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Spring 2021

### **MEMS 411: Portable Bridge Crane**

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Washington University in St. Louis

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JAMES MCKELVEY SCHOOL OF ENGINEERING

SP21 MEMS 411 Mechanical Engineering Design Project

Portable Crane Bridge

We designed and built a portable bridge crane for use in class demonstrations. The design was based off a typical gantry crane, which consists of a trolley spanning across two horizontal parallel beams that are part of a gantry with a payload hanging from the trolley. Our group also needed to design the gantry itself and ensure it was both stable enough to support the trolley and payload at the desired operation speeds as well as scaled properly for the desired use. This bridge crane needed to be sized so that it is portable enough to bring to and from class by Dr. Potter, but also large enough that it ideally can be seen by the entire lecture hall. The trolley on the bridge crane needed to move fast enough to swing a given payload and show some periodic motion along with some damping characteristics of the system. The trolley needed to have variable speed settings and the cable must have the ability to vary in length to show the effect of cable length on the payload's motion.

An interview was conducted with Dr. Potter to better understand his needs and the requirements of the product. His answers were able to help us create a list of user needs that was then narrowed down to a list of target specifications that the product should accomplish. A Gantt Chart was created to set a timeline for milestones of the project.

To kick off the design process, we put together a mock-up prototype of the Bridge Crane with common materials to see if we could quickly identify areas of the design that we would need to focus on. A function tree was made to list all of the functions of the Bridge Crane that we needed to design. A morphological chart was made to list all the ways we could design each of the functions. Finally, three designs were created using the options from the morphological chart to give a sense of how each piece would fit and work together.

An analytical hierarchy process was used to weight five selection criteria to see how they were valued when compared to each other. Then a weighted scoring matrix was used with the same five selection criteria on the three designs we came up with earlier to help us evaluate our concepts. This evaluation proved that we should move forward with building the Flat Side Bridge Crane model. Lastly, we found three engineering models that we believed would help us during the creation of our first prototype.

A computer automated design drawing was created using SolidWorks. Three performance goals for the prototype were decided on: the device's trolley can move  $\geq 1$  ft/s, the trolley stops before hitting the rails and is forced in the opposite direction, and the portable bridge crane weighs  $\leq 10$  lbs. Proofs of concept were forgone due to the fact that parts were added to the prototype and either worked or could be slightly adjusted to work without having to be removed. Two design rationales were given: a friction analysis of the trolley on the track, and a torque-speed curve of the stepper motor that was used.

Three model based decisions were explained: how long the trolley would need to stop if friction was the only force acting on it, the number of steps the motor will be able to take before the trolley hits a soft stop limit, and the maximum operable speed of the motor-trolley set-up before the motor stalls. A design for safety analysis was done to identify dangerous areas of the Bridge Crane. A design for manufacturing analysis was done to identify areas of the Bridge Crane that could be manufactured in quicker, more cost-efficient methods. A design for usability analysis was done to identify areas of the Bridge Crane that would be difficult for people of certain demographics to use.

In the end, the final prototype was different than the three initial designs that we came up with. The area that gave us the most resistance was the motor along with electrical components. The motor had to be changed for a larger, more-powerful model, and the motor driver had to be changed out a couple times. Despite not looking polished, the final prototype did meet two of the three stated performance goals: the total device weighed under ten pounds, and the soft stops were implemented. The fastest we were able to make the trolley go was about half of a foot per second. Items we recommend for future improvement would be: providing more current to the motor, use a dead axle on one side instead of using a dead motor, replacing the breadboard with a control box, and improve the leg stability.

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Bauer, Troy  
Eckels, Alex  
deSouza, Zarya

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# 1 Introduction

We will be designing and building a portable bridge crane for use in class demonstrations. The design will be based off a typical gantry crane, which consists of a trolley spanning across two horizontal parallel beams that are part of a gantry with a payload hanging from the trolley. Our group will also need to design the gantry itself and ensure it is both stable enough to support the trolley and payload at the desired operation speeds as well as scaled properly for the desired use. This bridge crane must be sized so that it is portable enough to bring to and from class by Professor Potter, but also large enough that it ideally can be seen by the entire lecture hall. The trolley on the bridge crane must move fast enough to swing a given payload and show some periodic motion along with some damping characteristics of the system. The trolley must have variable speed settings and the cable must have the ability to vary in length to show the effect of cable length on the payload's motion.

## 2 Problem Understanding

### 2.1 Existing Devices

#### 2.1.1 Existing Device #1: Gorbel 1000-Lb. Overhead Shop Bridge Crane



Figure 1: Gorbel Overhead Shop Bridge Crane (Source: Northern Tool + Equipment)

Link: [https://www.northerntool.com/shop/tools/product\\_200672587\\_200672587?cm\\_mmc=Google-pla&utm\\_source=Google\\_PLA&utm\\_medium=Material%20Handling%20%3E%20Hoists%20%26%20Lifts%20%2B%20Cranes&utm\\_campaign=Shop%20Crane&utm\\_content=56125&gclid=Cj0KCQiAvP6ABhCjARIsAH37rbwCB&gclsrc=aw.ds](https://www.northerntool.com/shop/tools/product_200672587_200672587?cm_mmc=Google-pla&utm_source=Google_PLA&utm_medium=Material%20Handling%20%3E%20Hoists%20%26%20Lifts%20%2B%20Cranes&utm_campaign=Shop%20Crane&utm_content=56125&gclid=Cj0KCQiAvP6ABhCjARIsAH37rbwCB&gclsrc=aw.ds)

Description: The Gorbel overhead shop bridge crane is an 8 ft x 15 ft x 10 ft crane that can carry loads of up to 1000 lbs on the single bridge that spans the two parallel runways. It is smaller and more conveniently set up than most other overhead cranes and can be used for projects in smaller indoor garages such as car restoration or other vehicle maintenance. The simpler design leads to an easier setup, however also limits the ultimate carrying capacity when compared to more heavy duty overhead cranes.

### 2.1.2 Existing Device #2: TAWI Double Girder Crane



Figure 2: TAWI Double Girder Crane (Source: TAWI Lifting Equipment)

Link: <https://www.tawi.com/en-us/products/overhead-bridge-cranes-en-us/double-girder-cranes>

Description: The bridge is made with two steel girders joined together in a triangular framework and powered by an electric motor. The addition of a second girder allows for the crane to handle more than a ten time increase in the load when compared to the single girder model. Both the bridge and trolley are equipped with a motor to aid the movement of loads up to 3,300 pounds. The motorized trolleys are able to travel at two different speeds and a frequency converter can be used to have more speed selections.



### 2.1.3 Existing Device #3: T-series Gantry Crane



Figure 3: T-Series Gantry Crane (Source: L.K. Goodwin CO.)

Link: [https://www.lkgoodwin.com/more\\_info/t\\_series\\_gantry\\_cranes/t\\_series\\_gantry\\_cranes.shtml](https://www.lkgoodwin.com/more_info/t_series_gantry_cranes/t_series_gantry_cranes.shtml)

Description: The T-Series Gantry crane is fully adjustable in span and height. The adjustable size with the wheels on the bottom makes this crane very portable as it can both fit through doorways as well as extend to two-stories high. It is very stable and sturdy so it can be used for many different purposes.

## 2.2 Patents

### 2.2.1 Gantry Cranes (US3645406A)

This patent for a Gantry Cranes that are typically used to transport railroad crates on and off the train. This crane can move around on its own and is completely controllable by the user. The two clamps positions relative to each other can be adjusted so that objects of different sizes can be carried. The crane can also weigh the object it is carrying. Therefore this eliminates the need to place the object onto a scale and then pick it up again afterwards. The system is highly maneuverable with the ability to rotate about any wheel.

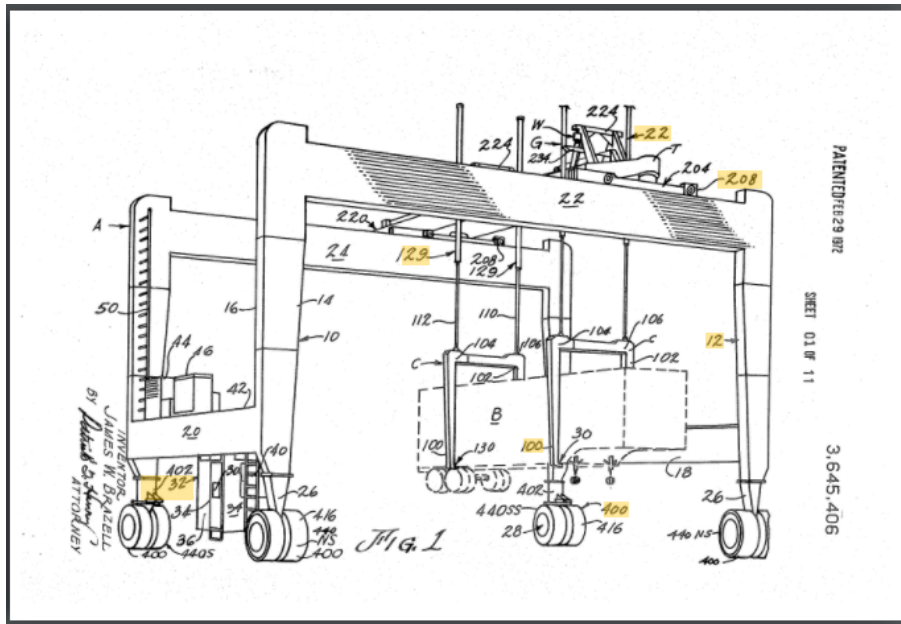


Figure 4: Patent Image for Gantry Crane

### 2.2.2 Bridge Crane (US6082562A)

US6082562A is a patent for a bridge crane with at least one main girder. It allows for a trolley or at least one fixed hoist gear on the girder(s). The end carriages support the main girder while having wheels that allow for manual movement of the girders in a parallel direction to the end carriages. Slides are placed between the girder and end carriage that allow for the longitudinal movement of the end carriage in relation to the main girder and a rotation of the end carriage and main girder in relation to each other.

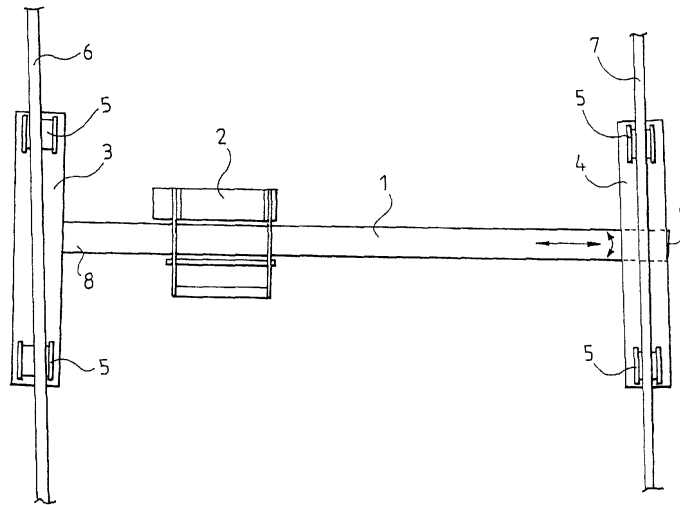


FIG. 1

Figure 5: Patent Images for Bridge Crane

## 2.3 Codes & Standards

### 2.3.1 Overhead and Gantry Cranes - Trolley Bumpers (ASME B30.2-1.8.3)

ASME B30.2-1.8.3 states that a trolley must have bumpers or equivalent automatic means. The bumpers must be able to stop the trolley when it is traveling at least 50 percent of its rated load speed and decelerate the trolley no faster than 1.4 meters per square second when traveling at least one third of its rated load speed. The bumper must be retained in the case of broken or loosened mounting connections. This code will be helpful in designing the hard stops for the trolley.

