ME 450 WN 2021
Digitizing the Dry-Erase Whiteboard

Team 26: Mahfuj Ahbab, Angelina Sallan, Justin Shim,
Nathan Stoetzel, Alexander Waye

University of Michigan, Ann Arbor
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Executive Summary

The modern dry-erase whiteboard has become a tried-and-true educational tool synonymous with teaching and brainstorming. The strengths of the dry-erase whiteboard are familiar to students and teachers alike. The dry-erase marker and whiteboard combination is an extremely easy and effective tool to quickly jot down ideas and collaborate, and the large surface area and high-contrast appearance makes words and drawings easy to visualize and discuss. However, the rise of digital hardware like the Apple iPad has highlighted important weaknesses with the dry-erase whiteboard. Running digital writing softwares like Microsoft OneNotes, devices like the iPad allow users to write on an "infinitely" large surface and quickly save past notes and ideas in a digital format such as a PDF. In addition, the process of scrolling, writing, and erasing are extremely intuitive. But with all the strengths of the digital writing experience, there are also an equal number of weaknesses. It is naturally more difficult to collaborate with digital writing tools, and some research shows that the lack of physical, haptic feedback when writing on a glass screen can hinder learning and handwriting quality [1].

Our goal was to create a small scale prototype that "digitizes" the dry-erase whiteboard. We succeeded in creating a physical prototype that more than triples the total writing area of a traditional whiteboard. This prototype can also erase markings made on the whiteboard without the user erasing by hand. We have also developed an algorithm to digitize the written work using a Raspberry Pi camera.

While this early prototype serves as a useful proof of concept, the design falls short in several key areas. The motor coupling was originally designed to use a set of gears, but the imprecise conveyor roller mounts allow the gears to become misaligned. The prototype also has exposed gearing which should be enclosed in a final product. There are a number of issues with the current writing surface that should also be resolved.

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Problem Description and Background

Often in group meetings, teams get together to share thoughts and generate new ideas by collaborating on a dry-erase whiteboard. But as the meeting progresses, at some point, the whiteboard will be filled to capacity with countless scribbles resembling ideas and possibilities. Though the brainstorming is not near its end, the board must be erased, and the session shifts to an unorganized rush to save the information on the board. The information will be saved, but it will likely be stored in various formats that don't capture the same spark or feel of the original whiteboard.

With the advances in modern digital technology, devices like personal tablets, digital whiteboards, or even iPhone apps have come to emulate parts of, or the entire, whiteboard experience. In addition, these technologies incorporate the benefits of modern operating systems such as an infinitely large digital writing surface and quick saving or cloud backup. Though these devices seem to solve the problem presented in the previous whiteboard situation, the experience of writing with a stylus and digital ink is not nearly as comfortable for users who have grown up with the familiar dry-erase marker sensation. Many of these digital surfaces are smoother than physical writing surfaces. It has been shown that both children and adults compensate for this decrease in proprioception by relying on increasing the pressure they use to write [2] and by relying more heavily on their eyesight [3]. As a result, writing quality can drop and be less legible, among other negative effects.

As illustrated below in Figure 1, there are several products that occupy the space of basic writing and erasing, electronic capabilities (like infinite writing area and quick saving), and the "natural" writing feeling. Dry-erase whiteboards, though extremely practical and effective, lack the benefits offered by digital technology. On the other hand, digital devices that allow users to erase and write still lack the "natural" writing feeling that we are all accustomed to. The motivation for this project is to create a physical prototype that "digitizes" the dry-erase whiteboard using a combination of mechanical design, embedded systems, and algorithm development. In doing so, we hope to push the dry-erase whiteboard into the digital world and fill a clear gap in the market.

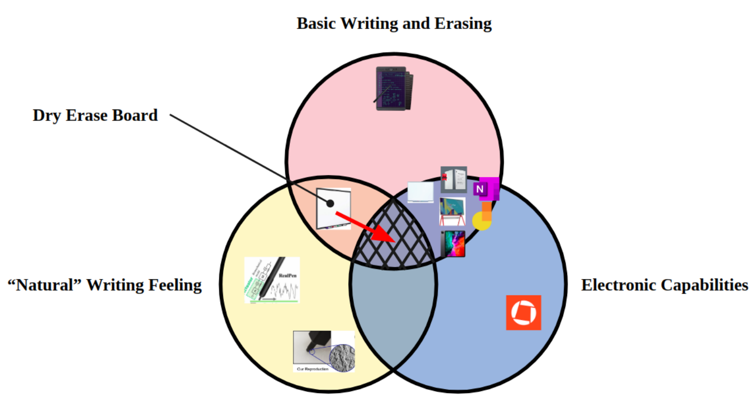


Figure 1. Diagram of the aspects of available products for note taking and office collaboration. Many products with the ability to take notes and use digital features attempt to add the natural feeling of writing but fall short. Our solution is to start with a physical product and add the electronic capabilities.

Benchmarking

To better understand the space and justify engineering requirements and specifications for our product, we benchmarked several existing products and conducted a thorough literature review on current relevant research. To illustrate the gap in the market for products that offer basic writing and erasing, digital capabilities, and the "natural" writing feeling, we benchmarked software products, handheld devices, and mounted products. Though these categories vary in size, price, and complexity, they all attempt to emulate or improve on aspects of the whiteboard experience.

Software Products

Three existing software products were benchmarked: Microsoft OneNote, Genius Scan, and Google Jamboard. Microsoft OneNote is a software used for basic digital writing and note-taking and features the full suite of digital capabilities. From our experience, OneNote takes few actions to write, erase, and scroll, making it an intuitive experience for users. However, it still lacks the natural writing feeling.

Genius Scan is a tool used by many students that allows them to transfer their physical writing into a PDF by utilizing a smartphone camera. Again, our testing shows that it is an intuitive experience to use, but is not an all-in-one solution to note taking.

Finally, Google Jamboard is a digital whiteboard software that is similar to Microsoft OneNote, the main difference being the ability to collaborate with multiple users at the same time.

From the benchmarked software solutions, we recognize the importance of an intuitive user experience that can be quantified by either the number of actions or time to write, erase, and scroll.

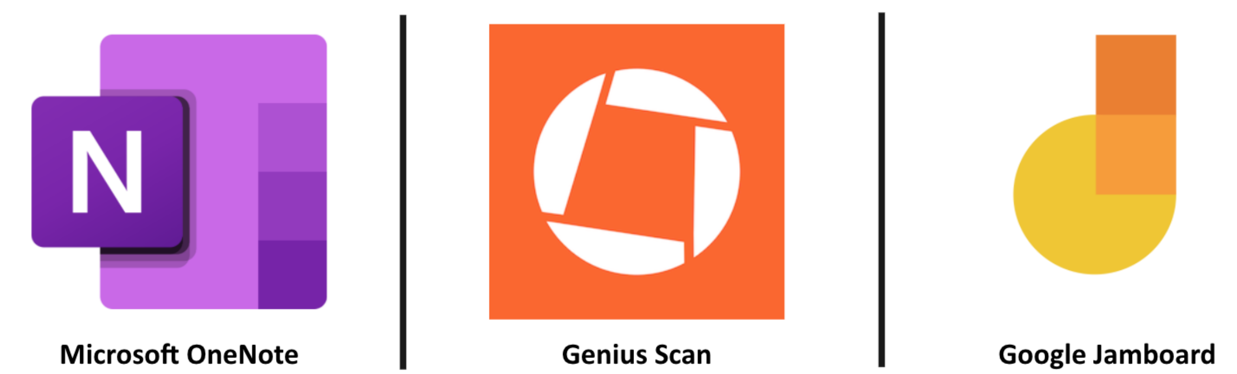


Figure 2. Benchmarked software products.

Handheld Products

Three tablet products were investigated: the Boogie Board Blackboard Letter, the reMarkable Tablet, and the Apple iPad. The Blackboard Letter is a low-end tablet which cuts costs by using a resistive touchpad to register writing, along with a companion app to save and access notes. The reMarkable tablet is a high-end digital notebook aimed at customers who highly value the natural writing experience.

reMarkable achieves this by utilizing a CANVAS display which mimics the feel of pen and paper. Finally, the Apple iPad is a high-end, general purpose tablet with note taking functionality.

From the analysis of handheld products we identified the major costs associated with digital notebooks, those being the touch screen technology and the operating system.

Figure 3. Benchmarked handheld products.

Mounted Products

Three mounted digital writing products were investigated: the generic dry erase board, the SMART Board 800 Series, and the Vibe Board. The generic whiteboard excelled in being low-cost and simple, however its inability to save work digitally is one we hope to address in our product. The SMART Board 800 Series is intended for classroom use, and it is unique in that it utilizes infrared sensors to detect touch. However, at a sticker price of several thousand dollars, it may prove prohibitively expensive for some. Furthermore, it comes with a suite of companion software which can make it difficult to use for the technologically unsavvy. Finally, the Vibe Board is a digital whiteboard intended for enterprise use. It utilizes capacitive touch technology to detect touch. Although less expensive than the SMART Board, it remains prohibitively expensive for some.

Figure 4. Benchmarked mounted products.

Benchmarking Summary

When benchmarking these existing products, we identified key features that made the digital writing experience superior to the physical one. At the same time, we identified key deficiencies in digital writing products compared to traditional whiteboards.

Perhaps the largest advantage of digital writing products over traditional whiteboards is their ability to save work in a digital format. This was common across all tablets, virtual whiteboards, and online writing softwares that we analyzed. The traditional whiteboard's inability to preserve written work greatly limits how effective they are for solving large, complex problems. Another factor which limits the traditional whiteboard is its limited writable surface area. Some digital writing products address this with virtual scrolling functionality.

The biggest advantage of a traditional whiteboard is simplicity and its associated benefits. The traditional whiteboard is affordable which cannot be said for all digital writing products, some of which cost several thousand dollars. A great deal of the price is due to proprietary software and firmware, costly accessories, and advanced touch technology. Some of these factors, such as proprietary software, can also make the devices tricky to use and troubleshoot.

Digital writing products that are not prohibitively expensive come with their own drawbacks. Many digital writing softwares, such as Microsoft OneNote or Google Jamboard, support synchronous and asynchronous collaboration. However, they require the use of an electronic stylus which fails to capture the tactile feel of a marker and whiteboard. Some products, such as the reMarkable Tablet, go to great lengths to bring the physical writing experience to a digital environment. However, tablets lack the functionality for real-time collaboration that is central to the whiteboard writing experience.

It is our goal to realize the saving and scrolling advantages of the digital writing experience while also retaining the tactile writing experience and collaborative nature of the traditional whiteboard, all at a reasonable price to the consumer. Figure 1 illustrates where our idea fits in the current digital and physical writing landscape.

Literature Review

To justify requirements and specifications for our device, we conducted a literature review examining the potential benefits and drawbacks of physical and digital writing. Piovarci emphasizes the importance of haptic feedback in the writing experiences and attempts to fabricate writing tools with feedback potential [4]. Specifically, Piovarci highlights the importance of haptic feedback for artists, which allows them to have precise, controlled strokes and avoid relying on hand-eye coordination. Furthermore, he argues that although digital technology has made great strides in attempting to replicate the appearance of physical writing tools like pencils and markers, the lack of haptic feedback is often a deal-breaker for artists. Although our product is not targeting artists, a similar sentiment seems to exist amongst the educational community.

In addition, there are possible differences in learning (memorization) between users of a digital pen or ink pen. Groups who are familiar with using e-ink can actually improve their learning ability with using e-ink over regular ink [1]. The problem though is that devices such as tablets are generally pretty expensive, so not all people may be familiar or comfortable with using e-ink. Therefore, a more cost-effective, physical product with digital capabilities would be of interest. Again, although this study doesn't directly study the dry-erase whiteboard, its statements are more general about the difference between the physical and digital writing experience.

Problem Statement

As explained above, there does not seem to be a product on the market that combines the electronic elements of digital note-taking softwares with the proprioceptive feedback of writing on a white board. Many of the solutions presented above attempt to take electronic products and add proprioceptive feedback. For example, some screen protectors on iPads add a frictional layer to the screen to increase the feedback when writing. These solutions prioritize the digital elements and add the physical elements to the digital solution. For this project we are attempting to add the digital features to a physical product.

Our goal is to create a small scale prototype that "digitizes" the dry-erase whiteboard. The prototype will

1) Increase the area of the writing surface without increasing the amount of space the board takes up on a wall or in a space.
2) Can be written on with commercially available dry erase markers in a way that resembles a typical dry erase board.
3) Allow users to save work that has been done on the board to a PDF file.

The prototype will use a combination of mechanical design, embedded systems, and algorithm development to accomplish these three features. In doing so, we hope to push the dry-erase whiteboard into the digital world and fill a clear gap in the market that affects office workers, students, teachers, and researchers.

Functional Requirements

Survey Feedback

We conducted a survey and asked the respondents general demographic questions along with their preferences with regards to writing mediums. To begin the respondents are asked how often they find themselves using a whiteboard and to identify the setting. This provides us with a general idea of where a whiteboard is typically used and who our main stakeholders are. 92.6% of respondents indicated that they use whiteboard in their academic life compared to 14.8% who use a whiteboard in their work life. The respondents were then asked how often they needed to erase their work in one session, 37% of respondents reported that they erased their whiteboard 3 or more times during one session, 33.3% erased their whiteboard 2 times and 29.6% only erased their whiteboard once during a session. We also asked the respondents to estimate how long erasing a full whiteboard took them, 59.3% claimed it took anywhere from 10-30 seconds. We asked the respondents to identify what method they prefer to write with and then asked what they liked and disliked about their selection. We received a range of answers but the two most prominent were typing on a laptop and the use of pen and paper. Then we asked the respondents to identify their likes and dislikes about using whiteboards. The general consensus was that users enjoy the erasabilty and feel of the whiteboard and its large size is optimal for collaborative work. The users general dislike was surrounded around the amount of time taken up by erasing, the limited amount of space, and the fact that the work written on the board cannot be saved. The survey responses can be seen in full in the appendix.

