

# **Linear Book Scanner**

**by**

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## EXECUTIVE SUMMARY

Book scanning is a rapidly developing field, largely due to the demands created by libraries digitizing their collections of literature. Through partnership with Google Inc., the University of Michigan was able to scan 4.4 million books of its 8 million-book collection. Currently, the university digitizes approximately 10,000 books a year even though their collection increases by 100,000 books in the same time span. The best commercially available tools are only able to reliably scan 200 pages per hour and can cost as much as \$100,000. In 2009 Dany Qumsiyeh, an employee at Google Inc. built an automated prism shaped book scanner for \$1,500 that was able to scan 200 pages per hour but lacked reliability. The objective of this design is to create a more cost effective alternative to commercial scanners based on this initial prism book scanner for the University of Michigan library in order to increase the number of books that they scan annually.

After meeting with our sponsors and the expected scanner operators, the user requirements for the scanner included: low cost, wide scan range, portable, user-friendliness, and a low noise level. Using a Quality Function Deployment (QFD) chart these user needs were translated into engineering specifications. The most important specifications included: pages per hour, failures per hour, range of book size, max book weight, time to operator proficiency, device lifetime, device price, device weight, and noise level. The most important of these being the pages per hour, and failures per hour. Using the initial prism scanner as a baseline, it was determined that this linear book scanner should be able to scan at least 200 pages per hour and minimize failures per hour.

Several concepts were evaluated, all of which were based on the original prism design. Essentially an extruded prism with a slot that pulls a page into a channel on one side with a vacuum slot, and then has the page exit the opposite side of the channel. The final design chosen was a shortened version of the initial prism scanner, where the page exits the channel on the reverse stroke in order to reduce the total length. This was chosen because of its high rankings in ease of manufacturing, assembly, scanning speed, and portability. This final design is almost completely made from sheet plastic (Delrin and Acrylic) so that it may be quickly cut on a laser engraver. The Delrin allows lower friction on the book while the Acrylic was more cost effective for structural members. This design also has an adjustable vacuum slot to locate the page suction in the optimum position, an improved saddle to provide better book support and an electronics chassis to allow easier access to the systems electronics.

The final design relies heavily on laser cutting of sheet acrylic and Delrin to reduce the manufacturing skill and labor. A unique fastener geometry was used that eliminates tapped holes, this greatly reduces labor. A sheet metal brake is required to bend 4 Delrin panels that the book slides on. Finally a mill and lathe are necessary to make the needed geometry in the vacuum tube.

The total cost of this design was under \$900, which is a significant reduction from the previous prototypes cost of \$1500. Upon testing the final design at 350 pages per hour a reduction was found in the number of failures compared to the initial prism scanner, and we also see methods to reduce the failures that have occurred.

A major challenge was the outfeed geometry. Several revisions were made to develop the unique geometry necessary to turn cleanly turn a page – this geometry may still need further refinement. The final prototypes base also has room for improvement. Overall the final design shows improvements to the initial prototype and has met most of the engineering specifications except for keeping the unit under 20lbs, even though in many regards it is actually more portable than the initial prism scanner.

## TABLE OF CONTENTS

Title Page	1
Executive Summary	2
Table of Contents	3
Introduction	4
Specifications	7
Concept Generation	10
Concept Selection	15
Concept Description	20
Parameter Analysis	22
Final Design	30
Fabrication Plan	39
Validation Results	44
Discussion	47
Recommendations	49
Conclusions	49
Acknowledgements	50
Appendices	
Appendix A: Bill of Materials	
Appendix B: Description of Engineering Changes after DR #3	
Appendix C: Material Selection and Environmental Impact	

## INTRODUCTION

### Motivation

Electronic text is becoming more and more available to the public, and with this trend there is a need to digitize books in libraries to make the information more available to the public, research more efficiently, and to archive information that only exists in older textbooks. Although the University of Michigan has over 8 million books, only 55% of them have been digitized in the past eight years [1].

The University of Michigan and Google, Inc. partnered together in 2004 with the vision to create new ways for users to access open library content from around the world [2]. Google was able to create digital copies of several million of the universities books but was forced to stop because of a lawsuit from the Authors Guild that began in 2005. Essentially the Authors Guild sued Google to prevent them from scanning the world's libraries because they felt it infringed on their copyrights. [3] The University of Michigan is still trying to digitize its book collection, but their current process takes too much labor per book to be efficient. A tool that would automate the scanning process would allow the university to scan a much larger percentage of their books.

In 2009 Dany Qumsiyeh, a Google engineer, created a device that costs \$1,500 and is designed to automatically scan books without removing the spine or damaging the book. [4] An open-source patent currently protects this device. The intent is for any small library to be able to make a linear book scanner and digitize their book collection. The Michigan Library would like to develop a better prototype that overcomes some of the downfalls of the current device and is therefore sponsoring the design and construction of this linear book scanner.

To understand the scale of this project and the impact an effective book scanner can have on the digitization process, here are a few facts. The University owns over 8 million books, buys 100,000 new books per year, but has only digitized 4.4 million of those books, and can only scan around 10,000 books per year [1].

We were able to take a tour of the Buhr Building at the University of Michigan to see firsthand the entire digitization process. They have four scanners that are in use. These include the Zeutschel 7000, Zeutschel 10000, Copibook I2S and their newest scanner, the Treventus ScanRobot® 2.0 MDS. Currently, the cost to scan a book ranges between \$30-100, this is mostly due to the amount of labor it takes to scan a book. Although this cost may seem reasonable for a book, it becomes impractical for several million books. Each book that the university scans has an operator at the scanner for each and every page scanned to check for errors and to operate the scanner. There is a clear need, as conveyed to us by our project sponsors, for a more efficient, reliable, and cost effective method to scanning books [1].

Michigan has partnered with 7 libraries and 11 other universities including the New York Public Library, Oxford University, and Stanford University amongst others [2]. These libraries form the information available on the Google Books Partner Program website. This website can provide basic bibliographic information, as well as four different viewing capabilities depending on copyrights and the discretion of the publisher or author. The Michigan Library is in the process of adding their collection of books onto this database.

### Existing Products

The follow section describes what kind of industrial book scanners currently exist to help fully understand why scanning books so labor intensive. The vast majority of book scanning that the university does is completely by hand, an operator manually turns each page of a book. [1]

**University of Michigan Book Scanners:** The Treventus Scanrobot 210 MDS is rated to scan up to 2,500 pages per hour (automatic mode) and about 1,000 pages/hour (semi-automatic mode). [5] It uses a wooden book cradle at an angle of 60 degrees to hold the book open, and uses air compression to scan and turn pages without damaging the book. Some other specs of the scanner include: scanning area from 1.97 x 1.97" in to 12.6 x 12.6", maximum thickness of 5.91 in, ability to scan paper from the 14th century to now, and 300 optical dots per inch resolution. The Treventus cost approximately \$250,000. [6] Although this machine is quoted as doing 2,500 pages per hour [5], the library has at best been able to get 200 pages per hour from it. [6] This is because the tool often needs an operator to re-adjust it, keep it running properly and to check for skipped pages. Even on a normal looking book in good condition it can skip as many as 20% of pages. [6]

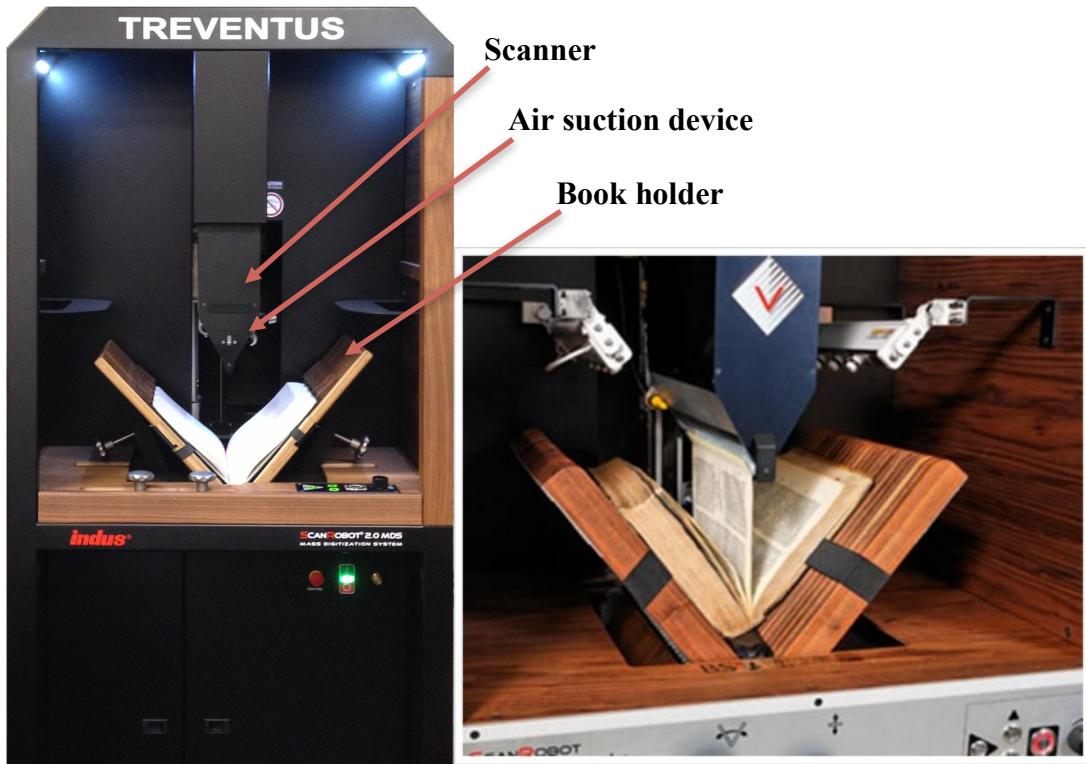
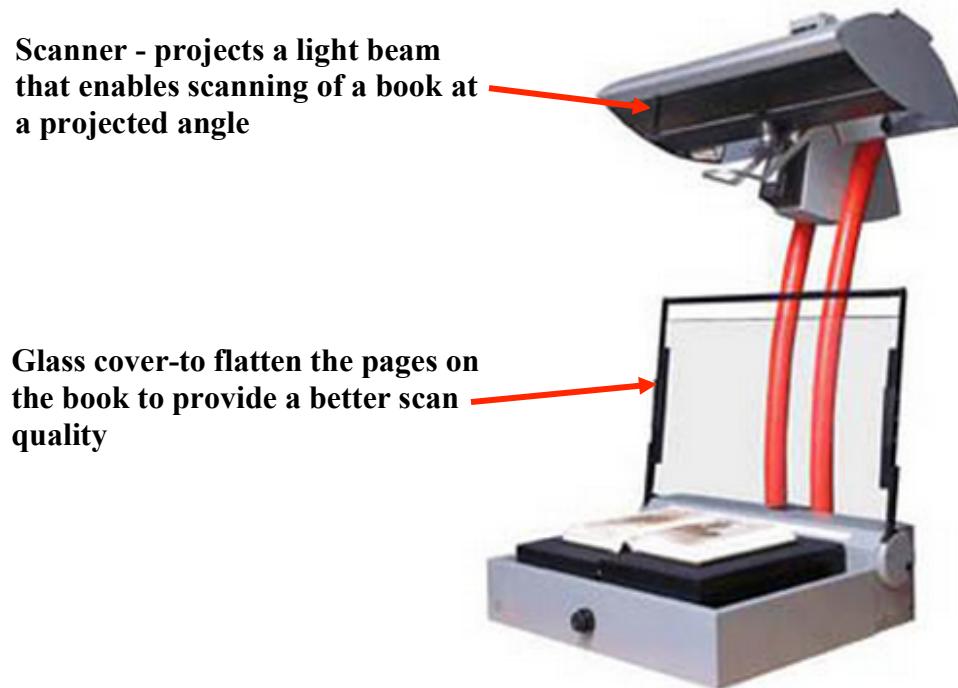


Figure 1: Front view of Treventus Scanrobot 210 MDS [left], Treventus scanning head [right]. [5]

The Treventus, shown in Figure 1, comes disassembled in smaller parts with assembly instructions for the user. The scanner head, located in the middle of the page above the book first moves into the gutter of the book. Then it applies vacuum to suck a page, as it moves up it scans the page. Finally as it reaches the page edge a blast of air ensures that the page falls the correct direction. This is repeated until the book is scanned.

The university also uses a Zeutschel 7,000, and a Zeutschel 10,000 book scanners from Kodak. The Zeutschel 7,000 was purchased in 2002 for around \$120,000 [5]. It only can scan 256 bit grey scale. The Zeutschel 10,000 was purchased in 2006 for approximately \$120,000 as well [6]. Both of these products are nearing the end of their life as they are no longer supported from their manufacturer and their proprietary software makes it exceedingly difficult to update and maintain the systems. Figure 2 shows the Zeutschel 7000, essentially a projection scanner is located in the upper head while the book sits in the book carriage below. The carriage has two floating tables that compensate for the differences in thickness, and then a glass cover is used to flatten the pages. Once in position, the pages are scanned from the top

unit with the projection scanner. The scanner is at such a large distance in order to reduce the page distortion as it sweeps through the scan. However it does still produce slightly trapezoidal scans, as the distance from the scanner to the page is not constant throughout the scan. An operator is required to manually turn and align each page which becomes a very labor intensive process.



**Figure 2: Zeutschel 7000 book scanner showing overhead scanning sensor and book carriage.**

The University Library also possesses a Copibook from Kirtas Technologies that cost \$56,000, and was obtained in 2009. [6] The next scanner purchased was the Digibook in 2011, for \$120,000. They also have a couple Epson 10000xI flatbed scanners purchased in 2011 that cost \$3500-4000 each. Lastly, there is a Atiz Bookdrive Pro scanning station V shaped cradle, with 2 software driven digital cameras), which cost \$25,000 in total. [6] These scanners are less efficient than the previously mentioned scanners and get much less use.

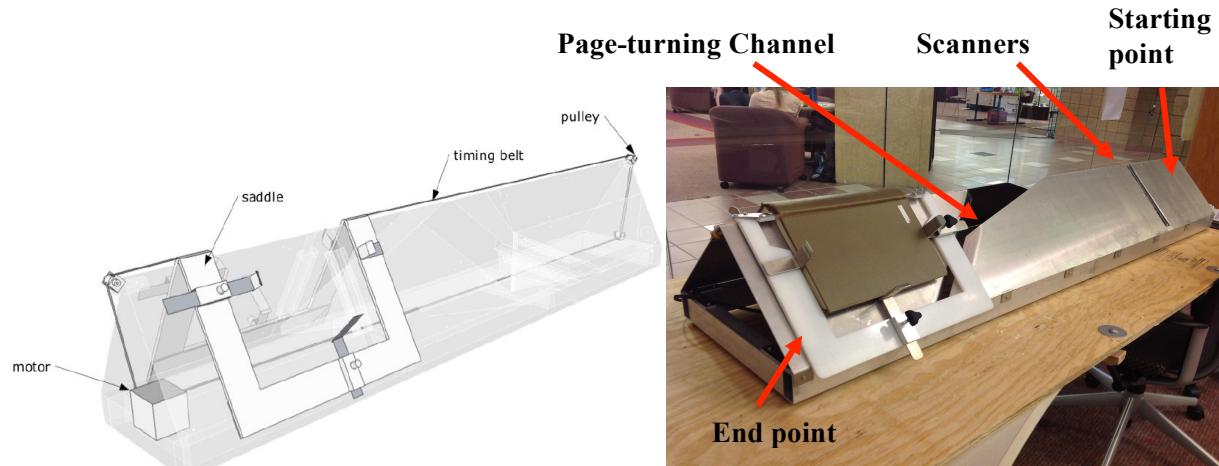
**Other Industrial Scanners:** 4 Digital Books, a company from Switzerland, has three automatic scanners on the market. The most basic scanner they sell, the DL mini-C, claims to have a productivity level of 1500 pages per hour, can detect double pages, and has the ability to correct mistakes after skipping over a page. It can scan books and magazines up to 10kg in weight and no more than 100mm in thickness. It also has 5 speed settings depending on fragility of the book. Its two Canon EOS 5D Mark II cameras provides resolution of 21 mega pixels per camera. [7] Prices were not listed on the website, but prices are assumed to be well over 5,000 dollars.

**Current Linear Book Scanner Prototype:** The current prototype built by Dany Qumsiyeh, our project mentor, as shown in Figure 3 has dimensions of 63 x13 x 9" and weighs around 20 pounds. The main purchased parts to this scanner are summarized in Table 1. [4]

**Table 1: Summary of main components to initial prism scanner.**

<b>Components</b>
Body
Saddle
Electronics
Stepper Motor
Timing Belt
Timing pulleys
Vacuum

As the book is traversing across the aluminum sheet metal body it gets scanned, then it passes the vacuum slots, enters into the page separator channel, and has one page turned by the exhaust from the air blower. In order to prevent damage to the pages, the page turning channel was designed greater than the length of books used. This scanner also has a beam break sensor located in the channel so that it can detect missed pages. In order to scan as much of the books gutter as possible the two scanners were placed offset of each other so that they can go closer to the top edge of the prism. The saddle for holding the book was made out of  $\frac{1}{4}$ " polypropylene and uses adjustable clamps for supporting the weight of the book. Currently, this design can scan approximately 60% of all sizes of books, ranging from 5.5 - 8" by 9.5 - 12". From preliminary testing, out of 50 books tested, 45% of them had 1 or 2 pages torn or folded. [8]



**Figure 3: Initial linear book scanner prototype.**

Ultimately the library would like a linear book scanner that is easy to use, affordable and is reliable enough so that an operator can walk away during the scanning process so as to reduce the total time and cost in scanning the universities book collection.

