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Group A: ASME Student Design Challenge

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FL19 MEMS 411 Mechanical Engineering Design Project

2020 ASME Design Challenge

Every year the American Society of Mechanical Engineers hosts a student design competition. The competition offers ASME student members nationwide the opportunity to present their creative solutions to a variety of challenging design problems. This year's student design competition is termed "Building to the Sky." Student teams are required to build a compact engineering system capable of manufacturing a tower made of only standard-sized sheets of paper. For this challenge, we constructed a prototype paper tower machine following the rules and restrictions listed by ASME as closely as possible. We began by selecting the tower shape and how we wanted our papers to be handled. Then, we worked on automating the process by building the machine from the base of the machine to the individual components such as a paper mold and sliding base. Adjustments were made along the way, sometimes because we considered a better alternative and sometimes because the mechanism simply did not function. Finally, we were able to create a prototype that could manufacture a tall, stable tower while following most of the limitations outlined for us. The machine still needs a few improvement to be qualified for the design challenge; however, we made incredible progress to find a creative solution to a complex design challenge.

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1 Introduction

The American Society of Mechanical Engineers (ASME) hosts a student design competition annually to challenge Mechanical Engineers to put their skills and academic knowledge to test. This year, ASME wants the future engineers to design a machine that would process paper. According to the competition rules, the modeled device should be able to take in sheets of paper (A4 or letter sized) one by one in order to construct a paper tower. The device should be able to fold, cut or mechanically join sheets without the use of any solid or liquid materials like glue or tape. The device is given a maximum of 10 minutes to make the tower and the paper tower it builds is expected to stand on ground without any human support once those 10 minutes are over. The ASME competition evaluates the performance of the device based on three qualities of the paper tower, namely, Taller, Faster and Stronger. But for this course, our main focus will be to design and build a machine that can build a tallest tower in least amount of time. Hence, the goal of this project is to standout in the first two aspects of the competition.

2 Problem Understanding

2.1 Existing Devices

The following sections show several devices that are similar to the design challenge this year.

2.1.1 Existing Device #1: Paper Airplane Folding Machine

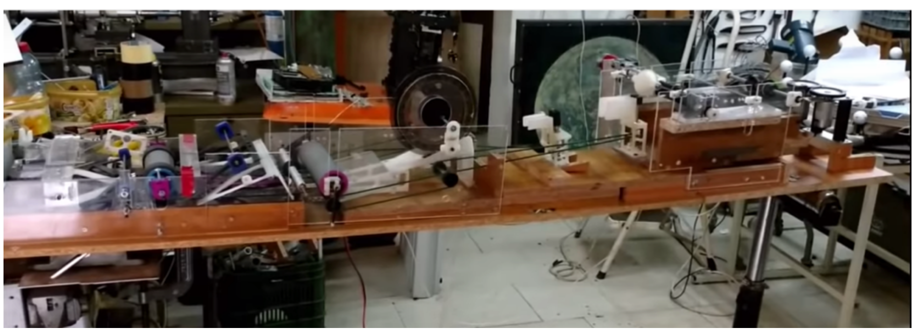


Figure 1: Paper Airplane Folding Machine (Source: Solid Smack)

Link: Paper Airplane Folding Machine
Description: This machine takes flat paper and loads it into the back tray. The paper is then rolled down the assembly line and folded by various components of the machine. The machine is autonomous and acts like a printer in the sense that it takes a sheet of paper from the top of the stack and then ran through the machine. Once the plane is finished, it is launched from the machine into the air. Once launched, the machine already works on making another airplane. The machine is made from recycled printer parts and custom 3D printed parts. It would be interesting to replicate the autonomous aspect of their machine and see how we can utilize it in our own design. It seems much easier than manually feeding the paper to the machines.

2.1.2 Existing Device #2: PAPERplus Shooter Paper Void Fill Machine

Figure 2: Paper Void Fill Machine (Source: Sales Master Corp)

Link: Paper Void Fill Machine
Description: The PAPERplus Shooter provides an economic, highly efficient design to increase production and save money and time. The paper shooter fires the crumpled paper directly into the empty box. The crimping feature provides a bulkier paper void, allowing for more mass with minimal paper use. The paper is dispensed from the center of the paper roll outward which provides a smooth and quick flow of paper. The system is powered by a foot pedal and includes a rotatable machine head and adjustable working height. The machine automatic layered paper dispensing and cutting. Is available in floor and tabletop models. The idea of crumpled paper taking up less mass but still using less paper. We may be able to replicate this idea with our design because crumpling paper means we can fill more space without using too much paper.

2.1.3 Existing Device #3: Robotic Oragami Folder

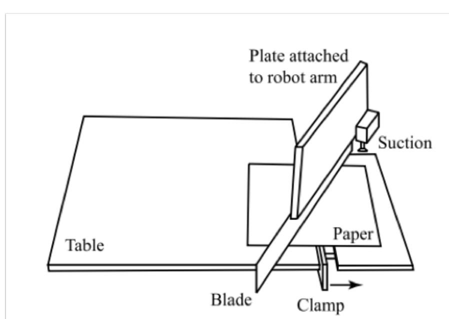


Figure 3: Paper Void Fill Machine (Source: GA Tech)

Link: Paper Void Fill Machine
Description: The paper is positioned on the table above a slot and the blade presses the paper into the slot. Friction holds the paper in the slot as the blade is removed and then the slot clamps shut forming the crease. The arm only provides one rotational degree of freedom at its wrist. The blade

sweeps across the paper and forces it to lie flat. The clamp is then released while the blade holds the paper against the table. The primary design included errors inherent in the frictional insertion of the paper into the slot. The accumulation of errors limits the number of folds that can be made reliably. However, the machine can fold a simple airplane design and a simplified fourteen-crease version of the samurai hat. Each of these designs takes about two minutes to fold.

2.2 Patents

2.2.1 Paper Feeder (US5029838A)

This is a patent for a paper feeder for a machine such as a copying machine. It includes a paper holding mechanism for holding the paper within in the paper feeding portion, a communicating mechanism for activating the paper holding mechanism in cooperation with the raising operation of the handle. We may be interested in putting a similar mechanism in the design for our machine. This would solve the issue of manually putting a sheet of paper into the mechanism and instead a single team member could pull the lever and a sheet of paper would be distributed. May need to simplify the design to accommodate total cost.

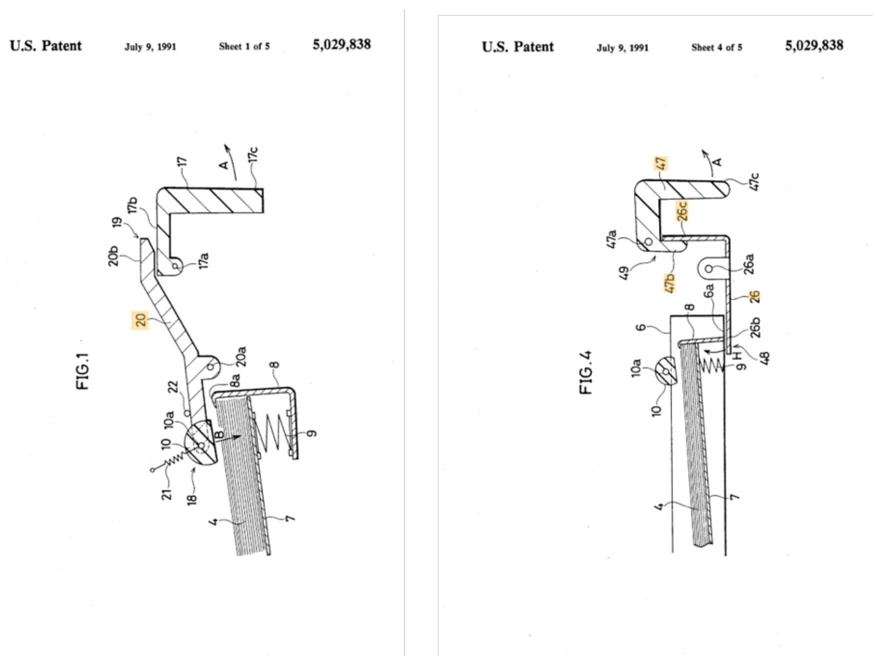


Figure 4: Patent for Paper Feeder

2.2.2 Method for Picking Up an Article Using A Robot Arm and Associated System (US9138895B2)

This patent describes a method to pick up an article using a robot arm. It also includes capturing images with a camera and processing the captured images to locate machine-readable symbol affixed to the article. The function of this is outside of the scope of our design project and a bit complex for a limited budget. The machine-readable symbol includes an orientation pattern which provides x, y and z coordinates of a gripping tool attached to the robot arm. The gripping function is appealing, but we are planning on manually choosing where to grab and eventually place the paper.

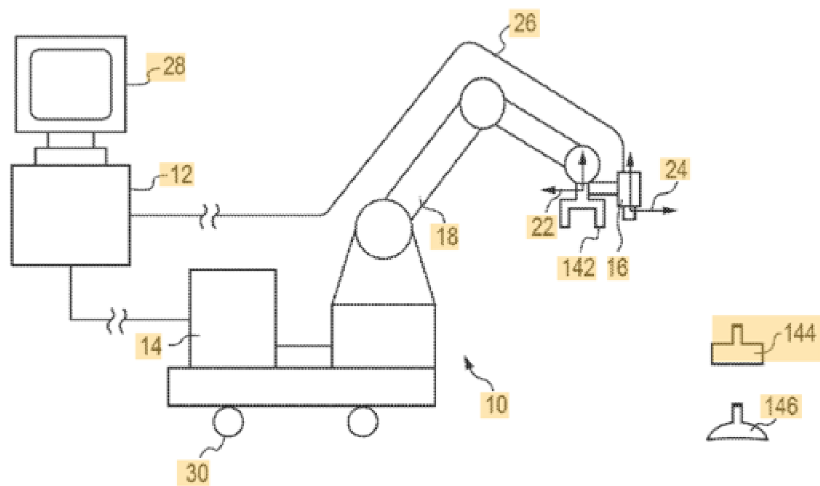


Figure 5: Patent for Method for Picking Up an Article Using A Robot Arm and Associated System

2.3 Codes & Standards

2.3.1 Electrical Standard for Industrial Machinery (NFPA 79)

This National Fire Protection Association standard sets specifications for the operation of industrial equipment. It provides the safeguard for operators, equipment and such from electrical hazards that could prove to be harmful. It also includes topics from operator interface, to wiring practices, to electrical motor safety.

2.3.2 The Industrial Robot Safety Standard (ANSI/RIA R15.06)

This American National Standard Institute and Robotics Industries Associations standard provides guidelines of creating and integrating robotic machinery, including robotic arms that could be implemented into our paper tower builder. In order to stack the papers into a tower we will need a dynamic mechanism similar such as a robotic arm in order to place the paper where we desire.

2.4 User Needs

2.4.1 Customer Interview

Interviewee: Steven Mumford
Location: Jolley Basement, Washington University in St. Louis, Danforth Campus
Date: September 6th, 2019
Setting: We discussed the basic competition rules and tried to figure out the meaning of some ambiguous statements regarding device restrictions. The customer indicated that, given the limited amount of time to complete the project, he wants the device to only fulfil two of the required aspects of paper tower performance. After this class discussion, we had an individual group question and

answer session. We then began to discuss paper tower designing strategies (using sheet of paper and making a tower by hand) in our project groups. The entire interview was conducted in the basement of Jolley, and took ∼50 min.

Interview Notes:

What are the typical uses of the device?

- For the customer to use the device in the ASME Student Design Competition in order to win it.

What are the current anticipated likes and dislikes of the product?

- The device is supposed to have arms that will use the sheets of paper to make the paper tower. We have two options: the device's arms could either be controlled using a remote controller and its functionality depends on how we move the arms during the competition or the device could be made autonomous where we could code the arms to work in a particular fashion in order to build a paper tower. The customer would really like the device to be autonomous (for easy use) but also understands that making the device autonomous is hard and therefore, leaves the option to us, the makers of the device. Hence, we would aim for an autonomous device for now but it won't be out top priority.

How easy and safe should be the functioning of the device?

- As long as the device doesn't have any unnecessary sharp or pointed edges and loose or open wires, it can be complex. University students or adults will be using the device so the functioning and structure of the device could be a bit complicated; complicated to an extent where the customer might need a demo of its usage at least once before he starts using it.

Any special requirements that the customer needs the device to meet apart from the Competition rules stated by ASME?

- The customer would like the insertion of the paper to be correct. In other words, either the insertion box of sheet of paper should be designed in such a way that the paper could only be added at 90 degree angle or if there is a possibility that the paper could be inserted at different angles, it should increase the efficiency and speed of the device.

2.4.2 Interpreted User Needs

Table 1 lists the main requirements, interpreted from our customer interview, that we need to keep in mind while we design and build this ASME Paper Tower Machine(PTM). It also ranks these interpreted requirements from 1 to 5 where 1 is least important and 5 is very important.

Table 1: Interpreted Customer Needs

Need Number	**Need**	**Importance**
1	The PTM is portable	3
2	The PTM is collapsible	4
3	The paper loading area is easy to use	5
4	The PTM doesn't exceed maximum allowed height at any point during the competition round	5
5	The PTM is safe for children	2
6	The PTM's batteries can last 10 minutes	5

2.5 Design Metrics

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	3	Dimension	cm	< 50	< 48
2	2	Total Boundary	m	2	2
3	1	PTM Maximum Height	cm	50	< 50
4	1	Tower Height Within 5 Minutes	m	> 1	> 1.5
5	1	Building Time	min	< 10	< 8