### 2.3.2 Overhead and Gantry Cranes - Clearance from Obstruction (1910.179(b)(6))

1910.179(b)(6)(i)-1910.179(b)(6)(ii) states the various clearance requirements around a gantry crane and the surrounding passenger walkways in order to ensure the safety of both the crane operator as well as any people passing nearby during operation. These standards also provide clearances so that objects will not interfere with the operation of the crane and cause a potential failure of the machine. Although the clearances needed as well as the risks of serious danger are much higher for a full scale gantry crane, the ideas of proper clearances can still be applied for our bridge crane to avoid potential hazards caused by a derauling of the trolley or the swinging of the payload.

## 2.4 User Needs

### 2.4.1 Customer Interview

Interviewee: Dr. James Jackson Potter

Location: Zoom

Date: February 4<sup>th</sup>, 2021

Setting: The whole interview was over zoom, and took ~35 min.

Interview Notes:

*What are you intending to use this device to do?*

- Using this device to demonstrate dynamics and controls to students.

*Where are you typically going to be using this device*

- Storing the device in office and transporting it into the classroom.

*Does this device need to be child safe?*

- Not particularly, my kids will likely not be coming to the school anytime soon.

*How fast does the cart need to travel?*

- Cart needs to travel at least 1 foot per second.
- If you can get the cart to be able to travel at multiple speeds, that would be best.
- Should be able to travel both forwards and backwards

*How heavy should the crane be?*

- Ideally under 10 lbs but can be up to 20 lbs.

*How stable should the crane be?*

- Must not be too wobbly when the cart comes to rest.
- Cart should be unaffected by the cable swing.

*What payload should it be able to carry?*

- Should be able to carry a tennis ball

*How portable do you want it to be?*

- The height should be about 60 centimeters and the length should be about 100 centimeters.
- It should be one or two parts so it can be easily held.
- It should be light enough that it can be easily carried across campus.

*Is there anything you can think of that we did not ask?*

- You should probably use a stepper motor
- Prioritize functionality over looks.
- Cable length can be manually adjusted.
- The cart should be operated with a controller.

### 2.4.2 Interpreted User Needs

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	Varying Speeds of crane cart	5
2	Cart must be fast enough to demonstrate dynamics	5
3	Cart movement controlled by controller	5
4	Crane must be seen from back of classroom	3
5	The crane must be stable	5
6	Cart must be able to travel forwards and backwards	5
7	The crane is portable	5
8	Source of power from battery or outlet	2
9	Soft stops implemented	4
10	Adjustable cable length (manual)	5
11	Adjustable cable length (automatic)	2
12	Must be able to carry small payload	4
13	Payload must be interchangeable	2

## 2.5 Design Metrics

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	7	Total Weight of Crane	<i>lb</i>	< 20	< 10
2	4,7	Height	<i>cm</i>	60 ± 5	60
3	4,7	Width	<i>cm</i>	100 ± 10	100
4	12	Payload weight	<i>kg</i>	0.2	1
5	2,1	Speed of Car	<i>ft/s</i>	1	> 1
6	10,11	Adjust Cable length	<i>cm</i>	30	45
7	5	Cart does not fall when crane is firmly shook	binary	Pass	Pass
8	9	Distance to stop	<i>cm</i>	10	5
9	9	Meets hard stop standards set by ASME B30.2-1.8.3	binary	Pass	Pass
10	5,7	Crane will operate within safe zone in accordance with CFR 1910.179(b)(6)	binary	Pass	Pass

## 2.6 Project Management

The Gantt chart in Figure 6 gives an overview of the project schedule.

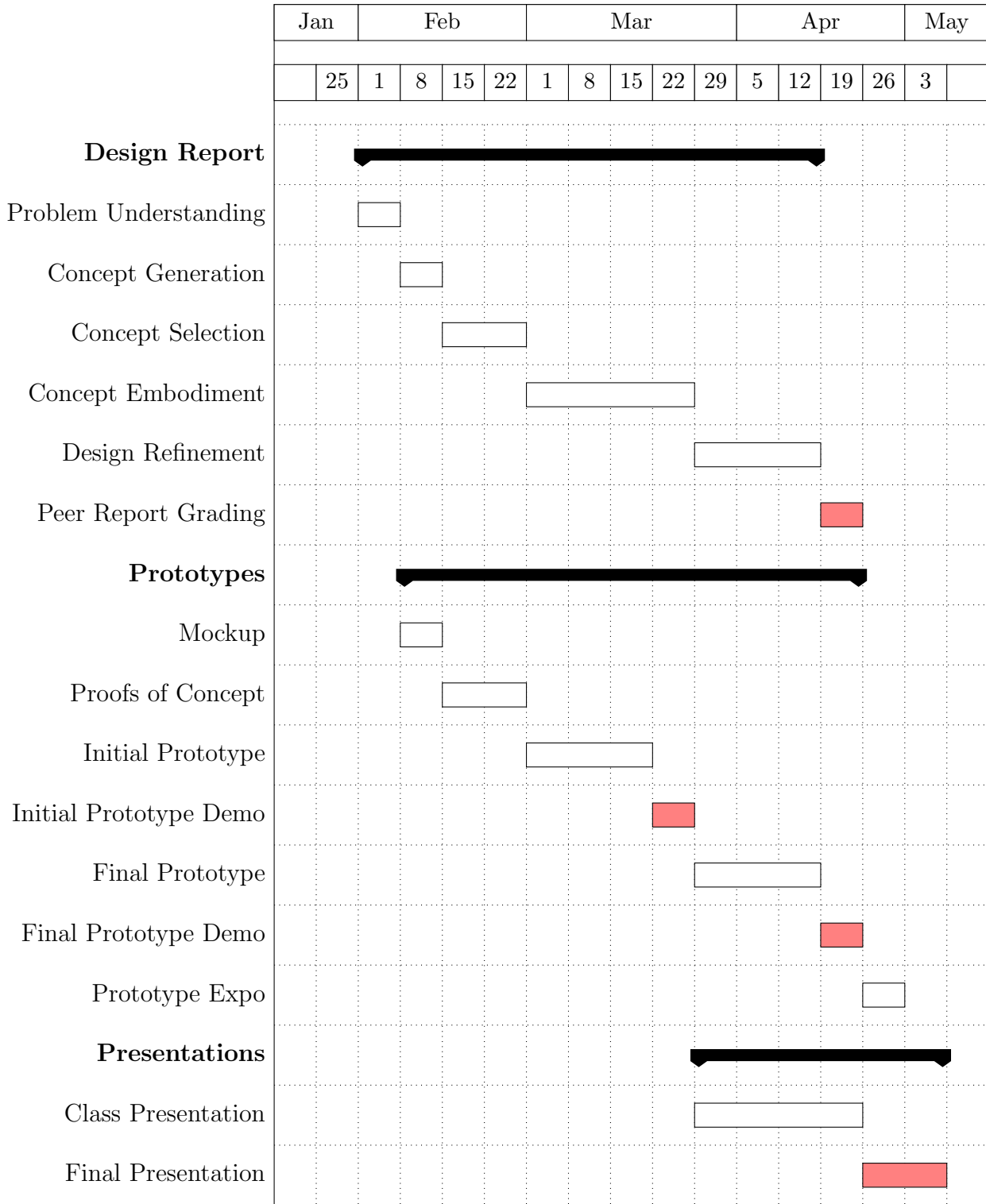


Figure 6: Gantt chart for design project

### 3 Concept Generation

#### 3.1 Mockup Prototype

To get a feel for the final product, a mock-up was created with materials commonly found in a house. Making a mock-up incorporating general ideas of what the final product is expected to look like allowed for ideas to be tested before construction became costly and time consuming. The first lesson learned is that the track needs to be made of a material with a large elastic modulus and the cart will need to be light. This will limit the amount of bending in the track that, otherwise, could impact the performance of the Bridge Crane. The next lesson learned is the support legs need to be long enough to allow room for the payload to swing and the support legs need to be heavy enough (or angled correctly) so that the Bridge Crane is rigid and will not shake when the cart moves. The last lesson learned is that the slot in the track for the payload needs to be wide enough that the string holding the payload does not rub against it. Otherwise, this could cause the Bridge Crane to perform worse than expected.



Figure 7: Mockup of Bridge Crane, isometric view



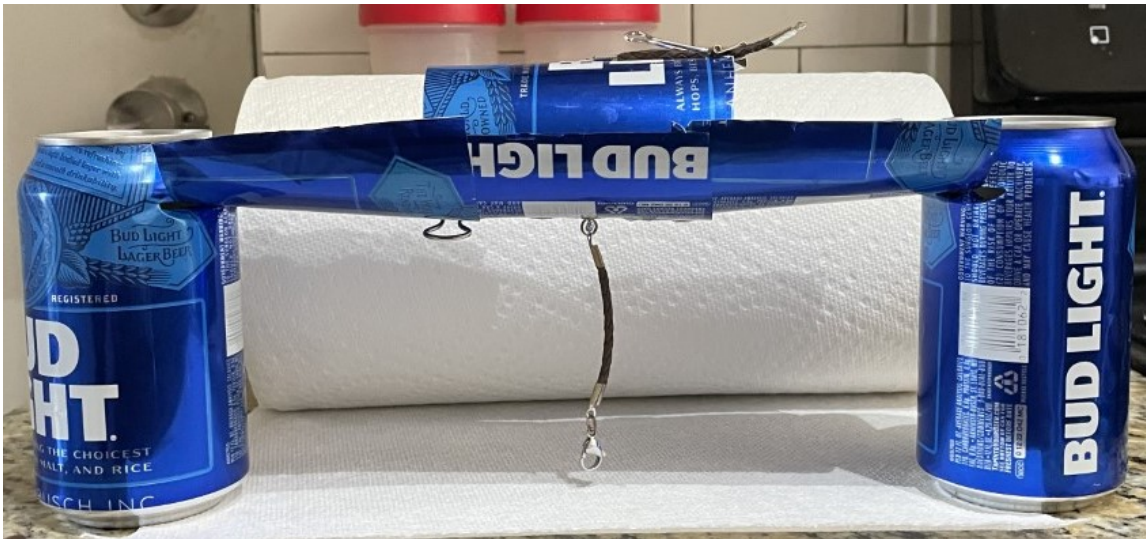
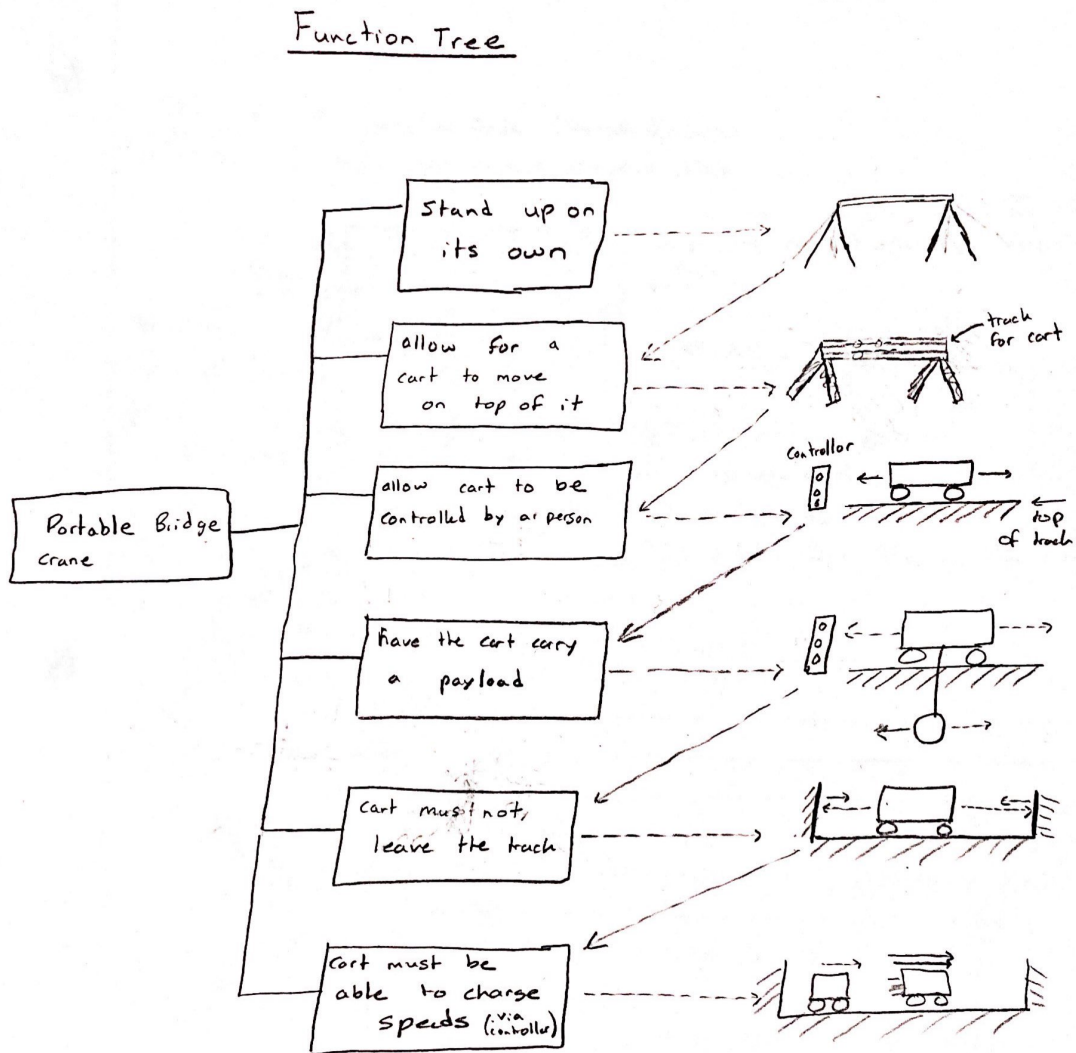