## SPECIFICATIONS

### Sponsor Requirements

After interviewing our clients we were able to identify the key characteristics required in a book scanner. The most important factors were book-scanning cost, book compatibility, portability, and user-friendliness. Less important requirements were also determined. These included the cost of the device, and that the design is easily disassemble for shipping, and that the device wasn't excessively loud while running.

**Cost:** Our clients expressed more concern over the cost of operation than the cost of the device. They currently spend from \$30-\$100 to scan an average book. The majority of this cost is due to the labor in their scanning process. A “specialty” book that either has extensive fold outs or some other non-standard feature may take significantly longer to scan and therefore the digital copy costs even more. Therefore, the main contributing factor to lowering cost of the overall process is to make the device efficient rather than cheap. The largest cost savings would come from reducing the amount of labor necessary to scan an average book.

**Book Compatibility:** Most commercial scanners have been designed to deal with the common types of books. These are books without foldouts and with pages from 4" x 6-3/4" up to 9-1/2" x 12". Our clients would like a device that can handle a wide range of “specialty” books. They also realized that if this weren’t possible a device that can handle common sizes, but still automates the process would greatly reduce the cost in digitizing their library.

**Portability:** The portability is not a major factor in the design of this book scanner. [1] This tool will most likely remain stationary for large batches of scans. However, our clients also expressed the possibility offering a future service of lending the scanner to smaller libraries. This would require some thought into making the unit portable and easy to assemble.

**User-Friendliness:** Although the end-users of this current prototype are trained in book scanning and may be able to learn a non-intuitive system, ultimately our sponsor’s goal is for this device to be accessible to a larger community to increase the number of books that get scanned. [1] Therefore an easy to use interface is an important component to the final product.

**Noise Level:** Since the scanner would be housed in the same space as the other scanners, most of which have operators, there is some concern regarding the noise level produced. The scanner should fulfill health and ergonomic requirements for ambient noise.

## Engineering Specifications

The qualitative sponsor requirements were then translated into engineering specifications that can be measured and tested. A quality function deployment (QFD) was performed to identify the key attributes of the design, and this is shown in Figure 4. The colors in the QFD chart represent the correlation between the engineering specifications and the client requirements where red is a high correlation, blue medium, green low and white has no correlation. Some of these correlations are somewhat obvious such as cost (per book) being highly correlated to pages and failures per hour.

Ranking	Engineering Spec.	Unit	Target	Significance	Client's Requirements					Importance
					Cost	Compatibility	Portability	User-friendliness	Undistracting	
1	Pages per hour	Pages/hour	200	9	7	9	5	10	4	189
2	Failures per hour	Failures/hour	0	10						210
3	Durability	Time to Failure	>1 year	6						186
4	Size range of book	Inches	6 x 9	8						216
5	Max weight of book	Pounds	6	7						189
6	Max weight of device	Pounds	20	6						90
7	Time to proficiency	Minutes	30	8	5					312
8	Price	\$	\$1000	5	3					105
9	Noise level	dB	40 dB	3						36
10	Book type/condition	IOBA Book Rank	Ranking: Poor	6						222

Figure 4: QFD chart used to determine specification ranking.

The QFD chart allowed the engineering specifications to be ranked. This has made it easier to determine what design characterizes are necessary. Further details on each engineering specification are listed below.

**Scanning Rate:** It was clear that the number of pages scanned per hour is an important indicator of success for this project. The commercial scanners in use by the library are only able to realistically scan 200 pages per hour with an operator. If we can achieve at least the same rate yet have the system be more automated, i.e. not require as much user intervention, then this will be a large improvement in the cost to scan a book. This goal of 200 pages per hour is for an average size book without any special foldouts or other features.

**Failures Rate:** While speed is important, it would be undesirable for the scanner to fail during a job and possibly harm a book. Therefore it is important to minimize the failure rate of the scanner. Although the ultimate goal is to have zero failures, since this prototype is largely based on the initial prism linear book scanner, the engineering specification is to minimize the failure rate while improving on the estimated 50% failure rate of the initial prototype.

**Book Specifications:** The range of books that this scanner can use is important. If the range is too large then the tool will be much larger than necessary for the average book, but if it is too small then it will only be useful for a very specific size of book. By accommodating books from 4" by 6-3/4" to 9-1/2" by 12" that are less than 6 lbs. and are in reasonable condition.

**Lifetime:** The lifetime of this scanner is important in that the more often it needs to be repaired the more it will cost to scan a book. With such an early stage prototype it would be exceedingly difficult to perform any meaningful lifetime calculations. The best estimate will be to evaluate what wear has occurred at the end of the validate testing and to judge if there seems to be any specific issue that will greatly reduce the life of the device. If there isn't a specific wear pattern it is safe to assume the scanner may have a long lifetime. So in order to satisfy this criteria by the end of the devices validation testing no component should show significant and or detrimental wear.

**Device Weight:** The weight and size of the device will have a direct impact its portability. The original prototype can be disassembled and fit a box that is 22" x 14" x 9" which allows it to be brought on a plane as carry-on luggage. [9] This should also be a reasonable target for the new design. The original prism scanner also weights 20 lbs., which is within the range of weights one average human can carry without injury [10]. Keeping within this weight should maintain the systems portability and allow it to be easy to transport.

**Time to Proficiency:** The training time required for a novice to operate the device should be low. Currently it takes between 1 and 4 hours to learn how to operate and to learn the key aspects in operating the universities current book scanners efficiently without errors. [1] We feel a reasonable goal would be to keep this training time under 30 minutes.

**Price:** The original prototype cost \$1,500. This project has a \$400 budget allocated to the course with an unclear budget from our sponsors. Our goal is to design a new scanner with a hard limit of \$1500, and to reduce the cost of the design if possible so that it is more accessible to the general community.

**Noise Level:** Since the scanner will be housed in the same space as the other book scanners and staff, the noise level of the scanner should be low enough that it does not disturb the employees. If we are able to keep the noise level below 55 dB which is less than an average office environment.

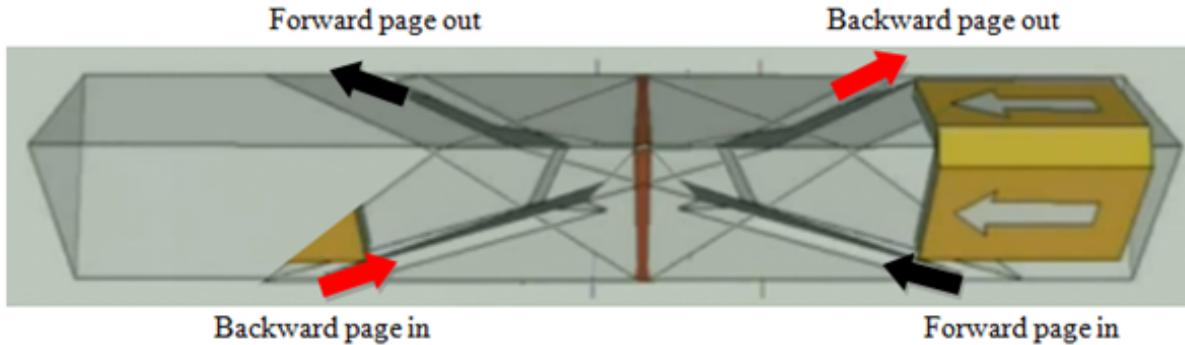
## CONCEPT GENERATION

In order to develop initial concepts for this linear book scanner, it was necessary to divide the design into appropriate subassemblies. These subassemblies included the frame geometry, vacuum slots, saddle, and overall assembly of the unit, drive system and fabrication materials. For each of these categories initial ideas were developed in a brainstorming session and unrealistic concepts were ruled out. These ideas were refined and then a selection process was used to determine the best path for each section.

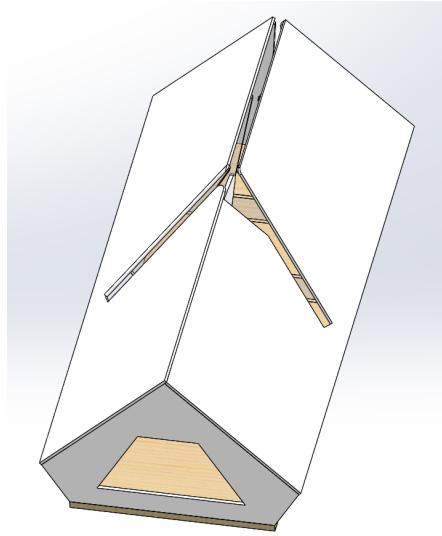
### Frame Geometry

Several concepts were generated for the frame geometry for the linear book scanner. These were based on the projects engineering specifications. Some of these were made nearly to scale out of cardboard to get a better understanding of how the tool operates. Two major geometry changes were developed. These were the “X-slot channel” and the “shortened” concept as shown in Figure 5 and Figure 6, pg. 11. The X-Slot design essentially takes the current book scanner geometry and imposes it in both directions of travel, so that the book turns a page each time it moves the length of the scanner. The shortened version reverses the direction of the exit channel and folds it back on the scanner. This causes the page to exit the channel on the return pass and allows for a shorter scanner length. Both of these concepts were generated in order to increase the scanning rate by decreasing the cycle time. The X-slot achieved this by turning a page on each stroke of the scanner whereas the current design only turns the page on the forward stroke. While the shortened version moves the page exit geometry to the front of the tool so that the total stroke is significantly shorter, increasing the scanning rate. The shortened version also improves the device portability because it allows the system to be shorter which makes it easier to transport.

Ultimately the goal is to design and manufacture a device that has a high scanning rate and low failure rate to reduce the cost per scanned book. Other geometries were considered that had cube and cylindrical shapes, however these didn't show any obvious gains while presenting a huge risk in that they greatly deviated from the current geometry. Making a large change from the current geometry would make it very difficult to tell if it would even be possible to make them work.



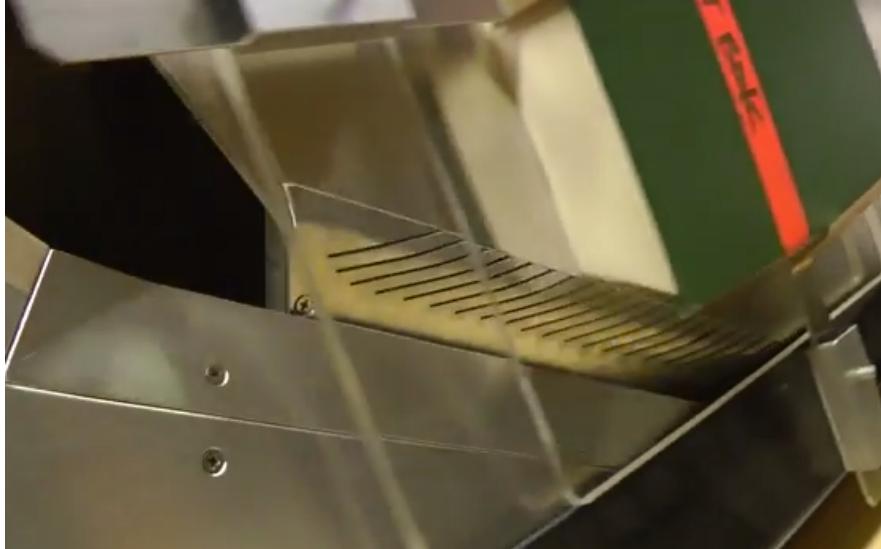
**Figure 5: Model showing proposed “X-slot” design and book path.**



**Figure 6: Model showing proposed “Shortened” design.**

### Vacuum Slots

After consulting the initial linear book scanner designer and testing the original prototype, it was determined that the vacuum suction needs to be concentrated at the page corner [11]. In order to scan a wide variety of book sizes a method was then necessary to change the location of the vacuum so that the correct vacuum setting may be made as a book is being loaded. Several concepts were developed including a sliding vacuum slot section, a sliding vacuum chamber behind a slotted edge, and a helical cylinder behind a slotted cylinder. A closer view of the current vacuum slot can be seen in Figure 7.



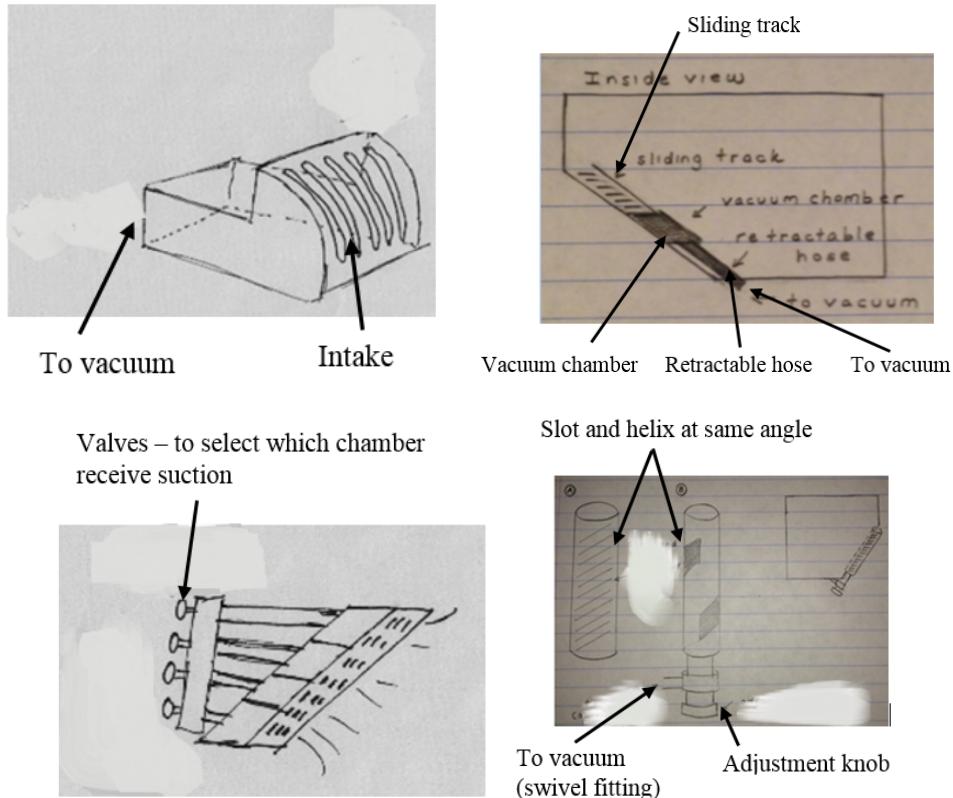
**Figure 7: Close up of initial linear book scanner vacuum slot.**

**Sliding Vacuum Slot:** The sliding vacuum slot concept would remove the slots and bend from the page turning edge of the current prototype completely. Suction would be delivered using a sliding vacuum slot section that would attach to the flat, un-slotted page turning edge. Figure 8 (upper left) shows a potential design for the sliding vacuum slot section.

**Sliding Vacuum Chamber:** The sliding vacuum chamber concept utilizes the current prototype's vacuum slot configuration and uses a sliding track-mounted chamber on the back of the page turning panel to direct suction. Figure 7 (upper right) shows the inside view of the page turning panel.

**Stationary-Segmented Vacuum:** The stationary-segmented vacuum concept also uses the current prototype's vacuum slot configuration but divides the rear chamber into four segments. These segments can individually be given suction using a valve system. Figure 7 (lower left) shows the stationary-segmented chamber concept incorporating a four-valve system.

**Helical Cylinder:** The nested helical cylinder vacuum concept redesigns the whole page turning edge. The bended slots are replaced with the nested cylinders as seen in Figure 7 (lower right). The outer cylinder consists of many angled vacuum slot cuts while the inner cylinder has a wide slot cut along a helix. By rotating the inner cylinder within the outer cylinder, specific vacuum slots can be activated.



