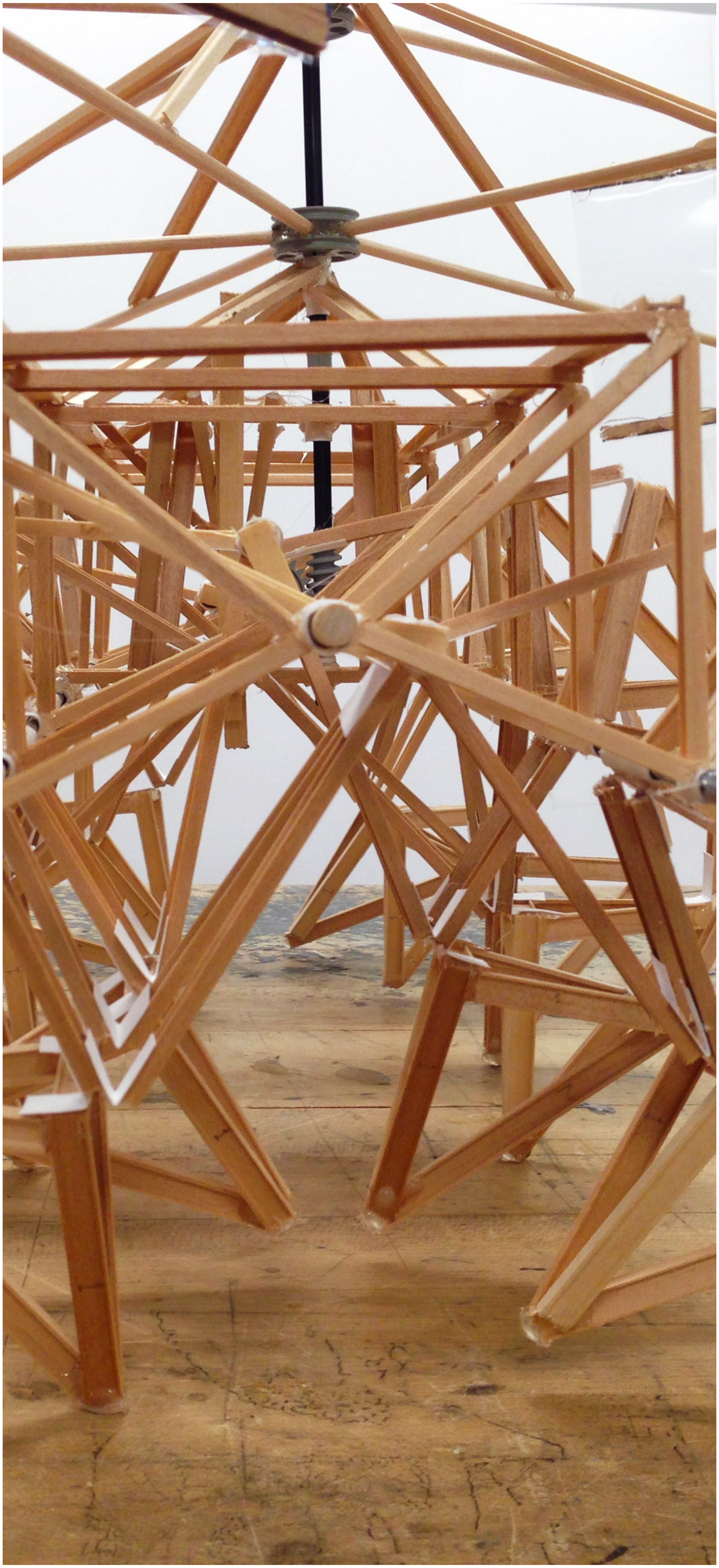

Wind Powered Walking Robot

Group 1

Timothy Elliott

Kenna Middleton

Jose Rodes

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1 Introduction

1.1 Problem statement

Build a 'Machine That Walks' using leg like linkages that is only powered by wind. It must walk a minimum of 4 meters to prove that it is capable of walking and at least half of the materials used must be recyclable or reusable within the greater St. Louis area. The machine must not exceed 10 kg and must fit in the volume of 30 cm x 60 cm x 40 cm and must be unable to be easily knocked over.

1.2 Team members

The design team consisted of Timothy Elliott, Kenna Middleton, and Jose Rodes.

2 Background Information Study

2.1 Design Brief

Design a machine that walks by harnessing the power of wind. Walking must be done with legs – that means no rolling or sliding on skis. The machine should be no larger than 30x40x60 cm in size and 10 kg in mass. Additionally, it should be able to walk 4 meters to demonstrate it is capable of locomotion.

2.2 Background Information

In 1990, the Dutch artist and engineer Theo Jansen started designing mechanical walking machines that have come to be known as Strandbeests. Today, these PVC structures have evolved to the point that they are able to roam beaches on their own by storing wind energy as compressed air in recycled bottles. The compressed air is then released by a collection of several different valves and allows several different 'beasts' to live self-sufficiently on the beaches. Below are pictures of two of Theo Jansen's Strandbeests walking the beaches.

Figure 1 – Theo Jansen Strandbeest

Figure 2 – Theo Jansen Strandbeest

More information and photos can be found at his website: http://www.strandbeest.com/. The key to Jansen's machines is his leg design. The leg design is the result of months of computer simulation and is unique in its ability to function like a wheel. When three legs are offset by 120° and rotate about a common driveshaft, the feet move in such a way that the driveshaft remains in the same plane. This is ideal in an engineering sense due to its stability. Because of the intricacy and novelty of Jansen's leg design, the ratios for his leg linkages have been labeled 'Theo Jansen Holy Numbers'. These ratios were used in the making of our design.

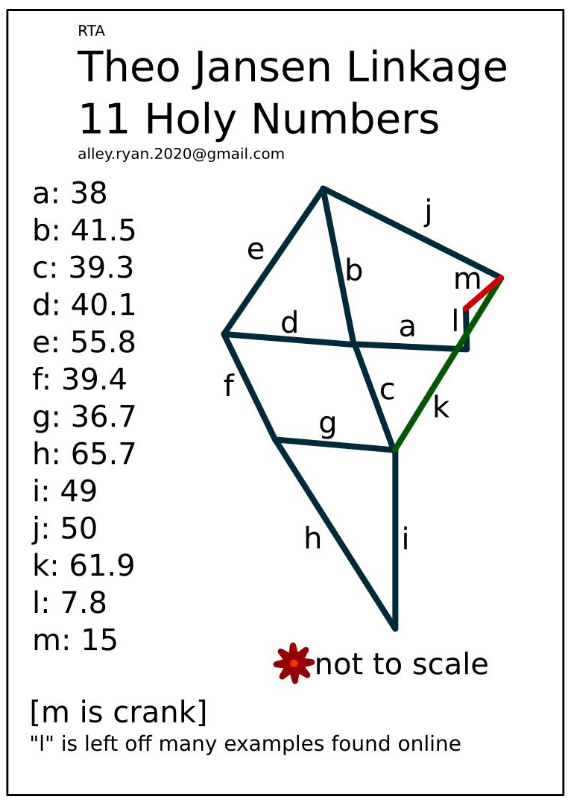


Figure 3 – Theo Jansen Holy Numbers

Though the leg system of our design is similar to Jansen's strandbeests, the system of harnessing wind power is different. Instead of using sails and compressed air, our design converts the horizontal motion of the wind directly into the rotational motion of the driveshaft by a vertical axis wind turbine. There were several designs to choose from, but these were narrowed down to two: a Savonius and a Giromill Darrieus vertical axis turbine. They are powered by drag and lift, respectively. Examples of each are shown below:

(a) (b)

Figure 4 – (a) A Savonius Wind Turbine, (b) A Giromill Darrieus Wind Turbine

Although there are no patents by Jansen, there are several patents on the turbines shown above. A Savonius patent is US 7762777 B2 and a Giromill Darrieus patent is US 1835018.

3 Concept Design and Specification

3.1 *User needs, metrics, and quantified needs equations.*

3.1.1 Record of the user needs interview

Below is the condensed result of the interview with our client. We asked him a series of question to further determine his needs for our design and then weighed the interpreted needs according to their perceived importance.

Table 1 - User needs Interview

Customer Data: Wind Powered Walking Robot (WPWR) Customer: Professor Mark Jakiela Address: Washington University Engineering School Date: 9 September 2014			
Question	Customer Statement	Interpreted Need	Importance
What should the size of the robot be?	The robot should be no bigger than 30cm x 60cm x 40cm	WPWR has a volume less than .072 m^3	4
How should the robot move?	The robot should walk or hop, not roll.	WPWR uses legs to walk.	5
	The robot should be wind powered. There should be no electronics used.	WPWR only requires the wind to move.	5
How heavy could the robot be?	The robot should weigh less than 10 kg.	WPWR has a mass less than 10 kg.	4
How far should the robot be able to walk?	The robot needs to be able to walk at least 4 m.	WPWR can walk over 4 meters.	3
How fast should the robot walk?	The robot should be able to walk the 4 m in roughly 1 minute.	WPWR has a minimum speed of 6.7 cm/s	3
Should the robot be recyclable?	At least half of the robot should be recyclable or compostable.	WPWR is made with at least 50% recyclable material.	5
	The robot should be able to be recycled in the St Louis area.	WPWR can be recycled in St Louis.	5
What surface should the robot be able to walk on?	The robot should be able to walk on more than one surface. It should be able to walk over carpet, title, etc.	WPWR can walk over multiple surfaces.	4

Should the robot be able to climb up different grades?	The robot can handle 3 degrees or less of elevation change.	WPWR can handle at least 3 degrees of elevation change.	3
Will the wind speed for the robot remain constant?	The robot should be able to accept wind from different directions.	WPWR can use different directions of wind.	4
How stable should the robot be in high wind speeds?	It should be stable in at least 30 mph wind and fall-tolerable.	WPWR cannot fall in 30 mph wind and must handle small impacts.	4

3.1.2 List of identified metrics

Table 2 - Identified Metrics

Need Number	Need	Importance	Importance Weight
1	WPWR has a volume less than .072 m^3	4	0.08
2	WPWR uses legs to walk.	5	0.10
3	WPWR only requires the wind to move.	5	0.10
4	WPWR has a mass less than 10 kg.	4	0.08
5	WPWR can walk over 4 m.	3	0.06
6	WPWR has a minimum speed of 6.7 cm/s	3	0.06
7	WPWR is made with at least 50% recyclable material.	5	0.10
8	WPWR can be recycled in St Louis.	5	0.10
9	WPWR can walk over multiple surfaces.	4	0.08
10	WPWR can handle at least 3 degrees of elevation change.	3	0.06
11	WPWR can use different directions of wind.	4	0.08
12	WPWR cannot fall in 30 mph wind and must handle small impacts.	4	0.08

Table 3 - Design Metrics

Metric Number	Associated Needs	Metric	Units	Min Value	Max Value
1	4, 6, 12	Mass	kg	0	10
2	5	Travel Distance	m	4	16
3	7	Recyclable	percentage	50	100
4	8	Recyclable in St Louis	Binary	0	1
5	6, 10	Speed	cm/s	6.7	20
6	1, 12	Total Volume	m^3	0	0.072
7	5, 9	Number of Walkable Surfaces	Integer	1	10
8	10	Elevation Change	degrees	3	10

9	3, 11	Acceptance of wind direction	integer	1	5
10	12	Possible Wind Speed	mph	20	40
11	2, 9, 10, 12	Has Legs	Binary	0	1

3.1.3 Table/list of quantified needs equations

Wind Powered Walking Robot		Metrics												
		Mass	Travel Distance	Recyleable	Recycleable in St Louis	Speed	Volume	# of Walkable Surfaces	Elevation Change	Acceptance of Wind Direction	Wind Speed To Move	Wind Speed Able to Handle	Has Legs	Importance Weight
Need#	Need	1	2	3	4	5	6	7	8	9	10	10	11	
1	WPWR has a volume less than .072 m^3						1.00							0.08
2	WPWR uses legs to walk.												1.00	0.10
3	WPWR only requires the wind to move.									0.50	0.50			0.10
4	WPWR has a mass less than 10 kg.	1.00												0.08
5	WPWR can walk over 4 m.		0.80					0.20						0.06
6	WPWR has a minimum speed of 6.7 cm/s	0.30				0.70								0.06
7	WPWR is made with at least 50% recycleable material.			1.00										0.10
8	WPWR can be recycled in St Louis.				1.00									0.10
9	WPWR can walk over multiple surfaces.							0.50					0.50	0.08
10	WPWR can handle at lease 3 degrees of elevation change.					0.20			0.60				0.20	0.06
11	WPWR can use different directions of wind.									1.00				0.08
12	WPWR cannot fall in 30 mph wind and must handle small impacts.	0.30					0.30					0.30	0.10	0.08
	Units	kg	m	Percent	Binary	cm/s	m^3	Integer	Degrees	Integer	mph	mph	Binary	
	Best Value	5.5	10	100	1	10	0.05	8	15	5	1	50	1	
	Worst Value	10	4	50	0	6	0.072	1	3	1	30	10	0	

Table 4 - Quantified Needs Equations

3.2 Four (4) concept drawings

The following four figures are our initial concept drawings. We each designed one individual machine and then combined the best features of each for the final concept.

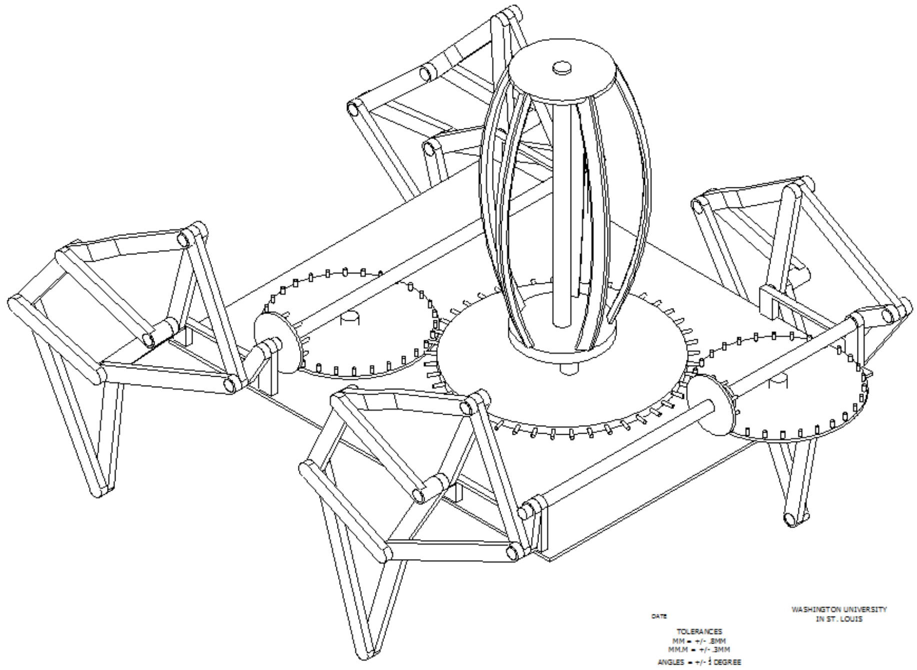


Figure 5 - Concept 1: Aragog the Acromantula

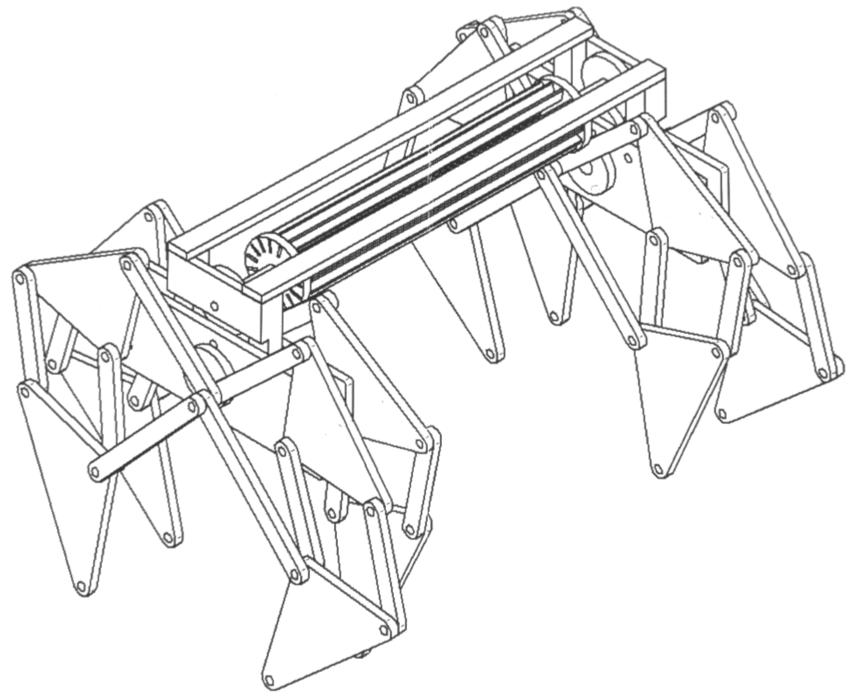


Figure 6 - Concept 2: The Bulldozer

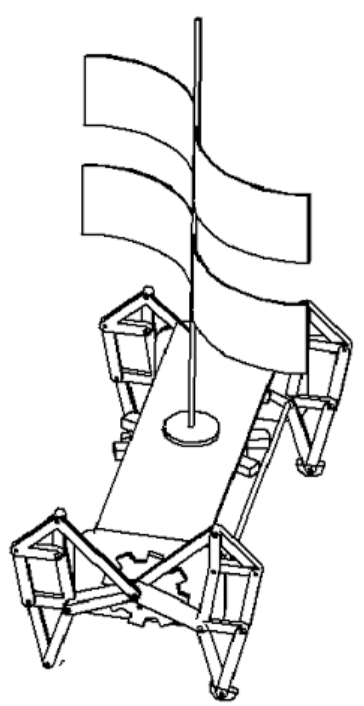


Figure 7 - Concept 3: The Great Bambino

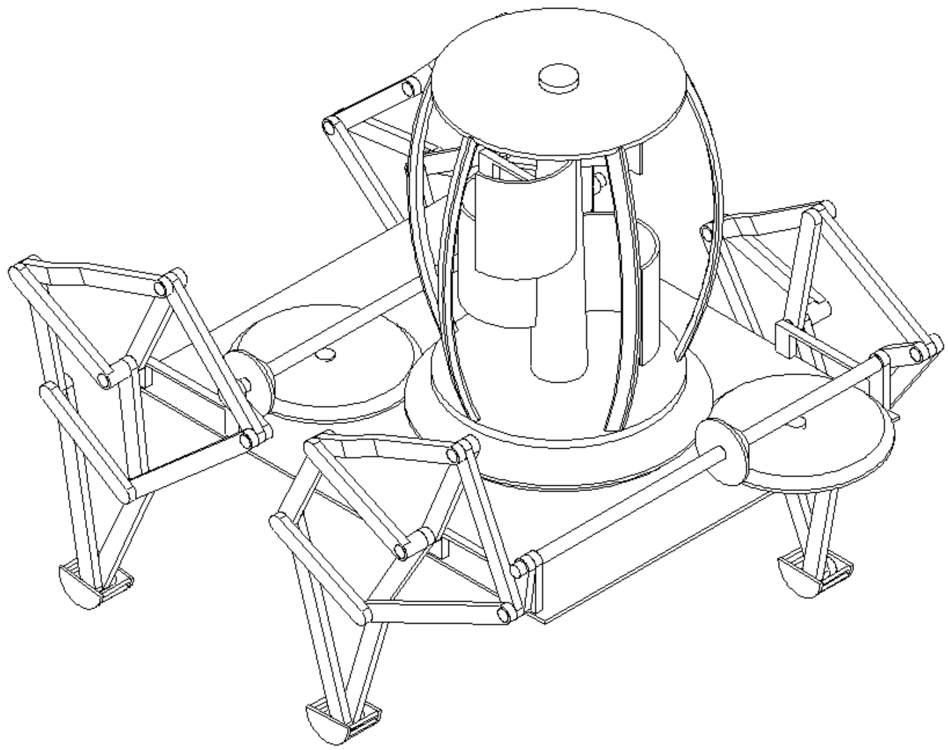


Figure 8 - Concept 4: BooBoo the Bear

3.3 *Concept selection process*

3.3.1 Concept scoring (not screening)

Table 5 - Concept Scoring

Wind Powered Walking Robot

		Metrics																				
		Mass	Travel Distance	Recyleable	Recycleable in St Louis	Speed	Volume	# of Walkable Surfaces	Elevation Change	Acceptance of Wind Direction	Wind Speed To Move	Wind Speed Able to Handle	Has Legs	Need Happiness 1	Need Happiness 2	Need Happiness 3	Need Happiness 4	Importance Weight	Total Happiness Value 1	Total Happiness Value 2	Total Happiness Value 3	Total Happiness Value 4
Need#	**Need**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**10**	**11**									
1	WPWR has a volume less than .072 m^3						1.00							0.55	1.00	0.55	0.55	0.08	0.04	0.08	0.04	0.04
2	WPWR uses legs to walk.												1.00	1.00	1.00	1.00	1.00	0.10	0.10	0.10	0.10	0.10
3	WPWR only requires the wind to move.									0.50	0.50			0.86	0.25	0.86	0.88	0.10	0.09	0.03	0.09	0.09
4	WPWR has a mass less than 10 kg.	1.00												0.67	0.67	0.00	0.89	0.08	0.05	0.05	0.00	0.07
5	WPWR can walk over 4 m.		0.80					0.20						0.70	0.03	0.62	0.89	0.06	0.04	0.00	0.04	0.05
6	WPWR has a minimum speed of 6.7 cm/s	0.30				0.70								0.55	0.20	0.26	0.79	0.06	0.03	0.01	0.02	0.05
7	WPWR is made with at least 50% recycleable material.			1.00										0.60	0.40	0.60	0.80	0.10	0.06	0.04	0.06	0.08
8	WPWR can be recycled in St Louis.				1.00									1.00	0.00	1.00	1.00	0.10	0.10	0.00	0.10	0.10
9	WPWR can walk over multiple surfaces.							0.50					0.50	0.57	0.57	0.71	0.71	0.08	0.05	0.05	0.06	0.06
10	WPWR can handle at lease 3 degrees of elevation change.					0.20			0.60				0.20	0.65	0.30	0.63	0.70	0.06	0.04	0.02	0.04	0.04
11	WPWR can use different directions of wind.									1.00				0.75	0.50	0.75	0.75	0.08	0.06	0.04	0.06	0.06
12	WPWR cannot fall in 30 mph wind and must handle small impacts.	0.30					0.30					0.30	0.10	0.69	0.86	0.34	0.72	0.08	0.06	0.07	0.03	0.06
	Units	kg	m	Percent	Binary	cm/s	m^3	Integer	Degrees	Integer	mph	mph	Binary	**Total Happiness**					**0.732**	**0.495**	**0.637**	**0.816**
	Best Value	5.5	10	100	1	10	0.05	8	15	5	1	50	1									
	Worst Value	10	4	50	0	6	0.072	1	3	1	30	10	0									
	(TIM) Actual Value 1	2.5	9	80	1	8	0.06	2	10	4	2	40	1									
	Normalized Metric Happiness 1	0.667	0.833	0.600	1.000	0.500	0.545	0.143	0.583	0.750	0.966	0.750	1.000									
	(Kenna) Actual Value 2	7	4	70	0	6	0.05	2	5	3	30	45	1									
	Normalized Metric Happiness 2	0.667	0.000	0.400	0.000	0.000	1.000	0.143	0.167	0.500	0.000	0.875	1.000									
	(Jose) Actual Value 3	10	8	80	1	7.5	0.06	4	10	4	2	20	1									
	Normalized Metric Happiness 3	0.000	0.667	0.600	1.000	0.375	0.545	0.429	0.583	0.750	0.966	0.250	1.000									
	Actual Value 4	6	10	90	1	9	0.06	4	10	4	1	35	1									
	Normalized Metric Happiness 4	0.889	1.000	0.800	1.000	0.750	0.545	0.429	0.583	0.750	1.000	0.625	1.000									

3.3.2 Preliminary analysis of each concept's physical feasibility

Concept 1 – Aragog the Acromantula

This design was made to be compact and spider-like when it moved along the ground. The legs are modeled after Theo Jansen's beach creatures and the wind is collected by a vertical axis wind turbine inspired by a Darrieus wind turbine. The wind power is then translated horizontally by cage gears. The advantage of having a vertical axis wind turbine is that it allows the robot to gather wind from every direction except from directly above or below. A foreseeable problem arises from the development of the wind turbine gear. Having the gear teeth come out of the center may be difficult when machining and/or 3D printing.

Concept 2 – The Bulldozer

Initially, this concept was designed after the way crabs walk along the beach and the multiple leg linkages connected by a 'spine' is most similar to Theo Jansen's animals. The 'spine' acts as the wind catcher in order to move the robot. The wind catcher is connected to several gears on either side of the robot to move the motor. This activates the leg like linkages and the robot begins to move. One of the problems in this design is in the connections of the two sets of legs. The gears to move the leg motors are contained in-between the sets of legs which causes trouble when looking for a place to mount the gears without getting in the way of the motion of the legs. Additionally, the wind turbine is set up in a way that requires a lot of wind to rotate the shaft. This will develop problems when less wind is available motion. Finally, an advantage of this system includes stability in high winds. This advantage comes from the minimal distance between the top of the robot and the ground.

Concept 3 – The Great Bambino

This wind powered walking machine consists of a vertical axis Savonius rotor that is attached to the apparatus, walking legs similar to Theo Jansen's design, and a gear transmission to transfer wind power into mechanical power. A Savonius rotor is chosen because it is oriented vertically and can gather winds coming from all directions. A gear transmission is used in the design to effectively transfer power by using highly efficient, 60° angle. Shafts are used to transfer energy to the legs. Theo Jansen's leg design gives the apparatus high stability, which is a crucial user need. Roller shoes were attached at the end of the joints so that the apparatus can walk on a number of surfaces.

Concept 4 – BooBoo the Bear

This concept has several different features from the other designs, but with subtle twists. The leg design takes after Theo Jansen's holy numbers. The legs create four points of contact with the ground. Each point of contact is made with a 'shoe' that sits at the base of each leg. The shoe allows for the robot to move smoothly along several different surfaces. The shoes also give the advantage of stability at each point of contact with the ground. Another feature of this concept is the wind turbine that takes after the Darrieus-Savonius design. This is a combination of two different wind turbines in which one blade design is rotated by drag and the other blade design is rotated by lift. By utilizing these two blade designs in one, the Darrieus-Savonius creates a very powerful and effective wind turbine. This wind turbine is attached to our robot by hollowing out the rotating shaft, creating a 'cap' that fits over a peg mounted onto the base. This creates valuable stability throughout the entire rotating rod.

3.3.3 Final summary

Winner: Concept 4 – BooBoo the Bear

This concept had several advantages over the other three designs. It can obtain wind from several different directions (unlike Concept 2), it is more stable than Concept 3, and it has an improved wind turbine design from Concept 1. The design is simple enough to be almost 100% 3D printable which, using the right plastic, can be made from recyclable material. This design, although it is most like Concept 1, has the same shoe design from Concept 3 making it stable upon several different surfaces. Also, in this design, the translation of the vertical rotation motor to the horizontal rotating leg motors involved a more efficient and successful process than Concept 1, 2, and 3. One final feature that was further evolved and more effective than the other designs was the attachment of the wind turbine to the main body. As talked about in the description of Concept 4, the act of rotating about a shaft that is contained within the wind turbine allows for stability along the entire vertical shaft, rather than stability at the base of the shaft as in Concept 1 and 3.

3.4 *Performance Goals*

The wind powered walking robot had the following performance goals:

1. WPWR has a volume less than .072 m^3
2. WPWR has a mass less than 10 kg.
3. WPWR can walk over 4 m.
4. WPWR has a minimum speed of 6.7 cm/s
5. WPWR is made with more than 50% recyclable material.
6. WPWR can be recycled in St Louis.
7. WPWR can walk over multiple surfaces.
8. WPWR can handle more than 3 degrees of elevation change.
9. WPWR utilizes multiple wind directions.
10. WPWR is stable in 30 mph wind and can handle small impacts.