Figure 8: Mockup of Bridge Crane, front view



Figure 9: Mockup of Bridge Crane, top view

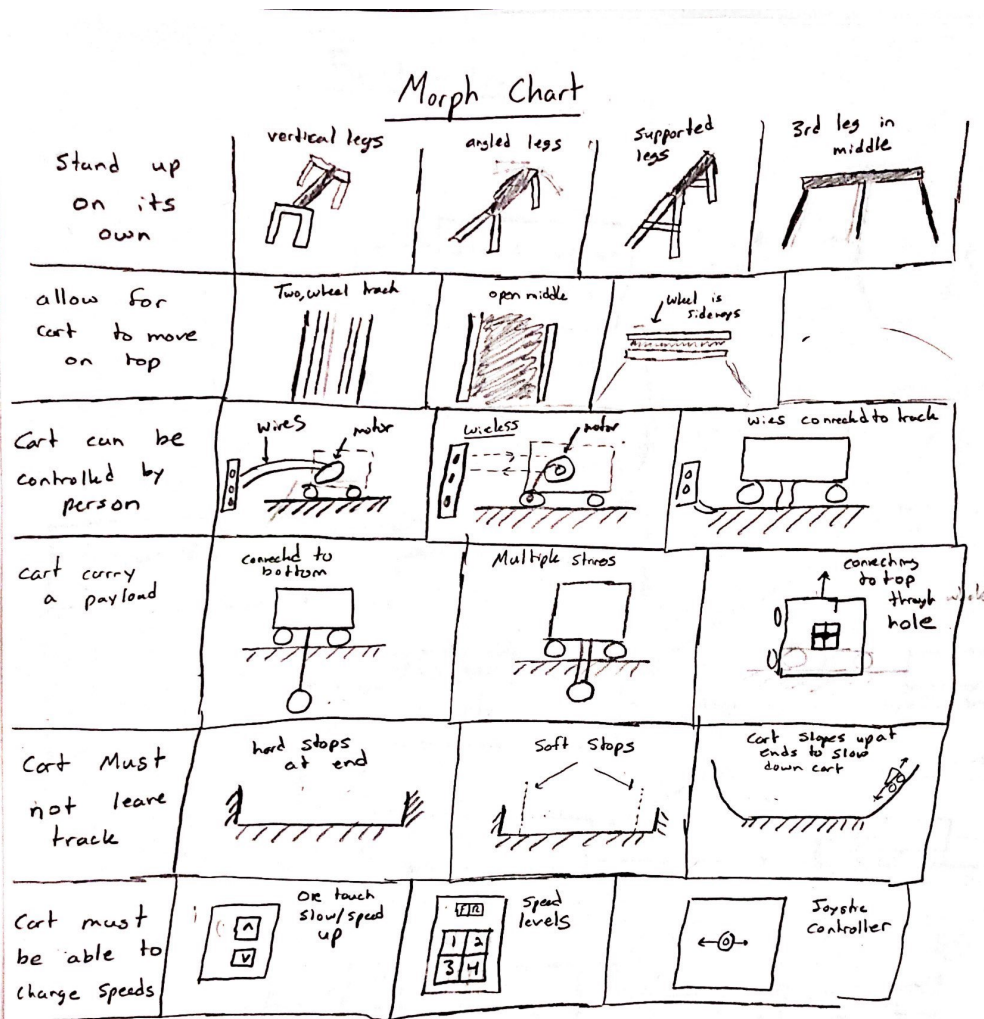
## 3.2 Functional Decomposition



CS Scanned with CamScanner

Figure 10: Function tree for portable bridge crane, hand-drawn and scanned

### 3.3 Morphological Chart

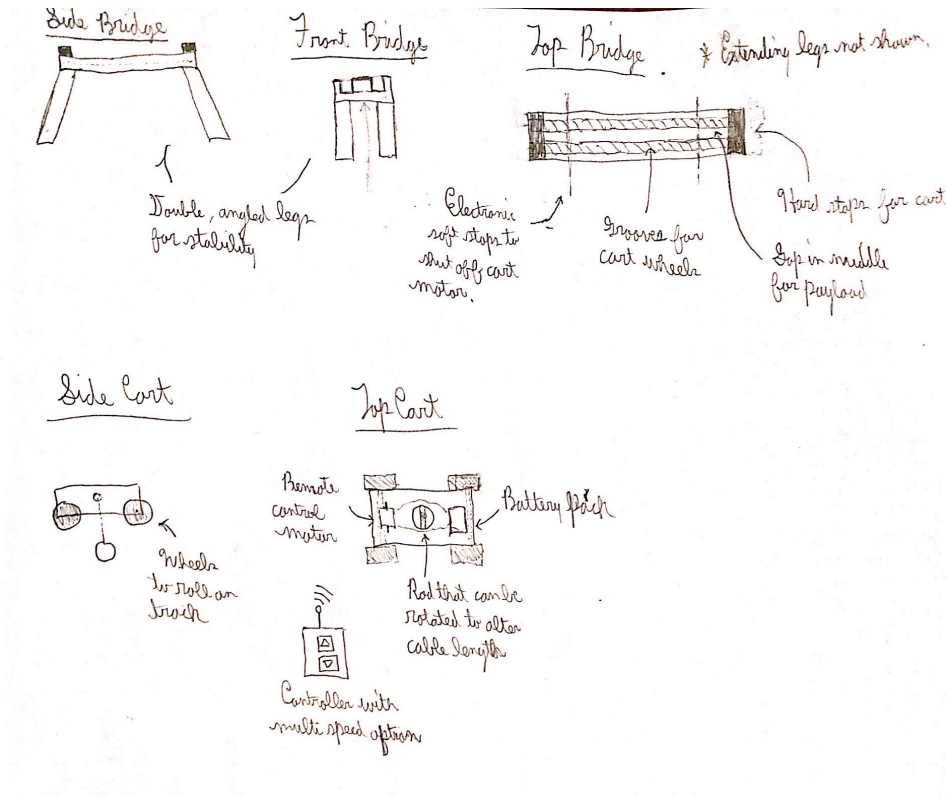


CS Scanned with CamScanner

Figure 11: Morphological Chart for bridge crane, hand drawn and scanned

### 3.4 Alternative Design Concepts

#### 3.4.1 Rolling Cart



Scanned with CamScanner

Figure 12: Preliminary sketches of bridge crane design

Description: A controller with multiple stepped speed inputs will control the cart motor, spinning the wheels and moving it at multiple speeds. It will roll on a flat track that has both rubber hard stops on the ends as well as electronic trigger soft stops that will terminate motor function once passed so the cart will slow to a stop without needing the hard stops every time. The track will have to parallel legs on each end that are attached at an angle to provide additional lateral stability. The cart wheels will roll on cut out grooves in the track, and the payload will hang through the cut out in the middle of the track. The payload cable will be attached to a peg in the middle of the cart that can be manually spun in order to increase or decrease cable length.

