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ASME Student Design Competition 2020

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SPRING 2020
Mechanical Engineering Independent Study

ASME Student Design Challenge 2020

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1 Introduction: Senior Design Project

Our initial work on the ASME design challenge, the focus of this independent study, occurred in our senior design class. A brief summary of the senior design project and our learning from that project is presented in this section.

1.1 Premise

Our customer, the 2020 ASME Student Design Challenge, requires that engineers design a compact contraption that can manufacture a tower using only standard sized sheets of paper. The challenge judges the success of the device the engineers create based on three different rounds: tower height, build speed, and tower strength. In the height round, the device will have 10 minutes to build the tallest tower possible. For the speed round, the device needs to build a 1.5-meter tower as fast as possible. Finally, for the strength round the device will have 10 minutes to build a tower capable of withstanding the heaviest load possible.

The paper tower machine must be capable of being stored within a 50cm x 50cm x 50cm box. During the process of making the tower, the contraption can mechanically manipulate the paper in any way it sees fit, but can not add any other items such as glue, staples and tape. Additionally, no part of the machine can exceed 50cm above the surface of the competition field. These restrictions are intended to increase difficulty of the challenge, requiring engineers to make a device that is still efficient under these limitations.

1.2 Approach to the 2020 ASME challenge

In this ASME challenge, the approach taken was using an accordion like stacking method, as seen in Fig.1.

Figure 1: Initial idea of Paper tower

With this approach, a simple press can be used to make the shape. Triangles are also sturdy...
shape, which will allow the tower to be as stable as possible when stacked. A stacking method in building the paper tower also meant that there won’t be any additional connections needed, such as glue, tape or staples. Additionally a single sheet of paper can be cut in half and be made into two accordion folds.

The paper tower building machine needs to have the following components:

- **Cutter**: A mechanism that cuts the paper
- **Press**: A mechanism that shapes the paper into the accordion shaped fold
- **Stacker**: A mechanism that orients the paper in the correct ways and stacks them
- **Transporter**: A way for the paper to travel throughout the machine.

Due to time constraints, for the senior design portion of this project we used drills to simulate an electrical system and omitted the lifter mechanism.

### 1.3 Initial/Final Prototype

![Figure 2: CAD Drawing](image-url)
Figure 2 shows an exploded view of the CAD model of our prototype. Figure 3 shows our prototype broken down into its sub-components: 1.) The cutter, 2.) Saran wrap transporter, 3.) press, and 4.) ramp.

1.3.1 Cutter

Our design needs to be able to take in the paper, as well as cut the paper into two pieces, and so we attached a motor an axle with a circular blade in the middle. As the paper is being pushed in the motor rotates the axle and blade, cutting the paper and pulling it into the machine.
1.3.2 Plastic Wrap Transport system

In our prototype, in order to transport the paper around, we have plastic wrap around two rollers. When the motors connected to the rollers turn on, the plastic wrap acts like a conveyor belt and transport the paper through the system. As the paper reaches the press, we turn off the motor, and slacken the saran wrap, so that when the press comes down it does not affect the folds.

Another mechanism that the initial prototype helped us develop was the Plastic Wrap Roller. Initially, we were unsure if the Plastic Wrap would be able to withstand repeated pressing without tearing, or if it would roll well enough to remove the paper from the press easily. However, repeated testing of the Plastic Wrap Roller, shown in Fig. 8 below, on the initial prototype allowed us to assuage both concerns.

1.3.3 Press

In the senior design prototype, we have matching presses for the top and bottom, where the bottom is fixed to the base of the prototype and the top is attached to a winch which is controlled by a motor attached to the top of the machine. In order to ensure that the press comes down with enough force to leave a fold, there are weights placed on the top press. When the winch is released, the top press drops quickly and implants a fold in the paper. The winch motor then re spools the rope attached to the top press, pulling the top press back to the top of the machine.
Figure 6: Weight applied to roller mechanic

Figure 7: Improved Harness System used in Final Prototype
1.3.4 Ramp

In order to get the paper to orient in different orientations, there are ramps placed for the two halves of paper cut. While the paper fold is sliding down, there is a nail stuck out in one of the ramps that forces the paper to change orientation and get the paper to stack in alternating degrees.

The structure of the ramp mechanism was changed after the initial prototype tests. These changes served to simplify the ramp structure and to increase the consistency of the paper stacking, and are shown in Fig. 8 below.

![Updated Ramp Used in Final Prototype](image)

Figure 8: Updated Ramp Used in Final Prototype

1.4 Problems and Issues

Our initial senior design prototype was functional, but also exposed many issues with stacking paper into a tower form. These issues are detailed in the following section, and influenced our decision to pursue a new type of tower for the independent study project.