**Figure 8: Various vacuum slot concepts: sliding slot (upper left), sliding chamber behind vacuum slot edge (upper right), segmented chamber (lower left), and helical cylinder (lower right).**

### Saddle

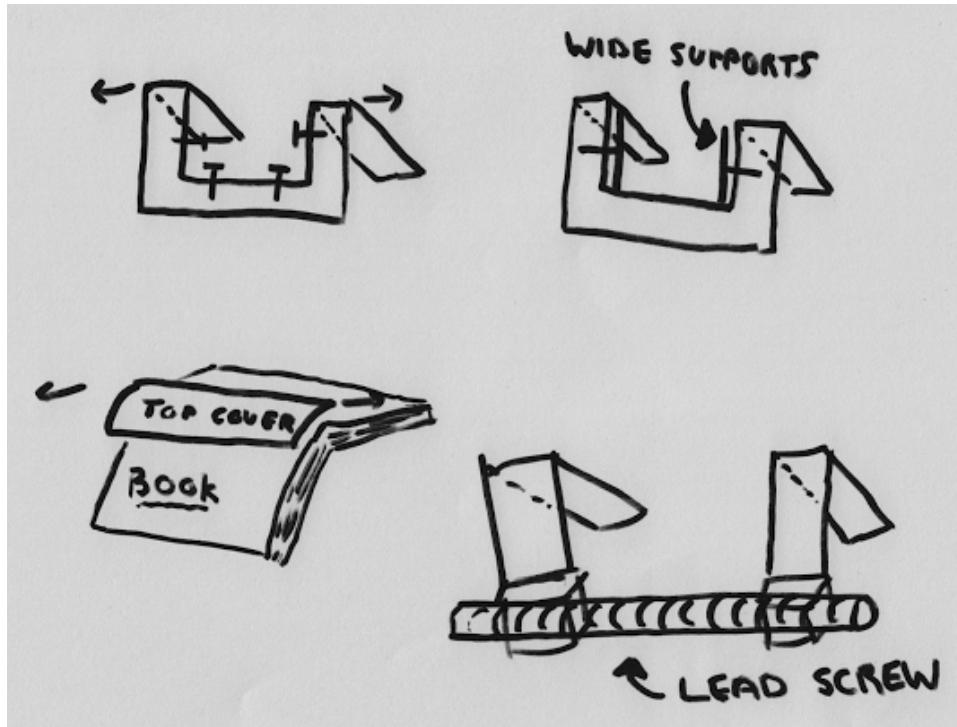
The saddle is used to hold the book as it moves across the linear book scanner. Three alternatives to the current prototypes design were developed. These ideas included "Wide Walled", "Top Cover", and "Lead Screw" and can be seen in Figure 9.

**Wide Wall:** The wide walled idea was generated in an effort to provide better book support, especially when the book's pages are concentrated to one side. The main component of this design would be a wider support surface in contact with the book.

**Top Cover:** The top cover concept would be support added to the current system on the top of the book. It would provide improved stability and support by securing the book from the spine. This may be accomplished with a flexible strap that would stretch to size for various book thicknesses.

**Lead Screw:** The lead screw concept was a very complex idea that would use the drive system to both move the book and support it during movement. Essentially two lead screws would support the saddle along the length of the scanner. Even though this design seemed unfeasible, we thought it was worth comparing since it was an innovative and creative idea.

These three concepts were the main design modifications evaluated with the saddle.



**Figure 9: Initial saddle designs showing current design (upper left), wider slots (upper right), top cover (lower left), lead screw (lower right).**

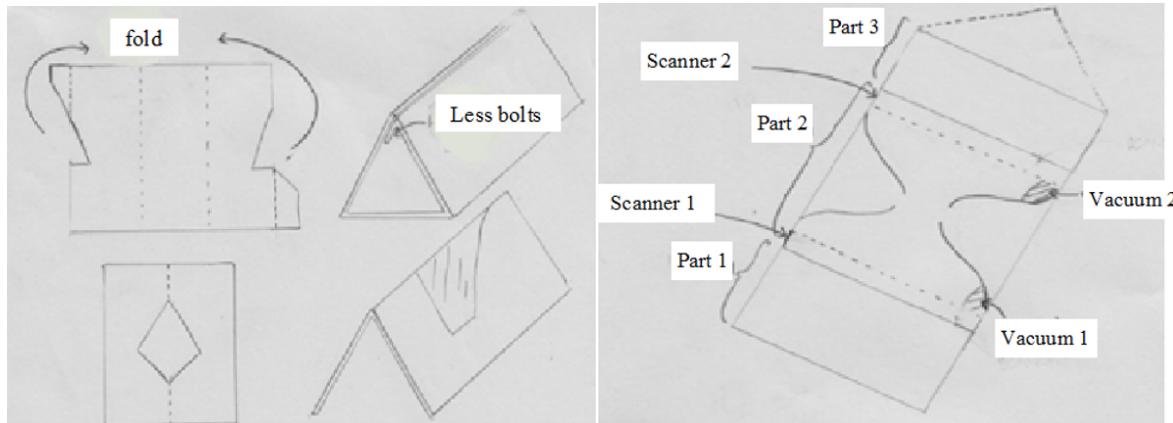
### Assembly

For the assembly of the device, we considered many ideas that would reduce the number of parts and steps required for construction. The goal is to make the assembly simple enough for someone without an engineering background to put together. Two general ideas emerged, a single sheet folded into the necessary shape and several distance segments made out of flat stock.

**Single Sheet:** The simplest form for assembly may be a single sheet of material that is folded twice into the triangular prism shape of the frame. This way, there would be significantly fewer fasteners required for the main frame of the device. This single sheet is shown in Figure 10 (left). A variation that would be easier to manufacture would be to have a single fold down the middle to create the platform on which the book sits.

**Flat Pack:** The alternative idea is somewhat like a flat-pack furniture model, in which one sheet of material is laser cut to create all the major pieces of the frame. The idea then evolved to laser etching the sheet into parts that could be assembled into 2 distinct segments of the scanner, the electronics and frame

portions. This assembly would allow for some modularity, making replacing major components easier. It would also improve on portability, as the individual segments would be much smaller than the whole scanner.



**Figure 10: Assembly methods for LBS showing scanner folded from a large sheet (left) and composed of many parts (right).**

### Drive System

The drive system is what moves the book across the LBS. The first consideration is what will actually give the book a linear movement. Several concepts were developed; these were drawn from linear movements in other mechanisms. The first was to use a timing belt; this is what the current prototype uses. Another idea was to use a lead screw much like a lathe uses a lead screw to move its carriage. Finally we considered a rack and pinion. This would have a motor mounted on the saddle and a rack along the length of the LBS. This is actually how a Canon 220 LIDE flatbed scanner moves its scanning bar.

The next issue with the drive system is what to use to produce the motion. In order for the scanner to produce scans that aren't distorted the drive system must be able to maintain a constant book velocity. Three options were considered. The first option was to use a stepper motor, this is what the current prototype uses. This would most likely use a chopper driver to control the motor, which are readily available and offer simple step, direction interfaces. The second option considered was a servo motor. A servo would require a closed-loop control, and a significantly more expensive driver and potentially more work to make the driver effective. The last drive system considered would be a linear cylinder, such as a ~4ft long pneumatic cylinder to push the book back and forth. This would require a complex valve system with dampers to maintain and vary the velocity.

### Materials

In order to determine what material would be best to fabricate the scanner out of, a list of possible materials was made. These are what materials may be used in the frame, and the components that book is in contact with. Table 2, pg. 15, shows the materials that we thought would be reasonable to work with.

**Table 2: Possible materials for frame and faces of linear book scanner.**

<b>Material</b>
Acrylic
Polyester (PETG)
Polyoxymethylene (Delrin)
Polypropylene
Aluminum
Stainless Steel

### **Electronics**

In order to manage the scope of this project, the general layout of the electronics will remain the same. A Linux computer will be used to run the scanners and give commands to a real time operating system (microcontroller) to control book movement. An open source program called ScanImage allows the scanners to be used through the command line, greatly simplifying scripting. This is the primary motivation for incorporating a Linux computer to coordinate the book movement to the scanning bars.

One important component of the electronics is how to detect a double feed situation where two pieces of paper are fed into the channel at the same time. Since this is a common issue with printers we decided to investigate how a printer can detect a double feed. A paper published by HP shows that when two pieces of paper are in contact they do not allow an ultrasonic sound wave to be transmitted through them, but when there is only a single piece of paper it transmits this sound wave with little attenuation [12]. Applying this information, the idea is to use an ultrasonic transducer to transmit a high frequency sound through the paper, and then detect this sound on the other side. If there is a lot of attenuation then there are multiple pieces of paper. This is because the small air gap between two pieces of paper dampens the sound. Since the components to do this are fairly low cost and this is how commercial printers detect double feeds we are not investigating alternative methods until we are unable to make this work. If possible we will attempt to add this type of sensor.

Another component of the electronics is the actual scanners. The most important aspect of the scanner is that it needs to be SANE compatible. SANE (Scanner Access Now Easy) is a set of open source drivers for Linux that allow scanners to be operated from the command line. This is critical to be able to quickly write a script that coordinates the scanning to the book movement. Canons line of LIDE scanners are some of the few scanners currently produced that are fully SANE compatible [13].

### **CONCEPT SELECTION**

The goal of the concept selection is to determine what concept will best meet the engineering specifications. The developed concepts were kept in their respective component groups for this selection process. After initially ruling out unrealistic concepts, we evaluated each the concepts within each component group based on the engineering specifications. Each component group used a unique list of criteria and weighting to determine overall score. The weight for criteria was on a scale of 1-3 (1 least important, 3 most important). Each component was evaluated on each of these criteria on a scale of -2 to +2 (-2 worst, +2 best), however the vacuum suction used a 1-4 weight system. The initial prototype had a neutral score of 0 for everything in order to use it as a baseline.

### **Geometry**

In order to determine what geometry concept would best satisfy the engineering specifications the Pugh chart as seen in Table 3, pg. 16, was created. A large emphasis was placed on the speed of the scan since the faster the machine can scan the better the scanning rate and cost per scanned book. Feasibility of

manufacturing, portability, ease of assembly and user experience were ranked as medium importance since they aren't high priority engineering specifications. Using this Pugh chart it became clear that the X-Slot design would not be practical. Since its geometry was significantly more complex than the initial design and the shortened there would be a high risk that it would fail during scanning and that it would be more difficult to manufacturer. The shortened design was a clear winner, as it should improve on the scanning rate as well as the portability of the current design without having a huge geometry change that would make a high risk of page turning failures.

**Table 3: Pugh chart used to determine specification ranking of the Linear Book Scanner geometry.**

Geometry	Weight	Initial	X-slots	Shortened
Feasibility of Manufacturing	2	0	-1	1
Risk in Possible Failures	1	0	-2	-1
Portability	2	0	-1	1
Ease of Assembly	2	0	-1	1
User Experience	2	0	0	0
Speed of Scanning	3	0	2	1
<b>Total (weighted)</b>	<b>0</b>	<b>-2</b>	<b>8</b>	

### Vacuum Slots

The vacuum slot designs were evaluated based on their adjustability, effectiveness at separating one page from a book, manufacturing feasibility, and ease of assembly and use. Each criterion's designated weight can be found in Table 4.

**Table 4: Pugh chart showing vacuum slot selection.**

Vacuum Slots	Weight	Current Prototype	Sliding Edge	Sliding Chamber	Segmented Chamber	Helical Cylinders
Adjustability	4	0	2	2	1	2
Page Separation	4	0	-1	0	0	1
Manufacturing Feasibility	3	0	-1	-2	1	0
Easy of Assembly/Use	2	0	-2	-2	-1	-1
<b>Total (weighted)</b>	<b>0</b>	<b>-3</b>	<b>-2</b>	<b>5</b>	<b>10</b>	

**Current Design:** The current prototype's vacuum section features a panel bent into the prism with a slotted vacuum edge. It requires no user input and is therefore easy to assemble and use but lacks adjustability. Though it is easy to manufacture, it is rather ineffective.

**Sliding Vacuum Slot:** The sliding edge concept, although innovative and adjustable, was easily ruled out. While this prototype would allow for isolated suction, we expect that the uneven edges associated with the movable slot would lead to more torn pages. Additionally, the use of a sliding track and complicated locking mechanism would make the manufacturing, assembly and use more difficult.

**Sliding Vacuum Chamber:** The sliding chamber concept capitalizes on the benefits of the sliding edge concept without causing issues with page separation. By retaining the current prototype's fully slotted bent edge and moving the slider inside the prism, we can achieve full adjustability while preventing any

negative effects on page separation. However this concept still uses many moving parts that make the assembly and use more difficult. It would be even more complex to manufacture due to the requirement of fitting the vacuum chamber flush against the curve of the slotted edge.

**Stationary-Segmented Vacuum:** The segmented chamber concept minimizes manufacturing, assembly, and use complexity at the expense of adjustability. A stationary chamber that selects the vacuum locations through a series of valves will only give rough adjustability to the vacuum location. This would be easy to manufacture and package, as the only moving parts would be valves. It should be easy to operate, as the user would only have to turn a valve. The page separation should be equivalent to the current prototype, as the vacuum panel face would go unchanged.

**Helical Cylinder:** The helical cylinder concept allows for full adjustability and improved page separation with minimal moving parts and easy operation. The curved surface of the slotted cylinder should help separate the pages and ensure that only one page is turned each pass. Additionally, the two cylinders can be easily manufactured at home using PVC pipe or more accurately manufactured using 3D printing. If the cylinders diameters are sized correctly they should provide a smooth fit that is loose enough to allow adjustment but tight enough to keep it at a set position.

Due to the many strengths of the nested helical cylinder vacuum slot, it is a clear choice for this linear book scanner.

### Saddle

A main issue with the first prototypes saddle is that the design lacks the ability to support the book flush to the frame. This leads to problems when the majority of pages are on one side of the book. For this design we plan to lengthen the supports, so that they are flush to the body of the design, as well as increase the thickness for greater support.

The “Top Cover” design concept was created to provide a snug fit for the book and provide for adjustability depending on the size of the book. “Wide Walled” is an idea that makes a simple design modification to enhance the support for the book. Lastly, the “Lead Screw” idea was to simply have the saddle connected to a lead screw and it would move with a helical gear drive system. The necessary criteria and the subsequent scores for each design can be seen in Table 5.

**Table 5: Pugh chart showing saddle selection.**

Saddle	Weight	Current Prototype	Top Cover	Wide Walled	Lead Screw
Feasibility of Manufacturing	3	0	-1	0	-2
Simplicity	2	0	-1	0	-2
Portability	1	0	0	0	-1
Ease of Assembly	3	0	-1	0	-1
User Experience	3	0	1	1	1
Pages per hour	1	0	0	0	0
<b>Total (weighted)</b>	<b>0</b>		<b>-5</b>	<b>3</b>	<b>-7</b>

In evaluating the criteria for saddle design we put emphasis on feasibility of manufacturing, ease of assembly, and user experience because there are many components to the saddle and the user has direct interaction with it. Simplicity had a medium ranking because it wasn't necessary to meet our design specifications. Finally, we gave little value to the saddle's portability and pages per hour, since we knew

the size of the saddle would not be an issue and our saddle design would not affect the rate of pages scanned.

The wide walled design will be used for this book scanner as the QFD in Table 5 shows it has a clear advantage over the other designs. The lead screw concept was very unrealistic and unnecessary since the main function was to support the book. The top cover design provided some benefits for the user experience, but probably increase book friction making it difficult to move the book. The Wide Walled concept actually builds off the current saddle, but it simply makes the supports more robust to increase stability. We think this design modification will work well since the current saddle already functions well.

### Assembly

The initial prototype requires a significant amount of parts and fasteners and is also sensitive to how it is assembled to compensate for part tolerances. Although this is okay for a prototype, it would be ideal to reduce the number of parts required for our design. Currently, the frame is composed of several large aluminum sheets mounted on a chassis; this works well but may be improved.

The most heavily weighted attributes that the assembly is measured against are feasibility, portability, ease of assembly, user-experience, and troubleshooting. The reasons for these weights are obvious, as the frame is essentially the entire volume of the scanner. The ease of which the parts can be made from raw material, then assembled, occasionally disassembled for troubleshooting are all heavily dependent on the assembly design. The same reasoning applied to the heavier weights on portability and user-experience; although they will likely vary depending on the preferences of future users of the scanner. The QFD used to determine the best assembly method is shown in Table 6.

**Table 6: Pugh chart used to determine best assembly method showing segments advantage.**

Assembly	Weight	Initial Prototype	Single Piece	2 segments (Bilateral)	2 Segments (Electronics & Scanner)	3 Segments
Ease of Manufacturing	3	0	-2	1	0	0
Simplicity	2	0	1	0	0	0
Portability	3	0	-1	0	1	2
Ease of Assembly	3	0	1	0	0	-1
User Experience	3	0	-1	0	1	1
Pages per hour	2	0	0	0	0	0
Troubleshooting	3	0	-1	0	1	1
<b>Total (weighted)</b>	<b>0</b>	<b>-5</b>	<b>3</b>	<b>9</b>	<b>9</b>	

We attempted to develop a “Single piece” design in which the entire frame would be made by bending a single sheet of material to create the triangular frame of the device. This would be the most ideal design to reduce parts, but fails in almost all other aspects of our evaluation. The segmented designs are divided into 3 categories: 2 segments (bilateral), 2 segments (electronics + scanner), and 3 segments. The bilateral 2 segment design is very similar to the initial prototype, but simply combines all of the separate aluminum pieces into 2 complete parts that would be placed on the 2 faces of the device. This design reduces the number of components and improves on ease of manufacturing when compared to a single piece, but doesn't provide additional advantages. The remaining segmented designs ranked the same and could both be considered. They also incorporate some modularity in the design as they are segmented by functionality, thereby allowing easy replacement of whole modules if needed.