2.6 Project Management

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

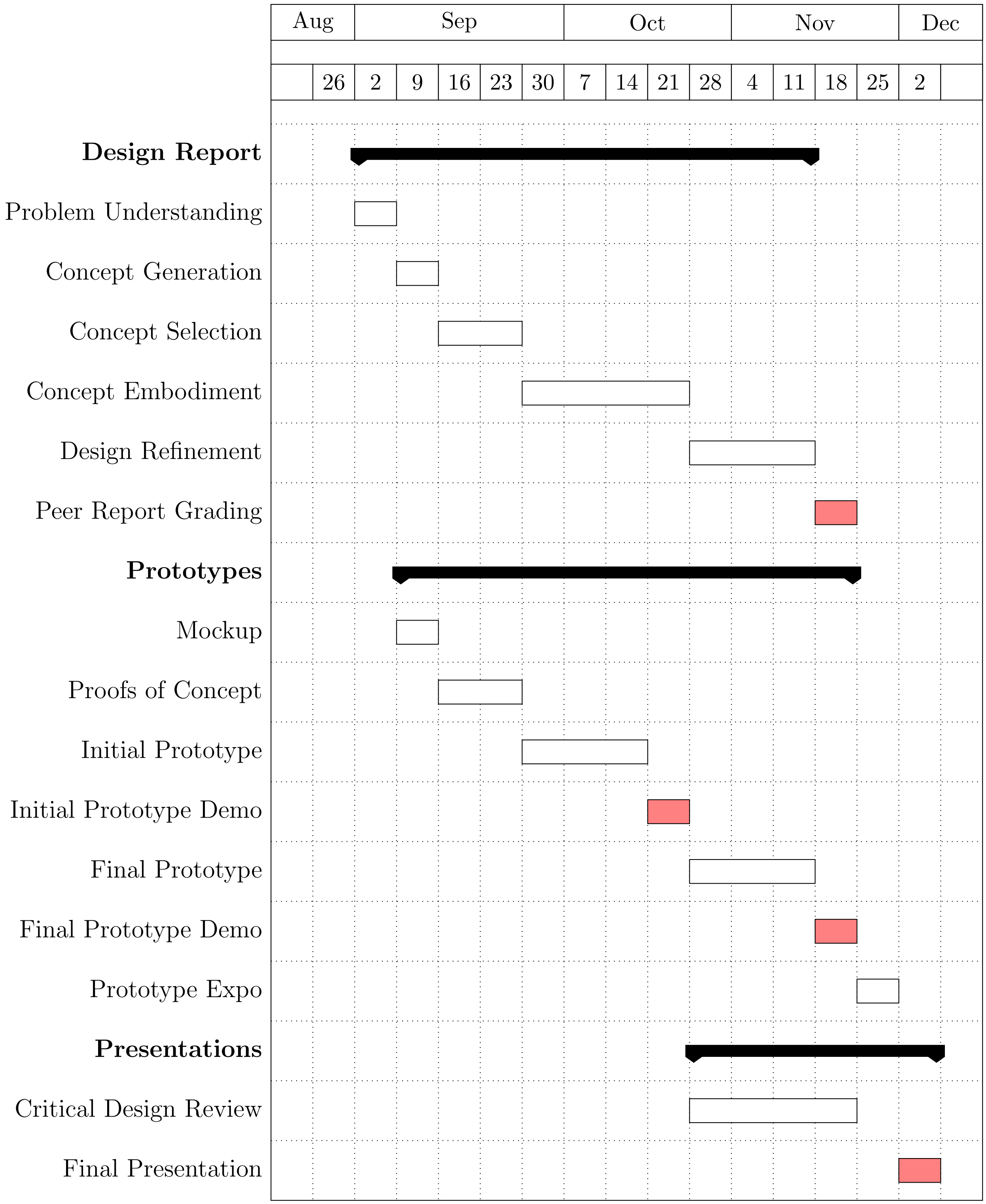


Figure 6: Gantt chart for design project

3 Concept Generation

3.1 Mockup Prototype

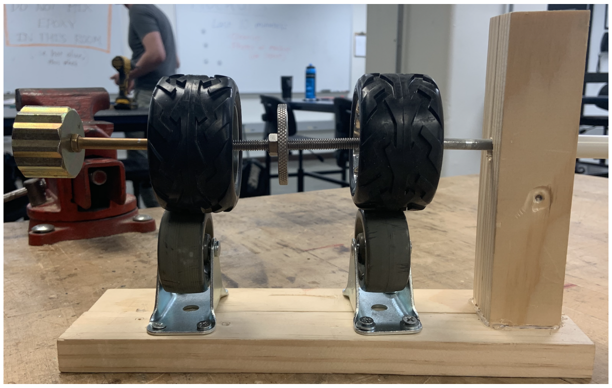


Figure 7: Photo of Mockup

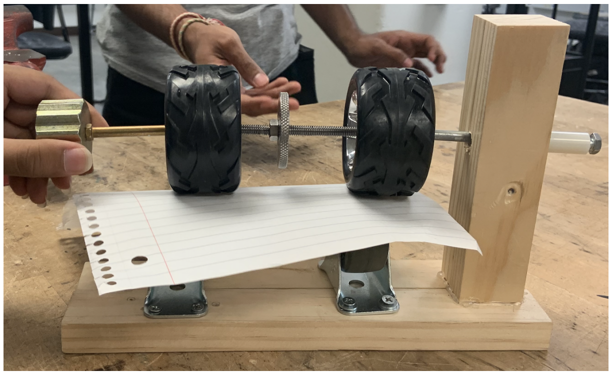


Figure 8: Photo of Mockup

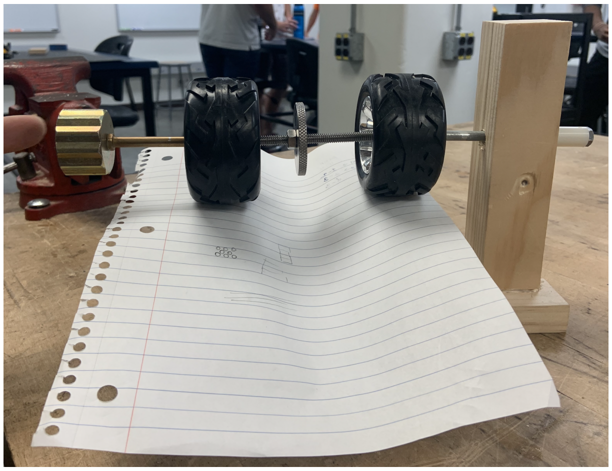


Figure 9: Photo of Mockup

Figure 1, Figure 2, and Figure 3 demonstrate our rough mock up for the initial design. This mock up represents the component of the machine that receives the paper and feeds paper into the Paper Tower Machine. The prototype includes four free spinning wheels that were adjusted perfectly to pinch and drag one sheet of paper similar to a printer or a copy machine. A wooden block is drilled and glued on the side to support the top two wheels and to keep these wheels secured. From our experience through the construction of the prototype, we found out that wheels were perfect solutions to draw around one piece of paper at a time. Also, we were able to learn that a paper-feeding mechanism, such as ours, is not a necessary part of the PTM, but is important nonetheless because of the increase in efficiency that such a mechanism can add to our machine.

3.2 Functional Decomposition

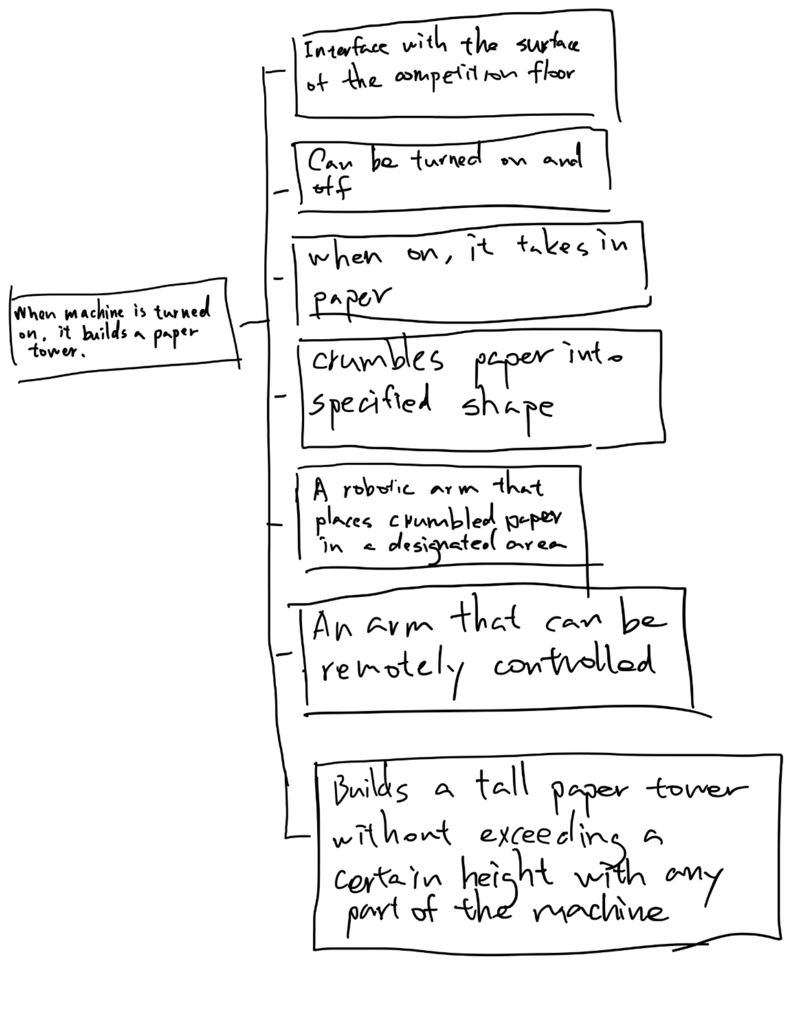


Figure 10: Function tree for Paper Tower Machine, hand-drawn and scanned

3.3 Morphological Chart

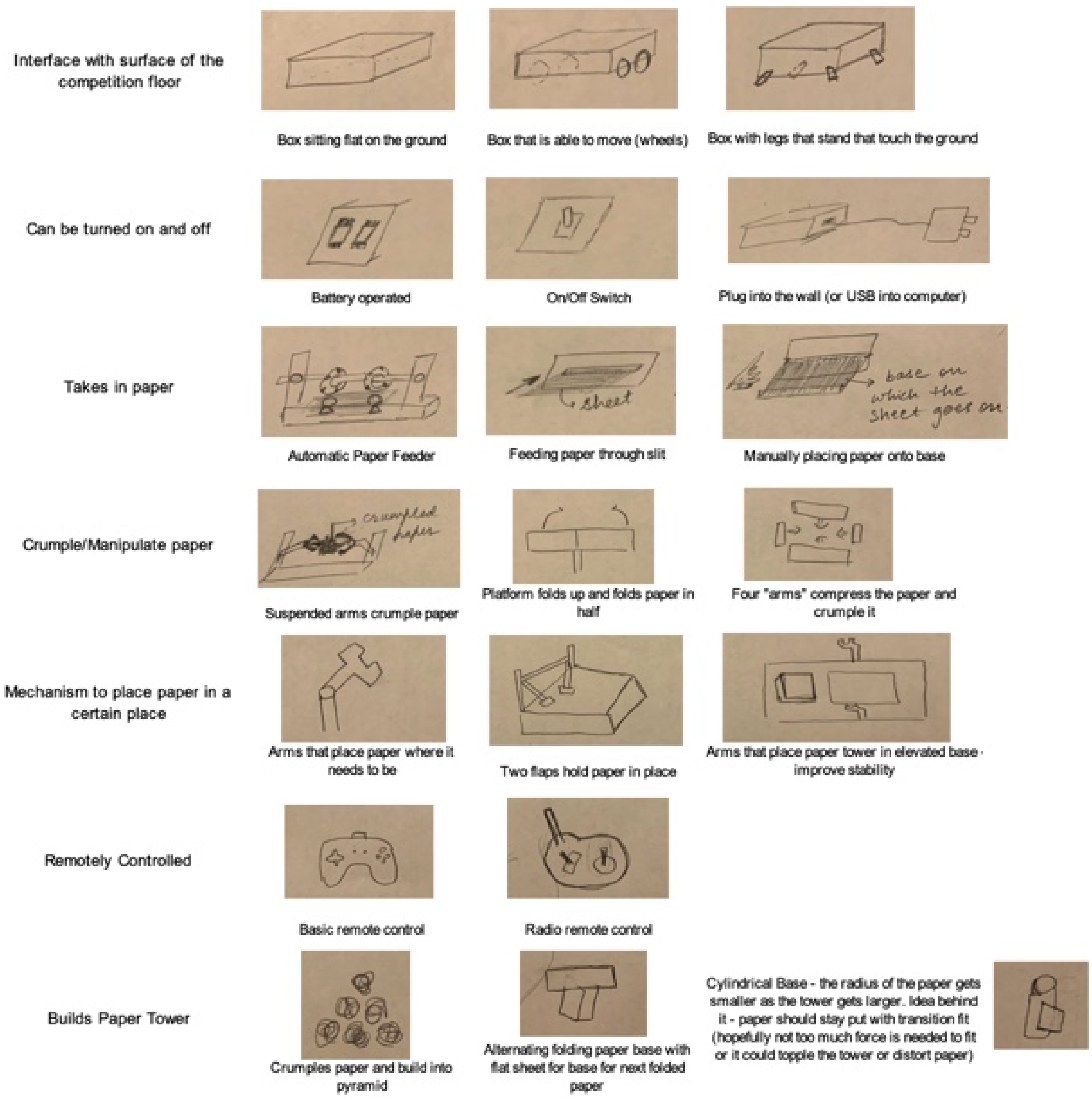


Figure 11: Morphological Chart for Paper Tower Machine

3.4 Alternative Design Concepts

3.4.1 Paper Tower Machine

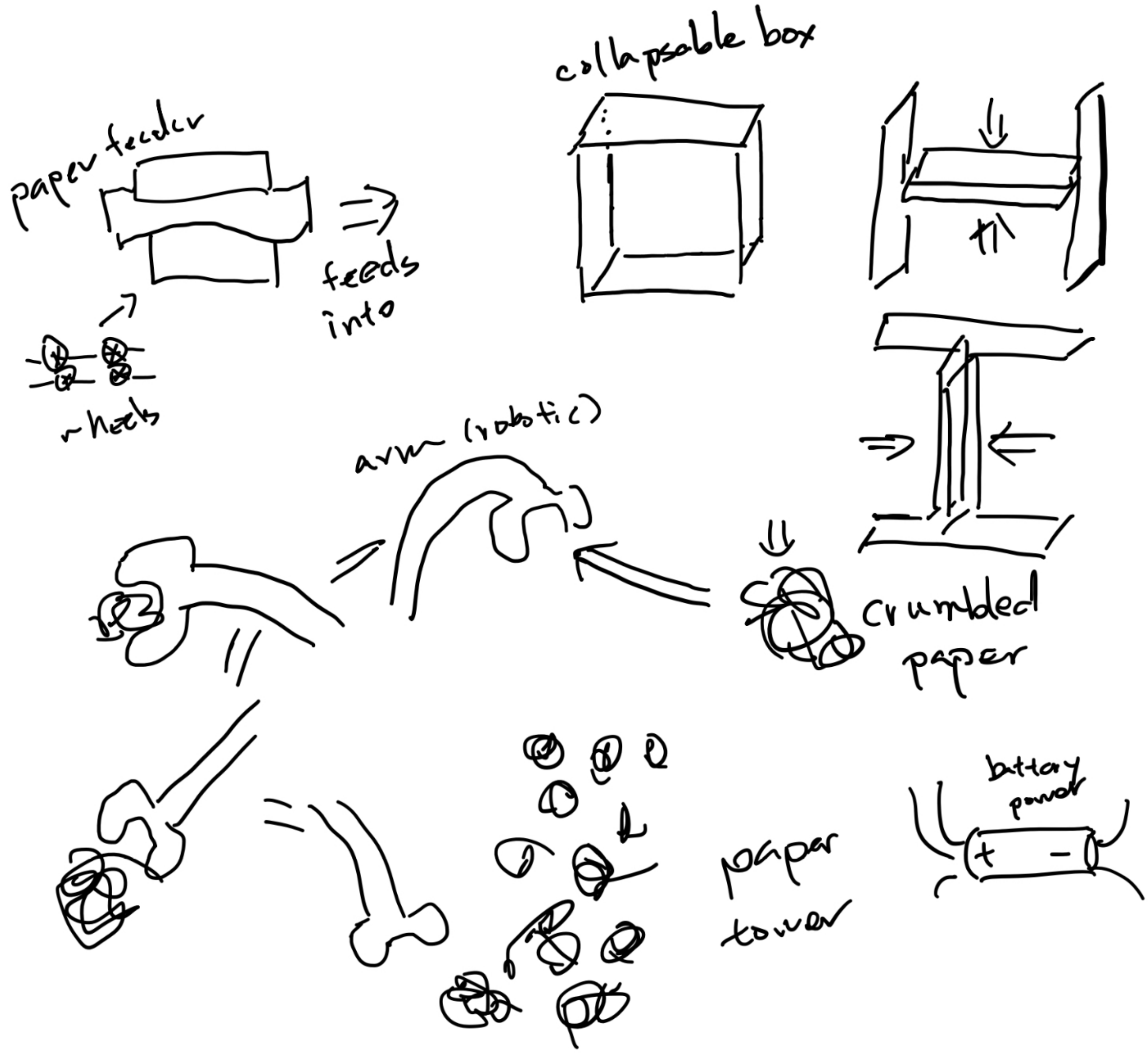


Figure 12: Preliminary sketches of Paper Tower Machine concept

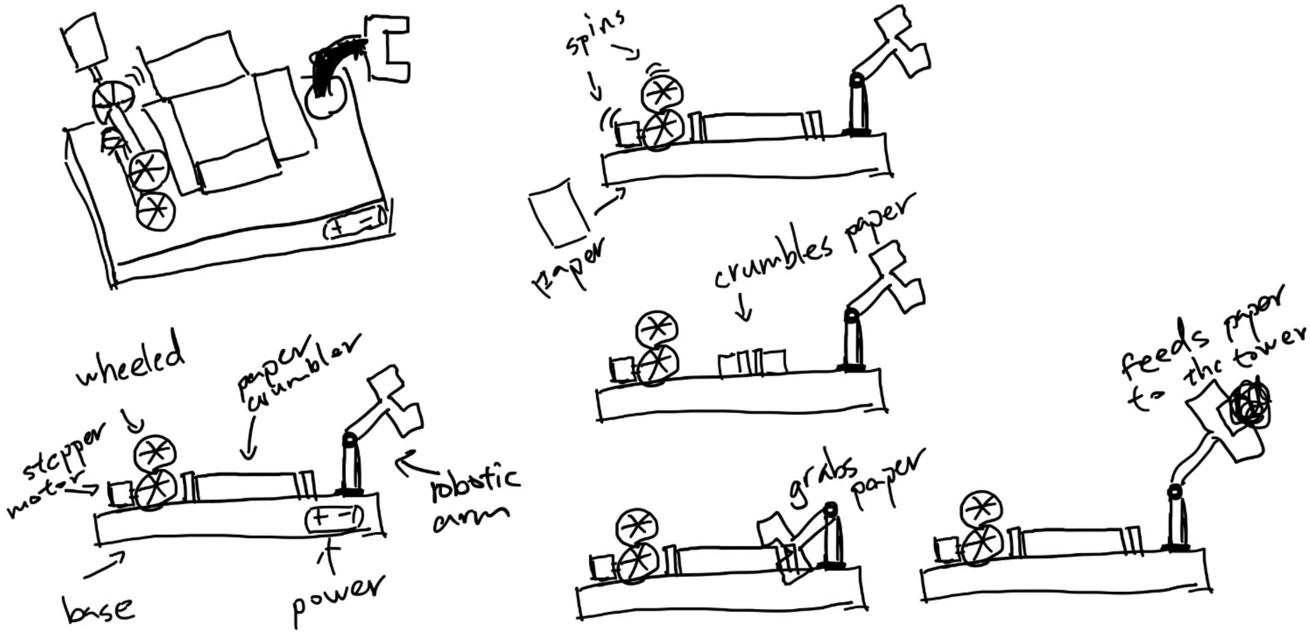


Figure 13: Final sketches of Paper Tower Machine concept

Solutions from morph chart:

1. Unit base sits on the floor
2. Battery that is removable to turn the machine on and off
3. Paper feeder that draws a piece of paper
4. Wooden walls that come together and crushes the paper into a ball
5. Robotic arm that grabs and places the crumpled paper
6. Remote that controls the arm
7. The robotic arm stuffs paper in a pile to build the tower

Description: Initially, paper would be fed into the machine. A stepper motor turning wheels would take in the paper and send the paper into the "paper crumbler." The top two wheels are joined at the center so they rotate concentrically, and the bottom two wheels mirror the top two wheels. The top wheels tightly lay on top of the bottom wheels to create a precise "drawing" motion(similar to "drawing" a card out of a deck). Once the paper is in the crumbling zone, two pieces of wood on opposite sides of each other would pinch and come together, then the other two pieces would do the same after the first two pieces have come together then returned to their original position. This motion from the machine should crumble the paper enough so that a remotely controlled robotic arm can grab the paper, and insert the paper into the paper tower that is being built. The stepper motor, paper crumbler, and the robotic arm are powered by a battery that is built into the base of the Paper Tower Machine.

3.4.2 Paper Tower Machine

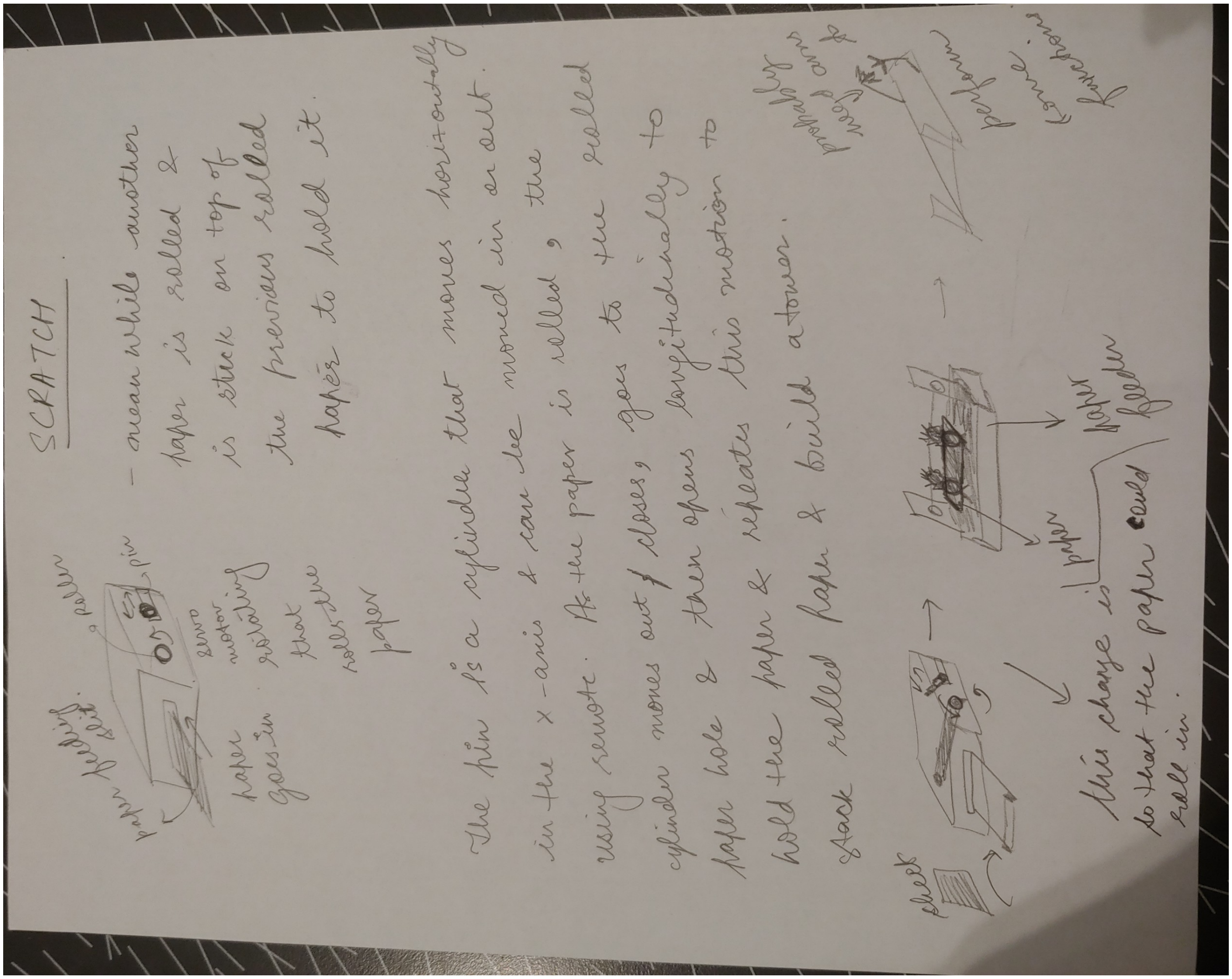


Figure 14: Preliminary sketches of Paper Tower Machine concept

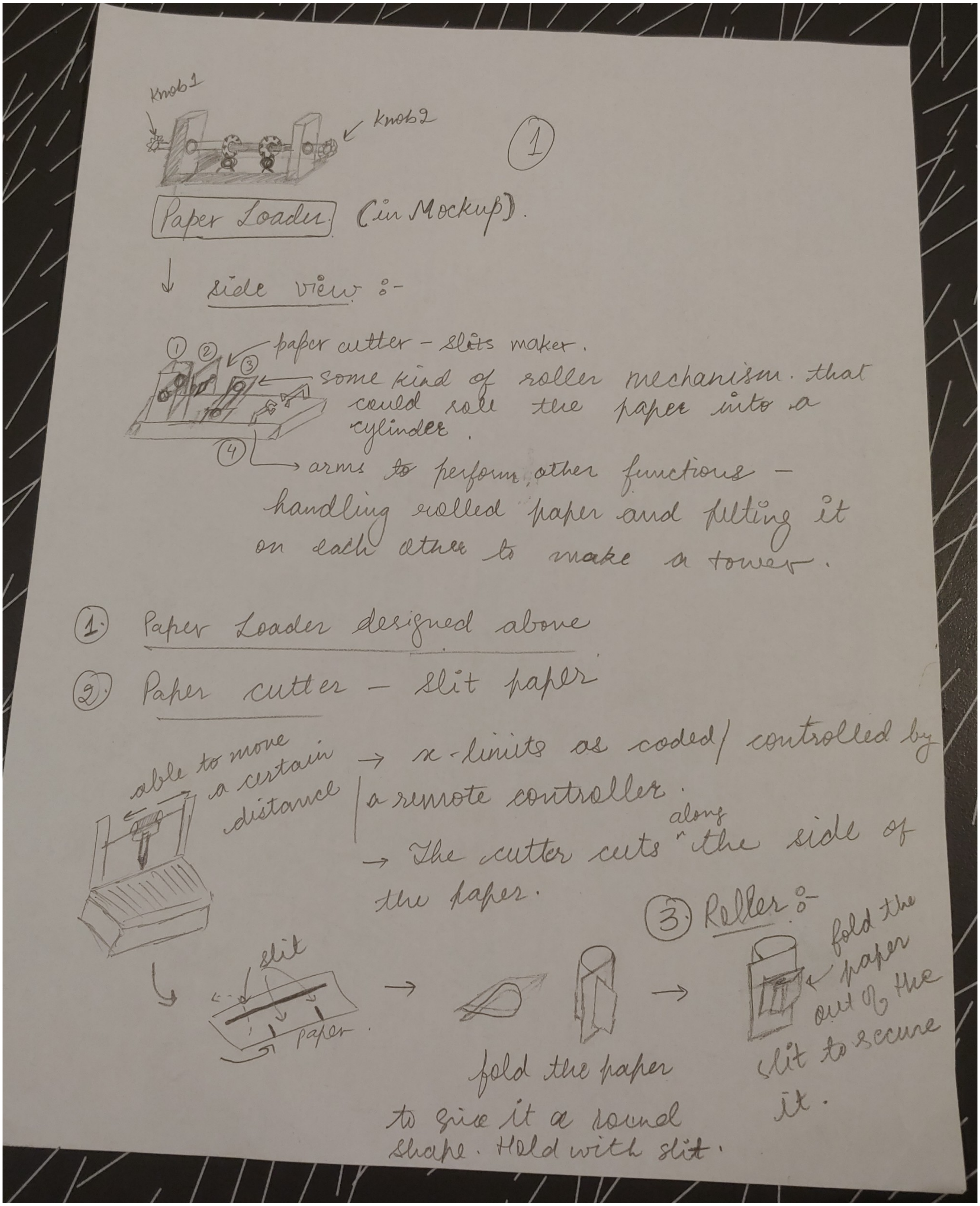


Figure 15: Final sketches of Paper Tower Machine concept - Part 1

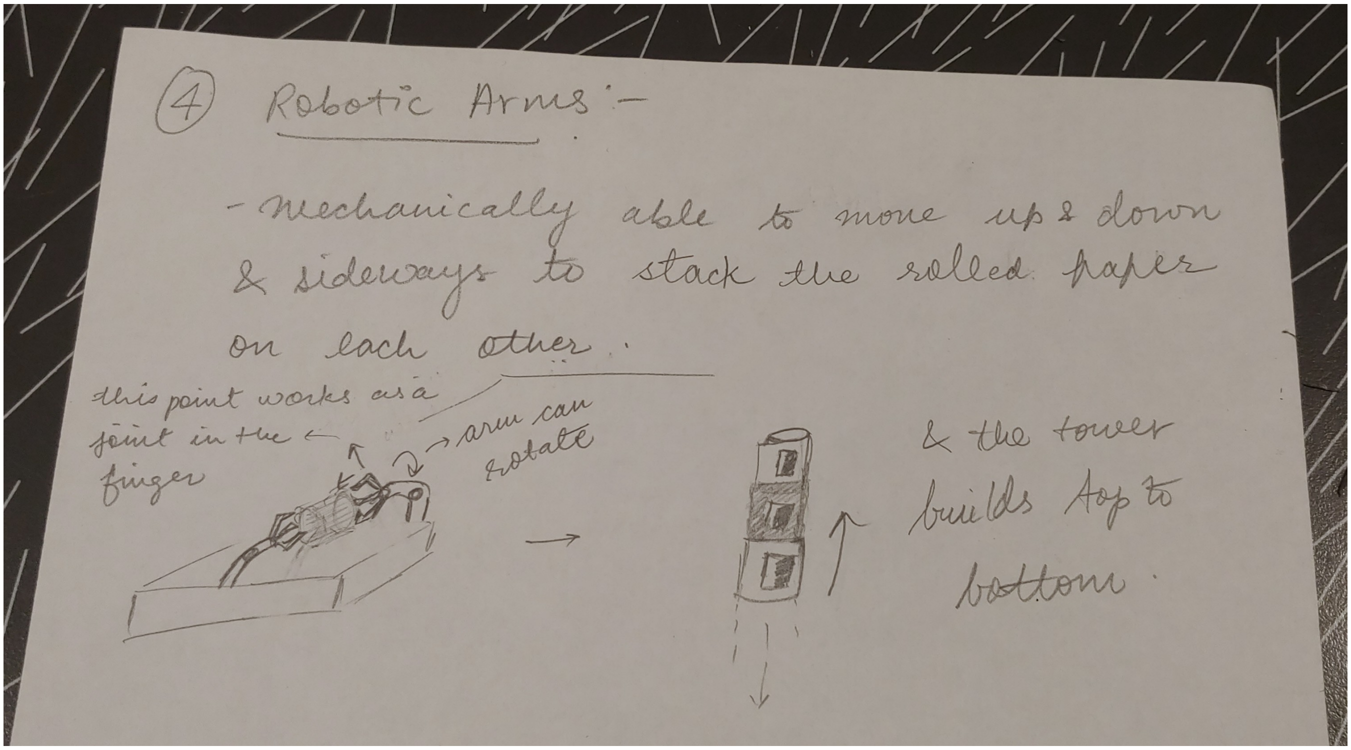


Figure 16: Cont. Final sketches of Paper Tower Machine concept - Part 2

Solutions from morph chart:

1. Machine rests on the floor since it has a firm square base
2. operated by the remote controller that turns the machine on.
3. make slits for the paper to be rolled in.
4. Robotic arm on motor; motion of arm fingers controlled by the remote.
5. fingers fold the paper coming out of the slit to hold the paper in its rolled form.
6. completely battery operated

Description:

All operations of the machine are controlled by a remote controller. As the machine is turned on, the paper feeder starts working i.e. the two servo motors one on each knob of the paper feeder starts to rotate to feed the paper in. The cutter (part 2 on the drawing) then cuts along the long side of the paper to make a slit through which the other long side of the paper can go in. The rolling and "joining" the paper is done by the Roller (part 3 on the drawing). The arms collect rolled paper and stick the rolled paper into each other to finally build a tower.