Functional Requirements

A set of functional requirements was determined based on the stakeholders' needs. In the case of this project, our team is the stakeholder and has collectively come up with the following functional requirements, shown in Table 1. The core of these requirements is that the product is a competitor to the average office whiteboard, offers more writing space than is physically available, and offers saving features for exporting work. Additionally, the ability of the board to self-erase is ideal. Other, lower priority, requirements are that the board can export the files wirelessly and that the board is simple to set up and mount into an arrangement. Table 1 lists each functional requirement in order of importance, as well as provides a short description for each.

Table 1. Ranked list of functional requirements with a corresponding description to detail the entailment of each requirement.

Rank	Requirement	Description
1	Maintain Natural Feel	Experience of using the board must compete with that of a standard office whiteboard in terms of writing and erasing feel, as well as function with commercial markers. This requirement is ranked #1 since we do not want the whiteboard "feel" to be lost.
2	Ability to Increase Writing Area	Primary goal of this product is to remove the need to erase once the board is filled. Once the board's capacity is reached, user should be able to expand in order to continue writing.
3	Ability to Save and Export Work	When a user is finished working during the session, written work can be saved and exported to a common file type to be shared with others.
4	Automatic Erasability	Board can be conveniently erased with minimal interaction from the user. Alternatively, the user can still erase by hand, if they so choose.
5	Ability to Retrieve Past Work	Just as the board can expand to increase the overall writable area, the board must also be able to retrieve the information that was hidden away in a quick and intuitive manner.
6	Intuitive User Interface	Overall, the board is quick and easy to understand. Any user can efficiently use the board during first confrontation.
7	Mountability	Board can be mounted to a wall or a stand without modification.
8	Quick and Easy to Set Up	Board can be quickly removed from mount and set up in another arrangement with speed and ease.

Engineering Specifications

Based on the list of functional requirements that were developed by our team, as stakeholder requirements, a corresponding set of specifications was created as a measurable and testable conclusion of our design's success. These specifications will guide our design space and concept generation processes, while also serving as benchmark for our prototype testing and evaluation of our final product.

The specifications for each corresponding requirement are shown in Table 2, below. For clarity, the requirements are repeated, in ranked order according to Table 1.

Maintain Natural Feel

The most important requirement for our project is that we do not stray away from the physical and tactile connection that brings users to choose to collaborate and present on whiteboards over their technological counterparts. While our team does not expect much design challenges around this requirement, as the materials and methods we expect to use will be that commonly associated with whiteboards, and thus, will likely maintain much of the tactile feel of writing with these tools. Due to the complexity of quantifying writing experience and similarity of proposed materials, this aspect will be quantified simply by prototyping the board and gathering survey results on the similarity of writing experience, as has been done for similar products [5]. Additionally, in order to keep with the expectations of a traditional whiteboard, our design must deliver on the promise of working with commercially available utensils, as well as give the user(s) the ability to erase with their hands as a simple and quick solution is misplaced ink.

Ability to Increase Writing Area

One of the important issues with traditional whiteboards, which we set out to solve, is the monotonous and time consuming act of erasing the board once it has reached its capacity. This, combined with the loss of information when the board is erased, leads to the solution of simply extending the writable area to increase the overall space of the whiteboard. The target size of this project is typical 3' x 4' whiteboards that can be used for collaborative and personal uses. Thus, one deliverable is to maintain this size for the visible area of the board at any time. Our second deliverable is answering the question of how much total space does this board need to have. We plan to collect survey data from students, professors, and researchers that frequently use whiteboards for school, work and personal use. We are collecting data to find how often these people erase the board. This data will be used to calculate how much total space would be most beneficial to the average user.

Ability to Save and Export Work

In order to quantify the saving and exportation of the work done on this board, we want to make sure that the file is stored in a relatively small file, as to be convenient for the user to store on their personal devices, as well as ensure that the file can be exported in a timely manner such that the exportation process is efficient. One of the most common and accessible file formats is a Portable Document Format, also commonly known as a PDF. The size of PDFs vary, but PDFs converted from images tend to be the largest. GeniusScan is a software product, developed by The Grizzly Labs, that allows users to use their phones in order to convert images into PDFs, and is one of our benchmarked products. According to the company's troubleshooting guide [6], each page in a converted PDF document can take up to 4 MB. Based on our previous deliverable of having five times the display area of the total writable area, and if we assume that each display area is one page in the exported PDF, then our final file would be about 20 MB. If we then incorporate a 10% safety factor, our specification becomes keeping the saved PDF file under 22 MB.

Automatic Erasability

In addition to the ability of this product to automatically erase, we would like to quantify the speed and quality of the erasing mechanism. The average size of a commercial whiteboard eraser is 5.25" x 2.5", which is an area of roughly 13 square inches or 0.091 square feet. If we approximate a comfortable linear speed of 2.65 feet per second, we calculate an erasing speed of 0.23 square feet per second. Using our total board size specification of 60 ft^2, we can calculate that the expected time to erase would be 247.74 seconds. This time, of course, is based on erasing solely by hand. If we are to incorporate automatic machine erasing, we should be able to reduce by at least 20%, thus our goal is a time of less than 200 seconds. Ideally, 100% of the board would be cleared, but to account for error, we also set a specification that greater than 95% of the board will be cleared in this time.

Ability to Retrieve Past Work

Incorporated into our requirement of "Ability to Increase Writing Area", in which the filled board is hidden to reveal a clean slate to continue writing, it is also imperative that the inverse of this operation is also available to the user. This ensures that the user can go back to work that was done previously in order to review or edit the material. The specifications for this requirement in terms of speed and ease mirror that of "Ability to Increase Writing Area".

Intuitive User Interface

In order to quantify the simplicity of the user interface, we need users to offer feedback after seeing and using the interface. Success in this regard occurs when more than 95% of users can perform the basic functions of the device in their first attempt at using the device. This specification was determined by our team on the basis that 100% of users can simply interact with the interface, with a 10% margin for error.

Mountability

In order for this board to be mountable, there needs to be a support structure that can support the weight of the board. Whether this board is mounted to a stationary wall or a movable stand, we must ensure that the structure can support the weight of the board. Therefore, we impose a total weight restriction of 50lbs, in which the final design cannot exceed. Additionally, for ease of mounting with common fastening hardware, we also impose a thickness constraint of 4 in. If the board exceeds this thickness specification, it may be too difficult to mount in many arrangements.

Quick and Easy Setup

In order to ensure ease of setup, we specify a setup time as a metric of both the overall speed and ease of assembling and mounting this design. Our team set a maximum setup and mount time of 10 minutes to ensure that the product is simple and quick to set up.

Table 2. Ranked list of requirements with associated specifications and deliverables.

Requirement	Specifications and Deliverables
Maintain Natural Feel	Survey data reports that >80% of users say that feel of writing is similar to that of a whiteboard [5]
	Uses commercially available whiteboard markers and erasers
	Can erase with both hands and typical whiteboard erasers
Ability to Increase Writing Area	Writable area visible at any time ("display" area) is at least 12 sq. ft.
	Total Writable Area is at least 3 times "display" area = 32 sq. ft.
	Can reveal new "display" area in less than 15 seconds
Ability to Save and Export Work	Handwritten work can be saved as a pdf file that is no greater than 22 MB [6]
	Work can be exported to a computer or phone in < 60 seconds
Automatic Erasability	>95% of writing can be cleared in no more than 200 seconds
Ability to Retrieve Past Work	All work written during session is saved for entire duration of session
Intuitive User Interface	>95% of people understand how to draw, erase, save and export files within 30s on first attempt for each task [4].
Mountability	Total weight of board does not exceed 80 lbs [7].
	Total thickness of writing surface must be less than 3 inches.
Quick and Easy to Set Up	Can be mounted by a team of two, in no more than 2 hours [8]

Concept Generation

Once the benchmarking process and specification outline were complete, we were ready to begin the concept generation phase of development. Our approach to concept generation was intended to promote divergent thinking; we developed several design ideas with little consideration for feasibility which would only stifle the creative process at this stage.

First, we derived key problems from our design specifications, ones that would certainly need to be addressed regardless of the final design. These key problems were Writing, Auto-erasing, expanding writable surface area, and sensing. From there, we utilized a mind map to map out several solutions to each problem. This method proved to be useful for generating a wide range of ideas for us to whittle down. Figure 5 depicts the final mind map.

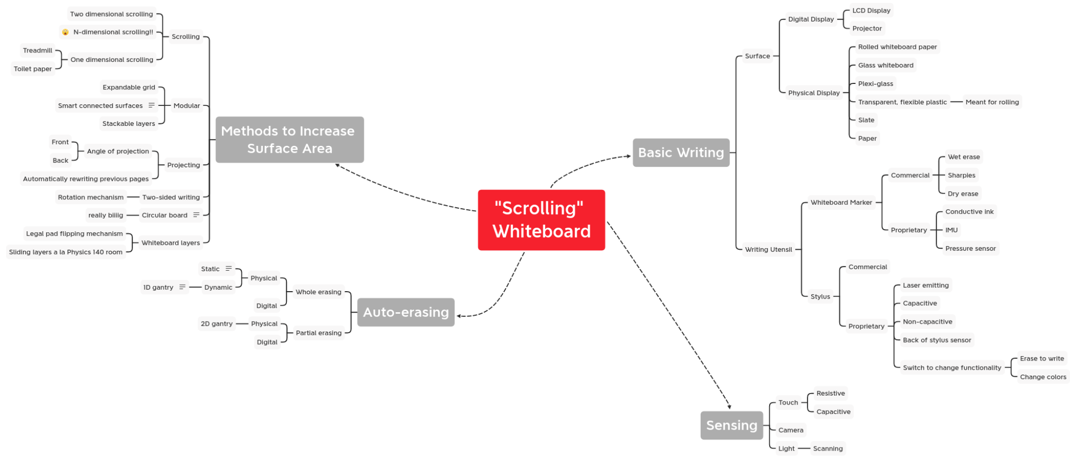


Figure 5. A mind map was developed during the concept generation phase to generate a wide range of solutions to key design problems.

Concept Development

During the concept development phase, we aimed to transition to a more structured approach to our design problem. While the concept generation process resulted in a wide array of ideas for each sub function, it was difficult to see how any one of the ideas could contribute to a comprehensive design solution. To achieve our more structured approach to our design problem, we used a morphological analysis chart shown in Figure 6 to categorize and organize the potential solutions in our mind map. Rows indicate different, previously determined subfunctions, while columns describe solutions to the respective subfunction. The subfunctions listed in the morphological analysis chart include: Writing Surface, Auto-Erasing, Adding Writing Space, and Digitizing. Solutions/parameters for each sub function were identified by finding commonalities between different feasible ideas in our mind map.

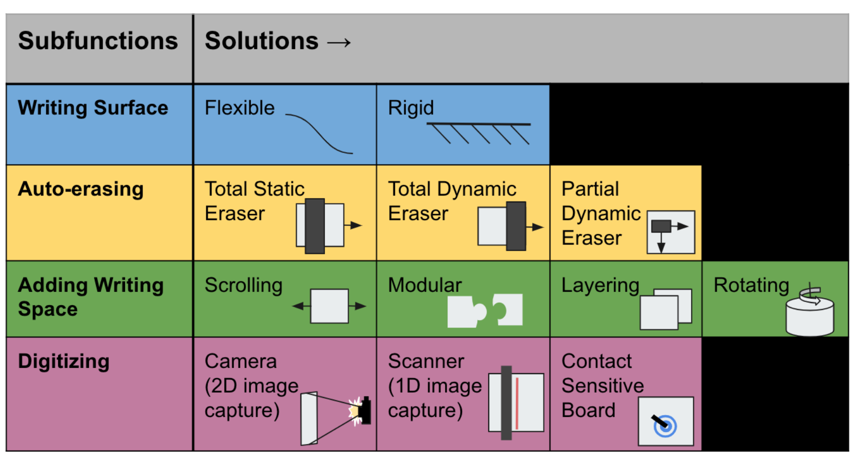


Figure 6. Table of subfunctions and solution ideations in the morphological analysis. The subfunctions determined are the flexibility of the writing surface, the type of erasing, the method of adding writing space, and the sensors used to convert from physical to digital writing.

For the writing surface subfunction, we identified two independent, abstract solutions: flexible and rigid. Writing surfaces are deemed flexible if the surface is innately flexible but also not directly attached to the hard backing surface. With this definition, a traditional dry-erase board would not be considered flexible, even though the laminate on the dry-erase surface is innately flexible. On the other hand, a design that involves laminate hovering closely above a hard backing surface would be deemed flexible. A writing surface is deemed rigid if the surface is directly attached to the hard backing surface. In addition to a traditional dry-erase board, a glass writing surface would be deemed rigid. These two solutions encapsulate the various writing surface materials and design concepts that were enumerated in our mind map.

For the auto-erasing subfunction, we identified three independent, abstract solutions: total, static erasing; total, dynamic erasing; and partial, dynamic erasing. These solutions themselves are the products of two underlying parameters for erasing solutions that we determined: total or partial and static or dynamic. With total erasing, the white board can only be erased all at once, while with partial erasing, the white board can erase in specific, user-defined areas of the board. With static erasing, the erasing mechanism doesn't have the ability to move with respect to the writing surface, while with dynamic erasing, the erasing mechanism does have the ability to. With these two categories of underlying parameters, we generated three solutions that encapsulate the various auto-erasing concepts that were enumerated in our mind map.