1.4.1 Hidden Complexity

Even though stacking paper to build a tower was the simplest stacking mechanism we could think of, it still required a large number of actuators. Although the folding mechanism was simple, the stacking was complicated and relied on how the paper lands and slides down a ramp, which is not easily controlled.

The large of actuators involved also increased the complexity of the building process as all the mechanisms depended on each other and needed to be in sync. For example, the press’s performance
was dependent partly on how well the cutter split the paper in two and put it into the roller, and the press also needed to place the paper well into the ramp. If there was a problem with the cutter, that will carry over to the press, which in turn carries to the ramp.

This whole project also omitted two key elements within the paper tower competition: the lifter and the electrical components. Due to time constraint, we bypassed these parts, but for the competition, these needed to be taken into account, which will further increase the complexity of an already complicated system.

1.4.2 Poor Performance

Another reason that we are not continuing to pursue the stacking design in this independent study is the issue of poor performance.

For each piece of paper processed by the machine, there was only a height average of 4cm added to the tower. The rate of the stacking is also low, clocking in at 4 pieces of paper per minute. With these rates, this design will do poorly on both the height, and speed portion of the competition. Our stack was also very difficult to align, so the tower is not very stable, and would do poorly on the strength portion.

1.4.3 Size

Another difficulty was to fit all of the components into legal competition size of 50cm x 50cm x 50cm. The box containing our paper tower machine and all its supplementary components need to fit within that size, and given that our final prototype was already at that size, it will be difficult to make the size limit. And again, this does not take into account the lifter component and electrical components, which adds more to the size problem.

1.5 New Direction

From this senior design, the main takeaway was that having individual stacking components for the tower increases the complexity greatly while also decreasing its efficiency. With this new information, one of the main priorities for the redesign is that the paper remains connected with one another instead of individual pieces. This will decrease a lot of the complexity and actuators needed to make the process in sync, while also hopefully increasing the efficiency.

As the year progressed, there were some updated rules for the ASME challenge regarding the paper tower. The main change was that the paper tower’s can be connected on the base. One of the main appeals with the stacking method was that the structure can be upheld by only the paper.

With this new update, and our new priorities to simplify the design, the main idea for the new design is to use a stapleless stapler, a device that will allow us to staple paper without staples, to connect the pieces of paper. Then it would be rolled up a cylindrical base and made to hold its form. This concept will be further explored in the next section.
2 Concept Generation

2.1 Mockup Prototype

The first step in developing the spiral tower concept into an actual design was to test the ability of a spiral paper tower to be self supporting and the heights that could be reached. These mock-ups were created using tape to join the pieces, a water bottle for the base, and hands to spin the paper around the tower. Fig. 9 shows a tower constructed in this manner, and Fig. 10 gives a better angle for viewing the large height to which the tower reached. Through this mockup, it was determined that each sheet of paper was generating 0.6 feet of height on the tower, a clear performance improvement over the previous stacking design’s best performance. However, as tape was used to make lateral connections between sheets in addition to the required end to end connections these tests could not determine whether the tower was self supporting. Fig. 11 shows another tower that was constructed in a similar manner but used a stapleless stapler to join pieces of paper instead of tape. This tower’s ability to remain standing without lateral support demonstrated that spiral paper towers could be self supporting if constructed properly.

Figure 9: Spiral Paper Tower Made With Tape
The next step was to test whether commercial stapless staplers could be easily actuated to create joins in paper. This was accomplished using a rudimentary CAM device, as shown in Figures 27 and 13. Although not shown in these images, these tests demonstrated that it was possible to make the joins required for the spiral paper tower using the CAM and stapleless stapler system.
Having established the viability of a spiral tower constructed with a stapless stapler, the next step was to test the mechanism for moving paper through the system. Shown below in Figure 14 is a piece of paper traveling through a mockup of the spiral paper tower device. To give paper a spiral shape, we used a 12 cm diameter PVC pipe to spiral the paper around. A timing belt
wrapped around the pipe would pull the paper up and around the pipe. To simulate the motor that would move the timing belt, we used a piece of wood with two idlers located at and spaced from the top and bottom of the pipe. This device influenced our design thoughts in a couple ways. First, the timing belt would only move if both the top and bottom idler/belt locations were pulled. Therefore, we would need one motor located at the top and bottom of the pipe to move the timing belt. Second, the timing belt kept slipping down the pipe. To keep the timing belt in place, we would need fixed belt guides along the belt’s path. The belt guides would need to be close to the pipe to support the belt while allowing the free movement of the belt and paper. Finally, spiralling paper around the pipe required us to insert paper up and around the bottom section of the pipe to be gripped by the timing belt. To accomplish this task, we would need to create a paper ramp system at the bottom of the pipe.

