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MEMS 411: Portable Bridge Crane with Pulleys

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SP21 MEMS 411 Mechanical Engineering Design Project

Portable Bridge Crane with Pulleys

This report recorded our journey on constructing a small bridge crane so that our customer Dr. Potter can carry it around. With features such as variable speed and adjustable cable length, the final prototype is expected to demonstrate some dynamic behaviors. Compared to other design concepts, adding pulleys to the design avoided the need to design wheels for transferring the trolley. The main performance goals included: the trolley could move at least 1 ft/s (30 cm/s); the trolley should stop before hitting the rail ends and could be driven to opposite direction; the weight of the bridge should be no more than 10 lbs (4.5 kg).

The bridge body, including the legs and the bridge, were made of wood, which added significant weight to our initial prototype. Although we attempted to use the timing belt for supporting the playe-load, we found that even a very light object could cause the belt to bend. Still, our initial prototype allowed the trolley from one side to the other. With a limit switch attached to one side, we verified that the trolley could stop before reaching the end of the track, and it could switch direction. However, our pulley diameter was too small to induce a faster rotational speed to satisfy out speed requirement. For our final prototype, we reduced the weight of the design to be 4.26 kg, which was within our weight limit. With a folding feature, it was also convenient for transit. Each end of the rail contained a limit switch to prevent the trolley from going beyond the path. By increasing the pulley diameter, we were able to accomplish the speed requirement. In addition, a remote controller was introduced to allow the user to vary the motion of the trolley. Therefore, we successfully met the key criteria for our design.

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1 Introduction

The bridge crane demonstrates dynamics behavior that the flexible mode has a natural frequency depends on the string length. In this project, a portable bridge crane is designed and made to demonstrate this dynamical phenomena by changing speed and string length. The portable bridge crane requires a light mass and a small size. At the same time, because it needs to be observed in a two-dimensional plane, the trolley must be able to move horizontally on a bridge with tracks, and the speed of the trolley needs to be controlled by a speed controllable motor. The crane needs to suspend a weight of 1 kg to demonstrate the change in natural frequency. The length of the rope needs to be adjustable. In addition, in order to ensure the stability of the instrument, it is necessary to reduce the impact force of the collision when the trolley hits the ends of the rail. Therefore, a soft stop is necessary to stop the motion of the cart before the collision at the end. In this way, the stability of the structure can be guaranteed in order to avoid tipping due to collision. Our portable bridge crane will demonstrate the effect of changing the speed and the string length on the natural frequency.

2 Problem Understanding

2.1 Existing Devices

Three commercial bridge cranes with similar concepts to this project are investigated. Although these three designs are much larger than this project in terms of scale, the design concepts are similar.

2.1.1 Existing Device #1: Semi Gantry Crane Specification

Figure 1: Semi Gantry Crane Specification (Source: Small Gantry Crane)

Link: https://weihuagantrycranes.com/small-gantry-crane/
Description: Semi Gantry Crane Specification is a large bridge crane. It can lift cargo in weight between 3 tons and 20 tons. Similar to our design, Semi Gantry Crane Specification uses rails to move blocks left and right. The cable under the block can hook up and carry the goods. The Semi Gantry Crane Specification is so large that it is generally used in a large warehouse, The moving speed of the trolley is about 20 m/min.

2.1.2 Existing Device #2: AQ-HD Small Overhead Crane Specifications

Figure 2: AQ-HD Small Overhead Crane Specifications (Source: Small Crane Supplier)

Link: https://ellsenoverheadbridgecrane.com/small-crane-supplier/
Description: AQ-HD Small Overhead Crane Specifications is an overhead crane without mechanical support on ground. The trolley moves forward and backward through the tracks on the sides of the ceiling, and it can move left and right on the middle track. AQ-HD Small Overhead Crane Specifications is similar to our design concept in that its cable is not controlled by a winch in length, and the entire cable is tied to the crane track with a hook.

2.1.3 Existing Device #3: Portable Gantry Crane

Figure 3: Portable Gantry Crane (Source: Lift Your Business)

Link: http://www.gantrycranedesign.com/portable-gantry-crane.html
Description: The Portable Gantry Crane is an small bridge crane, its track range is very small, and the trolley part is relatively large. Because the crane's base has roller wheels, it can move easily and freely. It is not speed controllable through the speed controller. The design of the cable is similar to our design concept because the crane hangs object below the hook.

2.2 Patents

2.2.1 Cranes comprising trolleys or crabs running on fixed or movable bridges or gantries (US2936907A)

This patent combines the overhead crane structure with the distance control of the trolley. A node is defined in every location, so the position of the trolley can be accurately controlled through the console. The length of the cable is controlled through the winch. A heavy payload is placed on one side to maintain moment equilibrium when lifting heavy weights.

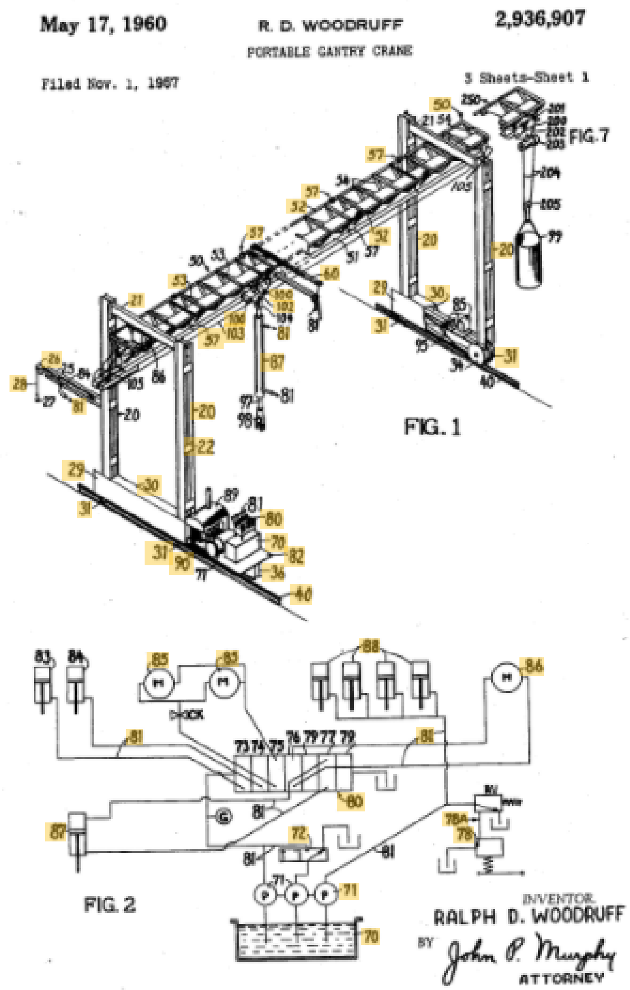


Figure 4: Patent Images for Portable gantry crane

2.2.2 Auxiliary devices for controlling movements of suspended loads, or preventing cable slack (US3921816A)

This patent shows that the overhead crane controls the trolley speed through a yoke. A bracket is used to connect the yoke to the crane leg. The yoke has four independently operated pulleys. One on each of the four corners of the crane structure. The advantage of this design is that the pulleys can provide more torque to the trolley system, which enable the trolley to carry more weights.

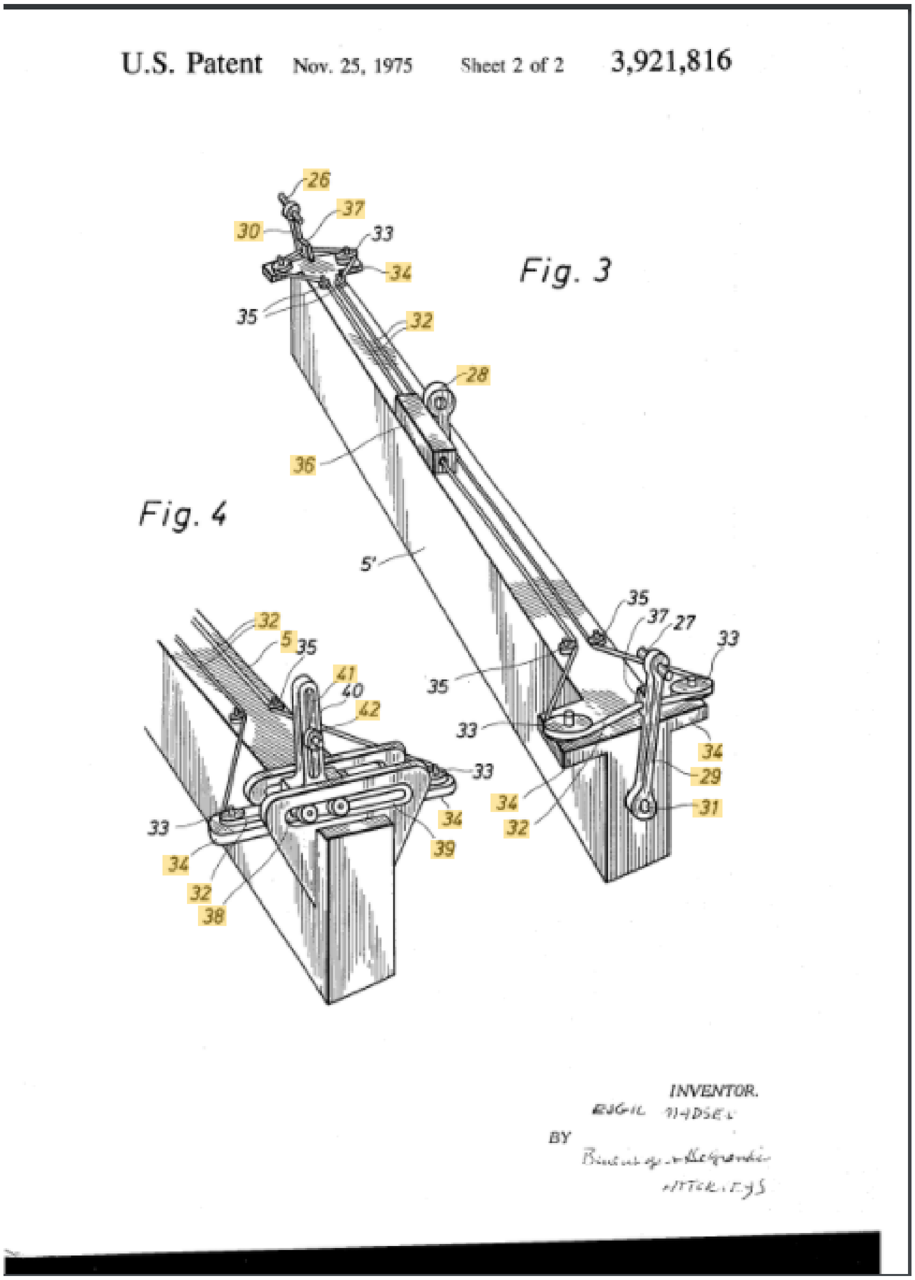


Figure 5: Patent Images for Overhead or gantry crane with a yoke

2.3 Codes & Standards

2.3.1 Cranes and Monorails (With Underhung Trolley or Bridge) (ASME B30.17-2010)

This ASME Standard sets standards for the installation of electrical control system on trolleys used in the bridge cranes. The monorail system mentioned in volume B30.17 is used in our design because our design is a monorail system. At the same time, this international standard also involves the requirements for the support system and suspension system of the bridge crane.

2.3.2 Below-the-Hook Lifting Devices (ASME B30.20 - 2016)

This ASME Standard sets the standard for below-the-hook lifting devices. Because a weight is going to be suspended on the portable bridge crane system, and the length of the string is going to be changed, this project involves below-the-hook lifting device application. We will use this standard to design the suspension system of our bridge crane.

2.4 User Needs

The first important user need is portable. The user wants to carry the device around so the system should be small in size and light in weight. The other important user need is that the system can change the speed and the string length to demonstrate the the change in natural frequency. Therefore, the trolley needs to be speed controllable, and the string needs to be length adjustable.

2.4.1 Customer Interview

Interviewee: Dr. James Jackson Potter
Location: On Zoom
Date: February 4^{th}, 2021
Setting: We arranged an online meeting time with our customers via email. The whole interview was conducted on Zoom and took approximately 30 min.

Interview Notes:
Do we need to design the product to be detachable so that the user can transport the product to different places?