## Drive System

The first stage of the drive system is to determine how to make the book move linearly across the book scanner. The different methods can be seen below, in Table 7. A belt would essentially be the current setup. There are severe issues with all other methods. For instance a rack and pinion as well as a lead screw would require very large expensive heavy components in order to run. These both also tend to require fairly high tolerances in order to mesh properly and run smoothly, this would add to the systems cost without any clear benefit. Then although a pneumatic piston would add a significant amount of cost (~4ft long cylinders tend to be expensive) it would also double the length of the tool in order to accommodate the pistons stroke.

**Table 7: Pugh chart used to determine optimum drive system.**

Drive System	Weight	Timing Belt	Rack and Pinion	Pneumatic	Lead Screw
Cost	1	0	-1	-2	-2
Ease of Assembly	1	0	-1	-2	-2
Max speed/power	3	0	0	2	-2
Trouble Shooting Ability	2	0	0	-2	-2
Durability	3	0	0	2	2
Safety	3	0	0	-1	-1
Volume	2	0	0	-2	-1
<b>Total (weighted)</b>	<b>0</b>	<b>-2</b>	<b>-3</b>	<b>-13</b>	

With a clear choice of a timing belt, the next choice is to decide what to use to drive it. The only realistic options are a servo or a stepper motor. A dc motor would be very difficult to get a consistent enough velocity to make a good scan; feedback would have to be used essentially turning it into a servo. The stepper has a clear advantage as the cost of the motor and control system is significantly lower than a servo. Also motors of the appropriate size are much more available. Generally servos are sold either for very light duty small hobby applications that would be far too small to move a book, or as much larger units intended for industrial equipment such as vertical milling centers. A disadvantage of using a stepper is that with a servo it would be possible to know how much force is being used to move the book, but this aspect isn't critical to the linear book scanners operation.

## Materials

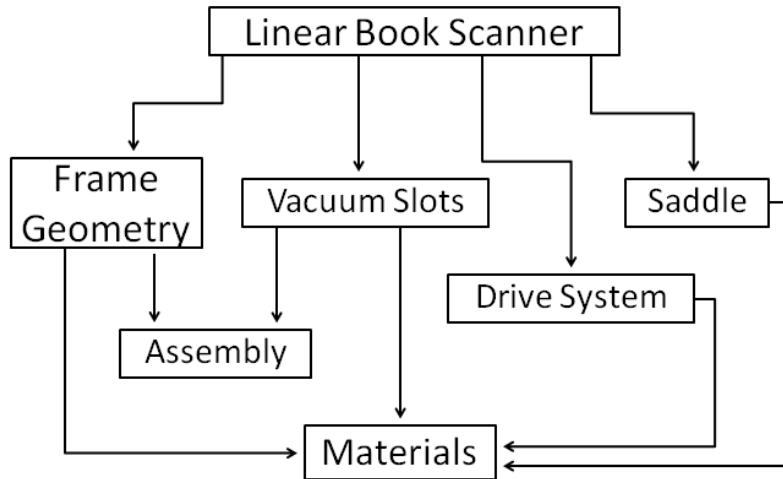
The two largest driving factors in the material selection for this project are the material cost and the manufacturing method. There are several plastics such as acrylic that can easily be cut on a laser engraver which many hobbyists have access to. Then other materials such as steel would require a larger laser cutter or water jet designed for sheet metal work. A somewhat non-scientific resource that was very helpful in the selection process was a document by a laser cutting service, Synrad [14]. This gave a qualitative description of how well different plastics could be laser cut as well as examples of what the cut surface looked like. Using this and some basic pricing research Table 8, pg. 20, was constructed.

**Table 8: Possible materials to use for frame and sides.**

Material	Cut With	\$/sqft
Acrylic	Laser Engraver	\$12
Polyoxymethylene (Delrin)	Laser Engraver	\$18
Polypropylene	Laser Engraver	\$5
Aluminum	Waterjet	\$10
Stainless Steel	Laser or Waterjet	\$23

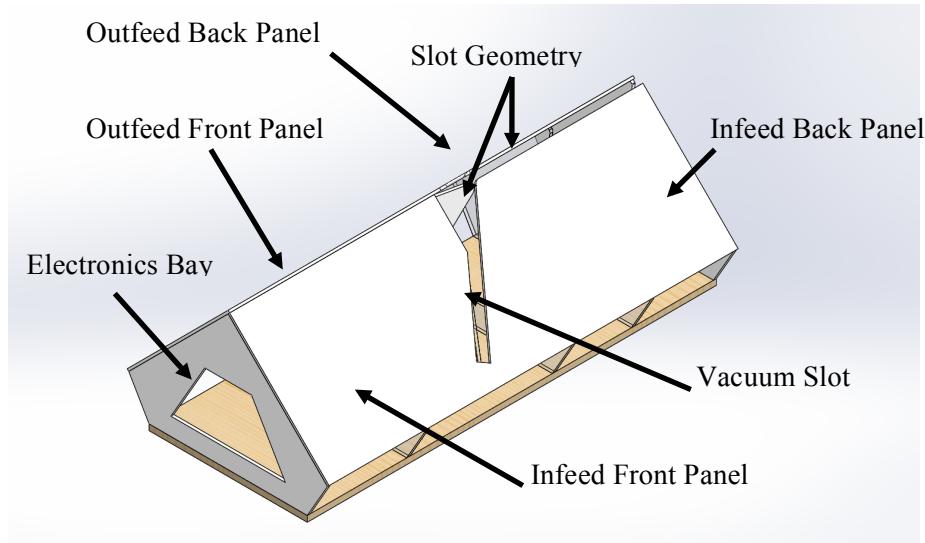
## CONCEPT DESCRIPTION

In order to have a clear understanding of how these chosen subcomponents work together it is helpful to have a functional decomposition as seen in Figure 11. This shows that although all components of this design are highly intertwined with each other, it does make sense to divide parts into different sub-assemblies. In this functional decomposition the arrows represent interactions between components, for instance the frame geometry will have an effect on how the tool is assembled.



**Figure 11: Functional decomposition of linear book scanner.**

In summary, the overall scanner design incorporates the shortened geometry using helical cylinders for the vacuum section. A timing belt will be used to slide a saddle with widened clamps from end to end of the scanner. Lastly, the scanner will be divided into sections for assembly. The overall view of the proposed design can be seen in Figure 12, pg. 21. This shows the overall geometry, how the slot the paper slides into is now doubled back on itself to save space. It also shows where the vacuum slot is placed which is used to grab the paper. Although it is difficult to tell in Figure 12, pg. 21, this model is made with  $\frac{1}{4}$ " acrylic, which will allow for rapid prototyping.



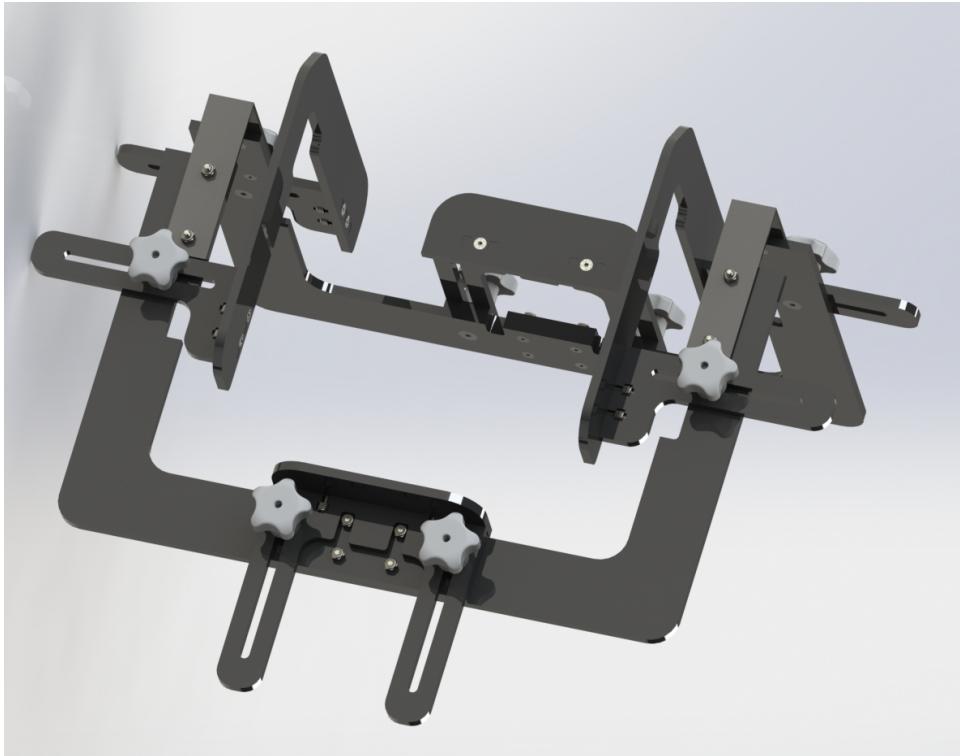
**Figure 12: Proposed linear book scanner assembly view.**

A more detailed view of the proposed vacuum slot can be seen in Figure 13. This shows the inner tube with the helix and the outer tube with the slots. It also shows the four panels of the design, the infeed front, infeed back, outfeed front and outfeed back panels that the book rides on.



**Figure 13: Proposed vacuum slot design.**

Finally a more detailed view of the wider saddle supports can be seen in Figure 14, pg. 22. This shows that the book should have more support as compared to the initial prototype.



**Figure 14: Proposed saddle design.**

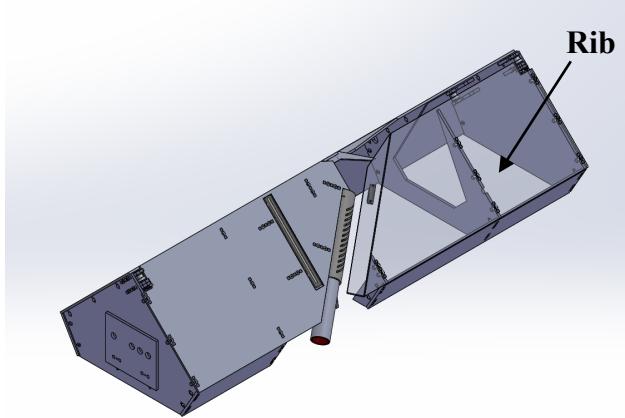
Another aspect of this linear book scanner in general is that a very convenient space to house the electronics. In Figure 12, pg. 21, that there is an opening where there would easily be enough space mount the necessary drivers and electronics on a rail that could then be slid out of the tool for work.

### **PARAMETER ANALYSIS**

The following section describes the engineering calculations necessary in designing this linear book scanner. When possible simple hand calculations were performed but in several occasions simple FEA's (Finite Element Analysis) were more practical due to the geometry involved.

### **Rib FEA**

A quick inspection of the frame geometry shows that most of the infeed and outfeed panels are well supported by solid ribs except for the very mid-section that has a rib with a large gap in the middle of it. This gap is necessary so that the book page can swing from the infeed to outfeed side, the larger the gap is the more room the page will have. Unfortunately, the larger this gap is the less support the two outfeed panels have. This rib can be seen in Figure 15.



**Figure 15: Location of rib with large gap.**

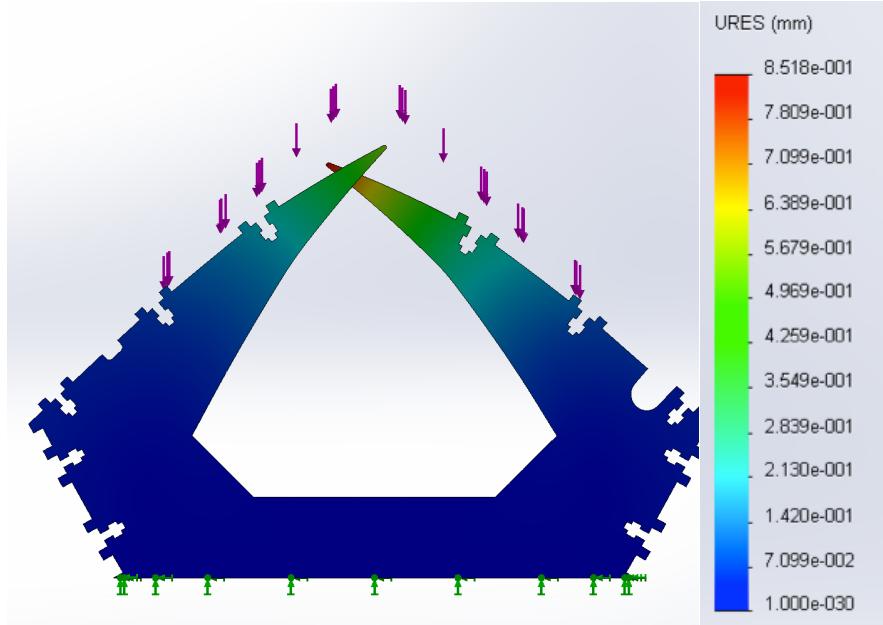
Due to the complex geometry of this rib a FEA was more feasible to perform instead of basic beam hand calculations. This rib is designed to be made out of  $\frac{1}{4}$ " acrylic, the material properties used are shown in Table 9. Considering that this component is designed to be made out of plastic it will most likely fail by excessive deformation (i.e. it will bend too far), and not by excessive stress. The stiffness of most engineering plastics is comparable, for instance Delrin has an elastic modulus 2.7 GPa while acrylics is 3.0 GPa and so their deflections will be comparable. Acrylic was a clear choice considering its cost per square foot is  $\sim \$10$  where  $\frac{1}{4}$ " Delrin is nearly \$30.

**Table 9: Material properties of acrylic.**

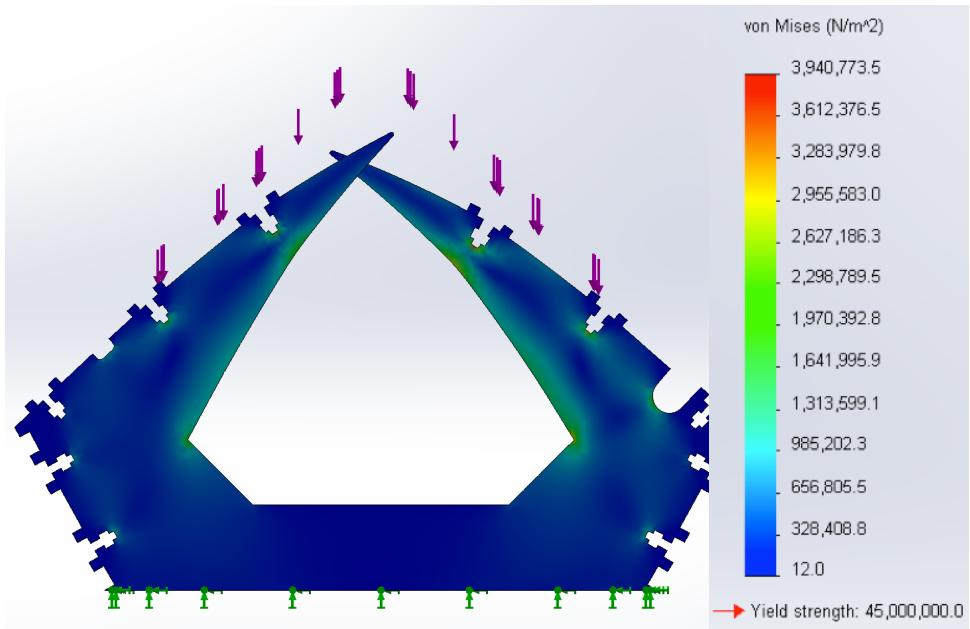
Prosperity	Value
Tensile Strength	45 MPa
Yield Strength	73 MPa
Elastic Modulus	3.0 GPa

A fixed constraint was placed at the bottom of the rib and forces placed vertically on the faces in contact with the Delrin side panels. The table below the device will support the rib from below, although it won't constrain it in every direction as shown in this simulation. This shouldn't change the final result because there are no resultant forces in those directions; essentially the simulation needs to be fully constrained to run.

A load of 30 lbs. was placed on the top of the rib going down to represent the weight of the book, saddle and a factor of safety, this is shown in Figure 16, pg. 24, by the purple arrows. Earlier the largest book was specified as 6 lbs., and the saddle weighs around 5 lbs. so this analysis should have a factor of safety between 2.5 and 3, which ensures the 0.75 in. gap between outfeed panels never completely closed up and pinches a book. The resulting deflections can be seen in Figure 15, pg. 24, where the largest deflection is 0.8 mm at the tip of the rib as expected. Then Figure 17, pg. 24, shows the stresses are well below the yield strength of the material.



