The City College of New York

Model Performance of a Controlled Descent Device

Group Members: Jamaal Lake, Jhun Martinez, Alisa Mizukami, Bajinder Singh, Misbah Syeda and Zhixuan Zhao

Mechanical Engineering 47400: Senior Design II

Professor Richard La Grotta

Due Date: 12/08/2020

Website: https://amizuka000.github.io/fireescape/

Summary

The purpose of this project was to design, build and test a personal fire escape system that can be used under fire-emergency situations in office buildings. After the event of 9/11 in New York City, engineers realized that there are needs for better escape systems for high-rise buildings. Nowadays, a lot of protocols have been established to evacuate buildings efficiently. However, it still takes a long time to get people out of the building. Therefore, the aim of this project is to design a personal fire escape system where an individual can jump off of a window and descend safely at a constant speed of 3 ft/s. Due to the COVID-19 pandemic, the entire senior design course was transitioned into a remote mode. Because this project required intensive manufacturing tools available at CCNY, it was not possible for the team to build an actual prototype and test it with the weight of a human being. Therefore, a model was built using 3D printed parts and resources available at online stores such as McMaster Carr and Amazon. Because we transitioned into building a model out of 3D printed parts, there were significant project requirement changes. Initially, the plan was to test 250 lbs on the system, however, we only tested a water bottle (1 - 2 lbs) on the system because 3D printed parts do not have the same strength as metals do. Additionally, the plan was to test the fire-escape-system from a maximum height of 100 feet, but due to the changing circumstances, the model was only tested from a height of 10 feet. Since descent speed is not dependent on the weight, there were no requirement changes to the descent speed rate of 3 ft/s. Before performing critical testing in which the speed of descent was calculated, there was intensive preliminary testing performed on the model to investigate its performance. There were numerous problems encountered in the preliminary testing phase and were resolved by the team in virtual and in-person meetings. As a result, the model was not able to meet all the requirements because it did not descend at 3 feet/s. However, our design was somewhat validated because the model created more friction than expected. On average, the descent speed was less than 0.1 feet/s, which is below our requirements. For next steps, we plan on changing the lever's dimensions to decrease the generated friction or change the rope and brake pad's materials to decrease the coefficient of friction.

Problem Description

Fire escapes are various types of emergency exits usually mounted on the outside of the building to provide a method of escaping in the event of a fire emergency. New York City has a dense population with residents living in apartments and connected buildings. Typical fire escapes observed in New York City's residential apartments are stairs outside the building leading down to the ground level. However, the problem with residential stair fire escapes is that it occupies a lot of space and requires maintenance. In addition, most buildings do not have enough space to implement fire escape stairs. Therefore, there was an attempt to design, build and test a personal fire escape system that will be easy to use, and will allow the user to descend at a constant speed. However, due to COVID-19, there were significant changes made to the requirements of this project as shown below in **Table 1**.

Table 1. Requirements modification due to remote class mode

Previous Requirements	Current Requirements
● Can handle up to **250 lbs** ● Maximum drop height of **100 feet** (equivalent to a building with 10 stories) ● Rope must be flexible and can withstand a certain amount of dynamic load ● Descent rate of 3 feet/s ● Clear markings on pre-installed hook and box ● Portable and lightweight ● Clear instructions ● Pre-installed hook and sturdy clasp ● Adjustable to different body sizes ● Must be slow enough to avoid obstructions during descent ● Fire Proof System	● Can handle up to **2 lbs** ● Maximum drop height of **10 feet** (equivalent to a building with 1 story) ● Rope must be flexible and can withstand a certain amount of dynamic load ● Descent rate of 3 feet/s

Since there was no access to CCNY Manufacturing Lab, a model was built by using 3D printed parts. Therefore, the maximum weight limit requirement was directly derived from the type of material used for the system; in this case, it was PLA and therefore, a reasonable weight requirement was decided upon in team discussions.

Trade Studies

The first trade study conducted was for the rope. The rope type is a significant design choice because it will be bearing all of the user's weight and will be subject to friction.

Three types of ropes were considered: nylon, technora, and galvanized steel. After ranking the three ropes for traits desired in the system, nylon was chosen as the most suitable rope for our scenario as shown below in **Table 2**.

Table 2. Trade studies for the rope types

¼ " Diameter:	**Nylon**	**Technora**	**Galv. Steel**
Availability 1 = hard to find, 3 = easy to find	3	1	2
Elastic Modulus 1 = weak, 3 = strong	2	1	3
Cost 1 = expensive, 3 = cheap	3	1	2
Weight 1 = heavy, 3 = light	3	2	1
Heat Resistance 1 = low , 3 = high resistance	2	3	1
Ease of Attachment 1 = hard , 3 = easy	3	2	1
Total /18	16	10	10

The second trade study conducted was for the 3D printing material. Since the system was scaled down and manufacturing shops were no longer accessible, using a durable metal such as the originally intended aluminum was no longer an option. Hence, it was crucial that a material was chosen that would simplify the manufacturing process but still be able to withstand the expected load of up to 10 lbs.

Three common types of 3D printed materials, PLA, ABS, and Nylon, were considered. After ranking the materials for desirable traits, PLA was chosen as the most suitable material for our case as shown below in **Table 3**.

Table 3. Trade studies for the 3D printing material types

	PLA	**ABS**	**Nylon**
Availability 1 = hard to find, 3 = easy to find	3	2	1
Durability 1 = flimsy, 3 = durable	1	2	3

Cost 1 = expensive, 3 = cheap	3	2	1
Ease of Printing 1 = difficult, 3 = easy	3	2	1
Heat Resistance 1 = low , 3 = high resistance	1	2	3
Strength 1 = weak , 3 = strong	3	2	1
Total /18	14	12	10