- I am trying to think if that would be a useful feature for me to have it break into different pieces. The advantage of having a break into many pieces is that I could stack them together and put them into a case and carry them around like a golf bag. And it would be easier to fit into vehicles. I have an SUV so it wouldn't be a problem. I think it would be useful, that would be good.

We have a question on the cable length, do we need to figure out a way to adjust the cable length?

- That can be a sample like a hook that you wind on it many times. There are some control techniques that you can use with variable cable length, that's a hard one. I think it would be fine if there is one that works.

Do we need to consider power conservation when designing the product?

- Don't worry too much about it. Don't choose the lowest power motor possible to save power, it not going to be that power-hungry compared to a lot of stuff. So I'm not too worried about the power consumption.

2.4.2 Interpreted User Needs

After talking with the customer, we summarized the customer's requirements for our product. These customer's needs offer valuable suggestions and guidelines for our design. Table 1 below is the rated customer's needs as our final product aims to full-fill.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The crane is easy to carry	5
2	The crane should be light	5
3	The trolley should have a speed limit and adjustable speeds	5
4	The crane can break into parts for transport	3
5	The cable length should be adjustable	3
6	The crane can carry certain weight	4
7	The crane should avoid using splintery materials	4
8	The rail should have soft stops	5
9	The crane should be power conservation	3

From the customer need table, the ”portable” requirement and ”speed control” requirement are the most outstanding ones. In addition, the user wants the system to be stable enough under collision and can function well enough to demonstrate the change in natural frequency.

2.5 Design Metrics

From the customers, the following design metrics is outlined to make sure the design is portable, speed controllable ,and well functioned to demonstrate the effect of changing in the speed and the string length on the natural frequency.

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1,2	Total weight	kg	7.5	5
2	1	Total height	cm	63	60
3	1	Total length	cm	103	100
4	3	Maximum speed of trolley	cm/s^2	25	30
5	5	Maximum length of cable	cm	≥ 70	≥ 80
6	6	Weight lifting capacity	kg	0.9	1
7	8	Distance between soft ends	cm	70	80
8	8	Distance between soft end and neighboring hard end	cm	3	6

3 Concept Generation

3.1 Mockup Prototype

By gathering several existing items, including chopsticks, small paper boxes, and a tea bag, we built a simple mockup to offer some insights for our bridge crane design. Figure 6 to 8 together provide a visualization of the mockup.

Figure 6: Front view of the mock-up.

The front view exhibits all the major components of the mockup. The legs are made up of chopsticks. The bigger box represents the bridge/rail, the smaller box is the trolley, and the tea bag is the cable and added load.

Figure 7: Top view of the mockup.

By observing the top view, one can notice a long cut in the middle of the bottom box. Making similar cuts on the bottom faces of the boxes allows the "cable" to move as we manually pull the small box.

Figure 8: Mockup exhibiting basic functions.

Figure 8 shows that we are able to move the "trolley" to either side of the "bridge". With one side of the smaller box open, we can pull out the string of the tea bag, fullfilling the customer need for a adjustable cable length.

3.2 Functional Decomposition

Our task is to design a bridge crane that is portable, speed controllable, and string length adjustable. In order to fulfill these requirements, five sub-functions as shown in Fig. 9 is listed for individual components.

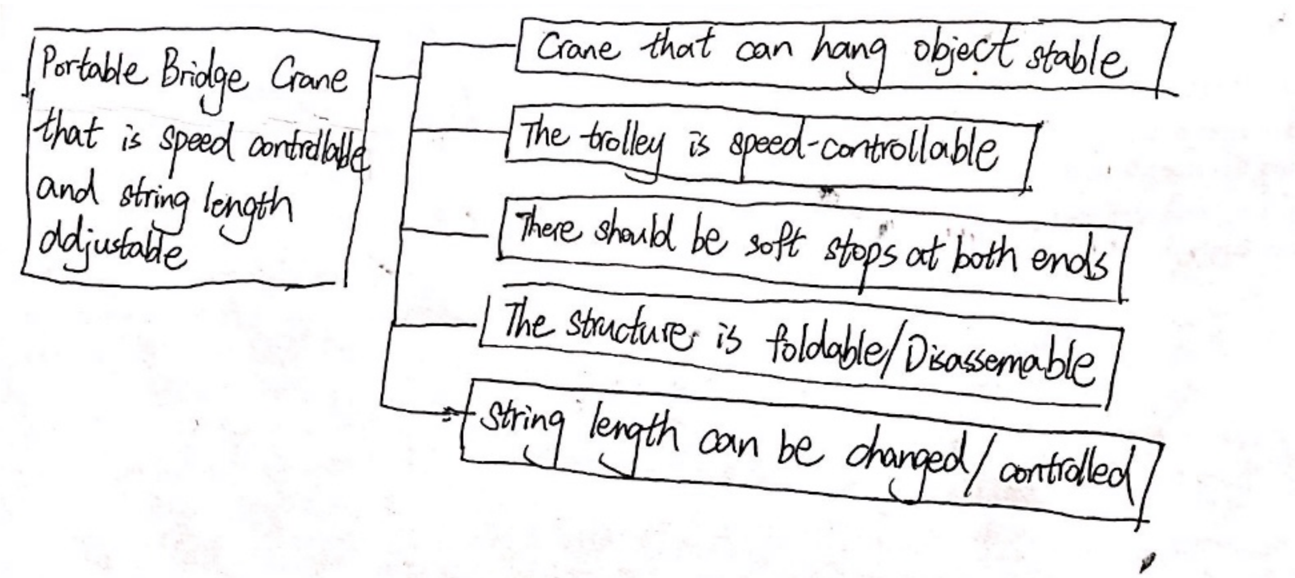


Figure 9: Function tree for Portable Bridge Crane, hand-drawn and scanned

3.3 Morphological Chart

Based on the subfunctions listed in the function tree, we created Fig. 10 to illustrate our ideas on possible components to satisfy the criteria for our product. This also serves as a guideline for our individual design concepts in the next section.

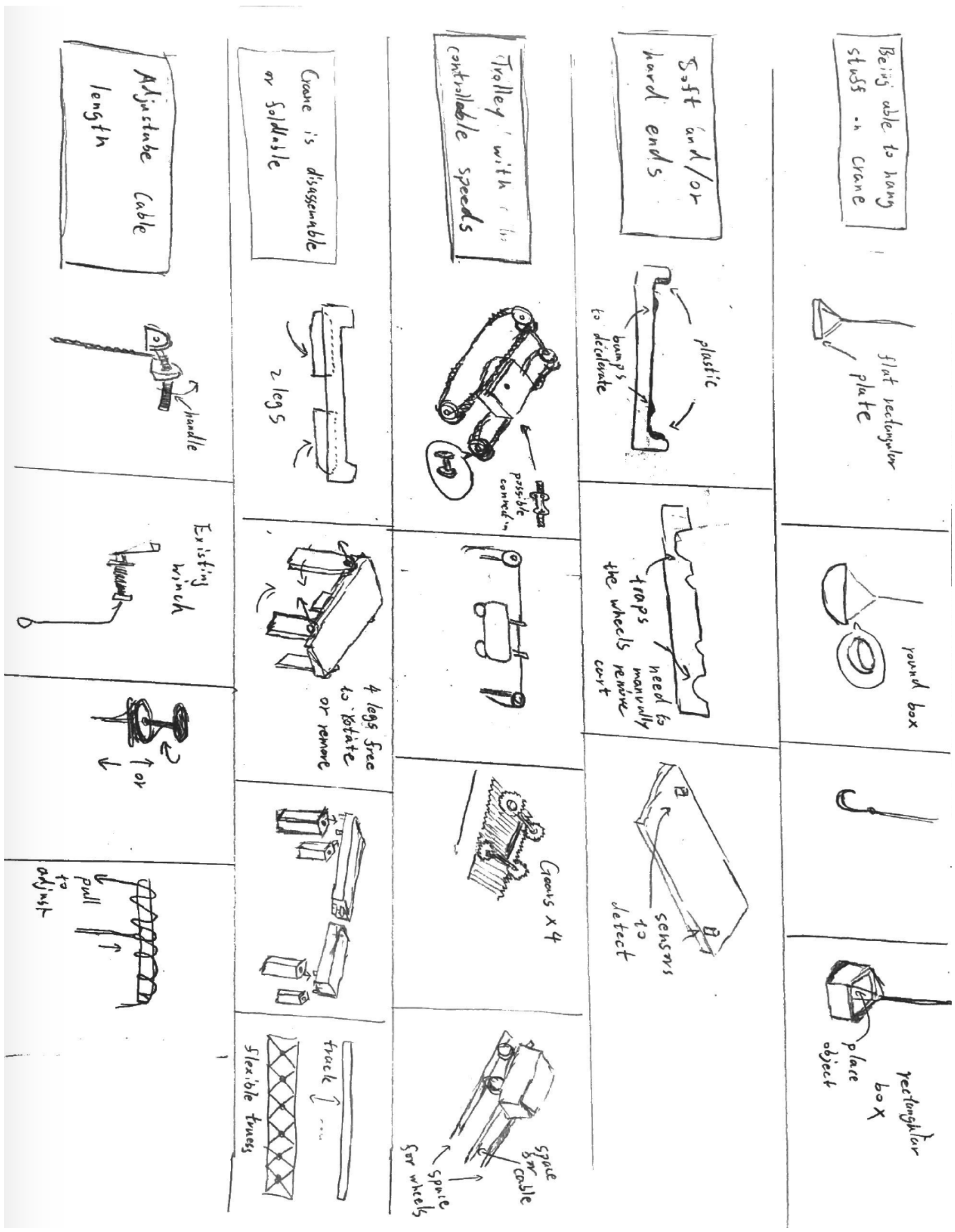


Figure 10: Morphological Chart for Portable Bridge Crane.

3.4 Alternative Design Concepts

3.4.1 Portable Bridge Crane with Gear

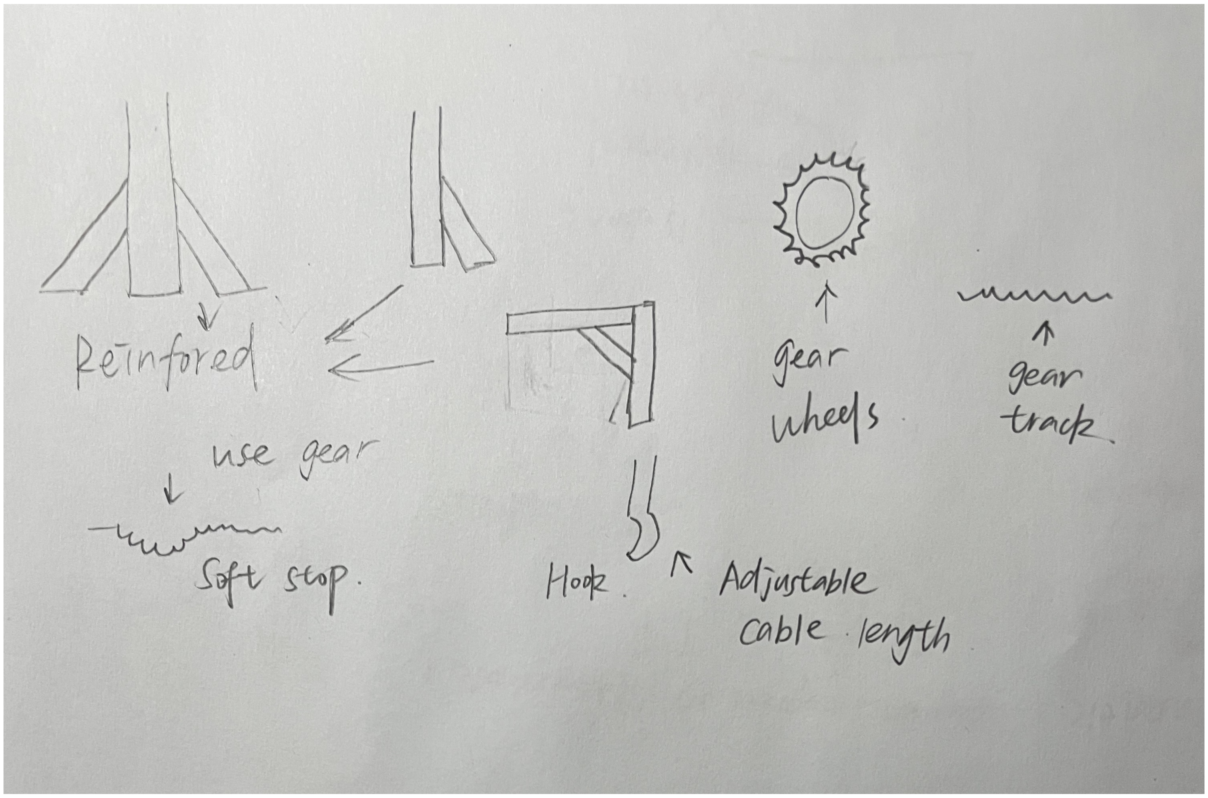


Figure 11: Preliminary sketches of portable bridge crane concept.