**Figure 16: Rib FEA showing max deflection of 0.8 mm.**



**Figure 17: Rib FEA showing von Mises stress with maximum stress of 3.9 MPa.**

Although it is difficult to judge if this deflection will negatively affect the failure rate, we feel it should be acceptable. The gap between the infeed back and outfeed back panels is 0.75" so at a minimum the deflection will not close the gap, pinching the page into the channel. Ultimately, testing of the scanner will be required to determine if this deflection is acceptable.

### Saddle Deflection

The saddle can be modeled as a simple U shape as shown in Figure 18. An important aspect of the saddle is its stiffness along the length of the book scanner. Since the timing belt connects to the top of the saddle belt tension will cause the saddle to deflect.

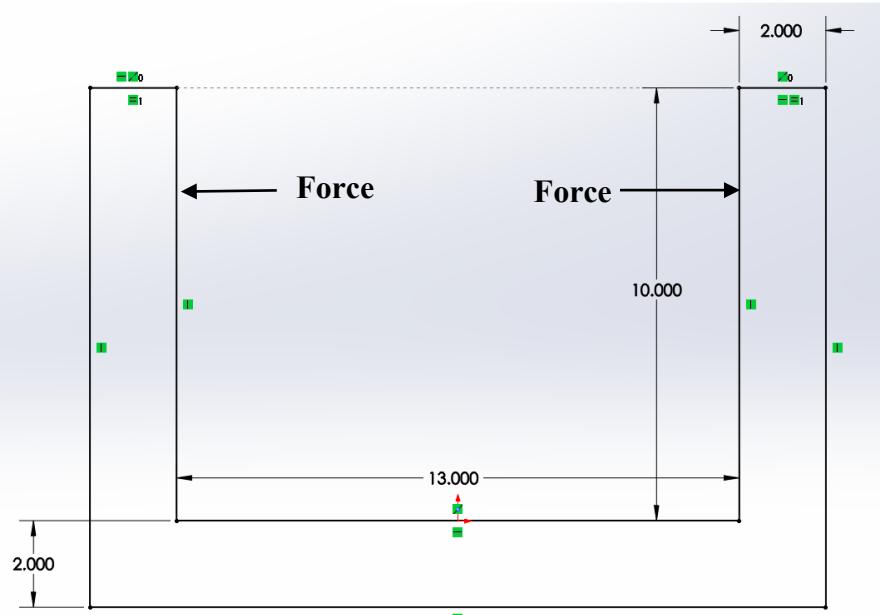
Although it is difficult to develop an actual number for the maximum allowable deflection before the belt will begin to slip on its pulley, we can at least get a rough estimate of this deflection for a variety of saddle member widths to make a more informed choice on the saddle dimensions. The width of the beams in Figure 18 (the 2 in dimension) represents what we varied to see differences in deflection. We want to minimize the width of the members in the saddle because the wider these are, the longer the linear book scanner has to be. The deflection of the vertical members was calculated using:

$$\delta = \frac{FL^3}{3EI} \quad \text{Eq. 1}$$

Then the amount the horizontal member bent was found using:

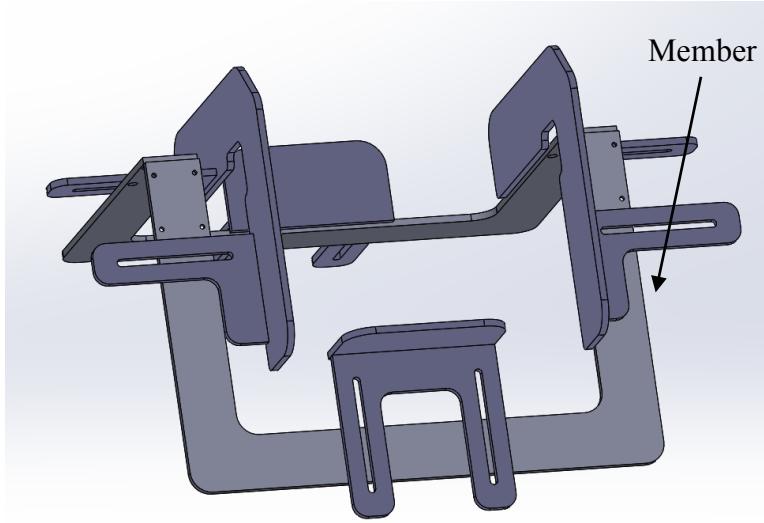
$$\theta = -\frac{ML}{2EI} \quad \text{Eq. 2}$$

This angle was used to see how far the vertical beams would move by taking the length of the beam and multiplying it by the sin of the angle. These deflections were then added to find the total deflection.



**Figure 18: FBD of saddle members.**

This member's location in the saddle assembly can be seen on the next page.



**Figure 19: Location of member in saddle assembly.**

To get a rough estimate, we modeled the two vertical members as cantilever beams with a load at the end. We then modeled the horizontal member as a beam with a moment on each end. This moment causes the beam to bend and makes the vertical beams project at an angle instead of being vertical. The sum of these deflections for several member widths can be seen in Table 10. The load was taken as the maximum force on the belt, which was 9 lbs. This force is from an estimate of the friction and dynamic forces found on the book, essentially the force required to move the book over the length of the scanner. From this information we chose a width of 2 inches as the width for the saddle members. We feel a deflection of 1/8" should be reasonable considering the belt is nearly 7 ft. long. Real world testing will better show how much deflection is acceptable but we feel this is a reasonable starting point.

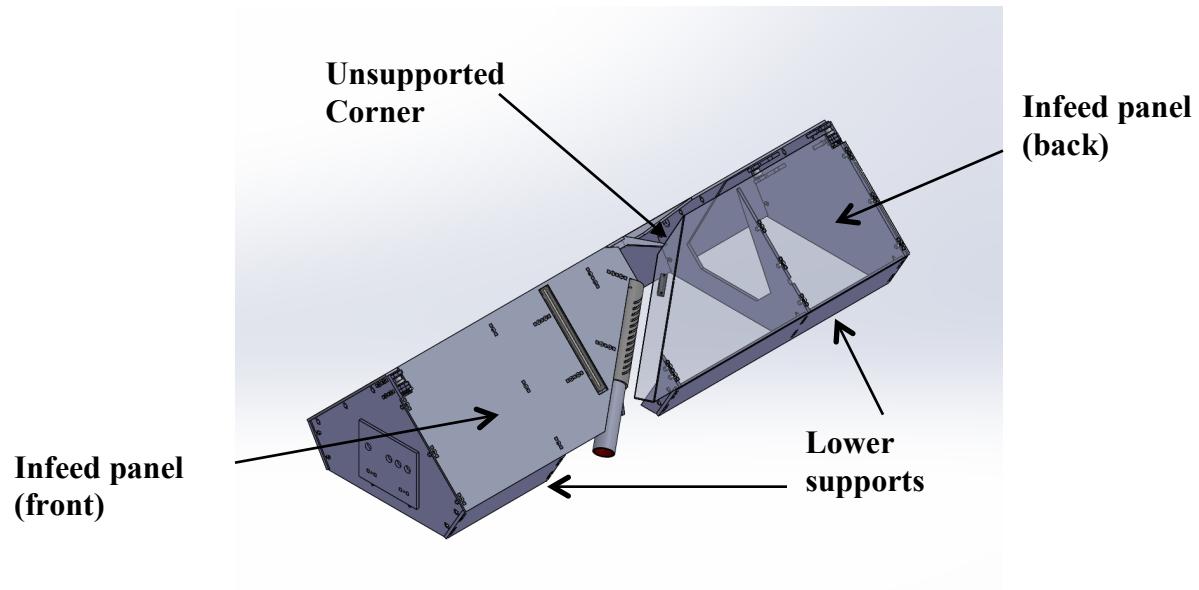
**Table 10: Total deflections for several widths of beams for saddle.**

Width (in)	Total Deflection (in)
1	1.01
1.25	0.52
1.5	0.3
1.75	0.19
2	0.13
2.5	0.08
3	0.04

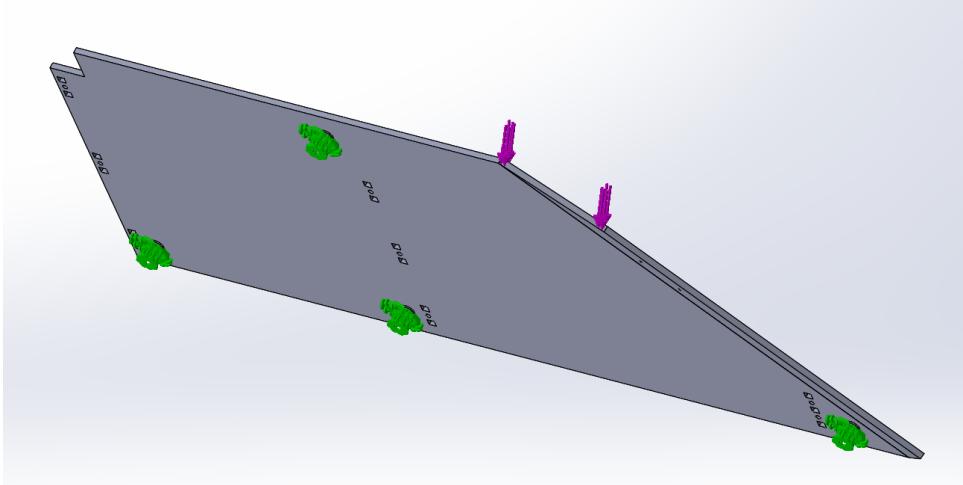
### Side Panel FEA

Another consideration is the stiffness of the outfeed side panels. The infeed panels receive a lot of support by the ribbing structure but the outfeed must have a large hole in the middle to accommodate the book page. We wanted to see how much the side will deflect with the amount of support it has from the ribs to understand if the gap between the sides at the top will close and pinch the book page. Figure 20, pg. 27, shows the location of this side panel. Figure 21, pg. 27, shows the locations of the load and constraints. The constraints assume the ribs it is mounted to hold it rigidly at the fastener locations. With a load of 6 lbs. (the saddle should be long enough so that only the book will load this unsupported section

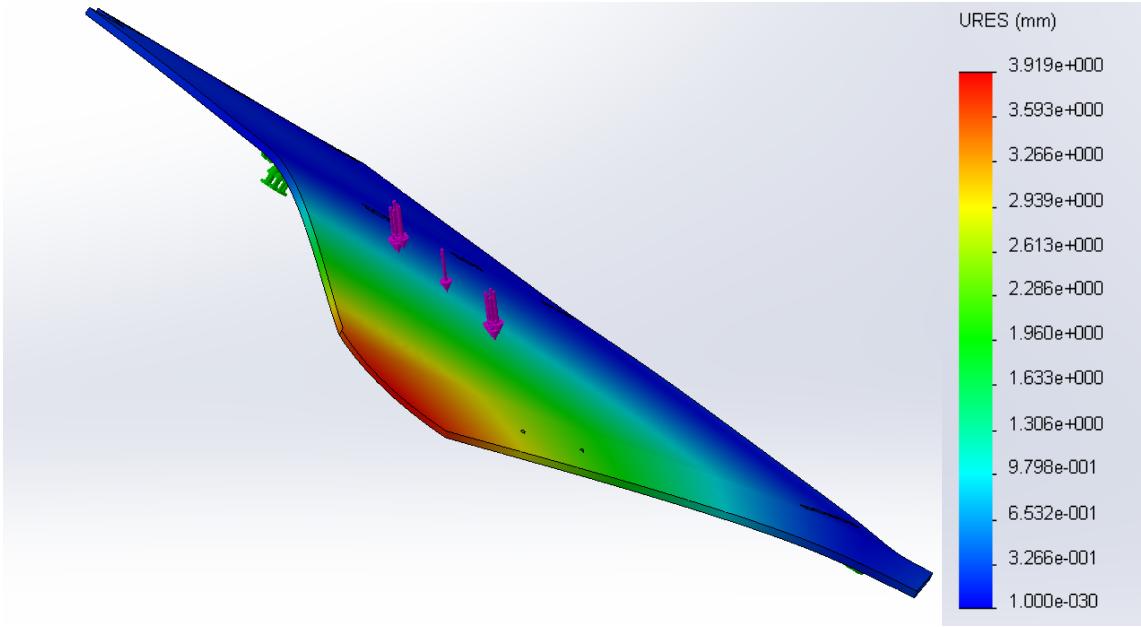
giving a factor of safety of 2) the maximum deflection was 0.15 in. This deflection is shown in Figure 22. This is compared to the gap between the sides, which is 0.75 in. We feel this deflection shouldn't hinder the operation of the scanner, but real world testing will be necessary to fully understand the geometry.



**Figure 20: Location of side panels with lower supports.**



**Figure 21: Location of loads and constraints on side panel.**



**Figure 22: FEA showing maximum side panel deflection of 3.9 mm.**

### Motor Analysis

It is important to understand the dynamic loads on the motor during operation to know how large the motor should be. To determine the required torque, estimates of the weight, acceleration, and friction of the saddle and book were made. These were used to determine the maximum torque on the motor.

First we expect the saddle and book to weigh at most 10 lbs. With an estimate of the max speed of the initial prototype of 0.5 m/s and the distance it accelerates to be 0.032 m the force due to accelerating the book and saddle was determined. Then the force due to friction was determined using an estimated friction coefficient of 0.3. This force was determined using Eq. 3-5. Then the torque was found using the radius of the current prototypes driving pulley (0.635 cm) and Eq. 6. Then the maximum operating speed of the motor was determined using Eq. 7. These calculations were made in a spreadsheet so that several estimates could be made depending on variations in loading, friction and pulley size.

$$F_{friction} = \mu_s * m_{saddle+book} * 9.81 \quad \text{Eq. 3}$$

$$a_{max} = v_{max}^2 / (2 * d_{accel}) \quad \text{Eq. 4}$$

$$F_{accel} = m_{saddle+book} * a_{max} \quad \text{Eq. 5}$$

$$T_{max} = (F_{friction} + F_{accel}) * r_{pulley} \quad \text{Eq. 6}$$

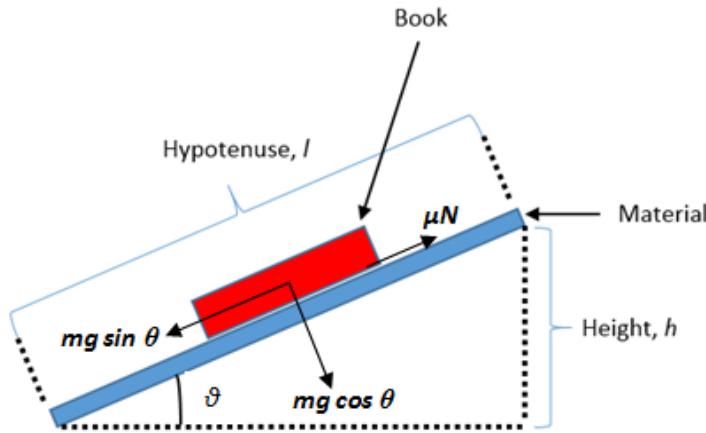
$$RPM_{max} = \frac{v_{max}}{r_{pulley}} * \frac{60}{2*pi} \quad \text{Eq. 7}$$

Using these estimates we found the maximum dynamic torque to be 0.20 Nm with a max motor speed of 750 RPM. Considering this is only a rough estimate we will select a motor that has a holding torque of 2 Nm because at higher speeds (750 RPM is a high speed for a stepper motor) the motors torque is

significantly lower than the holding torque. This selected motor size is also slightly larger then what the current design uses because the current prototype's motor occasionally stalls under heavy books. If needed available torque can be increased by using a smaller driving pulley at the expense of how fast the scanner can operate.

### Materials Analysis

Simple empirical testing was performed to determine the coefficient of friction between the pages of a book and our potential materials: Delrin, acrylic, polypropylene and aluminum. This testing was conducted by placing the book onto a flat sheet of the selected material with known dimensions. The sheet was then slowly tilted, increasing the angle until the book started to slip as shown in Figure 23. We then used the known length of the material,  $l$ , and the height at which slip occurred,  $h$ , to determine the angle at which slip occurred,  $\theta$ . This was used with Eq. 8 to find  $\mu_f$ , the coefficient of friction.



**Figure 23: Test setup to find coefficient of friction book pages and various materials.**

$$\begin{aligned} \mu_f mg \cos \theta &= mg \sin \theta \\ \mu_f &= \tan \theta \end{aligned} \quad \text{Eq. 8}$$

Two books of different page styles were tested for each material to produce more accurate results. The collected data is summarized in Table 11. This shows that Delrin has the lowest coefficient of friction with the pages of a book. Through our brief empirical testing, we determined Delrin will be the optimal material for sliding surfaces. Although it is more expensive then acrylic, it has a lower friction and is still possible to be laser cut.