4 Embodiment and fabrication plan

4.1 Embodiment drawing

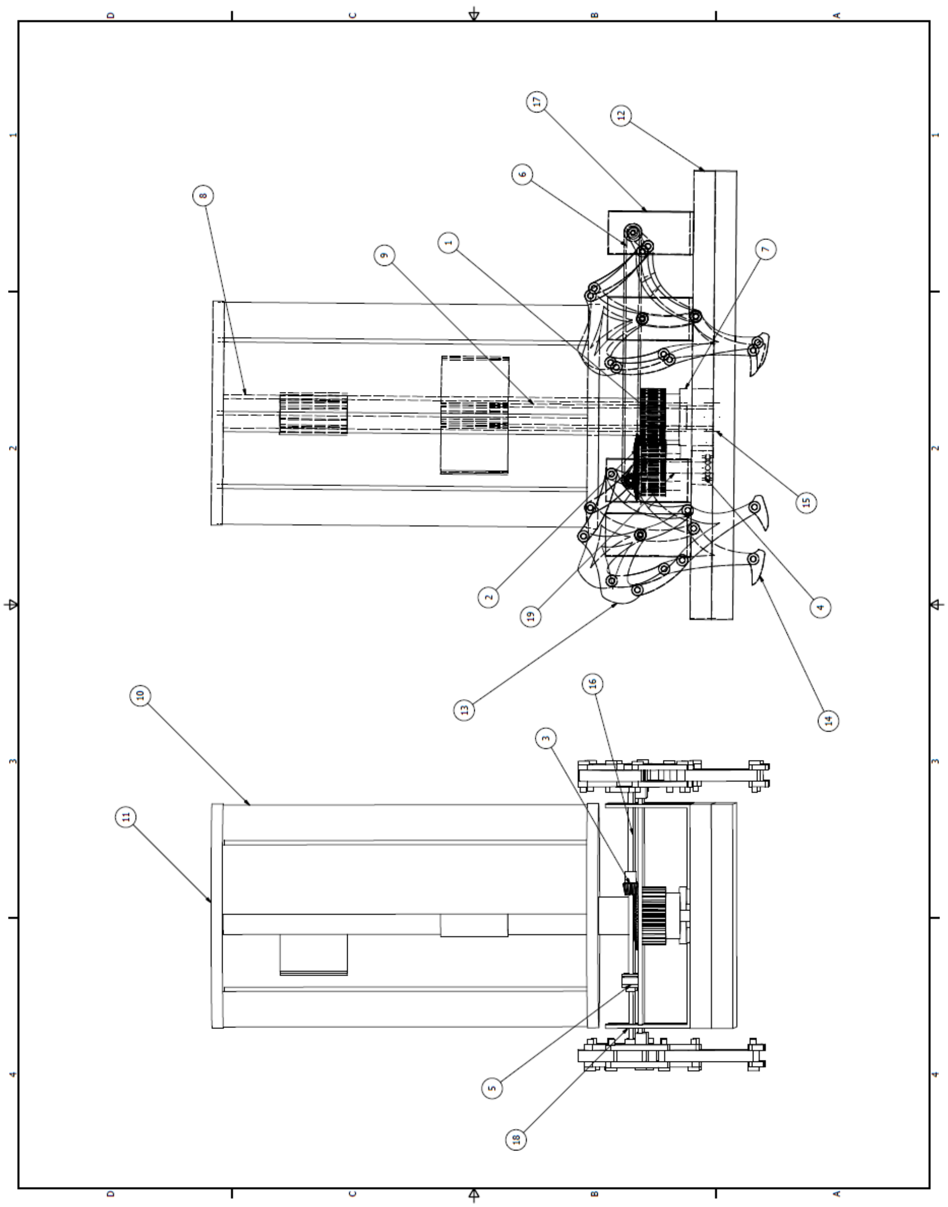


Figure 9 – Front and Right View of Embodiment Design

4.2 Parts List

Table 6 – Parts List with Cost and Part Number

Number	Part Name	Company	Part Number	Cost/Part	Number of Pieces	Total Cost
1	Gear 1	McMaster	57655K57	$ 14.97	2	$ 29.94
2	Gear 2	SDP-SI	A 1M 3MYZ1060	$ 4.29	1	$ 4.29
3	Pinion for Gear 2	SDP-SI	A 1M 3MYZ1012	$ 1.45	1	$ 1.45
4	Ball Bearing (10 mm ID)	McMaster	5972K326	$ 4.80	2	$ 9.60
5	Timing Belt Pulley	McMaster	1375K36	$ 9.42	2	$ 18.84
6	Timing Belt	McMaster	1679K176	$ 5.47	1	$ 5.47
7	Magnets	K&J Magnetics INC	RY0X04	$ 16.44	2	$ 32.88
8	Outer Shaft	Home Depot	202300506	$ 1.98	1	$ 1.98
9	Inner Shaft	Home Depot	202300504	$ 1.28	1	$ 1.28
10	Blades	Machined	-	$ -	4	$ -
11	Plates	3D Printed	-	$ 15.98	2	$ 31.97
12	Base	Home Depot	100322335	$ 7.48	1	$ 7.48
13	Leg	3D Printed	-	$ 6.14	4	$ 24.58
14	Rubber Feet	Stock	-	$ -	4	$ -
15	Inner Shaft Stabilizer	3D Printed	-	$ 0.84	1	$ 0.84
16	Horizontal Rotating Shaft	McMaster	6940T11	$ 7.21	4	$ 28.84
17	L-Bracket	Home Depot	100374962	$ 2.57	8	$ 20.56
18	Ball Bearing (4mm ID)	McMaster	7804K129	$ 7.46	4	$ 29.84
19	Vertical Rotating Shaft	McMaster	4634T36	$ 1.72	1	$ 1.72
TOTAL						$ 251.55

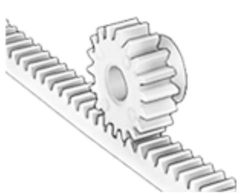
Table 7 – Parts List with Material and Estimated Weight

Number	Part Name	Material	Weight (kg)
1	Gear 1	Nylon	0.11
2	Gear 2	Acetal	0.019
3	Pinion for Gear 2	Acetal	0.018
4	Ball Bearing (10 mm ID)	Steel	
5	Timing Belt Pulley		
6	Timing Belt	Urethane	
7	Magnets	Neodymium	
8	Outer Shaft	PVC	0.173
9	Inner Shaft	PVC	0.044
10	Blades	Carboard & Paper	
11	Plates	ABS	0.666
12	Base	Douglas Fir	2.78
13	Leg	ABS	0.256
14	Rubber Feet	Rubber	0.028
15	Inner Shaft Stabilizer	ABS	0.035
16	Horizontal Rotating Shaft	6061 Aluminum	0.032
17	L-Bracket	Sheet Metal	0.944
18	Ball Bearing (4mm ID)	Stainless Steel	
19	Vertical Rotating Shaft	6061 Aluminum	0.015
TOTAL			5.12

4.3 Draft detail drawings for each manufactured part

1. **Gear 1**

Molded Nylon 14-1/2 Degree Angle Spur Gear
16 Pitch, 30 Teeth, 1.875" Pitch Diameter, 63/64" Bore



Each
ADD TO ORDER

In stock
$14.97 Each
57655K57

Number of Teeth	30
Pitch Diameter (A)	1.875"
Hub Diameter (B)	1 5/8"
OD (C)	2.00"
Overall Length (D)	1 3/8"
Face Width	7/8"
Bore Size	63/64"
Additional Specifications	Spur Gears 16 Pitch

2. Gear 2

Part Number: A 1M 3MYZ1060
1:5 Ratio / 1 MOD Bevel Gear Set With Mating Gear ->A 1M 3MYZ1012 (Sold Separate)

CAD Model | Catalog Page | Share | Email

Gear Ratio /mod.	1:5 / 1 Module
Teeth (pinion / Gear)	12/60 (Sold as Each)
Drawing Choice/mat'l	Gear (Acetal)
Bore /hub Style	10 / Plain Hub
Mating Part# / Bore	A 1M 3MYZ1012(4)
Pitch Dia.	60
Face Width	9.5
Overall Width	17.4
Pressure Angle	20 Degree
Mounting Distance	21

Quantity	**Price (USD)**
1 to 24	$4.29
25 to 99	$3.88
100 to 249	$3.51
250 to 999	$3.35
1000 and Up	$3.15

Availability 3 from stock.
Sell Unit Each
Quantity 1 Add to Cart

For breaks not shown or out of stock items, please call or email our sales department for delivery schedule and higher price breaks.
Phone: (800) 819-8900X491 Fax: (516) 326-8827 Email: sdp-sisupport@sdp-si.com

3. Pinion for Gear 2

Part Number: A 1M 3MYZ1012
1:5 Ratio / 1 MOD Bevel Gear Set With Mating Pinion ->A 1M 3MYZ1060 (Sold Separate)

CAD Model | Catalog Page | Share | Email

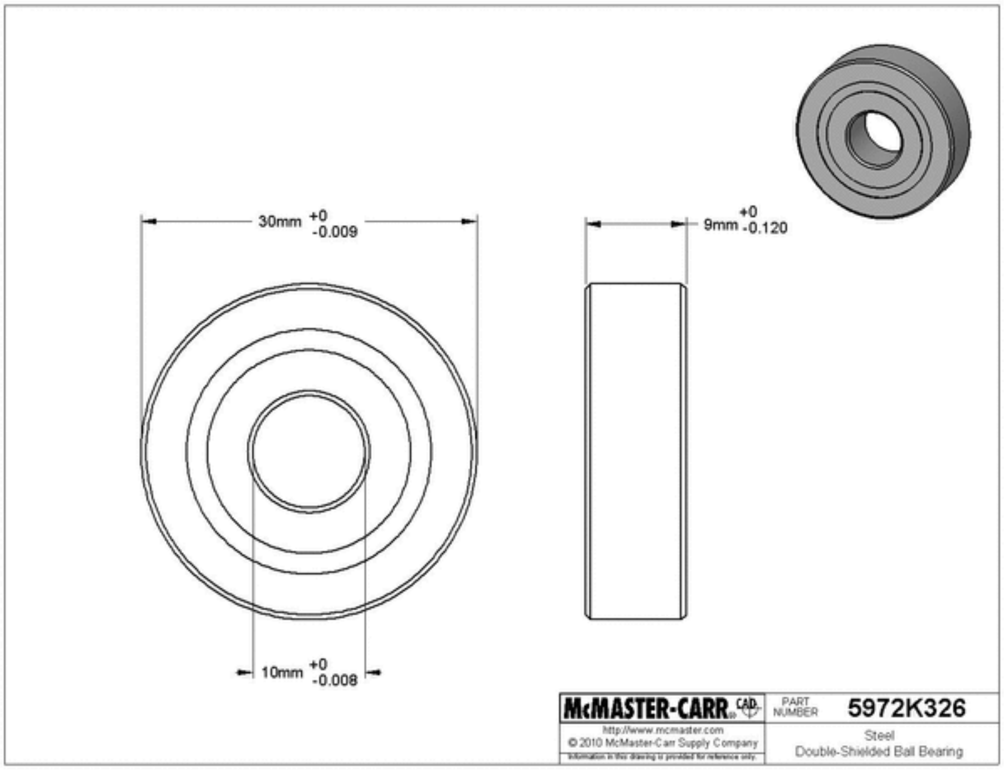
Gear Ratio /mod.	1:5 / 1 Module
Teeth (pinion / Gear)	12/60 (Sold as Each)
Drawing Choice/mat'l	Pinion (Acetal)
Bore /hub Style	4 / Plain Hub
Mating Part# / Bore	A 1M 3MYZ1060(10)
Pitch Dia.	12
Face Width	9.5
Overall Width	20.3
Pressure Angle	20 Degree
Mounting Distance	40.5

Quantity	**Price (USD)**
1 to 24	$1.45
25 to 99	$1.17
100 to 249	$1.01
250 to 999	$.92
1000 and Up	$.80

Availability 16 from stock.
Sell Unit Each
Quantity 1 Add to Cart

For breaks not shown or out of stock items, please call or email our sales department for delivery schedule and higher price breaks.
Phone: (800) 819-8900X491 Fax: (516) 326-8827 Email: sdp-sisupport@sdp-si.com

4. **Ball Bearing** (10 mm ID)



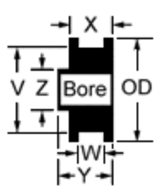
5. **Timing-Belt Pulley**

Mxl and XL Series Timing-Belt Pulley

1/4" Belt Width, .635" OD, 18 Teeth

Each
ADD TO ORDER

In stock
$9.42 Each
1375K36



OD	0.635"
Number of Teeth	18
Bore Size	3/16"
Pitch Diameter (V)	0.458"
(Z)	0.312"
(W)	0.29"
(X)	0.389"
(Y)	0.625"
Additional Specifications	Pulleys for MXL (Miniature Extra Light) Series Timing Belts—0.080" Pitch Fit 1/4" Belt Wd.

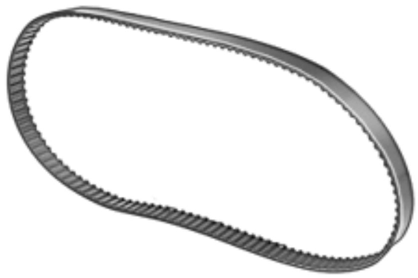
These small, lightweight pulleys fit your MXL and XL series timing belts. All are flanged (unless noted) and have a finished bore with set screw(s).

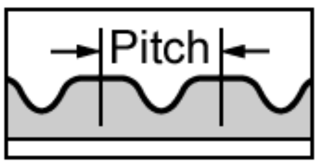
All are made of anodized aluminum.

6. Timing Belt

Trapezoidal Tooth Urethane Timing Belt

.080" Pitch, Trade Sz235mxl, 18.8" Outer Circle, 1/4" Wide





Each ADD TO ORDER

In stock
$5.47 Each
1679K176

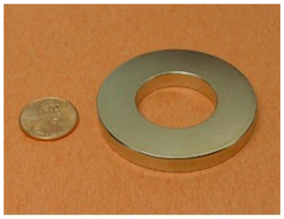
Trade Size	235MXL
Outer Circle	18.8"
Number of Teeth	235
Additional Specifications	1/4" Wide Urethane—Reinforcing cords are Kevlar.

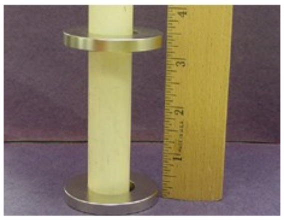
These trapezoidal-tooth MXL (Miniature Extra Light) belts mate with grooves in timing-belt pulleys. For use in a fully synchronized drive system. Have a 0.080" pitch. Color is black.

Urethane—These nonmarking belts run cleaner and are more chemical resistant than neoprene.

7. Magnet

RY0X04





Description | Technical | Downloads

Dimensions: 2" od x 1" id x 1/4" thick
Tolerances: ±0.004" x ±0.004" x ±0.004"
Material: NdFeB, Grade N42
Plating/Coating: Ni-Cu-Ni (Nickel)
Magnetization Direction: Axial (Poles on Flat Ends)
Weight: 2.55 oz. (72.4 g)
Pull Force, Case 1: 39.61 lbs
Pull Force, Case 2: 158.3 lbs
Max Operating Temp: 176ºF (80ºC)
Brmax: 13,200 Gauss
BHmax: 42 MGOe

These large rings are very strong and good for a variety of applications and experiments. They must be handled with care as they will pinch fingers and probably break if they are allowed to slam together.

Price: $16.81

8. Outer Shaft

VPC | Model # 2201 | Internet # 202300506 | Store SKU # 254977

1 in. x 2 ft. PVC Sch. 40 Pipe

Write the First Review +

$1.98 / each

Pick Up In Store FREE
Available for Pick Up: Today

148 In stock at:
Southtown #3011
Change Pick Up Store

1 | ADD TO CART | SAVE TO MY LIST

IN STOCK AT YOUR SELECTED STORE

Southtown #3011
Saint Louis, MO 63139
Change Pick Up Store +

148 In Stock

9. Inner Shaft

VPC | Model # 22015 | Internet # 202300504 | Store SKU # 253755

1/2 in. x 2 ft. PVC Sch. 40 Pipe

Write the First Review +

$1.28 / each

Pick Up In Store FREE
Available for Pick Up: Today

189 In stock at:
Southtown #3011
Change Pick Up Store

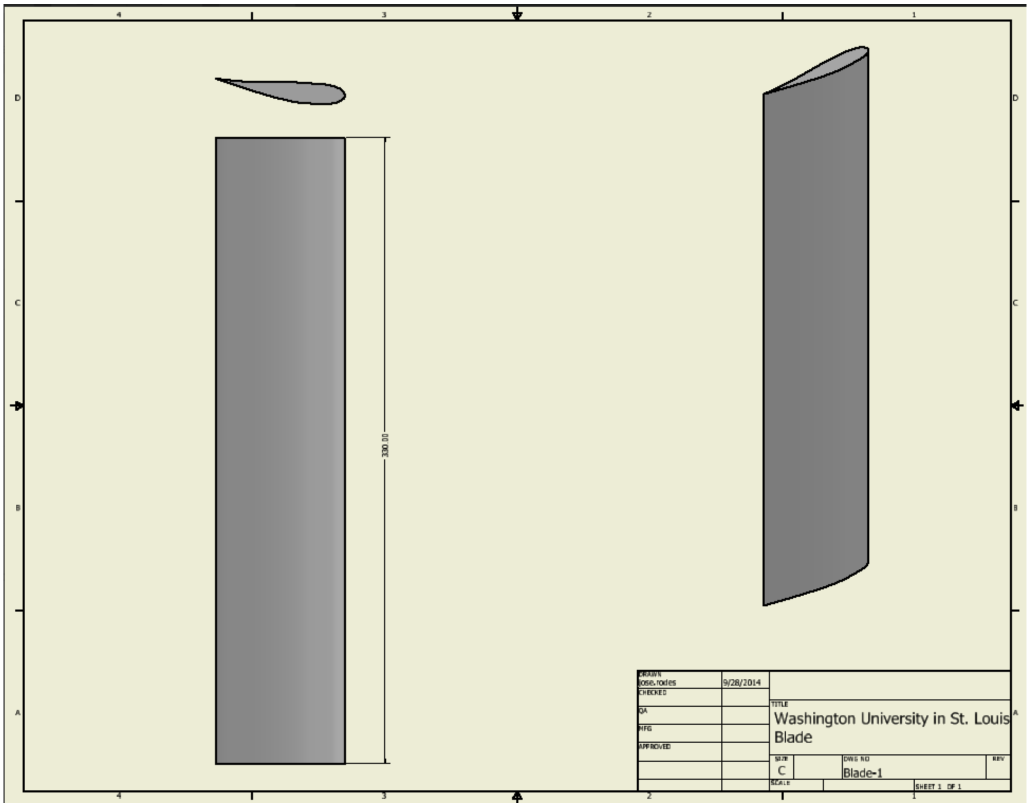
1 | ADD TO CART | SAVE TO MY LIST

IN STOCK AT YOUR SELECTED STORE

Southtown #3011
Saint Louis, MO 63139
Change Pick Up Store +

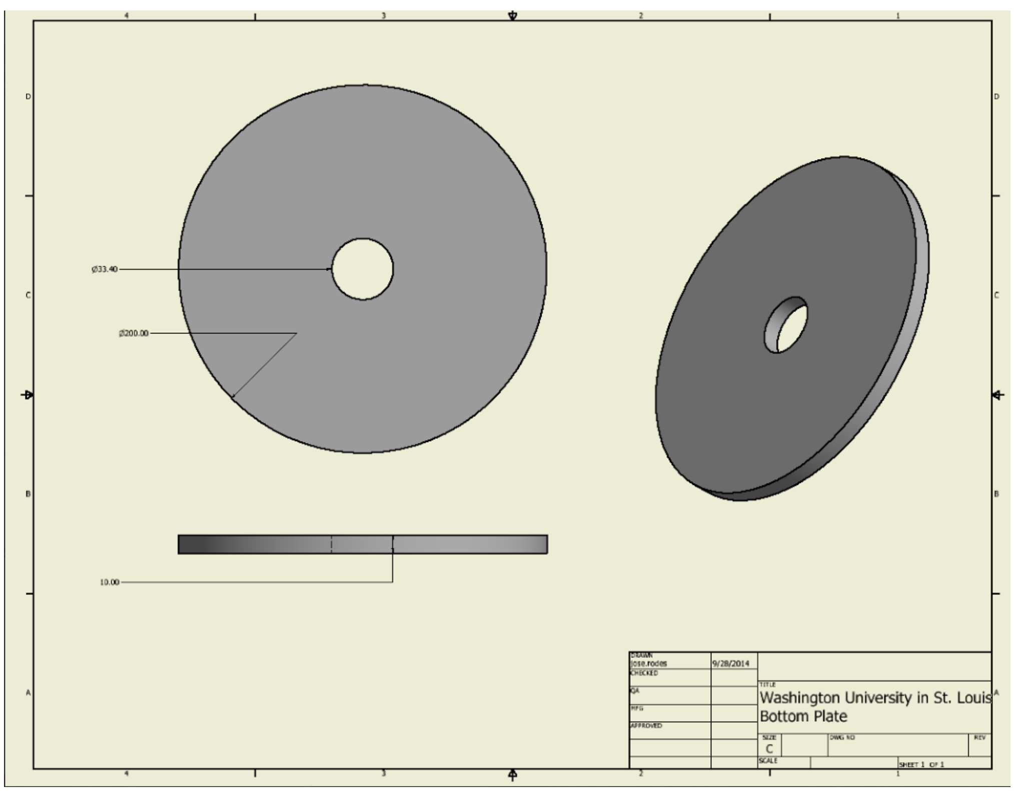
189 In Stock

10. Blades

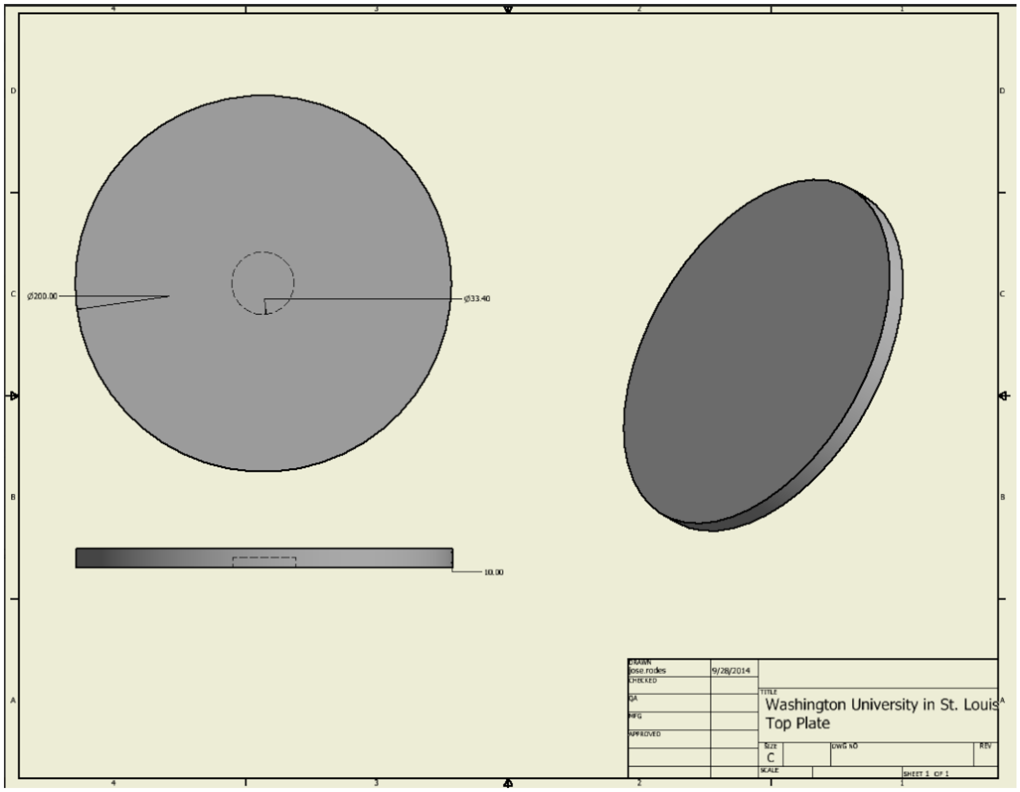


11. Plates

a. Bottom Plate

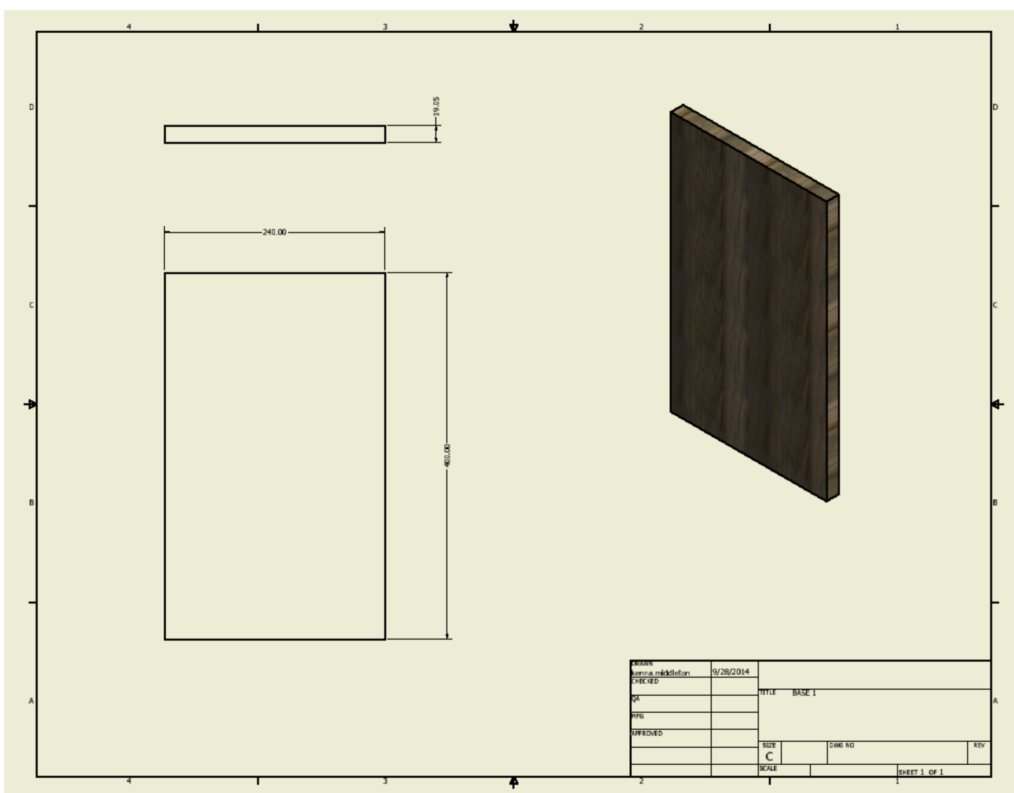


b. **Top Plate**

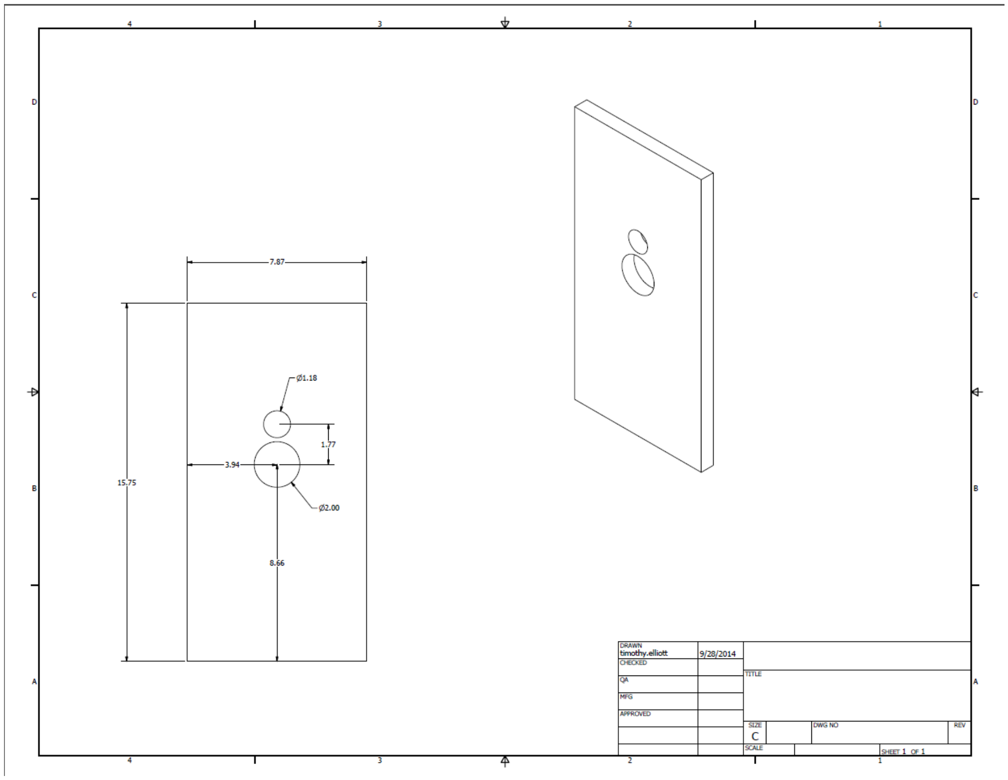


12. Base

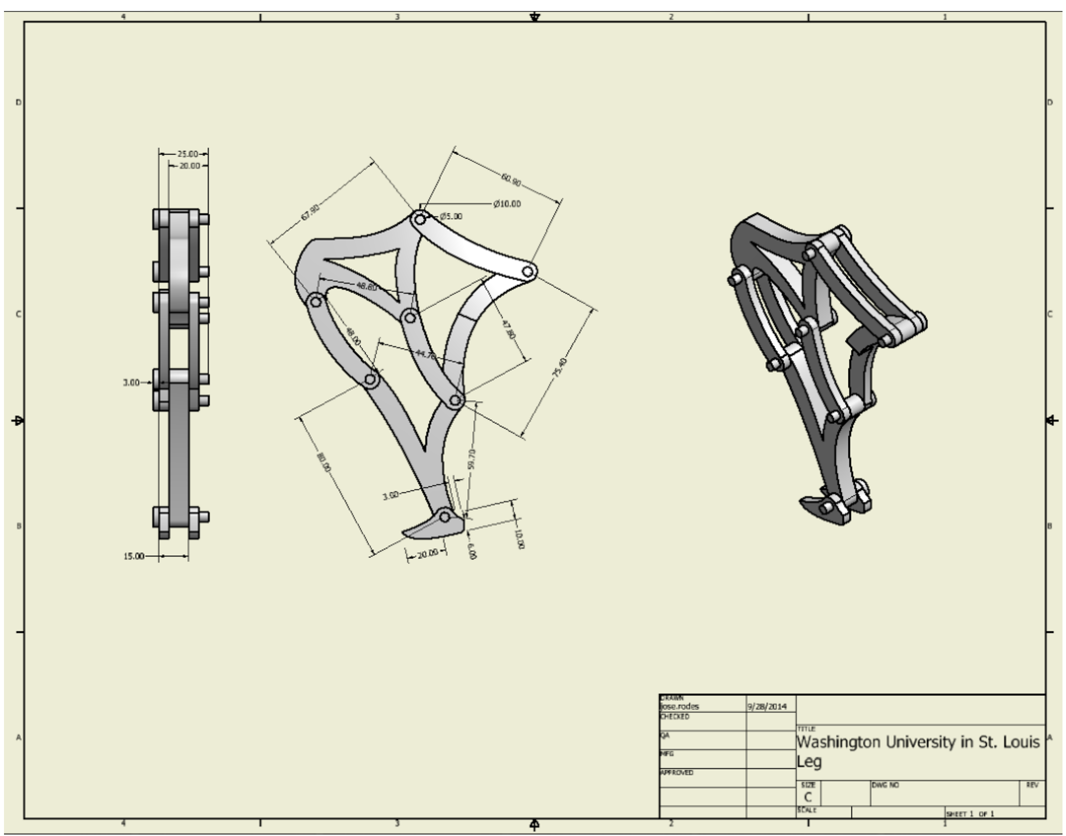
a. **Base 1**



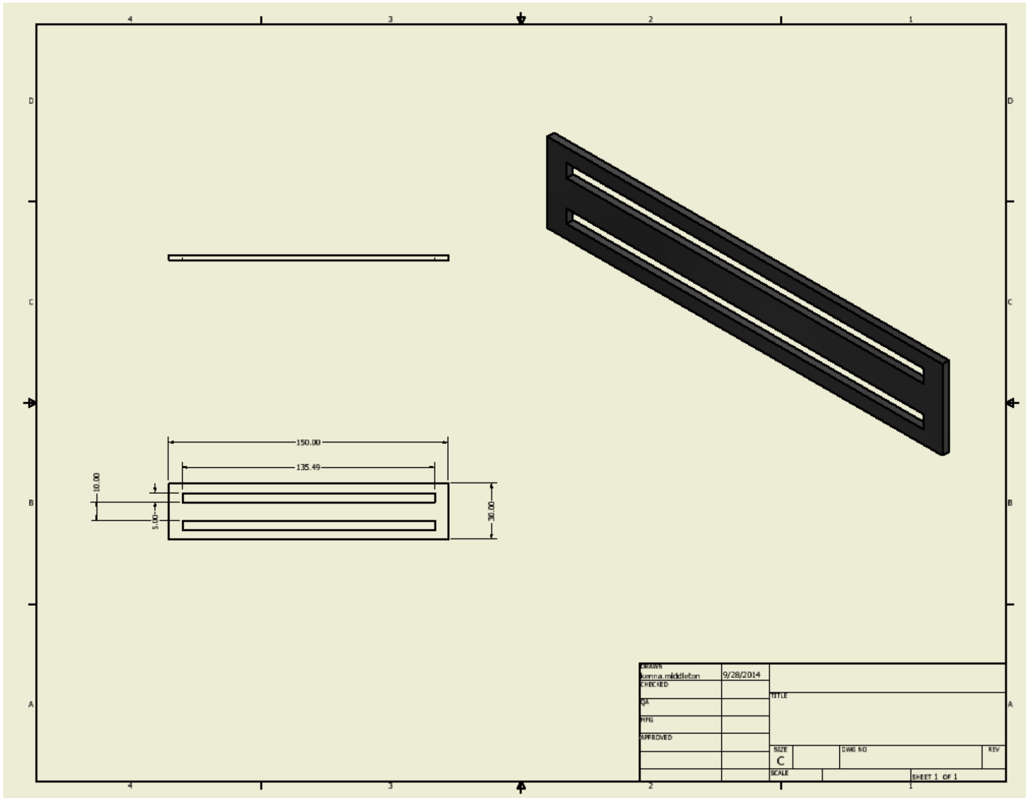
b. **Base 2**



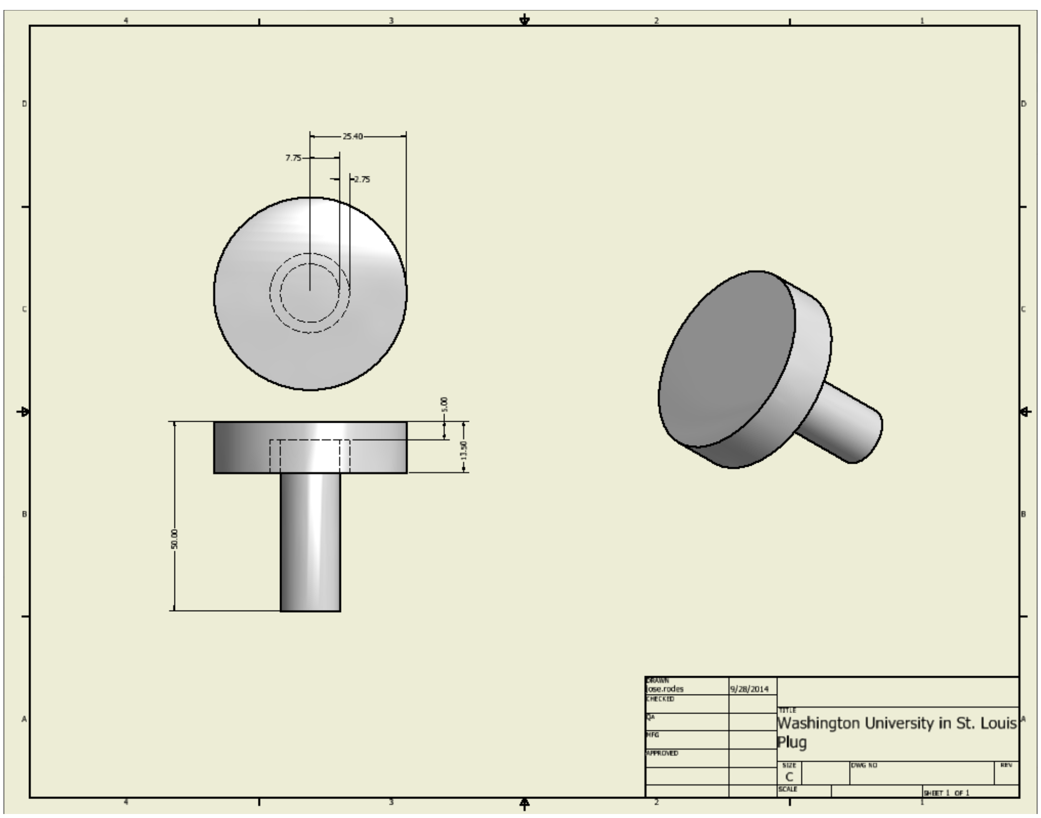
13. Leg



14. Rubber Feet

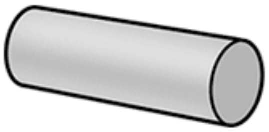


15. Inner Shaft Stabilizer



16. Horizontal Rotating Shaft

Multipurpose 6061 Aluminum
Tight-Tolerance Rod, 4mm Diameter



Each
ADD TO ORDER

In stock
$7.21 Each
6940T11

Diameter	4 mm
Diameter Tolerance	±0.013 mm
Length	1 ft.
Yield Strength	40,000 psi
Hardness	Soft (95 Brinell)
Temper	Heat Treated (T6511, except 4 to 6 mm are T6)
Additional Specifications	Tight-Tolerance Metric Rods—Precision Ground Meet ASTM B221, except 4 to 6 mm meet B211