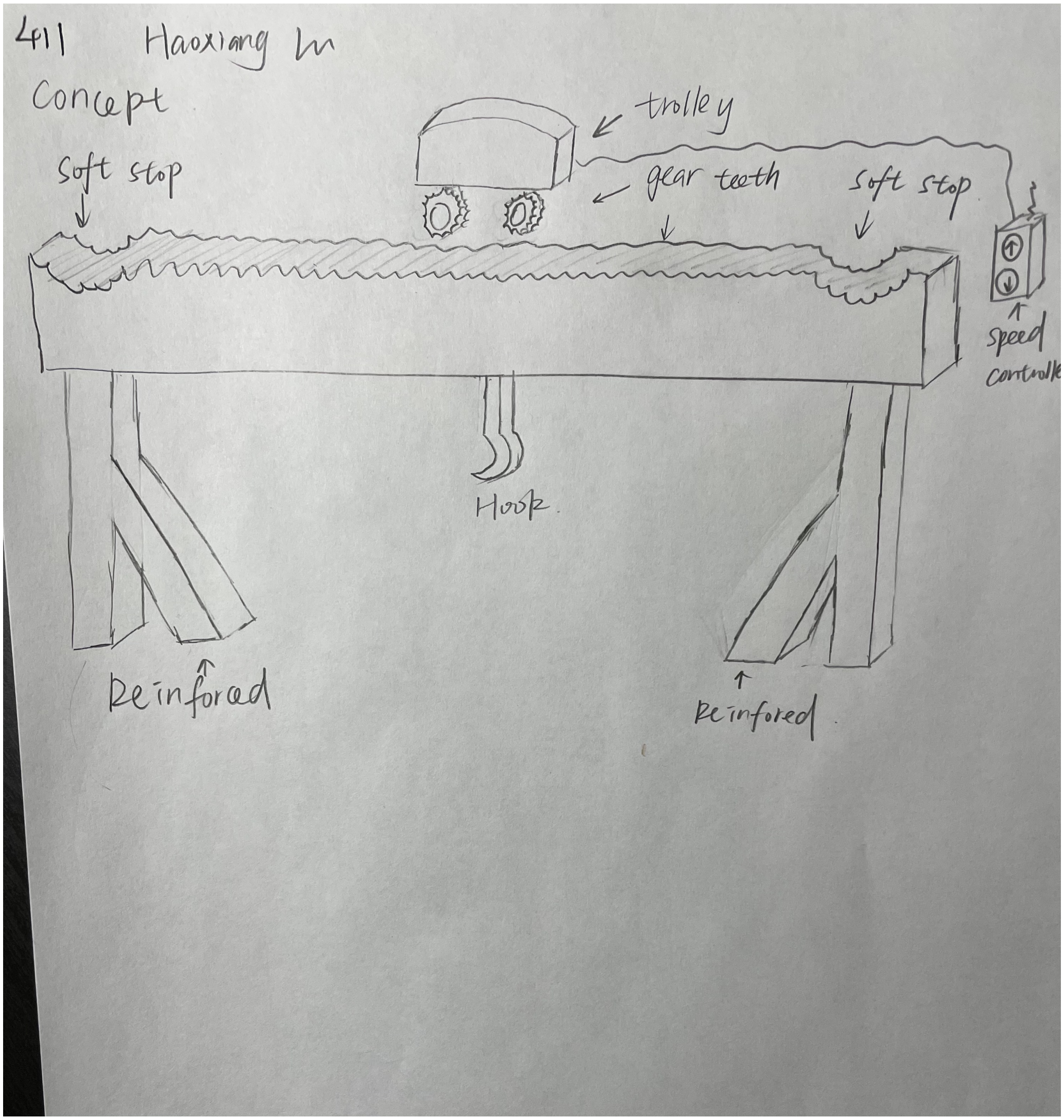


Figure 12: Final sketches of Robotic Arm concept

Description: The portable bridge crane with gears uses gears on the wheels and track of the rail. The speed of the trolley can be adjusted by the speed controller by controlling the gear rotational speed. It should be noted that there have soft stops designed by gear on both sides of the track to prevent the trolley from hitting both sides. The hook is used to adjust the length of the cable, the excess cable can be wrapped around the hook. On the bottom frame, there have reinforced legs to make the frame more stable.

3.4.2 Portable Bridge Crane with Pulleys

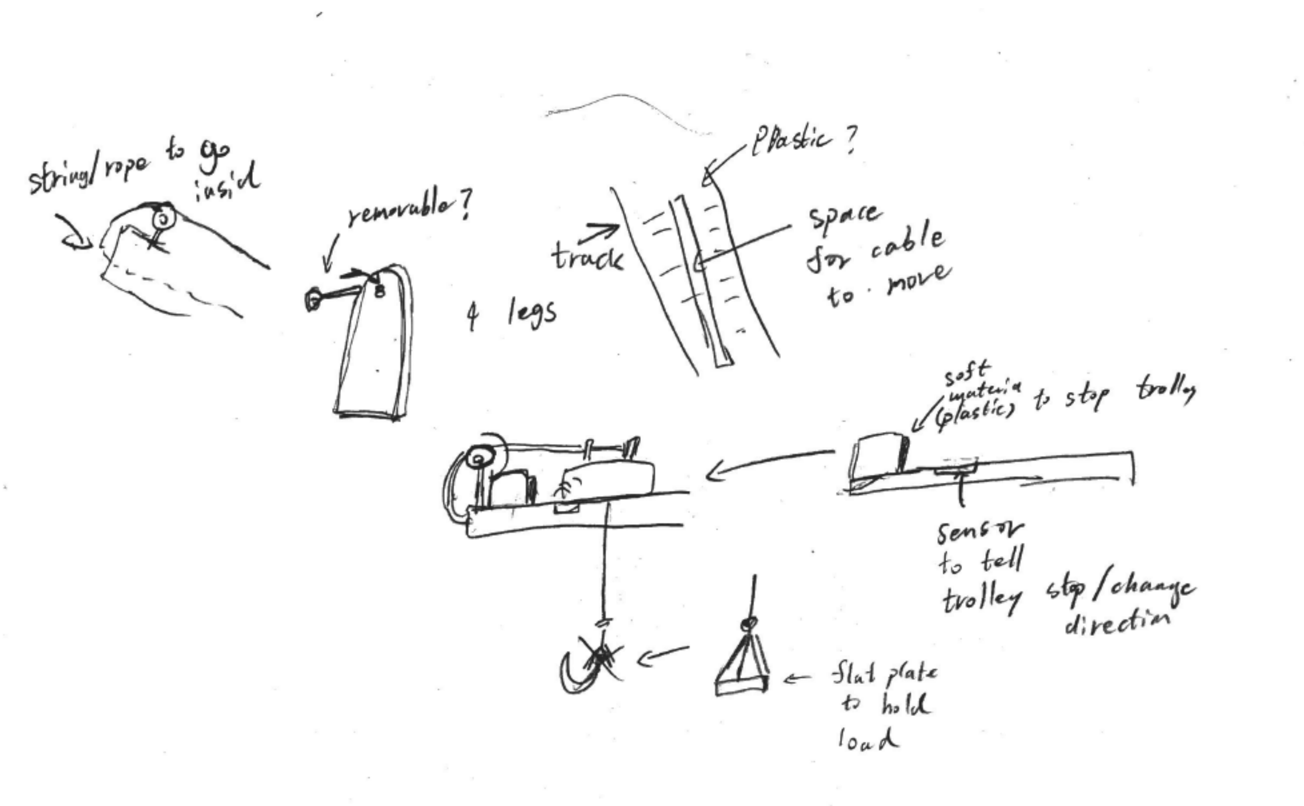


Figure 13: Preliminary sketches of portable bridge crane concept.

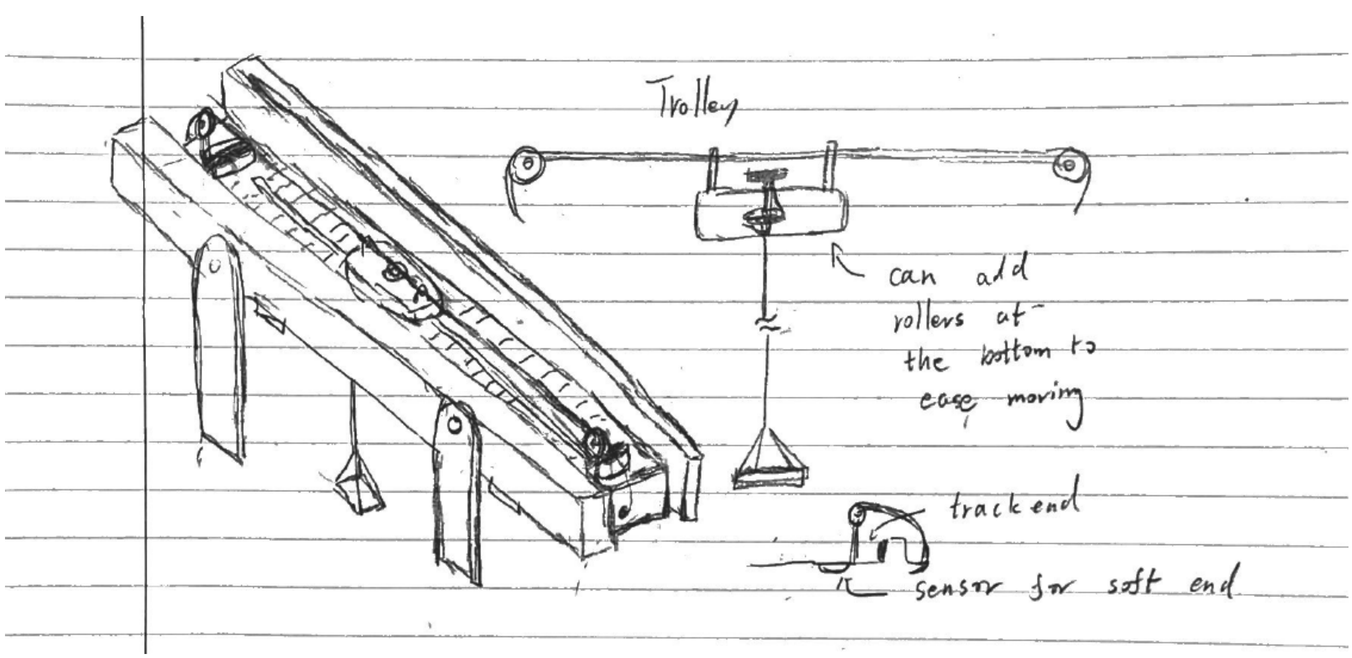


Figure 14: Final sketches of portable bridge crane concept.

Description: A motor will be put into the rollers (with wheels/rollers) to move the trolley along the track. Programming on Arduino allows the trolley to have adjustable/various speeds. The four legs can be oriented in different angles to minimize space for storage or transit, The trolley is attached to a string above the bridge to secure the direction of the trolley (only moving backward and forward). Turning the handle on the trolley allows users to manually change the cable length. One sensor is installed at each end of the track, and the sensor will tell the trolley (via codes in Arduino) to change direction/stop once the trolley is in contact with it.