**Table 11: Book friction on various tested materials.**

Material	Book	Angle, $\theta$ , (rads)	Coefficient of Friction, $\mu_f$
Acrylic	1	0.41	0.44
	2	0.39	0.41
Delrin	1	0.25	0.26
	2	0.21	0.21
Polypropylene	1	0.32	0.33
	2	0.24	0.24
Aluminum	1	0.36	0.37
	2	0.28	0.29

### **Slot Angle**

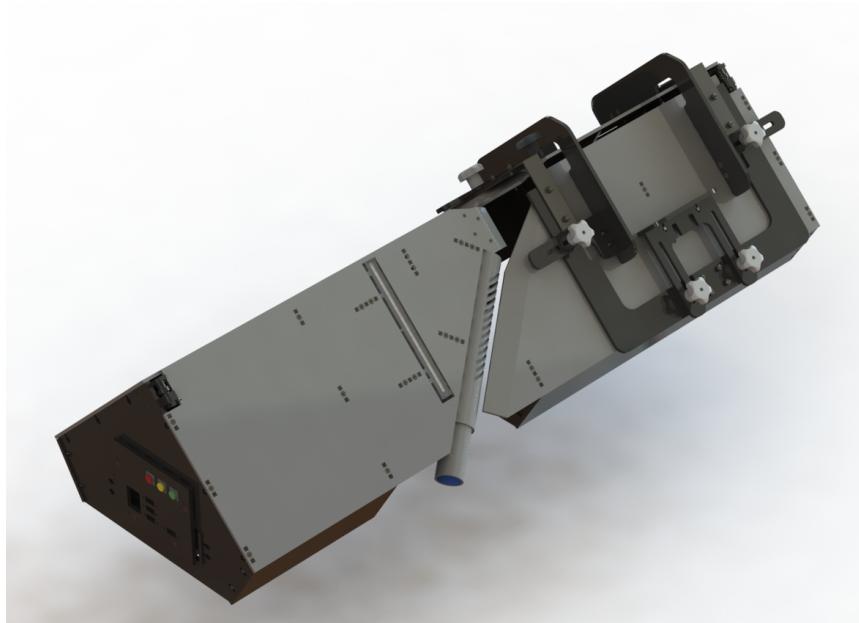
In order to determine what angle that was best for the entrance channel, we created three cardboard mock-ups with angles at 30, 45, and 60 degrees so that we could manually test the geometry involved in turning the page. The current prototype uses an entrance angle of 45 degrees. In order to define our terminology better, we defined the “slot angle” to be the angle from horizontal to the slot, in the plane of the body, and the “secondary angle” to be the angle at which the page bends into the vacuum slot.

We first tested a small book with dimensions of 5.5 x 8.75”, which travelled the smoothest in the 45 degree design. The 30 degree mockup was insufficient due to lack of support and the 60 degree channel lost contact with the corner before traveling the width of the book which would cause possible page damage. Next a larger book, 9 x 12.5” was tested. This ran best at 30 degrees and encountered problems at 60 degrees. Although a lower slot angle allows the page to take a longer time to turn, it makes the overall length of the scanner longer. Since we saw reasonable results with the 45 degree mockup and the initial design used 45 degrees we chose to also use a slot angle of 45 degrees.

## **FINAL DESIGN**

### **Overview**

The final design for this linear book scanner incorporates an improved saddle, a shorter page turning channel, and an adjustable helical vacuum. An isometric view of the designed linear book scanner can be seen in Figure 24. Then the final produced scanner is shown in Figure 25, pg. 31. An exploded view of the major components and subassemblies can be seen in Figure 26, pg. 31.



**Figure 24: Final linear book scanner design.**



Figure 25: Final linear book scanner as manufactured.

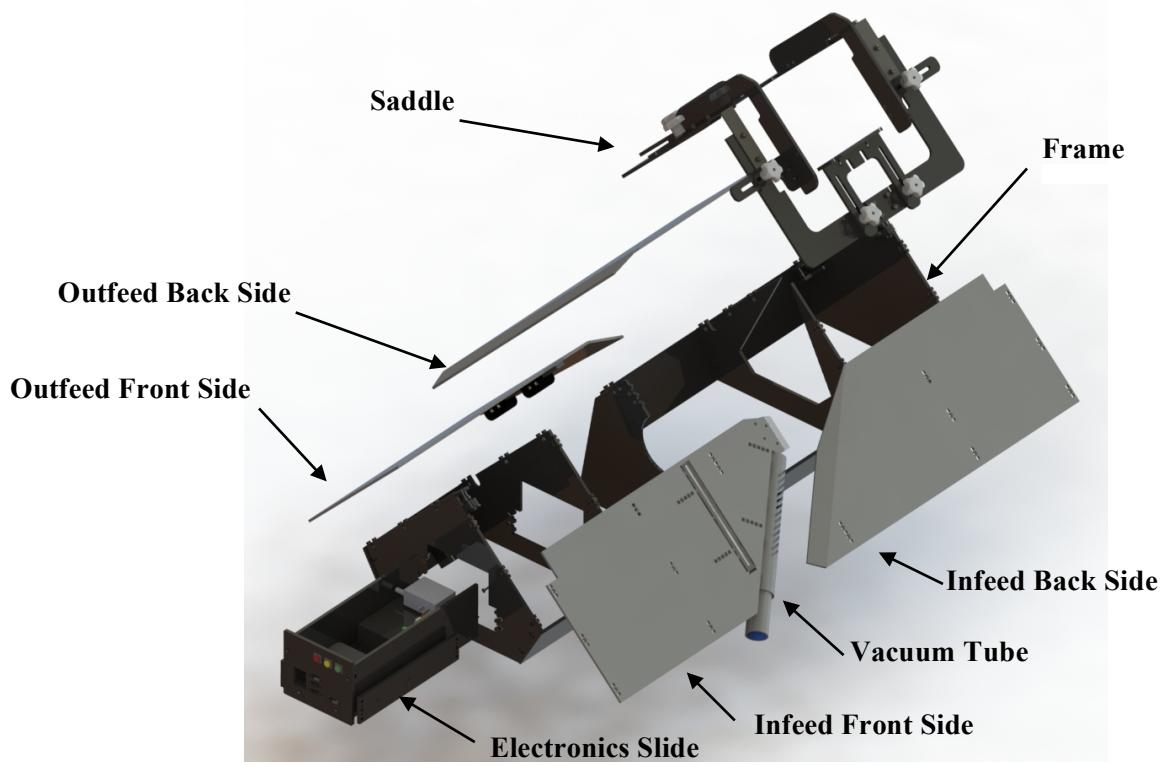
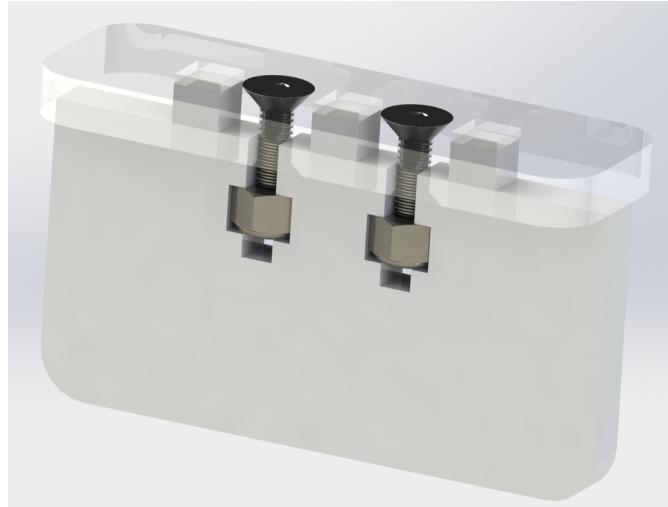


Figure 26: Exploded view showing major sub-assemblies.

## Fasteners

A unique fastener system was used to join the majority of parts in this linear book scanner. The geometry is shown in Figure 27. Essentially it allows larger fasteners to be used without having to tap any holes. This method has greatly reduced the manufacturing time of this linear book scanner. Also almost all fasteners used in the prototype were #8-32 flat head socket headed cap screws, which allows for easier assembly. This provides a good compromise between fastener strength, size and weight. See Appendix A, for a drawing of this fastener geometry.



**Figure 27: Fastener method used throughout linear book scanner.**

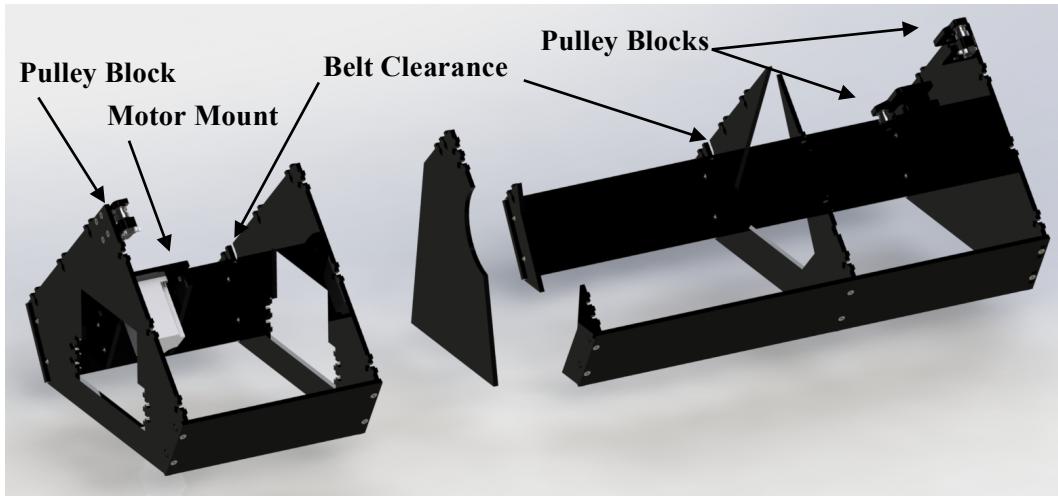
## Sub-Assembly Information

The follow section gives detailed information on the key ideas that went into each sub-assembly. The major sub-assemblies of the scanner are listed in Table 12.

**Table 12: Major sub-assemblies of final linear book scanner.**

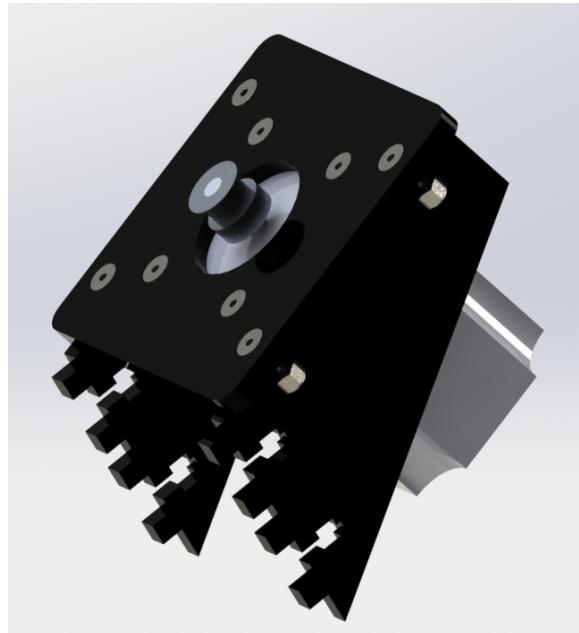
<b>Major Sub-Assemblies</b>
Frame
Saddle
Infeed Front Side
Infeed Back Side
Outfeed Front Side
Outfeed Back Side
Vacuum Tube
Motor Mount
Pulley Block
Electronics Slide

**Frame:** A more detailed view of the frame can be seen in Figure 28. Ribs were used to support the side panels and give the tool rigidity. The frame has three pulley blocks mounted to it to direct the timing belt. The motor mount is also directly mounted to the frame. The timing belt runs parallel to the outfeed panels so that it doesn't interfere with the page inside the channel. The 2<sup>nd</sup> and 5<sup>th</sup> rib has a slot cut out of it to allow the timing belt to run through the system.



**Figure 28:** Linear book scanner frame showing drivetrain.

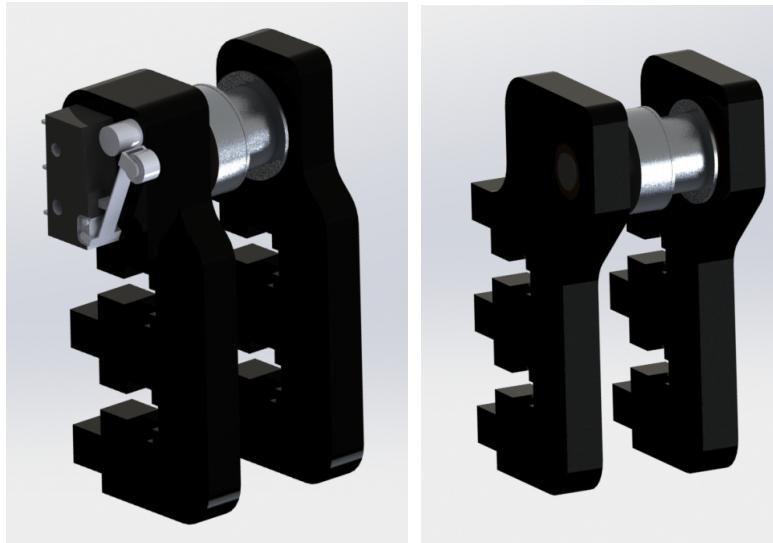
**Motor Mount:** The motor mount can be seen in Figure 29. It is composed of only three pieces and serves to mount the stepper motor in the correct location. Most stepper motors have face-mounting holes so the mount was simple to design. The three components for the mount were kept short to minimize deflections.



**Figure 29:** Linear book scanner motor mount.

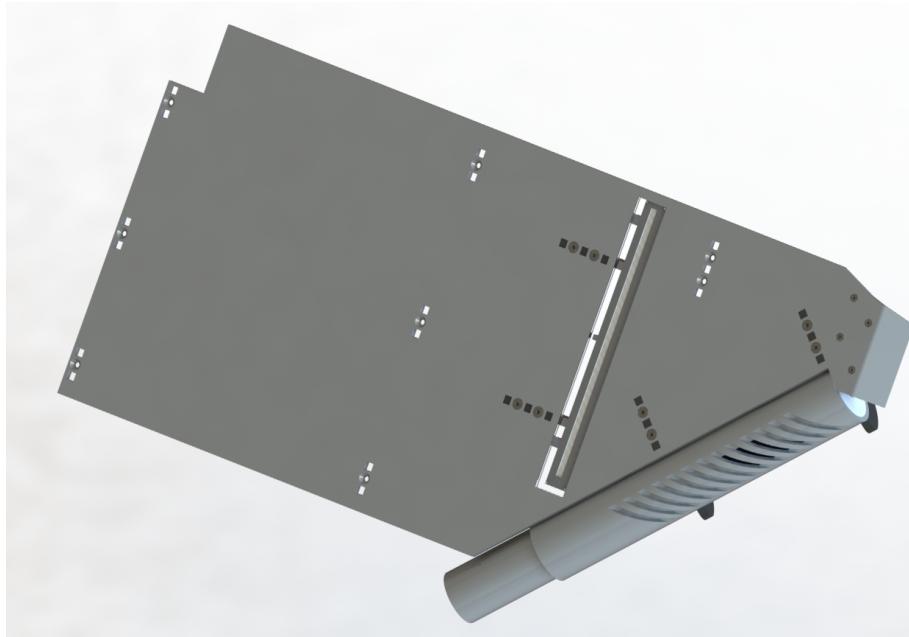
**Pulley Blocks:** Mounts were required to house the idle pulleys for the timing belt. Simple mounts were created that allow bronze bearings to be used to allow the pulley to rotate. Essentially a bushing gets pressed into an acrylic block, then the pulley is mounted on a  $\frac{1}{4}$ " shaft which rotates in this bearing.

These can be seen in Figure 30, pg. 34. They also incorporate limit switches so that the home and end positions of the saddle can be found. An offset version was required for the lower mount on the back of the linear book scanner to shift the timing belt away from the very end of the device to keep it from rubbing.



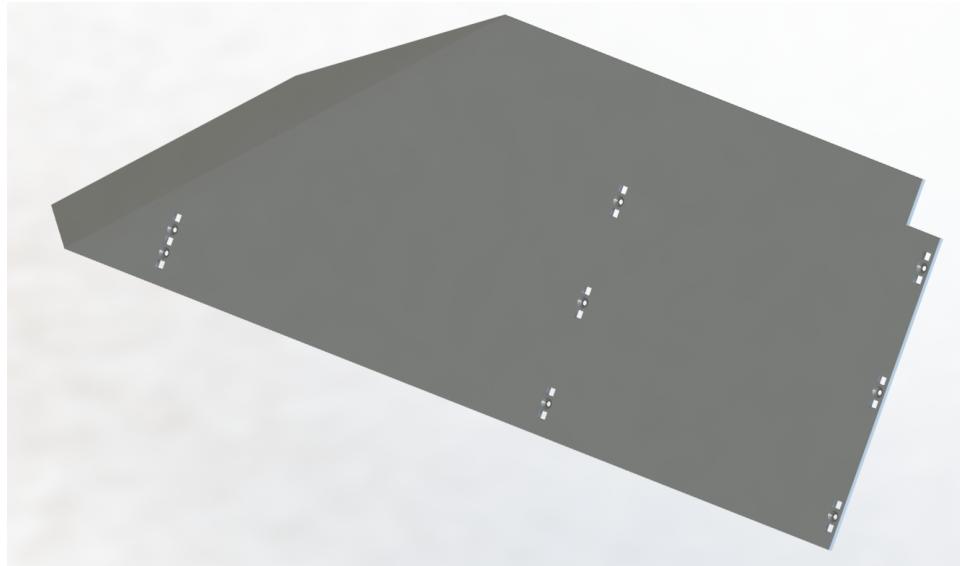
**Figure 30: Linear book scanner pulley blocks**

**Infeed Front Side:** The infeed front side panel houses a scanning bar and the vacuum tube. This panel assembly is shown in Figure 31. Care was taken to mount the scanner bars as far into the corner as possible so that most of the books gutter may be scanned. The top leading edge of the infeed front side panel is also critical for turning the page on the return stroke. The leading edge is what needs to move the page to keep the page from folding.