For the ability to add writing space, we identified three independent, abstract solutions: scrolling, modular, layering, and rotating. Scrolling solutions would aim to replicate the scrolling experience on a tablet or touchscreen surface. Modular solutions would increase the writing surface by allowing users to connect additional boards to the original writing surface. Layering solutions would increase the writing surface by revealing additional writing surface beneath the original writing surface. Rotating solutions would increase the writing surface by revealing new surfaces out of plane of the current surface. These four solutions encapsulate the various concepts for adding writing space that were enumerated in our mind map.

And finally, for the digitizing subfunction, we identified three independent, abstract solutions: 2D Image capture, 1D image capture, and a contact sensitive board. 2D image capture solutions would save writing on the board all at once, similar to how a camera functions. 1D image capture solutions would save writing on the board by traversing the board in one direction and "scanning" writing line-by-line, similar to how a printer scanner functions. Contact sensitive board solutions would save writing on the board in real-time by replicating the tablet, touch-screen experience. These three solutions encapsulate the various concepts for digitizing writing that were enumerated in our mind map.

Concept Evaluation

Using the morphological analysis table shown in Figure 6 above, we combined the subfunction solutions to generate $2 \times 3 \times 4 \times 3 = 72$ unique design concepts. For each of these solutions, we did a gut check based on how well each solution addressed the problem at hand and how feasible each design was. We narrowed the solution space down to 6 design candidates. We then compared the 6 candidates using a decision matrix to determine the design concept we would develop further.

Evaluation Criteria

Most of the proposed solutions met or could be modified to meet the design specifications shown in Table 2. Because of this, we need to find other criteria to compare the design concepts. We used the following criteria in our concept evaluation: ease of use, software simplicity, writing area to physical size ratio, mechanical simplicity, cost, manufacturability. We assigned weights to each criterion based on their relative importance.

Ease of use. We define ease of use as the ease of writing, erasing, saving, and accessing the added writing space. Designs that are easier to use received a higher score for this criterion than those that are harder to use. ince ease of use determines how effectively users interact with the final product, we determined that this is the most important evaluation criterion. We assigned a weight of 5 for ease of use.

Software simplicity. We define software simplicity as the ease of implementing the software and electronics required to digitize the writing on the board. Designs which have simple software requirements will receive a higher score for this criterion than those with complex software requirements. This is not a user-centered criterion, so we did not deem this the most important criterion. That being said, given the short timeline of this project and the relative inexperience of our team with software design, complex software could be a bottleneck in the implementation of our solution. For this reason, we assigned it a weight of 5.

Writing area to physical size ratio. We define the writing area to physical size ratio as the ratio of the total writing surface (including the area that may not be available for writing on at all times) to the amount of space our solution takes up in a room. Designs with large available writing areas that take up very little space receive higher scores for this criterion than those with small writing areas that take up a large amount of space. One of the driving purposes of this project is to find an economical use of a work space. For this reason, we assigned this criterion a weight of 4.

Mechanical simplicity. We define mechanical simplicity as the difficulty in implementing the mechanical aspects of a design candidate. Designs that have simple mechanical designs receive higher scores than those with complex mechanical designs. Similar to software simplicity, a complicated mechanical design may be a bottleneck implementation of our solution, but our team has more experience with mechanical design. For this reason, we assigned this criterion a weight of 3.

Cost. We define cost as the cost of implementing a design candidate. Designs with lower cost receive higher scores for this criterion than those that are expensive. A solution that is expensive to implement will likely be expensive to buy if this product is brought to market. We would like this product to be accessible to a large number of potential users, so we would like the cost to be low. Additionally, this project has a budget of $400. We do not see these being the biggest differentiator between our design candidates. For this reason, we assigned this criterion a weight of 2.

Manufacturability. We define manufacturability as the difficulty to manufacture a prototype of a design candidate. Designs that are easier to manufacture received a higher score for this criterion than those that are harder to manufacture. Designs that are difficult to manufacture may be more expensive, but they may also make prototyping the designs take longer. That being said, since this prototype will likely not need to be manufactured in mass production, we assigned this criterion a weight of 1.

Initial Concepts

Concept #1: Flexible, Total Static, Scrolling, 2D Image Capture

The first concept, as shown in Figure 7, was conceived with the scrolling method for adding writing space. The scrolling is achieved by stepper motors and idler wheels that function somewhat like a treadmill. However, rather than a continuous connection between the writing surface as it rolls past the edge of the board, the writing surface material actually rolls up onto a tube. As a result, the two tubes that serve to roll up the surface material are similar in nature to a roll of toilet paper, adjoined to the tube at the end of the roll. The stepper motors actuate both rolls of paper in tandem according to the direction of scrolling defined by the user. This design also features two static erasers that are initially above the writing surface but can be actuated downward to erase. Two static erasers are necessary to ensure that all writing can be erased at the end of either tube. Finally, to digitize and capture writing, the design features a thin "black box" at the back of the writing surface with a camera. The camera uses 2D image capture to save the writing in the form of a picture, and a black box is used to control the exposure of the camera.

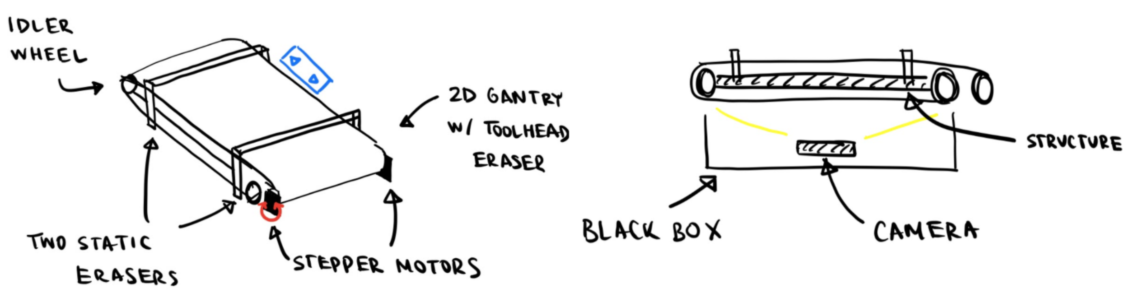


Figure 7. Diagram of concept #1

Concept #2: Rigid, No Erasing, Modular, Contact

Perhaps the most important feature of the second design is its departure from the scrolling mechanism found in Concepts 1, 4, and 5 in favor of using modularity to expand writable surface area. Each whiteboard 'tile' is fitted with male connectors on the top and left sides as well as female connectors on the bottom and right sides. It is also equipped with a resistive pad to detect touch and an Arduino to transmit relevant information to a master computer, in this case a Raspberry Pi. Each whiteboard tile communicates its unique ID to adjacent tiles and to the master computer. This information allows the master computer to 'construct' the whiteboard in virtual space. The master computer also receives touchpad readings from each whiteboard and uses this information to populate the virtual representation of the whiteboard with writing.

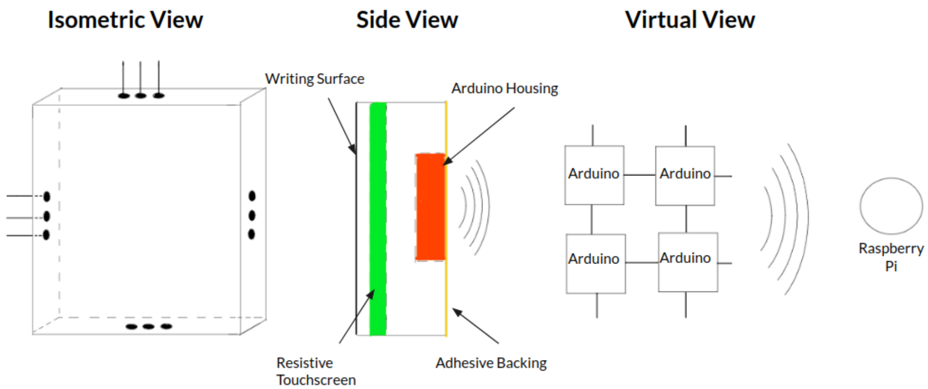


Figure 8. Diagram of design concept 2 showing two external views on the left and middle and a virtual representation of the network on the right.

The way the writing surface and touchpad interact allows for the physical representation of writing to be decoupled from its virtual representation. This is both a major strength and weakness of the design. It is a strength in that decoupling the physical and the virtual reduces the complexity of the interaction between them; it allows a relatively simple way to retain the natural writing feel and construct a virtual representation of that which is written. However, this decoupling complicates the erasing process, where coupling the physical and virtual writing representations would simplify the process.

Concept #3: Rigid, Total Dynamic, Rotating, 2D Image Capture

The third concept will be rotating about a stationary vertical axis that will move about its axis when pressure is applied by the user, making it independent of any motors. The mechanism will be a six sided polygon and each of the six sides will have a white board on it. On the inside of this enclosed and hollow hexagonal prism will be a camera rigidly mounted to the center axis along with a timed flash mechanism. For the work done on the whiteboard to be captured clearly, the whiteboards will have a percentage of opacity. Additionally on the outside of the prism one of the sides will have a cover hangin out from the top of the prism down to the bottom of the whiteboard to further control the lighting. By controlling the lighting with the flash system and cover, it ensures that the images captured will be uniform in clarity and no outside lighting will create blemishing discrepancies.

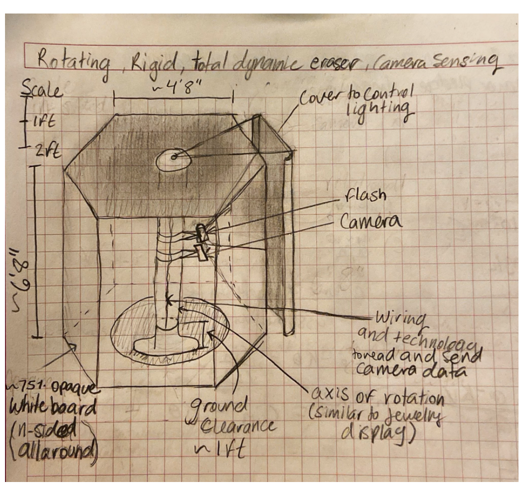


Figure 9. Concept #3 diagram.

Concept #4: Flexible, Partial Dynamic, Scrolling, 2D Image Capture

The fourth concept, as shown in Figure 10, is nearly identical to the first concept minus the total static erasing. Instead, the fourth concept uses partial dynamic erasing. This design features a 2D gantry with an eraser as a toolhead. The position of the toolhead can be controlled by the user according to where on the board the user wants to erase.

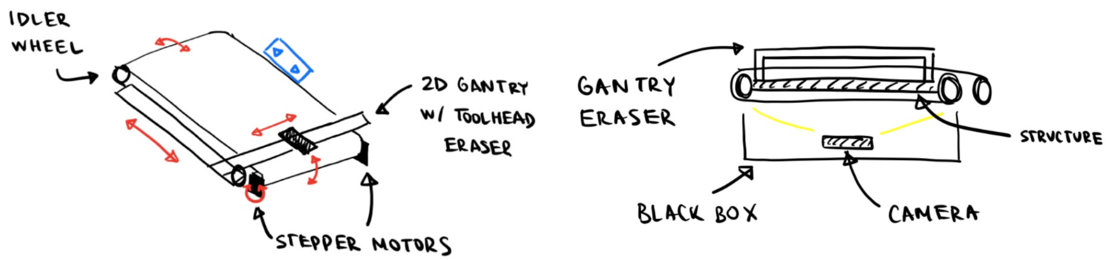


Figure 10. Diagram of concept #4.

Concept #5: Flexible, Dynamic, Scrolling, Scanner

The fifth concept, as shown in Figure 11 below, is similar to concepts 1 and 4. This design has a scrolling flexible writing surface. Scanning/erasing mechanism is attached to a 1D sliding gantry. The eraser mechanism can be engaged and disengaged when the user wants to erase. A capacitive touch control panel controls the scrolling of the writing surface and the movement of the scanning/erasing mechanism. The writing surface is attached to and wrapped around two driven cylinders and tensioned by an idler cylinder.

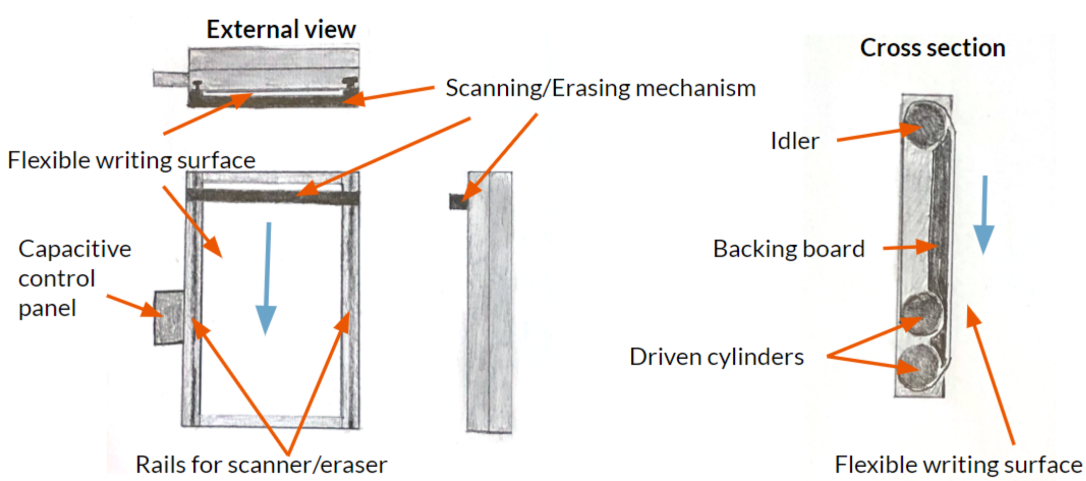


Figure 11. Diagram of design concept 5 showing three external views on the left and a cross section view of the internal mechanism shown on the right.