### 3.4.2 Flat Side Bridge

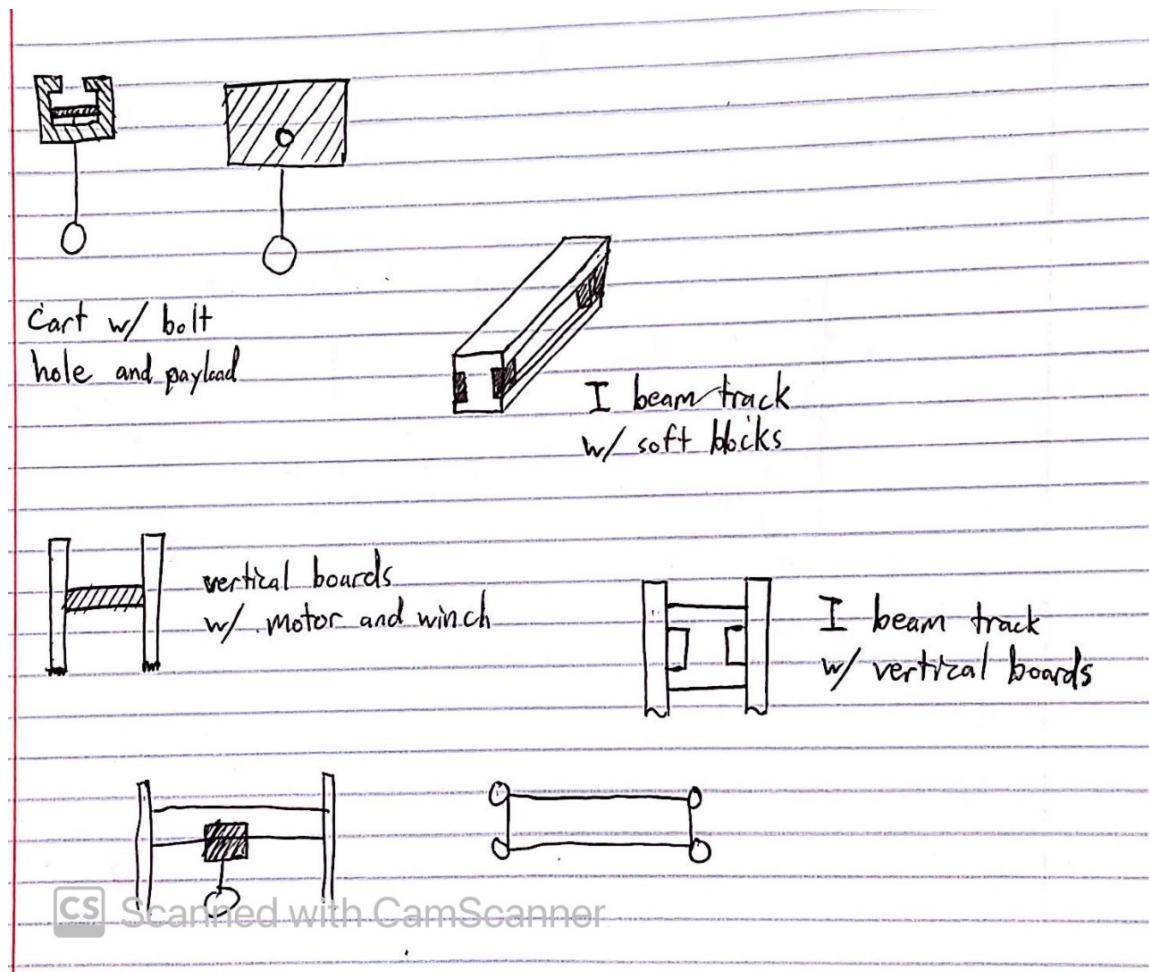


Figure 13: Preliminary sketches of under-hanging Bridge Crane concept

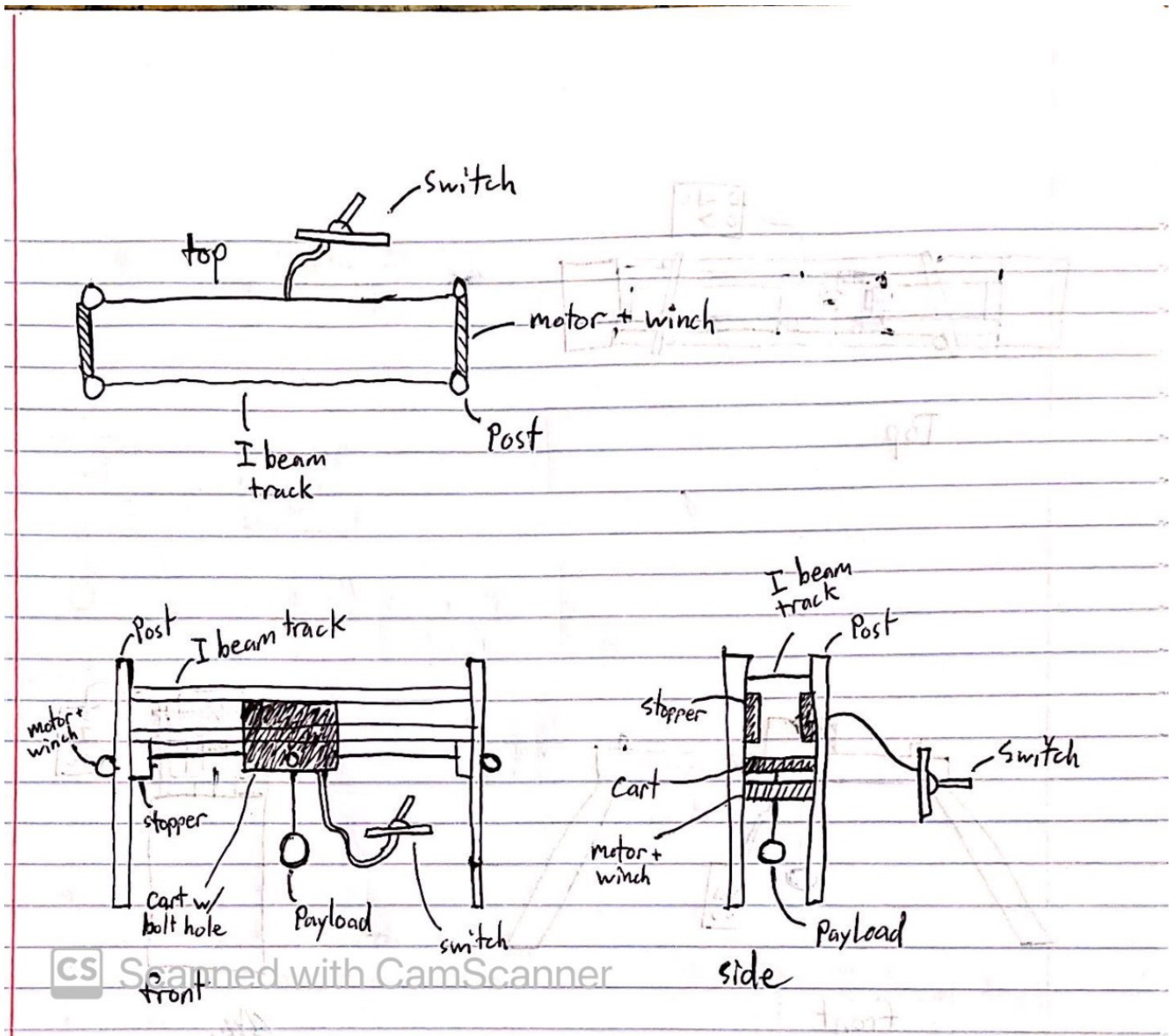


Figure 14: Final sketches of under-hanging Bridge Crane concept

Description: The switch controls the motors that are attached to the winches on each end of the Bridge Crane. This allows the cart to move in two directions at multiple speeds. The use of smooth materials for the I beam and cart reduce the friction generated when the cart is moved. By hanging the cart on the underside of the track, this allows the payload to swing without hitting the track.

### 3.4.3 Sloped Bridge Crane

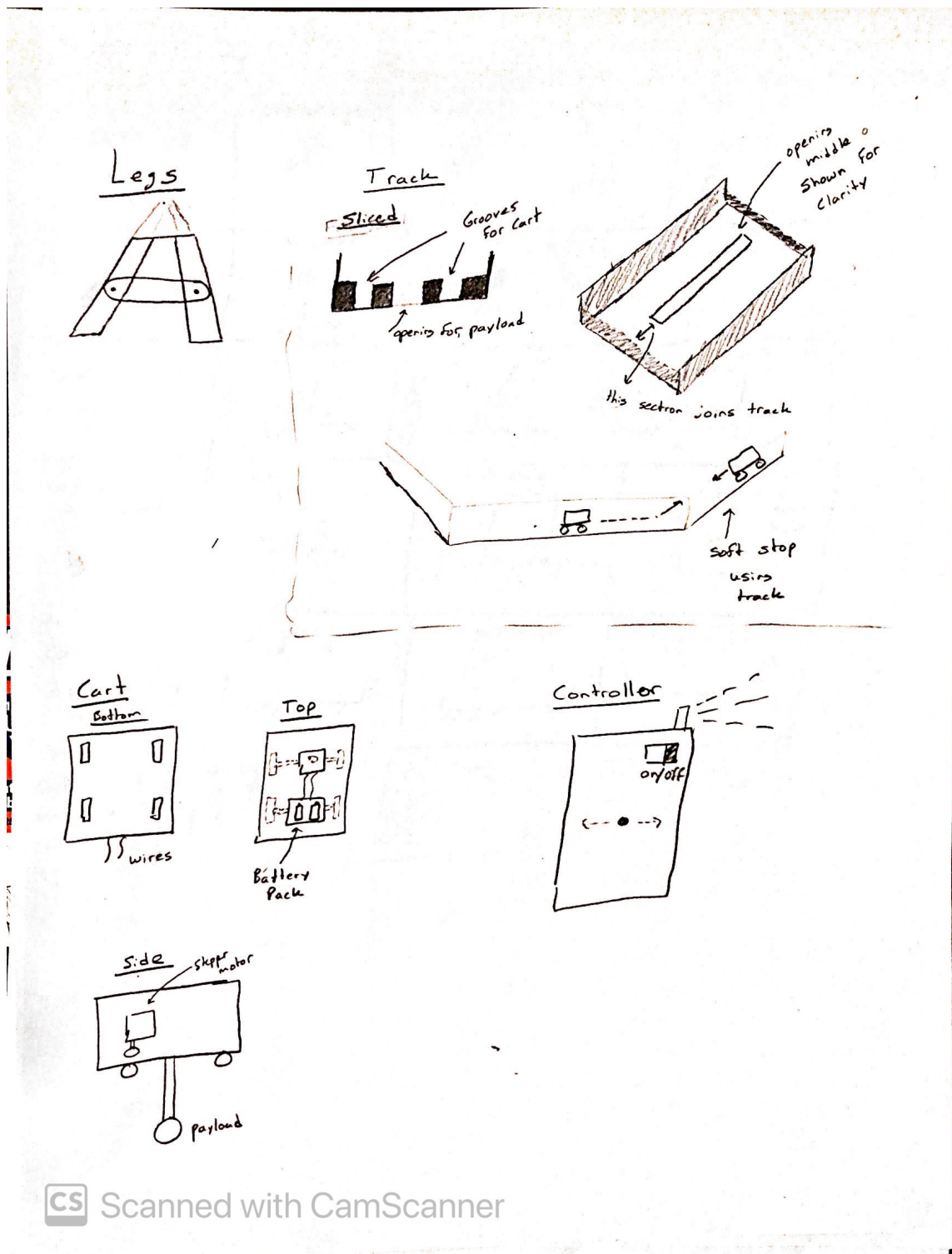


Figure 15: Preliminary sketches

Description: The sloped bridge crane is controlled the controller which has a joystick. The soft stops of this crane come from the sloped ends that will transfer the potential energy gained back

to kinetic energy going the opposite direction. The wires are connected to the track which the controller transmits to. The cart has 4 wheels that fit into the grooves of the track. The payload connects to the bottom of the cart. The structure is supported by wooden legs that are connected at the middle.



# 4 Concept Selection

## 4.1 Selection Criteria

	<b>Portability</b>	<b>Ease of Assembly</b>	<b>Safety</b>	<b>Reliability</b>	<b>Ease of Operation</b>		<b>Row Total</b>	<b>Weight Value</b>	<b>Weight (%)</b>
<b>Portability</b>	<b>1.00</b>	3.00	3.00	5.00	1.00		13.00	0.26	25.56
<b>Ease of Assembly</b>	0.33	<b>1.00</b>	0.33	0.20	0.11		1.98	0.04	3.89
<b>Safety</b>	0.33	3.00	<b>1.00</b>	0.20	0.14		4.68	0.09	9.20
<b>Reliability</b>	0.20	5.00	5.00	<b>1.00</b>	1.00		12.20	0.24	23.99
<b>Ease of Operation</b>	1.00	9.00	7.00	1.00	<b>1.00</b>		19.00	0.37	37.36
						<b>Column Total:</b>	<b>50.85</b>	<b>1.00</b>	<b>100.00</b>

Figure 16: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

## 4.2 Concept Evaluation

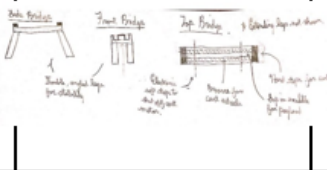

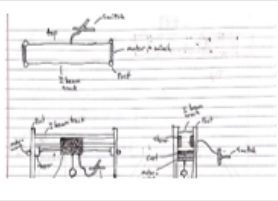
<b>Alternative Design Concepts</b>		<b>Flat Rolling Bridge</b>		<b>Ramp Rolling Bridge</b>		<b>Flat Slide Bridge</b>	
							
<b>Selection Criterion</b>	<b>Weight (%)</b>	<b>Rating</b>	<b>Weighted</b>	<b>Rating</b>	<b>Weighted</b>	<b>Rating</b>	<b>Weighted</b>
Portability	25.56	3	0.77	2	0.51	5	1.28
Ease of Assembly	3.89	3	0.12	3	0.12	4	0.16
Safety	9.20	3	0.28	3	0.28	4	0.37
Reliability	23.99	3	0.72	4	0.96	2	0.48
Ease of Operation	37.36	3	1.12	3	1.12	4	1.49
	<b>Total score</b>	<b>3.000</b>		<b>2.984</b>		<b>3.776</b>	
	<b>Rank</b>	<b>2</b>		<b>3</b>		<b>1</b>	

Figure 17: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

### 4.3 Evaluation Results

According to our evaluation, our third concept had the best score when it came to our 5 criteria. The slide bridge had the highest portability score, as it is just as easy to fold the bridge as the flat rolling bridge, but also has the added advantage of not having to worry about carrying a separate cart around, as the cart will be attached to the bridge. Both flat bridge concepts scored higher than the rolling bridge in portability since the inclined sides of the rolling bridge could cause folding problems. The sliding bridge also scored above average on ease of assembly, as fitting a sliding cart to the bridge will be easier than creating a bridge that is specifically fit and textured to provide grip for the tires of a rolling cart. This leaves much more room for a more simple design that does not necessarily need to be as precise. The flat bridge scored above average on safety as well, as the setup having a stepper motor on either side of the cart moving it each way through tension should help prevent any incidents of the cart leaving the track, as once the motor pulling the cart shuts off, there is no longer a possibility of the cart leaving the track as there is no more tensile force pulling it. There will also be hard stops in place in front of each motor to avoid a collision between cart and motor if by some way the cart accrues enough momentum to continue sliding. The sliding bridge did score below average on reliability, however, as there is a possibility the double tensile cable setup could experience problems with tangling cables if too much slack works its way into the system. The bridge crane will be designed with the goal of minimizing the risk of this type of event happening, however after extended use the risk of the double cable system experiencing some errors will increase when compared to just a rolling cart. Lastly, the slide bridge scored above average on ease of operation, as once the cart is set up on the slide track, there no longer needs to be any adjustment to the system for multiple uses. With the other cart systems, the user runs the risk of having to readjust the cart properly each time or having to worry about the cart losing traction on the track.