**Figure 31: Linear book scanner infeed front panel assembly.**

**Infeed Back Side:** The infeed back side panel assembly is currently only the Delrin side panel as shown in Figure 32. However in the future sensors could be added to this panel to detect how many pages are entering the middle channel.



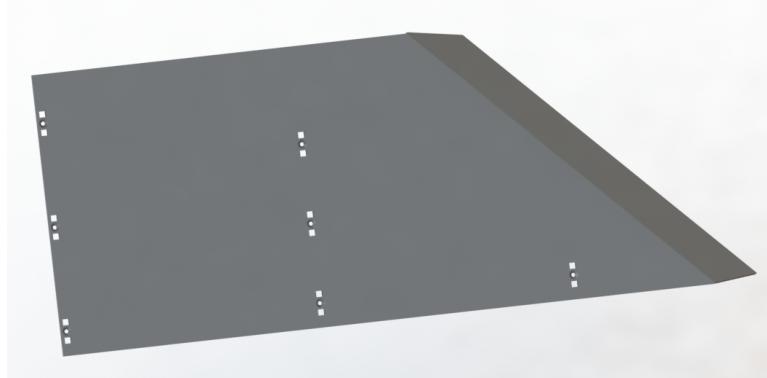
**Figure 32: Linear book scanner infeed back panel assembly.**

**Outfeed Front Side:** The outfeed front side panel houses the second scanning bar and has geometry to help the page exit the channel. The scanning bar is offset from the infeed in order to push it higher so that more of the books gutter can be scanned. The large bend is necessary so that the page will be turned by the leading edge of the infeed front panel. This sub assembly can be seen in Figure 33.



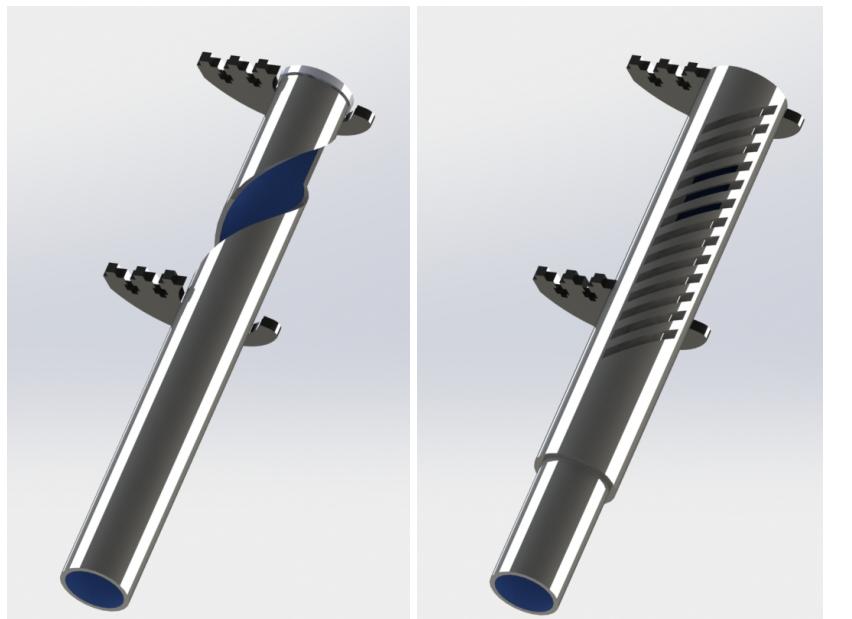
**Figure 33: Linear book scanner outfeed front panel assembly.**

**Outfeed Back Side:** The outfeed back side panel assembly is currently only the Delrin side panel as shown in Figure 34. However in the future sensors could be added to this panel to detect how many pages are entering the middle channel.



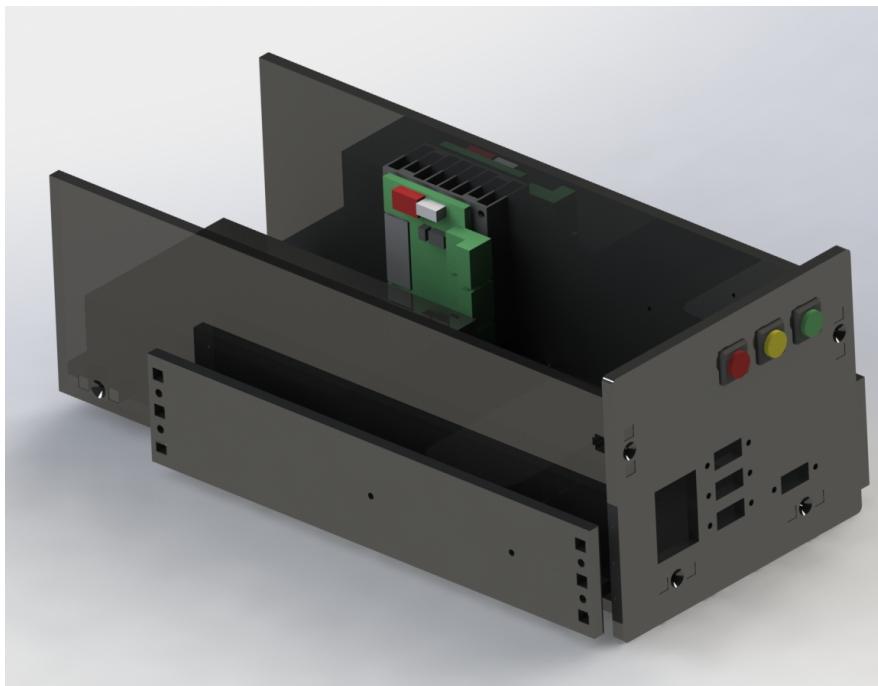
**Figure 34: Linear book scanner outfeed back panel assembly.**

**Vacuum Tube:** The vacuum tube assembly turns the pages. The outer tube has slots cut at a 45 degree angle so that they run parallel to the direction the book travels. Then the inner tube has a large helical slot so that its rotation can select which slots the vacuum provides suction on. Each tube has an end-cap that is used to direct the vacuum into the slots and also to mount the two tubes together. A  $\frac{1}{4}$  -20 SHCS with a nylock nut goes through a hole in the middle of these end caps so as to constrain the inner tube from falling out. By carefully tightening this fastener we can change how stiff the inner tube is to rotate. This vacuum tube assembly can be seen in Figure 35.



**Figure 35:** Vacuum tube assembly showing inner tube (left) and full assembly (right).

**Electronics Slide:** Finally the electronics slide sub assembly is used to house all of the linear book scanners electronics. Since it is on drawer slides it can be easily pulled out and accessed while testing. The electronics slide sub assembly is shown in Figure 36, it is essentially a three sided box with cutouts on the front for push buttons and USB ports.



**Figure 36:** Linear book scanner electronics slide.

## **Material Selection**

**Sliding Surfaces:** Delrin was used for sliding surfaces of our design; these include the four top faces, and the vacuum tube. Although Delrin is ~3x more expensive than acrylic it has a lower coefficient of friction with paper which is critical to the page sliding smoothly over the scanner.

**Structural Support:** Acrylic was used for the structural members in this linear book scanner. Acrylic offers similar strengths to Delrin at a much lower cost. It is also much easier to laser cut. This makes it a clear choice for components that the book doesn't slide on.

## **Slot Angle**

The slot angle used in the final design is 45°. This was found to be the best angle from testing with cardboard mockups of 30°, 45°, and 60°. Dany, the designer of the initial linear book scanner, also highly recommended that we design our prototype with a 45° slot angle [8]. Due to the nature of the project it is difficult to test small changes in slot angle, essentially a whole new scanner would have to be made. Therefore the 45° angle will be used unless it is shown to be fundamentally flawed.

## **Stepper Motor**

A NEMA 23 frame size stepper motor will be used for the final design. After initial testing it was shown that the NEMA 23 stepper motor used in the initial linear book scanner had more than enough torque to run this prototype. Currently it performs well even at half 0.5 A per phase which is half of its rated current.

## **Sensors**

Our design incorporates several sensors. First limit switches are used at either end of the scanner to detect the saddles position and to home the machine on start up. Then if time allows a short range IR sensor will be added to the infeed back panel in order to detect if a page enters. Lastly if possible we will implement sensors to detect if multiple pages are fed into the page turning channel.

## **Pre-Validation Testing**

Other components which we could not analyze without testing were the vacuum suction cylinders and the page exit geometry. Before validation testing, we will run the scanner with small, medium, and large size books to determine the necessary changes to these systems. The vacuum setting will also need to be optimized prior to validation. We will run one small, one medium, and one large book at each of the six vacuum settings to determine if there is an optimal power setting and to see how the optimal power setting correlates to book size. We also expect that the vacuum setting may vary based upon page weight/type. We are confident that through constant usage, library personnel can develop standards for optimal settings for the vast book types being tested as they have done so with other book scanners [6].

## **Final Design Validation**

The final design of the linear book scanner is essentially what has been produced. During the design process several modifications were made to the outfeed geometry. These updates are in the final revision of the CAD. So this prototype should be able to validate the design.

## **Final Design Operation**

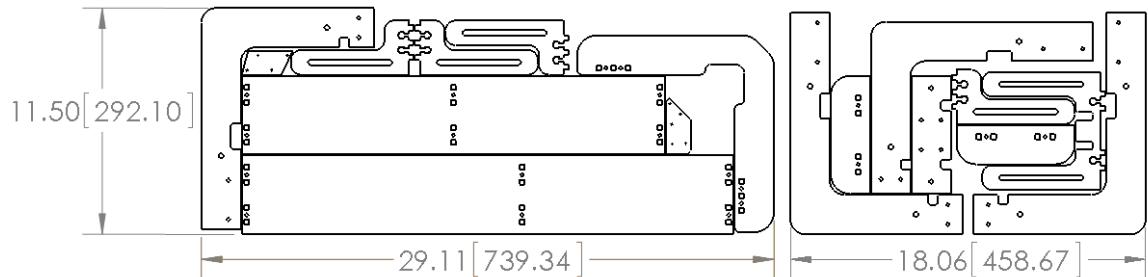
We expect the final manufactured design to perform well. In the event that modifications to the outfeed geometry are necessary we feel the current design will be easily modified to incorporate the necessary changes. The final design should be powered but may not be fully automated by the end of the design process. The focus for this project is the mechanical build and the computer science work to make all the necessary software to run a scanner like this isn't within the scope of this project.

## FABRICATION PLAN

The following section shows the methods used in fabricating this linear book scanner.

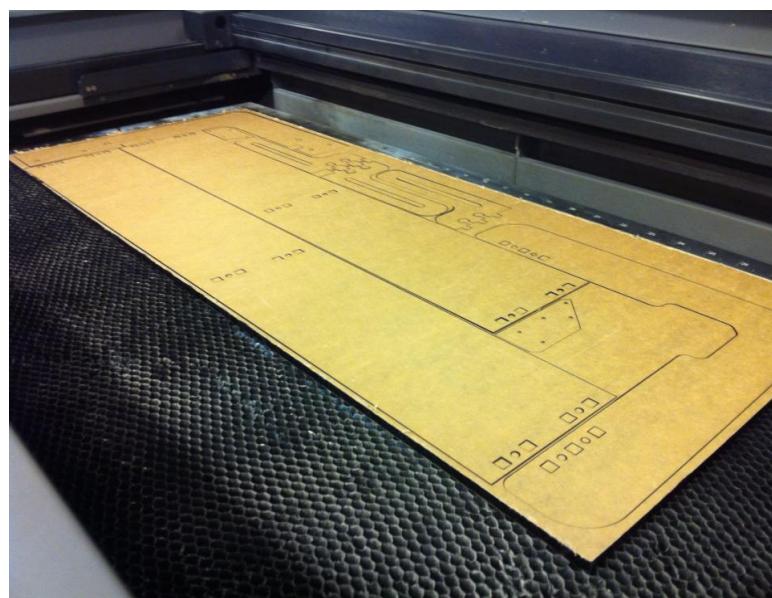
### Laser Cutting

Every part of the scanner with the exception of the vacuum tube is made using a laser cutter. To maximize efficiency of the cut, all the parts are designed to fit into 12" x 48" panels of acrylic and Delrin and are assembled to minimize wasted material. For example, Figure 37 shows how many of the saddle components were nested together onto one sheet.



**Figure 37: Sample ribs laser cutting drawing**

First we calibrated the laser cutter we were using for the material we had. By doing several iterations of different power, speed and pulses per inch, it was determined that 25% the power, 1.2% speed, and 1000 PPI was optimum for  $\frac{1}{4}$ " acrylic. Running a higher power then this resulted in the kerf of the laser growing from  $\sim 0.01$  to  $\sim 0.03$ . The optimum settings for  $3/16$ " Delrin were found to be 30% power, 3% speed, and 500 PPI. It was difficult to find settings for the Delrin that cut through the material but didn't cause the outgassing to catch fire. These settings minimized the fire but were not able to cut through in one pass. So each Delrin panel was cut 3 times in a row. A sample sheet being cut can be seen in Figure 38.



**Figure 38: Acrylic panel being laser cut.**

A laser cutter is likely a tool a DIY expert would have access to. Otherwise, online services such as Pololu custom laser cutting can also be used for a cost. Using a laser cutter, it is also much easier to make the project accessible to the public, as the builder would only need access to the projects .dxf files, which are readily available.

### Vacuum Tube

**Outer Vacuum Tube:** A mill was used to produce the outer vacuum tube. The specifications of the tube can be seen in Figure 37. Essentially the tube was placed in a vice on a rotary table. This was then angled at 45 degrees relative to the x-axis of the mill so that an end mill could cut the slots. Unfortunately we did not have access to a table saw, which would have made this part much quicker to make. These slots could easily be cut on a table saw with the blade raised to the slot depth, and a miter gauge set at 45 degrees. This vacuum tube can be seen in Figure 39.

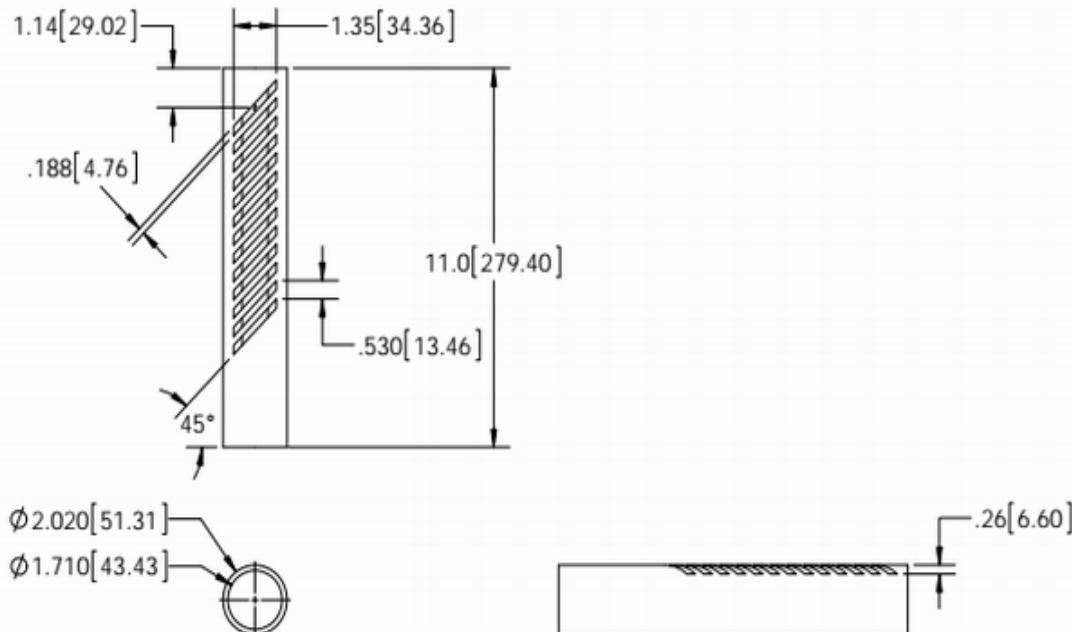
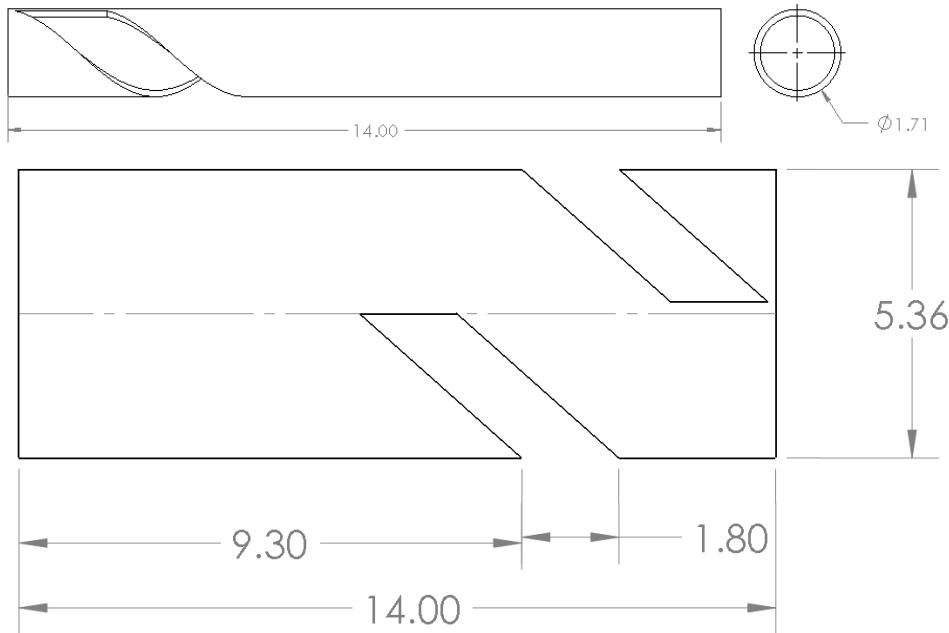


Figure 39: Drawing for milling outer vacuum tube.