Concept #6: Flexible, Dynamic, Layering, Scanner

The last concept, as shown in Figure 12, was conceived with the layering method for adding writing space. The concept as a whole can be equated to that of a large book, with rigid, dry-erase pages. The major difference between this mechanism and a book is that, in this concept, each board is affixed to a rail system with rollers at each corner that allow the boards to slide throughout the rail system. The boards are written on from the right side of the device and, once filled, can be flipped to the other side, which is positioned at a slightly increased height than the right side. A semi locking mechanism holds to boards in place, as the user continues to write. Once all boards are used, the user is finished writing, or more space is needed, the boards can be pushed through on the finished side. From here, the rail system is on a slight incline which causes the boards to slide at a slow velocity towards the right side. As the boards slide, a scanner will image the back side of the board. Once the board has reached the right side, a total dynamic eraser is used to clear the writing off the board and the board can be used again.

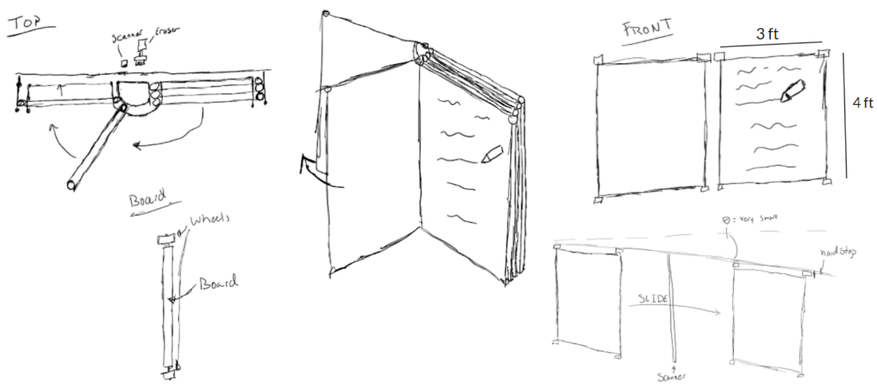


Figure 12. Concept 5, the layering method, is shown in the figure. Independent, rigid boards are attached to a binding rail system that acts somewhat like a book with rigid, dry-erase pages.

One flaw with this design is that the scanner mechanism can only scan one side of the board at a time. This means that either only one side of the boards can be used at a time, or the boards will need to loop through the scanner mechanism twice in order to scan both sides. Additionally, the scrolling will likely need to be manual, as this method will be quite difficult to automate for changing the "page".

Concept Selection

Once all of the concepts were shown and understood by the group, a decision matrix was created using the criteria defined above, and is shown in Figure 13.

Our analysis showed two designs to be very promising, three to be mildly promising, and one to be not promising. Concept 2, the modular whiteboard design, proved to be unpromising due to its prohibitive cost to manufacture as well as its potentially confusing user functionality. Concepts 1 and 5 proved promising because they utilize the scrolling method to effectively expand writable surface area. Additionally, they are both simple in terms of mechanics and software, and they are intuitive to use. In the end, Concept 5 was chosen as the final design due to the benefits granted by the dynamic eraser and scanner.

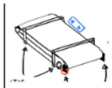
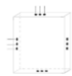
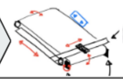
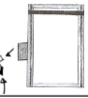
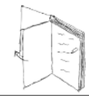
Candidate → Criteria ↓	Weight						
Ease of Use / Intuitive	5	1	-2	2	-1	2	1
Software Simplicity	4	2	-1	2	2	2	2
Writing Area: Physical Presence	4	2	0	-2	2	2	1
Mechanical Simplicity	3	2	1	2	0	1	-1
Cost	2	1	-2	0	1	1	1
Manufacturability	1	0	-2	-1	-1	1	-1
Total		29	-17	15	12	32	15

Figure 13. Decision matrix for the 6 outlined concepts. Each concept was graded against 6 weighted criteria. The final scores are totaled and the highest scoring concepts were concepts 1 and 5.

Detailed Design Solution

After our initial ideation and concept evaluation, we determined our final concept going forward. As this concept was being further developed, however, our team suggested a new concept: one that features the same aspects of our morphological analysis, but functions differently overall. Figure 14 shows a simple sketch of this new design. If the previous final concept was functionally equivalent to a roll of toilet paper, then this new concept is equivalent to a treadmill. Our team decided to continue to develop this concept as our final design since the benefits of this new design made the implementation of the eraser and scanner systems simpler. This is because the eraser and scanner mechanisms can now be implemented as static, while retaining the benefits of a dynamic eraser due to the continuous motion of the writing surface. Another benefit of this design is that the writing surface no longer rolls onto itself, as it did in the toilet paper concept.

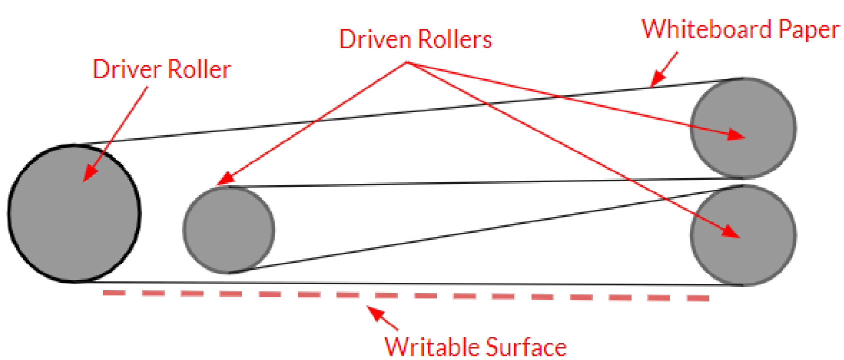


Figure 14. Sketch of the "treadmill" final design. A continuous sheet of whiteboard compatible paper is wrapped around the distribution of rollers and is driven by the driver roller.

Mechanical Model

As we continued to develop the design, we began to model the components of the system in a 3D modelling software, *SOLIDWORKS*. Figure 15, below, shows the isometric view of the structure and mechanical systems of the design with labels to show the positions of the driver and one of the driven rollers, as well as the stepper motor and hard backing, which improves the writing experience. Additionally, views of the back and side are included in Figure 16 for additional information. In this case, the back view is chosen rather than the front view since the hard backing surface obstructs the view of several components.

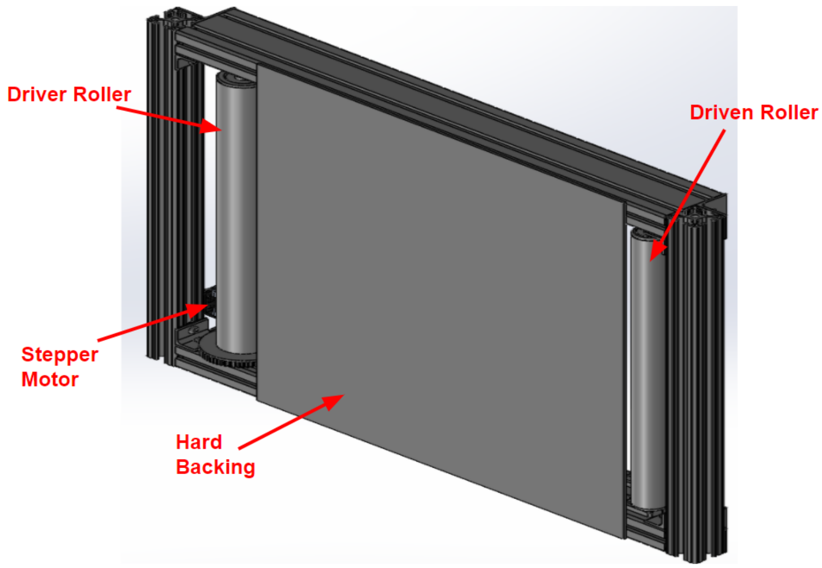


Figure 15. Isometric view of the CAD model of our design. Labels are added to the major components for clarity.

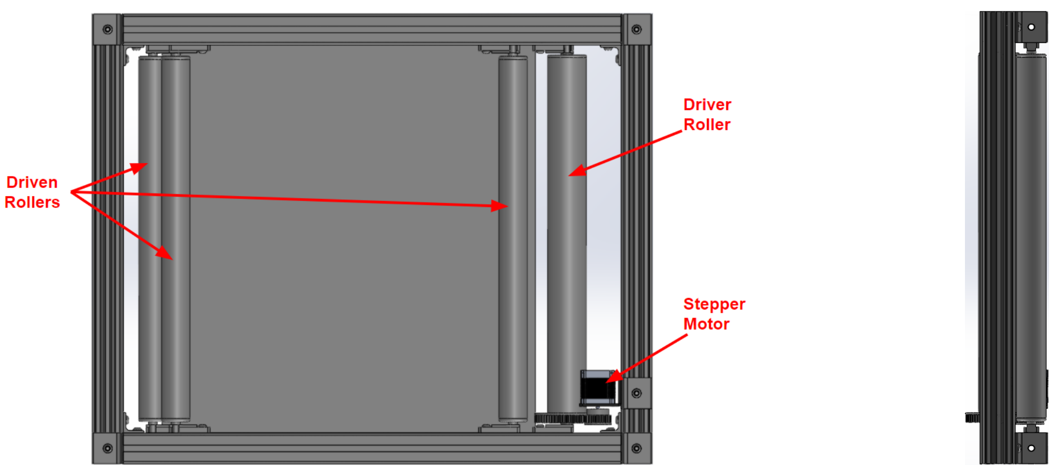


Figure 16. Rear view (left) and side profile (right) of the Computer Aided Design model. In the rear view, the locations of the key components are highlighted with labels.

Finally, we include an exploded view of the entire system in Figure 17, below. This is an isometric view of the system with each component individually isolated for clarity.

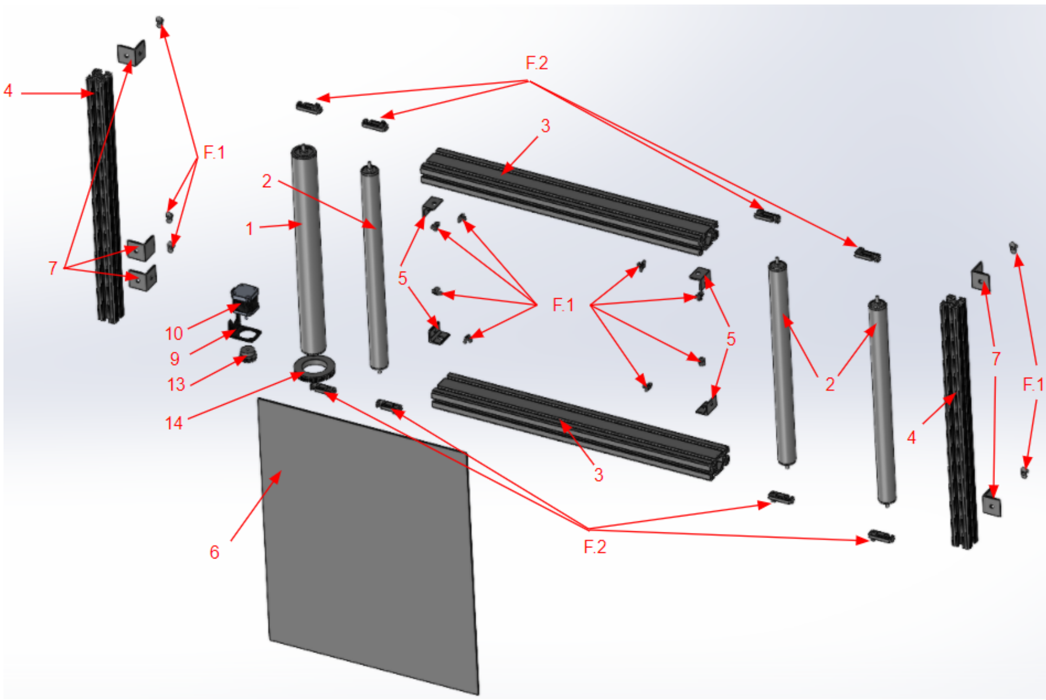


Figure 17. Exploded view of the CAD model. Each component is labelled with its corresponding number in the Bill of Materials.

Electrical Design

In order to save writing in a digital format, we require a stationary camera to capture images of the whiteboard. Furthermore, the camera needs to be in an unobtrusive position that's insensitive to fluctuations in the ambient light. Finally, there needs to be a controller to process the images and to synchronize the scrolling of the whiteboard with images captured by the stationary camera. Our design utilizes a Raspberry Pi 3 Model B as a controller and image processor, and it uses a Raspberry Pi Camera Module v2 to capture images. A diagram of the physical setup can be seen in Figure 18.

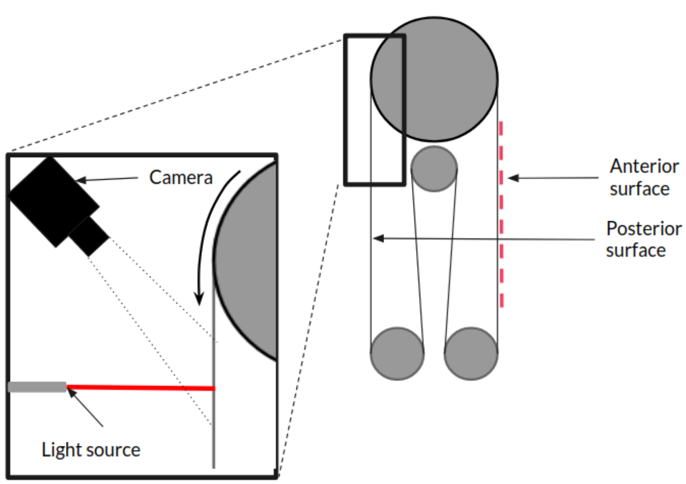


Figure 18. Physical diagram of the electrical system. The anterior and posterior writing surfaces are labeled.