3.4.3 Paper Tower Builder

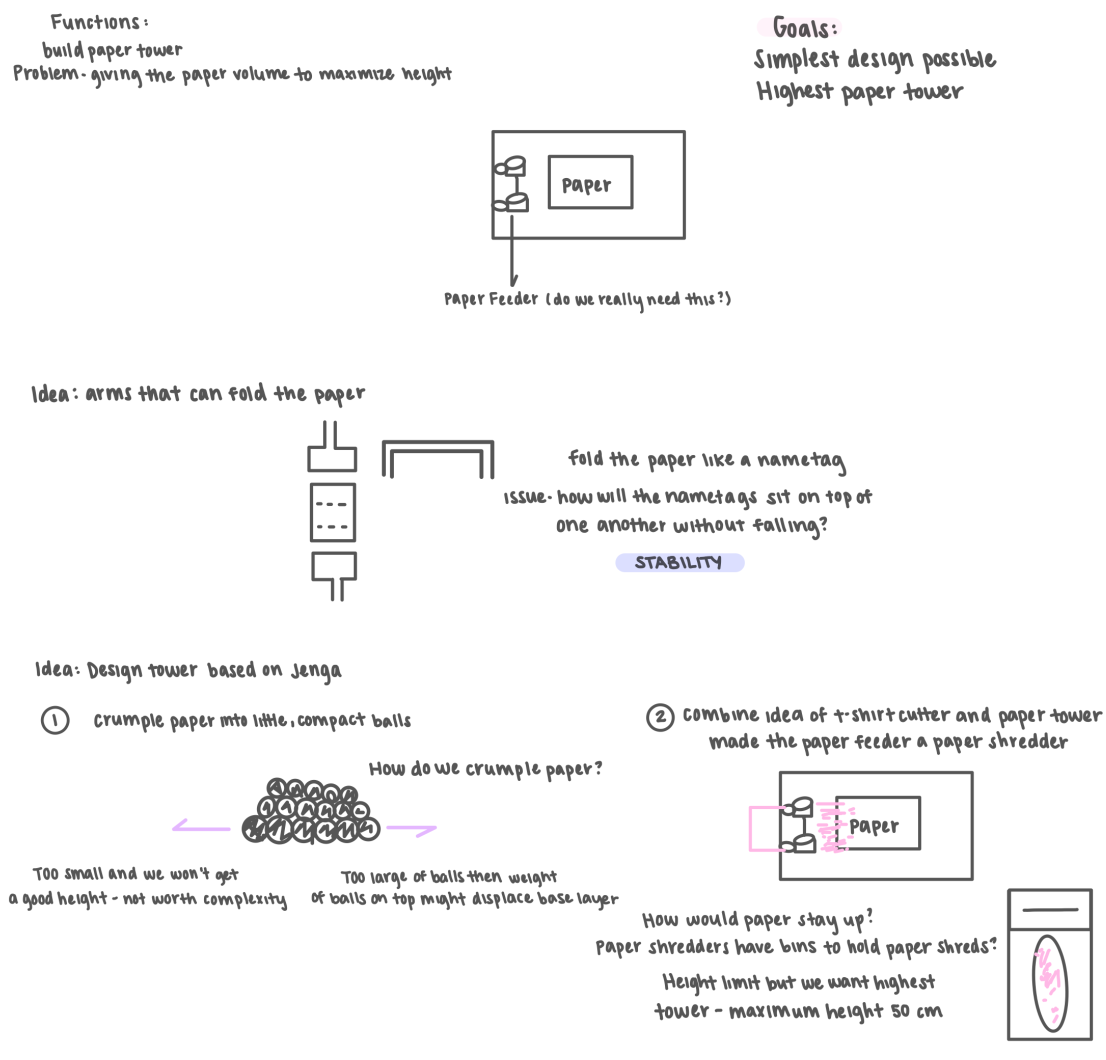


Figure 17: Preliminary sketches of Paper Tower Builder concept

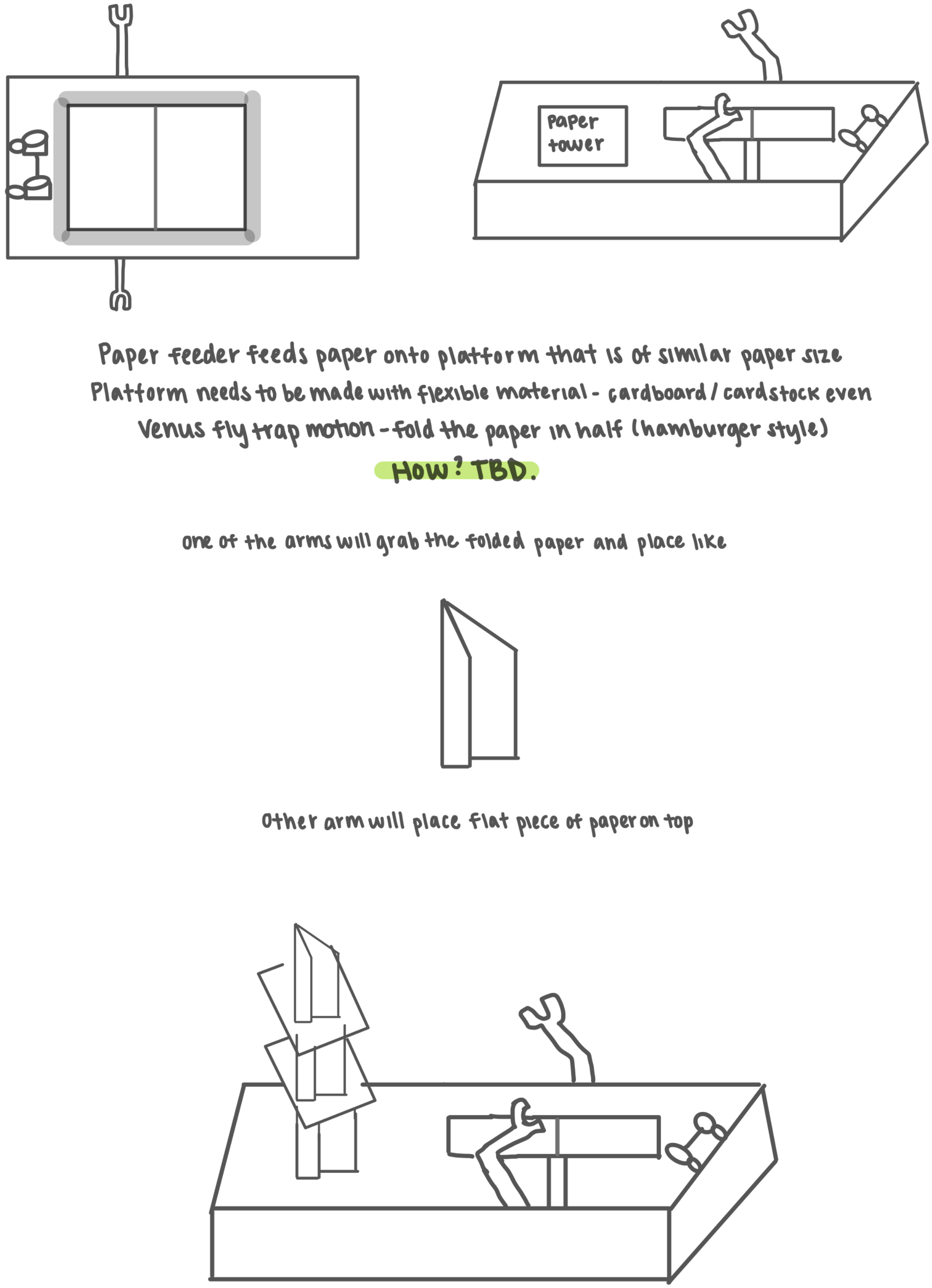


Figure 18: Final sketches of Paper Tower Builder concept

Solutions from morph chart:

1. Unit sits on floor/table
2. Arms controlled by remote controls - maybe game controller to allow for more rotational movement if not too complex
3. Includes paper feeder that places the paper onto the platform - may be more effective to hand place (for accuracy)
4. Platform is flexible and is used to fold the paper in half - could be motor operated.
5. Arms place the paper into the paper tower location - one arm places folded paper and another places a flat sheet on top. Create stable base for next folded paper.
6. Plugged into the wall or if small enough could connect to computer using USB

Description:

All operations of this machine are controlled by motors and remote controls. When the machine is turned on, the paper feeder (or hand, if design is simplified) will place the paper onto the platform. From there, a motor will control the platform to fold the paper in half. Either one side will completely fold over on the other or in a 'Venus Fly Trap' motion. The hard part about this is taking into account how much this will cause the whole mechanism to move which may disrupt the paper tower. This is why this design will sit flat on the floor rather than on wheels or stands. Hopefully this will increase the overall stability. Once the paper is folded, one of the arms will place it standing up in a designated location. Another piece of paper will be fed to the mechanism and will be placed on top of the folded paper as is by the other arm. The machine will continue from there. One of the main issues with this design is the height of the arms. Since there is a height constraint, the tower will need to be built from the bottom up in order to build a taller tower.

4 Concept Selection

4.1 Selection Criteria

From the ”weight(%)” column of the Analytic Heirarchy Process (AHP) shown in Fig. 1 below, it is inferred that the durability of batteries used and in turn, the paper folding machine is of the most importance. Hence, the batteries must last for at least a round of ten minutes, after which they can be replaced for another round. The cost of components and the ease on assembly are the second most important factors in the AHP as we are limited on money and tools available. The machine doesn’t have to move at all during the competition due to which portability isn’t an important factor for our machine. We are assuming that the machine is operated by a university student or by an adult (who knows how to use the remote control to operate the machine safely) at all times. We are also assuming that there aren’t any children present during the ASME competition. Hence, safety and usage of the machine are of extremely low importance.

	Ease on manufacturing and assembly	**Cost of components**	**Portability**	**Safe for children**	**Ease in usage**	**Durability/Battery Life**	**Row Total**	**Weight Value**	**Weight (%)**
Ease on manufacturing and assembly	**1.00**	0.33	7.00	9.00	7.00	0.11	24.44	0.21	21.18%
Cost of components	3.00	**1.00**	7.00	9.00	5.00	0.14	25.14	0.22	21.79%
Portability	0.14	0.14	**1.00**	7.00	0.33	0.11	8.73	0.08	7.57%
Safe for children	0.11	0.11	0.14	**1.00**	0.14	0.11	1.62	0.01	1.40%
Ease in usage	0.14	0.20	3.00	7.00	**1.00**	0.11	11.45	0.10	9.93%
Durability/Battery Life	9.00	7.00	9.00	9.00	9.00	**1.00**	44.00	0.38	38.13%
						Column Total:	**115.39**	**1.00**	**100%**

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

4.2 Concept Evaluation

The Weighted Scoring Matrix (WSM), shown in Fig. 2 below, evaluates our group’s four alternative design concepts for folding a sheet of paper into the desirable shape of a ”drop”. The four different design concepts evaluated in WSM are Moving Cylinder Mechanism, Conveyor Belt, Drop Mold and Robotic Arm.

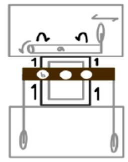
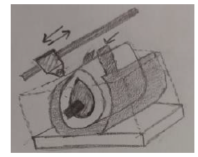
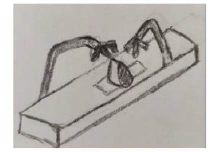
Alternative Deisgn Concepts		 *Moving Cylinder Mechanism*		 *Conveyer Belt*		 *Drop Mold*		 *Robotic Arm*	
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Ease on manufacturing and assembly	21.18%	2	0.42	3	0.64	3	0.64	5	1.06
Cost efficiency	21.79%	3	0.65	2	0.44	5	1.09	1	0.22
Portability	7.57%	3	0.23	3	0.23	4	0.30	2	0.15
Safe for children	1.40%	2	0.03	1	0.01	5	0.07	4	0.06
Ease in usage	9.93%	4	0.40	3	0.30	5	0.50	1	0.10
Durability/Battery Life	38.13%	4	1.53	3	1.14	5	1.91	2	0.76
	Total score	**3.255**		**2.754**		**4.501**		**2.346**	
	Rank	**2**		**3**		**1**		**4**	

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

4.3 Evaluation Results

According to WSM's ranking, the Drop Mold concept would work the best for a machine with battery life, ease on manufacturing and assembly and cost efficiency as its most important design and building criterion. The winning concept is discussed in comparison to other concepts in detail below.

4.3.1 Concept Comparison

Drop Mold design concept is ranked on top in the Weighted Scoring Matrix (WSM) shown in Fig. 2 above. As the AHP shows that battery life, ease on manufacturing and cost efficiency are the most prioritized criterion, the Drop mold design concept takes into account all three user requirements. It is rated 5 for battery life because only the wheels need to be in action to move the paper ahead in the mold. This is easier than keeping a robotic arm or a combination of wheels and conveyor belt or a rod moving up and down continuously in action with same output performance for ten minutes. Even though the moving cylinder Mechanism have comparatively high rates for portability and ease in usage, these criterion aren't vital to achieve the end result or the intimate goal of this part of the machine which is produce drop shaped sheets of paper attached to one another. The movement of the staple-less stapler is also fairly easy in the drop mold concept.

4.3.2 Component details of the winning concept: Drop Mold

Figure 3 gives a drawing of the paper folding part of the machine with labelled components. Part 1 in the fig. 3 is a simple square base of 50X50 centimeters from the bottom and has a round cut on the top surface, labelled as part 2. This surface is "cut out of the square box" in such a way that it matches our desired shape of paper. Part 3, attached to only one side surface of the box, is a 3-D printed drop-shaped piece. The distance between parts 2 and 3 is just enough to slide in 2 sheets of paper. Part 4 is a staple-less stapler that moves to-and-fro along the length of the machine on a rod labelled as part 5. Part 6 consists of two small extended pieces of part 2 to give direction to both the ends of paper. The Paper is inserted from one side of part 6, the paper follows the drop-shaped path available, and comes out of the other side. The staple-less stapler is then made to move on the rod to staple the sheet at-least twice to secure it properly. The paper is pushed sideways to allow next sheet of paper inside the drop mold and to secure it to the previous sheet.

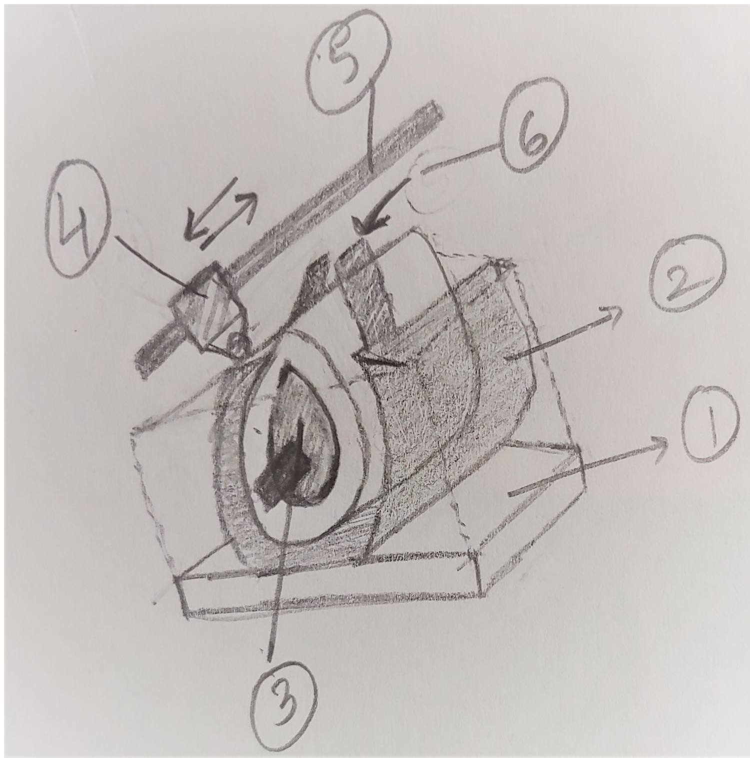


Figure 21: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.4 Engineering Models/Relationships

4.4.1 Stability

As you can see in Fig.22, there is a general relationship between the size of the base and the maximum height to maintain safety.

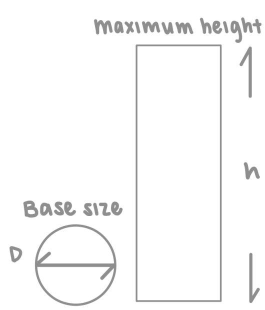


Figure 22: Physics behind Stability

The stability of our tower depends on the diameter of our base. In general, a safe height for the tower will be 3x the diameter of the base. In this case, it'd be easier if we had a set height that we could use to calculate the needed diameter. The shape of the base is not necessarily a perfect circle, so we will have to account this into the calculation for an ideal base size. But we want to make a tower that stands on its own and is ultimately safe so we will keep this relationship in mind as we continue.