### 4.4 Engineering Models/Relationships

#### Model 1

A Torque vs Motor Speed curve is helpful to determine the stepper motor we need and what motor speeds and toques we need to achieve to move the cart at varying speeds. Depending on the model of stepper motor, it will also give us a limit to the weight of the cart. The pull-out torque is the highest amount of torque applied to the motor before it loses synchronism (stops) [1].

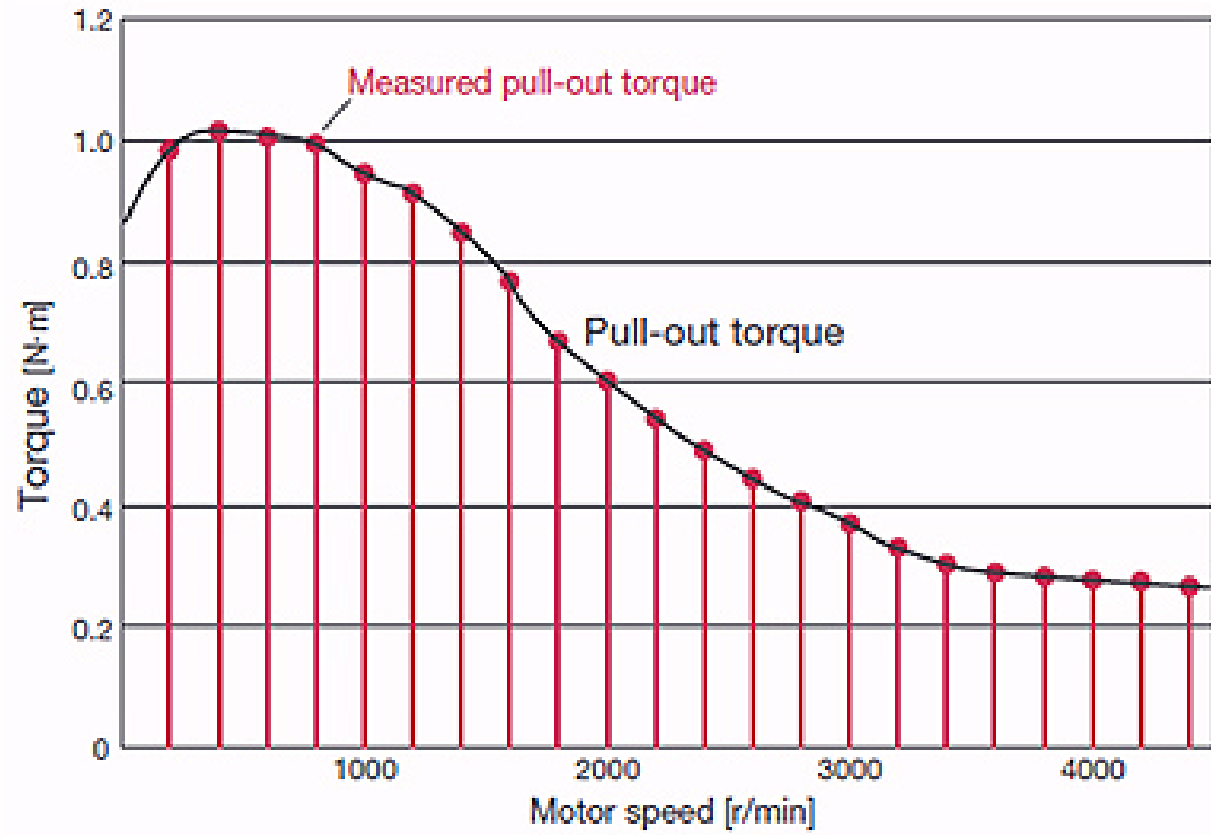
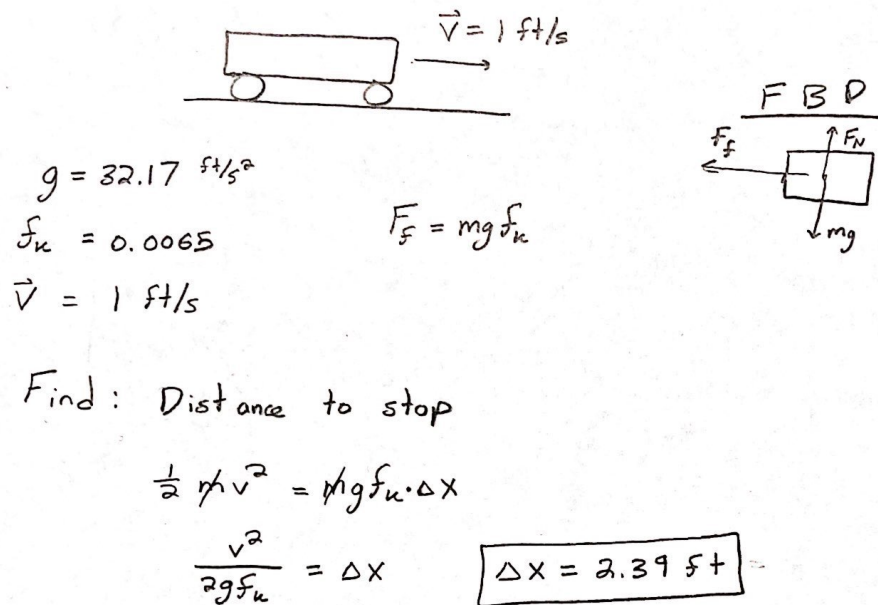


Figure 18: Torque vs. Motor Speed for a Stepper Motor

## Model 2



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Figure 19: Friction in the track

This model was used to calculate the friction in the track. This helps us determine the required length of track and the whether or not we could let friction stop the cart.  $g$  is the gravitational constant,  $v$  is the velocity of the cart,  $f_k$  is the coefficient of friction, and  $F_f$  is the force of friction. The work done by friction was equated to the initial kinetic energy of the cart. From the requirements of the cart, the velocity was  $1 \text{ m/s}$ . Doing research about carts sliding on a track, the friction coefficient of  $0.0065$  was determined [2].

## Model 3

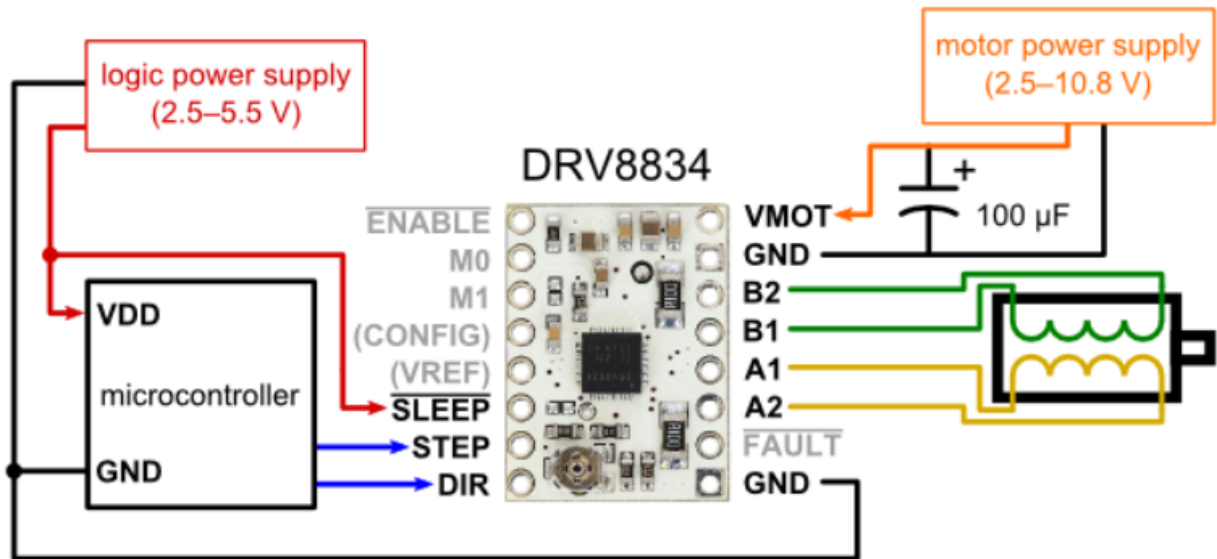


Figure 20: Motor Driver Wiring Diagram

This model shows a potential wiring setup for connecting a stepper motor and driver to a microcontroller and power source. This will obviously be very useful if we choose to use this particular driver, however if we choose to use a different driver or microcontroller in the future, finding a diagram similar to this for any motor driver we choose will be both easy to do and very useful to us when wiring our system [3].

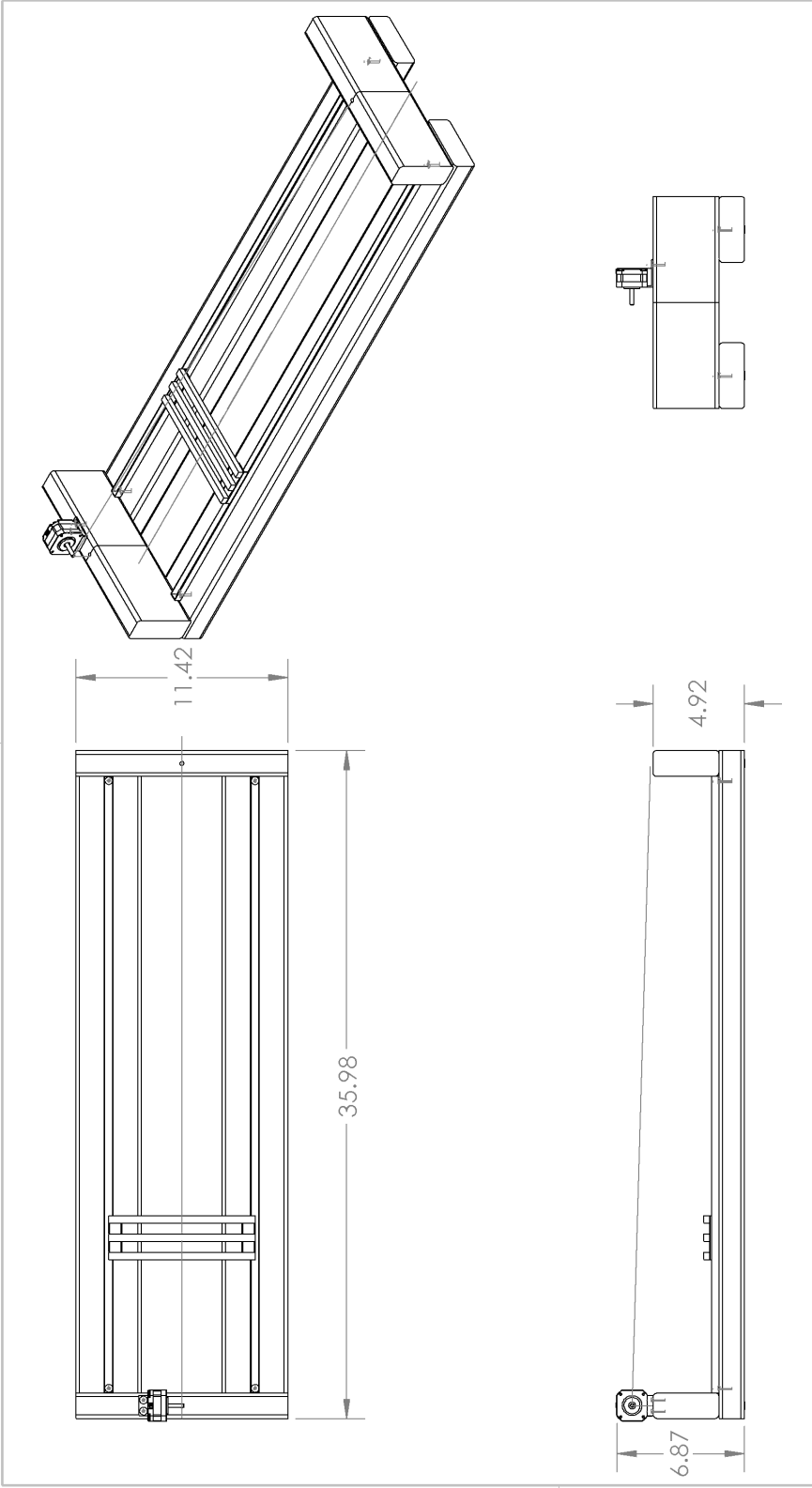
## 5 Concept Embodiment

### 5.1 Initial Embodiment

The initial concept embodiment can be seen below in three separate SolidWorks drawings. These show multiple views of the entire initial bridge crane assembly as well as its individual components.