3.4.3 Cart Crane with Truss Structure

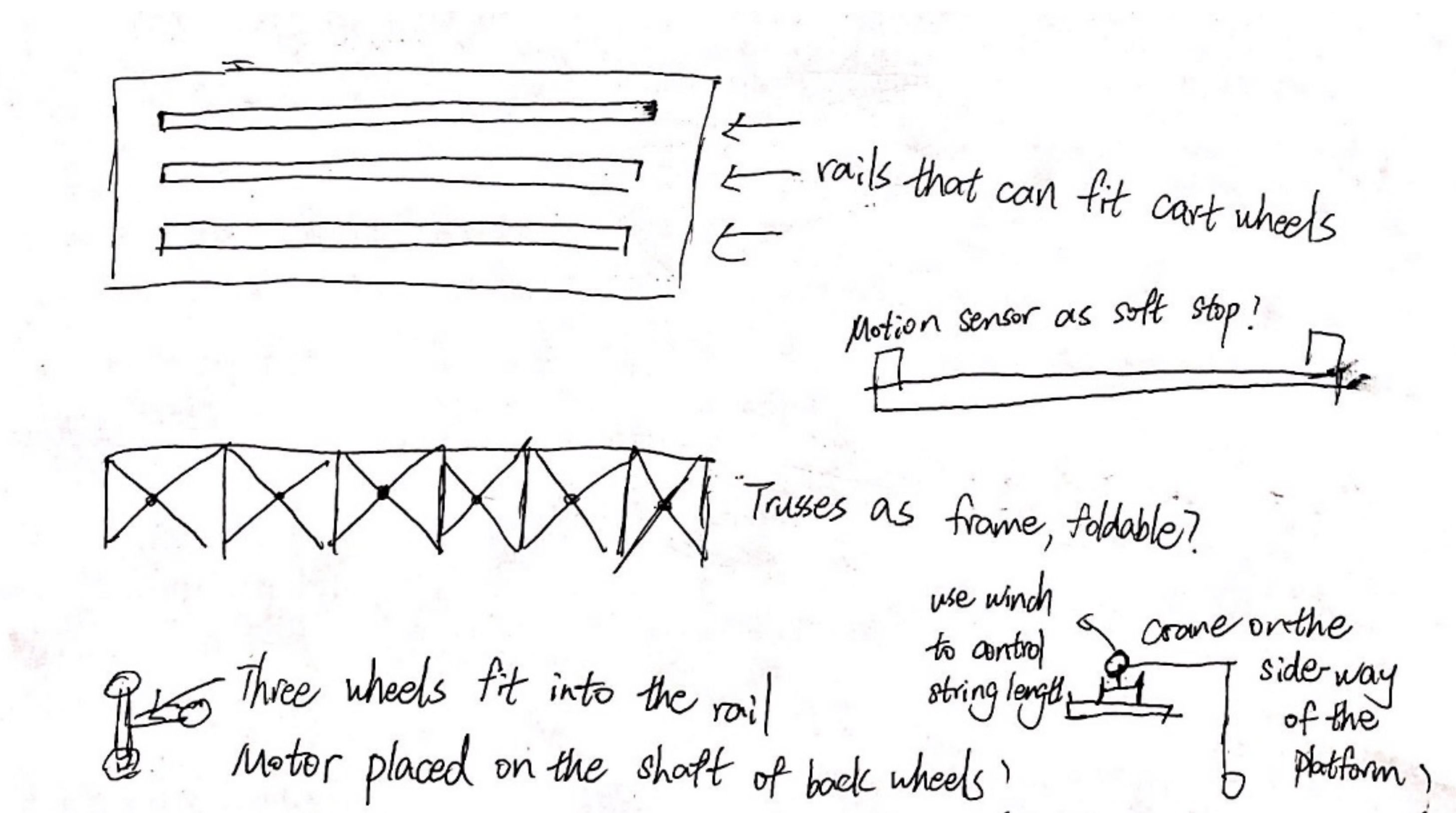


Figure 15: Preliminary sketches of portable bridge crane concept.

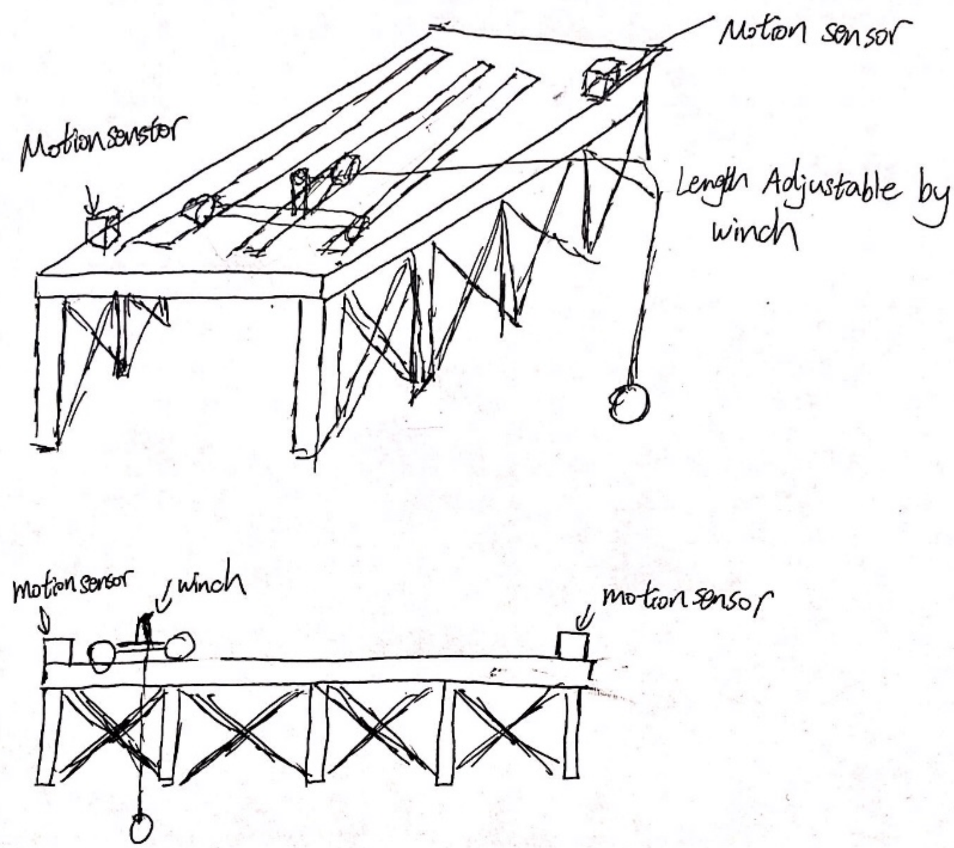


Figure 16: Final sketches of portable bridge crane concept.

Description: In this design, a cart with three wheels are driven by stepper motor on the rear wheel to provide power. The platform has three rail lines for each wheel. This structure is supported by truss structure to maintain stability. Motion sensors are used as soft stops. The string is on the side way and a winch is used to control the length of the string. Arduino will be used to program the motor and winch in order to control the cart speed and to adjust the string length.

3.4.4 Simple Bridge Crane Concept

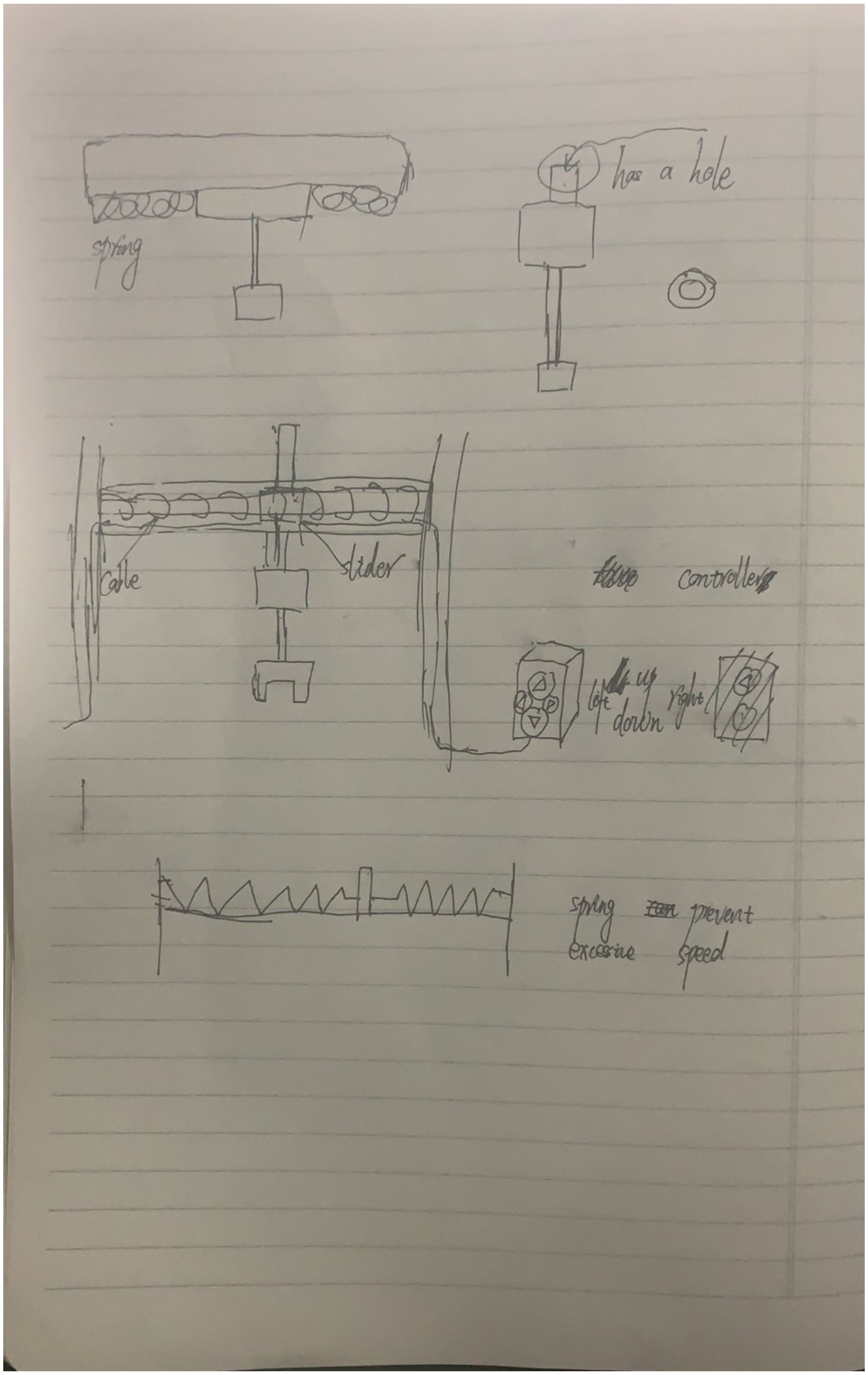


Figure 17: Preliminary sketches of Simple bridge crane.