4.4.2 Paper Folding

Figure 23 shows an example of a paper grabbing and folding mechanism that we would like to emulate. The printer pulls the paper through the device and it utilizes rollers to flip it and push it out to the tray.

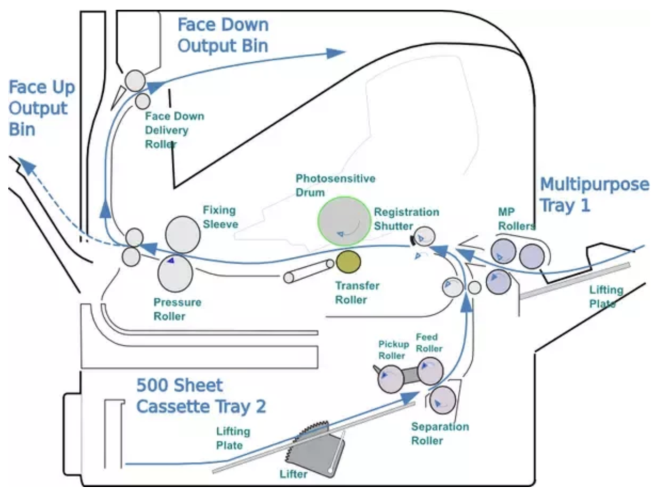


Figure 23: Paper Folding Models[1]

We'd like to replicate this design as we think of a way to get the paper to roll around the circular rod that will create the diameter of the base. We are thinking of simplifying this mechanism but still using rollers to lift the paper up and around the pipe in order to fold and "staple" it.

4.4.3 Friction Feeder

Figure 24 is a Friction Feeder commonly used in the printing industry that involve conveyor transport of paper. Our rolled paper requires a system that can feed the paper tube down stream to be stapled and we could implement this method.

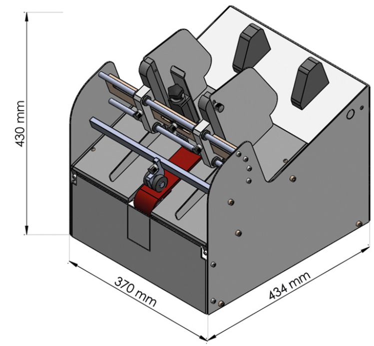


Figure 24: Friction Feeder[2]

The Feeder can displace paper but does not require access to both sides of the paper. One side of our paper will still be wrapped around a tube so, if we want to continue adding paper, a feeder idea such as this one can come in handy.

1. "What Mechanism Inside Printers Make it Pick the Paper Sheet on the Top Correctly from a Stack of Papers?" *Quora*. Accessed at: https://www.quora.com/What-mechanism-inside-printers-makes-it-pick-the-paper-sheet-on-the-top-correctly-from-a-stack-of-papers

2. Savema Friction Feeder (SVM 100-A1) *Savema*. Accessed at: http://www.savema.com.tr/en/urun/en/47_friction-feeder--svm-100-a1-

5 Concept Embodiment

5.1 Initial Embodiment

The following figures are the top/right/side views, isometric view, and the bill of materials of the initial design. The image is also rotated and includes the basic dimensions of the design.

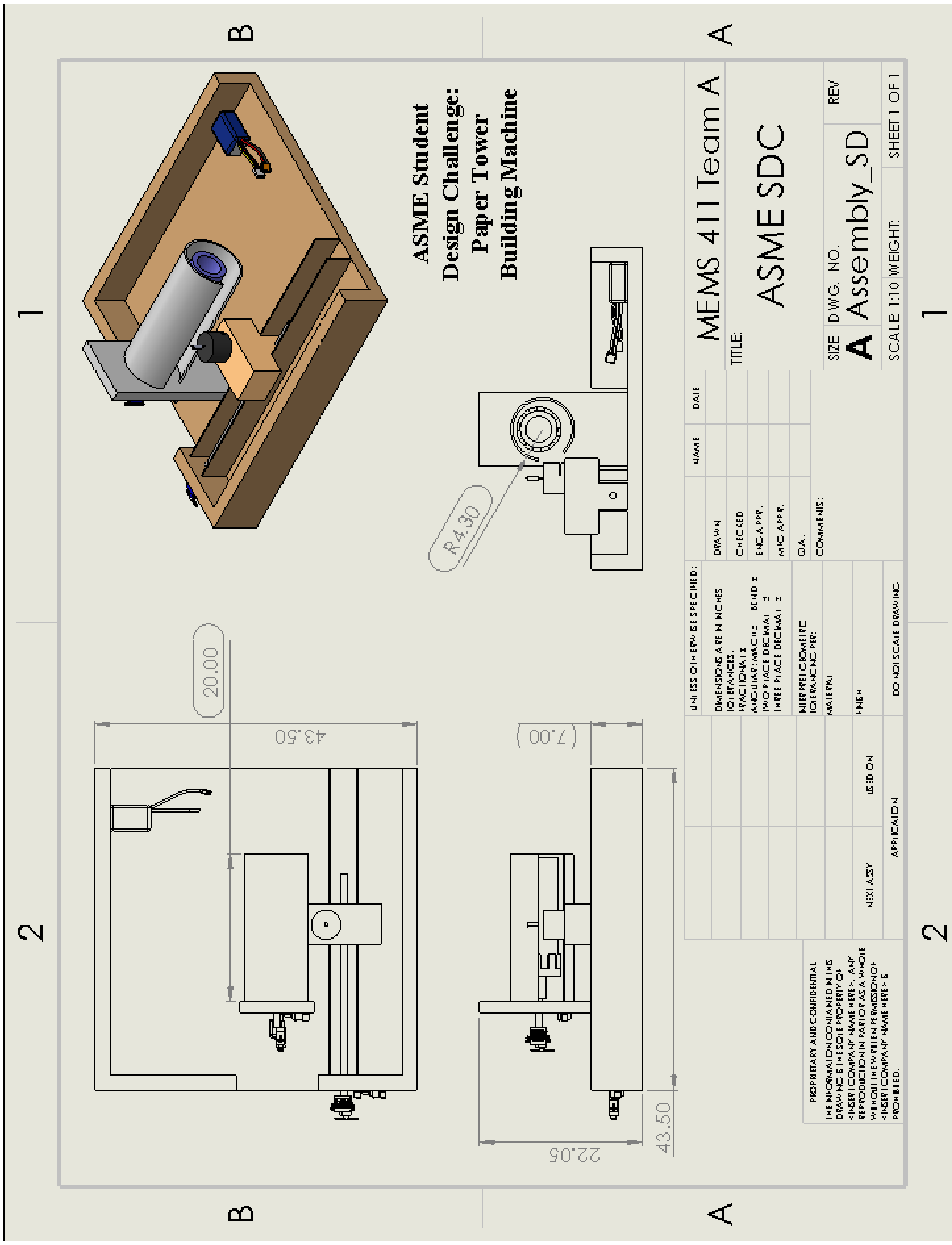


Figure 25: Assembled projected views with overall dimensions

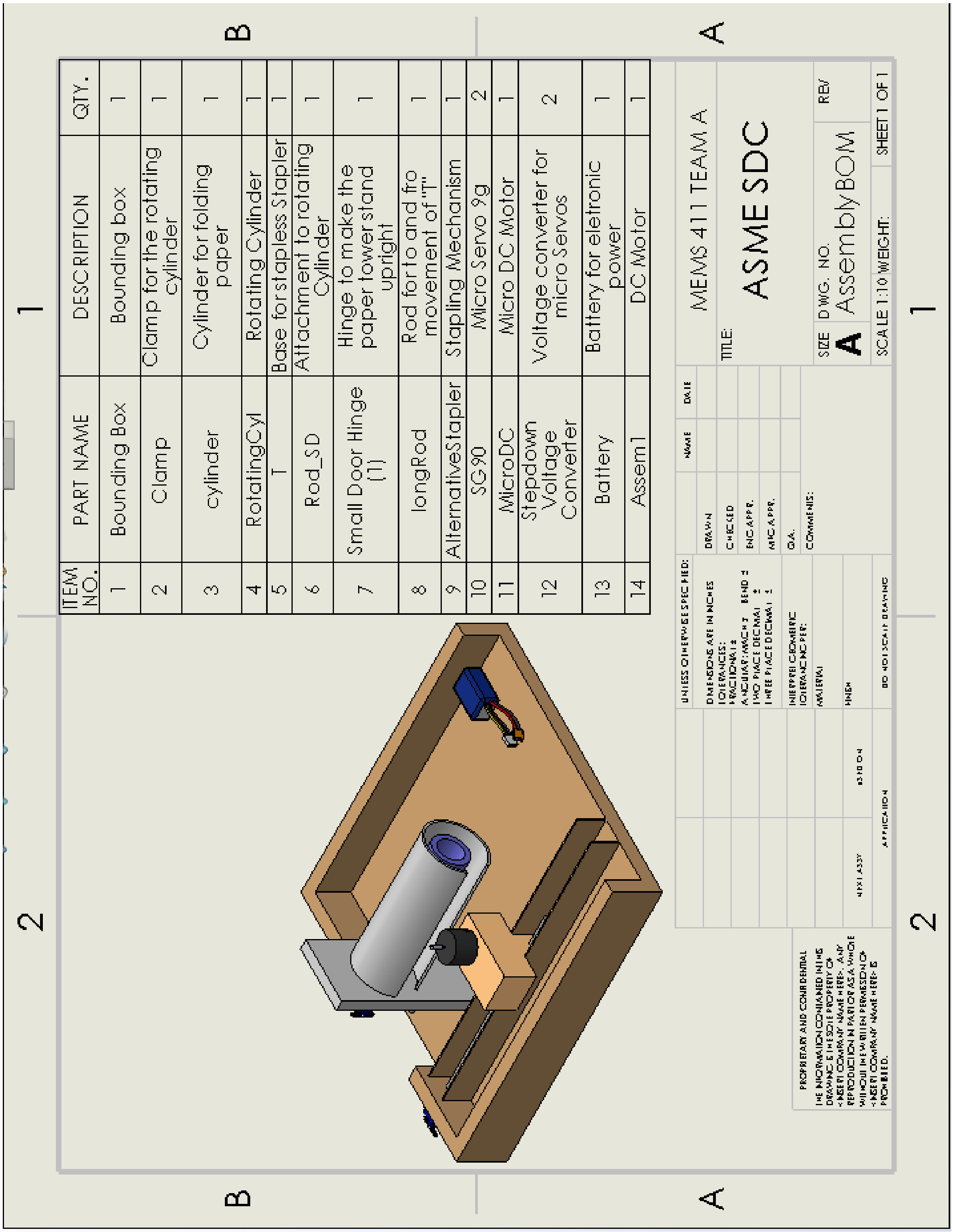


Figure 26: Assembled isometric view with bill of materials (BOM)

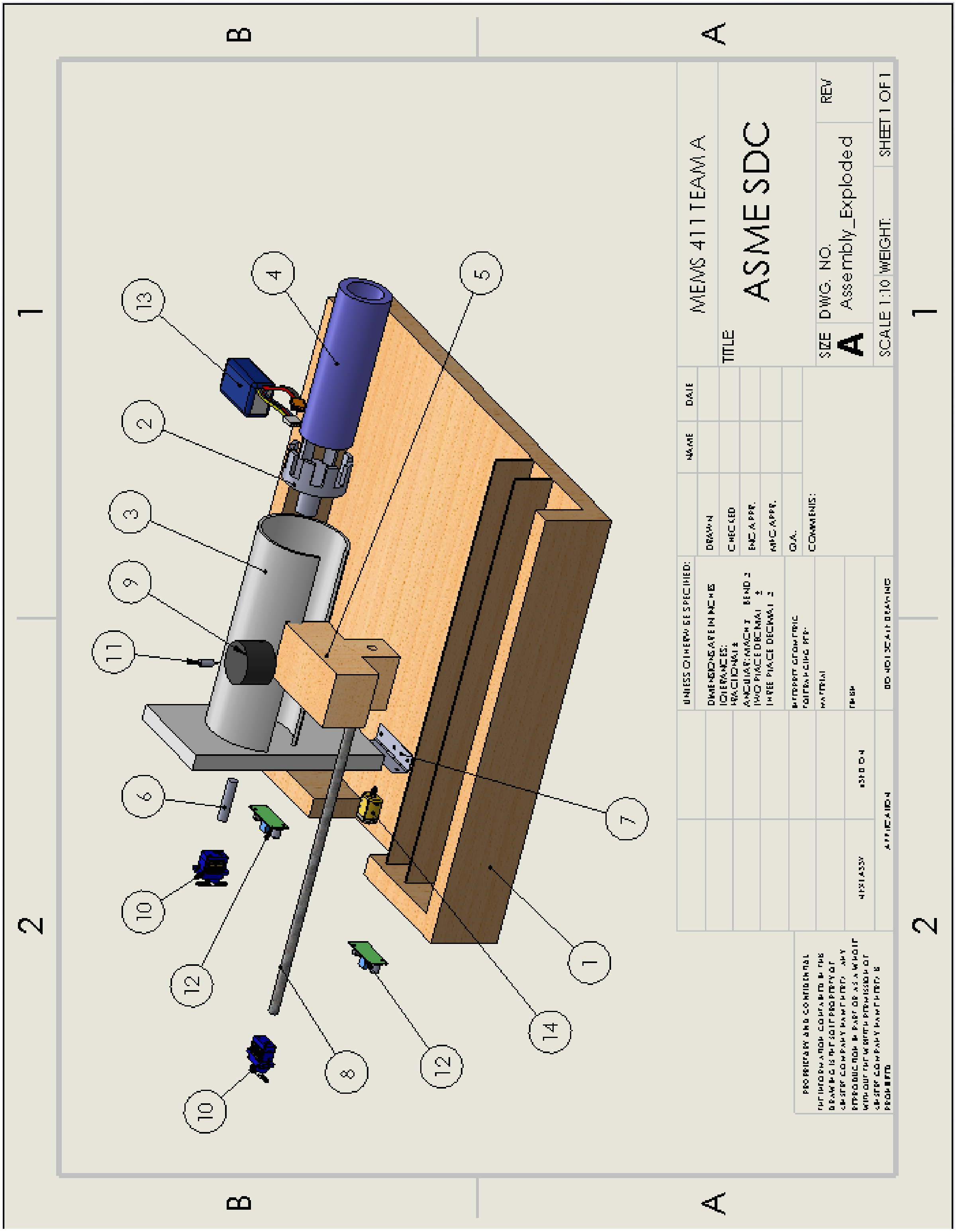


Figure 27: Exploded view with callout to BOM

5.2 Design Rationale for Initial Prototype Components

5.2.1 Shape of Base

Our main priority for the prototype was to create a reliable, relatively cheap design in case it didn't end up working out. We found the blue, 3D printed cylinder, which you can see in Fig. 29, in the Jolley basement. While testing it out, we realized that we would need the diameter to be larger than the diameter of the 3D printed cylinder but still have enough room to "staple" the sheets together. We found a PVC pipe with an outer radius of 8.6 cm and cut a slit into it large enough for the paper to get in and out. After feeding the paper through and lining the ends of the paper up, we get an average diameter of 6.1 cm. Based on the stability equation we brought up in Section 4, we could only yield a tower of 18 cm. However, we found that the teardrop shape diameter is stable for a tower >50 cm. We believe that for the shape of our base, an average diameter of 6.1 cm will be able to sustain a taller tower as well.

5.2.2 Material of Paper Feeding Mechanism

We used the basic idea of the paper folding mechanism that we outlined in Fig. 23 to create out paper feeding mechanism. Rather than creating two smaller cylinders that would rotate and push the paper through, we included one larger cylinder that rotates and guides the paper through the other housing unit. We took the friction feeder into account when we decided to use the PVC piping. We were originally using a cardboard tube but soon realized that the paper got stuck on the material irregularities located on the inside of the housing. The pipe reduced the friction between the paper and the wall of the housing which ensures a smoother path for the paper.