1

2



A

1

2

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES		DRAWN	
TOLERANCES:		CHECKED	
FRACTIONAL ±		ENG APPR.	
ANGULAR: MACH ±		MFG APPR.	
BEND ±		Q.A.	
TWO PLACE DECIMAL ±		COMMENTS:	
THREE PLACE DECIMAL ±			
INTERPRET GEOMETRIC TOLERANCING PER:			
MATERIAL			
FINISH			
NEXT ASSY	USED ON		
APPLICATION			
DO NOT SCALE DRAWING			

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**TITLE:** Bridge Crane Group Z

**SIZE:** A    **DWG. NO.:**    **REV:**    **SCALE:** 1:8    **WEIGHT:**    **SHEET 1 OF 3**

B

1

2

B

Figure 21: Assembled projected views with overall dimensions

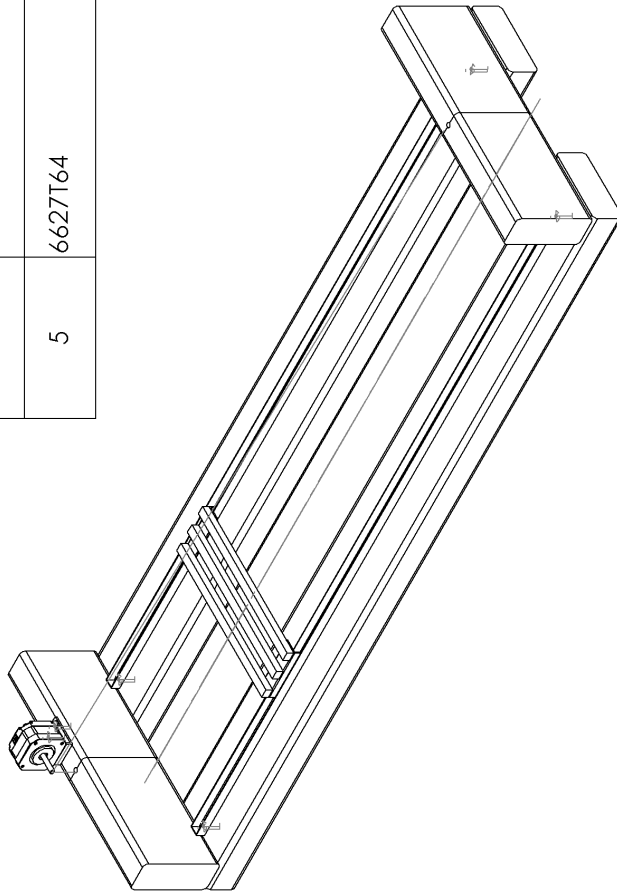
1

2

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Bridge	Assembly Bridge	1
2	Cart	Assembly Cart	1
3	92210A382	Stainless Steel Flat Head Screw, 10-24 thread size, 4" long	4
4	91253A283	Stainless Steel Flat Head Screw, 12-24 thread size, 3/4" long	6
5	6627T64	Nema 17 Bipolar (84oz.in) Stepper Motor with cable	1

B

B



A

A

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES	DRAWN		
FRACTIONAL ±	CHECKED		
ANGULAR: MACH ±	ENG APPR.		
TWO PLACE DECIMAL ±	MFG APPR.		
THREE PLACE DECIMAL ±	Q.A.		
INTERPRET GEOMETRIC TOLERANCING PER:	COMMENTS:		
MATERIAL			
FINISH			
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 SIZE: **A** DWG. NO.: \_\_\_\_\_ REV \_\_\_\_\_  
 SCALE: 1:8 WEIGHT: \_\_\_\_\_ SHEET 2 OF 3

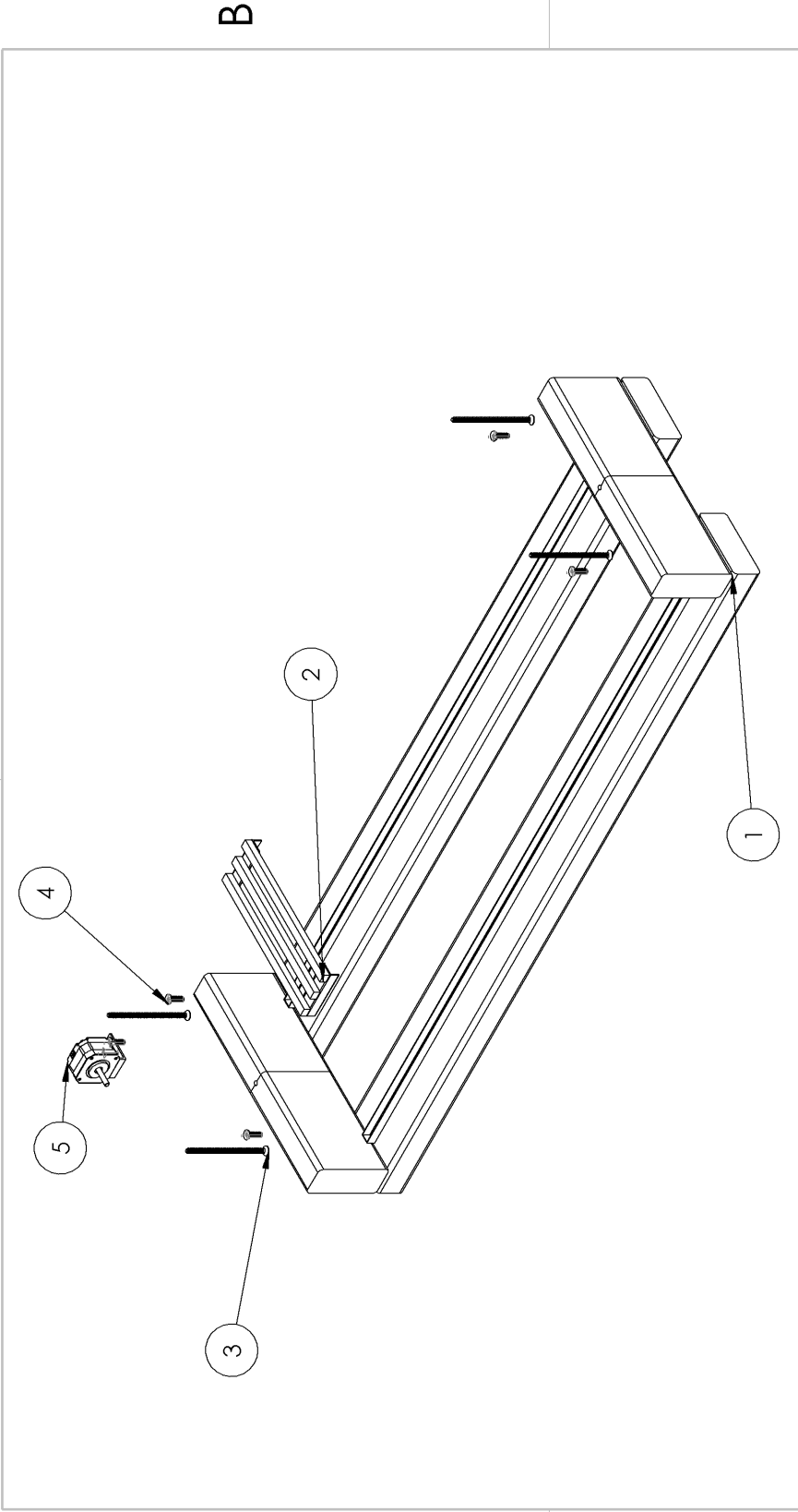
1

2

Figure 22: Assembled isometric view with bill of materials (BOM)

1

2



B

B

A

A

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES			
TOLERANCES:		DRAWN	
FRACTIONAL ±		CHECKED	
ANGULAR: MACH ±		ENG APPR.	
TWO PLACE DECIMAL ±		MFG APPR.	
THREE PLACE DECIMAL ±		Q.A.	
INTERPRET GEOMETRIC TOLERANCING PER:		COMMENTS:	
MATERIAL			
FINISH			
NEXT ASSY	USED ON		
APPLICATION			
DO NOT SCALE DRAWING			

TITLE: **Bridge Crane Group Z**

SIZE DWG. NO. **A** REV

SCALE: 1:8 WEIGHT: SHEET 3 OF 3

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1

2

Figure 23: Exploded view with callout to BOM



## Prototype Performance Goals

1. The device's trolley can move  $\geq 1$  ft/s
2. The trolley stops before hitting the rails and is forced in the opposite direction
3. The portable bridge crane weighs  $\leq 10$  lbs

## 5.2 Proofs-of-Concept

The selected design was slowly built, with each section serving as its own proof-of-concept. Once the proof-of-concept was completed and it was decided to fit within the expected requirements, it was added to the initial prototype build. For example, the frame of the bridge crane was put together and then measured to make sure that it was not too long and that it was light enough to meet the weight requirement and be considered portable. Sections of the frame were adjusted to fit the rails, the motor, and pulley system. With smaller items, like the trolley, the design was able to be built, tested, and then rebuilt until it was believed to be optimized. The initial prototype was also influenced by the engineering models shown below.

### Design Rationale

An original friction analysis was done in section 4. Another friction analysis is done here with our new design and updated values.

## Friction on track

Side



Front



$m$  = mass of cart

$g$  = gravity

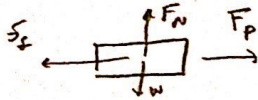
$\mu$  = friction coefficient

$m = .1 \text{ kg}$

$g = 9.81 \text{ m/s}^2$

Wood on aluminum  $\rightarrow \mu = 0.22$

FBD



★ Find pulling force needed

$$F_p = \mu_s F_N = \mu_s mg$$

$$F_p = 0.21 \text{ N}$$



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Figure 24: Model for friction on track

This model finds the force needed on the cart to overcome the force of friction. This helped us determine the torque needed by the motor. We needed the motor to rotate fast enough to meet our design requirement of 1 ft/s, but also enough torque to pull the cart. This friction analysis helped us identify a baseline torque needed to pull the cart.

To find the speed at which to run the motor, a torque-speed curve for the stepper motor was referenced.