17. L-Bracket

Simpson Strong-Tie | Model # A33 | Internet # 100374962 | Store SKU # 461458

A33 12-Gauge Angle

★★★★★ (1) | Write a Review + | Questions & Answers (1) +

$2.57 / each

Ship to Home FREE with $45 Order
Estimated Arrival: OCT 6 - OCT 8

Pick Up In Store FREE
Available for Pick Up: Today

1 | ADD TO CART | SAVE TO MY LIST

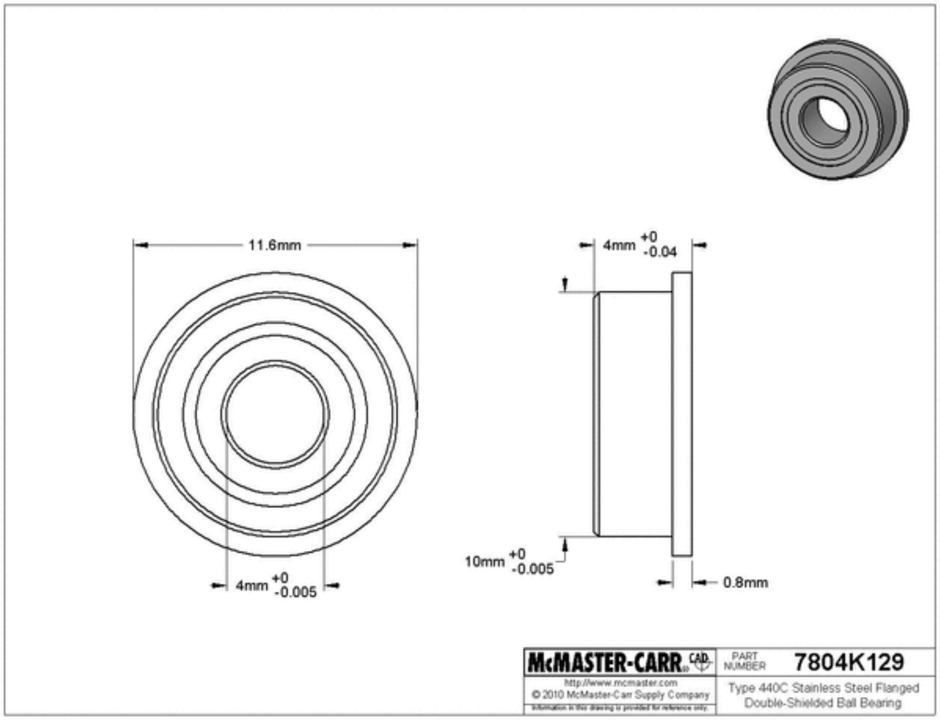
Item cannot be shipped to the following state(s): AK,GU,HI,PR,VI

IN STOCK AT YOUR SELECTED STORE

Southtown #3011
Saint Louis, MO 63139
Change Pick Up Store +

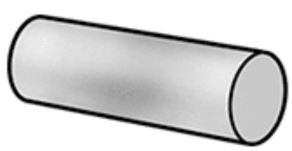
99 In Stock
Aisle 25, Bay 0FL

18. Ball-Bearing (4mm ID)



19. Vertical Rotating Shaft

Multipurpose 6061 Aluminum
10 mm Diameter



Length, ft.
✓1

Each

ADD TO ORDER

In stock
$1.72 Each
4634T36

Diameter	10 mm
Diameter Tolerance	±0.20 mm
Length	1 ft.
Yield Strength	35,000 psi
Hardness	Soft (80 Brinell)
Temper	Heat Treated (T6)
Additional Specifications	Metric Rods—Unpolished Meet ASTM B221

4.4 *Design Rational*

4.4.1 Power Required to Move the Leg

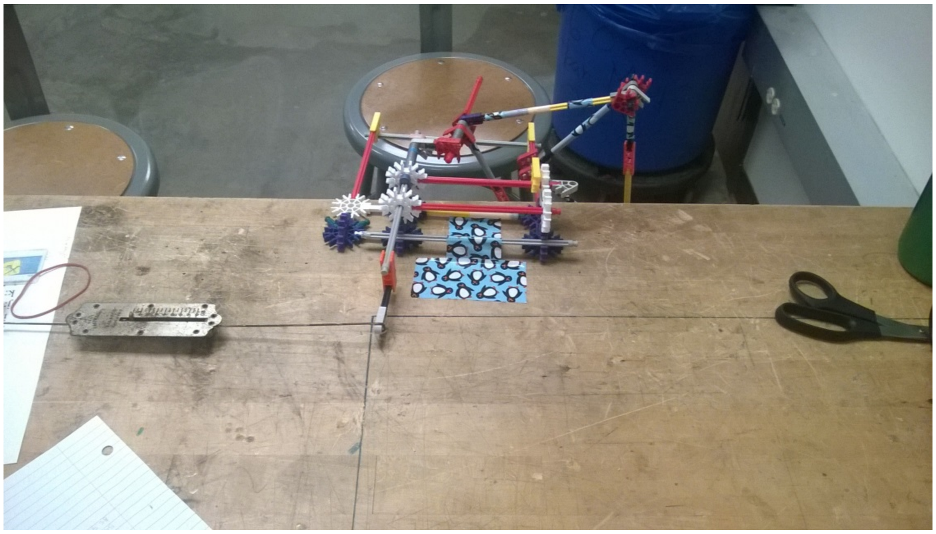


Figure 10 - Equipment setup to gather power required for the leg's movement

In the picture above, we created a prototype of the Jansen's leg. By doing this, we were able to calculate the power required to move the leg. A spring scale was connected to the driveshaft and measured the force needed to move the crank. As seen in figure 11, a maximum force of 3 ounces was required to move the leg. The length of the orange connector on the crank was measured to determine the torque required to drive the leg.

$$\tau = F_{applied} d_{connector} = (0.84\ N)(0.02024\ m) = 0.017\ Nm$$

Now, the power required will depend on the angular velocity of the crank. Based on the client wanting the machine to walk 4 meters in one minute, we assume the Jansen's leg will have to move at roughly1 Hz or 2π rad/s. Thus,

$$P_{leg} = \tau\omega = (0.017\ Nm)\left(2\pi\,\frac{rad}{s}\right) = 0.1068\ W$$

Since there are four legs in our walking machine, we will need 4 times the amount of power. So, the total power required is 0.4273 W. Of course, we are only taking into account the power required to move the prototype. Our assembly might be slightly heavier and this could increase the power needed. We are also forgetting the power drawn by friction and the power needed to overcome the weight of the machine since the power measured was obtained with a leg that was not bearing any weight.

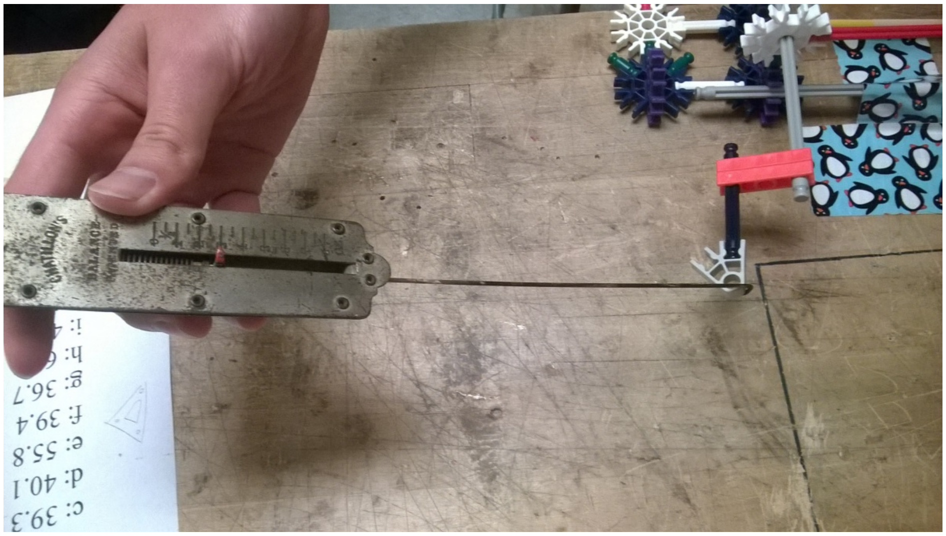


Figure 11 - Measurement of the force required to turn the crank hooked up to Jansen's Leg

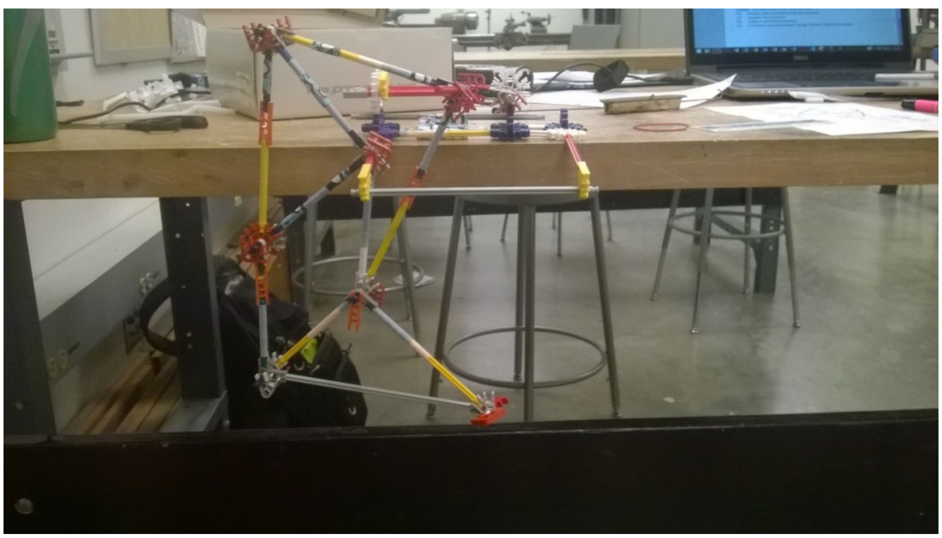


Figure 12 - Jansen's Leg prototype

4.4.2 Vertical Axis Wind Turbine

According to *Wind Energy Explained: Theory, Design and Application* by J.F. Manwell, the major advantage of vertical axis wind turbine is that there is no need for a yaw system. That is, the rotor can accept wind from any direction. This is why we chose a vertical axis wind turbine. The blades were designed using an airfoil simulation from a NASA Java applet called FoilSim III[1]. This applet simulates airfoil exposed to different air velocities and altitudes. It generates a series of points that surrounds an airfoil. These points can then be scaled and connected using CAD software to model the blades. Using airfoil cross-section for the blades, we are ensuring the most aerodynamic wind turbine.

[1] http://www.grc.nasa.gov/WWW/k-12/airplane/foil3.html

5 Engineering analysis

5.1 Engineering analysis proposal

ANALYSIS TASKS AGREEMENT

PROJECT: Wind Walker Group 1

NAMES: Kenna Middleton, Jose Rodes, Tim Elliott

INSTRUCTOR: Mark Jakil

The following engineering analysis tasks will be performed:

Before the prototype:

1. Gear analysis
   a. WHY: This will allow us to understand the power lost from the wind turbine to the leg linkages. Knowing the maximum allowed power lost will help us to choose the correct design for the gear system.
   b. HOW: We will use the gear analysis section in the book required for the Machine Elements class taught in the spring of 2014.
2. Wind Turbine analysis
   a. WHY: We need to pick the correct material for the wind turbine to maximize the power utilized.
   b. HOW: We will be using derived formulas from the book *Wind Energy Explained: Theory, Design, and Application* by J. F. Manwell. This book also contains recommended materials for wind turbine design.
3. Material and Construction
   a. WHY: In order to make the robot over 50% recyclable, we need to research and analyze what material is available to us and feasible for our customer requirements.
   b. HOW: We will research the available recyclable location within the greater St. Louis area. Additionally, we will research the advantages of using the materials and the building techniques required for their manufacture.

After the prototype:

1. Analyze the power efficiency of the Jansen leg design
   a. WHY: This will further our analysis of the power needed from the wind to drive our robot. This will also answer our question: How much power is needed to drive the legs?
   b. HOW: move the leg linkages with a rubber band or spring and calculate the force needed to move the legs using the spring constant. From here we can derive the energy lost.
2. Joint and Bearing Selection
   a. WHY: Choosing the joint and bearings used in the leg linkage design have a direct impact on the efficiency of the robot.
   b. HOW: By utilizing the Machine Elements textbook along with the power efficiency analysis from the prototype, we will be able to determine the best joint and bearings choices.

OK

Mark J. Jakiela

Mark JAKIELA

23 SEP. 2014.

Figure 13 – Signed Copy of Analysis Proposal by Customer, Page 1

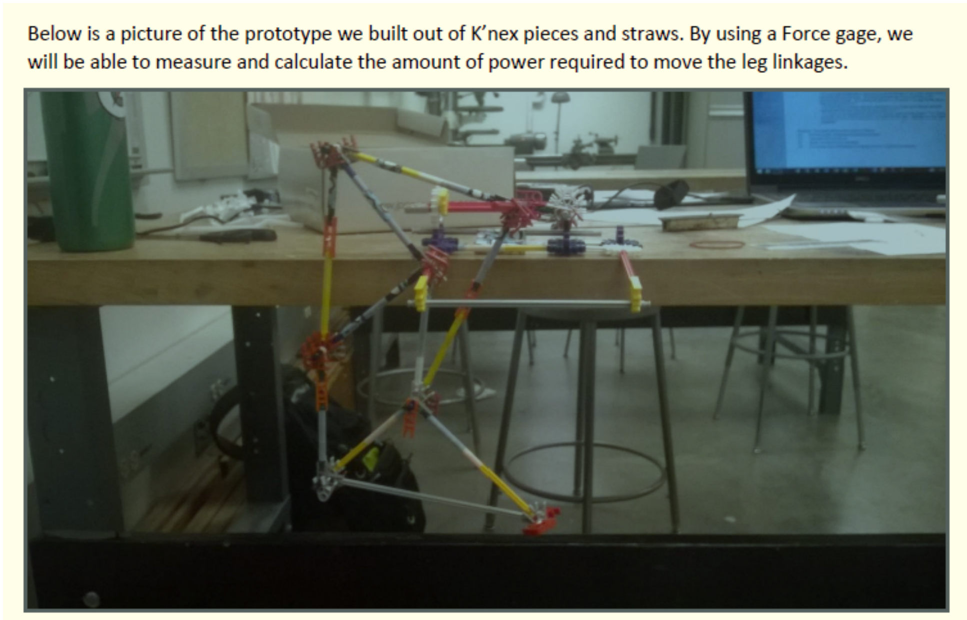

Below is a picture of the prototype we built out of K'nex pieces and straws. By using a Force gage, we will be able to measure and calculate the amount of power required to move the leg linkages.

Figure 14 – Signed Copy of Analysis Proposal by Customer, Page 2

5.2 *Engineering analysis results*

5.2.1 Motivation

For our wind walking robot, the most important factors in its success is calculating the amount of energy lost in the leg and gear design and comparing that to the maximum amount of energy obtained from the wind by our turbine. These two analyses help us determine specific parameters allowing for further calculations to take place.

5.2.2 Summary of analysis

In order to make our wind powered robot to walk, we decided to do two prototypes: kinetic legs and paper/cardboard rotor. These prototypes will help us determine the power acquired from the wind as well as the torque required to move a leg. In order to obtain these values, we used the definition of torque and, with a spring, determined how much torque was needed to move the leg. Then, in the turbine prototype, we taped a piece of paper to one of the blades and determined the angular velocity of the turbine by counting how many times the piece of paper passed as the turbine rotated due to the wind. We compared this value with the actual velocity of the wind and determined the power coefficient of the turbine. All of these values will be shown in the results section.

Later in the process, after our first prototype was done, we had some issues with the stability and torque transmission. As a result, we calculated how much load the legs were taking, the gear transmission required for transferring torque to the legs, and how much power was in the wind. Again, these will be shown in detail in the results section. Below are some pictures of our prototypes.

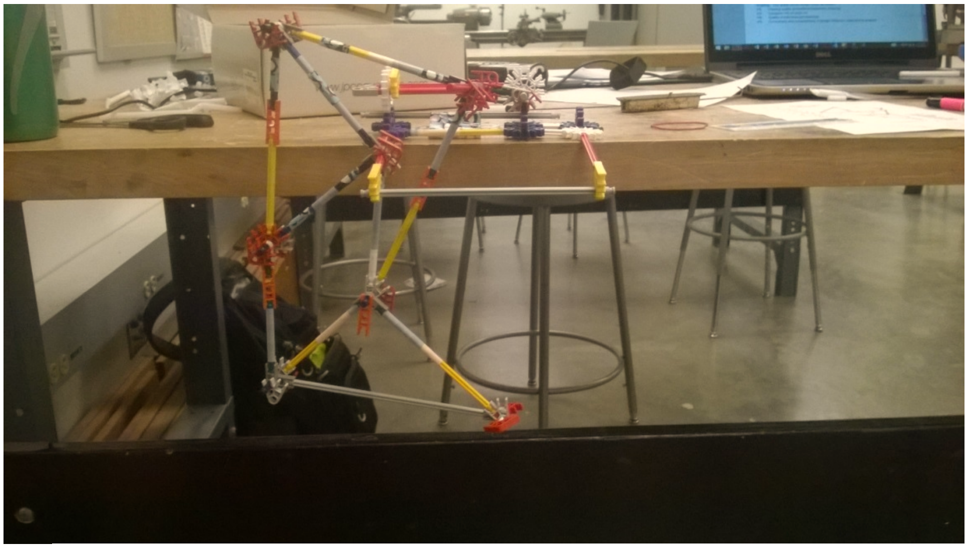


Figure 15 – Jansen's Leg Prototype

Figure 16 – Turbine Prototype

5.2.3 Methodology

For both our prototypes, we obtained useful data that helped us build our final prototype. First, we built a turbine prototype out of paper and cardboard. After a couple of testing rounds, we noticed that our turbine paper shaft was having a lot of stability difficulties and the blades were bending a lot. Nevertheless, we got a maximum rotational speed of about 2 Hz or 12.57 rad/s.

The power in the wind is defined as

$$P_{wind} = \frac{1}{2}\rho A V^3 = 16.86\ W$$

The coefficient of power was calculated using the following equation

$$P_{turbine} = \frac{1}{4\pi} H \Omega_{rotor} R \rho B c U_{rel}^2 \int_0^{2\pi} C_d \cos\left(\frac{2}{3\frac{\Omega R}{V_{wind}}}\cos(\phi)\right) d\phi$$ [2]

$$U_{rel}^2 = V_{wind}^2 \left(\frac{4}{9} + \left(\frac{\Omega R}{V_{wind}}\right)^2\right)$$

Where C_d=0.8 and V_{wind}=6.4 m/s. Using the parameters of our design, we got a power of 0.133 W or 0.1 ft.lbf/s.

Table 8 – Parameters and Associated Values

PARAMETERS	VALUE
Blade number (B)	5
Height (H) (m)	0.35
Rotor Radius (R) (m)	0.3
Density (ρ) (kg/m³)	1.225
Chord (c) (m)	0.68
Rotor Speed (Ω) (rad/s)	12.57

Gear Transmission

In the initial prototype, we had a 1:2 gear ratio supplying torque to the legs.

$$\frac{N_{shaft\ gear}}{N_{turbine\ gear}} = \frac{T_{shaft\ gear}}{T_{turbine\ gear}} = \frac{1}{2}$$

However, when we tested it, we noticed that even though we doubled the torque on the shaft, it was not enough torque. As a result, we switched our transmission to a worm gear in the final design.

Weight/Torque of the Machine

[2] J.F. Manwell. Wind Energy Explained. 2nd Edition.

The mass of the initial prototype was 0.6 kg, which has a load of 5.886 N. The velocity required for the machine is 4m/min or 0.0667 m/s. Since, by definition, Power=Force x velocity, the power needed to overcome friction and move is 0.393 W. Now, we did a prototype of a leg using k'nex pieces.

In Figure 15, we created a prototype of the Jansen's leg. By doing this, we were able to calculate the power required to move the leg. As seen in Figure 18, a spring scale was used to measure the force needed to move the crank. This was measured to be 3 ounces. We also measured the length of the orange connector on the crank because the length multiplied by the force applied yields the required torque.

$$\tau = F_{applied} d_{connector} = (0.84\ N)(0.02024\ m) = 0.017\ Nm$$

The required power depends on the angular velocity of the crank. We assumed 1 Hz or 2π rad/s. Thus,

$$P_{leg} = \tau\omega = (0.017\ Nm)\left(2\pi\,\frac{rad}{s}\right) = 0.1068\ W$$

Since we have four legs in our walking machine, we will need 4 times the amount of power above. So, the total power required is 0.4273 W. The legs we used in the initial prototype are a bit heavier that the ones we used in this experiment. Also, the turbine and the base of our initial prototype were too heavy for the four legs to handle. This means that more legs and more torque are required in order to lower the loading force in each leg and increase the power driving the legs.

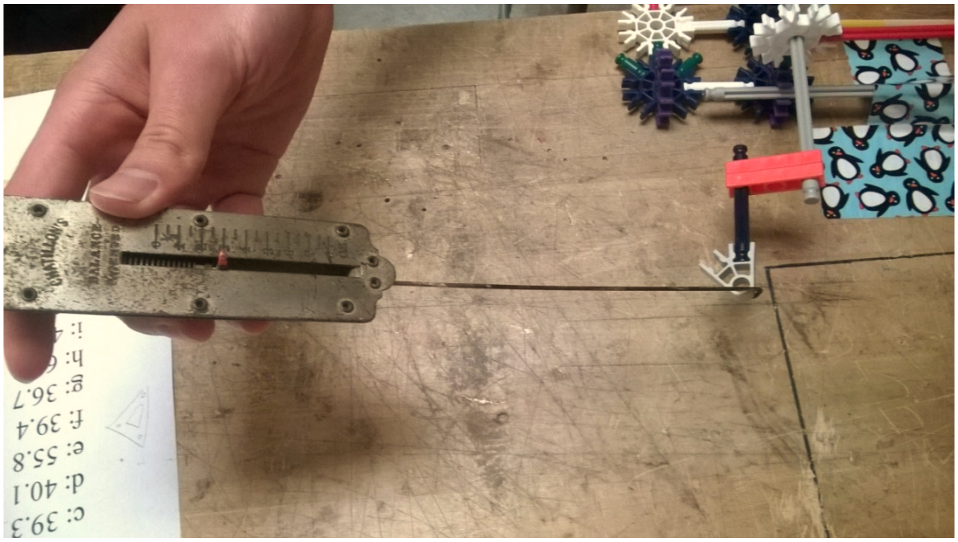


Figure 18 – Analysis of Required Force

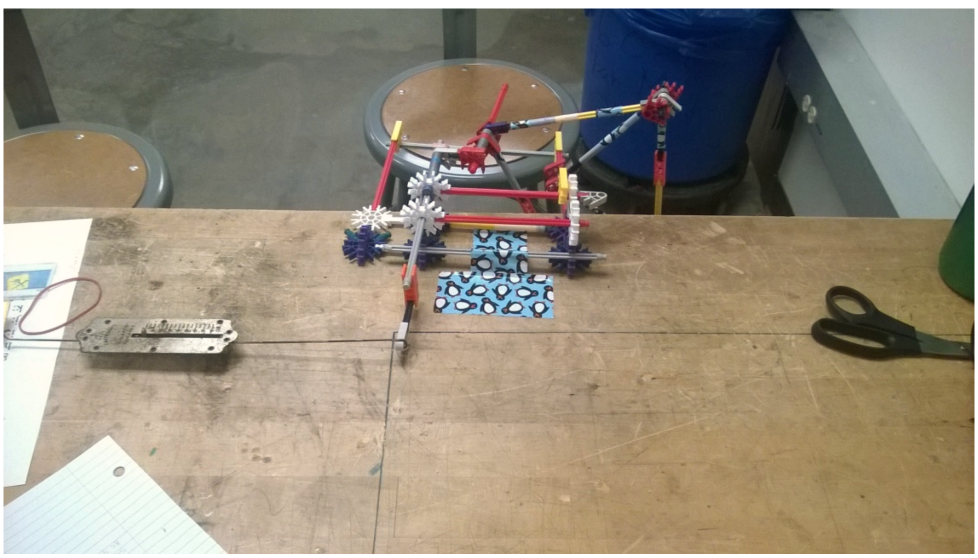


Figure 19 – Measurement of the Force Required to Turn the Crank Hooked Up to Leg Prototype

5.2.4 Results

Based on the calculated tip speed ratio of 0.59, Manwell suggests using a less aerodynamic turbine similar to water pumped windmills, which require much torque. Thus, our final prototype has a turbine with scoops. These scoops, with their large gathering area and long lever arms, catch the air efficiently and provide large torque to the machine.

In our final prototype, we used two Lego worm gears and one Lego spur gear. The worm gears were attached to the shaft of the turbine and the spur gear was attached to the driveshaft of the legs. This system is usually called worm drive and allows for great torque production. In our case, one rotation of the turbine resulted in 1/24th of a rotation of the driveshaft. This large reduction in speed results in a large increase in torque.

Recall that the turbine in our initial prototype produced approximately 0.133 W. Because of the small amount of power that our machine has to work with, we decided to make two major changed for the final prototype. First, we designed everything with great emphasis on weight. Second, we increased the number of legs from 2 pairs to 6 pairs. Both of these changes reduced the amount of load in each leg, which reduced the amount of torque required to drive the leg system.

5.2.5 Significance

For the material choice in the initial prototype, we used a PVC pipe for the turbine. The airfoil blades were laser cut from balsa wood. The frame was also made out of balsa wood. The legs were 3D printed from ABS plastic. The aluminum bars were used to hold the legs together. The gears were laser cut from balsa wood and ceramic magnets were used to provide less friction between the rotor and the frame. There are also standing legs to provide more stability on the machine and reduce the weight that each driven leg has to support.

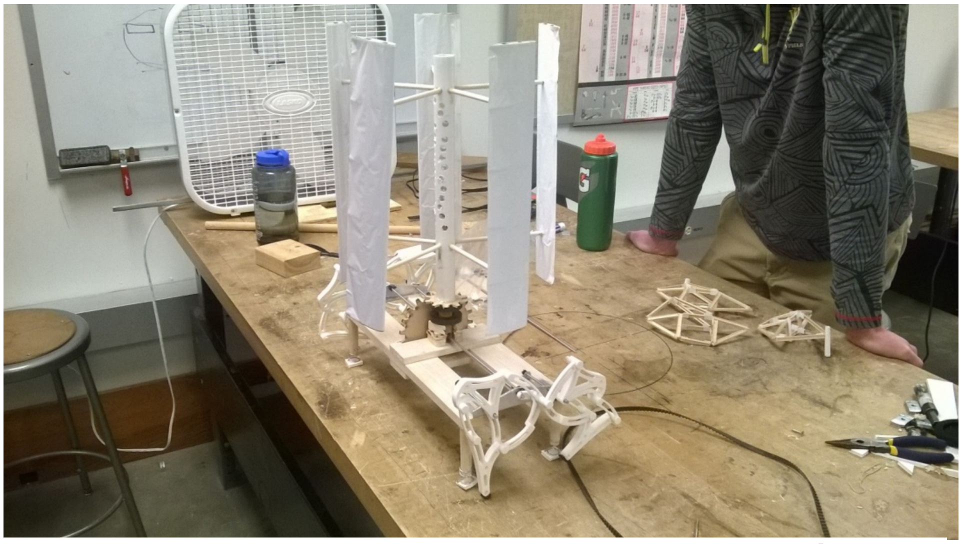


Figure 20 – Initial Prototype

The final prototype is completely different from the initial prototype because the design needed a big overhaul. The need for weight reduction and increased stability led to the changes. The material choices of the final prototype were much more lighter (balsawood, paper, cardboard, Lego pieces and thin plastic).

Figure 21 – Final Prototype

5.2.6 Codes and Standards

Due to the nature of this project, there were no codes or standards that were present to influence any revisions to our designs.