Figure 14: Spiral Paper Tower Device Mockup
2.2 Functional Decomposition

Figure 15 shows a function tree for our design.

Figure 15: Function tree for Spiral Tower Concept
2.3 Morphological Chart

Figure 16 shows a morphological chart of our spiral tower design.

Figure 16: Morphological Chart for Spiral Tower Concept
2.4 Alternative Design Concepts

2.4.1 Spiral Tower Machine

Figure 17: Sketches of Spiral Tower

Solutions from morph chart:

1. Paper Intake: Manual Insertion
2. Paper Manipulation - Join: Stapleless Stapler
3. Paper Manipulation - Reorient - Ramp
4. Move Paper Up Tower in Spiral - Continuous Belt
5. Power Supply: Battery
6. Control Device: Wired Video Game Controller

Description:

Paper is manually inserted into the device and is pushed forwards until it overlaps with the last piece of paper that was inserted. Two stapless staplers, one on each side, are actuated to join the two sheets of paper along their shorter edge. At this point, the piece of paper is pulled forwards by its connection to the other paper in the system. As the paper approaches the tower it is pushed up a fixed ramp which reorients the paper to align with the belt path. When the paper reaches the tower, it is trapped between the belt and the tower. Crucially, the top edge of the new sheet of paper overlaps with the bottom edge of a piece of paper that is already on the tower. At this point, the motion of the belt pulls the paper up the tower until it reaches the top of the tower. Without the constraining force from the belt, the paper attempts to push outwards. However, since the bottom edge of the paper is now trapped under another sheet that is still trapped under the belt, the paper remains in a cylindrical shape. Additionally, the friction between the paper and the lower sheet prevents the paper from slipping downwards. This allows the spiral tower device to create a paper structure that is much taller than the tower is built around.
3 Concept Selection

3.1 Selection Criteria

An Analytic Hierarchy Process (AHP) was combined with a Weighted Scoring Matrix (WSM) in our original design project to determine the best version of a paper tower device that utilized stacking. The AHP from the original design process can be seen in Figure 18. We developed a new AHP to compare our previously generated stacking designs to the spiral tower design explored in this report. The AHP used for this comparison is shown in 19. The goal of the criteria used in the original AHP was to determine which design would be best at creating a tower that met the performance goals of height, speed, strength, and reliability. However, the criteria used in the original AHP were very general. This made it difficult to accurately score each design with respect to each criterion and reduced the correlation between high scores and good real world performance. The criteria used in the new AHP were chosen with respect to the same goals as the original, but are more specific than their counterparts and allow more direct comparisons to be made between designs. Additionally, the updated criteria were based on the factors that contributed to design success in the development of our original stacking design. As a result, scores using the updated criteria track more closely with actual device performance.

The lessons learned from our original design process are clearly reflected in the category weights assigned from the updated AHP process. For example, in the original AHP, the highest weighted category and the only category with a weight above 30 percent was tower build speed. However, through the original design process we learned that since increasing the number of actuators adds more potential limiting steps and increases the time required to synchronize actuators, devices with more actuators were both harder to build and processed paper slower. As a result, the actuator criterion in the updated AHP is weighted much more heavily than the corresponding complexity metric in the original AHP and has a similar weight to the tower build speed criterion. Additionally, one key flaw we discovered with stacking mechanisms through our original design process was that when paper components become misaligned relative to each other the overall reliability and performance of the device suffers. This led to a new reliability criterion in our AHP, and a high weight reflecting its importance to design success.

<table>
<thead>
<tr>
<th>Total Component Complexity</th>
<th>Tower Build Speed (to 1.5 m)</th>
<th>Tower Build Speed</th>
<th>Tower Build Height</th>
<th>Tower Build Reliability</th>
<th>Ease of Satisfying Competition Rules</th>
<th>Row Total</th>
<th>Weight Value</th>
<th>Weight (%)</th>
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<tr>
<td>1.00</td>
<td>5.00</td>
<td>0.50</td>
<td>0.33</td>
<td>0.50</td>
<td>1.00</td>
<td>7.03</td>
<td>0.11</td>
<td>11.49%</td>
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<td>Tower Build Strength</td>
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<td>3.00</td>
<td>1.00</td>
<td>2.00</td>
<td>2.00</td>
<td>3.92</td>
<td>0.06</td>
<td>6.40%</td>
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<tr>
<td>Tower Build Speed</td>
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<td>1.00</td>
<td>2.00</td>
<td>4.00</td>
<td>19.00</td>
<td>0.31</td>
<td>31.03%</td>
<td></td>
</tr>
<tr>
<td>Tower Build Height</td>
<td>3.00</td>
<td>1.00</td>
<td>1.00</td>
<td>5.00</td>
<td>1.00</td>
<td>11.00</td>
<td>0.18</td>
<td>17.96%</td>
</tr>
<tr>
<td>Tower Build Reliability</td>
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<td>0.50</td>
<td>0.25</td>
<td>1.00</td>
<td>0.20</td>
<td>12.20</td>
<td>0.20</td>
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<tr>
<td>Ease of Satisfying Competition Rules</td>
<td>1.00</td>
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<td>0.25</td>
<td>0.33</td>
<td>1.00</td>
<td>8.08</td>
<td>0.13</td>
<td>13.20%</td>
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</table>