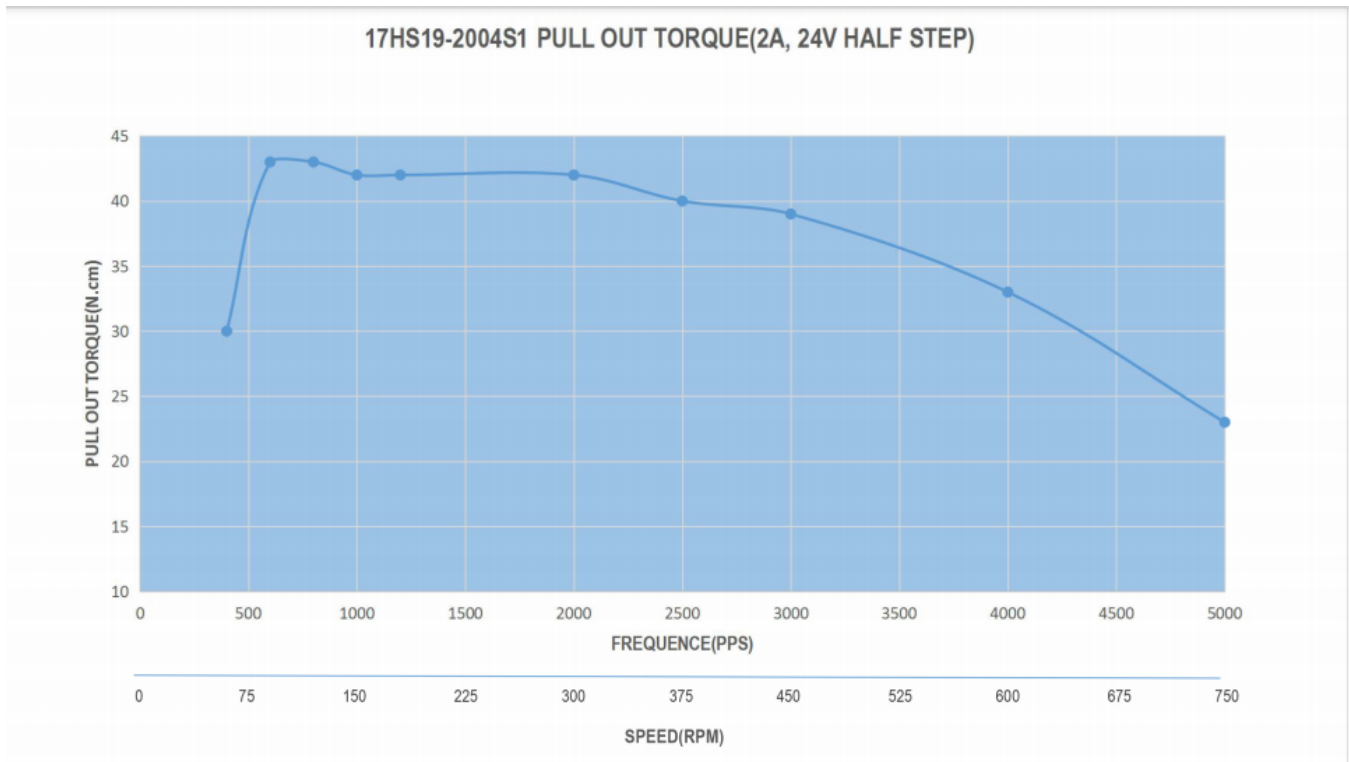


Figure 25: Torque-Speed curve for the stepper motor [4]

Because Fig. 25 shows the highest torque occurs around 2 revolutions per second (rps), that setting was tried first. A setting of 1 rps was deemed too slow to meet the requirements and did not have enough torque to move the trolley. A setting of 3 rps was tried to see if the trolley could be moved faster, but it did not have enough torque to consistently move the trolley. A setting of 2 rps did not move the trolley fast enough to meet the requirement of travelling  $\geq 1$  ft/s, so weight and friction on the trolley will have to be reduced.

The finished initial prototype looks different from the selected concept for many reasons. The frame of the bridge crane, and therefore the track, was changed because the current design was easier to assemble and lighter than in the selected concept. The use of one motor instead of two was decided to reduce the complexity and margin for error of the code. The shape of the cart was changed to reduce weight and friction as found in the engineering models shown earlier; the shape was also a function of the frame shape. The buttons on the controller were substituted for the control switch because the buttons were quicker and cheaper to acquire while serving the same purpose. The payload was not attached due to the legs not being attached and the lack of meeting the trolley speed requirement without the payload. The legs were not attached due to the unlevel construction of the frame and the weight requirement. If the legs were added, it can be assumed that significant work would be needed to relevel to the bridge crane and the bridge crane would be over the weight requirement.

## 6 Design Refinement

## 6.1 Model-Based Design Decisions

### 6.1.1 Stop Distance Analysis

This model is used to determine the necessary distance needed for the cart to come to a stop as a result of purely sliding friction. This analysis was performed previously, however the design has since changed from a rolling cart to a sliding cart, resulting in a significantly higher coefficient of friction between the cart and track [5]. Similar to the first analysis, the work done by friction was equated to the initial kinetic energy of the cart when it is operated at the desired speed of 1 ft/s. From that equation, the distance required for the cart to completely stop was then calculated. This model can be used with the model below to successfully implement soft stops into the system in order to avoid full speed collisions with the hard stops.

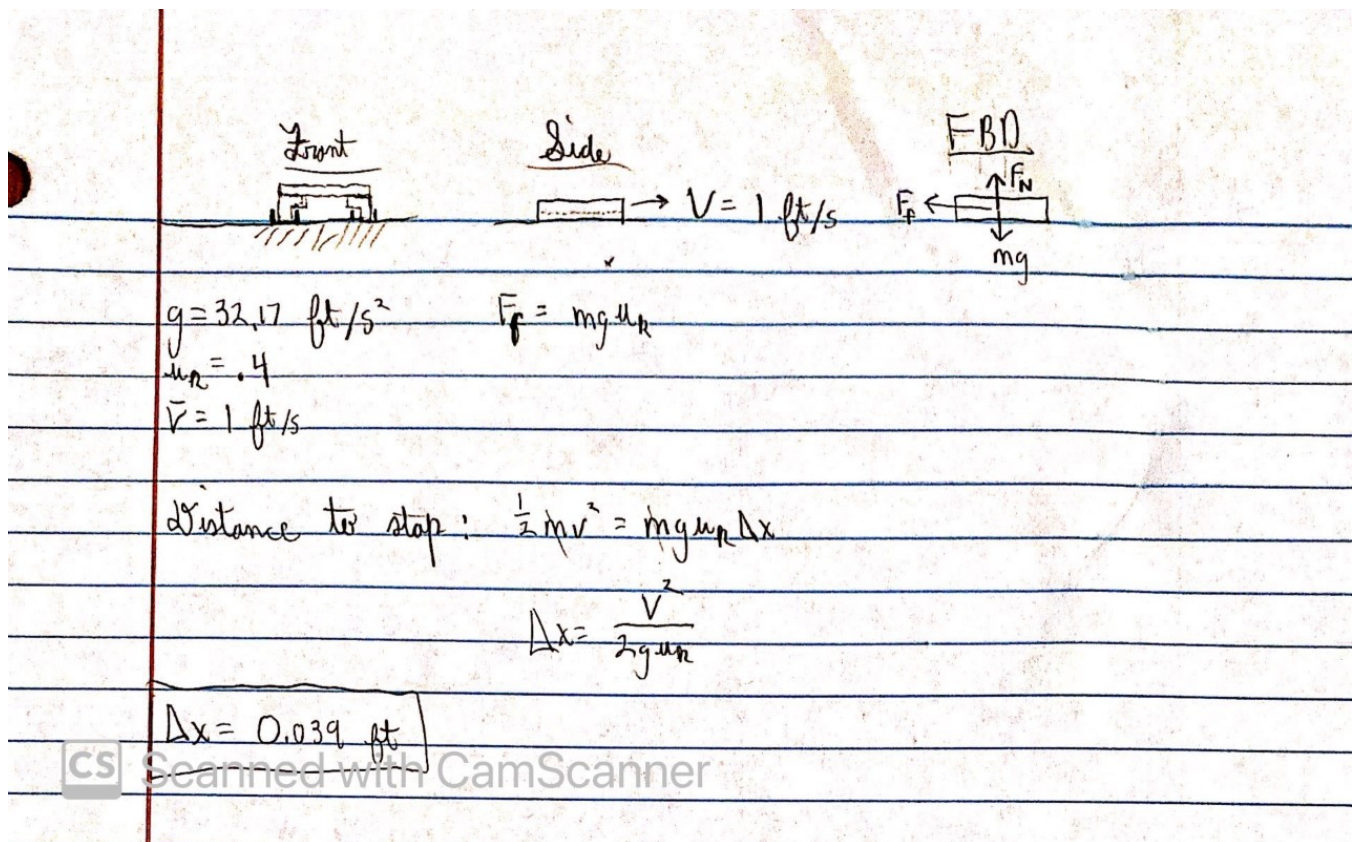
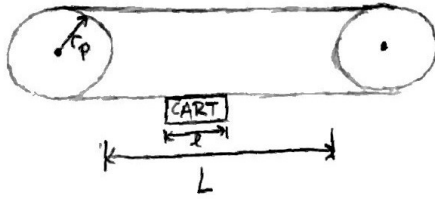


Figure 26: Stop distance for sliding cart

### 6.1.2 Soft Stop Limit Analysis

This model is used for determining the number of steps the motor will take before it hits the soft stop. Instead of simply guessing the correct amount of steps to use between the start point and the end of usable track, using this model will enable us to correctly implement the code the first time. This also ensures that we will not accidentally destroy the device through the guess and check method. Additionally, the model includes a calculation for time to travel from the defined zero point to the soft stop limit, which is a prototype performance goal. With an estimated motor speed from limited testing, the cart has a top speed of about 0.5 ft/sec. To reach the prototype performance goal of 1 ft/sec with the current setup, the motor needs to rotate at 179 RPM.



$r_p \equiv$  radius of pulley = 0.64 in  
 $l \equiv$  length of cart = 3 in  
 $L \equiv$  length of usable track = 30 in  
 $\omega \equiv$  angular speed = 75 rev/min  
 $n_s \equiv$  number of steps per motor revolution = 200

Assume:

- Cart starts in middle of track
- defined as zero

$$d_L = \text{distance from zero to soft stop limit} = \frac{1}{2}(L-l) = \frac{1}{2}(30\text{in} - 3\text{in}) = 13.5\text{in}$$

(linear)

$$d_s = \text{distance per step} = \frac{\pi(2r_p)}{n_s} = \frac{2\pi(0.64\text{in})}{200} = 0.02\text{in/step}$$

(linear)

$$n_{lim} = \text{number of steps from zero to limit} = d_L/d_s = \frac{13.5\text{in}}{0.02\text{in/step}} = \boxed{675\text{ steps}}$$

$$t_{lim} = \text{travel time from zero to limit} = d_s \cdot n_{lim} / (2\pi r_p \cdot \omega)$$

$$= 0.02\text{in/step} \cdot 675\text{ steps} / (2\pi(0.64\text{in}) \cdot 75\text{ rev/min} \cdot (\frac{1\text{min}}{60\text{sec}}))$$

$$= 2.69\text{ sec}$$

$$\omega' = \text{angular speed necessary for 1 ft/sec cart speed} = \frac{v}{r_p} = \frac{12\text{in/sec}}{0.64\text{in}} = 18.75\text{ rad/s} = \boxed{179\text{ RPM}}$$

Figure 27: Model for number of motor steps to soft stop

### 6.1.3 Torque - Motor Speed Analysis

Using the Torque Speed curve seen earlier (shown again in fig. 28), the pull-out torque and motor speed can be optimized.