6 Working prototype

6.1 Preliminary working prototype

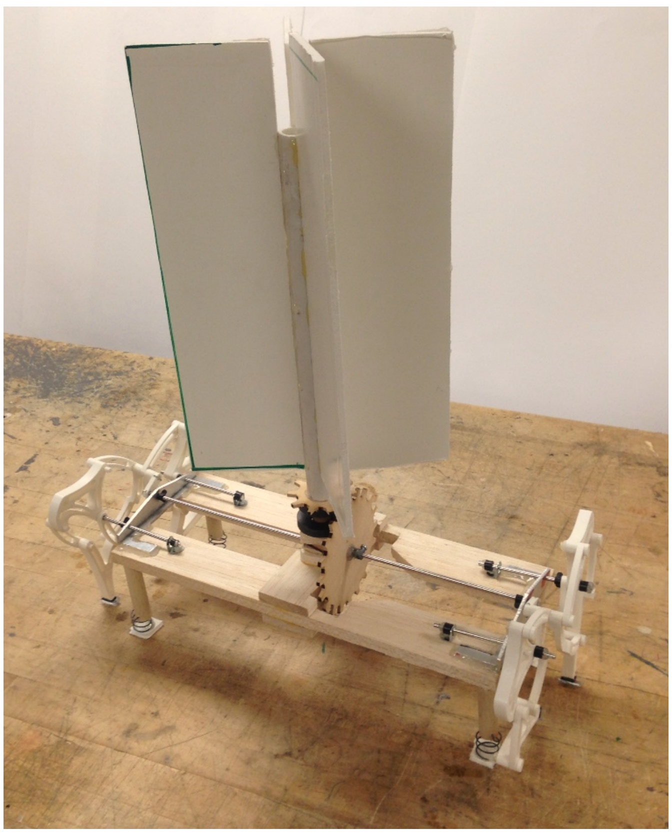


Figure 22 – Preliminary Working Prototype

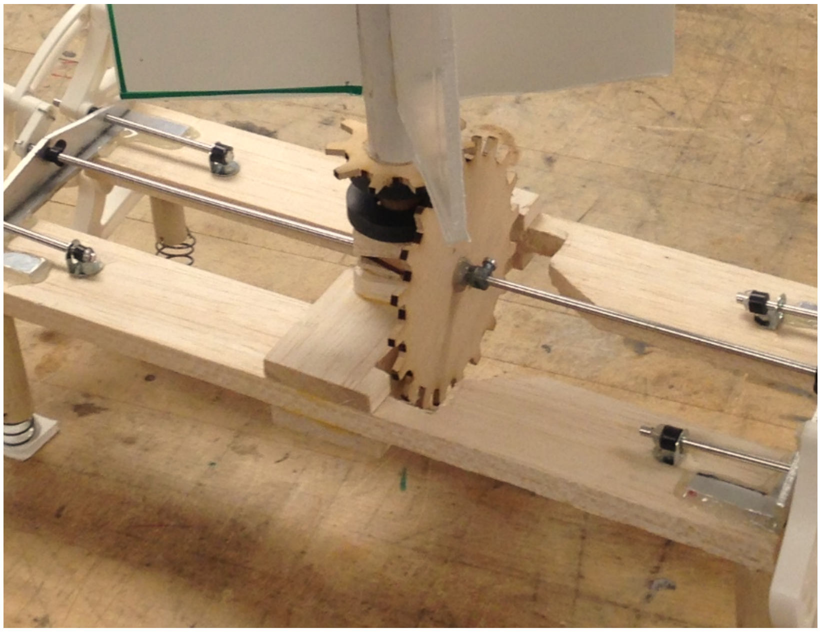


Figure 23 – Gear System for Preliminary Prototype

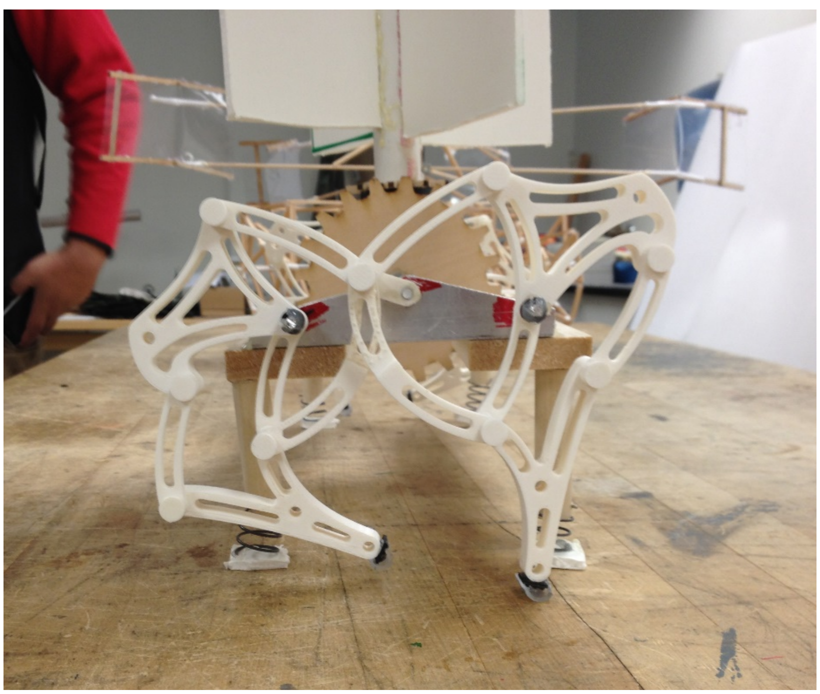


Figure 24 – 3D Printed Leg Design for Preliminary Prototype

6.2 Final working prototype

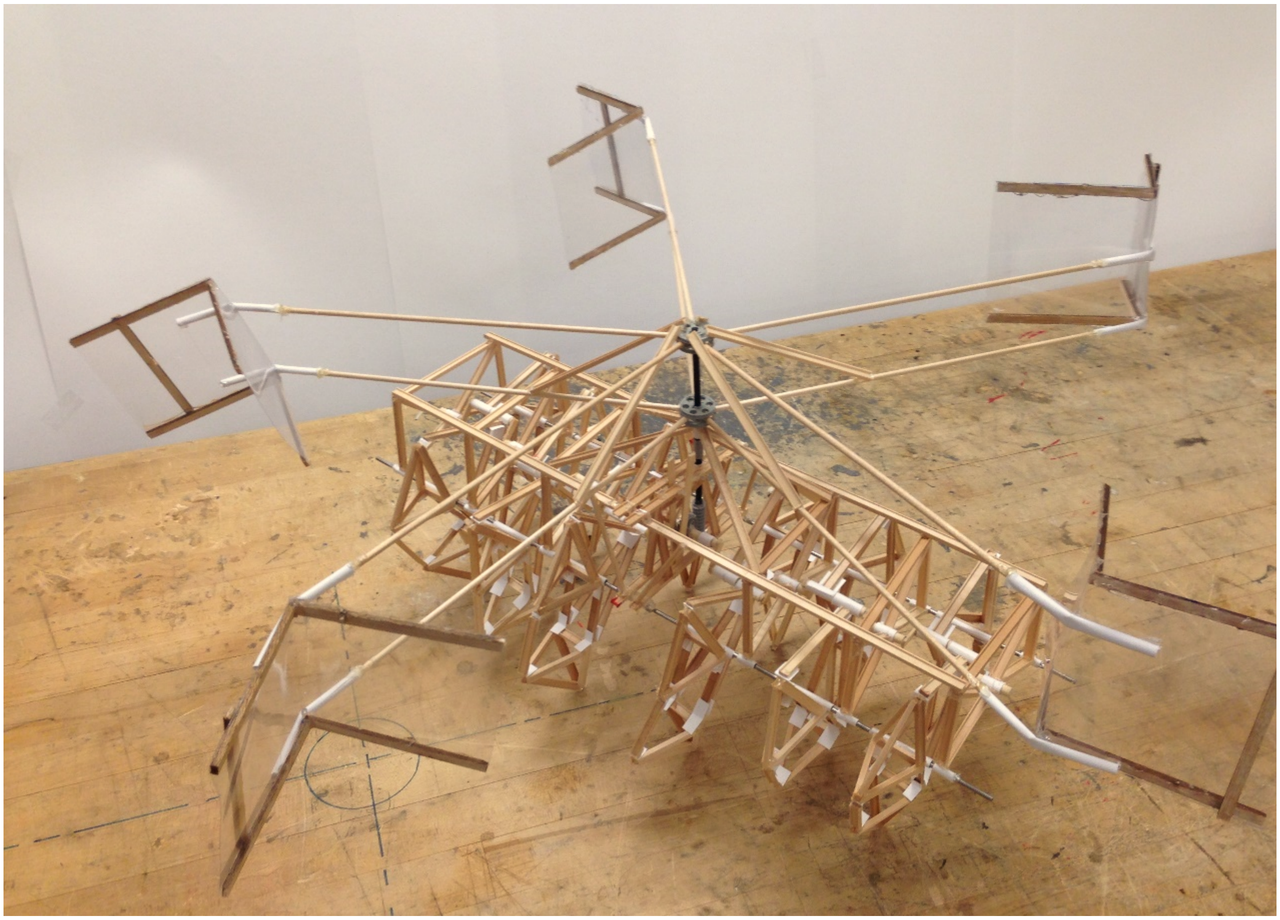


Figure 25 – Final Working Prototype

As seen in Figure 25, many things were changed from the initial prototype. The total pairs of legs were increased from two to 6. The number of legs was increased because the initial prototype showed that the wind walker was unable to adequately balance itself and walk with just two pairs of legs. Additionally, rather than being manufactured from ABS plastic, the new legs were manufactured from balsa wood, hot glue, and paper joints. This allowed for a lightweight, sturdy construction that could easily support and move the entire structure. The leg shape was also changed to include more triangular pyramids for increased structural support. Finally, by using folding paper joints instead of rotating plastic joints, the friction in the leg system was reduced.

Figure 26 – Blade Design for Final Working Prototype

The final blade design was adopted from a Savonius wind turbine. This turbine uses drag to spin, allowing the wind turbine to start easier with a smaller amount of wind. The difference between this design and the initial working prototype is that the radius of the turbine is larger, creating a larger amount of transmitted torque to the gear system, and subsequently the legs.

Figure 27 – Gear System for Final Working Prototype

To rotate the wind power, the initial prototype used a peg system with a 2:1 ratio (in other words, for every two rotations of the turbine there would be one rotation of the legs). However, the 2:1 ratio required a large amount of torque to turn the legs. In the final prototype, a Lego worm gear, seen in figure 26, was used. This gear system has roughly a 24:1 ratio and allows the turbine to easily rotate while transmitting a large amount of torque into the leg system.

6.3 Video of final prototype

A video of the final prototype successfully walking can be viewed at https://www.youtube.com/watch?v=BVN09oOBqa4.

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.

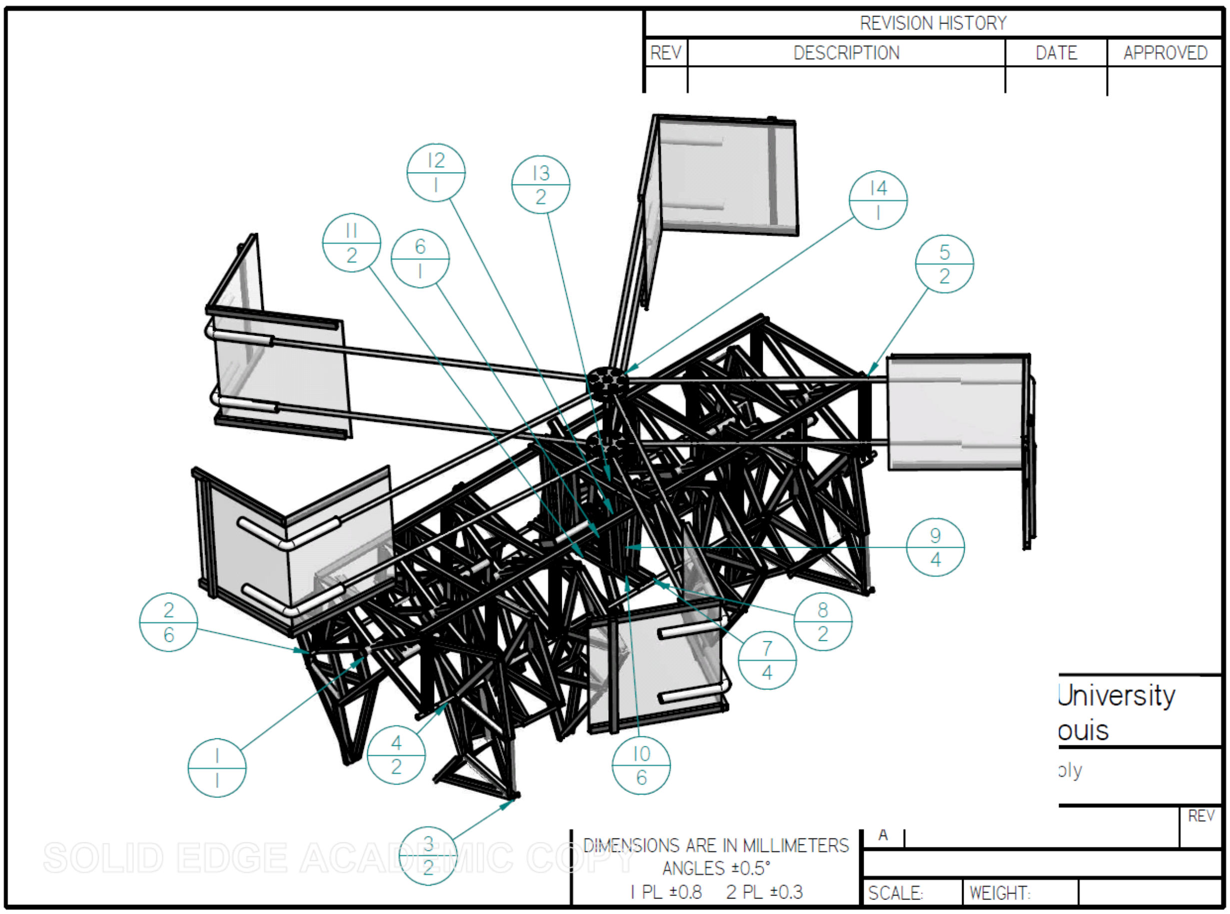


Figure 28 – Final Assembly Drawing. See Appendix A for Parts List

7.1.2 Sourcing instructions

All final drawings were made in the Solid Edge ST5 offered on the Washington University School computers.

7.2 Final Presentation

7.2.1 Presentation Slides

The following figures are screenshots of our final PowerPoint presentation.

Figure 29 – Slide 1

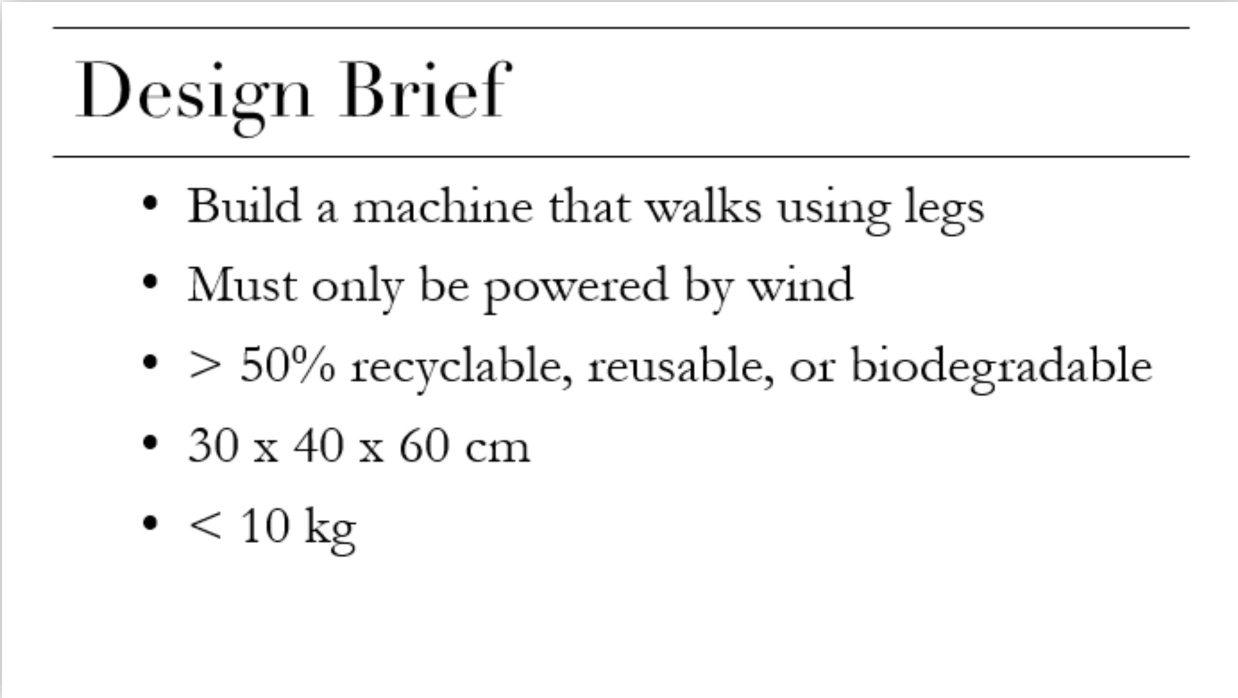


Figure 30 – Slide 2

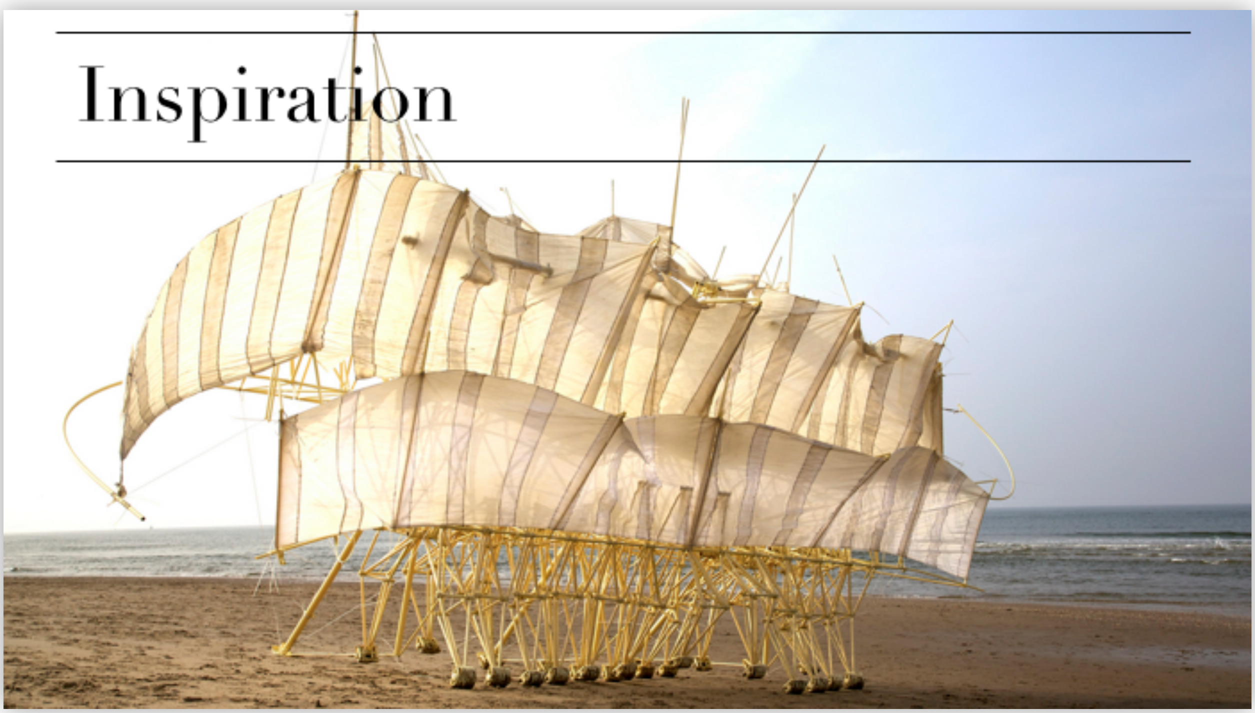


Figure 31 – Slide 3

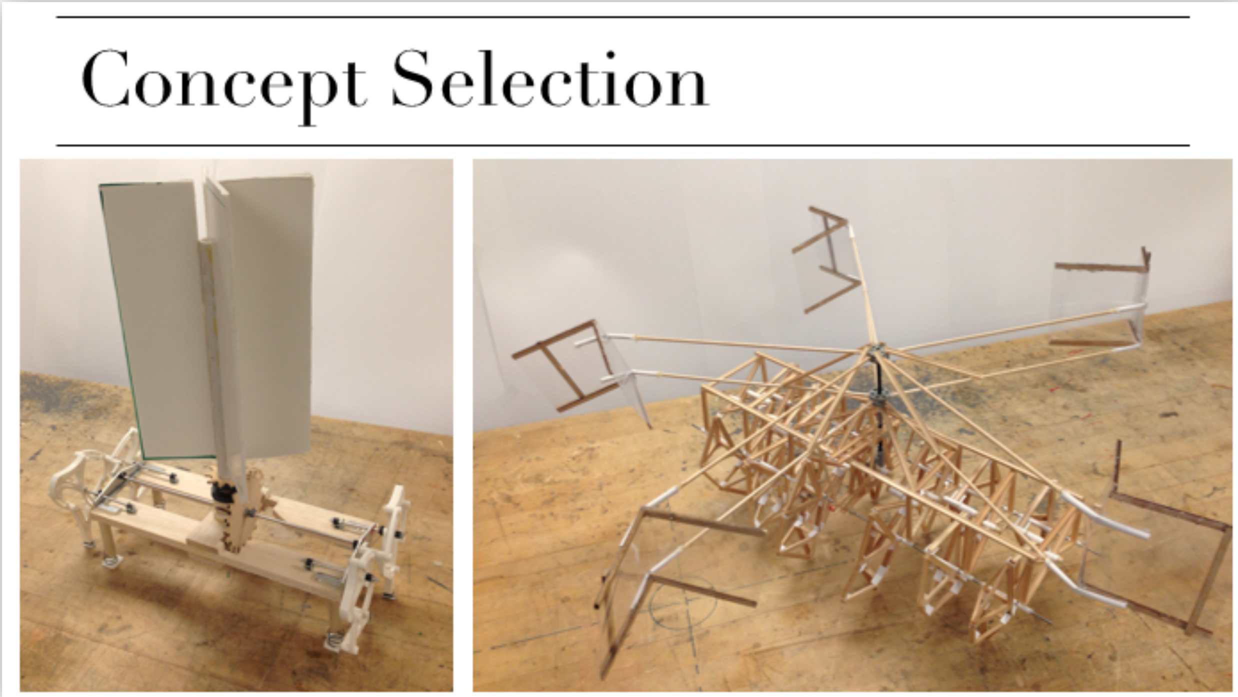


Figure 32 – Slide 4

The fifth slide is omitted because it was devoted to showing the video of the Wind Walking Robot working. This same video can be found in Section 6.3.

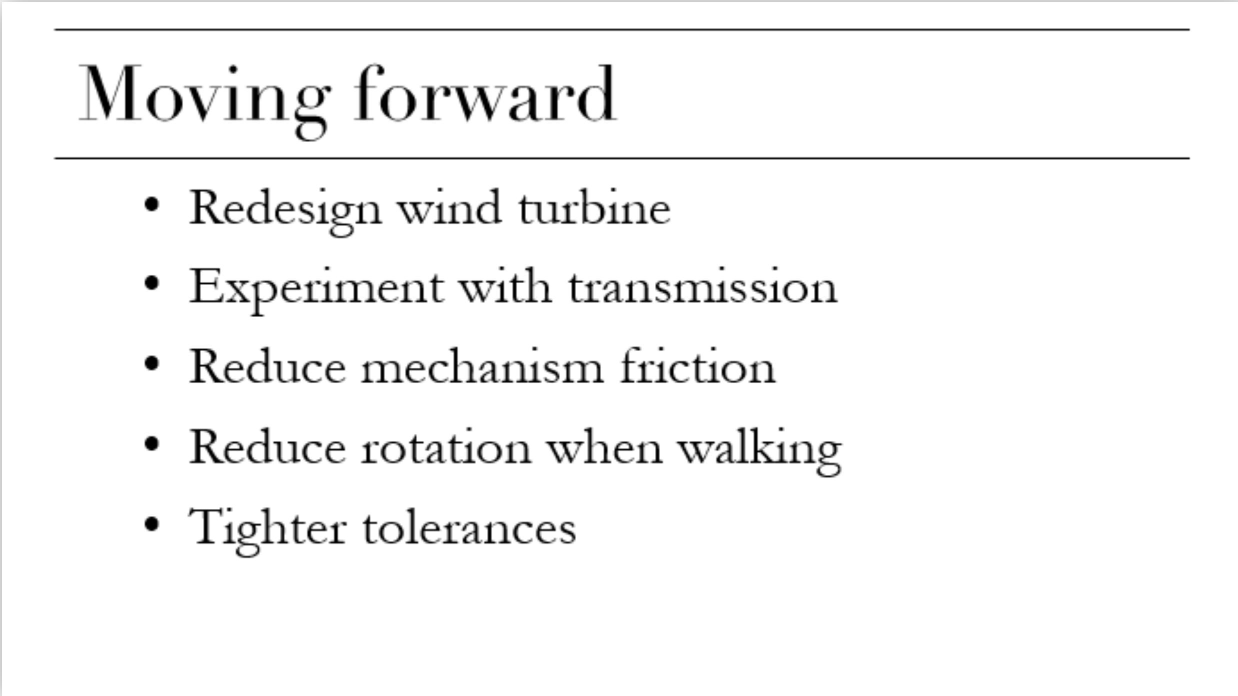


Figure 33 – Slide 6

7.2.2 Video Presentation

A video showcasing our final PowerPoint presentation can be viewed at https://www.youtube.com/watch?v=LqleHNlCH9Y&list=UU_yfKksGM9qLT4iJvLoipNg.

7.3 Teardown

TEARDOWN TASKS AGREEMENT

PROJECT: WW Group 1 NAMES: Kenna Widdows INSTRUCTOR: Dr. Jakiela

Tim Hutt

Jose Rodes

The following teardown/cleanup tasks will be performed:

- Clean the work area (sweep the floor)
- Salvage some parts from our prototype (springs, wood pieces, aluminum rod pieces, 3D printed parts).
- Dispose of the rest of the parts.

Instructor comments on completion of teardown/cleanup tasks:

Instructor signature: Mark J. Jakiela Print instructor name: JAKIELA

Date: 12/3/2014

(Group members should initial near their name above.)

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 metrics in the design were mostly met in our final prototype. We managed to make it walk over 4 meters but it did not achieve the suggested speed of 4 meters per minute. Much more than 50% of the materials we used were recyclable in St. Louis or compostable. The dimensions on our prototype were 40X58X58 cm, which is a little over the dimensions on our metrics (30X40X60 cm). Our prototype weighs about 300 grams, which is well under the 10 kg limit. The turbine on our final prototype can gather wind from directions only parallel to the prototype's frame. Also, the prototype can walk over at least 7° slopes and three different rough surfaces (rubber, wood, cement). The prototype does, indeed, use legs to walk. Additionally, the final prototype cannot handle 30 mph wind speeds (it could handle half of that speed). It can definitely handle small impacts, however the impacts must not be substantial due to the material choices used. With a little more time, we could change to plastic and aluminum to make it more durable.

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?

There were not many issues when sourcing for our parts. We had an issue with one request from SDP SI. We took a screenshot of the request but had to email the instructor to make sure the parts were actually ordered. Thus, when asking for a part request, we thought it would be better if the school had an account for at least five major part providers. This will help with the part request process for both students and professors.

8.3 Discuss the overall experience:

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

We expected this project to be difficult and time consuming. However, it was such an involved project with many design changes throughout the semester that required much more time than we expected. It was also more difficult than expected because of how many individual components had to be designed and tested and then redesigned until all of the components successfully worked together. There were many places where the machine could fail, so designing all of the solutions to these problems that arose were both time consuming and challenging.

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

Our project description essentially said to build a wind powered walking machine that uses legs to walk. We definitely accomplished this description. The result of our final project is a wind powered walking machine that uses Theo Jansen's leg linkage mechanism and is driven by a vertical axis wind turbine.

8.3.3 Did your team function well as a group?

We heard and took into account all of our ideas for the major part of our design process. There were some drastic changes that we had to account for near the end of the final prototype stage that tested our team's dynamic. We realized that we had to compromise to make this project a success and some sacrifices had to be made. Overall, we worked very well as a group.

8.3.4 Were your team member's skills complementary?

Artistry and creativity were necessary in the design process. All of us offered creative ideas to improve our design and our unique backgrounds allowed us to suggest different ideas from each other.

8.3.5 Did your team share the workload equally?

Overall, we tried to distribute the workload evenly. When we weren't working together to come up with design improvements, we were working individually building prototypes, modeling components, and running calculations. All of us spent a lot of time on this project and we feel proud of the final product.

8.3.6 Was any needed skill missing from the group?

We needed some expertise analyzing the turbine and gear transmission for our prototype and were fortunate enough to be able to consult our professors about it. We also could have used some expertise using software that could ease the design process of the final prototype.

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

Our customer was Professor Jakiela and we consulted with him during the entire design and building process.

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

Yes, it changed a bit. The dimensional constraint and suggested speed of 4 meters in one minute appeared to relax as the semester went on. It was more important that the machine walks than it fit exactly within the dimensions originally outlined.

8.3.9 Has the project enhanced your design skills?

This project has improved all of our design skills. We can easily replicate all the design processes and effectively follow the steps of good engineering design (background research, concept selection, embodiment and fabrication, engineering analysis).

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

Yes. We would all feel very comfortable doing a design project assignment at a job.

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

Jose would try to do the RC Glider project because it seemed very challenging but very exciting.