The camera is placed between the mounting wall and posterior writing surface with a light source to illuminate a section of the posterior surface. Upon user input, the controller will synchronize the motor and camera to capture several images of the anterior writing surface. Specifically, the controller will scroll the anterior surface to the posterior surface where the light source and camera can capture it in several increments. Saved images will then be filtered by light to exclude everything outside of the illuminated areas of the writing surface. Finally, images are concatenated together to form a scanned image of the whiteboard.

Final Physical Prototype

Our team's semester of problem definition, concept generation, and engineering analysis culminated in a final physical prototype. In this section, we will discuss the final product of the design process, while highlighting the functions that worked well and those that did not: our scrolling feature worked well by hand, but complications with the motor's interaction with the gear mesh caused the motorized scrolling to be too slow at low speeds and inoperational at high speeds.

Final Product

The physical iteration is quite similar to the virtual, CAD models for our device. Figure 19, below, shows the physical system from the front view. As discussed in previous sections, the whiteboard surface is flexible and is weaved through the rollers in the manner shown in Figure 14. An acrylic sheet is fastened to the frame in order to support a hard writing surface.

Figure 19. Physical prototype of scrolling whiteboard.

Scrolling Mechanism

The scrolling feature is achieved through the use of conveyor rollers and the tensioning of the writing surface. This feature is automated by a stepper motor that is mounted to a 3D printed gear. This gear meshes with another 3D printed gear that is press fit to the driver roller. Figure 20 shows a close up view of the power transmission system that involves the motor and meshing gears.

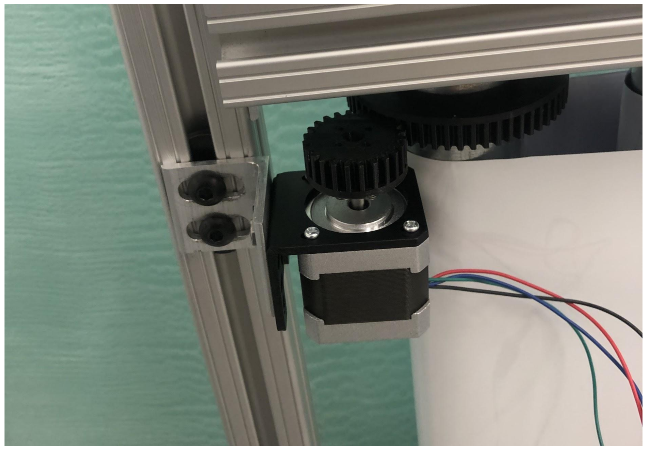


Figure 20. Close up view of the power transmission system.

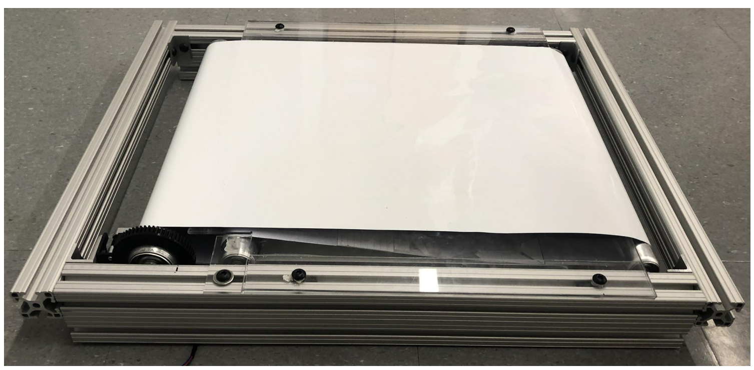


Figure 21. Side view showing conveyor rollers.

Automatic Erasing

The automatic erasing feature is accomplished by fastening a sheet of felt, a common whiteboard eraser material, around the surface of the middle roller. As shown in Figure 22, the writing surface will invert at this point and contact the eraser material. Preliminary testing suggests that erasing will not occur as long as a non-slip condition can be enforced. Sufficient tensioning of the surface will ensure that the middle roller turns along with the entire system during normal operation. When erasing is desired, however, the system features a mechanical stop to force slip on this roller. Figure 23, below, shows this mechanism, which is a simple cantilever, manufactured with excess acrylic, that will contact the roller surface when pressure is applied at the end. In order to ensure that a forced slip condition occurs, our team increased the coefficient of friction between the cantilever and the roller by applying a hot-melt adhesive to the cantilever.

Figure 22. View from the top left of the system, a reminder of the respective location of the middle roller, which can be seen coated in a layer of black colored felt.

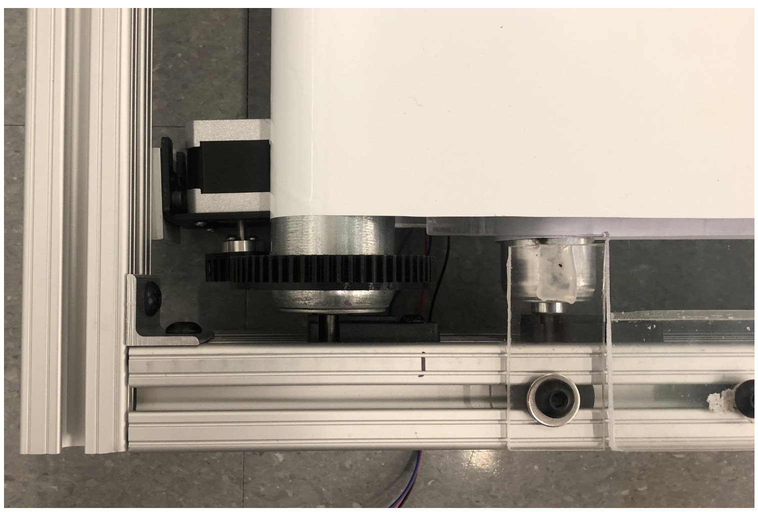


Figure 23. View from the bottom left of the system, showing the integration of the eraser stop. The cantilever can be seen on the right, hovering over the middle roller, which is held from rotating when the cantilever is engaged.

Camera Imaging System

The camera imaging system is the least integrated in our final product. While this system does function as expected, the camera is not currently mounted to the system. The current implementation is to hold the camera some distance away from the system to take direct photos. Ideally, the camera would be mounted to the frame of the system and use image correction software to correct the distortion resulting from imaging from an angle.

Engineering Analysis

In order to develop a complete, final model for the assembly of our product, we need to perform various modes of engineering analysis for the functions within each of our subsystems. In this section, we will present the corresponding analysis for the justification of the design decisions that were made for each subsystem of the overall design. These subsystems align with our morphological analysis, presented earlier in Figure 6 on page 11, and are the material selection of the writing surface, materials and design considerations relating to the eraser subsystem, motor selection to ensure scrolling functionality, and digitization tools and their benefits.

Writing Surface

To pick our writing surface material we researched multiple different materials and performed tests on the types we had available to us. The material selected needed to meet our previously set requirements. The material had to be less than or equal to $1/16^{th}$ of an inch thick, it needed to be compatible with dry erase markers indicating the material needed to be a non-porous material. Additionally, due to the nature of our final design the material needed to be flexible up to a minimum bend radius of smaller than $11/16^{th}$ of an inch, the radius of our smallest roller. The four materials we narrowed our selection down to include a 8'x 25'moisture resistant polyethylene film intended to be a tarp cover at $24.51, a 2'x 6' clear plastic vinyl PVC waterproof dining table protector at $38.69, a 6'x 3'PET film dry erase wall decal at $49.99, and a 6'x 4'plastic Post-It dry erase whiteboard film at $79.63. Our design called for a material that is about 2'x13' so upon further research in hopes of decreasing the price point of our writing surface material and finding one that was already cut to our required size we found our writing surface material. We selected a 1.5'x 11' peel and stick dry erase whiteboard wall paper at $19.61 on Amazon. And adjusted our design to accommodate the size of the writing surface which aided us in bringing our total cost down.

Our final design concept works similarly to a treadmill or conveyor belt. This type of design will require our writing surface to be connected at the ends and attached to the mechanism with a certain amount of tension to keep it in place. The selected writing surface material comes with an adhesive backing and according to the reviews, the adhesive is strong. The team has discussed other options should the provided adhesive fail to hold the material together over the rollers. The second option would be to use either Loctite or crazy glue to strengthen the bond between the two end pieces of the writing surface. Should the glue fail our team has discussed the possibility of stitching the two end pieces together. Stitching is the least favored option for the sole concern of hindering the users experience along with concerns of thickening the writing surface material making it not compatible with the rollers.

Marker Testing

Before designing the automatic eraser mechanism for the whiteboard we needed to answer several questions:

1. Are we going to use dry erase markers or wet erase markers?
2. How much pressure (and potentially how much water) is required to erase dry and wet erase markers?
3. How much sliding is required to erase the markers?
4. What material should we use to erase?

To answer these questions we conducted a series of low fidelity tests. The results of these tests inform the final designs.

We began by comparing wet and dry erase markers. We made marks on a sheet of plastic (PET), which was the anticipated writing surface material, using both wet erase markers and dry erase markers. We then rolled a rolling pin wrapped in aluminum foil over the sheet with moderate pressure to simulate the sheet rolling over the conveyors. None of the marks were erased under this condition except for the dry erase marker that was still wet. These markings did not completely erase, but they smudged onto the roller. When the dry erase markings were left for a short time to dry they were not erased. In a follow up experiment to this, the roller coated in aluminum foil was dragged over the sheet. No markings were erased under these conditions.

These two tests were repeated with the roller wrapped in a microfiber cloth rather than aluminum foil. When the roller was rolled over the sheet no markings were removed, but when the roller was slid over the sheet the dry erase markings were completely removed. The results from the above experiments are summarized in the table below.

Table 3. Summary of low fidelity eraser testing

Trial #	Wet/Dry erase	Roller material	Slide/Roll	Markings erased
1	Dry	Aluminum	Roll	No
2	Wet	Aluminum	Roll	No
3	Dry	Aluminum	Slide	No
4	Wet	Aluminum	Slide	No
5	Dry	Microfiber	Roll	No
6	Wet	Microfiber	Roll	No
7	Dry	Microfiber	Slide	Yes
8	Wet	Microfiber	Slide	No

From these tests we concluded that the middle roller could be used as an eraser if we wrap it in a microfiber/felt cloth and allow it to rotated with the writing surface (no slip condition) when we do not want to erase and hold it stationary (enforce slip condition) when we want to erase. We also confirmed that we will be able to use dry erase rather than wet erase markers. This simplifies the erasing process since we do not need to worry about refilling the water, applying water to the writing surface, and smudging marks on the writing surface which were some of the main problems we identified with wet erase markers.

Friction Testing

With the basic design for the eraser selected, we needed to determine how to stop the middle roller from rotating when we are erasing. We are going to stop the roller from rotating by using an actuator to press a stopper against the roller. To determine the size and stroke of the actuator we need to understand the friction forces in the system.

To determine the coefficient of friction of several material combinations we conducted a tilt test. We placed once material on a flat surface made from the second material and tilted the flat surface until the first material slid on the surface. The angle of the tilted surface was measured at the point of sliding and the angle was converted to a coefficient of friction using the following formula.

$$\mu_{static} = tan(\theta_{slide}) \tag{1}$$

where μ_{static} is the coefficient of static friction and θ_{slide} is the angle where the objects began to slide. The tests were completed three times for each material combination.

Table 4. Summary of results from friction tests

Materials	θ_{slide}	μ_{static}
paper/felt	16.67°±0.67°	0.30±0.01
aluminum/moldable eraser	68.33°±8.97°	2.82±1.52
PET/felt	10.00°±2.00°	0.18±0.04

Motor Selection

To select a motor that was adequate for our performance requirements, we wanted to ensure that the motor would be able to accommodate the torque and speed requirements. Furthermore, we wanted to ensure that the experience of using the device was similar to that of a digital device like a tablet.

Therefore, we conducted basic tests to determine the approximate linear speed of a tablet. A tablet, stopwatch combination was used to determine the time it takes for the tablet to travel one screen length with a slow, medium, and fast scroll. In the setup shown below in Figure 24, we conducted three trials at each speed in order to determine an approximate upper bound on scrolling speed. The results of our experiment are shown in Table 5, which shows the fastest average measured travel speed is 0.182 m/s.

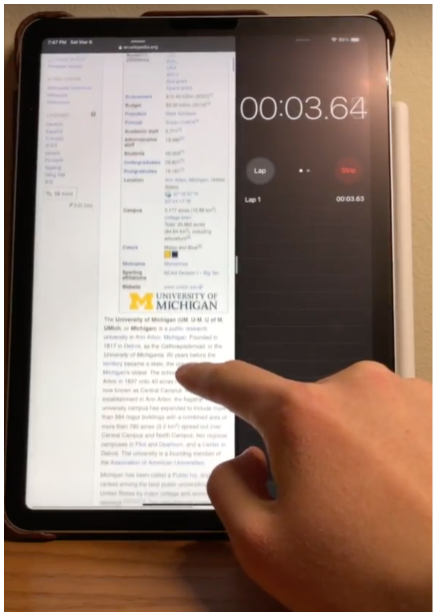


Figure 24. Approximate scrolling speeds for a tablet were determined in the experimental setup shown below. The length of the tablet is approximately 0.267 m, and a stopwatch and slow motion camera were used to determine duration of travel.