5.2.3 Stapler Track

Originally, we wanted to have our stapler on a rod that would move to a desired location and "staple" the sheets of paper. We soon discovered how difficult it'd be to determine ideal stapling locations. We also planned on the mechanism being completely autonomous. We changed this plan because we discovered that there are many sources of error that can occur during these processes. For example, we would need both sides of the paper to simultaneously and perfectly slide into the mouth of the stapler. Before the demo, we tried to build a tower with this method while speeding up the process to see how this would look like in real time while automated. The off-centered stapled sheets affected the stability of our tower even before 50 cm was reached. Instead, we are now manually moving the stapler mechanism. Therefore, we will be able to determine an appropriate placement for a "staple" and allow us more control over the tower if things start to go wrong.

5.3 Prototype Performance Goals

- Fits inside 50 x 50 x 50 cm "bounding box."
- Can make 50 cm-long connected paper tower in less than or equal to 5 minutes.
- Can rotate tower uprights, stays up without support.

Two of our performance goals were met during the initial demonstration. We fit the bulk of the mechanism within the 50 x 50 x 50 cm bounding box and our design could build a 50-cm long connected paper tower. However, we were unable to rotate the tower upright. While we are adding an additional mechanism to erect the paper tower, we hope to also automate the process within the next few weeks.

5.4 Proofs-of-Concept

The three figures below show our proof-of-concept prototype. The initial goal for our group was to come up with a feasible paper shape that could make a sturdy tower. We started with the idea of cones, but soon found that it would be too difficult and tedious to create that shape. We also considered boxes, jig saw, and ”one-fold” but these ideas were also not plausible. We finally agreed on a ”teardrop” shape because it has a large enough diameter to provide a sturdy base and is relatively easy to create as you can see in Fig.30.

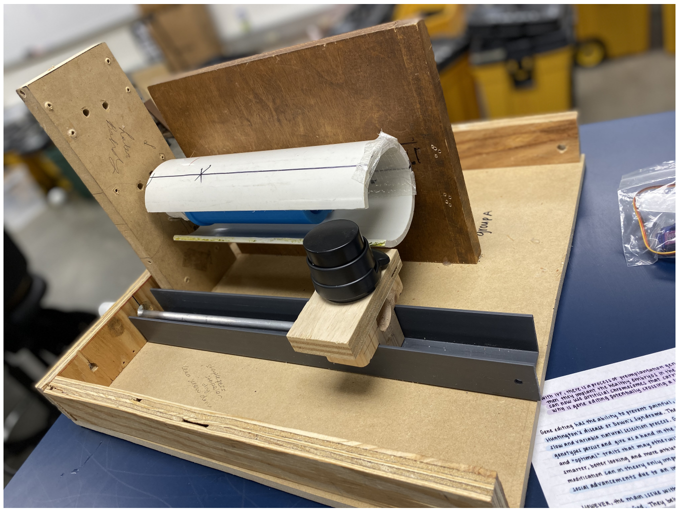


Figure 28: Side view of our initial prototype mechanism including staple-less stapler.

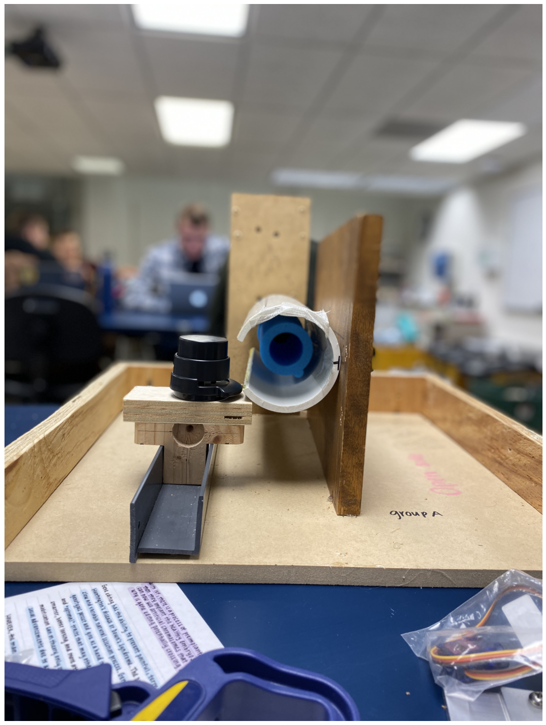


Figure 29: Front view of our initial prototype mechanism. This picture specifically highlights the mechanism that will be used to manipulate the paper into the ”teardrop” shape.

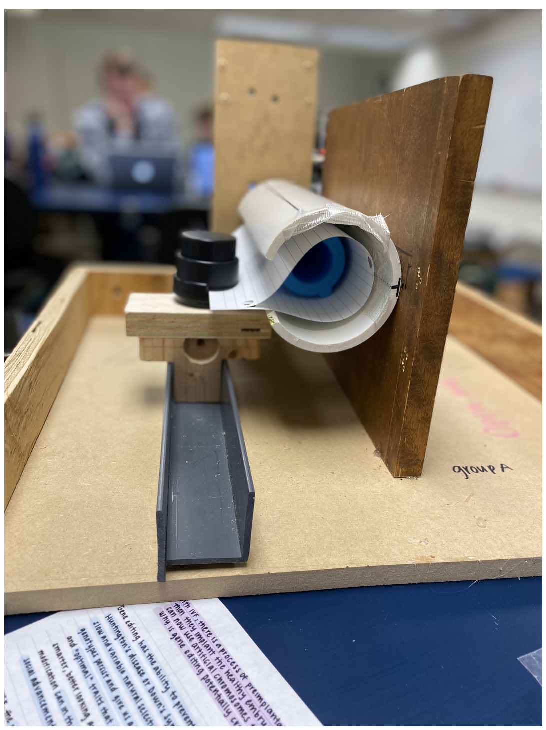


Figure 30: The initial prototype mechanism in action with a sheet of A4 lined paper.

5.5 Initial Prototype Changes

5.5.1 Paper Rolling Mechanism

On our initial prototype, the paper rolling mechanism was comprised of two cylinders. The inside cylinder would help to guide the paper along the wall of the pipe and out the other end. For our original demo, we were doing this manually. However, we had to alter the design in order to satisfy our third prototype performance goal. Right now, our outer cylinder is attached to the dark brown wall as seen in Fig. 29. The blue, inner cylinder is glued to the light brown plank and then placed inside of the pipe cylinder. We made the decision that we were going to get rid of the dark brown wall and mount the pipe to the same wall as the blue cylinder. Rather than mounting the blue cylinder to the wall with glue, which restricts it's movement, we noted that we'd have to make this part rotate. We plan on attaching the inner cylinder to a DC motor that will hopefully guide the paper through the pipe automatically. This new wall will be attached to the base of the box with a hinge and connected to another DC motor. With this, we will be able to lower that wall and use it as the base for our standing tower.

5.5.2 Staple-less Stapler

The staple-less stapler was an integral component of our mechanism. As much as we tried to integrate it into our mechanism, we have decided to go another path. We found that it would be difficult to perfectly align each side of the paper inside of the stapler. During our demo, we tried to complete this but it was difficult even by hand. We would need to add another two clamps to hold the paper together on either side of the stapler. We decided that this made our mechanism too complex. We also determined that the stapler needed a greater amount of force than we anticipated, which could have affected the stability of our tower in the long-run. In addition, we considered taking apart the staple-less stapler and replacing the bottom part to make the jaw wider but the staple would not work without most of the mechanism intact. However, we decided to keep the concept of the staple-less stapler.

6 Working Prototypes

6.1 Initial Prototype

Our initial prototype can be seen below. Originally our design had two walls adjacent to one another. As you can see in Fig. 31, the outer cylinder was mounted to the dark brown wall while the inner cylinder was mounted to the light brown wall. Both of these walls were secured to the base by hot glue. In this prototype, the inner cylinder was hot glued to the wall, limiting its rotation. The object of this prototype was to prove that our device had the potential to build a stable, high tower. As you can see, we used a store bought stapleless stapler. For the sake of the demo, we used this component. However, we were planning on 3D printing a simpler stapling device that could be attached to a servo motor and controlled by our remote. It sits on top of a T-shaped piece of wood with a hole drilled halfway through. There is a rod inserted into the base that is used to manually move the stapler in the track.

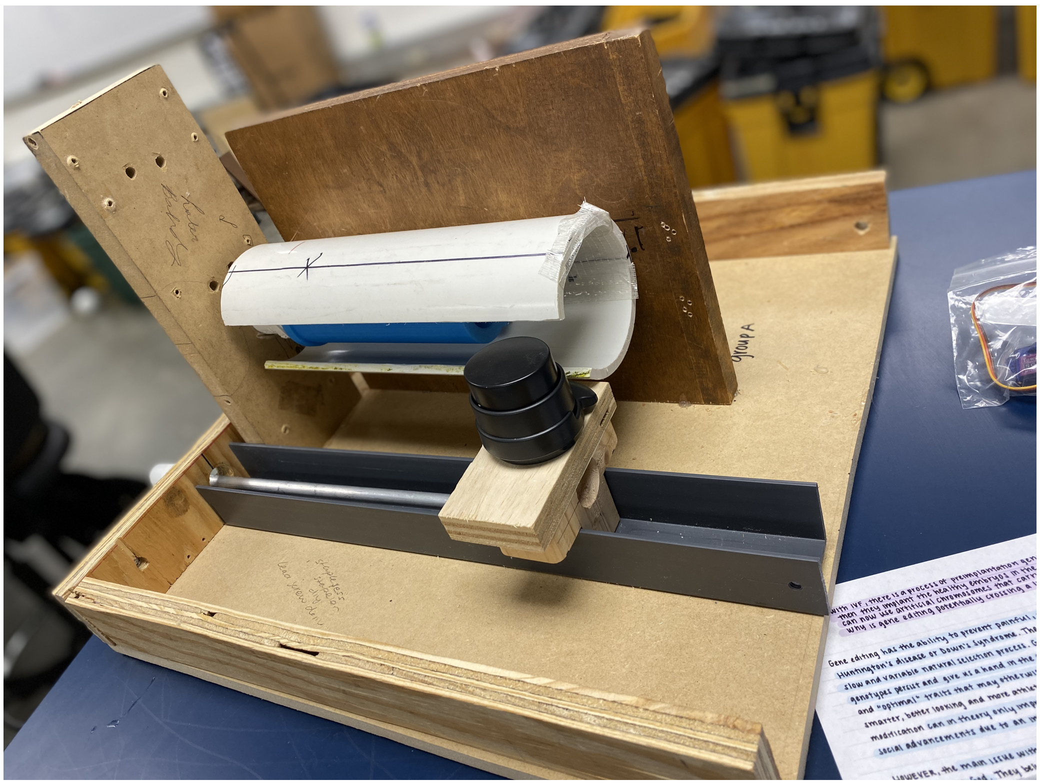


Figure 31: Initial prototype of mechanism on demo day.

6.2 Redesigning

During the initial prototype demo, Dr. Potter informed us that the mechanism could interface with the machine once the competition time expired. At the time, we were planning on making the light brown wall seen in Fig. 31 fall down and support the tower in a vertical position. The dark brown wall, also seen in Fig. 31, would also fall into a vertical position so that the tower would not interface with it while standing. However, with this new information, we decided to place both cylinders on the same wall. As you can see in the figure below, both cylinders are on the wall that will support the tower once it falls into the vertical position. The single wall is attached to the base with a hinge and a doorstop was drilled into the back to minimize the vibrations or disruption to the tower when the wall fell onto the floor. We drilled this doorstop until the wall was parallel to the surface it fell on. However, we did this without considering other factors such as the screws used to to hinge the wall to the base or the motors and cables attached to the inner cylinder.

Figure 32: Redesigning the initial prototype.

We planned on building a mechanism that would be placed next to the hinged wall. We were thinking of creating a door stop that could be turned on our command which would then prompt the wall to fall. One of our motors that we received was attached to a cardboard arrow that would point in a different direction when prompted by the remote. Rather than using the arrow, we mounted a piece of wood onto a plastic adaptor attached to the motor. The wood blocked the wall from falling down while it was interfacing with the wall. However, when we changed the orientation of the piece, it would become parallel with the wall. This would allow the wall to fall into it's horizontal position. The figure seen on the following page shows what the hinge is meant to do and what the wall and tower look like in the upright position.

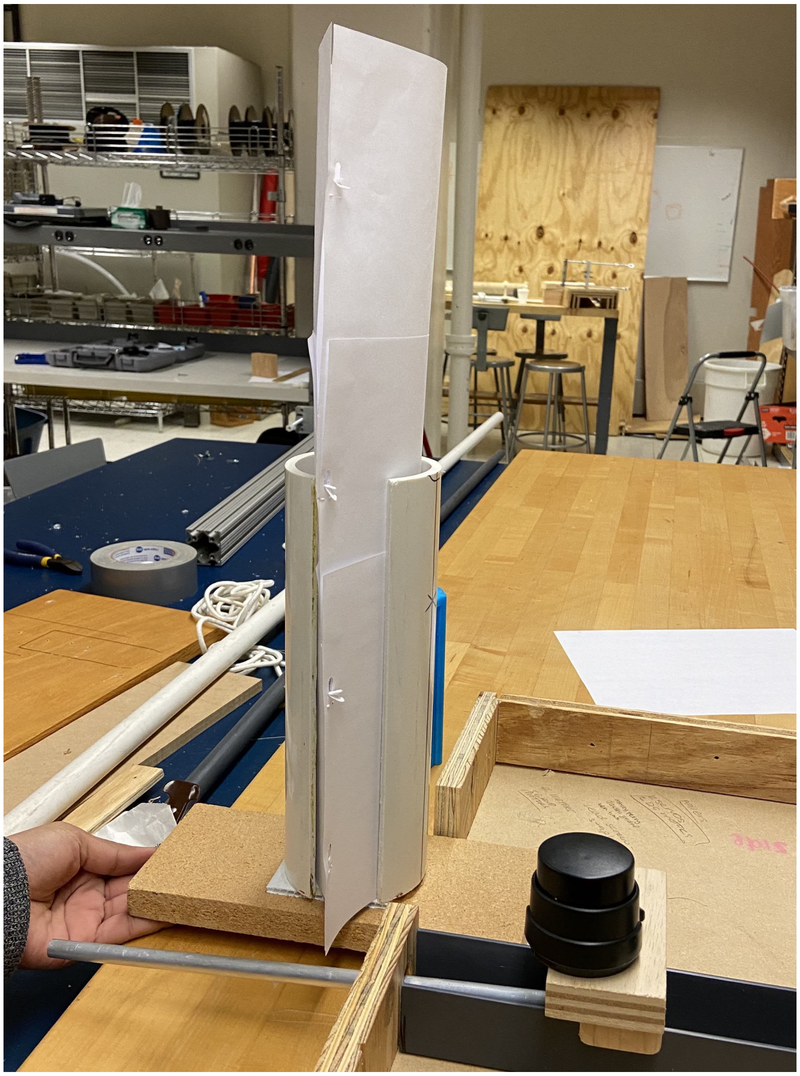


Figure 33: When the hinge wall is released, the tower will maintain an upright position.

6.3 Final Prototype

The final prototype included all of the electronics that we were using. Looking at Fig. 34, you can see that the general design of the mechanism is similar to that of the initial and redesigned prototype. In this picture you can see that both cylinders are mounted to the hinged wall that is held in place to the board.