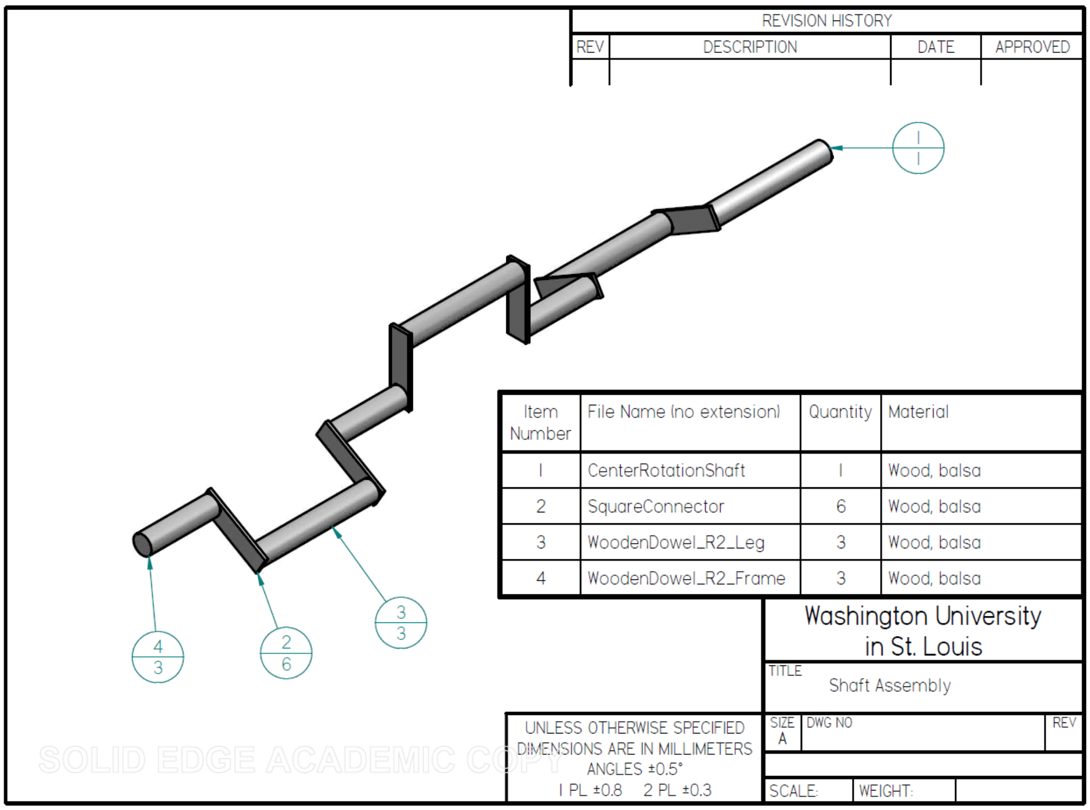
9 Appendix A - Parts List

Item Number	File Name (no extension)	Quantity	Material
1	RotatingShaft	2	
2	SubFrame	6	
3	LegAssembly1	12	
4	AlRod	2	Aluminum, 1060
5	TopConnector	2	Wood, balsa
6	LegoGear	1	
7	Top&BottomConnector	4	Wood, balsa
8	LowerSupportRoll	2	Paper
9	SupportDowel	4	Wood, balsa
10	CrossConnector	6	Wood, balsa
11	GearSupport	2	Wood, balsa
12	Roll2	1	Paper
13	TurbineShaftRoll	2	Paper
14	NewRotor	1	

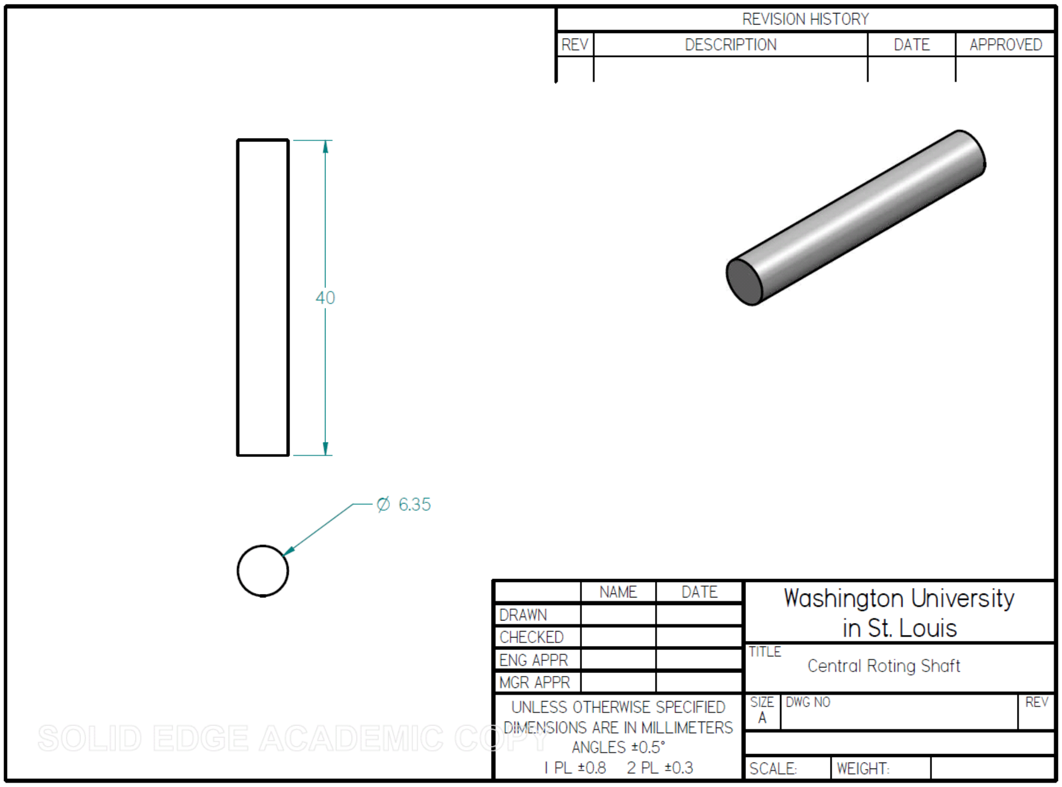
10 Appendix B - Bill of Materials

Number	Part Name	Company	Part Number	Cost/Part	Number of Pieces	Total Cost
1	I-Beam	Wash U. Bookstore		$ 1.72	30	$ 51.60
2	Hot Glue	Stock	-	$ -	N/A	$ -
3	Carboard Paper					
4	Plastic					
5	Lego Parts	Stock	-	$ -		$ -
6	Drinking Straws	Stock	-	$ -		$ -
7	Wooden Dowel					
8	Al Rods	Stock	-	$ -	2	$ -

11 Appendix C - CAD Models



Item Number	File Name (no extension)	Quantity	Material
1	CenterRotationShaft	1	Wood, balsa
2	SquareConnector	6	Wood, balsa
3	WoodenDowel_R2_Leg	3	Wood, balsa
4	WoodenDowel_R2_Frame	3	Wood, balsa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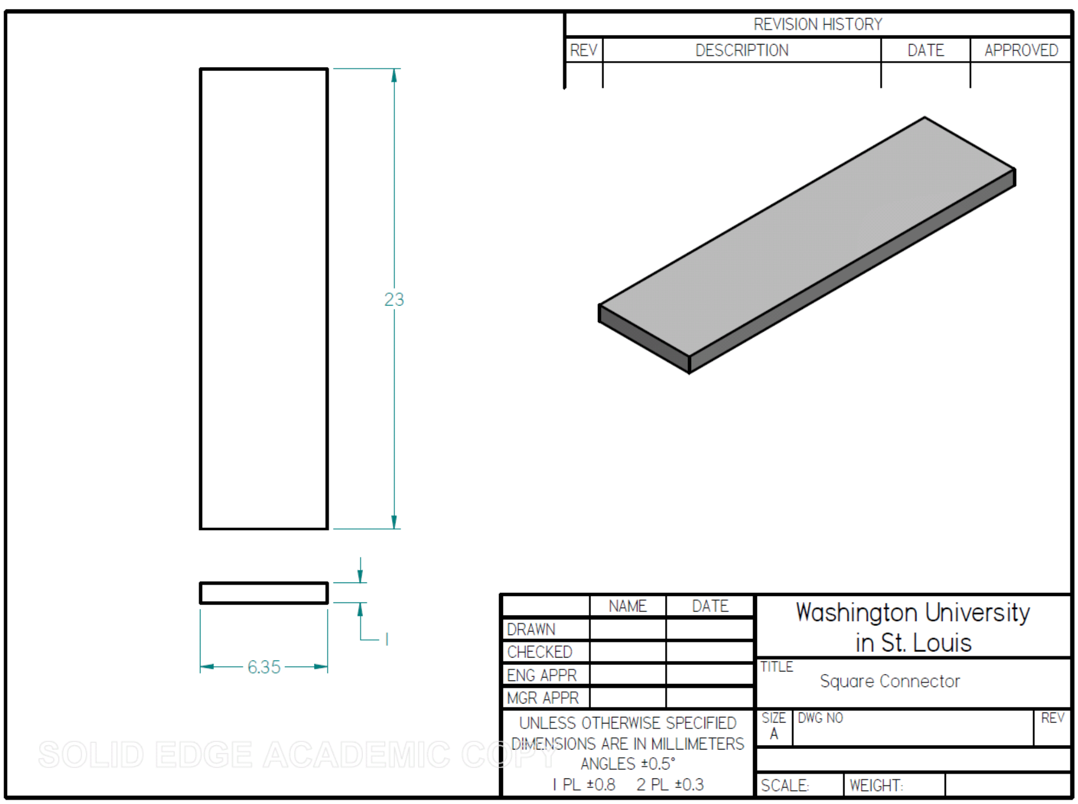
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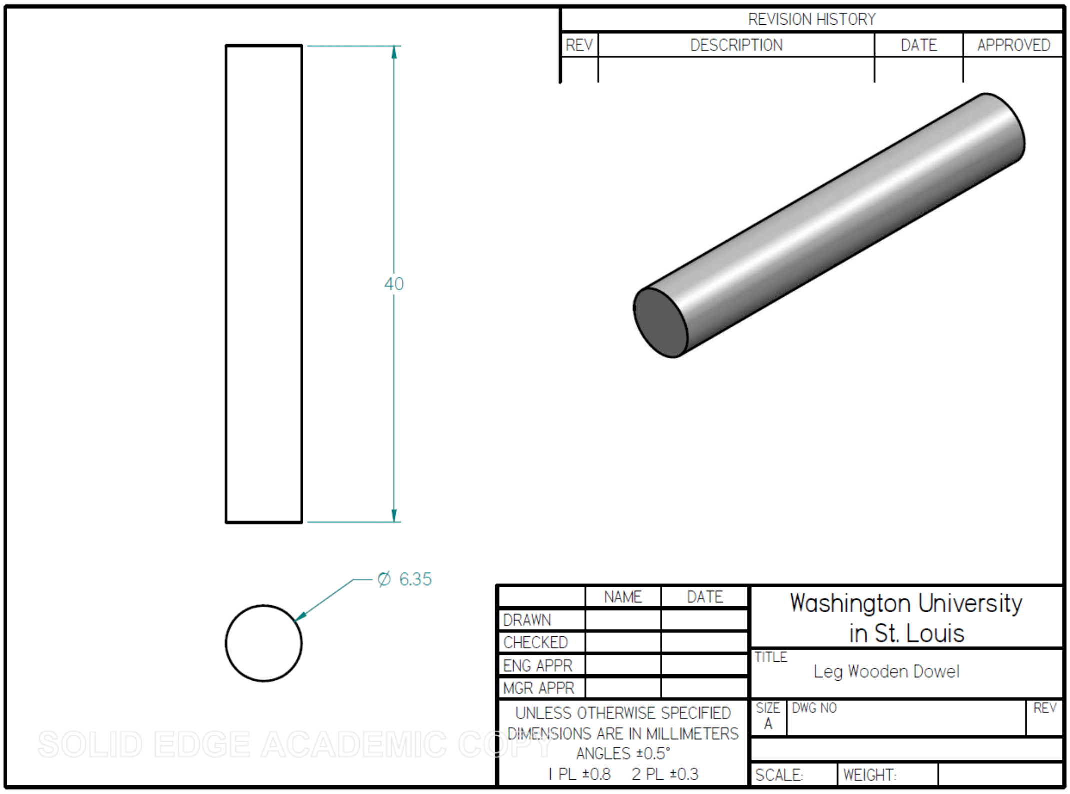
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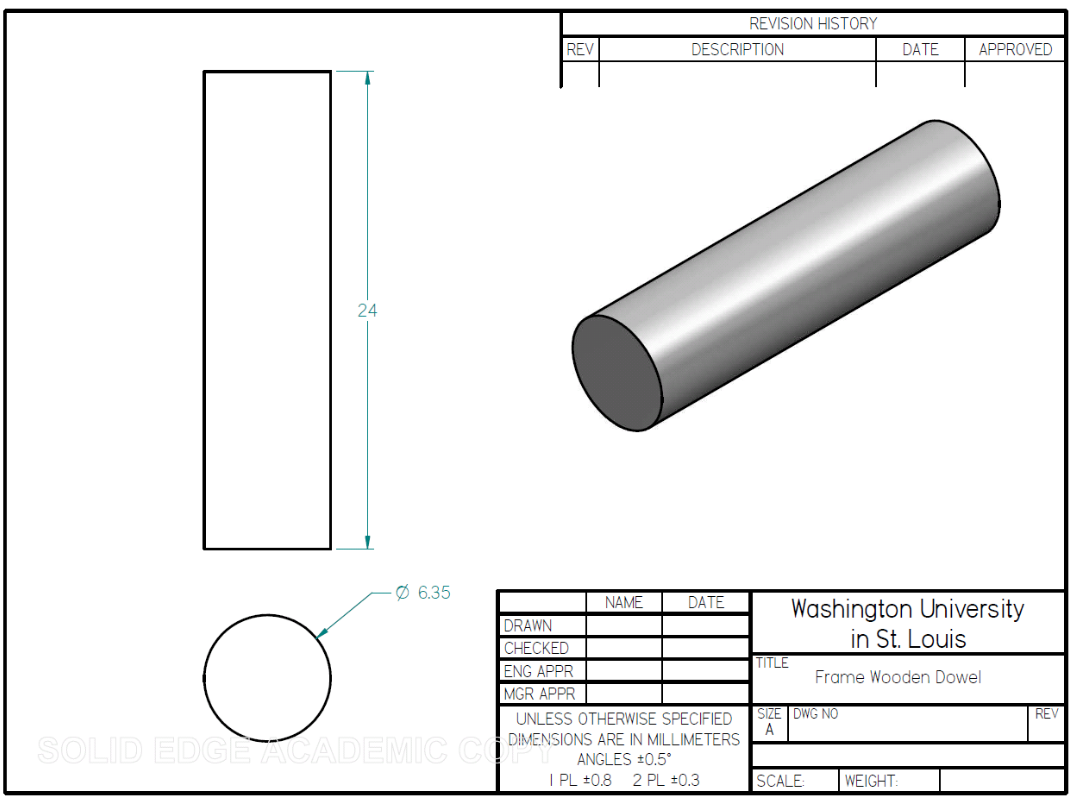
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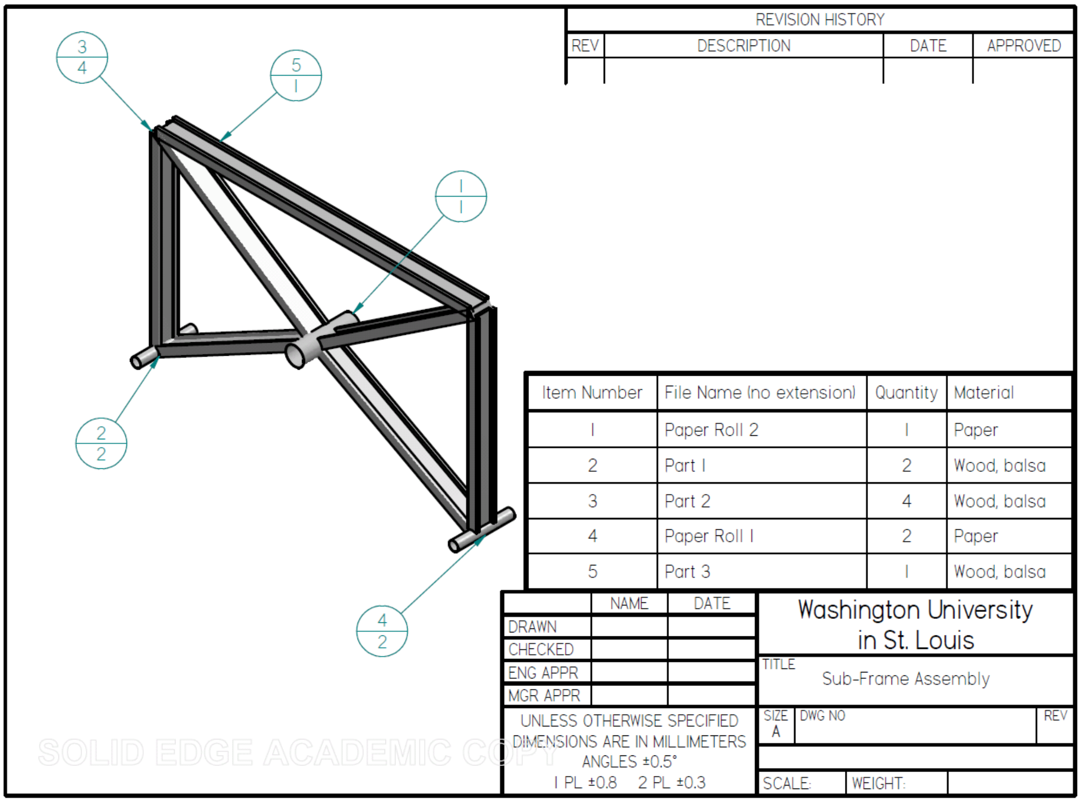

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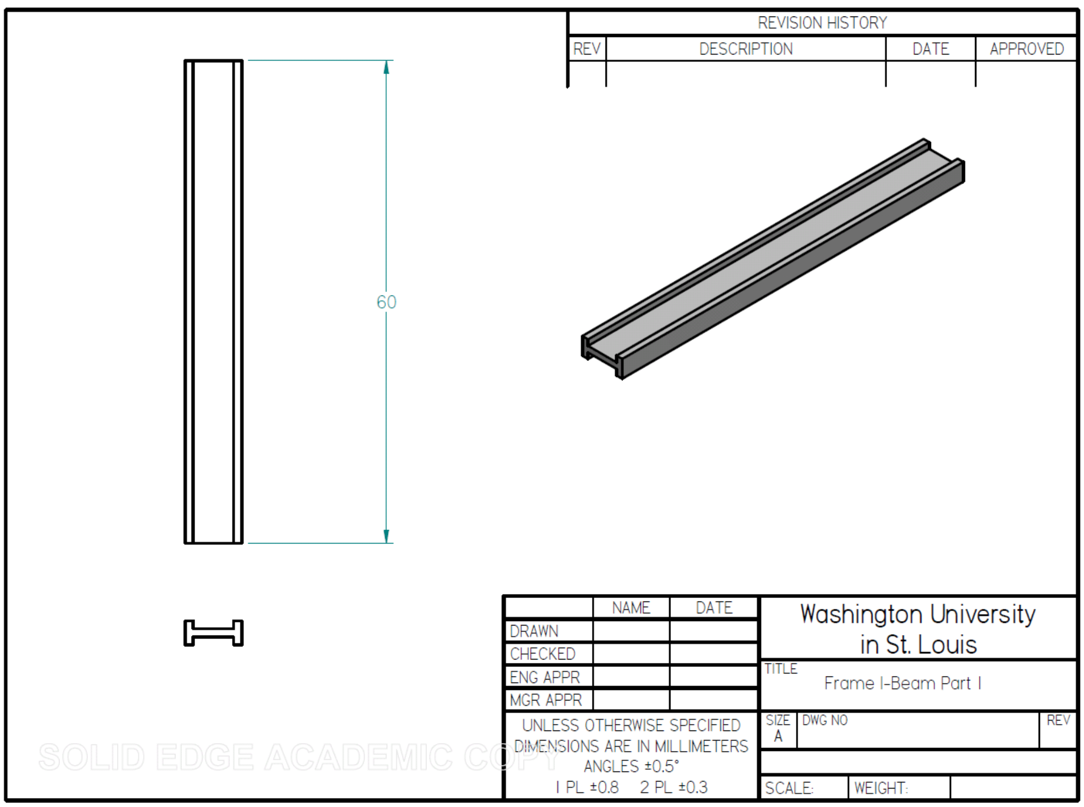
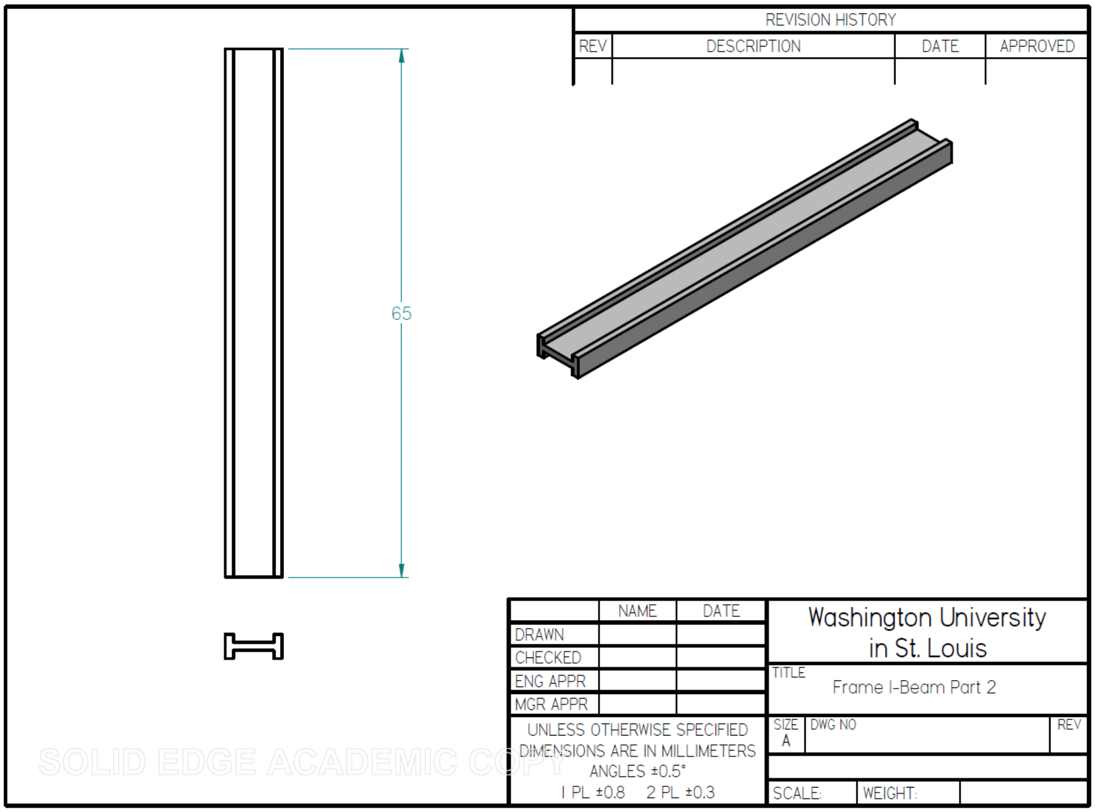
4	Paper Roll 1	2	Paper
5	Part 3	1	Wood, balsa





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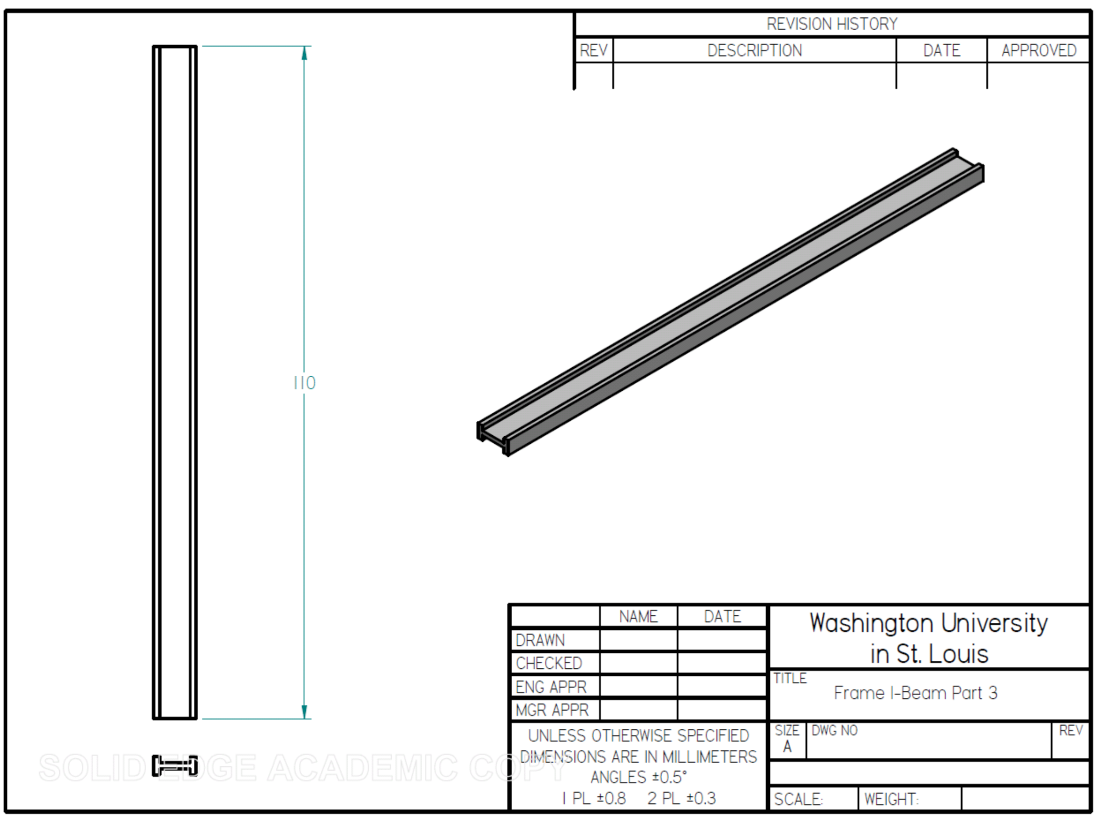

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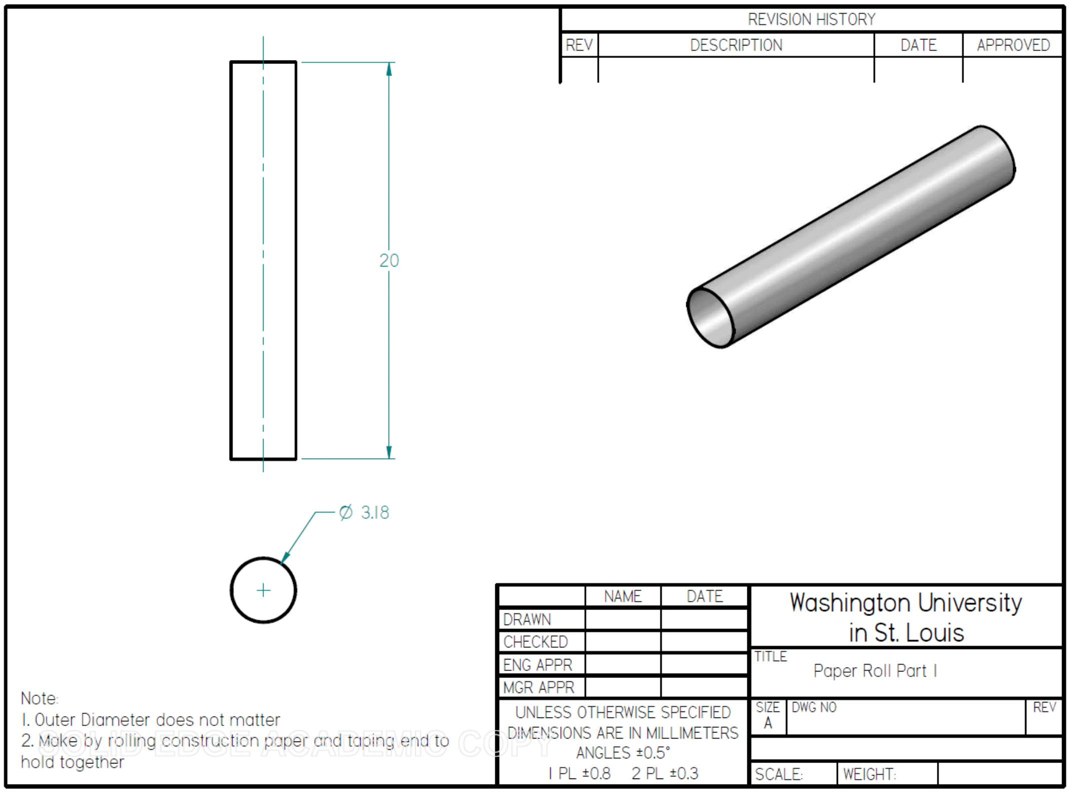
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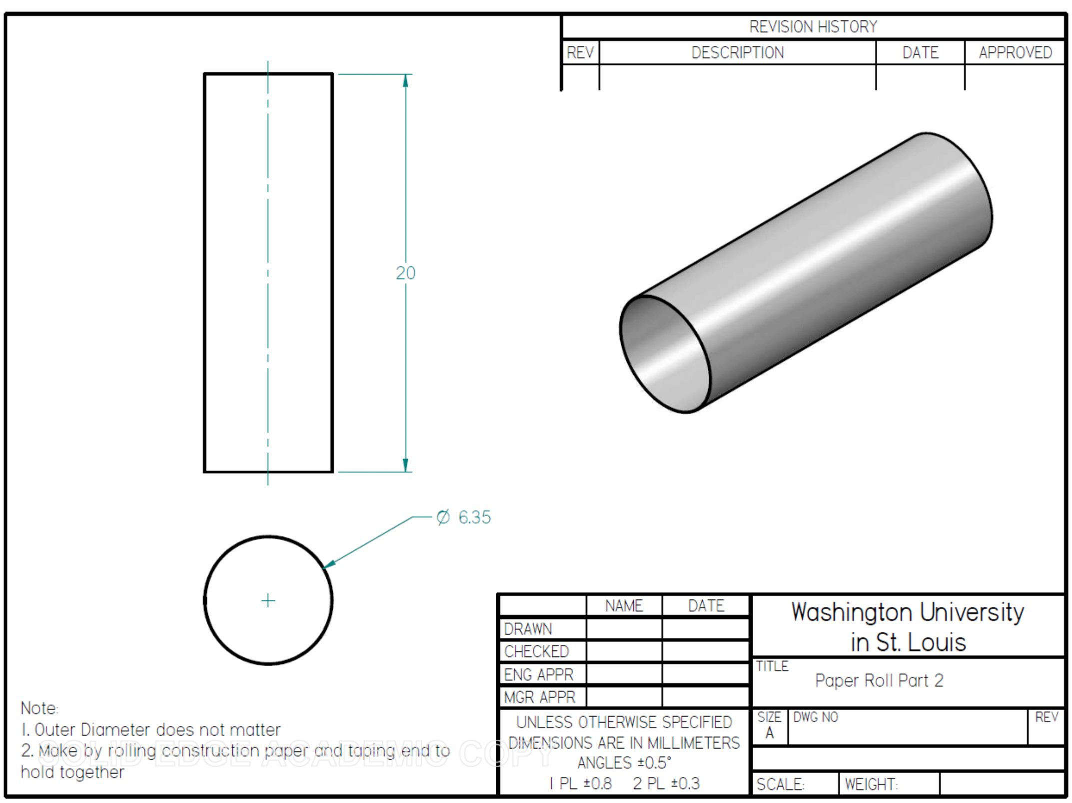
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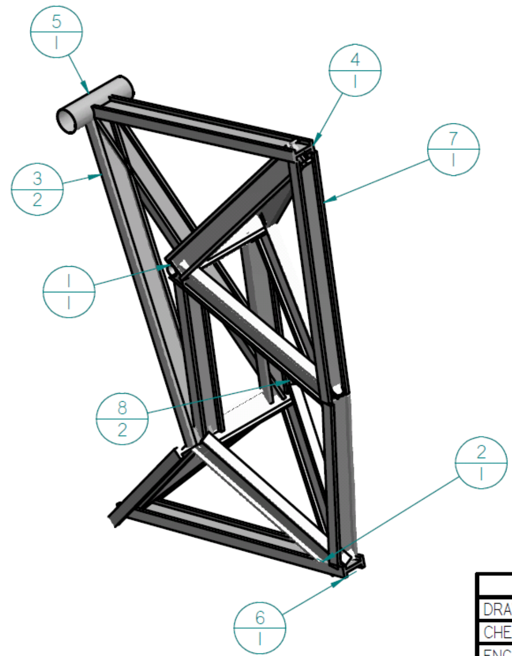

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4	Part 8	1	Wood, balsa
5	Paper Roll 2	1	Paper
6	Triangle Assembly 1	1	
7	Trianble Assembly 2	1	
8	Part 6	2	Wood, balsa

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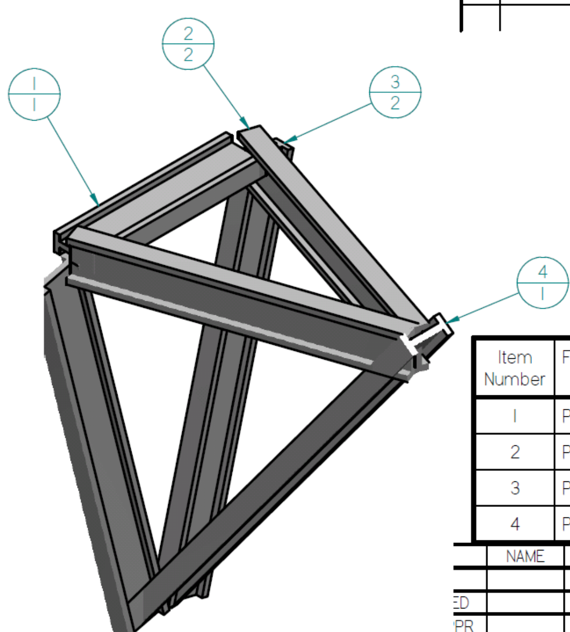

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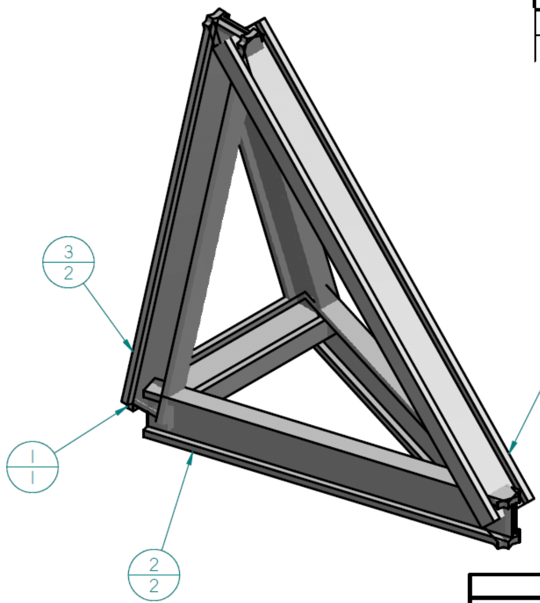