Table 5. Summary of results from tablet scrolling speed. Three trials were conducted at each speed condition. The radius of the driven gear of the system is 24 mm, and the conversion factor from rad/s to pulses per second (PPS) is 1 rad/s = 31.83 pulses/second (PPS).

	Average Speed (m/s)
Slow Scroll	0.025
Medium Scroll	0.036
Fast Scroll	0.182

With the known radius of the driven gear of the device (24 mm) and the known conversion factor from rad/s to pulses per second (PPS), the necessary speed requirement to achieve speeds at least as fast as the tablet is 222.8 PPS.

After approximating the necessary linear speed of the tablet, we approximated the rotational inertia of our device to determine the load torque on our device. To do so, we used knowledge of the geometry of the driver roller, driven roller, and writing surface to determine individual mass and system inertia. The total system inertia is approximated to be the sum of the individual inertias of the individual components of the system. Note that inertia of the motor, which has yet to be selected, was deemed negligible.The total system inertia was determined to be 5.1 x 10^{-3} kg m^2.

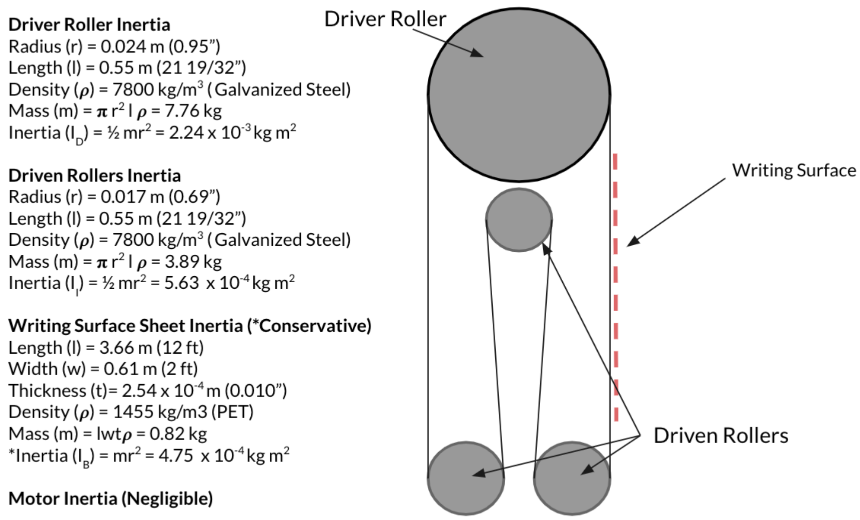


Figure 25. Indication of parameters and estimates used to approximate system inertia parameters. The total system inertia is determined to be a sum of the individual inertias of the driven roller, driver roller, and writing surface. In particular, the rotational inertia of the writing surface is estimated to be the product of the total mass of the writing surface and the radius squared.

Finally, given the upper bound speed requirement of 222.8 PPS, a total system inertia of 5.1 x 10^{-3} kg m^2, and a safety factor of 2 to accommodate for any underestimates of speed and inertia, a motor that could achieve the necessary torque and speed requirements was selected. For our system, we selected the NEMA 17-size stepper motor with the torque speed curve shown below. As shown, the motor is fully capable of achieving the necessary torque and speed requirements for our device.

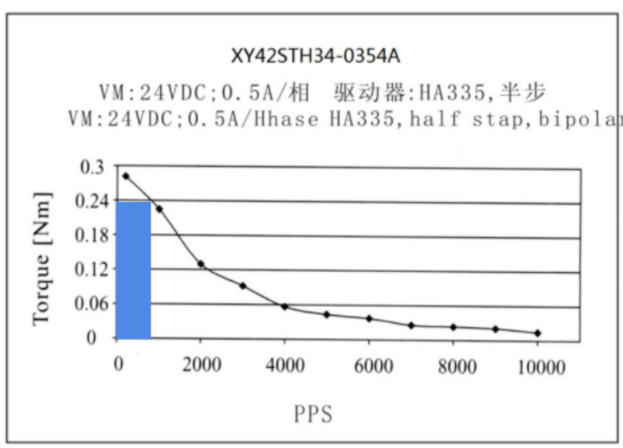


Figure 26. Torque-speed curve for the NEMA 17-size stepper motor selected For our device. The blue rectangle indicates the approximate operating region of our motor, with an additional SF = 2.

By properly speccing the motor, we avoid any potential issues with burning out the motor by exceeding the holding torque, the torque at which the stepper motor starts to skip steps. Furthermore, we ensure that the experience of using our device will be similar to that of a digital tablet.

Risk Assessment

We completed a failure modes and effects analysis (FMEA) to assess the risk of a number of potential failure modes of the prototype. Early experimentation with the prototype revealed several potentially catastrophic system failures which would need to be addressed. The most risky failure modes (those with the highest risk priority number are discussed below.

The failure mode with the highest risk is the potential for a user to jam fingers, clothing, or accessories into the gearing system on accident during operation. This failure mode would cause harm to the user and lock the scrolling mechanism. Currently the gearing for the power transmission system is exposed. This risk can be mitigated by covering the gearing. In a final product this gearing should be mounted in an injection molded plastic frame.

The failure mode with the second highest risk is the writing surface bonded overlap. In experimentation, we noticed that the overlapped bonded region of the writing surface would peel up slightly and get caught on the backing material. If this were to completely peel off the writing surface would become completely detached from the board. This risk could be mitigated by sewing the writing surface rather than bonding them with an adhesive. We may also be able to mitigate this risk by using a thermal bond.

The failure mode with the third highest risk is the misalignment of the gears. In experimentation we noticed that the gears were misaligned and could not reliably be aligned since the conveyor rollers were not mounted with tight tolerances. This caused the scrolling mechanism to fail. This risk can be mitigated by using a chain and sprocket or a belt to drive the driven roller. A chain and sprocket is a better solution here since a belt may slip and lose the motor's index position for coordinating imaging of the writing surface. Additional lower priority risks are shown in the table below:

Table 6. FMEA Summary

Component	Potential Failure Mode	Potential Effect of Failure	Severity	Causes	Occurrence	Controls	Detection	RPN
Writing surface	Skewing	Locking of the mechanism	7	Misalignment in the rollers	6	Measuring alignment	1	42
Writing surface	Slipping over the rollers	The writing surface remains stationary while the rollers spin	5	Lack of friction between the driving roller and the writing surface	3	Proper tensioning of the conveyor rollers	1	15
Writing surface	Tearing of material	Surface loses tension and will fall off of the rollers	9	Sharp edges on backing material	2	Backing material edges sanded smooth	1	18
Writing surface	Undoing of bonded overlap	Surface loses tension and will fall off of the rollers	9	Edges peel up	7	None	2	126
Eraser mechanism	Middle roller rolls and causes a stick condition at the writing surface	The markings do not erase fully	2	Lack of friction force between the eraser button and the middle roller or too much friction between roller and writing	7	Hot glue patch on the eraser button	2	28

				surface				
Eraser mechanism	**Felt gets too dirty to erase**	**The markings do not erase**	**3**	**Overuse of erasing feature**	**1**	**None**	**3**	**9**
Transmission system	**Gears misalign**	**Locking of motor so that surface cannot scroll**	**7**	**Misalignment of motor mount or driven roller**	**5**	**None**	**3**	**105**
Transmission system	**User fingers or clothing gets stuck in gears**	**Harm to user or user's property and locking of the gear**	**10**	**Exposed gearing**	**5**	**None**	**3**	**150**
Transmission system	**Gear teeth breaking**	**Inability to scroll**	**7**	**Fatigue or overloading of gears**	**2**	**Gears have back support bracing**	**3**	**42**
Frame	**Bracket bolts loosen**	**Frame becomes less rigid**	**3**	**Vibrations in the transmission system**	**2**	**None**	**5**	**30**
Conveyor rollers	**Roller mounts loosen**	**Writing surface loses tension**	**7**	**Vibrations and prolonged tension**	**2**	**None**	**2**	**28**

Verification

At the conclusion of the assembly of the product, we must revisit the specifications that were laid out earlier and assess the success or failure of the device in fulfilling them. In this section, we will discuss each specification, divided by the respective functional requirement, and the procedures performed to determine if it was met or not. Refer to Table 2 on page for the specification definitions.

Maintain Natural Feel

This requirement of maintaining the natural writing feel of a standard whiteboard had three specifications. Because of the material selected for the writing surface, we ensured that at least 2 of the specifications would be fulfilled, that being usability with commercial markers and quality of life erasing by being able to use commercial erasers, as well as the user's own hand.

The final specification involves performing a blind study to determine if volunteers possessed the ability to differentiate our product from a standard whiteboard. Given the time constraints, we were unable to perform this experiment. However, the biased opinions of the 5 members of our team agree that this whiteboard is of acceptable feel, and thus, we believe that this specification is satisfied.

Ability to Increase Writing Area

Under this category, the specifications aimed to meet are that the product has a display area of 12 square feet, total writable area is at least 3 times the display area, and that a completely new display area could be revealed in 15 seconds or less. Our final product features a display area that is roughly 20" x 16" for an area of 2.2 square feet. This is much lower than the specification, but can be justified when we consider that our physical product is simply a prototype. We believe that we can scale up the size of the product easily and thus, we consider this specification to be met.

The total size of the writable area is 76" x 16", which is then an area of 8.4 square feet, which is 3.8 times as much as the display area. And, thus, we consider the second specification to be met as well.

As for the final specification, while the original design concept featured a motor to actuate the motion of the writing surface. While this is still ideal and the intended functionality of the product, we were unable to succeed in using the motor to automate this process due to complications with the motor's interaction with the gear mesh. Because the specification does not mention the use of a motor or automatic capabilities, we were able to satisfy this specification by simply scrolling the board by hand. The bearings in the rollers provide a smooth enough glide that moving the board manually is easy and can easily reveal a new display area in well under 15 seconds.

Ability to Save and Export Work

The first specification under this requirement is that the images can be saved as a pdf that is no greater than 22 MB. This specification is mostly met in that the average size of 4 images taken from the camera is 16 MB, which is within the specification, but is saved as a series of .JPEG and not a .PDF file.

The second specification is that the data can be transferred to a personal device, such as a computer, within 60 seconds. In our system, the images are saved to a microSD card, which can be removed from our processor and inserted into a compatible device. Users of this product would ideally insert their own personal SD card into the system, and then retrieving their images would be as simple as removing the card from the system. For this reason, we consider this specification to be satisfied.

Automatic Erasability

The specification created for the auto-erasing feature specifies that at least 90% of the writing can be erased in 200 seconds. To test this, our team put markings of varying intensities at various locations on the current display area. Then, whilst engaging the eraser, scrolled the display area in a complete loop until it came back to the front. Figure 27, below, shows the before and after effects of this feature. The complete scrolling process took no more than 60 seconds overall and the writing was almost completely gone. From this test, we conclude that our device meets this specification.

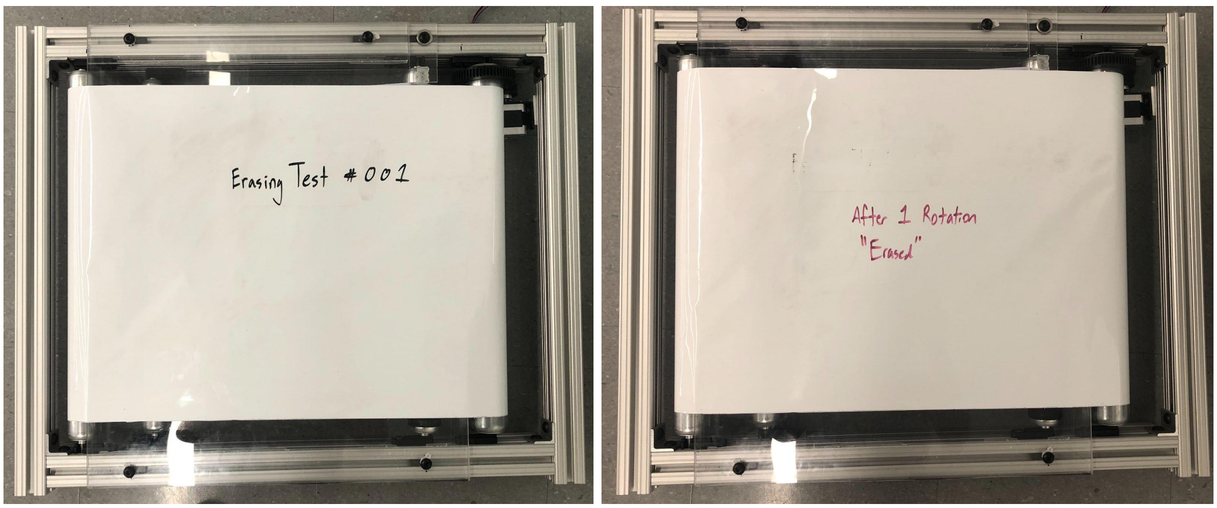


Figure 27. Left: Writing is applied to blank writing surface before the surface is looped through the system while the eraser is engaged. **Right:** Result of the test. Original writing is completely erased and the result is recorded in red ink with a description that says "Erased".

Ability to Retrieve Past Work

This requirement specifies that all written work is saved for the entire duration of the session. For our design, this means that no unintended erasing occurs. Analysis of the functionality of our product reveals that the only spot of concern for unintended erasing occurs at the middle roller. We discussed previously that preliminary testing suggests that this will not be a problem as long as a non-slip condition is maintained. To test this specification, we performed a test similar to the test for the eraser mechanism, although this time not engaging the eraser and performing multiple passes. Writing was marked on the board and the surface was looped through the system 3 times total. After the third pass, it was determined that an insignificant amount of erasing or smudging occurred. Figure 28, below, shows the writing before and after 3 complete passes. Therefore, our product succeeds in this specification.