Solution Summary

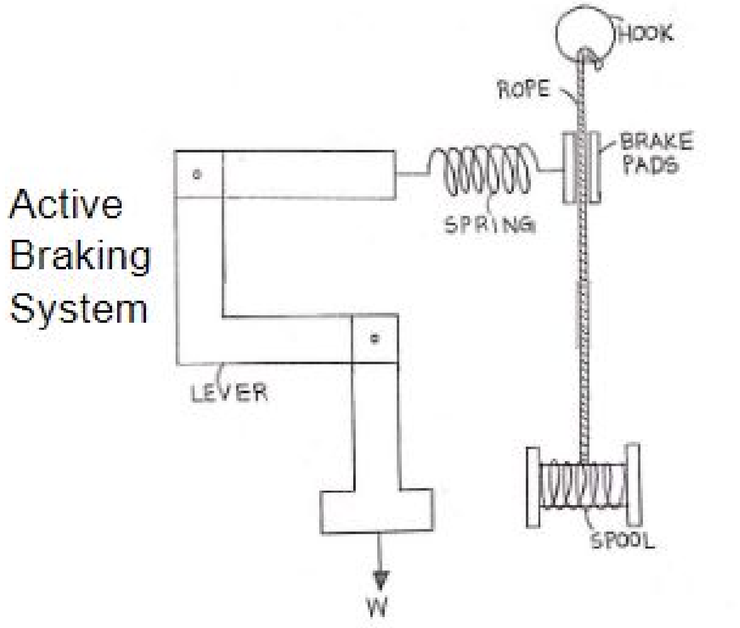

Figure 1. Design working principle

As shown above in **Figure 1**, the design mechanism for the fire-escape-system consists of a bell crank lever, a spring, brake pads and a rope. The active braking system is the most important part of this design as it inputs the weight of the object hanging and compresses the brake pads with the equal amount of force. Theoretically, this should create enough friction on the rope and be able to slow down the hanging object at a constant speed. A 3D model of the initial product is shown below in **Figure 2** with dimensions in inches.

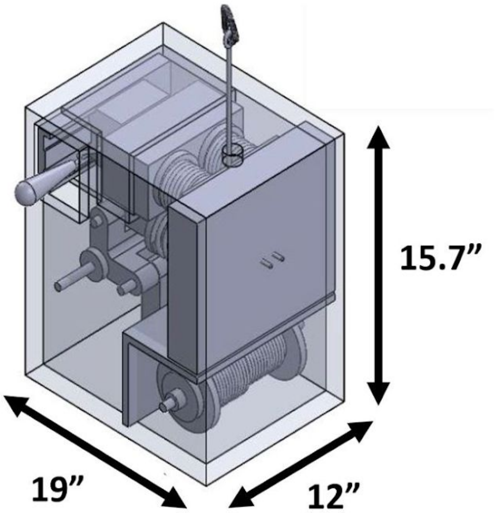

Figure 2. Initial 3D model of the fire-escape-system (units in inches)

Scaling Analysis

Since the requirements were significantly modified, the product was extremely downscaled. The spring was used to relate the downscaling in force to downscaling in size. The analysis is as follows:

Our initial weight requirement for the system was 50 lbs - 250 lbs, which was downscaled to 1 lb - 10 lbs.

The spring constant for the lower end of the weight requirement spectrum was first calculated.

$$W_1 = 1\ lb$$
$$F_1 = 1\ lb \times 4.45\ N/lbs = 4.45\ N$$

This force corresponds 1:1 with the friction on the brake pads. Using the coefficient of friction between nylon and rubber of 0.76, the normal force is determined to be:

$$F_N = F_{friction} / \mu = (4.45\ N) / (0.76) = 5.86\ N$$

This normal force corresponds to the force in the spring:

$$F_N = F_{spring} = 5.86\ N$$

The spring constant in the spring can then be calculated, with a displacement x of 28.4 mm:

$$k_1 = F_{spring} / x_1 = (5.86\ N) / (28.4\ mm) = 0.2307\ N/mm \qquad (1)$$

The spring constant for the higher end was then obtained:

$$W_2 = 10\ lbs$$
$$F_2 = 10\ lb \times 4.45\ N/lbs = 44.5\ N$$
$$F_N = F_{friction} / \mu = (44.5\ N) / (0.76) = 58.6\ N$$
$$F_N = F_{spring} = 58.6\ N$$

Assuming displacement *x* of 50.8 mm,

$$k_1 = F_{spring} / x_2 = (58.6\ N) / (50.8\ mm) = 1.154\ N/mm \qquad (2)$$

Using values (1) and (2), the optimal spring constant was determined:

$$k_{optimal} = (k_1 + k_2) / 2 = (0.2307\ N/mm + 1.154\ N/mm) / 2 = 0.6924\ N/mm$$

Using this spring constant value as a starting point and optimization of additional spring specifications using the spring calculator website yields a new spring free length. Additionally, the system case dimensions are listed.

$$L_{old} = 110\ mm$$
$$L_{new} = 40\ mm$$

$$Case\ length\ (old) = 19''$$
$$Case\ width\ (old) = 12''$$
$$Case\ height\ (old) = 15.7''$$

Therefore, using this downscale of the spring free length, the system downscale can be calculated using proportions:

$$\frac{Case\ length\ (old)}{L_{old}} = \frac{Case\ length\ (new)}{L_{new}} \rightarrow \frac{19''}{110\ mm} = \frac{Case\ length\ (new)}{40\ mm} \rightarrow \text{Case length (new) = 6.9 in}$$

$$\frac{Case\ width\ (old)}{L_{old}} = \frac{Case\ width\ (new)}{L_{new}} \rightarrow \frac{12''}{110\ mm} = \frac{Case\ width\ (new)}{40\ mm} \rightarrow \text{Case width (new) = 4.36 in}$$

$$\frac{Case\ height\ (old)}{L_{old}} = \frac{Case\ height\ (new)}{L_{new}} \rightarrow \frac{15.7''}{110\ mm} = \frac{Case\ height\ (new)}{40\ mm} \rightarrow \text{Case height (new) = 5.71 in}$$

The system's new dimensions are therefore 6.9 in x 4.36 in x 5.71 in.