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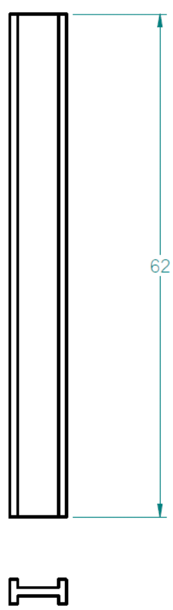

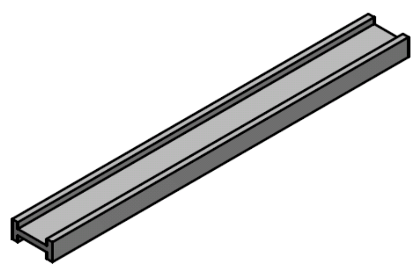

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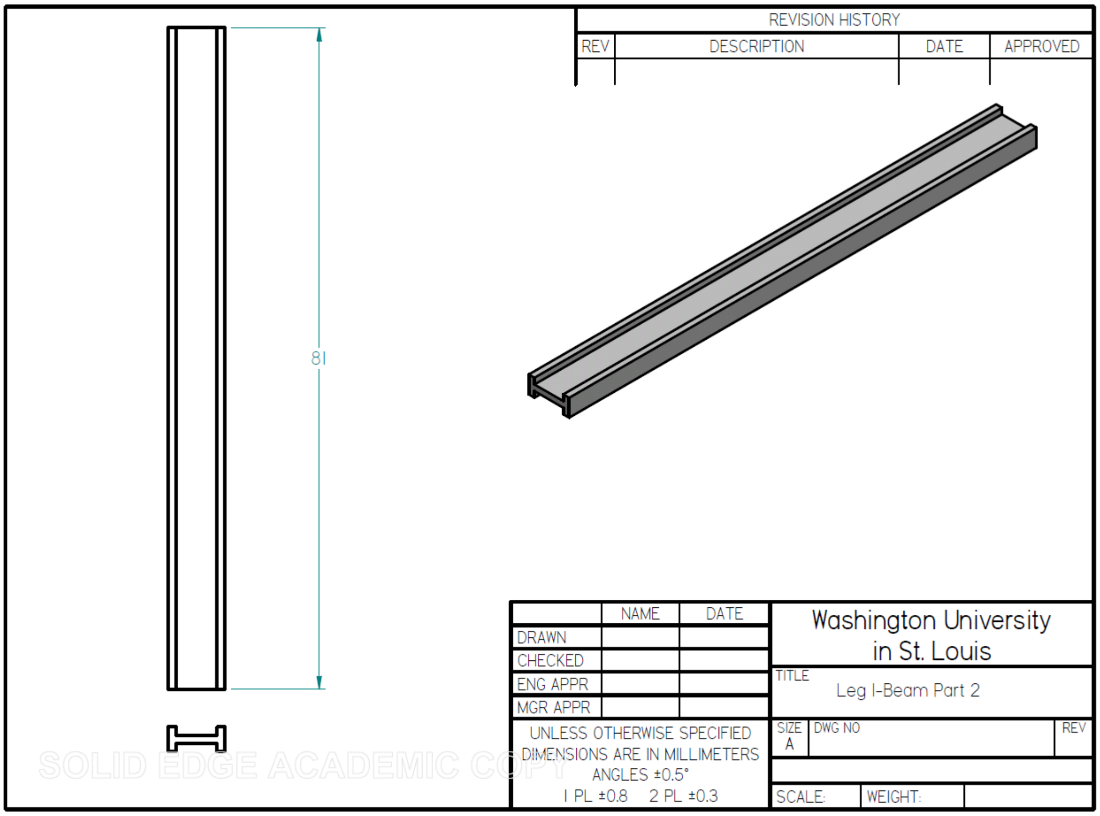
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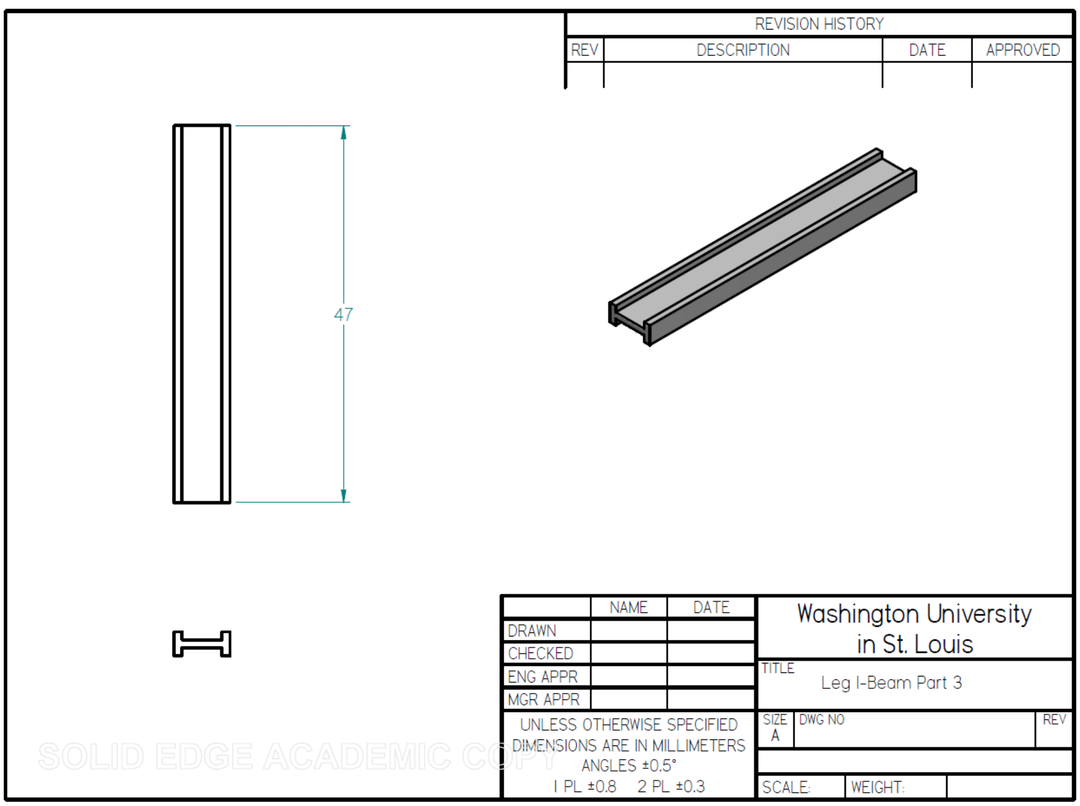
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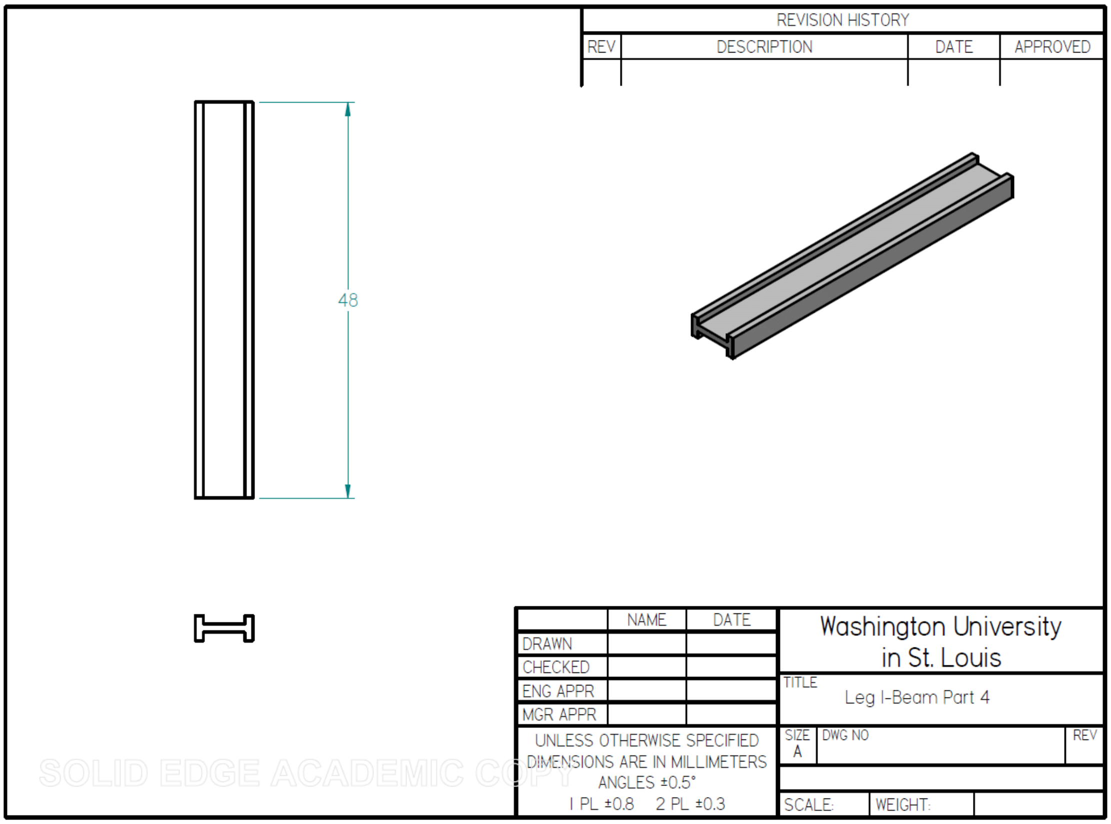
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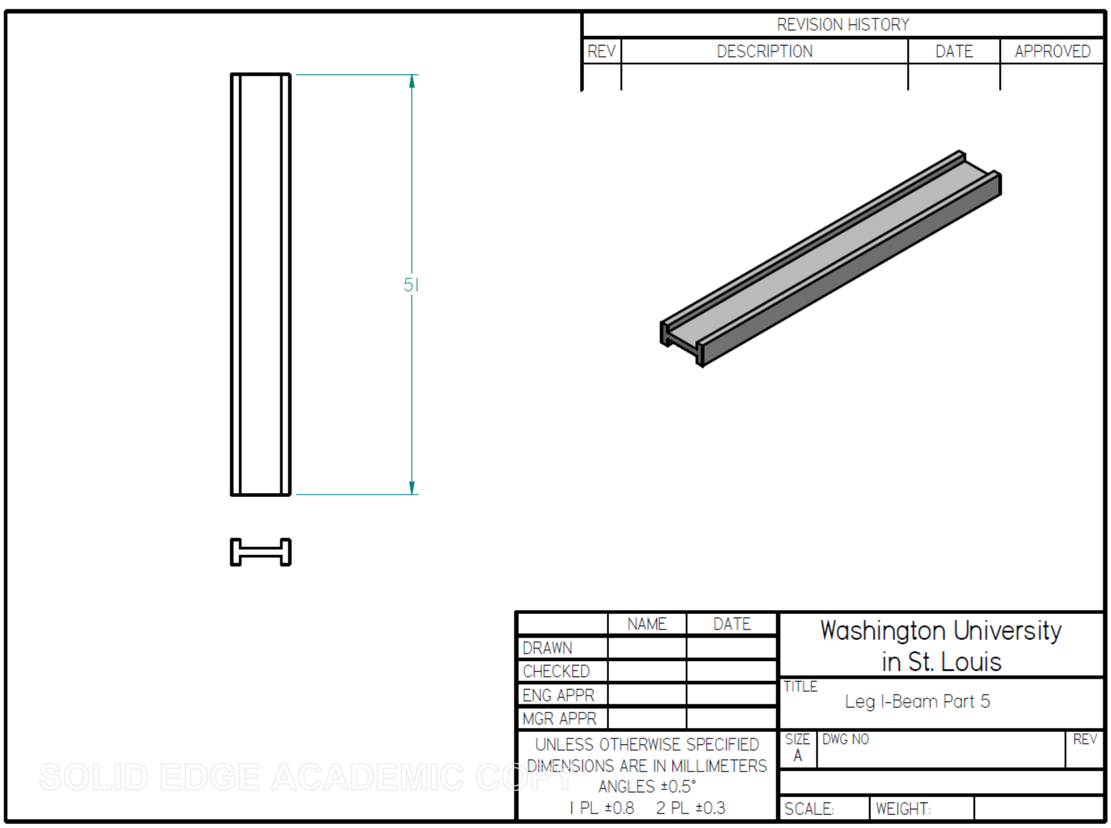
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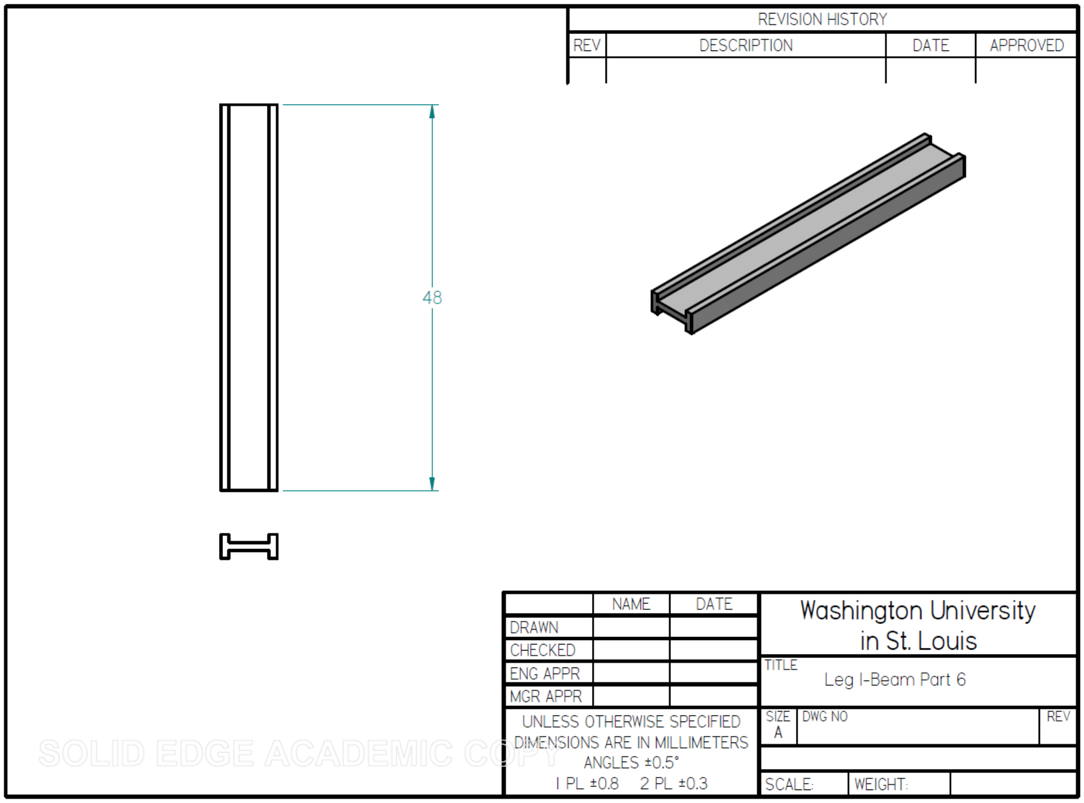
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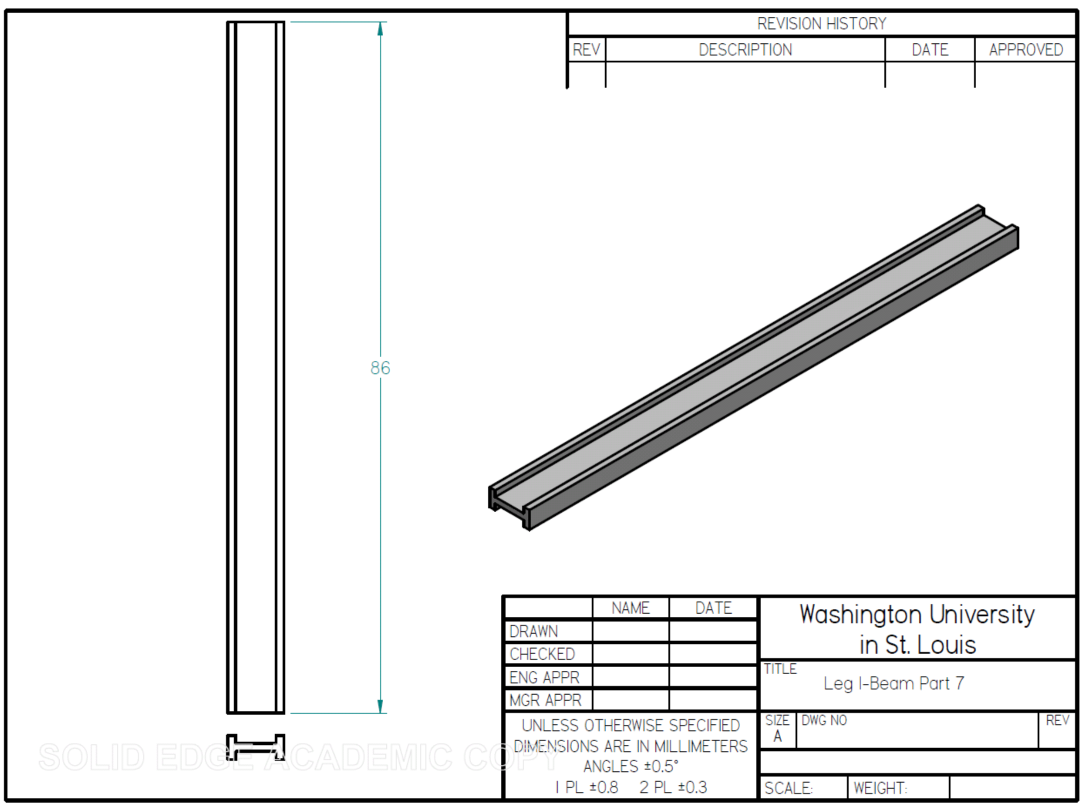
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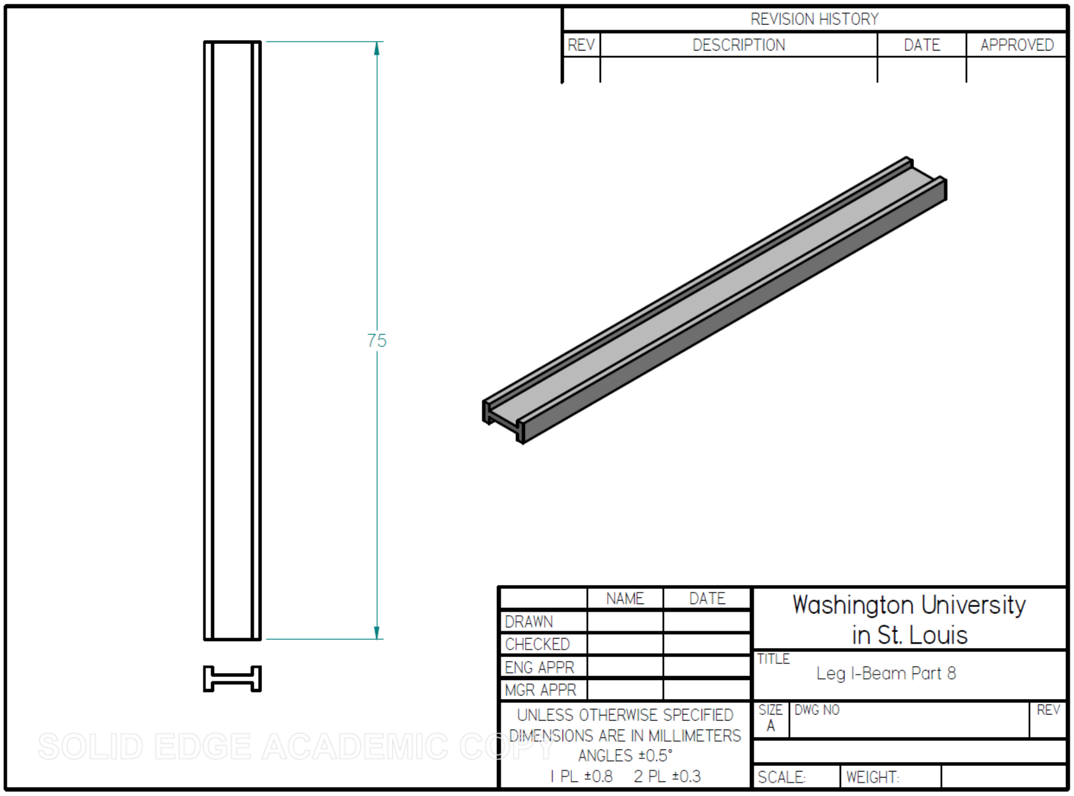
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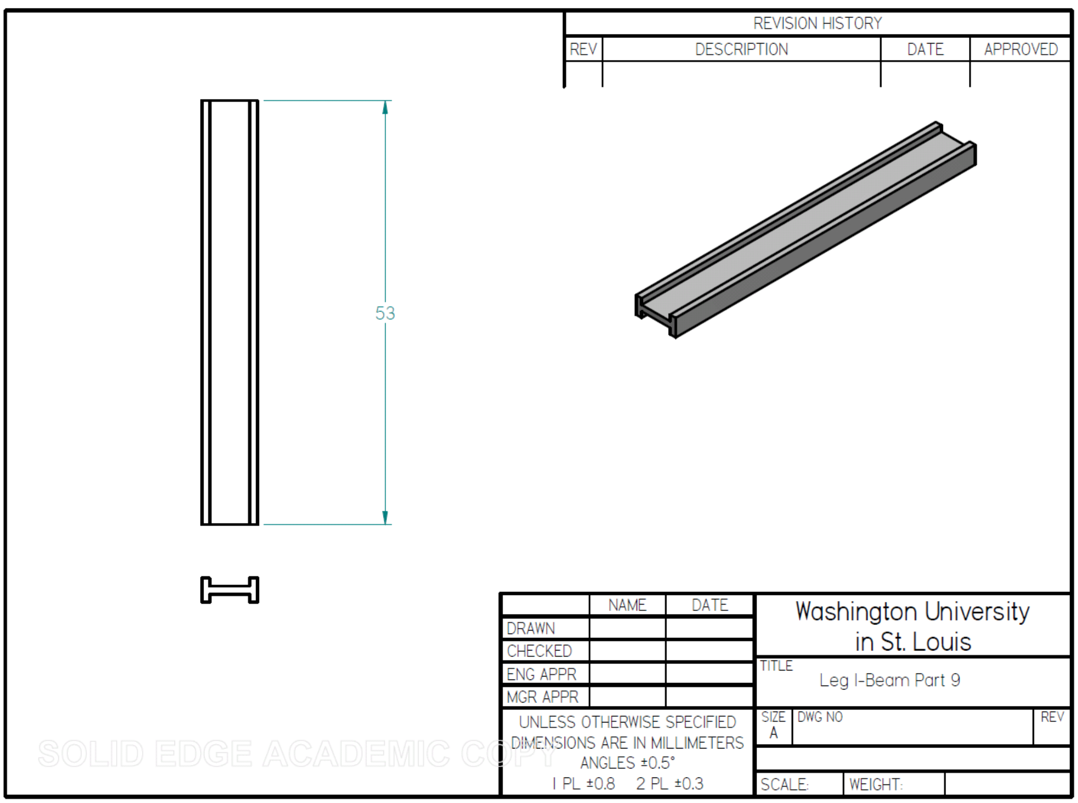
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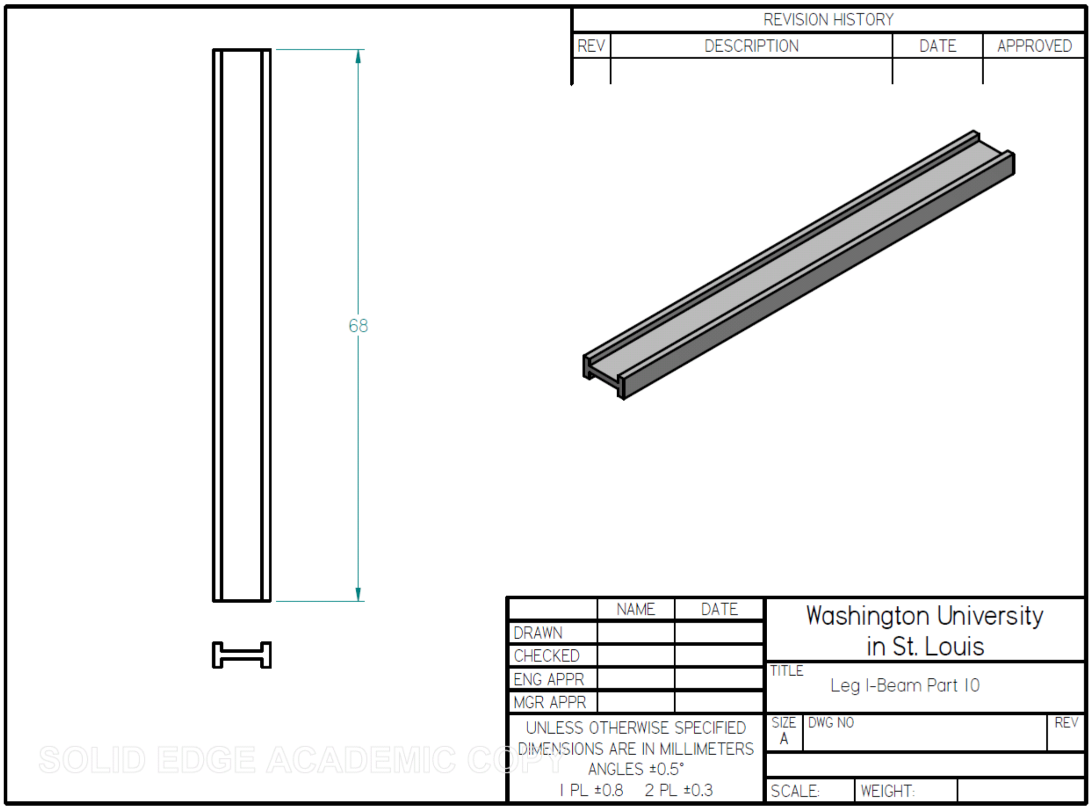
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UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±0.5°
1 PL ±0.8 2 PL ±0.3
Washington University in St. Louis
TITLE
Leg I-Beam Part 10
SIZE A
DWG NO
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SCALE:
WEIGHT:
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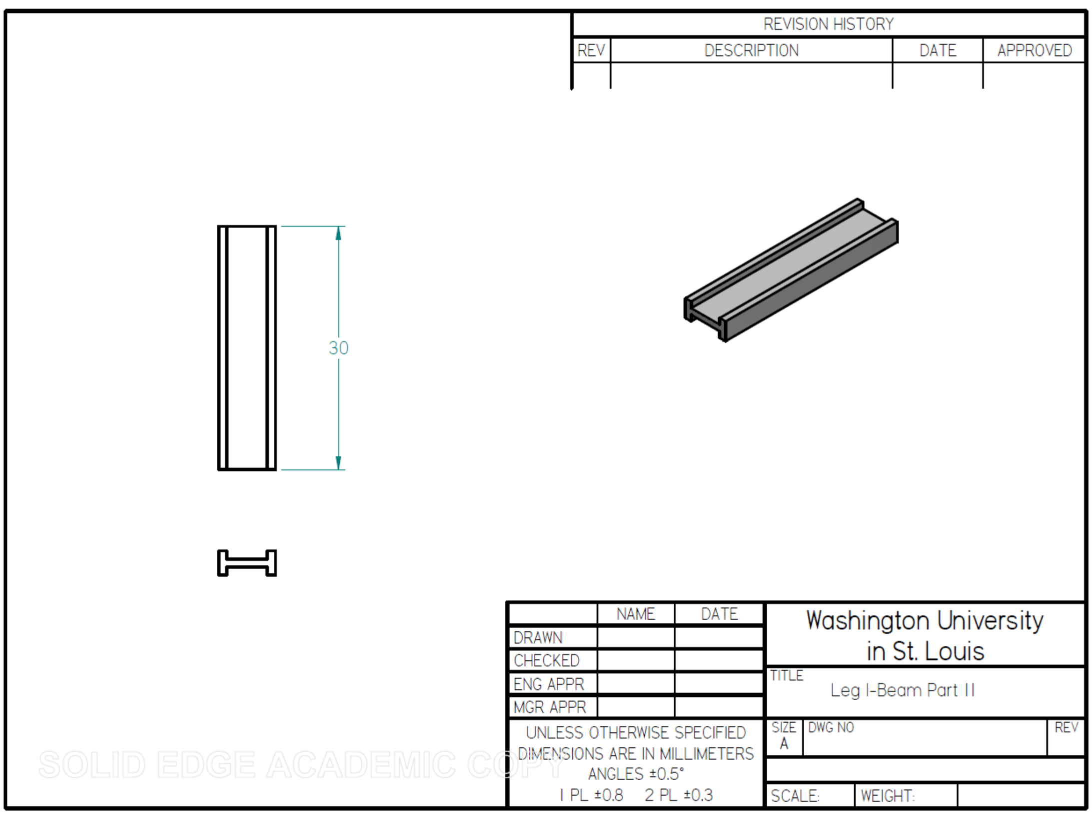
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Washington University in St. Louis
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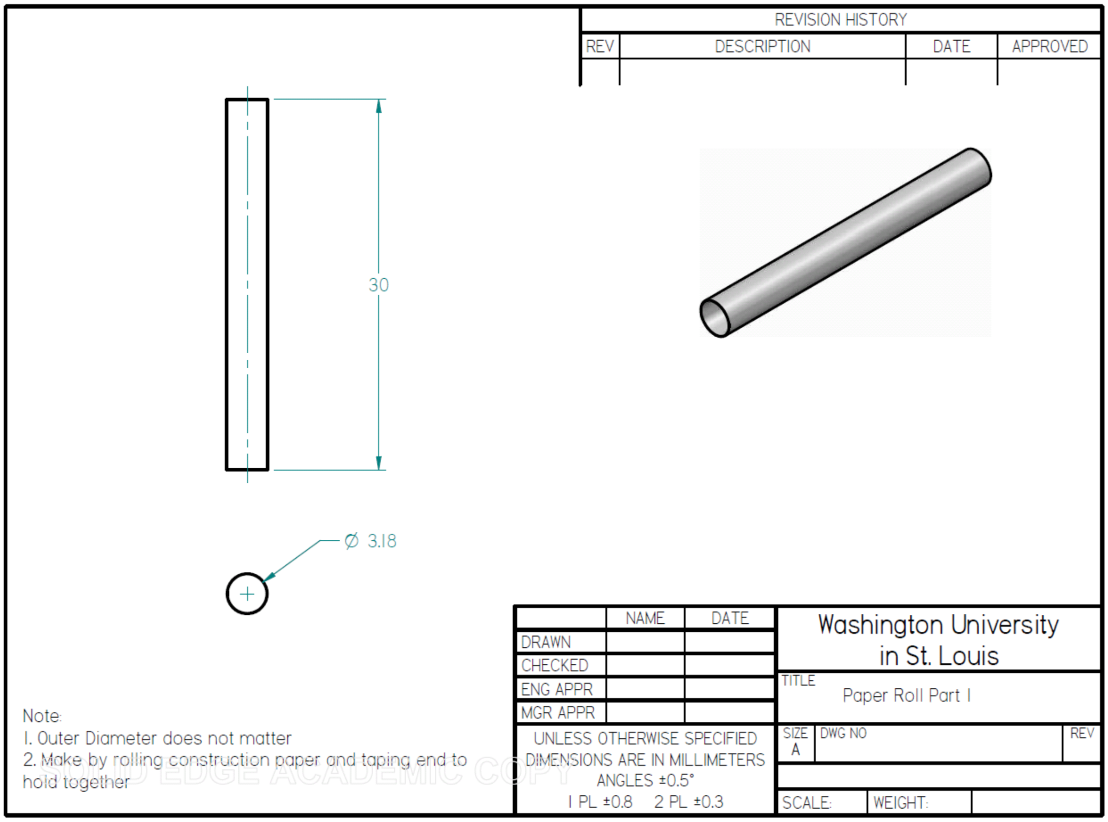
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Washington University in St. Louis
TITLE
Paper Roll Part 1
SIZE A
DWG NO
REV
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±0.5°
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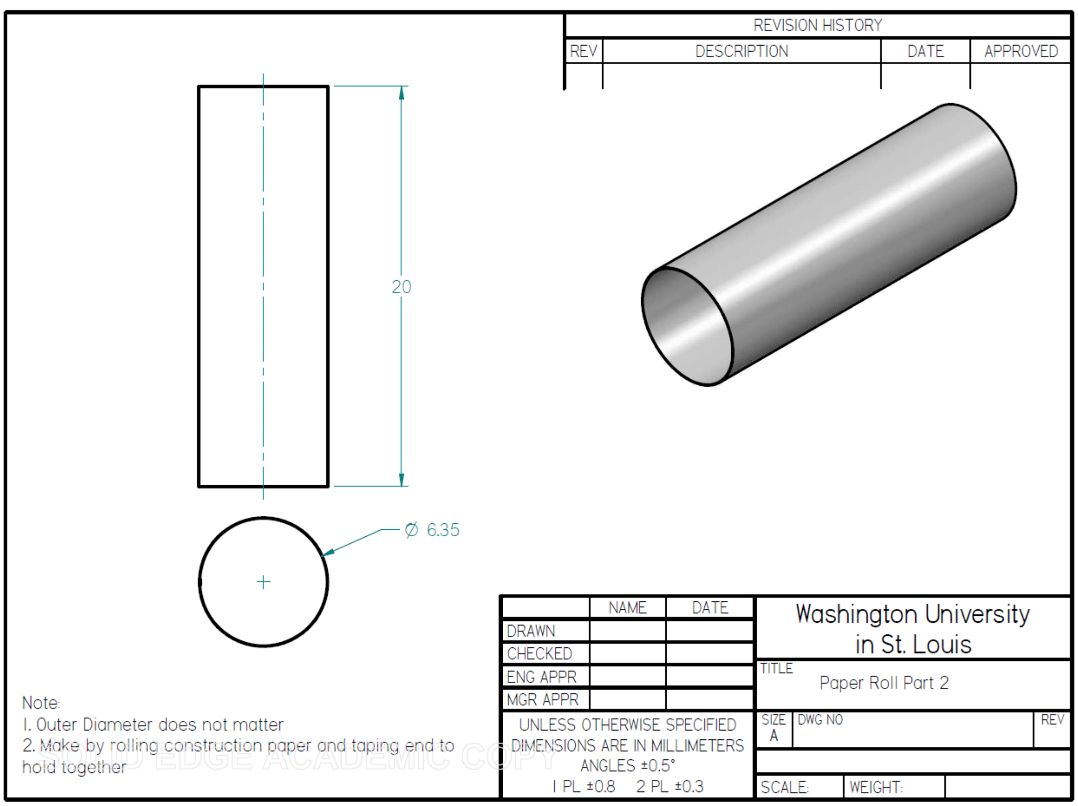
SCALE:
WEIGHT:
Note:
1. Outer Diameter does not matter
2. Make by rolling construction paper and taping end to hold together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Washington University in St. Louis
TITLE
Paper Roll Part 2
SIZE A
DWG NO
REV
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±0.5°
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SCALE:
WEIGHT:
Note:
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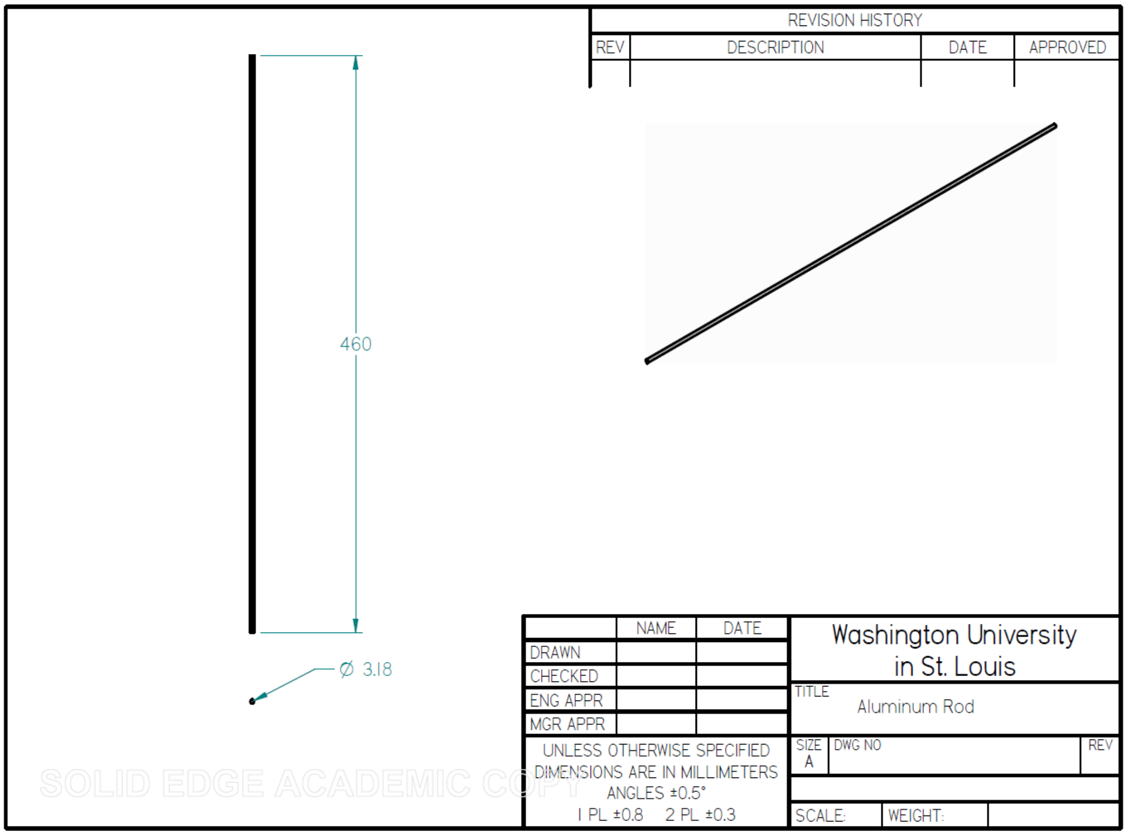
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UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±0.5°
1 PL ±0.8 2 PL ±0.3
Washington University
in St. Louis
TITLE
Aluminum Rod
SIZE
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DWG NO
REV
SCALE:
WEIGHT:
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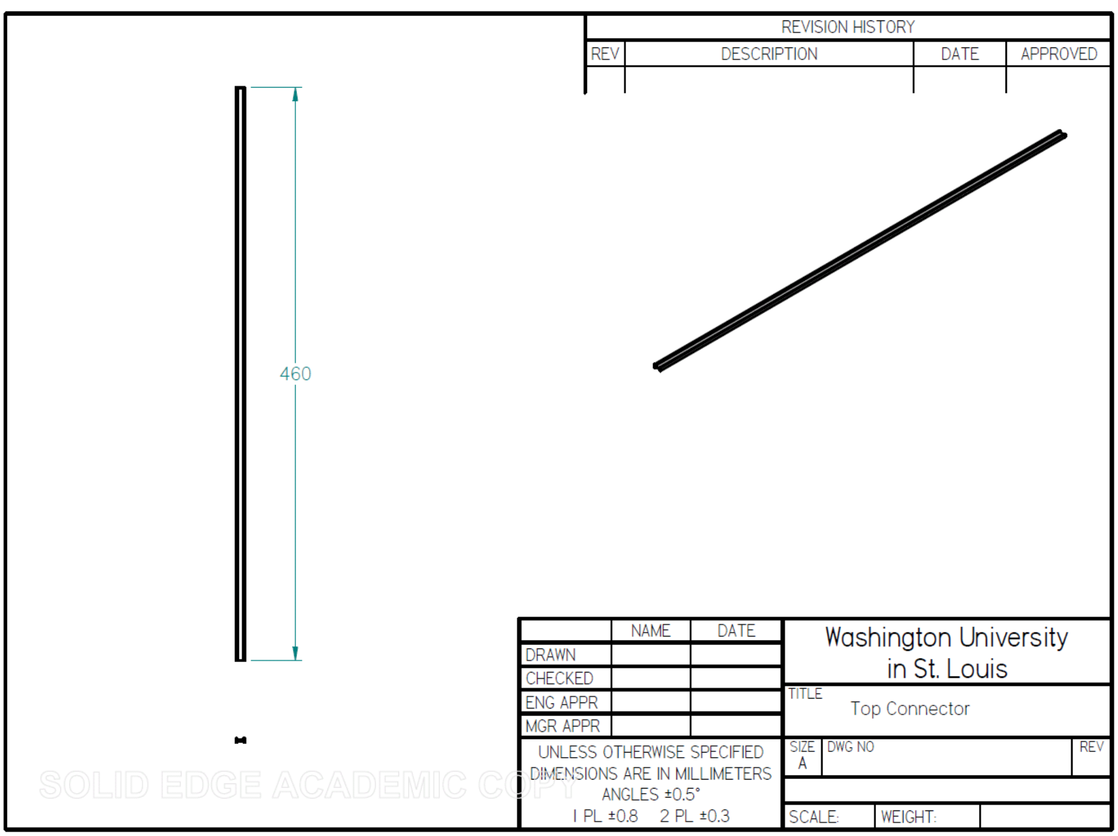
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DIMENSIONS ARE IN MILLIMETERS