Column Total: 61.23 1.00 100%

Figure 18: Original Analytic Hierarchy Process (AHP) to determine scoring matrix weights
3.2 Concept Evaluation

Figure 20 on the next page shows the results of the application of a Weighted Scoring Matrix with weights from our original AHP to both our original stacking design concepts and our new spiral tower concept. Figure 21 shows the same but uses the updated AHP to determine the weights.
### Alternative Design Concepts

<table>
<thead>
<tr>
<th>Selection Criteria</th>
<th>Weighted Rating</th>
<th>Weighted Rating</th>
<th>Weighted Rating</th>
<th>Weighted Rating</th>
<th>Total Score</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Component Complexity</td>
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<td>0.57</td>
<td>1</td>
<td>0.11</td>
<td>1.196</td>
<td>5</td>
</tr>
<tr>
<td>Tower Board Height</td>
<td>31.0885132</td>
<td>0.69</td>
<td>2</td>
<td>0.18</td>
<td>1.397</td>
<td>4</td>
</tr>
<tr>
<td>Tower Board Speed</td>
<td>17.8676106</td>
<td>1.00</td>
<td>3</td>
<td>0.60</td>
<td>1.82</td>
<td>3</td>
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<tr>
<td>Tower Board Stability</td>
<td>16.8527867</td>
<td>1.00</td>
<td>3</td>
<td>0.60</td>
<td>1.82</td>
<td>3</td>
</tr>
<tr>
<td>Tower Board Reliability</td>
<td>15.2008909</td>
<td>0.69</td>
<td>2</td>
<td>0.26</td>
<td>1.196</td>
<td>5</td>
</tr>
<tr>
<td>Total Score</td>
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<td>2</td>
<td>3</td>
<td>1.767</td>
<td>4.888</td>
<td>5</td>
</tr>
<tr>
<td>Weighted Score</td>
<td>3.310</td>
<td>2</td>
<td>3</td>
<td>1.767</td>
<td>3.310</td>
<td>2</td>
</tr>
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</table>

**Figure 20:** Weighted Scoring Matrix (WSM) for choosing between alternative concepts using original AHP.
<table>
<thead>
<tr>
<th>Alternative Design Concepts</th>
<th>Weight (No)</th>
<th>Weighted Rating</th>
<th>Weighted Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spiral Tower</td>
<td>3.44%</td>
<td>1.72</td>
<td>0.69</td>
</tr>
<tr>
<td>Dome Tower Builder</td>
<td>10.87%</td>
<td>0.55</td>
<td>0.22</td>
</tr>
<tr>
<td>Triangular Shell</td>
<td>17.44%</td>
<td>0.87</td>
<td>0.22</td>
</tr>
<tr>
<td>Accordion Folding</td>
<td>32.00%</td>
<td>1.00</td>
<td>0.34</td>
</tr>
<tr>
<td>Total Score</td>
<td>4.00%</td>
<td>0.15</td>
<td>0.06</td>
</tr>
<tr>
<td>Rank</td>
<td>1.00%</td>
<td>0.10</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Figure 21: Weighted Scoring Matrix (WSM) for choosing between alternative concepts using new AHP
3.3 Evaluation Results

The weights generated by both the original and new AHPs were combined with a scoring of the spiral tower design and the stacking designs from our original design process to generate the Weighted Scoring Matrices (WSMs) shown in Figures 20 and 21. The spiral tower was the highest ranked design in both matrices. It had the fewest actuated components, which gave it high scores on complexity in both matrices. It also had the highest height per sheet, giving it good scores on both height metrics. Unlike all of the stacking designs in which sheets of paper were not directly connected, the direct paper connections in the spiral tower gave it another high score on the reliability metrics. Additionally, since the speed limiting step in the spiral tower was the relatively quick stapler actuation the spiral tower scored the highest on both speed metrics as well. The only criteria which was competitive for the stacking designs was the strength criteria, but as this was relatively low ranked in both systems this barely influenced the relative design rankings. Overall, the AHP and weighted scoring process confirmed our intuition that the new spiral tower design was the best design for the paper tower building task.