The model was therefore scaled down to those dimensions. However, to further simplify the design, the hard brake was removed as the system was light enough to be braked by hand. Additionally, the spool was removed as the drop distance of 10 ft as opposed to 100 ft did not require one. Finally, a decision was made to remove the spring in the bell crank lever arm because the force transmitted to the brake pads would remain the same whether a spring or a solid material was used. The design changes can be seen below in **Figure 3**:

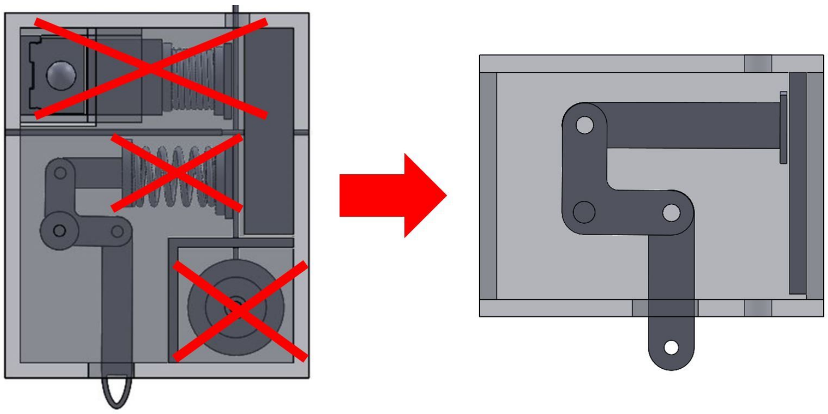

Figure 3. Parts removed for the modified design

This brought down the final scaled design to a size of 4 in x 2.4 in x 3 in.

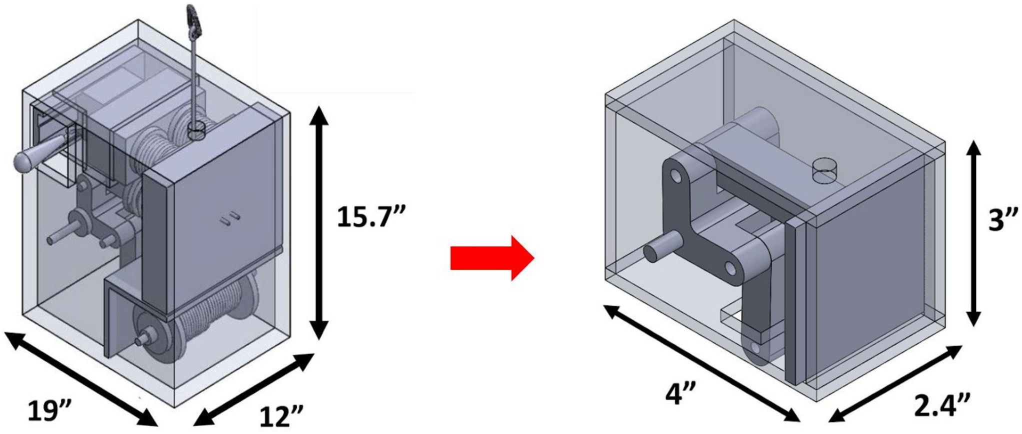

Figure 4. Initial vs. Final 3D model of the fire-escape-system (units in inches)

The part drawings for the scaled parts are illustrated below in **Figures 5-10**:

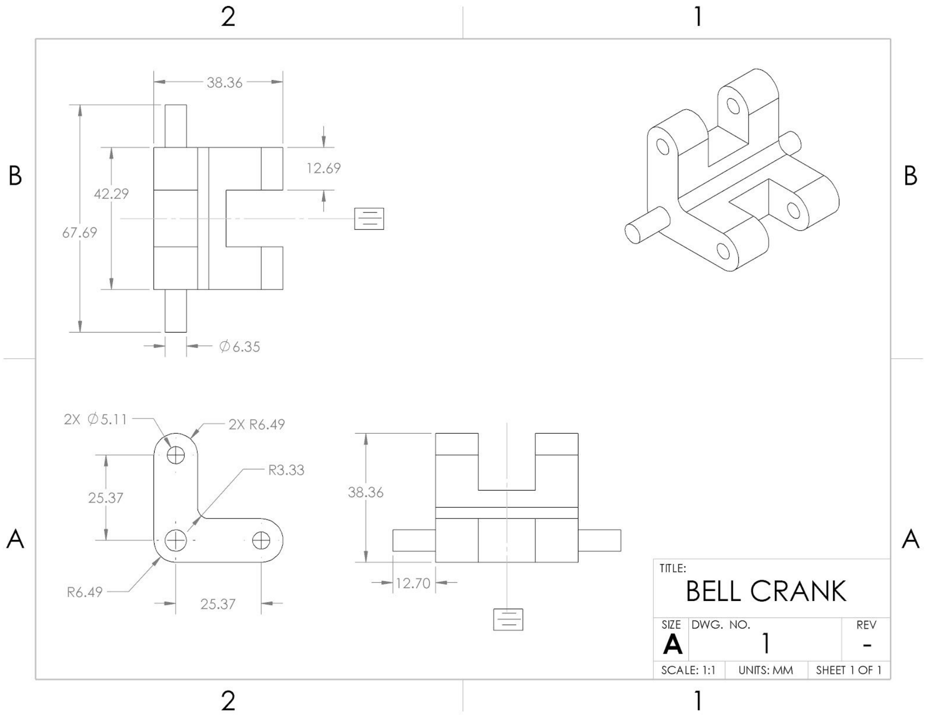

Figure 5. Engineering drawing of the bell crank

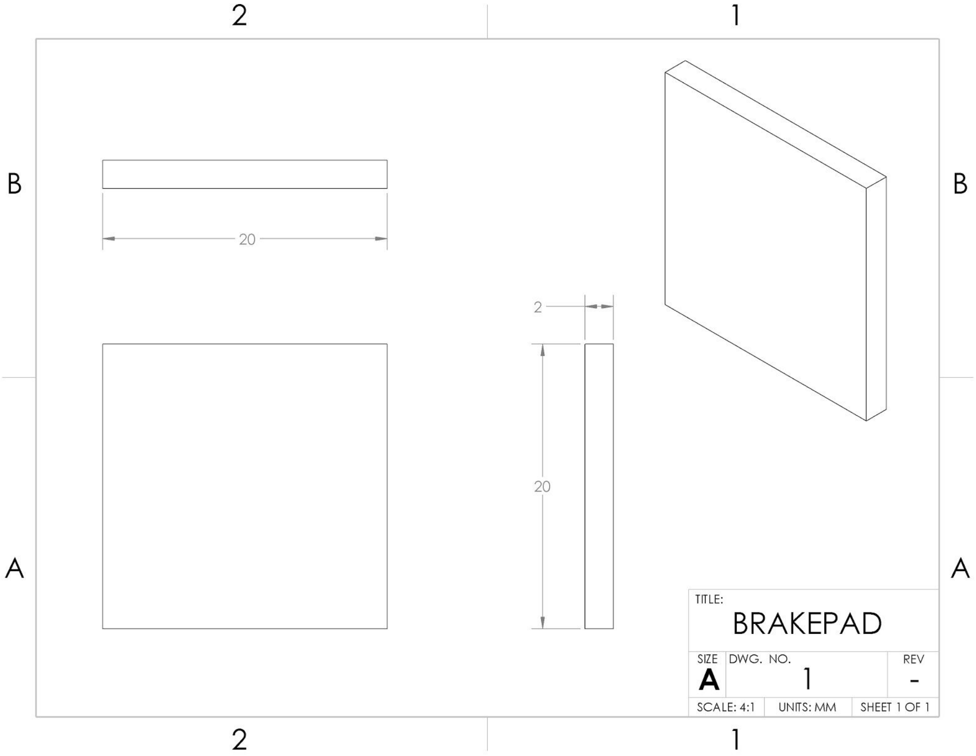

Figure 6. Engineering drawing of the brake pad

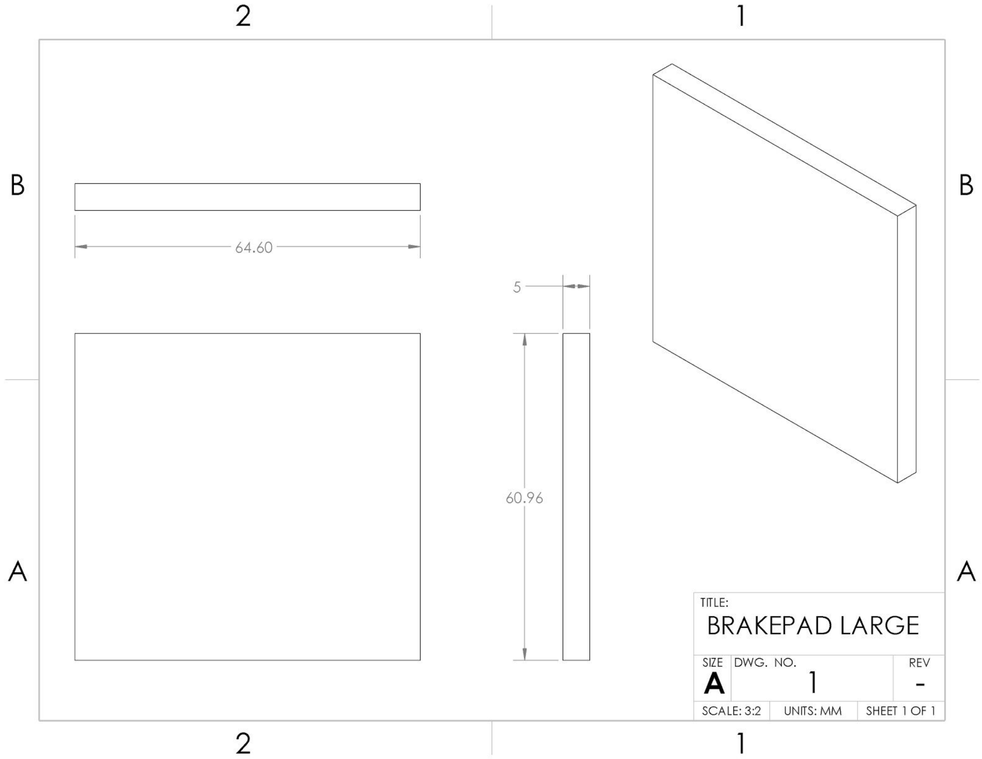

Figure 7. Engineering drawing of the large brake pad

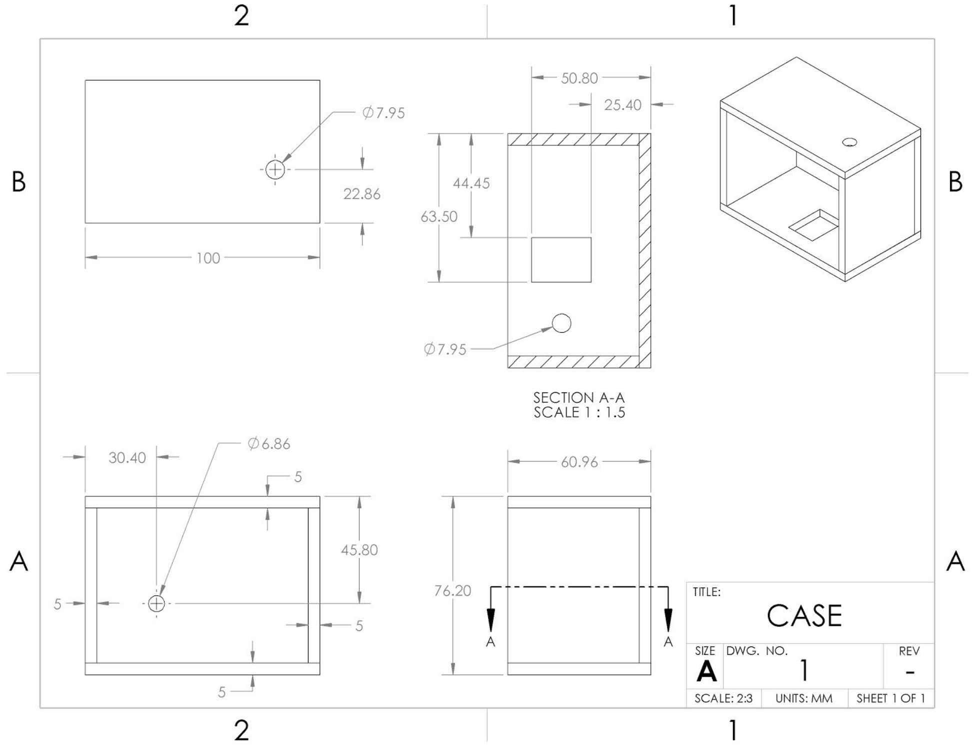

Figure 8. Engineering drawing of the case

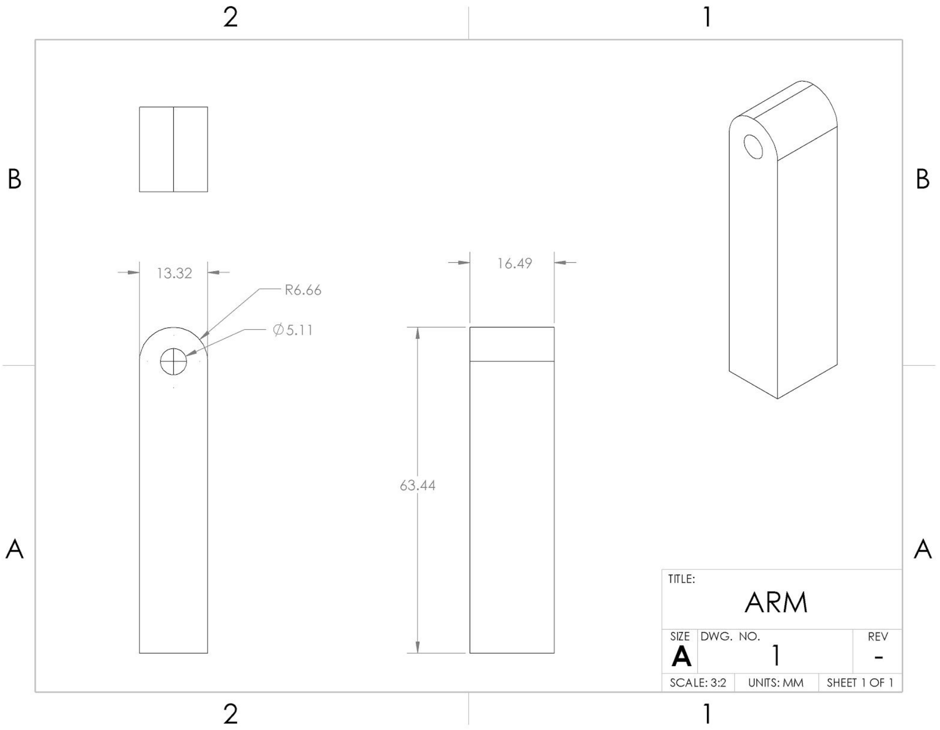

Figure 9. Engineering drawing of the arm

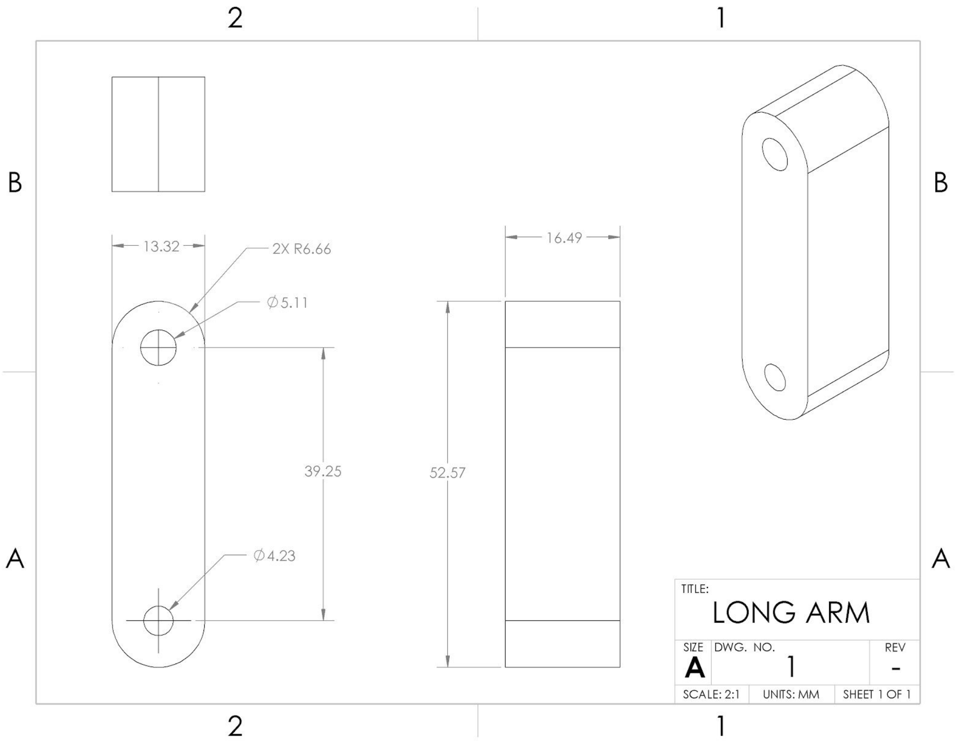

Figure 10. Engineering drawing of the long arm

Materials

Since the manufacturing shop could not be accessed, a decision was made to utilize 3D printed parts for the product instead. Although this would reduce the strength of the system, it was concluded that the parts should still be able to withstand the reduced weight of 10 lbs.

In order to increase visibility of the interior parts, clear acrylic panels were installed on the front and back side of the system. These acrylic panels were purchased online from McMaster-Carr.

Additionally, to allow easy deconstruction of the system, the case was to be put together using L-brackets. These brackets were also purchased online from McMaster-Carr.

The brake pad material, ROOS 2-Piece Self-Stick Rubber Anti-Skid Pad Furniture and Floor Protectors (Black), was purchased online. The coefficient of friction could not be determined, but it was advertised as rubber and therefore the value was assumed to be 0.76 as used in previous calculations.

Predicted Product Performance

The requirements for this modified system are as follows:

- Can handle up to 2 lbs.
- Rope must be flexible and can withstand a certain amount of dynamic load
- Descent rate of 3 feet/s
- Maximum drop height of 10 feet

Weight performance

The weight the system must be able to handle is 2 lbs. This weight is mainly held together by the bell crank, which is made out of a 3D printed part with 10% infill density. The general recommendation for functional parts is an infill density of above 20%, and therefore there was uncertainty as to whether the crucial crank part will withstand the weight. However, because it was intended to be an initial prototype, we decided to do initial testing and reprint later with a stronger infill if there are any issues.