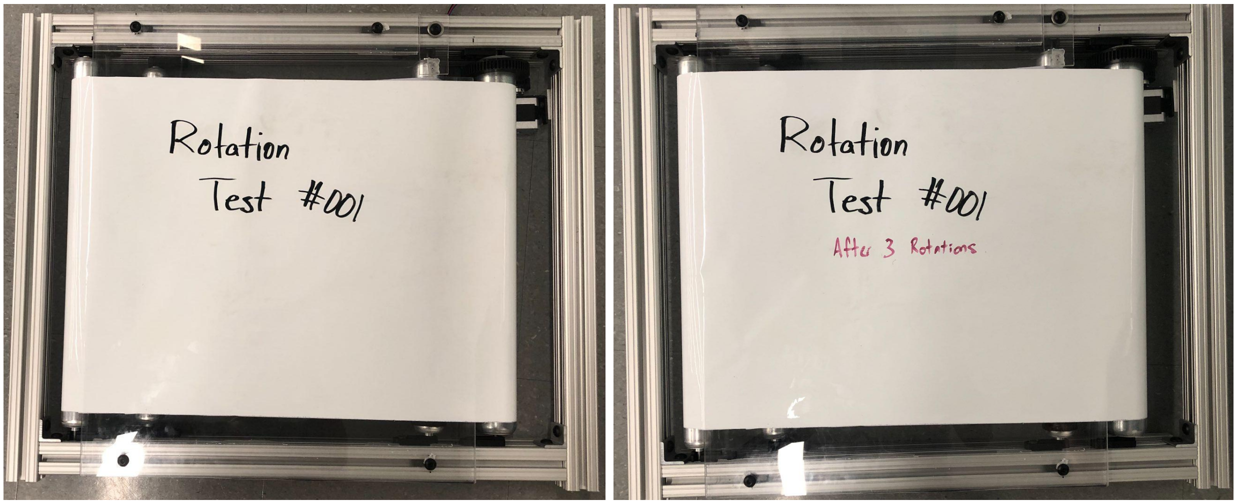


Figure 28. Left: Writing is applied onto a blank writing surface. The surface is then looped through the system 3 times. **Right:** Result of the test is shown with a description of the result written in red ink. Negligible erasing occurred in 3 rotations, confirming that work is maintained throughout the work session.

Intuitive User Interface

In order to ensure an intuitive user interface, we specified that a survey should reveal that more than 95% of new users are capable of executing on each of the features of the product within 30 seconds of being tasked. This is another test that would involve a large group of volunteers and, again, was not tested due to time constraints.

Mountability

The mountability requirement contains specifications that outline the weight of the product being less than 80 pounds and the thickness being less than 3 inches. We were unable to weigh the final device due to lack of time and equipment. Additionally, the final weight would be slightly increased if we were to integrate the camera and processor into the frame. Although we do not know the actual weight of the mechanism, our team was surprised by the heaviness of the prototype, which is primarily due to the 8020 aluminum framing. For this reason, we do not think that this specification is met and therefore need to consider ways to reduce the overall weight of the product.

The second specification requires that the overall thickness of the system be less than 3 inches. This specification has also failed since our current prototype is measured at an overall thickness of roughly 4 inches due to the radius of the driven gear.

Quick and Easy Setup

The ease of setup is a requirement that was of low importance compared to other requirements. This requirement is specified by being able to be mounted by a team of two in less than 2 hours. Currently, our final product does not feature any direct support for mounting. However, mounting could be achieved fairly easily given the modular nature of the T-slotted framing used for the device’s structure. However, we say that our product fails this requirement due to the lack of implementation.

Discussion and Recommendations

While the prototype is a successful proof of concept, it has also highlighted a number of issues with the current design that should be improved if it were taken to market. The power transmission has a number of shortcomings. While the motor is powerful enough to operate at the torques and speeds we desire, the power transmission system locks up due to misalignment of the gears. This problem stems from the fact that one of the gears is press fit onto a conveyor roller. This conveyor roller is not mounted with adequate tolerances to allow the gears to function properly. To fix this problem, we should change the power transmission from gearing to chain and sprocket. Chain and sprocket would allow the conveyor tolerances to be high while also maintaining the indexing required for proper imaging.

The writing surface has two large problems. First, the surface is connected into a loop using the bond adhesive that came on the writing surface. In early experimentation, we noticed that the writing surface can peel up at the edges. If it peels all the way through the bond area, the writing surface will detach from the system. To fix this problem, the writing surface should be sewn together or thermally bonded rather than bonded with an adhesive. The second major problem with the writing surface is that it will shift along the rollers. If it shifts too far, it runs into the gear or off of the roller causing locking of the system. This happens because the rollers are not perpendicular to the frame. This problem cannot be fixed using our current framing material (T-slotted 8020 framing), but if we switched to an injection molded frame the roller positions could be better controlled by fixing the writing surface skewing.

The eraser mechanism currently does not function as intended since the motor is not able to automatically control the scrolling, but even more so the driven roller does not have enough friction to overcome the friction provided by the middle erasing roller. To fix this problem, the driven roller should be coated in felt since the coefficient of friction between the writing surface and felt is higher than that between the writing surface and aluminum.

Since the framing is currently four separate parts connected with L-brackets, the frame is not very stiff. This can be an issue since the frame stiffness is related to the roller positions. An injection molded frame may fix this issue since it would be one single part rather than four.

As of now, the imaging system is not fully implemented into the system. Specifically, the mounting for the camera has not been finalized yet. From a mechanical standpoint, this is a challenging design problem because we want our device to be space efficient. Therefore, it is in our best interest to keep the camera as close to the back writing surface as possible. However, doing so lends itself to challenging software challenges. By positioning the camera close to the back writing surface, we limit the view of the camera due to the fixed focal length. One possible solution is to orient the camera at an angle to increase the field of view and post-process the image with a perspective correct afterwards. In fact, an algorithm and Python Libraries have already been used to implement a basic script that accomplishes this task, but the mounting of the camera is yet to be determined.

Conclusion

The goal of this project was to develop a small scale prototype to increase the available writing surface area and digitize the traditional whiteboard by allowing users to save their work. We generated a large number of potential solution concepts. Using these initial design concepts in conjunction with survey feedback we developed a method for increasing the total writing area of a traditional whiteboard by more than a factor of three. This is done by wrapping a flexible writing surface around a series of conveyor rollers. The surface scrolls using a stepper motor which moves the conveyor rollers through a gear mesh. We have also implemented an automatic erasing system which enforces a slipping condition at the middle roller, which is layered with a felt. When the writing surface slips across this felt surface, erasing occurs. We have also developed an algorithm for combining scanned images of the writing surface with a Raspberry Pi camera.

Authors

Mahfuj Ahbab: Mahfuj Ahbab is a graduating senior in mechanical engineering at the University of Michigan. He has experience in computational fluid dynamics and quantitative finance. In his free time, Mahfuj likes to exercise and read extensively.

Angelina Sallan: Angelina Sallan is a junior at the University of Michigan majoring Mechanical Engineering and minoring in Environmental Engineering. She will earn a bachelor's degree in 2022 in addition to her associates degree in science. She is a member of The Society of Women Engineers, and the Fundraising Chair of The Chaldean American Student Association. She Is currently employed as a Student Co-Op at DTE Energy.

Justin Shim: Justin Shim is a senior at the University of Michigan majoring in Mechanical Engineering and minoring in Computer Science and Multidisciplinary Design. He has experience conducting research in nonlinear dynamics and designing mechatronic systems with the Northrop Grumman Automated Satellite Harness Assembly Team. Outside of his studies, Justin likes to run, hike, and take photos.

Nathan Stoetzel: Nathan Stoetzel is a senior at the University of Michigan majoring in Mechanical Engineering. He will graduate with a bachelors in May 2021. He has experience with part design and manufacturing processes at Steelcase. His interest in problem solving has led to a passion for collecting and solving an extensive collection of Rubik's cube-like puzzles. He also enjoys working with computers and being outdoors.

Alexander Waye: Alex Waye is a senior mechanical engineering student at the University of Michigan graduating in May 2021. He has held a number of positions on the University of Michigan Solar Car Team mainly focusing on vehicle structural design and analysis. He has also held several co-op positions at The Timken Company working in automotive applications and manufacturing research and development.

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References

[1] Osugi, Kiyoyuki, Aya S., Ihara, Kae, Nakajima, Akiyuki, Kake, Kizuku, Ishimaru, Yusuke, Yokota, and Yasushi, Naruse. "Differences in Brain Activity After Learning With the Use of a Digital Pen vs. an Ink Pen—An Electroencephalography Study".Frontiers in Human Neuroscience 13 (2019): 275.

[2] Wann, J. and I. Nimmo-Smith. "The control of pen pressure in handwriting: A subtle point." Human Movement Science 10 (1991): 223-246.

[3] Alamargot, Denis, and Marie-France Morin. "Does Handwriting on a Tablet Screen Affect Students' Graphomotor Execution? A Comparison between Grades Two and Nine." Human Movement Science 44 (2015): 32–41. https://doi.org/10.1016/j.humov.2015.08.011.

[4] Piovarči, Michal, et al. "Fabrication-in-the-loop co-optimization of surfaces and styli for drawing haptics." *ACM Transactions on Graphics (TOG)* 39.4 (2020): 116-1.

[5] Bianchi, A., Bianchi-Berthouze, N., Cho, Y., Marquardt, N., 2016, "RealPen: Providing Realism in Handwriting Tasks on Touch Surfaces using Auditory-Tactile Feedback," UIST '16. ACM, 195-204. https://alsoplantsfly.com/files/2016/Cho_RealPen_UIST16.pdf

[6] The Grizzly Labs. 2020. "Troubleshooting". Genius Scan. https://help.thegrizzlylabs.com/article/139-genius-scan-is-taking-too-much-space-what-can-i-do#:~:text=Each%20page%20in%20a%20document,original%20image%20and%20enhanced%20image).

[7] "TV weight: Fact and Fiction," How much do TVs weigh?, CNET, posted June 17, 2013, https://www.cnet.com/news/tv-weight-fact-and-fiction/#:~:text=Zach%20Eyman%3A%20%22A%20good%20rule,much%20everything%20below%2060%20inches.

[8] "TV Mounting," Frequently Asked Questions: How long does it take to install a television mount?, Home Depot, updated 2020, https://www.homedepot.com/services/c/tv-mounting/07027f83d

Appendix

Engineering Standards

One engineering standard that was used in the development of the scrolling whiteboard was ISO 28762:2021(E) which is a standard covering vitreous and porcelain enamels used for writing surfaces. We used this standard to select candidate writing surface materials. For our early prototype, we selected an off-the-shelf writing surface that met this standard.

Engineering Inclusivity

We also want to consider inclusivity aspects of our design. We should ensure that the product is available and usable for all individuals. Our solution is already geared towards accessibility since we aim to incorporate features that are only available on digital devices into a product that is physically accessible. However, there are more aspects of inclusion that we can consider. For example, we consider that our board may be too high for some people to reach. Although this problem is aided by the scrolling capabilities of the board, in that the user could simply scroll down the area that cannot be reached, we can solve this problem even better by designing our mount mechanism to be rotatable, such that the product can be turned on its side in order for the board to be more accessible to vertically challenged individuals.

Environmental Context Assessment

For a technology to be sustainable, it must 1) make significant progress toward an unmet and important environmental or social challenge and 2) not lead to undesirable consequences in its lifecycle that overshadow the environmental or social benefits. The scrolling whiteboard may lead to significant progress in classrooms since it may be a cheaper alternative to existing smartboards. The scrolling whiteboard may also be more intuitive to set up and use than existing smartboards. There is potential for the scrolling whiteboard to lead to undesirable consequences. For example, the useful life of the scrolling whiteboard is likely shorter than that of existing traditional whiteboards due to the mechanical and electrical complexities, so there is potential for increasing waste at the end of the scrolling whiteboard's lifecycle if the scrolling whiteboard replaces all standard whiteboards. Determining whether these consequences overshadow the benefits depends on the extent to which the scrolling whiteboard is adopted, but in all more work may need to be done to ensure the scrolling whiteboard is a sustainable product.

Social Context Assessment

In addition to the criteria in the Environmental Context Assessment, for a technology to be sustainable, it must also 1) be likely to be adopted and self-sustaining in the market, 2) not be so likely to succeed economically that the planetary or social systems will be worse off, and 3) be resilient to disruptions in business as usual. Based on the success of products like the SMART Board, the scrolling whiteboard is likely to be adopted and self-sustaining in the market. The market for this product is not large enough to make the planet worse off. Since the scrolling whiteboard is an improvement on traditional whiteboards, this product may not be resilient to economic downturn, since consumers can buy cheaper traditional whiteboards rather than a more capable but also more costly scrolling whiteboard. The price would need to be reduced if this product were to be sustainable. The cost of the whiteboard could be reduced by eliminating the stepper motor. We have shown in testing that the board can be scrolled by hand with moderate ease. If we wanted to eliminate the motor, we could optimize the design for hand scrolling, which would decrease the price.

Ethical Decision Making

To consider ethical impacts of our design, we must make sure that our solution does not cause any unnecessary or unwarranted harm to individuals, animals, or the environment. The parts of our product that could be harmful are any motors or actuators, the materials used, and electronic components. We will make sure that our final concept will protect the users from moving components, use materials that are safe for the user and the environment, and be safe to use overall, notably from an electrical and structural standpoint. We encountered no significant ethical dilemmas in the development of our solution.