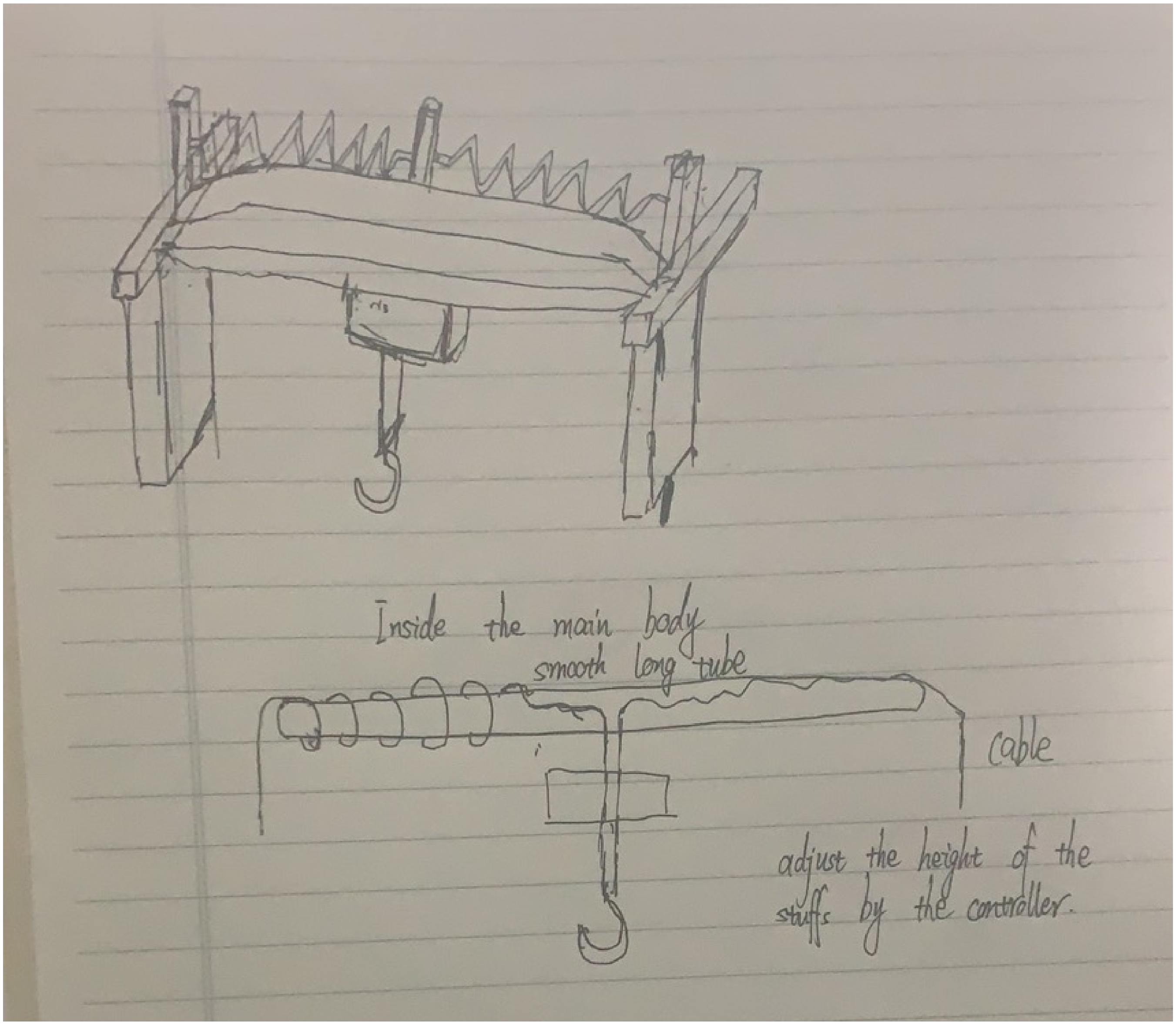


Figure 18: Final sketches of Simple bridge crane.

Description: Simple springs are arranged on the left and right sides above the main bridge to prevent the trolley on the track from hitting violently when it reaches the left and right ends. This can also prevent the suspended objects from violently shaking and causing falling off or collision accidents. At the same time, a smooth and slender tube is set inside the main body to place the rope for hanging objects. The cable passes through the small holes on both sides, and the suspension height can be controlled by the controller for expansion and contraction.This design not only ensures that the bridge crane can work as desired, but also makes the overall mechanism more concise.

4 Concept Selection

4.1 Selection Criteria

Figure 19 below shows the selection criteria for our design. In our design, system stability, speed controllability, and portability are the three most dominant criterion for our design.

	Portability	Ease of assemble	Speed controllability	System stability	Cost		Row Total	Weight Value	Weight (%)
Portability	**1.00**	3.00	1.00	0.33	5.00		10.33	0.22	22.33
Ease of assemble	0.33	**1.00**	0.33	0.20	5.00		6.87	0.15	14.84
Speed controllability	1.00	1.00	**1.00**	0.33	5.00		8.33	0.18	18.01
System stability	3.00	5.00	3.00	**1.00**	7.00		19.00	0.41	41.06
Cost	0.20	0.20	0.20	0.14	**1.00**		1.74	0.04	3.77
						Column Total:	**46.28**	**1.00**	**100.00**

Figure 19: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

Based on the selection criteria chart, Fig. 20 below shows the weighted scoring matrix (WSM). The Portable Bridge Crane with Pulleys was evaluated to be the best concept from the WSM.

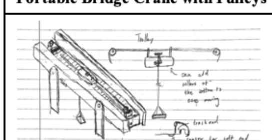
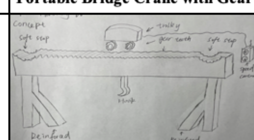
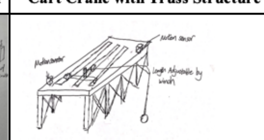
Alternative Deisgn Concepts		**Portable Bridge Crane with Pulleys**		**Portable Bridge Crane with Gear**		**Cart Crane with Truss Structure**		**Simple Bridge Crane**	
									
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Portability	22.33	4	0.89	5	1.12	4	0.89	3	0.67
Ease of assemble	14.84	3	0.45	3	0.45	4	0.59	3	0.45
Speed controllability	18.01	4	0.72	3	0.54	3	0.54	2	0.36
System stability	41.06	4	1.64	3	1.23	4	1.64	4	1.64
Cost	3.77	3	0.11	2	0.08	2	0.08	2	0.08
	Total score	**3.814**		**3.409**		**3.745**		**3.193**	
	Rank	**1**		**3**		**2**		**4**	

Figure 20: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

Because our most dominant criterion are chosen to be system stability, portability, and speed controllability, the Portable Bridge Crane with Pulleys excels because it has the highest overall rating of these criterion. In this concept, the pulleys will be responsible for controlling the direction and the speed of the trolley and the legs are retractable using rotary joints. No physical moving carts or trolleys will be involved in this design to minimize the impact force. Although Portable Bridge Crane with Gear has the best portability, the Portable Bridge Crane with Pulleys has the second best portability because the legs are retractable and the pulleys are disassemble. For the ease of assemble criterion, the selected concept may need some time to assemble the pulleys and the string, but should be acceptable. Therefore, it has the second highest score for the ease of assemble criterion. For the speed controllability, the selected concept will have the easiest speed control because instead of controlling the linear speed, we can control the rotational speed of the pulley. The control of the pulley rotational speed can be directly achieved by the control of the motor rotational speed. Thus, the selected concept has the highest speed controllability score. The system would also be very stable because there is no direct collisions between objects in this design. Therefore, the structure will not tip due to collisions. The cost is a relatively unimportant factor, but the selected concept has the highest score because we don't need to purchase carts or other moving objects. In conclusion, the Portable Bridge Crane with Pulleys is the selected concept because it has the highest overall score in portability, ease of assemble, speed controllability, system stability, and cost.

4.4 Engineering Models/Relationships

4.4.1 Pendulum Motion Model

The motion of the ball for the bridge crane is shown in the figure 27 below.

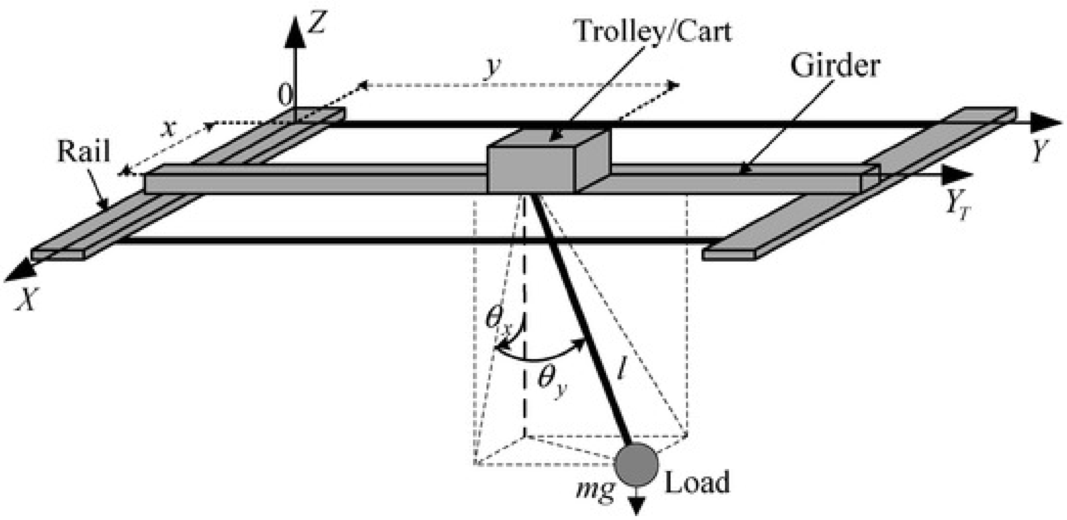


Figure 21: The motion of the ball for the bridge crane [1].

$$T = 2\pi\sqrt{\frac{l}{g}} \tag{1}$$

Where l is the length of the string, T is the pendulum period, and g is the gravitational constant. Therefore, by adjusting the length of the string, we should be able to observe the difference in period. The model relies on small angle approximation[1].

This model can be applied to our design because the one objective of our project is to observe how the difference in string length and trolley speed can affect the vibration frequency. This preliminary model indicates that the increase in length will increase the period and decrease the frequency. The mass of the object is independent of the period and frequency. This theoretical conclusion can be compared with our design result.

4.4.2 Trolley Motion Model

Figure 22 below is a potential engineering trolley model followed by two governing equations[2]. The model serves as a simple approach for our trolley's motion.

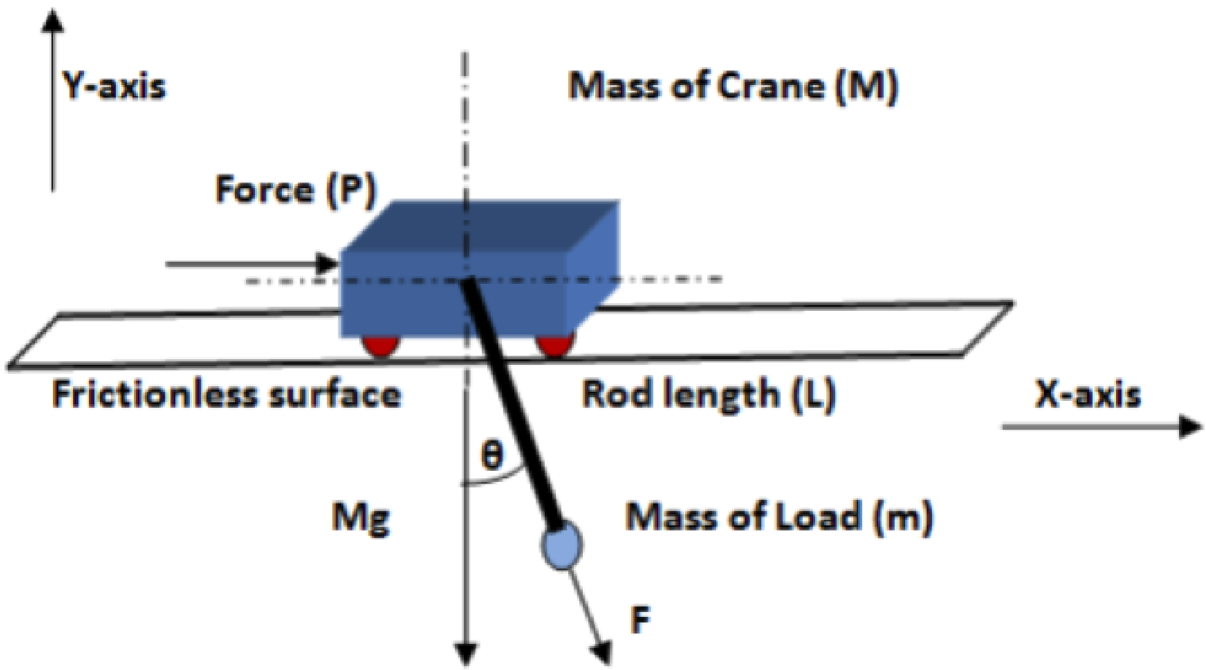


Figure 22: Potential trolley model[2].

$$\ddot{\theta} = \frac{-[u\cos(\theta) + m\sin(\theta)(L\theta^2\cos(\theta) + g) + Mg\sin(\theta)]}{(M + m\sin^2(\theta))L} \tag{2}$$

$$\ddot{x} = \frac{u + m\sin(\theta)(L\theta^2 + g\cos(\theta))}{M + m\sin^2(\theta)} \tag{3}$$

Where u is a control variable, M is the mass of the crane, m is the load attached to the cable (with negligible mass) with length L. Gravity g and the applied force P induce the motion of the trolley. θ is the angle of inclination of rod with respect to the vertical axis. The model assumes the bridge surface is frictionless[2].

By plugging in arbitrary numbers for the masses and cable length, the model helps us estimate how much transnational acceleration we need/are allowed to achieve our desired speeds. Since we already have design limits for the cable length and load mass from our customer interview, this model helps us set up limits on the allowable weight of the trolley. To avoid large vibration due to the added load, the model suggests that the angle of oscillation is an important factor to consider.

4.4.3 Stepper Motor Model

The motor of the design is a stepper motor, allowing for precise movements or "steps", and it is shown in Fig. 28 below.