Rope performance

The rope, which is assumed to be nylon, is flexible and therefore fits one of our requirements. To determine whether it can withstand the dynamic load from a 2 lb object, an equation for minimum breaking load for dry nylon ropes was used, where d is the diameter of the rope in meters. This equation was verified with the results we obtained for a 6 mm rope from the engineering toolbox last semester.

https://www.orcina.com/webhelp/OrcaFlex/Content/html/Ropewire,Minimumbreakingloads.htm

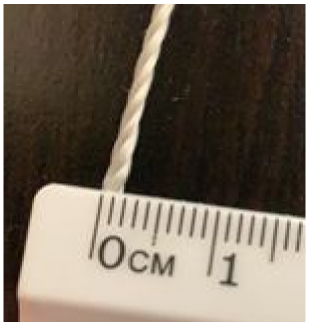

Figure 11. Rope to be used

For our rope diameter of 2 mm,

$$Minimum\ breaking\ load\ =\ 163950 \times d^2$$

$$Minimum\ breaking\ load\ =\ 163950 \times (0.002\ m)^2$$

$$Minimum\ breaking\ load\ =\ 0.65\ kN\ =\ 146\ lbf$$

Therefore, the rope can withstand up to 146 lbf. This is much higher than the weight of 2 lbs, or the expected impact force of double the weight which equals 4 lbs. Therefore, the rope we will be using is safe for the system.

Descent speed

The descent speed, which was to be controlled using a length of rope covered in lubricant, will now be adjusted by the force applied when the system is initially released so that the system will move from being kept stationary by static friction to being in motion and slowed down by kinetic friction. Therefore, more force is placed to push the system down initially, the faster the system should go. Because the force applied is adjustable, the descent speed should be easily adjustable to reach the requirement of 3 ft/s.

Test Plan

Preliminary Testing

The preliminary testing of this model was very important as it brought up many unexpected problems that we did not think of. After successful completion of the model's assembly, one of the first tests performed was to see if the bell crank lever behaves the way it should be.

Preliminary Test Case 1: *Checking bell crank lever motion*

The bell crank lever has two arms: bottom and top arm. The bottom arm is connected to the weight which causes the top arm to move linearly to the right. This motion produces friction on the rope as the top arm is compressing the rope with a brake pad. Therefore, the major requirement is that when the weight is applied and the top arm is compressing the rope, it must stay fixed in order to apply friction continuously during the descent.

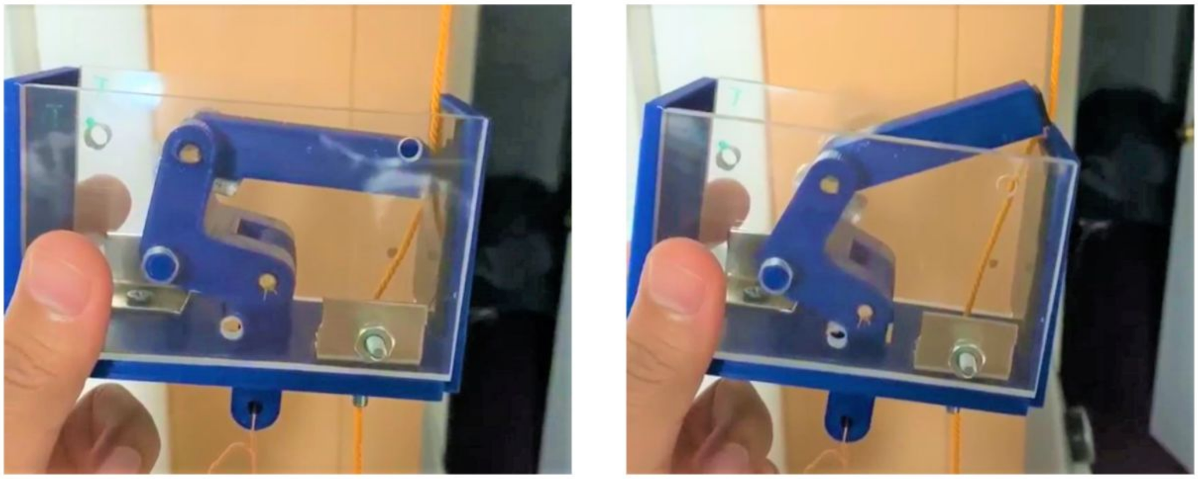

Figure 12. Top arm testing as the model descends

As we can clearly see from the testing, the top arm compressed the rope when weight was initially applied to the lever, however, as the model was slightly let go, the top arm shooted up because of the friction created by the rope itself. It was noted that the top arm is connected to the lever with a pin, and the pin allowed rotation about its axis. In order to fix this issue, we thought about how we can eliminate the rotation about the pin's rotation but this would have required intensive changes to the model's geometry. Therefore, we noticed there was plenty of spacing between the lever and the top arm **(Figure 13)**, and decided to add padding and glued the padding to the top arm. Because of the glued padding, the top arm was fixed to the lever even though there was a pin. The glued padding allowed the top to stay in place while the model descended.

Figure 13. Glued padding added to restrict top arm rotation

Preliminary Test Case 2: *Checking center of gravity*

After fixing the top arm, we decided to conduct a test where we attached a stapler to the system. However, when we let go, the system fell at free fall, but we noticed that the system titled a lot as seen below in **Figure 14**.

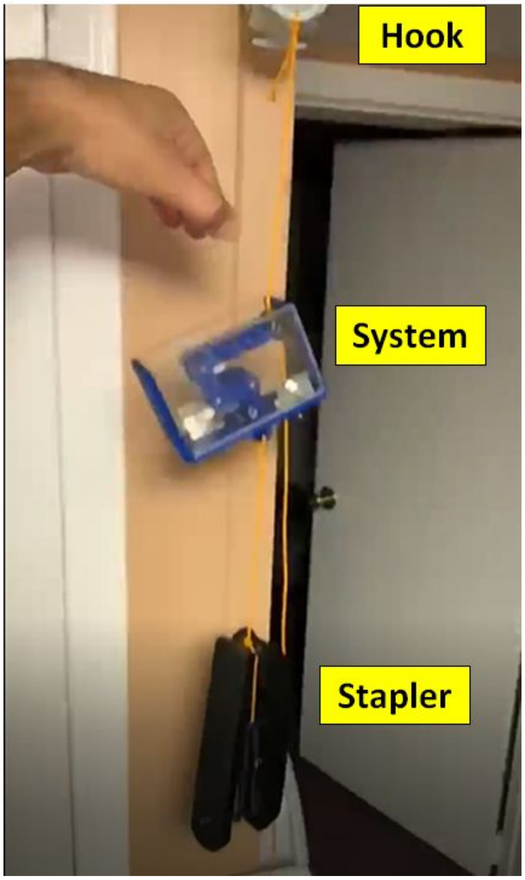

Figure 14. System tilting to the left as it descends

From this test, we observed that the braking system is not working because the system is falling at free fall speed, however, we observed that because the system is tilting to the left, it might be causing the braking system to disengage. In order to mitigate the tilting problem, we had to analyze what was causing the tilt. In **Figure 15** below, we can notice that when the combination lock was applied as the weight, it did not align with the direction of the hook. Therefore, the direction of the rope path was changed so that it aligns with the direction of the weight's force.