The order of the stacking devices is the same in both matrices, which demonstrates that the updated criteria still highly rates the accordion folding device we implemented in our original design process. However, the difference in score between the spiral tower and the highest scoring stacking design was only 1.498 in the original scoring matrix as compared to 2.59 in the updated matrix. Additionally, the difference between the accordion folding device and the next highest scoring stacking design was 1.543 in the original scoring matrix but only 0.106 in the updated matrix. The wider gap between the accordion and spiral methods in the updated matrix more accurately reflects the difference in value of the two designs, since the updated criteria is more grounded in actual performance results. Similarly, the small gap between the accordion folding device and the other devices in the updated matrix indicates that stacking devices are fundamentally less well suited for the paper tower building task than spiral designs.

3.4 Engineering Models/Relationships

Due to the current pandemic situation, the physical project was cut short before many design optimizations were made. However, initial work on optimizing the towers belt system had already begun. One such model is presented below.

3.4.1 Belt Guide Positions

In order to keep the belt from becoming misaligned on the tower, belt guides are necessary to constrain the path of the belt. Sample calculations for determining the angular and vertical positions of the belt guides given the tower dimensions, paper dimensions, and number of belt guides is shown in below.

Shown in Fig. 22 on the next page is a mathematical model of the length and width of a the press that is able to completely fold a piece of paper with a specific length and width. The optimal angle and height of the press triangles is still unknown, but once they have been determined the formula from this model can be used to determine the number of triangle needed for each face of the press and from that, the overall dimensions of the press.
Figure 22: Development of Mathematical Model for Calculating Belt Guide Locations from Tower Shape and Number of Belt Guides
4 Working Prototype

With the time we could work on our spiral paper tower device, we were able to build a prototype as seen in Figure 23. We were only able to set up the belt drive system for our device. The belt drive system embodies everything that works to move the paper up the pipe and into a spiral shape. Just like our mockup, we used the same PVC pipe and timing belt to build the prototype. We built everything on top a 50 by 50 cm wood board base. The pipe was secured to the base by first friction fitting it to a slightly smaller circular wood piece screwed to the base and then with a bracket. Figure 23 shows the four new components to our device in colored circles: stepper motors (yellow), belt guide (green), idlers (blue) and timing belt tensioner (red).
We set up two stepper motors with an Adafruit Motor Shield V2 and programmed them with an Arduino to move the timing belt. Figure 23 only shows our top stepper motor, while our second stepper motor is secured to the base next to the tensioner. With the Arduino code in Appendix A, we programmed both stepper motors to work at the same time to move the timing belt. We had the timing belt moving continuously just by plugging our system to a power source.

To prevent the timing belt from slipping up the pipe, we created a 3D printed belt guide. As seen in Figures 23 and 24, the belt guide maintains the timing belt at a fixed location on the pipe. The belt guide has an edge that prevents the timing belt from moving up while still allowing for the belt and paper to move around the pipe. The belt guide’s edge is also curved to the pipe’s diameter and is less than millimeter from touching the pipe.

![Figure 24: Belt Guide](image)

Finally, to prevent the timing belt from slipping on the stepper motors we added idlers and a timing belt tensioner as seen in Figure 23. One idler was added next to the top stepper motor to wrap the timing belt around the motor’s gear more. The second idler prevents the timing belt from sliding past a wood support. The tensioner also wraps the timing belt around the bottom stepper motor’s gear while tensioning the timing belt. Figures 23 and 25 show our created tensioner as a simple idler attached to a small sliding wood piece that is restricted from moving up by a piece of surgical tubing. Essentially, the surgical tubing presses down on the idler which tensions the timing belt.
Figure 25: Timing Belt Tensioner
5 Design Refinement

After the design of our initial prototype, there were lots of improvements that were planned in order to enhance the spiral tower’s ability and make sure the design functions within the rules of the ASME challenge.

5.1 Stapleless stapler CAM system

In our initial prototype, the main focus was on the spiral tower itself. Due to that, the connections between the paper during the test run was done by manually stapling the system, not mechanically. One of the improvements planned for the final prototype was to be able build a separate mechanism that can incorporate the CAM and Shaft to mechanically staple the paper.

The stapleless stapler was disassembled and studied to see what modifications can and should be made. A typical stapleless stapler’s interior can be seen in Fig.26.