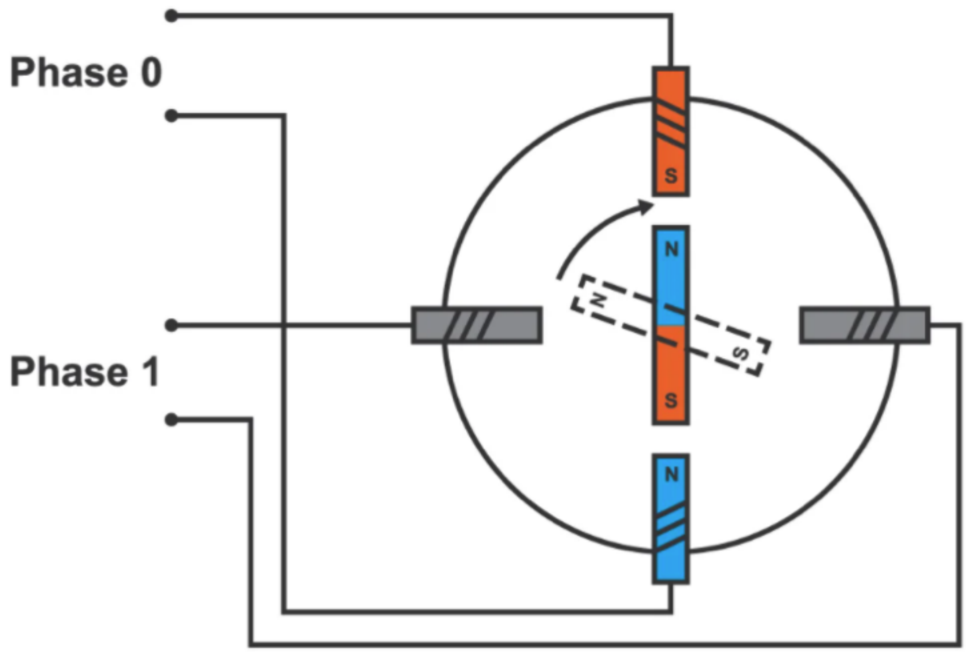


Figure 23: Schematic of a stepper motor[3].

Since we are using stepper motor in our application, it is important to use some of the useful stepper motor equations:

$$\text{Max Speed} = \frac{V}{2LI_{max}spr} \tag{4}$$

$$\text{Minimum Time per Step} = \frac{2LI_{max}}{V} \tag{5}$$

$$P_{max} = I_{max}V \tag{6}$$

Where V is the supplied voltage, I_{max} is the maximum current, L is the stepper motor inductance, P_{max} is the maximum power from the stepper motor, and *spr* is steps per revolution[3].

These equations allow us to estimate the maximum power from the data from the motor specification sheet. By applying these equations, we can estimate the maximum power and minimum time per step. These equations can also guide us how the stepper motor works and verifies our decision to use a stepper motor for our design. As a result, we would be able to make sure that our selected motor can satisfy the customer need given the power it provided.

5 Concept Embodiment

5.1 Initial Embodiment

Figures 24 to 26 below are the CAD drawing of the Initial Prototype assembly ftom top view, right view, side view, isometric view, and exploded view. An arbitrary load (a 2x2x2 in. cube) is tied up to the cable at the bottom). Our performance goals include:

- The trolley move $\geq$ 1 ft/sec.
- The trolley stops before hitting the rail ends and can be driven opposite direction
- The weight of the bridge is no more than 10 lbs.

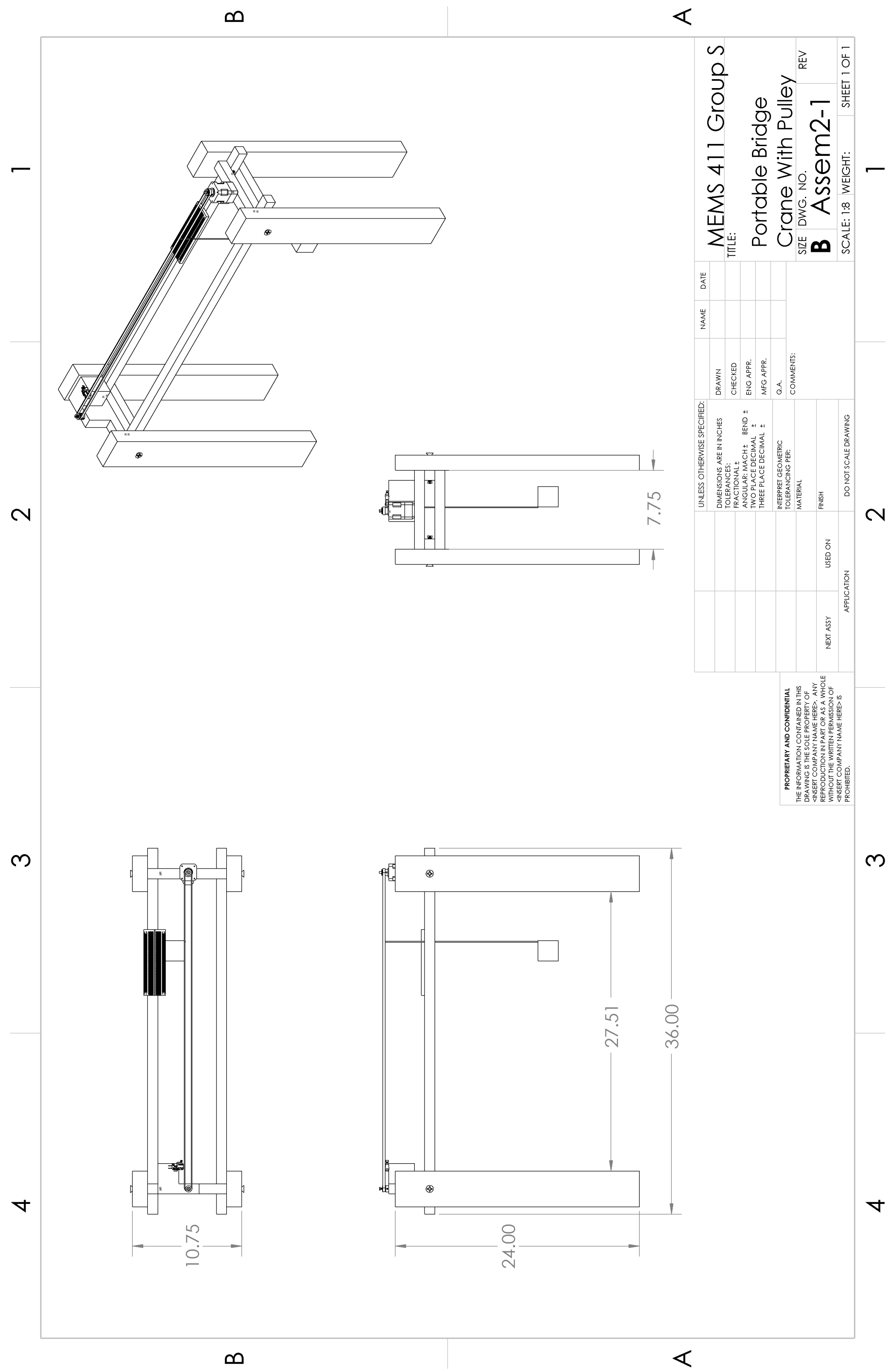
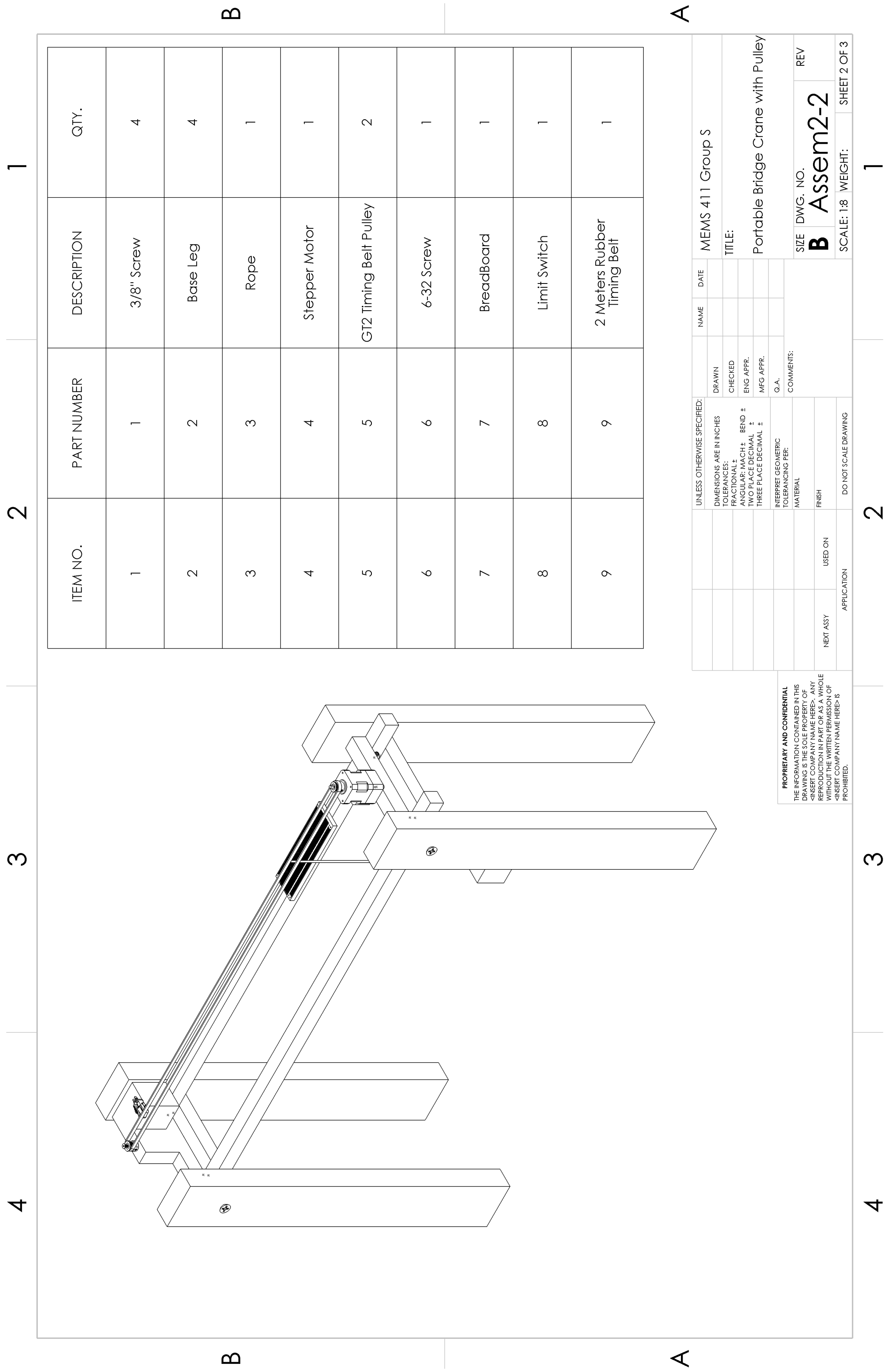


Figure 24: Assembled projected views with overall dimensions



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1	3/8" Screw	4
2	2	Base Leg	4
3	3	Rope	1
4	4	Stepper Motor	1
5	5	GT2 Timing Belt Pulley	2
6	6	6-32 Screw	1
7	7	BreadBoard	1
8	8	Limit Switch	1
9	9	2 Meters Rubber Timing Belt	1

Figure 25: Assembled isometric view with bill of materials (BOM)