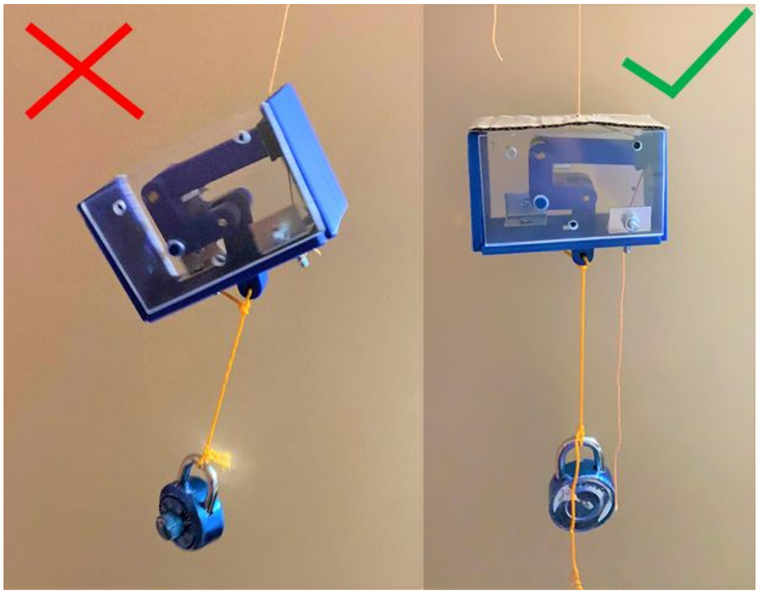

Figure 15. Tilt problem fixed by redirecting rope path

Preliminary Testing Case: Creating a permanent lock

After fixing the tilt problem, another set of testing was conducted with a combination lock weight. As can be seen from **Figure 16** below, the system does not tilt anymore, however, the system still fell at free fall speed, which meant that the braking system still was not working as expected.

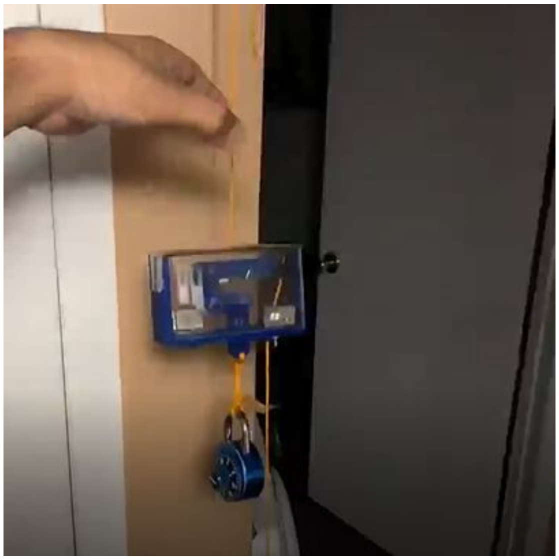

Figure 16. Non-tilted system falling at free fall

Therefore, we had to investigate more into the problem to see what was causing the braking system to disengage as the system was let go from a certain height. One of the observations we made was that as soon as we let go of the system, the weight that is connected to the bottom tends to float as if it is not even connected to the bottom arm. If, as soon as we let go of the system, the weight is floating, then the system will definitely fall at free fall speed because the braking system is disengaged. This can be seen in **Figure 17** below.

Figure 17. Weight floating as it is coming down

We observed that this was happening because the bottom arm is allowed to freely translate in multiple directions when it really should be translating in one direction: up and down. Therefore, we realized we need a permanent locking system after the weight is applied on the bottom arm so that it is not allowed to move. This would fix the weight floating problem and keep the braking system engaged. In order to think of a simple fix, we found a binder clip that fit perfectly and locked the bottom arm in place and did not allow it to move after the weight was applied.

Figure 18. Binder clip attached

This solution seemed to fix our problems as the braking system kept engaged. However, we noticed that the rope was shifting out of the brake pads due to tolerances in hole-drilling, therefore, by drilling proper holes, we were able to make sure the rope would not come out of the brake pads. Even though there was a binder clip keeping the bottom arm locked, the system was still falling down at free-fall speed because the rope would slip out of the brake pads, thus, there was no friction created. Once we re-routed the rope path properly, we noticed the braking system was engaged without major problems. With that being said, we moved into critical testing of the model.

Critical Testing

Since the model passed the preliminary testing phase, it was ready to move on to the critical testing phase. The requirements for critical testing was quite simple:

- Drop the model from an approximately 10 feet height
- Test with different weights (combination lock, stapler, water bottle, and umbrella)
- Record the time it takes to bring down the weight

In order to conduct testing, we met up at Forest Hills, NY and found a place where we can test our model. We were not able to find a spot where we can drop from 10 feet. However, we were able to drop it from a 7 feet height as shown below in **Figure 19**.

Figure 19. Drop test height of 7 feet

From this height, different weights were tested and the Test Results section of this report shows the descent speeds of all the different weights.

Test Results

The test results are summarized in the table below for a height of 7 ft.

Table 4. Critical testing results for different weights

Objects	Weight (lbs.)	Fall time (s)	Speed (ft/s)	Free Fall Speed (ft/s)
Combination lock	0.35	infinity	0	21.223
Combination lock + Stapler	1.1	120	0.0583	21.223
Water Bottle	1.2	120	0.0583	21.223
Stapler + Bottle	1.95	90	0.0778	21.223
Combination lock + Stapler + Bottle + Umbrella	2.94	120	0.0583	21.223

The descent speed is plotted against the weight:

Figure 20. Weight versus descent speed

The descent is approximately constant across all weights, which is expected of the weight-independent design. However, the system did not go down at all with the weight of the combination lock. This is likely because the impact force of the system with the combination lock being dropped is not enough to overcome the friction between the brake pads that initially keep the system at rest. This suggests that the system has a minimum weight requirement in between 0.35 lbs and 1.1 lbs. This aligns well with the initial unscaled system being designed for a minimum of 50 lbs, and the new scaled system design requirement of 1 lb.