From previous tests, it takes a significant amount of force in order to get the stapleless stapler to work. The springs can be seen in Fig.26, which are pretty stiff. The springs’ stiffness allows for good connections of up to five pieces of paper, but for our tower’s function, we only need to connect two pieces of paper. One of the springs were removed to decrease the amount of force needed to staple, and the stapleless stapler still functioned properly. Also from disassembling the stapleless stapler, not all of the support pieces need to be intact to function.
One of the obstacles with the CAM and shaft mechanism was that it needed to fix the stapleless stapler so that it is stable, while at the same time being able to have room in the bottom so that it can take in paper. This meant that the stapleless stapler cannot be fixed to the bottom of the base. The model for the initial housing can be seen in Fig. 28. A 3-D printed housing system was made so that it can hold the stapleless stapler fixed on the side, while being able to have a degree of freedom up and down so that it can actuate. The same cam and shaft system would be used to actuate the stapler. Two housing systems for the stapleless stapler will be made, one on each side of the paper as it is taken in.

However, once testing this housing, we realized that with ledges on the side, the paper is unable
to enter and be stapled. A new design for the housing has not been made yet.

5.2 Belt guides

One of the main issues and leading causes for jamming and inefficiency within the spiral tower were the belt guides. With such a small clearance space, it had a hard balancing act between providing enough room for the paper to enter, and not being too far that it does not guide the paper. The initial belt guides can be seen in Fig.29.

![Figure 29: Belt guides used. The top images are the original, and the bottom is the improved design.](image)

With our initial design, the belt guides were square and sharp, leading to a lot of contact between the tower and the guide. The improved belt guide was designed so that instead of a square shape, it matched the curvature of the tower specifically. This change increased the smoothness of the spiral tower.

Another improvement concerning the belt guides was the need for a guide at the bottom of the paper tower. In our initial prototype, the paper at times would start to crinkle and fold as the bottom corner became caught with the base, causing jamming. We found that a well placed belt guide at the very bottom of the tower can prevent the paper from starting to rise and stay within the tower causing the process to be a lot smoother.

5.3 Electronics

One other important component needed for the final prototype was a controller. The rules of the competition state that the mechanism for the spiral tower needed to be handled with a controller. Our plan was to take a console controller and configure it with the electronics so that it can be used to control the different motors.

Also, more motors needed to be attached with the stapleless stapler housing mentioned earlier so that the CAM shaft is continuously running. Throughout all of this, it is important that these new additions also fall within the size constraint of the competition.
5.4 Overall Tower Improvements

These were the main overall tower improvements that were planned for the final prototype. These improvements were necessary in order to follow the rules of the ASME challenge, as well as increase the efficiency of the spiral tower. Unfortunately, due to circumstances, the physical manifestation of these improvements never came to fruition.

6 Performance Results

Here, the performance results of the spiral tower will be compared to the paper stacking design from senior design.

As stated before, the results from the paper tower in senior design was 4 cm. of height per piece of paper, and a rate of 4 pieces of paper per minute. This gives a total of 16 cm. per minute.

Fig. 30 is a photograph of the spiral tower in its most updated form after running for approximately 30 seconds. This picture is what will be used to reference the spiral tower’s performance.

![Figure 30: Spiral tower picture taken after 30 seconds](image)

6.1 Speed

The spiral tower rose approximately 3/4 a full sheet of printer paper’s length (210 cm) in a minute. In comparison, the stacking design was only able to achieve a height increase of 16cm in a
minute. The spiral tower has a clear advantage in speed over the stacking design, producing over 10x the height in a minute’s duration.

6.2 Height

Similar to the speed test, the spiral tower was much more efficient than the stacking design. For every piece of paper, the stacking design prototype provided around 8cm. height, while the paper tower can provide approximately a whole sheet of paper’s length (210cm). The advantage for this criterion falls in favor of the spiral tower.

6.3 Strength

In terms of strength, neither structure was subjected to a strength test where weights would have been put on top of it. Instead, the stability of the structure can be inspected. As mentioned earlier, the original senior design prototype was extremely unstable, and would therefore be doubtful in being able to support weight. On the other hand, the spiral tower was able to keep connected as it steadily grew. Even though no test was properly run for these two structures, in terms of stability, which can be correlated to strength, the spiral tower also won in this case.

6.4 Final Results

Even though no formal testing was completed on the spiral tower, the spiral tower performed much better on the measured performance indicators for speed, height, and strength than the stacking design.
7 Digital ASME E-Fest: SDC Competition

7.1 1st Place: Milwaukee School of Engineering "Front Pocket"

7.1.1 Mockup

This team began by testing several different types of paper tower structures, shown in Fig. 31. Each tower was then scored based on the weighted scoring matrix shown in Fig. 32. Based on the results of this scoring, team Front Pocket decided to pursue the friction tower concept.