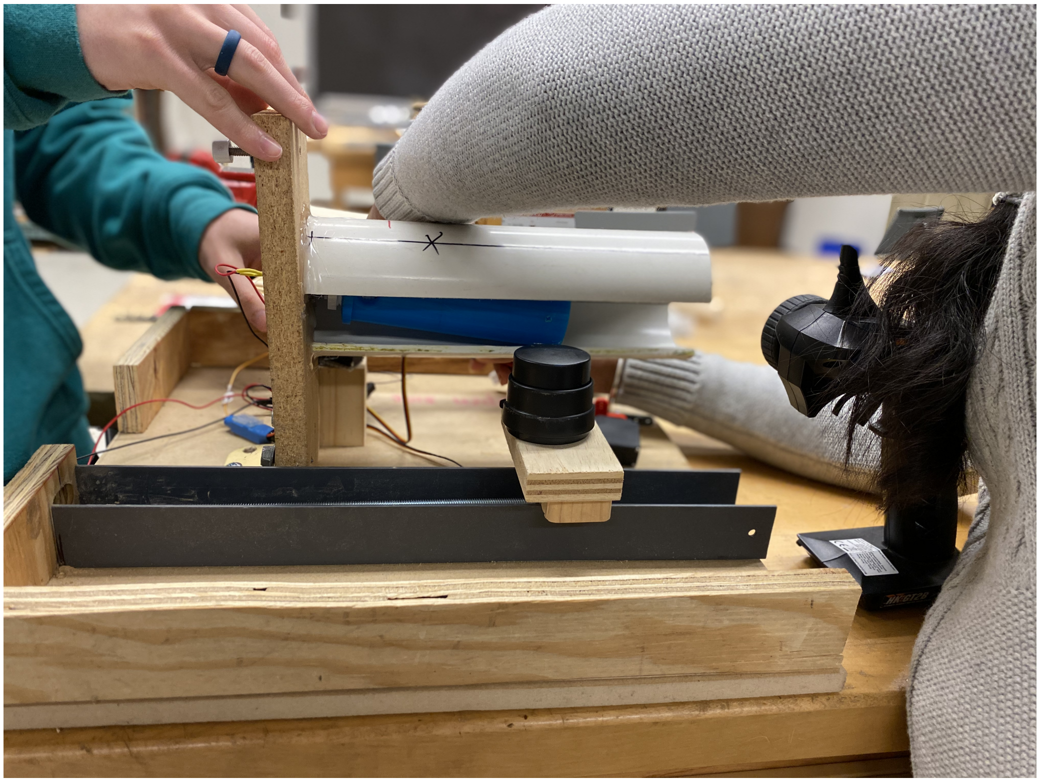


Figure 34: Side view of final prototype.

However the real differences between prototypes can be seen in Fig. 35 Unlike the initial prototype, the inner cylinder is attached to the motor through the hinged wall. The rotating cylinder acts as the motion that will prompt the paper to follow the path of the outer cylinder without manual interference. Another main difference is the rod used to move the stapleless stapler through the track. In order to make the back and forth motion automated, we needed a threaded rod. We used T-nuts to "thread" the wood so that the rod would be able to move through it and therefore moving the stapler. We planned on making the hole bigger and placing the motor inside of it similar to that of the rotating cylinder. This would ensure that we met our 50 x 50 x 50 cm bounding box condition as well as give us a longer range of motion for the stapler if needed. We also found that the doorstop on the back of the hinged wall was unnecessary. We struggled to find screws that were stubby enough to secure the hinge to our base without poking through in the bottom. Therefore, we had to settle for rather large screws. This added an additional height and angle to the wall that we did not anticipate. In the end, it worked out because the wires of the motor were protected and the integrity of the tower was not affected once the wall fell.

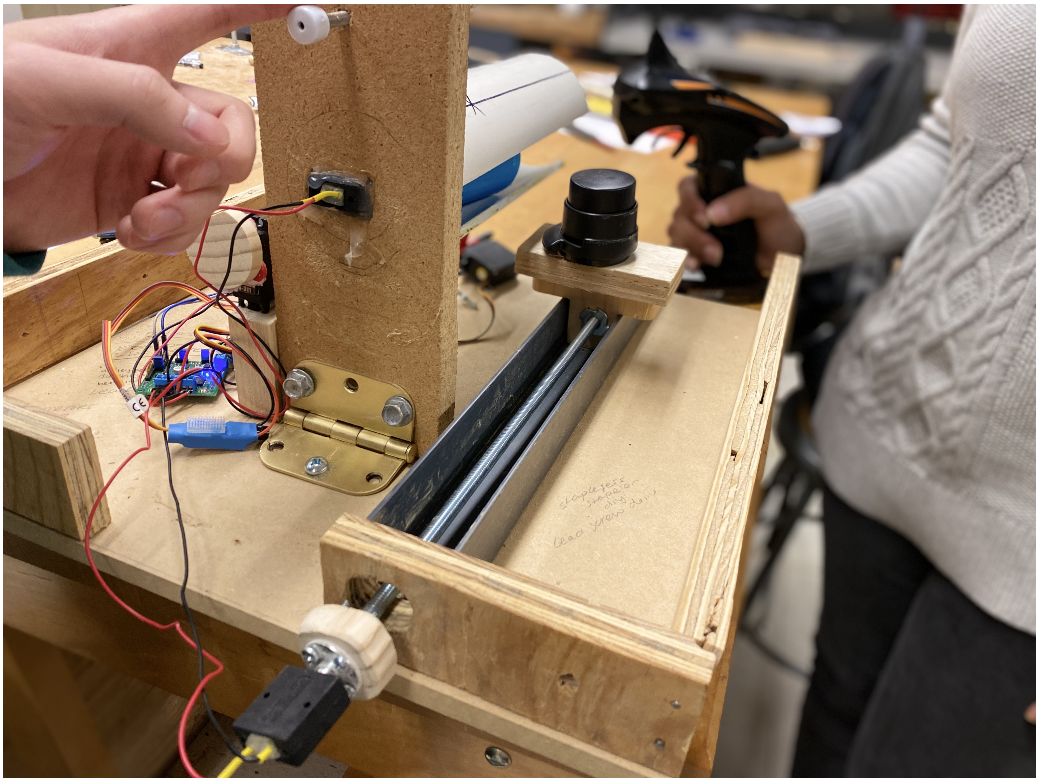


Figure 35: Back view of final prototype.

Some smaller issues that were unresolved in our final prototype include the stapler and mechanism used to keep the door up. As stated earlier, we wanted to create a smaller, simpler version of the stapler. However, due to the time constraints of the project we did not have the time to go through the necessary prototype iterations. We scrambled to find another way to use the stapler and make it automated. We decided that the force needed to push the stapler down would be rather large and grueling for an actuator to do. We believe that it may have taken a long time and because we were working within a 10 minute window for the competition, it wouldn't be ideal. Therefore for the context of this class, we decided to manually staple the pieces of paper together. In Fig. 35, you can see the mechanism that we built to hold the wall into place standing adjacent to the wall. However, once everything was put together we realized that the wall was too front-heavy. The two cylinders and motors were forcing the hinged wall the opposite way. Not only was it causing the hinge-base interaction to weaken, but it also made our device unnecessary. If we were to have more time, we considered spring loading the wall so that it would want to fall backwards regardless of the weight on it. If we used this alternative, we could keep the mechanism that held the wall up. Another alternative that was considered included a mechanism that pushed the wall down rather than holding it up.

7 Design Refinement

7.1 FEM Stress/Deflection Analysis

For our FEM we ran a static study. While deciding which component to test, we had a difficult time choosing one that would undergo large stresses or deflections. We considered the inner, rotating cylinder but found that the force of the paper would be negligible. We decided to test the T-shaped stand that the stapler will be sitting on because it will undergo the most force. The loads that we chose included the weight of the stapler which was approximately 0.44 N. We added an additional load of 7 N to account for the load that will be placed on the stapler during each use. We did not adjust the mesh during this study. We don't believe that this accurately mimic's the real-world machine's conditions because of a variety of reasons. For starters, the 7 N is not an exact measurement. We looked up an approximate amount of force that was needed to work the mechanism. However, the resource was not clear if this was the force needed to staple two pieces of paper or 5+. Our material that we used in this study was Balsa wood; however, the wood that we built the T out of was much stronger. We used Balsa because it was the only wood on SolidWorks with information for the elastic modulus which was necessary to run the study. The load in the study is also dispersed across the top of the component; however, we believe that the overall load in usage will be isolated to the location of the stapler.

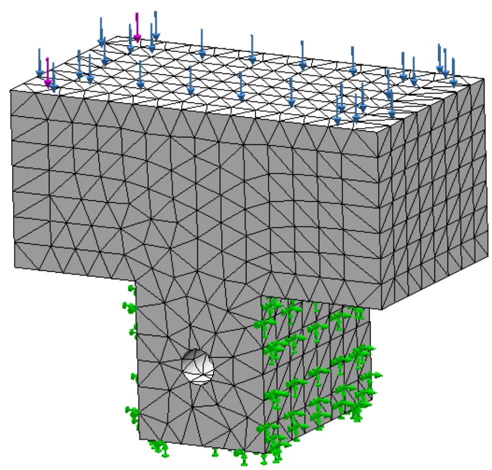


Figure 36: View of the Unloaded model with mesh, loads, and boundary conditions.

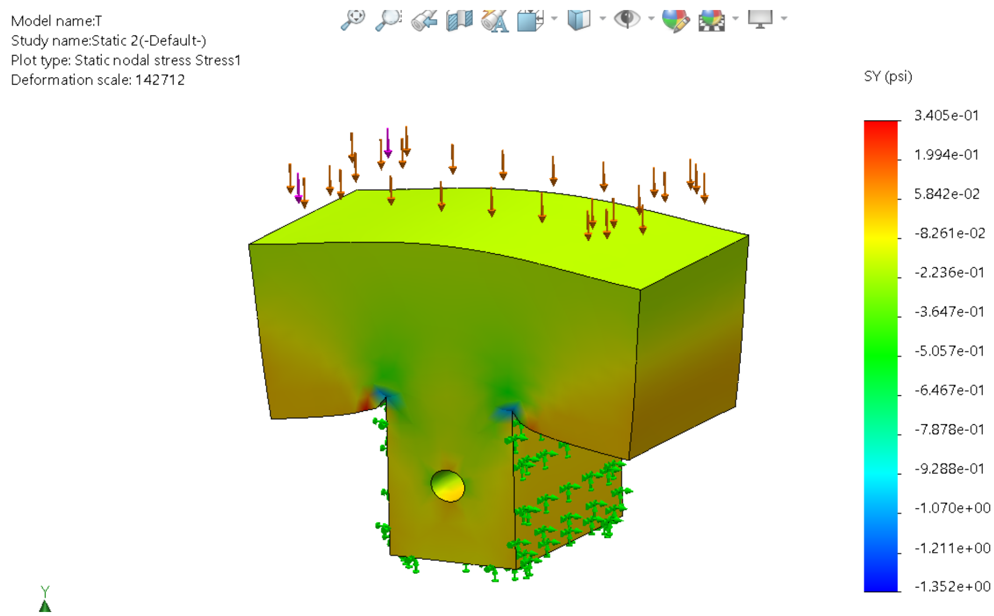


Figure 37: A view of the loaded model with color-coded stress and legend.

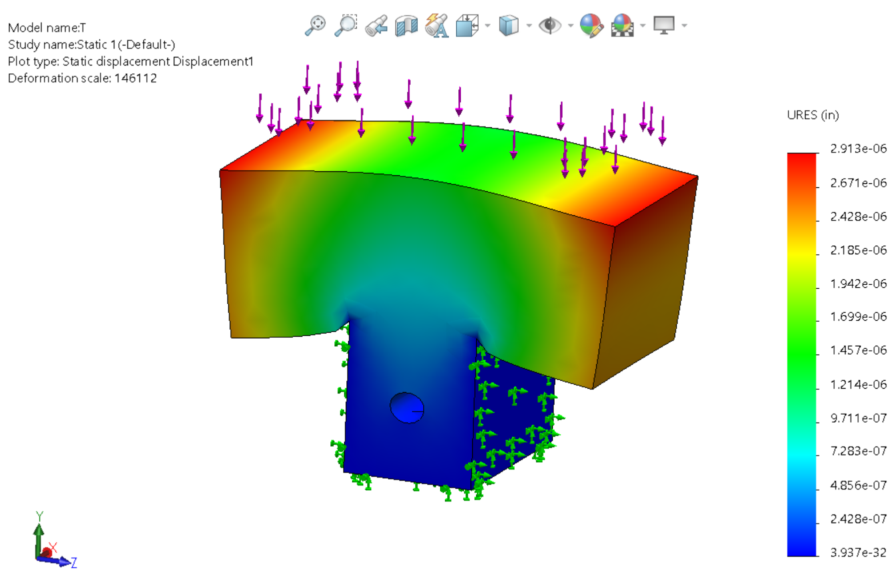


Figure 38: A view of the loaded model with color-coded deflection and legend.

We believe that the wood that we used is Beech; therefore, we found that the yield strength is 1150 psi. The maximum normal stress that we used is 0.3647 psi. We used the maximum-normal-stress-theory because the only significant force is normal and caused by the weight of the stapler and manual force. The factor of safety is below:

$$F_s = \frac{1150}{0.3647} \tag{1}$$

$$F_s = 3153 \tag{2}$$

The predicted deflection seemed tolerable because it was minimal. In reality, the maximum deflection will actually be smaller because the type of wood that we are using is stronger. In theory the maximum deflection would not need to be too large in order to cause significant problems with our design. A critical aspect of our design is that the paper feeds perfectly into the hole of the stapler. Therefore, any deflection could cause the paper and mouth of the stapler to be misaligned.

7.2 DFM Analysis

The first test that we ran was the Mill/Drill only process. Our part only failed because the hole depth to diameter ratio was larger than the allotted amount which was 2.75. The second test that we ran was the Injection Molding manufacturing process. It failed because our wall thickness surpassed the maximum allowed value of 0.30 cm. You can see the results of both tests in the figures below.

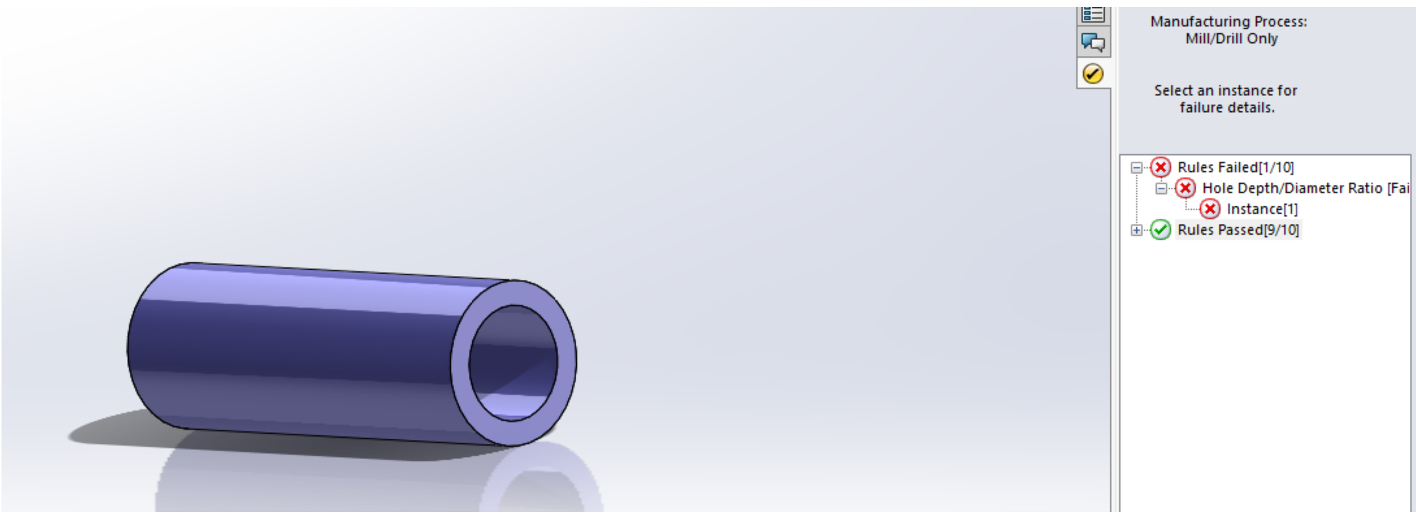


Figure 39: DFM Analysis of Mill/Drill Only Manufacturing Process.