ANGLES ±0.5°
1 PL ±0.8 2 PL ±0.3
Washington University
in St. Louis
TITLE
Top Connector
SIZE
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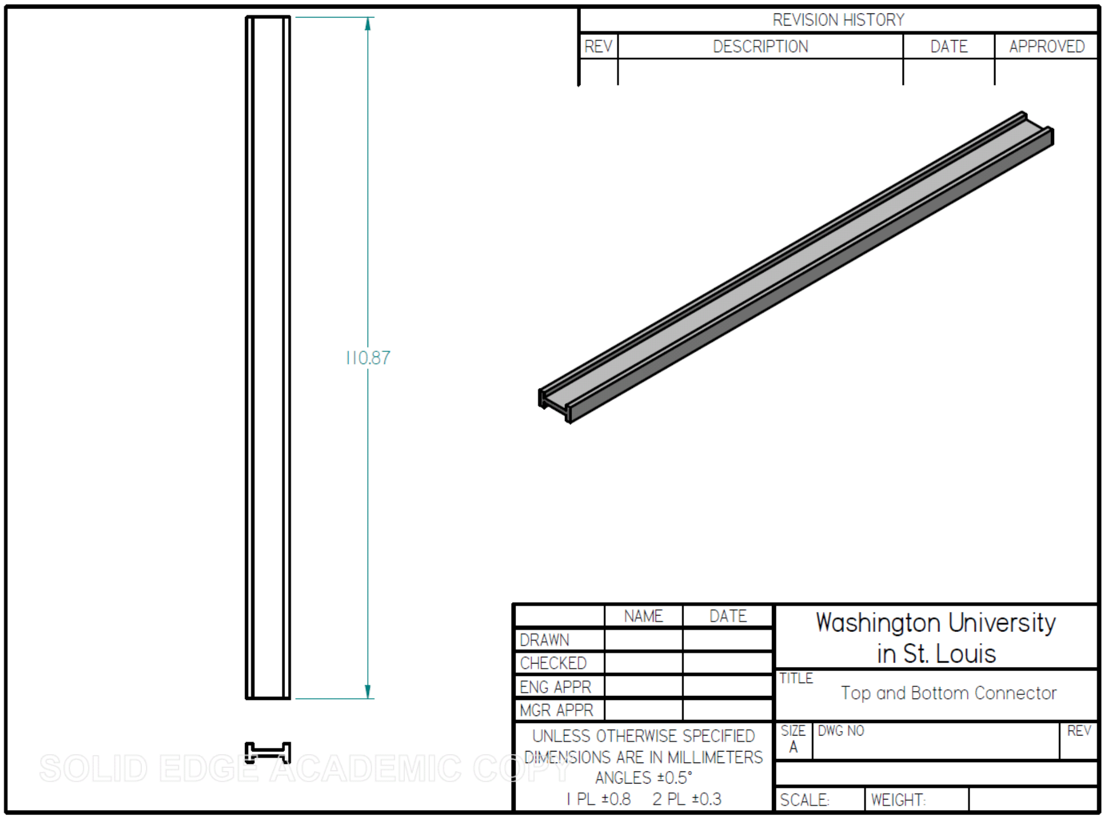
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DIMENSIONS ARE IN MILLIMETERS
ANGLES ±0.5°
1 PL ±0.8 2 PL ±0.3
Washington University
in St. Louis
TITLE
Top and Bottom Connector
SIZE
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SCALE:
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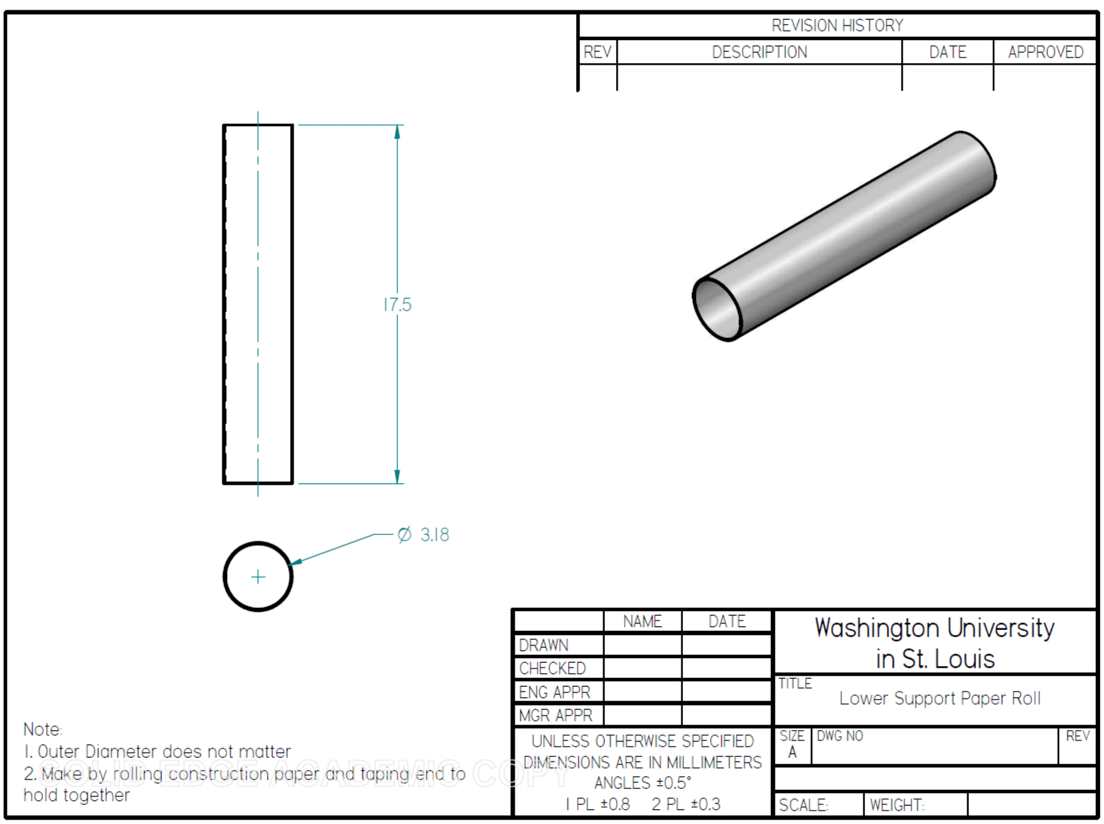
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APPROVED
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Ø 3.18
Note:
1. Outer Diameter does not matter
2. Make by rolling construction paper and taping end to hold together
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±0.5°
1 PL ±0.8 2 PL ±0.3
Washington University
in St. Louis
TITLE
Lower Support Paper Roll
SIZE
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SCALE:
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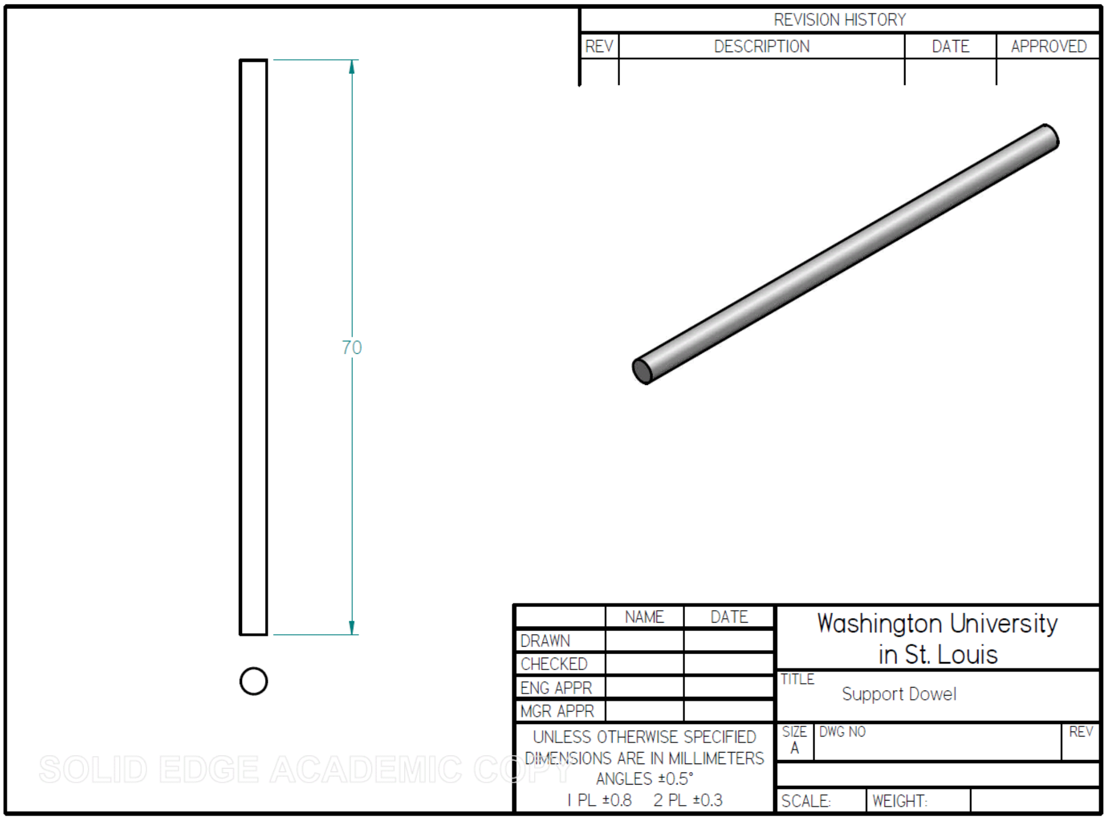
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NAME
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DIMENSIONS ARE IN MILLIMETERS
ANGLES ±0.5°
1 PL ±0.8 2 PL ±0.3
Washington University in St. Louis
TITLE
Support Dowel
SIZE A
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WEIGHT:
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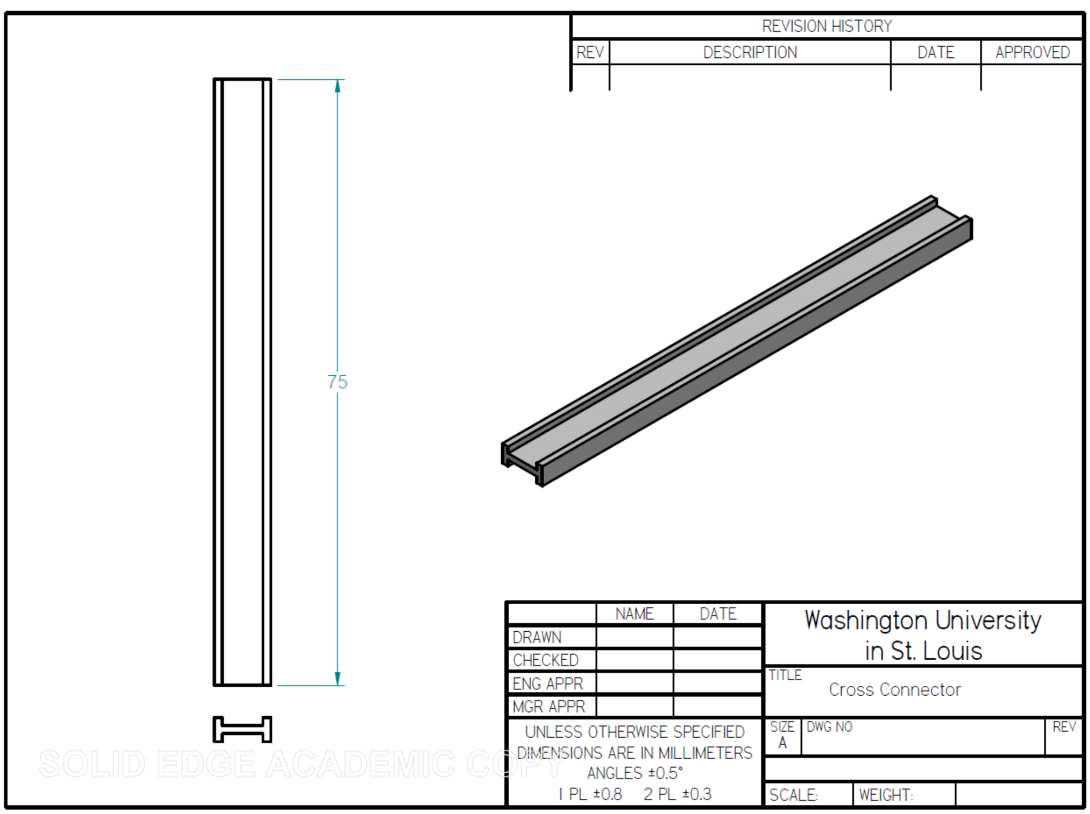
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DESCRIPTION
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APPROVED
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DIMENSIONS ARE IN MILLIMETERS
ANGLES ±0.5°
1 PL ±0.8 2 PL ±0.3
Washington University in St. Louis
TITLE
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SIZE A
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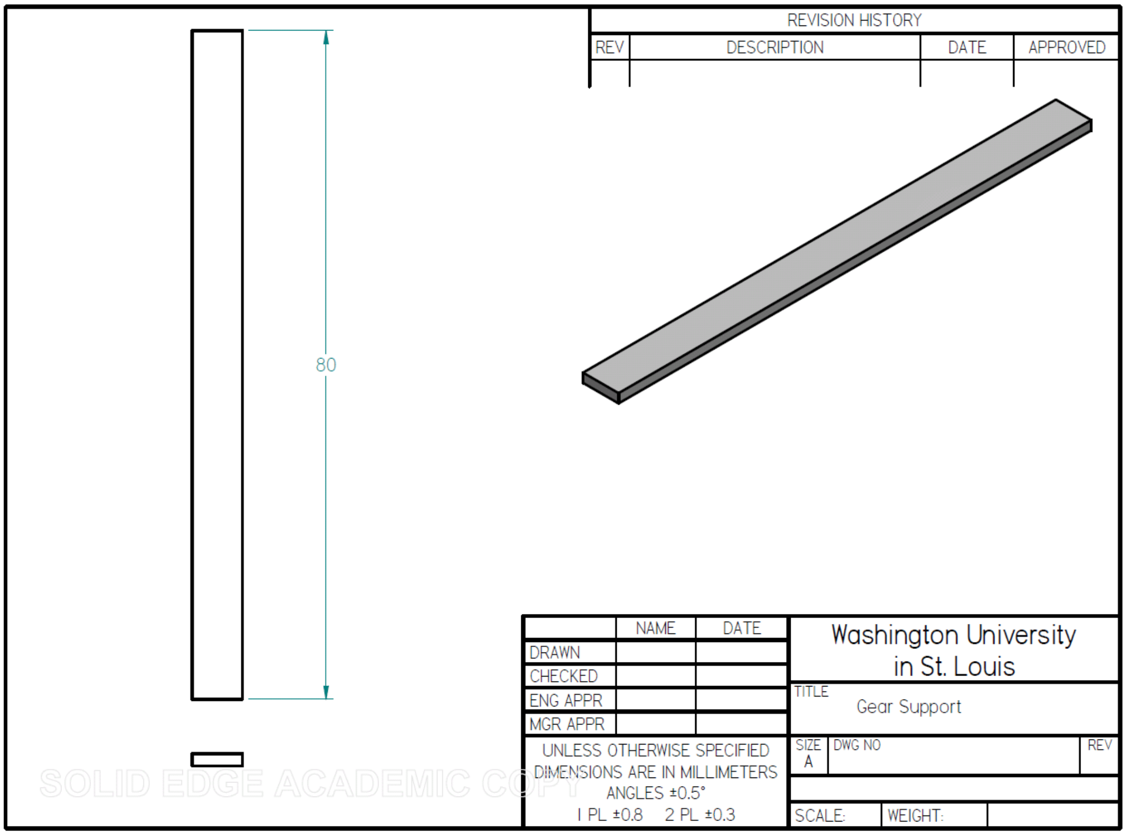
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DIMENSIONS ARE IN MILLIMETERS
ANGLES ±0.5°
1 PL ±0.8 2 PL ±0.3
Washington University in St. Louis
TITLE
Gear Support
SIZE A
DWG NO
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SCALE:
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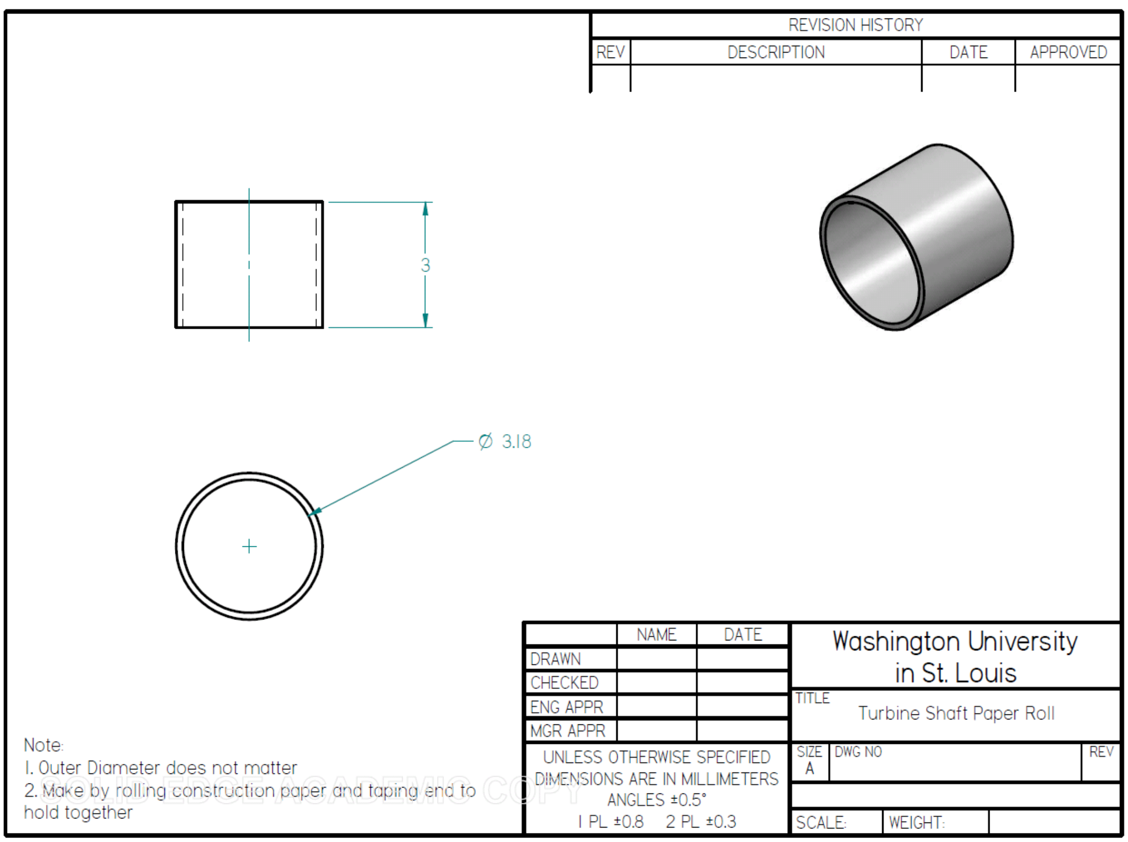
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DESCRIPTION
DATE
APPROVED
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Ø 3.18
Note:
1. Outer Diameter does not matter
2. Make by rolling construction paper and taping end to hold together
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±0.5°
1 PL ±0.8 2 PL ±0.3
Washington University in St. Louis
TITLE
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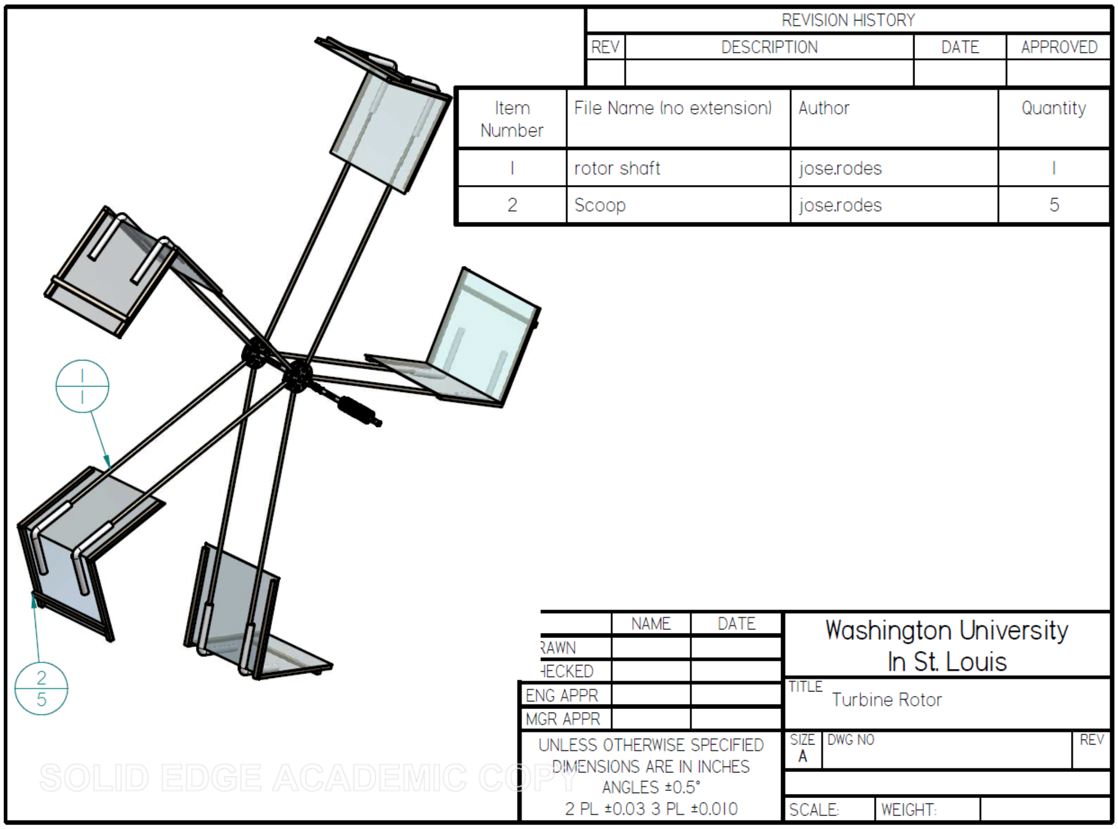
SIZE A
DWG NO
REV
SCALE:
WEIGHT:



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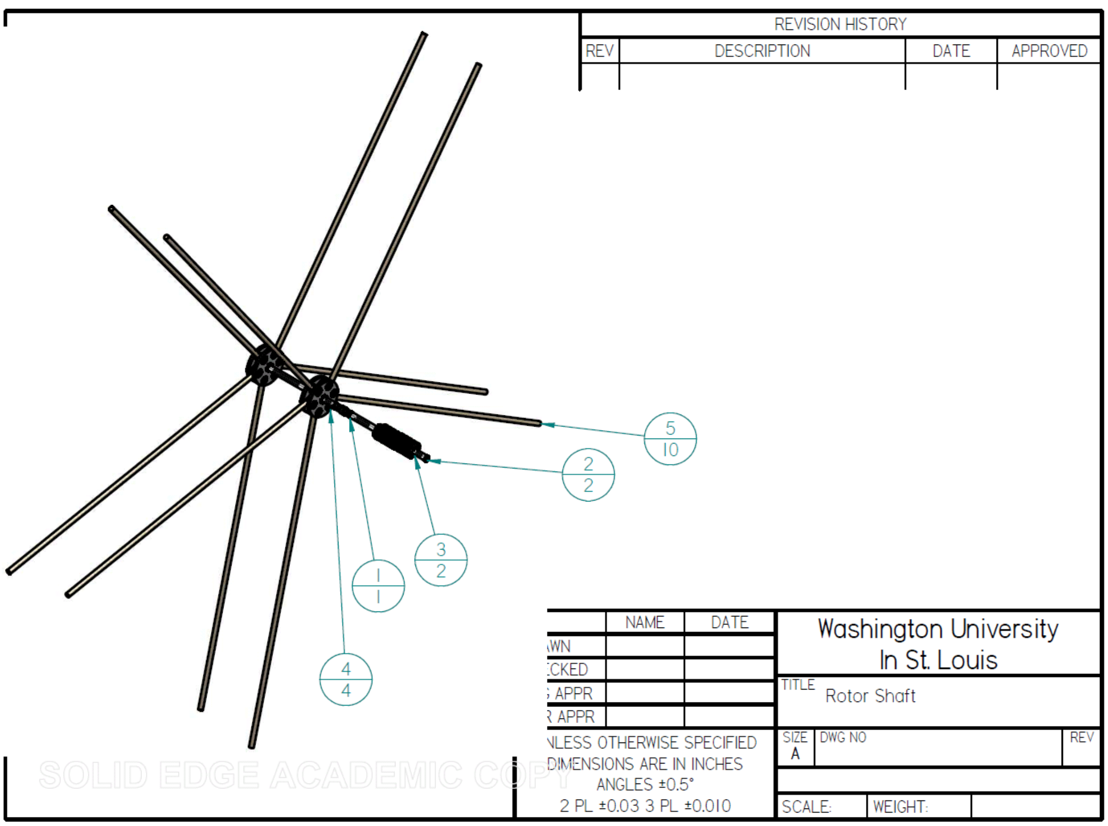
2	Scoop	jose.rodes	5



Item Number	File Name (no extension)	Author	Quantity
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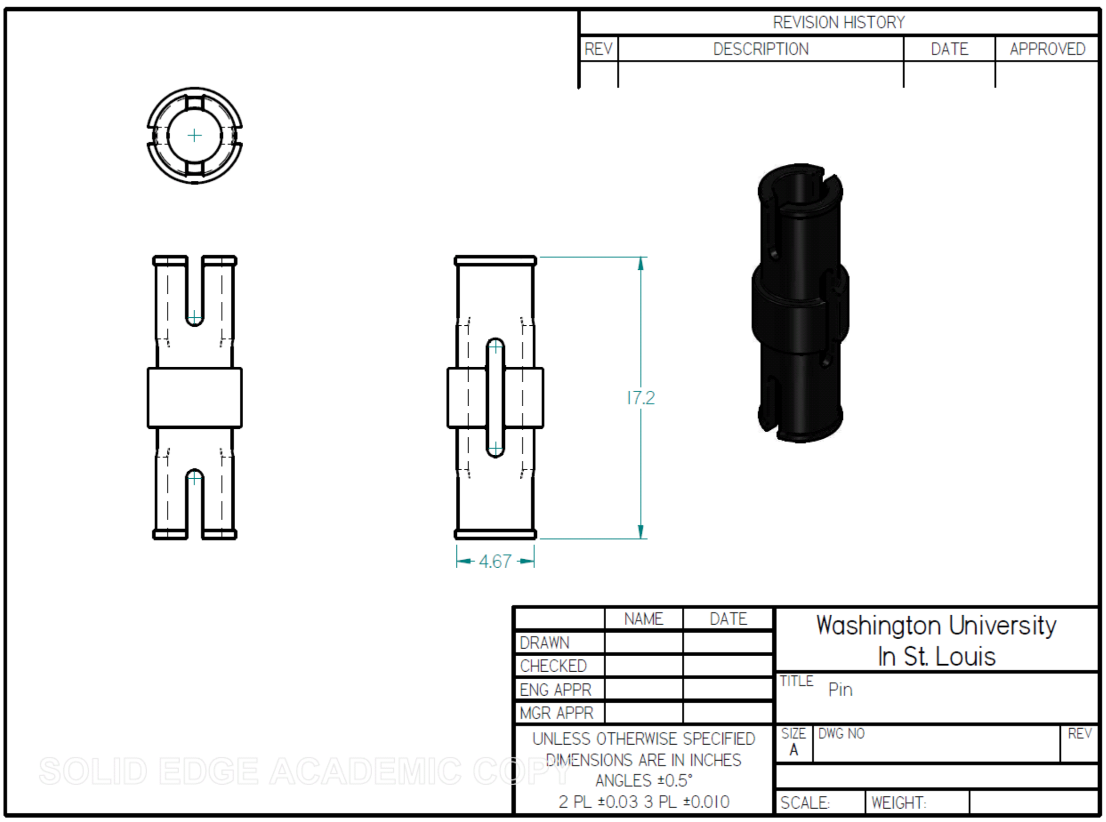
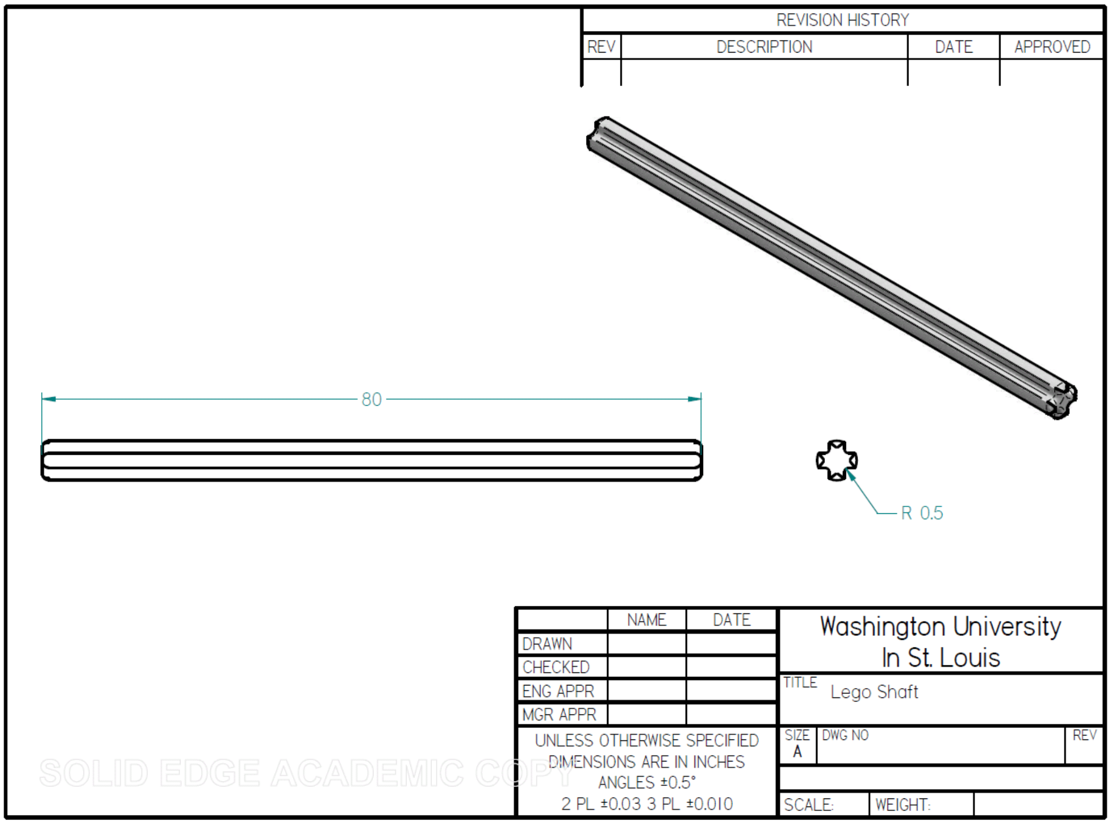
3	Wormgear	jose.rodes	2
4	gearwheel	jose.rodes	4
5	branch-shaft	jose.rodes	10

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MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±0.5°
2 PL ±0.03 3 PL ±0.010
Washington University
In St. Louis
TITLE
Lego Shaft
SIZE
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WEIGHT:
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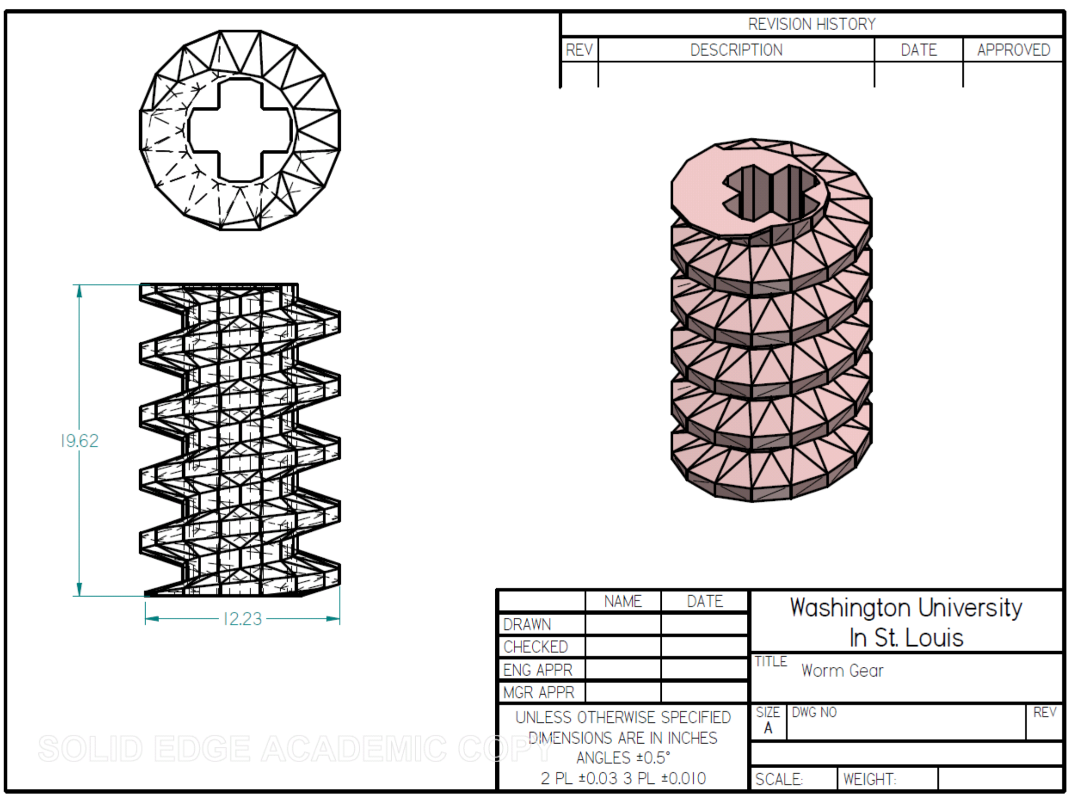
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UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±0.5°
2 PL ±0.03 3 PL ±0.010
Washington University
In St. Louis
TITLE
Worm Gear
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WEIGHT:
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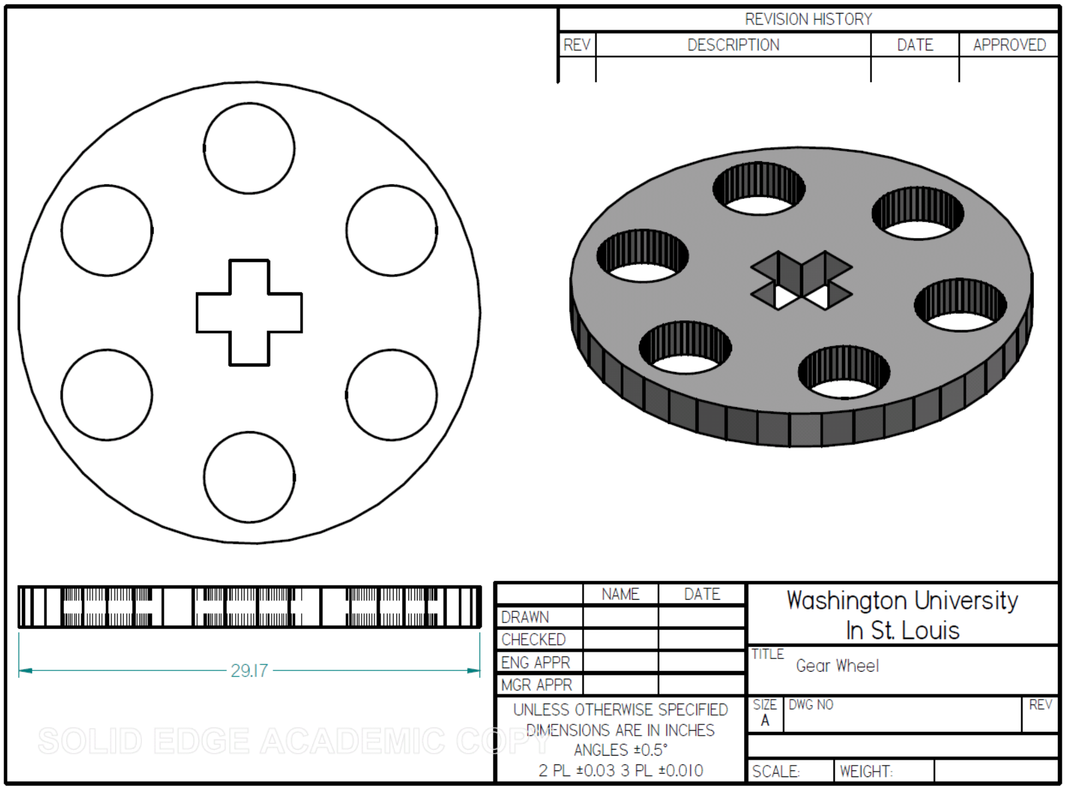
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Washington University
In St. Louis
TITLE
Gear Wheel
SIZE
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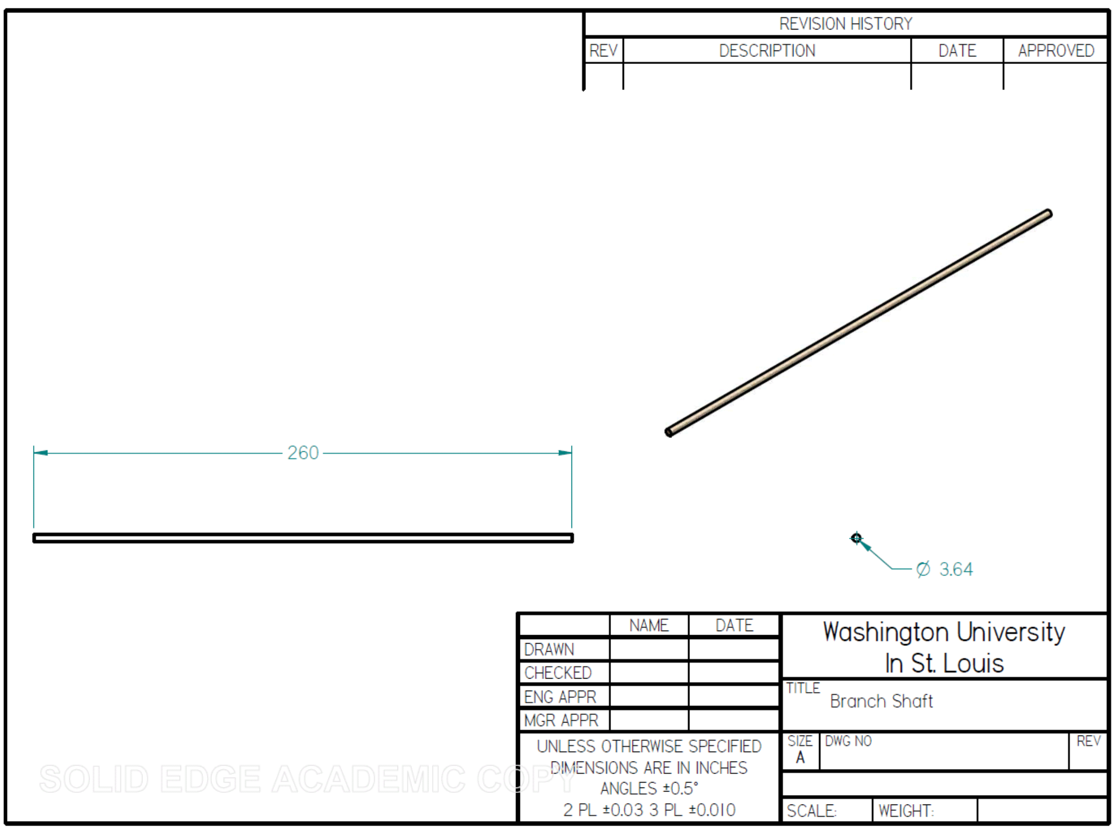
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Washington University
In St. Louis
TITLE
Branch Shaft
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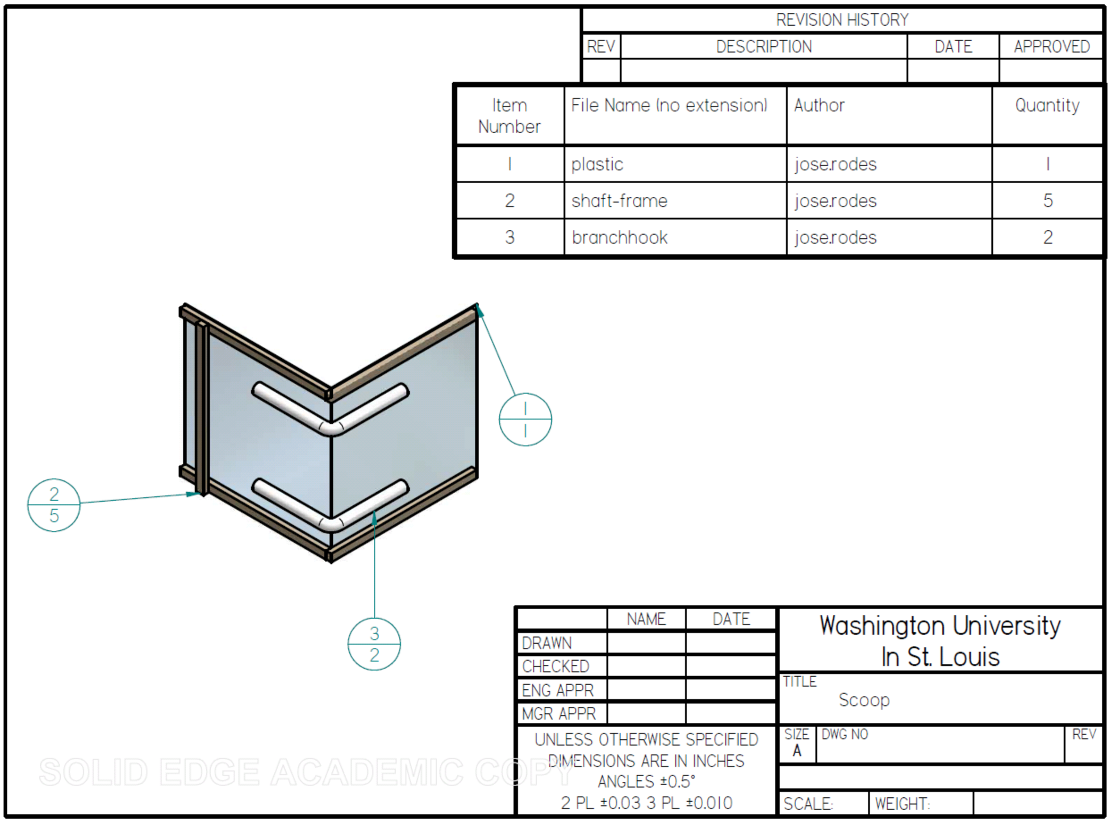
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DATE
APPROVED
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Author
Quantity
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2 shaft-frame jose.rodes 5
3 branchhook jose.rodes 2
1
1
2
5
3
2
NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
Washington University In St. Louis
TITLE
Scoop
SIZE A
DWG NO
REV
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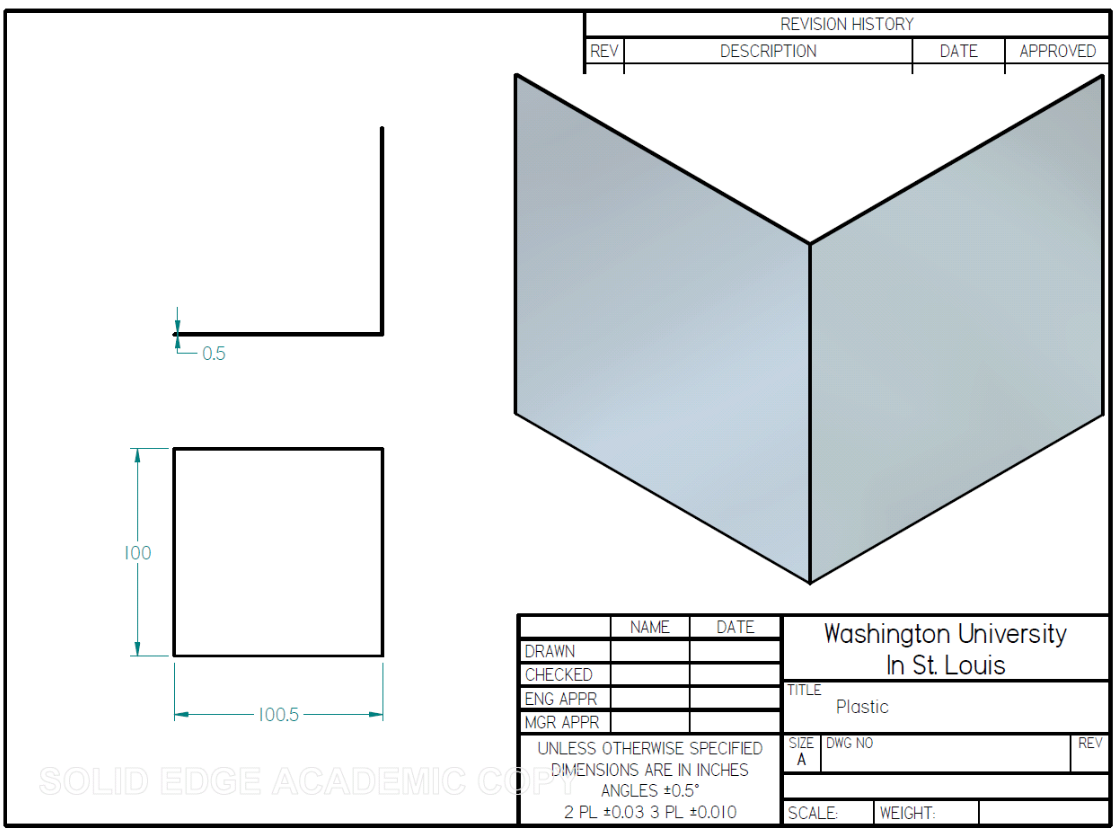
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MGR APPR
Washington University In St. Louis
TITLE
Plastic
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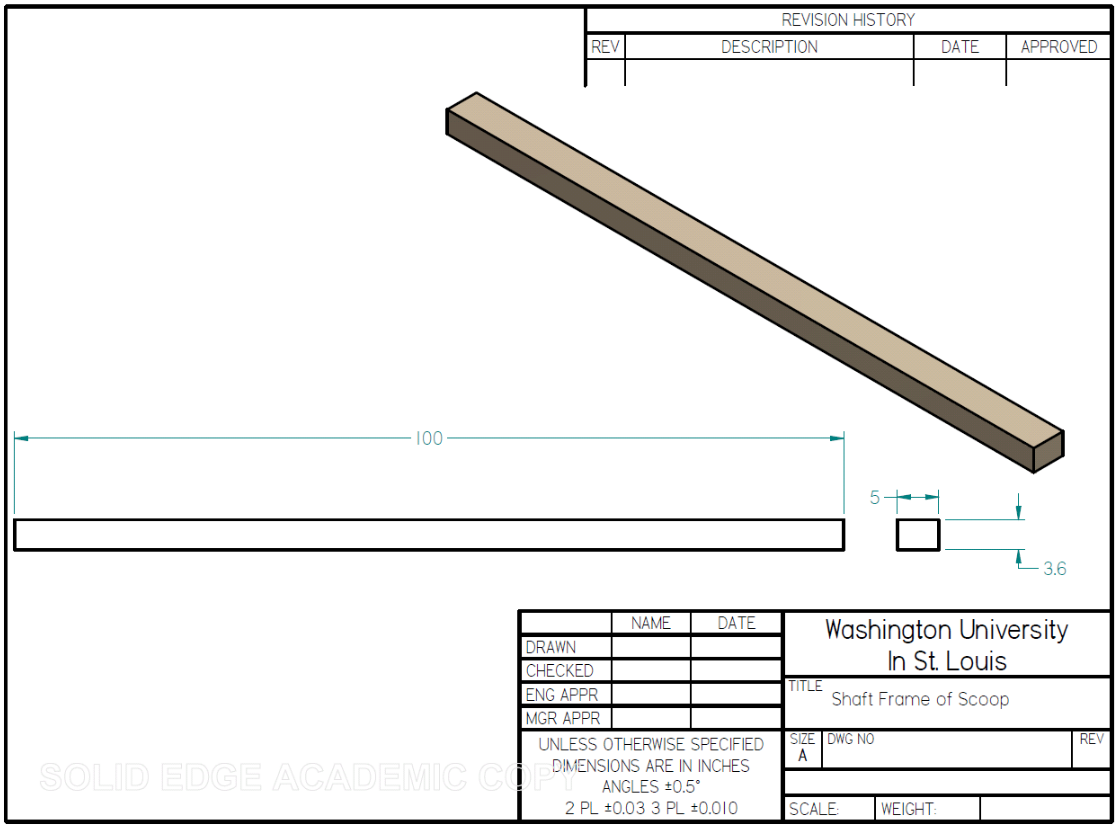
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MGR APPR
Washington University
In St. Louis
TITLE
Shaft Frame of Scoop
UNLESS OTHERWISE SPECIFIED
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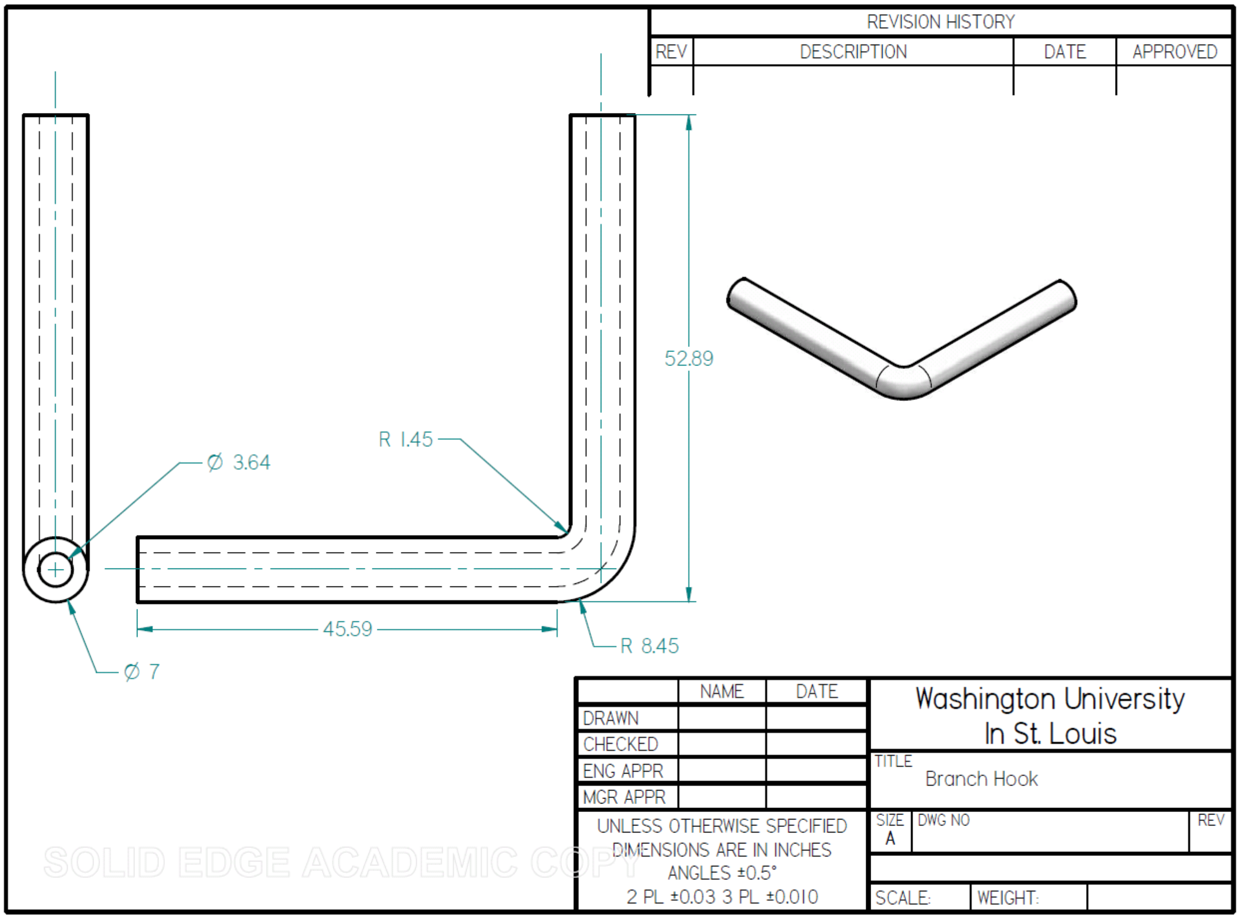
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NAME
DATE
DRAWN
CHECKED
ENG APPR
MGR APPR
Washington University
In St. Louis
TITLE
Branch Hook
SIZE
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DWG NO
REV
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
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WEIGHT:
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12 Annotated Bibliography

"Complex Linkage Mechanisms – Theo Jansen Mechanism 51018." *ROBOTS ROBOTICS RSS*. ROBOT Developer Center, 24 Apr. 2013. Web. 8 Dec. 2014. <http://www.robotee.com/index.php/complex-linkage-mechanisms-theo-jansen-mechanism-2-51018/>.

This website contains detailed information about the Jansen Mechanism as well as animations of it in motion. There is also a paper detailing the mechanics and math behind the mechanism. This proved helpful in understanding exactly how our machine's feet would interact with the ground as it walked.

Jansen, Theo. "Theo Jansen's STRANDBEEST." *STRANDBEEST*. Web. 8 Dec. 2014. <http://www.strandbeest.com/>.

This is Theo Jansen's website. It has information about how his strandbeests work and offers insight to how and why he has designed his creatures the way he has. This is a solid starting point for background information regarding wind powered walking machines.

Marie, Darrieus G. Turbine Having Its Rotating Shaft Transverse to the Flow of the Current. Leblanc Vickers Maurice Sa, assignee. Patent US1835018 A. 8 Dec. 1931. Web. 8 Dec. 2014. <http://www.google.com/patents/US1835018>.

This is the patent for a Darrieus turbine. It offers insight to the design of an effective lift-based wind turbine.

Vanderhye, Robert A., Brendon Nunes, and Gregory J. Lowe-Wylde. Savonius Wind Turbine Construction. Robert A. Vanderhye, assignee. Patent US7762777 B2. 27 July 2010. Web. 8 Dec. 2014. <http://www.google.com/patents/US7762777>.

This is the patent for a Savonius wind turbine. It offers insight to the design of an effective drag-based wind turbine.