![Mockup Images](image1.png)

**Figure 31: Front Pocket - Paper Tower Mockups**

<table>
<thead>
<tr>
<th>Mechanical Joining</th>
<th>Accordion Tower</th>
<th>Friction Tower</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image2.png" alt="Mockup Images" /></td>
<td><img src="image3.png" alt="Mockup Images" /></td>
<td><img src="image4.png" alt="Mockup Images" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weight</th>
<th>Ease of manufacturing tower</th>
<th>Reliability of the tower</th>
<th>Speed of construction</th>
<th>Strength of the tower (5kg/min)</th>
<th>Height of the tower (1.5m)</th>
<th>Weighted Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>[1-5]</td>
<td>[1-5]</td>
<td>[1-5]</td>
<td>[1-5]</td>
<td>[1-5]</td>
<td></td>
</tr>
<tr>
<td>Accordion</td>
<td>32%</td>
<td>30%</td>
<td>19%</td>
<td>10%</td>
<td>9%</td>
<td></td>
</tr>
<tr>
<td>108.8</td>
<td>54</td>
<td>57</td>
<td>12</td>
<td>18</td>
<td></td>
<td>249.8</td>
</tr>
<tr>
<td>2.2</td>
<td>2.4</td>
<td>3.2</td>
<td>2.2</td>
<td>3.6</td>
<td></td>
<td>257.6</td>
</tr>
<tr>
<td>Paper Staples</td>
<td>70.4</td>
<td>72</td>
<td>60.8</td>
<td>22</td>
<td>32.4</td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>3.8</td>
<td>3.4</td>
<td>5</td>
<td>4.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Friction tower</td>
<td>108.8</td>
<td>114</td>
<td>64.6</td>
<td>50</td>
<td>41.4</td>
<td>378.8</td>
</tr>
</tbody>
</table>

**Figure 32: Front Pocket - Scoring Matrix**
7.1.2 Prototypes and Revisions

Figures 33, 34, and 35 show team Front Pocket’s initial prototypes and revised prototypes. Paper is fed into the extruded aluminum body and is wrapped around a central cylinder so that each subsequent piece overlaps tightly with the piece that preceded it. The cylinder is driven by a single stepper motor at the base of the device. To advance the paper vertically, several motor driven omni wheels are positioned along the body of the device. Throughout the revisions, additional components were added to help constrain the path of the paper during both the feeding and wrapping processes.

![Revision 1](image1)
![Revision 2](image2)
![Revision 3](image3)

Figure 33: Front Pocket - Original Prototypes

![Revision 1](image4)
![Revision 2](image5)
![Revision 3](image6)

Figure 34: Front Pocket - First Design Revision
7.1.3 Results

Figure 41 displays the results for the speed, height, strength, and elimination test, as well as images of the final design.

Device Performance Summary

- Maximum height reached in 10 min: 4.8m
- Fastest speed to 1.5m: 1:08
- Maximum weight held at 1.5 height: 2kg
- Best elimination round time: 1:30
7.1.4 Optimizations

Team Front Pocket’s major optimization was building their prototype design out of an extruded aluminum frame. This allowed them to rapidly test different configurations of motors, wheels, and other elements and allowed them to go through several more design revisions than our team. Additionally, their system used IR sensors as a control device. While this likely did not increase their performance by much, it stood out as an innovative approach to system control.

7.2 2nd Place: Milwaukee School of Engineering ”Paper Jams”

7.2.1 Mockup

When prototyping, the team decided to go with a cylindrical shape for the tower. The tower was split into two types of functions to compensate for the different testing phases: one design for the speed and height test, and another for the the strength test.

For the speed and height test, the tower would be formed by essentially using the friction of the paper when they overlapped one another. It will also be using a collar tag type of connection to more firmly make these connections. For the strength test, the tower will consist of rolls of paper to hold up the weight. The mockup tests for the two design can be seen in Fig. 37.

![Tower Design](image)

Figure 37: Mockup designs for the two designs
7.2.2 Components and Final Design

The different components for the paper tower can be seen in Fig. 38. The paper goes in through a paper feeder, which guided along a track where it is secured by a slit and allows the paper to wind on itself. The weight of the tower is supported by a Donut, and then the component is lifted with a rack and pinion mechanism.

![Figure 38: Components of the design](image)

The final CAD model can be seen in Fig. 39 and the actual final prototype in the 50cmx50cmx50cm box can be seen in Fig. 40.

![Figure 39: CAD model](image)
7.2.3 Results

Figure 41 displays the results of the height and speed tests while Fig. 42 displays the results of the strength test. No results were recorded for the elimination challenge.

### Tower Building – Height & Speed

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Pieces of Paper</th>
<th>Time Required [min]</th>
<th>Height [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>26</td>
<td>5.8</td>
<td>4.62</td>
</tr>
<tr>
<td>Speed</td>
<td>9</td>
<td>2.0</td>
<td>1.60</td>
</tr>
</tbody>
</table>

Figure 41: Height and Speed test
7.2.4 Optimization

The focus of this team seemed to be to limit the actuators needed and to use mainly the cylindrical shape as the backbone for the design. The paper was altered very minimally, as it was only fed and wound up, using the friction in between to serve as the connection, giving pretty good height. The strength portion also only relied on winding up the paper. The decision to split the different tests to two designs proved to be helpful.