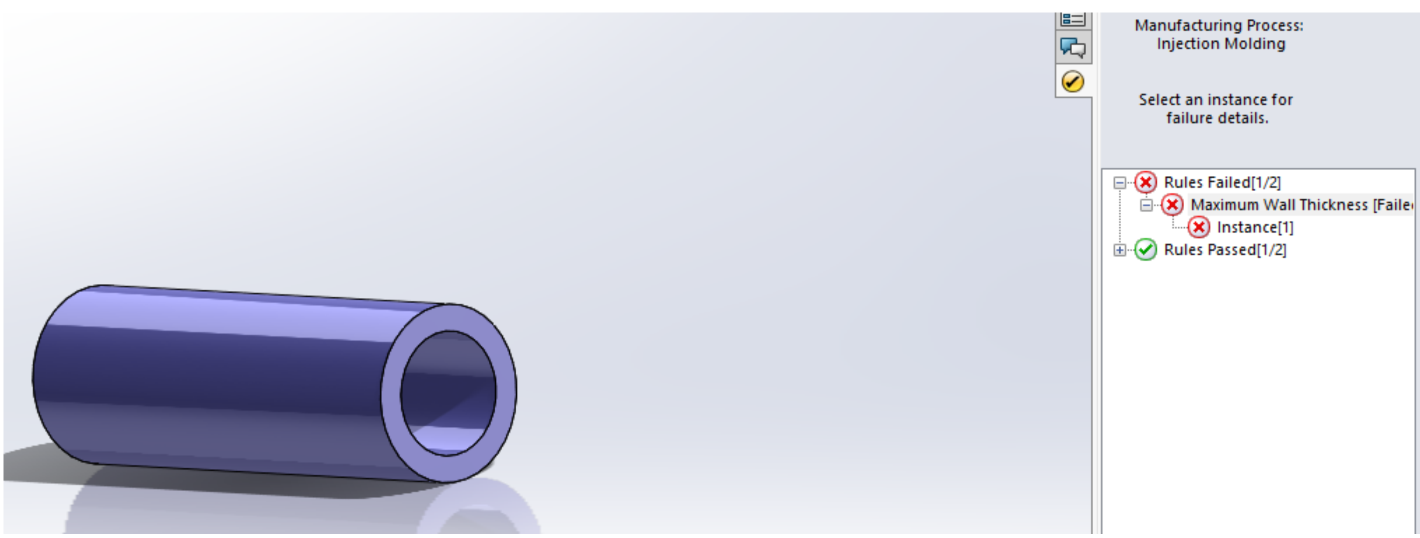


Figure 40: DFM Analysis of Injection Molding Manufacturing Process.

7.3 Design for Safety

7.3.1 Risk #1: Hinge Failure

Description: If the part behind the wall fails to maintain its vertical position while the tower is being built then that can cause injury. If the wall were to fall randomly, the other components of our device may follow with it. For example, if the wall fell while the stapler was in action then the stapler could also fly off as the wall is falling.
Severity: We believe that this is would be a catastrophic risk because not only can people potentially get hurt but it could also affect our performance in the competition.
Probability: The likelihood that this will occur is seldom. During our design process the wall has fallen a number of times; however, we have not put up the stopper that will hold it in place yet. Once we put this component in, the wall should be safely secured in the vertical position.
Mitigating Steps: We have tried to mitigate this risk by putting a doorstop on the back of the falling wall. If the hinge does fall, this will make it so that the impact with the ground isn't as detrimental to the overall mechanism.

7.3.2 Risk #2: Electrical Injuries

Description: The electrical components of our device are going to be placed inside of the box. The circuit board, wires and motors will be exposed. We are sure that the competition will take place indoors so we were not designing for our machine to get wet. However, if someone were to accidentally spill something on our mechanism there is no housing that will protect our electronics.
Severity: We believe that this is a marginal risk. The odds of someone spilling water or another beverage on our electronics is slim.
Probability: We believe that due to the nature of the competition, our machine will be in dry conditions and other engineers will recognize the danger or having open beverage containers around electronics. Therefore, the probability of this risk being realized is seldom because accidents can still occur.
Mitigating Steps: We could mitigate this risk by building a housing component for our electronics. Therefore it will be weather and accident-proof.

7.3.3 Risk #3: Holding Hazards

Description: The bounding box that holds our mechanism is unrefined. While building it, we used wood that broke apart after nails entered. Therefore, there are a lot of places where one could get a splinter or even cut themselves on some hangnails.
Severity: We believe that this is a critical risk just because anyone who interfaces with the mechanism could potentially hurt themselves.
Probability: Overall, the probability of this occurring is likely. In a perfect world, an engineer would only interface with the bounding box to carry it into the competition area and placing it on the ground. However, during this time one could potentially hurt themselves.
Mitigating Steps: In the case of hang-nails we have tried to mitigate the situation by putting hot glue over the nails that were sticking out. We could also sand down the wood to reduce the chances of getting splinters.

7.3.4 Risk #4: Exposed Threads

Description: The construction of our paper tower machine included a threaded rod that would motion the staple-less stapler back and forth on a track. The threaded rod is completely exposed and any contact with it while the machine is being operated could cut the user.
Severity: The severity of this risk is critical. If a person holds the threaded rod while the electrical motor is turning the rod, there could be deep cuts on the body that cannot be ignored.
Probability: The probability is "seldom" because it is unlikely that someone would hold the rod while the machine is operated on. However, a person stapling the papers could slip accidentally and come in contact with the threaded rod so we cannot completely neglect the probability.
Mitigating Steps: We could rid of this risk by covering the threaded rod, for example, with a plastic pipe. We could also cover the entire track with a wooden cover.

7.3.5 Risk #5: Weight

Description: In general, our mechanism is heavy. The wall that holds the paper manipulating device was has not been proven to hold both the PVC cylinder and the inner PLA cylinder. Including the motor, the wall may not be able to support our mechanism.
Severity: This is a catastrophic risk because if the wall is unable to maintain all of these components then we won't necessarily have a tower.
Probability: We believe that the probability that paper manipulating mechanism becomes dismembered from the wall is unlikely because we refined our wall choice to include a thicker wall.
Mitigating Steps: As stated earlier, we changed the earlier wall from a thinner piece of wood to a thicker one. We are hoping that this wall will be able to house our whole mechanism without weight being a problem.

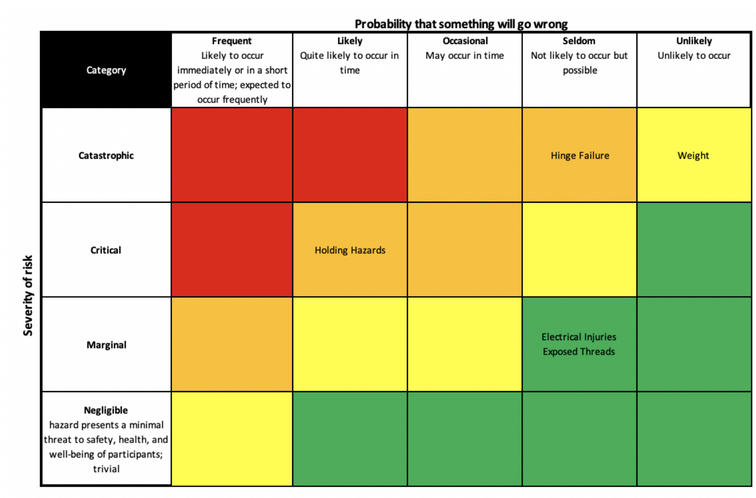


Figure 41: Heat Map of our Potential Risks

The figure above is a "heat map" of the potential risks of our machine. "Hinge Failure" and "Holding Hazards" are assessed to be similarly "risky". However, we believe that the "Holding Hazard" should be prioritized in the design for safety because of the likeliness of such thing to occur. "Hinge Failure" is next in our priority because of the severity of such failure to happen.

Furthermore, the "weight" risk is next in our assessment map because it could be a catastrophic event that is very unlikely to occur. The least of our priorities are the "Electrical Injuries" and "Exposed Threads" because of the low severity and low likelihood of occurrence.

7.4 Design for Manufacturing

7.4.1 Draft Analysis

In order to modify the part, we included a draft of 3 degrees on all "vertical" walls that are shown in yellow. We also added a 3 degree draft on the through hole located at the bottom of the part. We did not modify the thickness of the wall during this process. The before and after pictures are shown below.

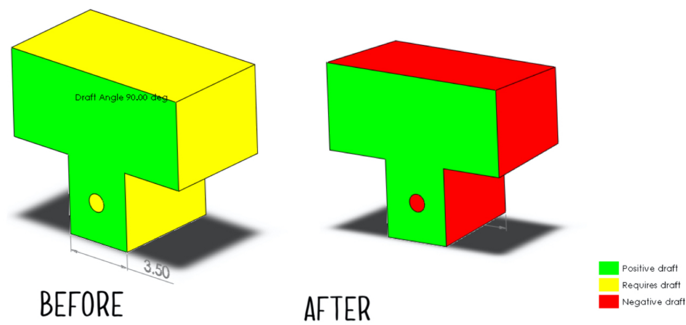


Figure 42: Before and After Images of Stapler Holder Using SolidWorks "Draft Analysis"

7.5 Design for Usability

7.5.1 Vision

We haven't really used any materials or electronics that are colored. In general, our machine would be pretty simple to use if you were color-blind. The only thing that I can think of is the fact that our machine is very monochromatic. For those of who are losing their vision, it may be difficult to differentiate different components of our design. For example, a majority of our design is made from wood and therefore is various shades of brown.

7.5.2 Hearing

The only part of our design that is dependent on hearing are the motors. However, in terms of safety they aren't really necessary. If one is able to see the parts of our machine moving, then they should know whether or not the motors work properly without having to hear it.

7.5.3 Physical

The most grueling part of our design is the staple-less stapler. For those of who have physical impairments such as arthritis or muscle weakness, they may find it difficult to use this feature. Because it takes a large amount of force to push down on the stapler and firmly secure the pieces of paper together, some may not be able to do this. This could eventually affect the integrity and stability of the tower as a whole. If warranted more time, we would plan on finding a better method of “stapling” the pieces of paper together. We were looking at another technology that is commonly used for smaller stacks of paper called seaming. Ideally, we would be able to automate this feature to close and seam the paper together without manual use.

7.5.4 Control

Since we are manually stapling the paper together, the process could cause excessive fatigue. As stated earlier, the force of pushing down on the stapler is large and would need to be consistent throughout the entire process. If someone were to get distracted or tired during the process, it could lead to the pieces of paper not being securely fastened to one another. Therefore, it could cause the tower to fall over in the end. However, we don't believe that this will be a problem in our case. Because the competition time is only 10 minutes, we believe that fatigue will not be an issue. One way to control the distraction aspect would be to take turns between group members for fastening the paper. Therefore, group members would not be bored or distracted by the repetitive pattern and would be allowed to focus on other parts of the machinery that needs to be manipulated.

8 Discussion

8.1 Project Development and Evolution

Does the final project result align with its initial project description?

- For the most part, our mechanism can build a stable paper tower without the use of glue, staples, etc. However, the goals of the project state that the tower should be built without the aid of manual help. After a group member feed the paper into the machine, it should be able to complete the rest of the tasks without our help. The staple-less stapler that we are using requires a large amount of force in order to fully attach the pieces of paper together. We tried to create a new mechanism but realized that the time constraint would not allow for the various prototype iterations that we would need. Therefore, in the context of this class, we decided to manually staple the papers together which violates the project requirements.

Was the project more or less difficult than expected?

- The project was more difficult than we expected it to be. At first, we didn't have a clear idea on what direction we were going to go. We decided to spend a bulk of our time trying to tinker with multiple ideas until we found a concept that was feasible and realistic. Each of our group members had various ideas but it was difficult to stick to one and develop it further. Since the competition rules and customer desires were so open-ended, we struggled coming up with a solid start and going from there.

On which part(s) of the design process should your group have spent more time? Which parts required less time?

- We spent a lot of our time trying to determine a suitable shape for the paper. We were looking for a shape that would yield a stable tower and a simple manipulation model. For example, cubes would have been too complex to build because the amount of actuators needed. Because we spent a majority of our time in the early stages of design, we felt rushed to complete other aspects such as the automation of the staple track and inner cylinder. Even though the paper manipulation component is the bulk of our design, we didn't consider the fact that things could potentially go wrong later on in the process. Therefore, we had little to no time to address these issues.

Was there a component of the prototype that was significantly easier or harder to make/assemble than expected?

- Once we understood that the device could interface with the tower at the end, we decided to build the paper manipulation component on a wall that could stand vertically and horizontally. While vertical, it would be used to build the tower sideways but at the end of the competition time, it would switch to horizontal and the tower would stand. We designed a component that would hold the wall vertical until it was time for it to be horizontal. However, when the time came we realized that there was too much weight on the front of the wall. Therefore, it was not inclined to fall backwards. Rather than a mechanism that holds the wall up, we needed one that pushes the wall down. What we expected to be an easy component ended up being a little more difficult.

In hindsight, was there another design concept that might have been more successful than the chosen concept?

- There were a lot of routes that could have been taken for this project. However, one of the biggest problems that we found with others was the inability to attach the pieces of paper to one another. We considered designs where we folded the paper and placed it 90 degrees in relation to one another. Since we were aiming for the highest tower, we decided that this type of design would not be adequate.

8.2 Design Resources

How did your group decide which codes and standards were most relevant? Did they influence your design concepts?

- The Codes Standards for our group were chosen mainly to decrease the risk of our machine. Our electrical motors were a electrical hazard that was addressed in our risk section. Initially, we considered using robotic arms for several aspects of the design; however, the idea was considered too complex and we did not use any robotic parts in our machine, the robotic safety standard was then obsolete.

Was your group missing any critical information when it generated and evaluated concepts?

- When the initial concepts were evaluated, we did not consider the complexity required for the concept to function properly. The basic idea of the concept worked for our purpose but we failed to consider how the idea has to be incorporated into our design. For example, we did not consider how we would rotate the mold upright to stand the tower in the upwards position, and we did not account for the additional space needed that could exceed the limitations given to us in the rules.

Were there additional engineering analyses that could have helped guide your design?

- Our design included a staple-less stapler that proved to be too stiff to be automatically pressed down. Additional engineering analysis on the force required to use the staple-less stapler could have helped us pick a specific mechanism such as an actuator that could accommodate the required force and help us automate the stapling process of the machine.

If you were able to redo the course, what would you have done differently the second time around?

– The tools and material we used were limited to what we could find in the studio. The second time around, we could plan out what materials are strong enough, stiff enough... etc, and we could ask for assistance on what tools to use to minimize breakage and failing problems while maximizing efficiency.

Given more time and money, what upgrades could be made to the working prototype?

– An initial concept incorporated a robotic arm that could perform complex tasks and help us automate the machine. If our group had more funding we could add a robotic arm that could staple the paper, move the paper tower, erect the tower... etc and reduce the amount of motors we needed. If we had more time we would definitely spend it refining our design. Our prototype would be functional if we had time to specify every hole drilled and every screw turned.

8.3 Team Organization

Were team members' skills complementary? Are there additional skills that would have benefited this project?

– Our team skills are well complimentary. One member had advanced knowledge of Solid Works and constructed the drawings according to our design. Another member was incredibly organized in all aspects and made sure all deadlines were known and met. Another member operated machines and tools and built the machine. Each teammate had a niche that is set around their strength and catered to the teams needs while supporting each other. Additional skills in woodshop would be helpful; knowledge in woodshop could help the team build a better machine and expedite the process.

Does this design experience inspire your group to attempt other design projects? If so, what type of projects?

– Yes, this design experience inspired our group to attempt the ASME design challenge the next year. The design challenge will not be announced until next year; however, we want to follow the design process discussed in this course and attempt the challenge through prototyping when the challenge is announced and construct a mechanism that could attend the ASME conference.