For the remaining weights, the descent speed was all less than 0.1 ft/s, which is much lower than the intended 3 ft/s. This was something unexpected because we were hoping the system would fall at a greater speed. One possible cause of this is the lack of proper calculation done with the friction. The friction is between the brake pads and the rope itself. It is very possible that the coefficient of friction between those two materials is very high, which is causing a very slow descent.

Additionally, we noticed that as the system was going down, it was rotating very fast. We noticed this as something very unexpected but something that is a design problem. If a human being was to use a system like this, they would be spinning as they fall and could be very dizzy once they are on the ground. We observed that this was possibly due to the type of rope we are using. If the rope used is not stiff enough, the whole system would rotate. In order to verify this hypothesis, we checked if an iPhone would rotate with its charging cable.

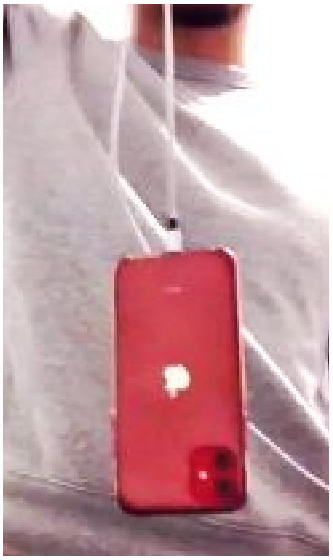

Figure 21. iPhone not rotating due to stiffer rope

As we can observe from **Figure 21** shown above, using a stiffer rope prevents rotation as the rope itself does not allow the object to rotate because of its structural properties. Therefore, this would be something that would be considered in our next steps for this project.

Next Steps

Overall, we have evidence that the model does work the way we expected to work but the descent speed is very slow mainly due to excessive friction being generated by the braking system. Below are some of the next steps we can implement to this design to see if the descent speed can be any faster:

1. **Change lever dimensions**

   It is important to notice that the bell crank lever's arms are equal in length. Therefore, whatever the force of the weight is, that force is translated into linear motion which causes the braking system to engage with brake pads compressing the rope. If the object's weight is 1 lbs, the bell crank lever translates linearly to insert a force of 1 lbf on the brake pads which is what is creating friction. Therefore, if we modify the dimensions of the lever as shown in **Figure 22** below, theoretically, we will be able to decrease friction.

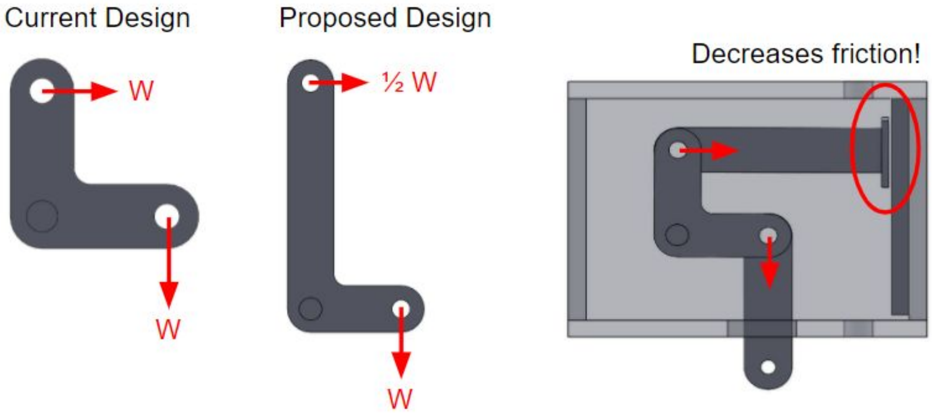

Figure 22. Proposed modification of lever dimensions to decrease friction

   As we can see, by changing the lever dimensions, the upper arm would be twice the length of the bottom arm. This would decrease the translated force in half which would end up decreasing friction and result in a faster descent. This is an iterative process which would require multiple calculations to figure out which lengths are proper to use for a faster descent. This could be done using a MATLAB code in the future. After the dimensions are calculated, the same manufacturing process will be repeated, and the same testing procedure will be implemented to investigate whether or not the descent speed is faster.

2. **Changing brake pad and rope material**

Another way to reduce friction is to change the brake pad and rope material. As of right now, we are using a nylon rope and rubber brake pads ordered from Amazon. We can use other materials which have a lower coefficient of friction, which can eventually speed up the descent rate.

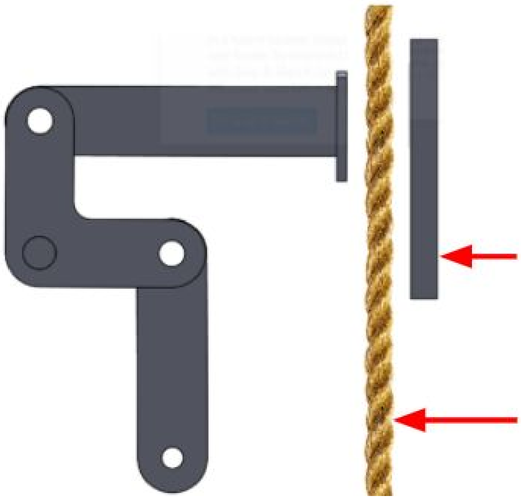

Figure 23. Changing rope and brake pad material

Similar to the last suggestion, this would also be an iterative procedure to figure out which materials would work best in terms of decreasing the coefficient of friction. The manufacturing process would remain the same and so would the testing procedure.

3. **Adding a hard brake system**

It is important to notice that because of COVID-19's impact on our project, one of the major design components left out was the hard brake system. The purpose of the hard brake system was to make sure the user remains at rest when they are about to jump out of the building. The hard-brake system would allow the user to register its weight onto the active brake system (lever) and then the user would deactivate the hard-brake system to allow controlled descent. Of course, before implementing the hard-brake system to our design, first, we would have to make sure that the active braking system is working as expected. In this project, the hard-brake system, was us holding the system at rest and then letting it drop, however, in reality, the user would just jump out, and so we need something that can keep the user at rest. This is the main purpose of the hard-brake system which is very important in our final product.