7.3 3rd Place: University of Illinois Urbana Champaign

The team built two different devices for the competition. One paper tower device was used for the speed and height rounds of the competition, while the other device was used exclusively for the strength round. As seen in Figure 43, the team created a vertical paper tower design for the speed and height rounds. The design has semi-folded pieces of paper wrapped around each other and stapled together with the red stapleless stapler.
The team’s final vertical paper tower device uses LEGO™ Technic Wheels to move the vertical paper tower up while a stapleless stapler activated with a linear actuator staples the sheets of paper together. This system is elevated by an aluminum base that allows the operator to feed semi-folded sheets of paper into the bottom of the device. The team had three iterations of the stapleless stapler and paper funnel system that would properly control the paper’s movement into the stapleless staple. This system also keeps the wheels stationary. The team’s vertical paper tower device is shown in Figure 44.
Finally, the team used rolled sheets of paper as their paper tower for the strength round. Essentially, the team would insert rolled sheets of paper into orange cups that would rotate 90 degrees from a horizontal position with a servo motor. Each rolled sheet of paper would be inserted inside the previous sheet in the orange cup. The paper tower is composed of three paper pillars supported by a triangular base. Figure 45 shows the strength paper tower device in a testing position.
Overall, the team had good results for each of the rounds. For the speed round, the vertical paper tower device took 59 seconds to build a 1.5 meter high paper tower. For the height round, the vertical paper tower device built a 2.55 meter paper tower in ten minutes. Lastly in the strength round, the strength paper tower device created a paper tower that could hold 18 pounds.

8 Conclusion

The paper tower challenge was a difficult engineering task and required students to construct a sturdy tower out of an especially finicky material. Our approach, connecting paper sheets with a stapless stapler and rolling the paper up a cylindrical tower, is in line with the fundamental concept of each of the winning designs. As a result, we believe that if our device had been completed it would have been able to construct a respectable paper tower. However, two of the winning teams used pure friction to connect their pieces of paper and the third team utilized the stapless stapler in a different manner than our team. In retrospect, we should have done more initial testing in the paper tower mockup phase as this would have allowed us to weigh the merits of these alternative approaches. Additionally, our team encountered significant difficulty in attempting to design for all three challenges simultaneously. Two of the top placing teams solved this issue by using different designs for the height/speed and strength competitions, which we did not consider. However, we are satisfied with the design process and prototype that were created in this project, given the circumstances under which the project took place.
A Arduino Code

```cpp
#include <Wire.h>
#include <AccelStepper.h>
#include <Adafruit_MotorShield.h>
#include <Adafruit_PWMServoDriver.h>

// Create the motor shield object with the default I2C address
Adafruit_MotorShield AFMS = Adafruit_MotorShield();
// Or, create it with a different I2C address (say for stacking)
// Adafruit_MotorShield AFMS = Adafruit_MotorShield(0x61);

// Connect a stepper motor with 200 steps per revolution (1.8 degree)
// to motor port #2 (M3 and M4)
Adafruit_StepperMotor *myMotor1 = AFMS.getStepper(200, 1);
Adafruit_StepperMotor *myMotor2 = AFMS.getStepper(200, 2);

void setup() {
  Serial.begin(9600); // set up Serial library at 9600 bps
  Serial.println("Stepper test!");
  AFMS.begin(); // create with the default frequency 1.6KHz
  //AFMS.begin(1000); // OR with a different frequency, say 1KHz
  TWBR = ((F_CPU / 400000L) - 16) / 2; // Change the i2c clock to 400KHz
  myMotor1->setSpeed(180); // 10 rpm
  myMotor2->setSpeed(180);
}

void loop() {
  // Serial.println("Double coil steps");
  // myMotor1->step(600, FORWARD, DOUBLE);
  // myMotor2->step(600, FORWARD, DOUBLE);
  // myMotor1->step(600, BACKWARD, DOUBLE);
  // myMotor2->step(600, BACKWARD, DOUBLE);
  // delay(2000);

  for (int s = 0; s < 200; s++) {
    myMotor1->step(1, FORWARD, DOUBLE);
    myMotor2->step(1, FORWARD, DOUBLE);
  }
  //delay(2000);

  // for (int s = 0; s < 600; s++) {
  //  myMotor1->step(1, BACKWARD, DOUBLE);
  //  myMotor2->step(3, BACKWARD, DOUBLE);
  // }
  // delay(2000);

  //myMotor->release();
}
```