Survey Feedback

The feedback received from our preliminary survey can be found at the following link: https://docs.google.com/spreadsheets/d/1V-vFrVJBzBUFCx880EaVOrFdHFb3NwmAKYrCLUBihrE/edit#gid=357108317

Bill of Materials

Figure A.1 shows the complete bill of materials for this project. An interactive version can be found at https://docs.google.com/spreadsheets/d/1etaWwLbn7OPywNH09FsUxewDODxImSIUxyLU9b9SReQ/edit?usp=sharing

MECHANICAL SYSTEM								
Part No.	Part Title	Material	Supplier	Quantity of Part	Quantity to Order	Price per Part ($)	Price	Notes
	TOTAL						314.54	
1	Driver Roller	1.9" Dia. Conveyor Roller, Aluminum	McMaster	1	1	12.24	12.24	https://www.mcmaster.com/5890K314/
2	Idle Roller	1-¾" Dia. Conveyor Roller, Aluminum	McMaster	3	3	8.71	26.13	https://www.mcmaster.com/2282T37/
3	T-Slotted Frame, Horizontal	24" Long Double Six Slot Rail, Silver, 3" High x 1-1/2" Wide, Hollow, Aluminum	McMaster	2	2	25.17	50.34	https://www.mcmaster.com/47065T108-47065T159/
4	T-Slotted Frame, Vertical	48" Long Single Six Slot Rail, Silver, 1-1/2" High x 1-1/2" Wide, Hollow, Aluminum	McMaster	1	1	26.00	26.00	https://www.mcmaster.com/47065T102-47065T146/
5	Frame Bracket	Multipurpose 6061 Aluminum 90 Degree Angle Stock	McMaster	4	1	2.98	2.98	https://www.mcmaster.com/8982K4-8982K401/
6	Hard Backing	Clear Cast Acrylic Sheet, 24" x 24" x 1/8"	McMaster	1	1	20.36	20.36	https://www.mcmaster.com/8589K43/
7	Frame Outside Bracket	Multipurpose 6061 Aluminum 90 Degree Angle Stock	McMaster	4	1	5.06	5.06	https://www.mcmaster.com/8982K13-8982K131/
8	Writing Surface	White Board Wallpaper, White Board Roll, Stick on White Boards for Wall, 1.5x11ft Peel and Stick Dry Erase Roll, Stain-Proof, Super Sticky Whiteboard Sticker Wall Decal for Wall/Table/Door,3 Markers	Amazon	1	1	19.61	19.61	https://www.amazon.com/dp/B07CNZ3F42/ref=sspa_dk_detail_2?psc=1&pd_rd_i=B07CNZ3F42&
9	Motor Mounting Bracket	Stamped Aluminum L-Bracket for NEMA 17 Stepper Motors	Pololu	1	1	3.95	3.95	https://www.pololu.com/product/2266/resources
10	Stepper Motor	Stepper Motor: Bipolar, 200 Steps/Rev, 42×38mm, 2.8V, 1.7 A/Phase	Pololu	1	1	17.95	17.95	https://www.pololu.com/product/2267/resources
11	Stepper Motor Driver Carrier	A4988 Stepper Motor Driver Carrier	Pololu	1	1	5.95	5.95	https://www.pololu.com/product/1182
12	Universal Aluminum Mounting Hub	Universal Aluminum Mounting Hub for 5mm Shaft, #4-40 Holes (2-Pack)	Pololu	2	1	7.49	7.49	https://www.pololu.com/product/1203
13	Motor Mount Bracket	Multipurpose 6061 Aluminum 90 Degree Angle Stock	McMaster	1	1	0	0.00	
14	Driver Gear	PLA	n/a	1	1	0	0.00	
15	Driven Gear	PLA	n/a	1	1	0	0.00	
ELECTRICAL SYSTEM								
E.1	Raspberry Pi 3 Model B	1GB RAM, WiFi/Bluetooth functionality	Amazon	1	1	38.18	38.18	https://www.amazon.com/Raspberry-Pi-MS-004-00000024-Model-Board/dp/B01LPLPBS8/ref=sr_1_9?dchild=1&
E.2	DC-DC Power converter	24V to 5V	Amazon	1	1	12.49	12.49	https://www.amazon.com/Converter-Regulator-Adapter-Reducer-Electronics/dp/B07Q5W1BG3/ref=sr_1_3?crid=
E.3	Stepper Motor Driver Heatsink, FYSETC	Aluminum	Amazon	1	1	10.99	10.99	https://www.amazon.com/gp/product/B07FDWCR12/ref=ppx_yo_dt_b_asin_title_o05_s00?ie=UTF8&psc=1
FASTENERS								
F.1	T-Slotted Frame Screw and Nut Set (4 Pack)	End-Feed Single Nut with Button Head 5/16"-18 Thread	McMaster	13	4	2.38	9.52	https://www.mcmaster.com/47065T215/
F.2	Converyer Roller Mounting Bracket	Conveyor Roller Mounting Bracket	McMaster	8	10	4.53	45.30	https://www.mcmaster.com/2028N1/
Eraser System								
X.1	Felt Sheet	Felt	JOANN Fabrics	1	1		0.00	

Figure A.1. Bill of Materials.

Part Drawings

This section contains the engineering drawings for the parts that were machined by our team.

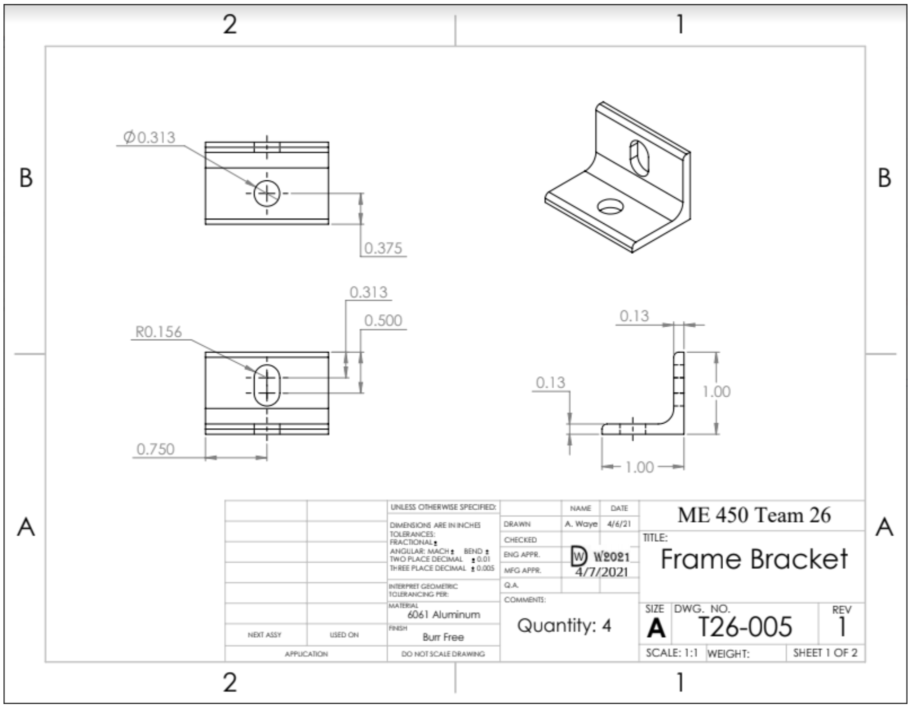

Figure A.2. Engineering drawing for the frame structure bracket.

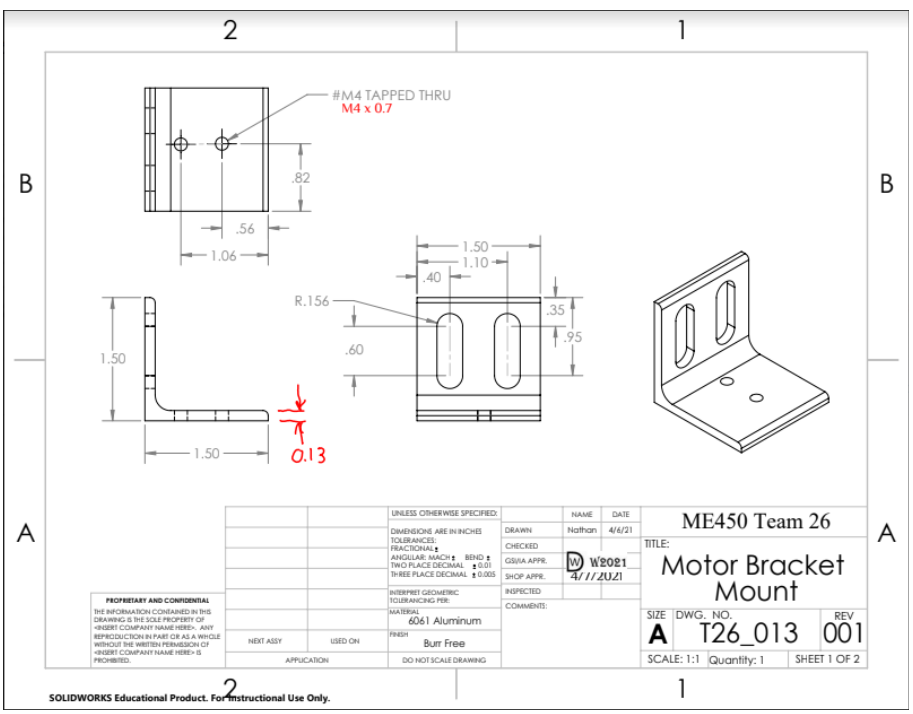

Figure A.3. Engineering drawing for the motor mount bracket.

Manufacturing Plans

This section contains the manufacturing plans for the parts machined by our team.

PART NUMBER: ME450-T26-005
PART TITLE: FRAME BRACKET
TEAM NAME: TEAM 26
MATERIAL: 6061 ALUMINUM 90 DEGREE ANGLE STOCK 1" x 1" x 1/8" THICK

Step	Process Description	Machine	Fixture	Tool(s)	Speed (RPM)
1	Cut stock to > 0.125 in. of final length and deburr	Band Saw	N/A	File	300
2	Place part in vise with > 0.125 in. sticking out	Mill	Vise, stop	N/A	N/A
3	Mill end of part 0.030" at a time until fully machined	Mill	Vise, stop	~~3/8"~~ 3/4" flute endmill, collet	~~1000~~ 500
4	Remove part and deburr	Mill	Vise, stop	File	N/A
5	Repeat steps 3-4 so that both ends are machined and parallel	Mill	Vise, stop	~~3/8"~~ flute endmill, collet, file	~~1000~~
6	Remove part and measurewith calipers and bring to 1.50" length	Mill	Vise, stop	~~3/8"~~ flute endmill, collet, file, calipers	~~1000~~
7	Install drill chuck and edge finder, insert part, find datum	Mill	Vise, stop	Drill chuck, edge finder	1000
8	Centerdrill and drill tru hole into face	Mill	Vise, stop	Drill chuck, centerdrill, 5/16" drill bit	1000
9	Remove part and flip to other face, confirm datum	Mill	Vise, stop	Drill chuck, edge finder	1000
10	Install 5/16" endmill and collet, use plunge method to mill slots	Mill	Vise, stop	5/16" Flute endmill, collet	1200
11	Remove part and deburr. Clean mill and station.			File	

Figure A.4. Manufacturing plan for the frame structural bracket.

PART NUMBER: ME450-T26-013
PART TITLE: Motor Bracket Mount
TEAM NAME: TEAM 26
MATERIAL: 6061 Aluminum 90 degree Angle Stock, 1.5" x 1.5" x 1/8" THICK

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	CUT STOCK TO >.125 IN. OF FINAL LENGTH AND DEBURR	BAND SAW	N/A	FILE	300
2	PLACE PART IN VISE WITH >.125" STICKING OUT	MILL	VISE, STOP	N/A	
3	MILL END OF PART 0.030" AT A TIME UNTIL FULLY MACHINED	MILL	VISE, STOP	~~3/8"~~ FLUTE ENDMILL, COLLET Long 3/4"	500 ~~1000~~
4	REMOVE PART AND DEBURR	MILL		FILE	
5	REPEAT STEPS 2-4 SO THAT BOTH ENDS ARE MACHINED AND PARALLEL	MILL	VISE, STOP	~~3/8"~~ FLUTE ENDMILL, COLLET, FILE	~~1000~~
6	REMOVE PART AND MEASURE WITH CALIPERS AND BRING TO 1.5" LENGTH	MILL	VISE, STOP	~~3/8"~~ FLUTE ENDMILL, COLLET, CALIPERS, FILE	~~1000~~
7	INSTALL DRILL CHUCK AND EDGE FINDER, INSERT PART,AND FIND DATUM	MILL	VISE, STOP	DRILL CHUCK, EDGE FINDER	1000
8	CENTERDRILL AND DRILL THRU HOLES INTO FACE	MILL	VISE, STOP	DRILL CHUCK, CENTERDRILL, #30 TAP DRILL	1000 1600
9	REMOVE PART AND FLIP TO OTHER FACE, CONFIRM DATUM	MILL	VISE, STOP	DRILL CHUCK, EDGE FINDER	1000
10	INSTALL 5/16" ENDMILL AND COLLET, USE PLUNGE METHOD TO MILL SLOTS	MILL	VISE, STOP	5/16" FLUTE ENDMILL, COLLET	1200
11	REMOVE PART, CLEAN, AND TAP DRILLED HOLES WITH #M4 TAP SCREW			FILE, #M4 TAP SCREW	

Figure A.5. Manufacturing plan for the motor mounting bracket.