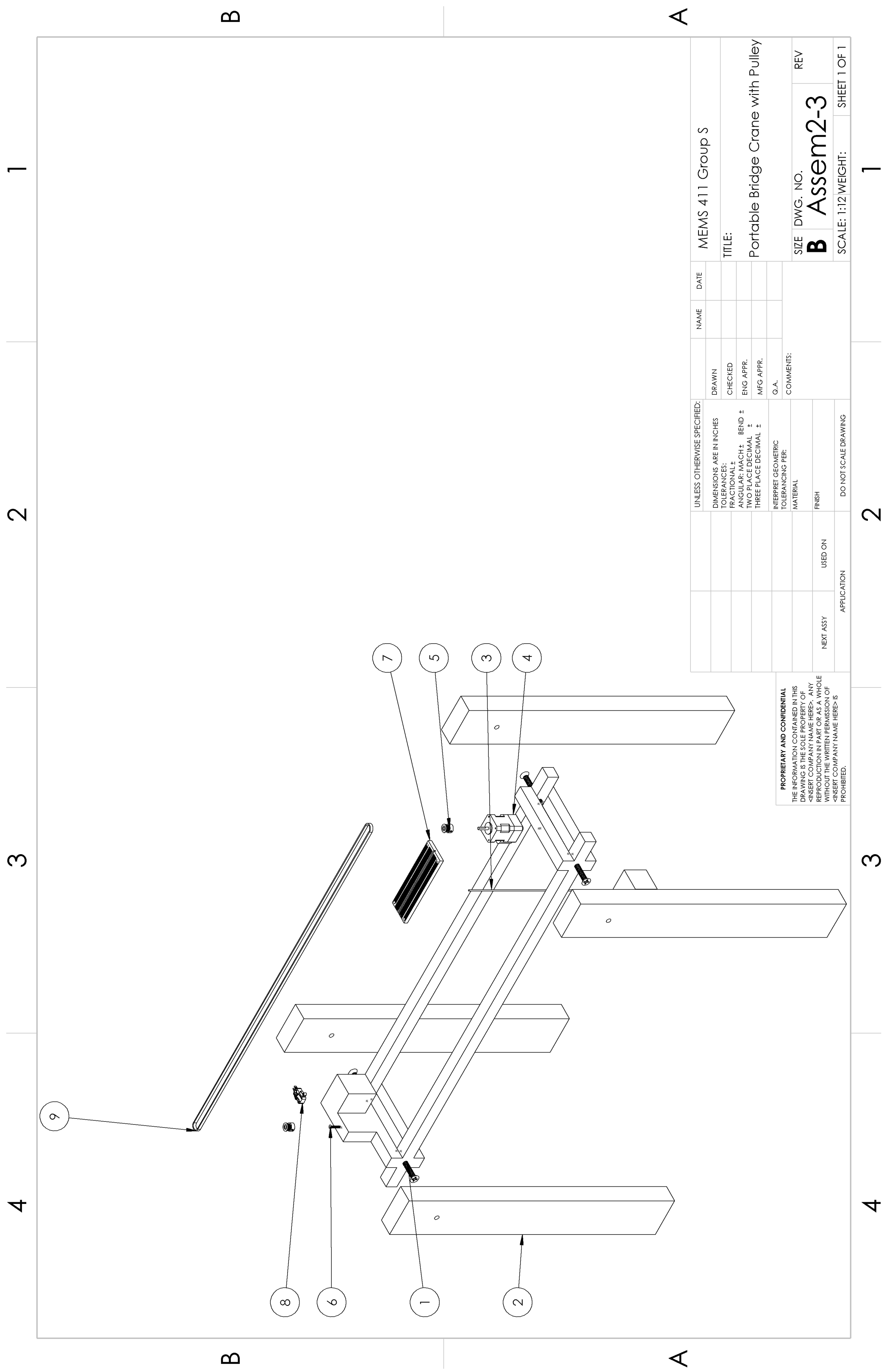


Figure 26: Exploded view with callout to BOM

5.2 Proofs-of-Concept

Based upon our proofs-of-concept testings and prototypes constructed in the studio, we made some significant changes on our initial prototype compared to the concept we selected from section 4. , we had to reduce the volumes of the legs and the bridge body, and our initial prototype features in removing as many wood as possible from the bridge body. A screw with 3/8" diameter is used for securing each leg to one side of the bridge, allowing the user to freely adjust the leg angles.

In contrast to the concept selected from section 4, our initial prototype removes a significant amount of wood from the bridge. This is because making the cut according to the original concept is hard to achieve with the available tools, and our current design also helps reduce the weight of the bridge crane. With the use of pulley-belt system, there is no need to make a trolley with wheels, for the belt is able to transfer the cable and added load. An Arduino breadboard is placed on one side of the bridge controlling the motion of the stepper motor. A limit switch is attached to the end of the bridge opposite to the motor side. Once a bump near the cable hits the switch, the motor will stop. Releasing the switch will cause to motor to rotate in a reversed direction.

6 Design Refinement

6.1 Model-Based Design Decisions

We are keeping the 2 Engineering models from section 4 for our final product with an additional model based on our concept selection. We removed the model for the motion of the trolley because our the Pulley Bridge Crane concept does not require wheels for the trolley. Instead, the motion of the trolley will depend on the pulleys and timing belt.

6.1.1 Pendulum Motion Model

The motion of the ball for the bridge crane is shown in the figure 27 below.

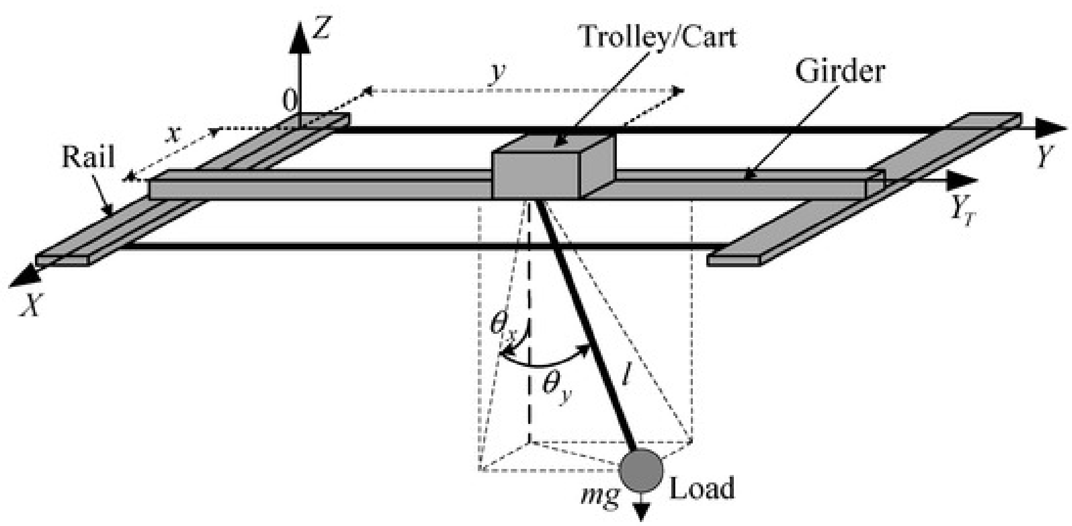


Figure 27: The motion of the ball for the bridge crane [1].

$$T = 2\pi\sqrt{\frac{l}{g}} \tag{7}$$

Where l is the length of the string, T is the pendulum period, and g is the gravitational constant. Therefore, by adjusting the length of the string, we should be able to observe the difference in period. The model assumes the motion is in small angle[1].

This model can be applied to our design because one objective of our project is to observe how the difference in string length and trolley speed can affect the vibration frequency. This preliminary model indicates that the natural frequency is independent of trolley speed. Only the increase in length will increase the period and decrease the frequency. In order to observe a specific frequency, we can used to calculate the length of the string. In addition, the mass of the object is independent of the period and frequency. This theoretical conclusion can be compared with our design result. For example, if the string length is 1 m, the expected period would be 2 seconds and the frequency would be 0.5 Hz because $2\pi\sqrt{\frac{1m}{9.8m/s^2}}$ is 2 second.

6.1.2 Stepper Motor Model

The motor of the design is a stepper motor, allowing for precise movements or "steps", and it is shown in Fig. 28 below.

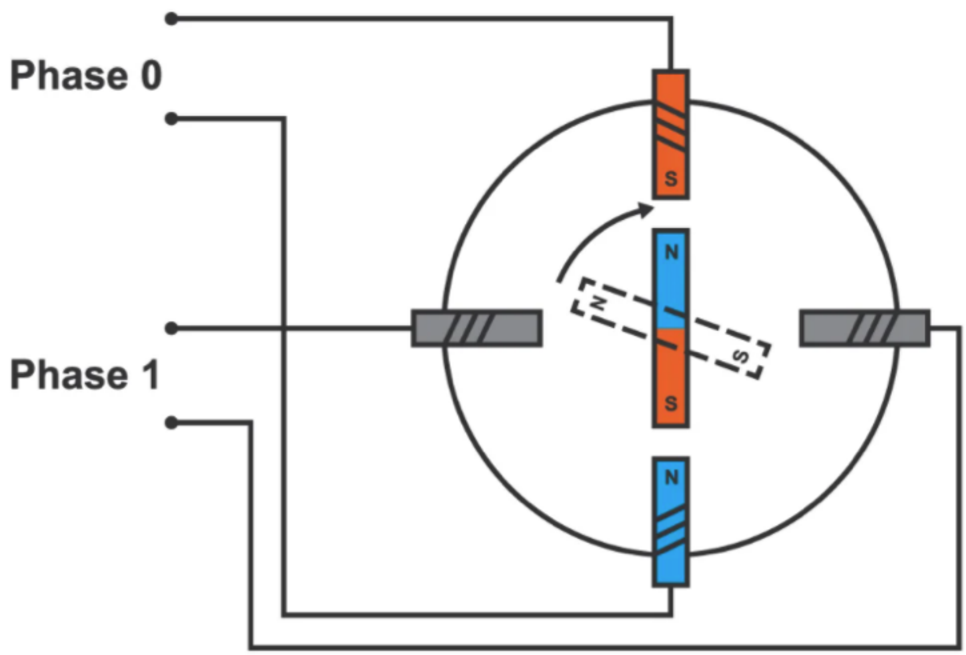


Figure 28: Schematic of a stepper motor[3].

Since we are using stepper motor in our application, it is important to use some of the useful stepper motor equations:

$$\text{Max Speed} = \frac{V}{2LI_{max}spr} \tag{8}$$

$$\text{Minimum Time per Step} = \frac{2LI_{max}}{V} \tag{9}$$

$$P_{max} = I_{max}V \tag{10}$$

Where V is the supplied voltage, I_{max} is the maximum current, L is the stepper motor inductance, P_{max} is the maximum power from the stepper motor, and *spr* is steps per revolution[3].

These equations allow us to estimate the maximum power from the data from the motor specification sheet. By applying these equations, we can estimate the maximum power and minimum time per step. These equations can also guide us how the stepper motor works and verifies our decision to use a stepper motor for our design. As a result, we would be able to make sure that our selected motor can satisfy the customer need given the power it provided.

For Pololu NEMA 14-size hybrid bipolar stepping motor that we picked, the voltage V is 10 V, the maximum current I_{max} is 0.5 A, the inductance L is 13.5 mH, and *spr* is 200 steps per revolution. Therefore, the theoretical minimum time per step is 1.35 mS. The maximum rotational speed for the motor is calculated to be 3.704 rev/s by $\frac{10}{2*0.5*13.5*10^{-3}*200}$.

6.1.3 Pulley-belt Model

Besides the above models from section 4, we would like to include one more model for our final design. This is because the concept we selected involves a pulley-belt system, so we need to consider this extra feature. Figure 29 below is our selected Engineering model for our pulley-belt feature.

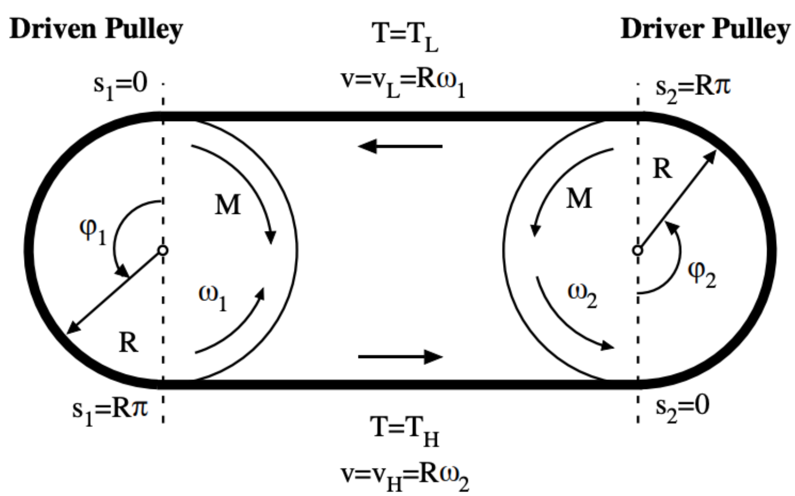


Figure 29: Schematic of pulley-belt system[4].