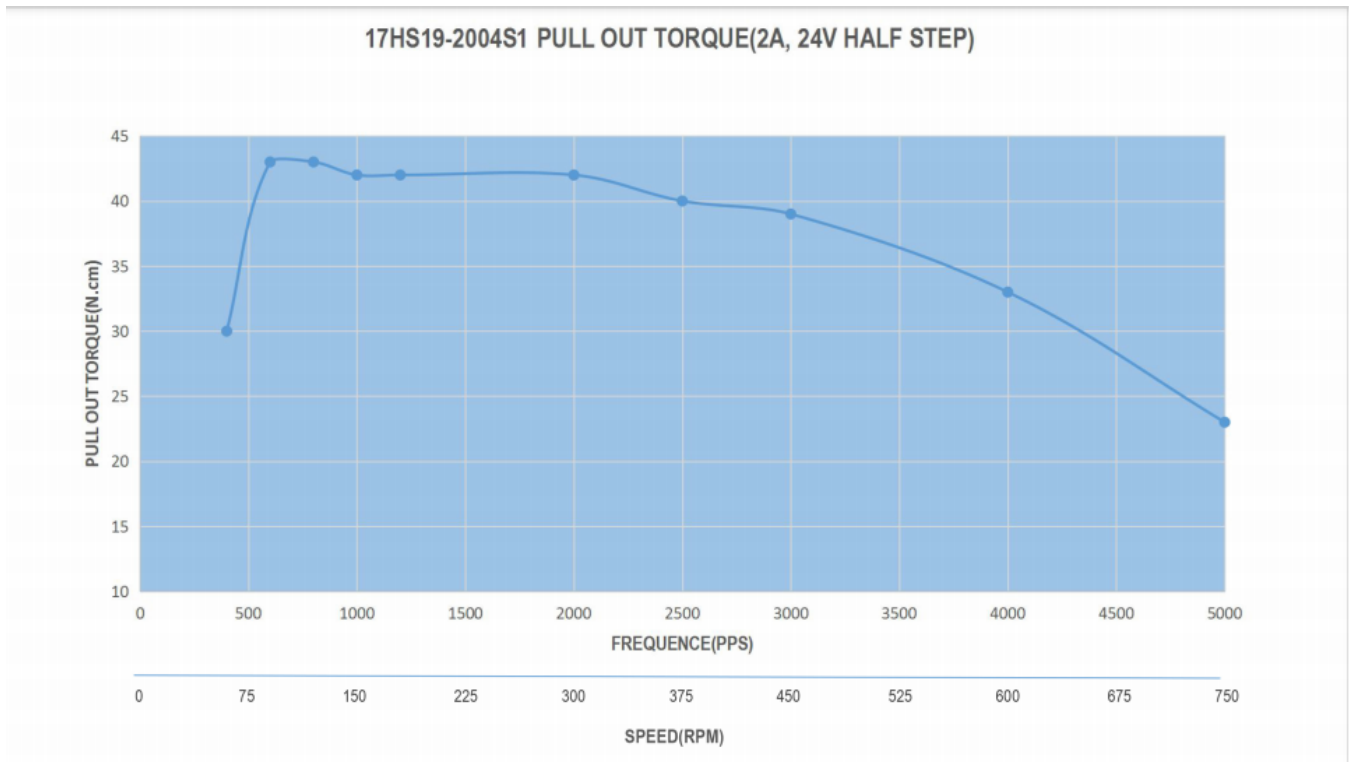


Figure 28: Torque-Speed curve for the stepper motor [4]

The minimum angular speed needed without stalling to make the cart travel at a speed of one foot per second is 179 revolutions per minute (RPM), as shown in fig. 27. With that information, fig. 28 can be referenced to find the pull-out torque to be about 42 Newton-centimeters (N-cm). Fig. 28 shows that the angular speed of the stepper motor can reach 300 RPM before the pull-out torque of 42 N-cm is exceeded and the motor stalls. This shows that the trolley can be made to travel up to 1.67 feet per second before the stepper motor stalls.

## 6.2 Design for Safety

### 6.2.1 Risk #1: Cart Crashing into hard stops

**Description:** This risk occurs when the cart crashes into the end of the track. This would happen if our soft stops failed and the user was not paying attention and held down one direction of the button for too long. If a child was using our device this may be more likely to happen.

**Severity:** The severity is marginal because the cart is fairly robust and not traveling at a high speed. The cart would not break and the device would still be in tact.

**Probability:** Occasional. If the user does not properly center the cart in the middle the soft stops may not activate and work according to plan.

**Mitigating Steps:** The probability could be reduced by having instructions on our device so that everyone who uses it understands how the soft stops work.

### 6.2.2 Risk #2: Motor catching on fire

**Description:** If the motor overheats or short circuits it could catch on fire. Likely this would not occur, but this would occur in a situation where something was not properly connected or if something on the breadboard came loose.

**Severity:** Critical. If the device actually did catch on fire it could cause major damage to the environment it is in.

**Probability:** Unlikely. It is unlikely that this would occur as the motor has safety faults built into it that make it hard for it to catch on fire.

**Mitigating Steps:** We can mitigate this risk by using a fire safe motor as well as making sure that all of the connections are good before using the device.

### 6.2.3 Risk #3: Device Falling over

**Description:** If someone pushed hard on the device it would fall over. This would likely only happen if people were fooling around near the device or if someone was not paying attention and walked into it.

**Severity:** Marginal. If someone knocked the device over they would likely not be hurt at all. The device itself would probably break, but the person would not be injured.

**Probability:** Unlikely. This likely will never happen as the device is stable enough to not tip due to small bumps.

**Mitigating Steps:** We can mitigate this risk by designing our structure to be more stable. If we fasten down all of our parts then if the device got knocked over the components would not go flying everywhere.

### 6.2.4 Risk #4: Fingers caught in belt

**Description:** If someone had their fingers too close to the belt they could get them tangled up with the belt. This would happen if someones hands were too close to the belt during operation or not paying attention.

**Severity:** Marginal. If someone actually did get their fingers caught it would likley not injure the person at all and just knock the belt off the pulley.

**Probability:** Seldom. This probably won't happen if the user is paying attention.

**Mitigating Steps:** There really aren't any mitigating steps. The user needs to be paying attention, but outside of that there is not much to do.

### 6.2.5 Risk #5: Hit by Payload

**Description:** This could occur if a sharp object is used for the payload or if the payload comes dislodged and hits someone.

**Severity:** Marginal. Unless the user made bad choices, a sharp object would not be used and the worst that would happen is that a tennis ball hit someone.

**Probability:** Seldom. It is hard to know how often this would happen, but in all our tests so far this has never been an issue. Also even if the payload did come dislodged it is unlikely that it would actually hit someone.

**Mitigating Steps:** To mitigate this risk, the user could not use sharp objects in the payload and we can make sure that the payload is fastened down before operation.

		Probability that something will go wrong				
Category		Frequent Likely to occur immediately or in a short period of time; expected to occur frequently	Likely Quite likely to occur in time	Occasional May occur in time	Seldom Not likely to occur but possible	Unlikely Unlikely to occur
Severity of risk	Catastrophic					
	Critical					Motor Catching on fire
	Marginal			Cart crashing into hard stops	Fingers caught in belt Hit by payload	Device falling over
	Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial					

Figure 29: Heat map of risks

Based on our heat map the highest priority item is risk 1 with cart crashing into the hard stops. After that the next highest priority is motor catching on fire. Next, based off the chart, the fingers caught in payload and the payload hitting someone are of equal importance. Lastly, the device tipping over is the least important. You could argue, based on the chart, that the motor catching on fire is of equal importance to fingers getting caught in the belt or getting hit by the payload, but I prioritized severity over likely-hood in this case. Most of our focus in going to be directed towards making our soft-stops robust so that we can avoid our main risk 1.

### 6.3 Design for Manufacturing

In the making of the prototype, manufacturability of the bridge crane was not considered. This lead to a prototype that, while it completes the customer needs and design requirements, is not optimized for manufacturing time or costs.

*Totally Necessary Components:*

- Bridge crane frame
- Support legs
- Guide rails for trolley
- Trolley
- Payload
- Stepper Motor



- Trolley movement belt
- Controller

The support legs must be a separate piece so that they can fold to reduce the size of the bridge crane during transport. The trolley must be a separate piece because it needs to move back and forth for the bridge crane to be functional. The payload must be a separate piece so that the length of the string can be adjusted and so it does not become tangled during transport. The stepper motor must be a separate piece in case it becomes damaged and must be replaced.

To reduce the overall number of parts, some parts could be combined. If portability becomes less important, then the support legs can be attached in a fixed position to the bridge crane frame or the support legs and frame can even be manufactured as one part. If the length of the string holding the payload does not need to be adjusted, then the payload and trolley can be manufactured as one piece. The guide rails for the trolley can be replaced with similar sized cuts in the frame of the bridge crane.

## 6.4 Design for Usability

Vision impairments such as nearsightedness could affect the use of the bridge crane, as it is intended to be used as an example for students in a lecture hall. If the bridge crane and payload are too small, students that are sitting a far distance away in a large lecture hall may not be able to properly observe the dynamics of the demonstration and will therefore not receive the desired effect of the device. This problem can be addressed by making the bridge crane and payload as large as possible so it can be easily viewed even at a distance. Additionally, if the operator of the bridge crane is farsighted, he or she may not be able to identify the different operational buttons correctly and may accidentally move the cart in an unwanted direction, making it more difficult to execute the desired demonstration. This can be mitigated by making the buttons as large and differentiated as possible to avoid visual confusion.

Hearing impairments involving certain levels of hearing loss may not affect the direct operation of the bridge crane, but may affect the potential safety. If the driving stepper motor were to begin to malfunction, specific noises can typically be heard that would indicate a potential overheating hazard. Someone who is experiences a significant enough level of hearing loss would not be able to hear these audio cues and would therefore not be able to stop the device or make an adjustment before the motor had already burned out and needed replacement. As this impairment does not directly affect the usability of the device but instead more of the potential hazard prevention, there does not exist a specific design change that can be implemented to make it more usable.

Physical impairments such as arthritis, muscle weakness, or limb immobilization can all affect the usability of the device as it is meant to be portable between multiple places. Someone with a physical impairment that would affect his or her ability to carry the bridge crane would negatively impact the overall use of the device as it could no longer be carried to lectures. To address this potential problem, the device aimed to be designed as small, lightweight, and overall portable as possible so that it can be carried even by someone who may be experiencing a significant level of physical impairment.

Control impairments caused by factors such as fatigue or distraction could affect both the longevity of the device as well as the user safety during operation. If the user is distracted or tired, he or she may not be paying attention to the movement of the cart along the bridge track and could therefore run the cart into the hard stops at full speed. This isn't the best for the overall operational health of the bridge crane, but it will not cause a significant hazard to the system or

user. To avoid this, soft stops will also be implemented into the stepper motor programming that are designed to cut operation of the motor after a certain distance so that the cart does not slam into the hard stops at full speed. A distracted or disoriented user could also put him or herself in danger by potentially pinching their hands in the cable pulley system, which would potentially be annoying and slightly painful, but not harmful to the user or device to a significant degree. The best way to mitigate this problem would be to put some sort of housing or covering over the stepper motor so that the user cannot physically get their hands close enough to cause problems, however this would also hinder the overall portability of the device as well as make it more difficult to make changes or fix problems that are caused by the motor or pulley at that location.

## **7 Final Prototype**

### **7.1 Overview**

In the end, the final prototype was different than the three initial designs that we came up with. The area that gave us the most resistance was the motor along with electrical components. The motor had to be changed for a larger, more-powerful model, and the motor driver had to be changed out a couple times. Despite not looking polished, the final prototype did meet two of the three stated performance goals: the total device weighed under ten pounds, and the soft stops were implemented. Items we recommend for future improvement would be: providing more current to the motor, use a dead axle on one side instead of using a dead motor, replacing the breadboard with a control box, and improve the leg stability.

### **7.2 Documentation**

The soft stops successfully stopped the trolley from moving when it reached a few inches from the edge of the track on either side. The entire set-up weighed only eight pounds. The fastest we were able to make the trolley go was about half of a foot per second.

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