The key equation of interest is the velocity of the moving belt, for this directly reflects our trolley speed, which is given by:

$$V = R * \omega \tag{11}$$

Where V is the translational speed of the timing belt [m/s], R is the radius of the pulley [m], and ω is the rotational speed generated by the stepper motor. Thus, we can control the speed of the trolley by adjusting the size of the pulley and the speed of the steeper motor.

In our initial prototype testing, we used two pulleys with $R = 8$mm, but it was to small in reach our desired maximum linear speed (0.3m/s). For the next iteration, we are switching to pulleys with $R = 13.75$mm to achieve a higher linear speed. Using Eq.11, we verified that the rotational speed required from the motor is 3.47 rev/s, which is below our design limit ($\omega_{max} = 3.7$ rev/s).

6.2 Design for Safety

When using our design, there are some safety considerations that need to be paid attention to. Our team enumerated the five most common risks and prioritized them according to the specific conditions of use.

6.2.1 Risk #1: Structure Tipping

Description: The structure falls on one side due to collision.
Severity: Catastrophic
Probability: Seldom
Mitigating Steps: Use soft stop to reduce the collision force.

6.2.2 Risk #2: Trolley off Rail

Description: The trolley goes out of the rail due to out-of-plane forces.
Severity: Marginal
Probability: Likely
Mitigating Steps: Make sure the belt stays on the rail by increasing the tension of the belt.

6.2.3 Risk #3: Trolley Stall

Description: The motor does not provide enough power to carry the weight to move in a certain speed.
Severity: Negligible
Probability: Likely
Mitigating Steps: Make sure the motor generates enough power for the customer need.

6.2.4 Risk #4: Structure Fall Down

Description: The structure collapses due to too much weight is added to the structure.
Severity: Catastrophic
Probability: Unlikely
Mitigating Steps: Make the support more solid and stable.

6.2.5 Risk #5: String stuck intro wheels

Description: The trolley string stuck into pulley wheels.
Severity: Critical
Probability: Occasional
Mitigating Steps: Use a soft stop to stop the trolley strings before it hits the pulley wheel.

Severity of risk / 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
Catastrophic				Structure Tipping	Structure Fall Down
Critical			String stuck intro wheels		
Marginal		Trolley off Rail			
Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial		Trolley Stall			

Figure 30: Heat Map for Risk Assessment

In heat map, we believe that the highest risk priority is ”Structure Tipping”, because it has a seldom probability of occurrence but the severity is catastrophic. The second highest should be ”String Stuck intro wheels”, because this is a critical hazard and may occasional happen. The trolley string may stuck into the pulley wheels. Although the problem is easy to fix, it potentially may damage the string. Another risk is ”Trolley off Rail”. Although it is a marginal severity, the probability of occurrence will be likely. To maintain the belt on the rail is a key objective of the next phase design. The next risk is ”Structure Fall Down”. Although the damage it causes is catastrophic, it is almost impossible to happen given that the support structure is carefully designed. Finally, ”Trolley Stall” will happen if too much weight is hooked on the trolley, but the severity is negligible.

6.3 Design for Manufacturing

Based upon the CAD model and actual testings of our initial prototype, we construct the following table to list the parts of the theoretically necessary components for our refined product.

Table 3: List of components

Component	Quantity
Wooden legs	4
3ft wooden rod	2
Cable	1
Stepper motor	1
2mm wide timing belt	1
Handle	1
Arduino breadboard	1
Pulley	2
Limit switch	2
3/8" diameter screw	4
5/32" diameter screw	1
0.75 in. long wooden rod	4
Variable speed controller	1

Thus, the total number of unique parts for our design is 13, including 5 screws as fasteners.

The Theoretically Necessary Components (TNC) with brief descriptions are listed below:

• Legs - Legs are used to support the structure. They are foldable so that the user can carry the whole design around. Using a hand drill allows a user to easily replace the legs.

• Bridge body - Bridge body is the main component that supports the weight of play-load and other upper-level parts.

• Control system - Control system consists of the variable speed controller, limit switches, and the Arduino breadboard. This contributes to the speed control and soft stop features of the product. Once the switch is pressed, it tells the motor to switch direction. We also want the user to use the controller to change the speed and direction before the trolley reaches the limit switch.

• Motor system - Motor system is used to drive the trolley. It consists of the stepper motor, pulleys, and timing belt. The timing belt will transfer the linear speed to the trolley.

• Trolley - Trolley component is used control the cable length. It mainly consists of the handle and the adjustable cable.

Hypothetically, we could minimize the number of TNC by combining the bridge with the control system. This is because our control system only receives and sends out signals to control the motions of the motor system and trolley, so it can be fixed on the bridge and does not need to move relative to the bridge body.

6.4 Design for Usability

6.4.1 Vision Impairment

Vision impairment may have some influence on using our device because the users need to control the speed using a control board. If someone has vision impairment, he or she may have trouble in identifying the buttons. Therefore, it would be good the align the button sequentially. For example, the first button increases the speed and the second button decreases the speed. In this configuration, everyone can use it.

6.4.2 Hearing Impairment

Hearing impairment would not have a lot of influence in this system. Because this system is primarily a visual demonstration and has no relationship with the hearing function, hearing impairment would not affect the usage of our design. However, some alarms or unusual sounds may be ignored by the person with hearing impairment. Under this circumstance, we will use some warning light if something malfunctions.

6.4.3 Physical Impairment

Physical impairment has major influence in using our product. Because we are designing a portable bridge crane, we are assuming that 5 kg is a reasonable weight for normal person to carry around. For one with physical impairment, it is possible that this assumption is not valid. Therefore, designing some wheels to reduce the need for carrying it is a potential solution.

6.4.4 Control Impairment

Control impairment would have minimum effect on using this system. Because we will preprogram with an Arduino board, the only variable the user can adjust is just the speed. The only difficulty is to change the string length. Therefore, for control impairment users, they can still use the system safely. A way to make the system safer is that to set a maximum speed so the speed is limited in a safe range.

7 Final Prototype

7.1 Overview

For the final prototype, we 3-D printed a trolley and handle. By coiling the cotton cable around the handle, we were able to run the trolley with different cable lengths. Using the remote controller, a user can manipulate the motion of the trolley, such as switching directions and putting it to rest by using our controller. The limit switch on each side remains the soft stop to prevent the trolley from going beyond the desired path. Since stability is a big concern, we attached the rectangular pieces as helper legs to increase the contact surface with the ground. So in short, we added some extra components to our final design, including the rail, trolley, and the helper legs. Still, the design weights 4.26 kg, which falls within our design goal of 10lbs. The key lies in our legs. In our review on the initial prototype, our weight concentrated on the legs, For this final design, instead of keeping the original 4 legs, we kept 2 of them and cut them in half. As a result, the weight of the legs got reduced to about a half compared to that of the initial prototype. Increasing the diameter of each pulley returned a maximum transnational speed of roughly 1 ft/s as desired. Therefore, we accomplished all three performance goals for this design.

7.2 Documentation

The top view, right view, and front view of the final prototype are shown in Figure 31,32,33,respectively.

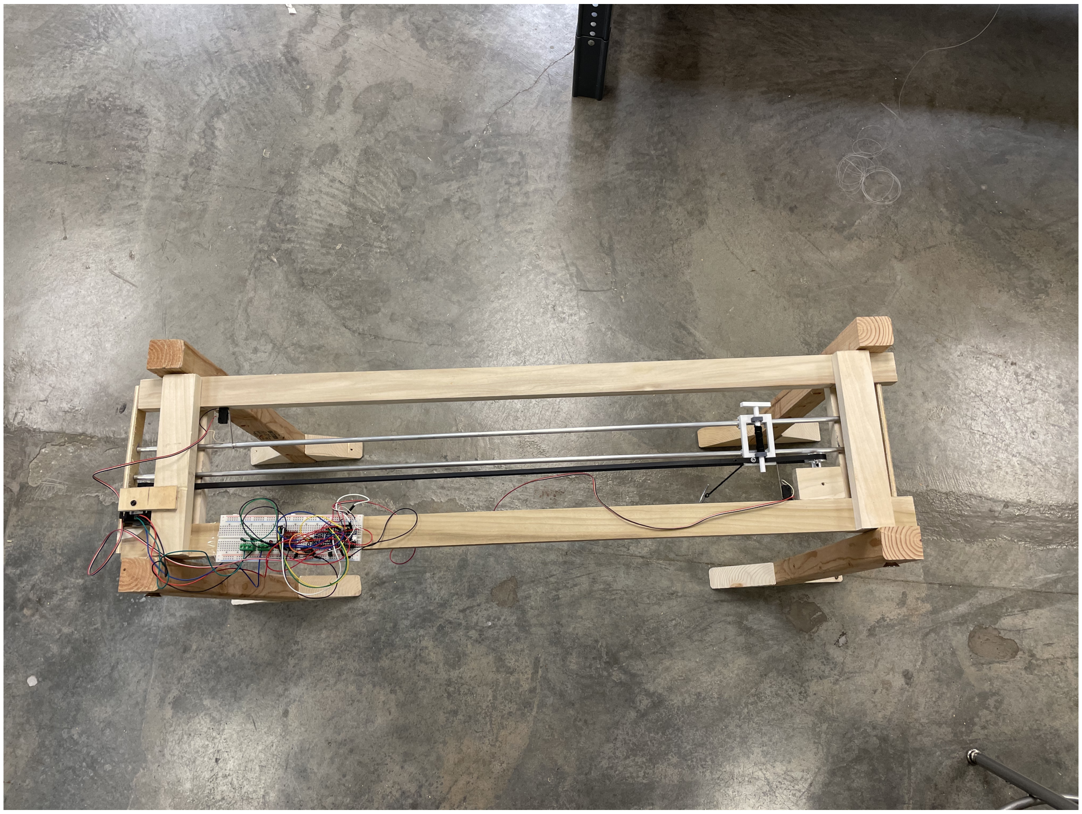


Figure 31: The top view of the final prototype.

Figure 32: The right view of the final prototype.

Figure 33: The front view of the final prototype.

The figure of remote control with instruction is shown in Figure 34 below. Pressing either the “Up arrow” or ”down arrow” button reverses the motor direction; pressing either the ”left arrow” or ”right arrow” button turns on the motor; pressing the ”OK” button turns off the motor.

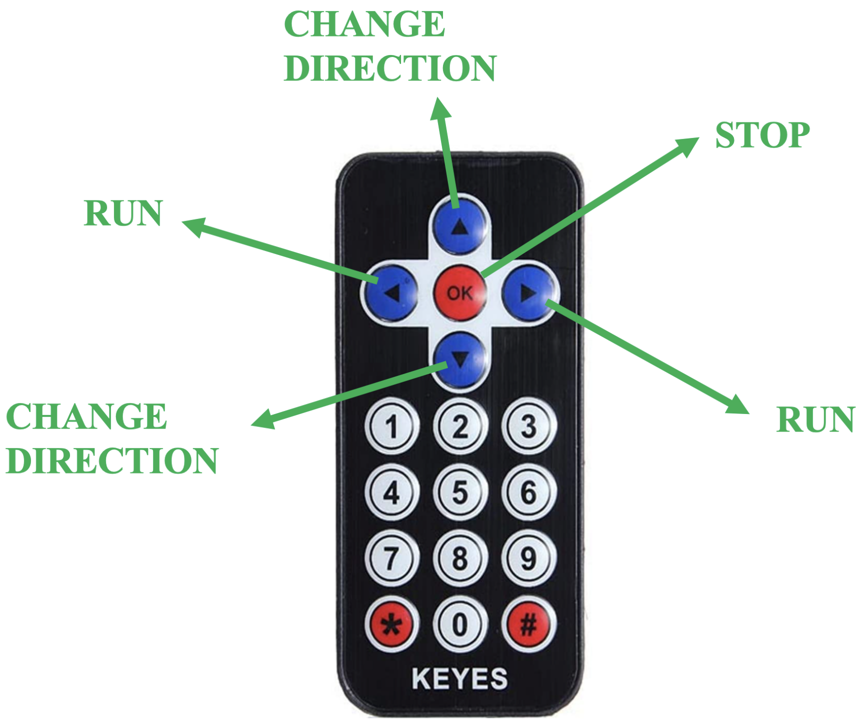


Figure 34: The remote control with instruction.

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