**Inner Vacuum Tube:** A dremel with an abrasive cut off wheel was used to create the helical slot of the inner vacuum tube. First the part was unfolded in CAD so that a flat pattern of the outside profile could be printed in a 1:1 scale. The part and the unfolded diagram can be seen in Figure 40. Then this unfolded diagram was cut to size and wrapped around the inner Delrin tube. The profile was traced and then cut with the abrasive wheel. Although it is somewhat difficult to get a perfectly clean edge this method is easy to control, extremely fast and gives a decent result.



**Figure 40: Inner vacuum tube (top) and unfolded inner vacuum tube (bottom).**

### Misc. Manufacturing Components

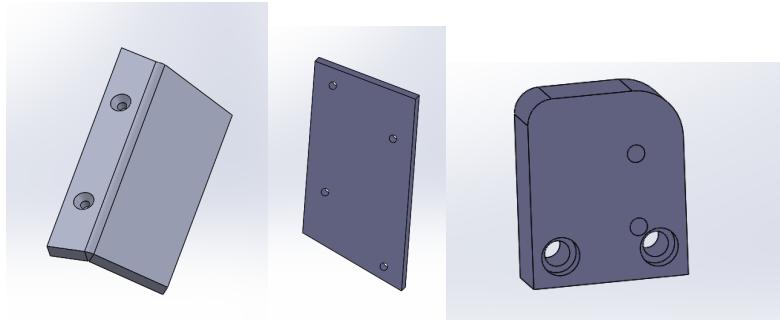
**Countersinking:** In order to make the bolts flush with the acrylic and Delrin panels the bolt holes had to be countersunk. A simple hand drill with a countersink bit was used to countersink these holes, and the countersink used can be seen in Figure 41. Since the drill bit will follow the existing laser cut hole, it is possible to quickly and easily countersink the holes with just a hand drill. We found it was necessary to not use a stop collar as it prevents the chips from exiting the flutes of the countersink. Some care is required to reach the correct depth for the countersink.



**Figure 41: Countersink used to keep bolts flush with panels.**

### Threading

There are a total of 10 holes on this linear book scanner that must be tapped. These were for 4-40 screws to hold the limit switches onto the pulley blocks, as well as to hold an extension onto the infeed panel that was designed after the panel was cut. In future revisions this extension would be part of the infeed front panel. Figure 42 shows that these components required tapping.



**Figure 42: Components requiring tapped holes, infeed-horn extension (left), mounting plate (center) and limit switch mount (right).**

## Assembly

The following describes the assembly methods used for this linear book scanner. Although we show one order of assembly, through extensive work on the scanner we have found that there are numerous orders in which it can be assembled.

**General Assembly Method:** The vast majority of the components in this scanner are assembled using the fastener geometry shown in Figure 27, page 32. This is a very easy system to assemble. First insert the pegs from a panel into the corresponding holes in the corresponding panel. Then place two nylock nuts into their slots, and insert the flat head socket headed cap screws into their holes, screwing them into the nuts, and finally tighten them with a hex wrench.

**Special Assembly Methods:** Three special modules will require non-fastener assembly. First, the outer vacuum cylinder will need to be glued to its support brackets. This will be accomplished by attaching the brackets to the panel, aligning the vacuum cylinder in proper position, and then gluing it firmly. Double sided tape may also be used. It is recommended to test the location of the vacuum cylinder before permanently attaching it as it is fairly secure without any adhesive. Second, the belt pulley apparatuses will need to be assembled before installation. This will require pressing brass bushings into the laser cut holes on the side pieces and then placing a pulley on an inserted shaft. This can be seen more clearly in the assembly diagrams below. Third, the glass scanner covers will need to be glued to the scanner support brackets. This will be done in the same way as the vacuum cylinder.

## Final Assembly

After all the pieces have been cut and special modules have been assembled, they can be fastened together with #8-32 flat head socket headed cap screws. Because every piece of the scanner is assembled using the same fastener, there should be no difficulties aside from proper assembly steps. This will also allow for easy replacement of parts, when necessary. Using the linear book scanners design files an assembly manual was created.

The assembly will be composed of 4 major steps; these are the assembly of the 1) front outfeed, 2) front infeed, 3) base, and 4) everything else. The steps can easily be reproduced by others wishing to reproduce the scanner in the future.

The following section is the linear book scanners assembly manual.

# **Linear Book Scanner Assembly Manual**

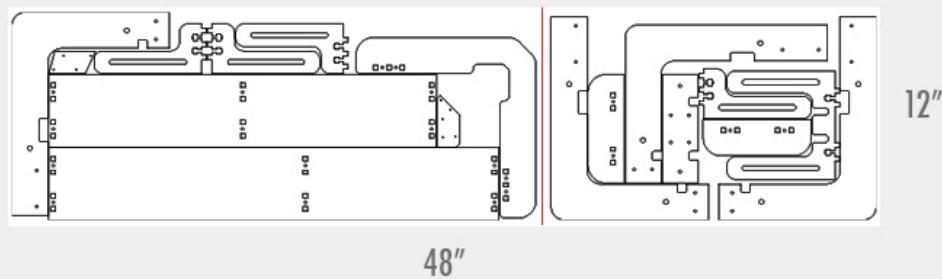
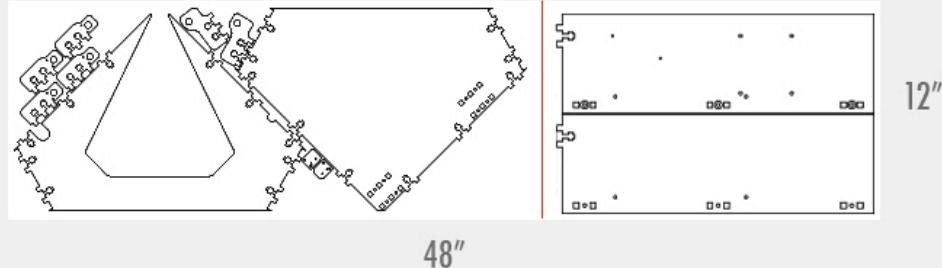
Design Team: Eric Gu, Shawn Wright, Zach Quanbeck, Jit Lim, Ryan Snyder

# Project Background



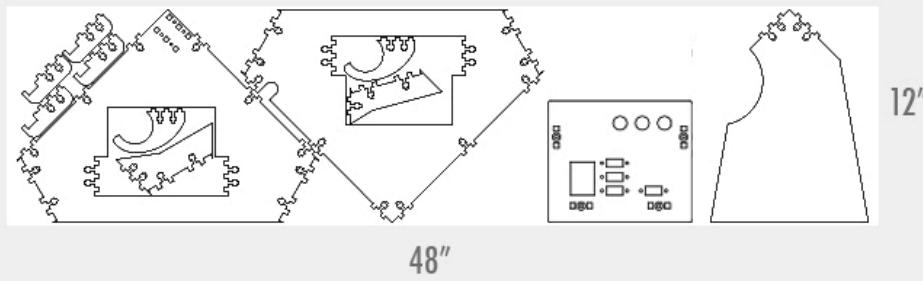
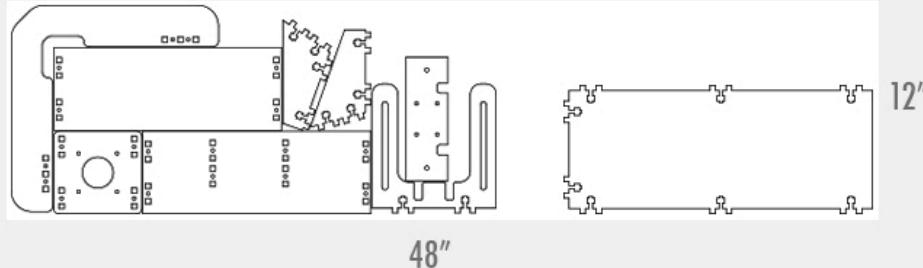
Book scanning is a rapidly developing technology, due in large part to the demands created by libraries digitizing as much literature as possible. Through partnership with Google Inc., the University of Michigan was able to scan 4.4 million books from its 8 million-book collection. Currently, the university digitizes about 10,000 books per year while increasing the size of its collection by 100,000 books in the same time span. The objective of our design is to create more cost effective alternative to commercial scanners in order to increase the number of books scanned by Michigan annually.

# Lasercutting: Acrylic



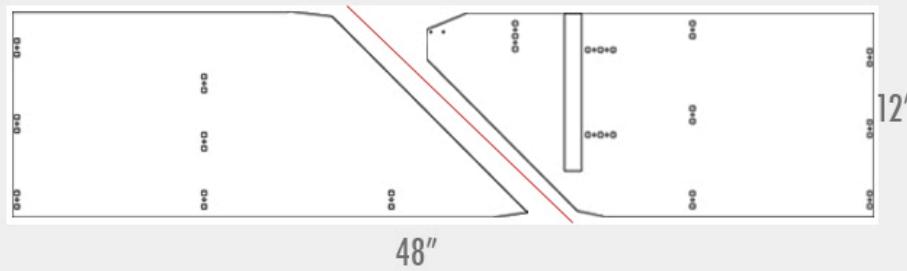
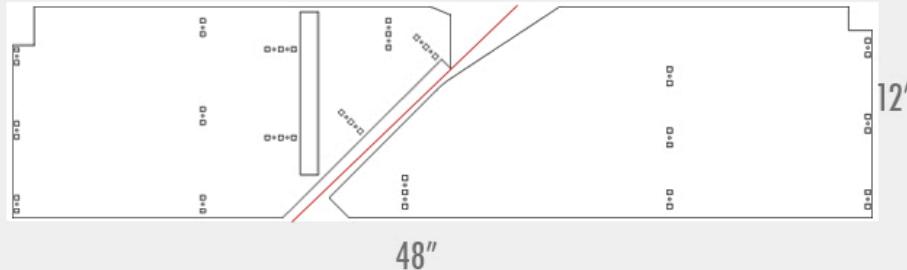
— Bandsaw cut

# Lasercutting: Acrylic



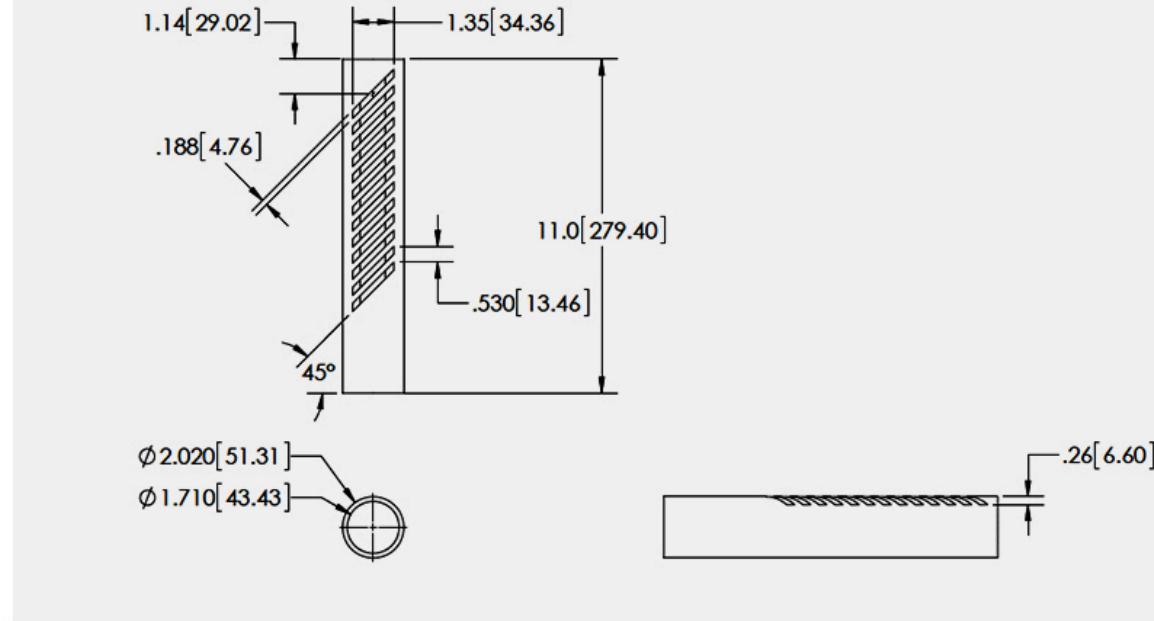
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# Lasercutting: Delrin

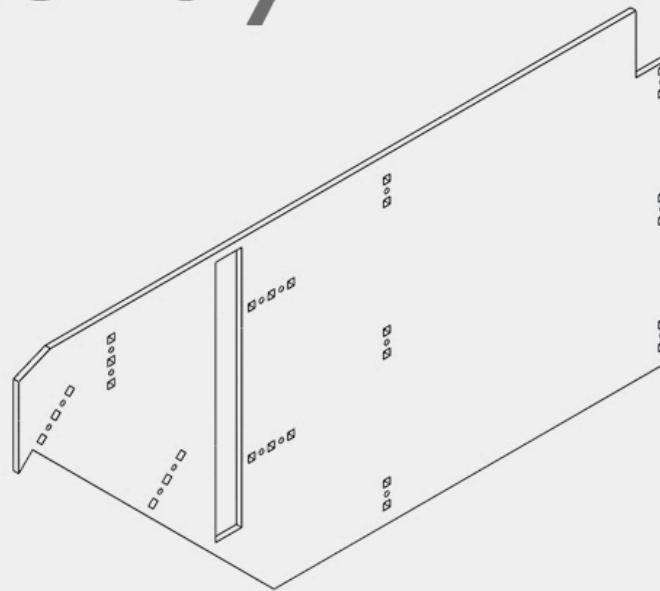


Bandsaw cut

# Milling: Vacuum Tube



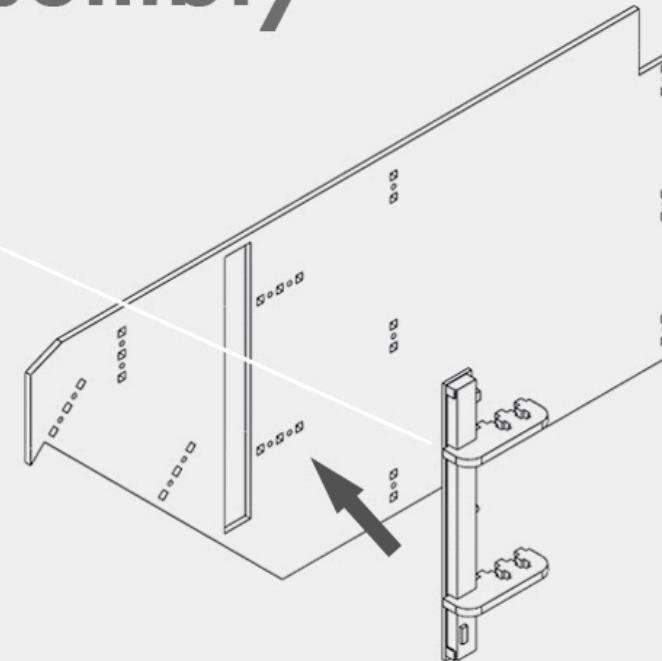
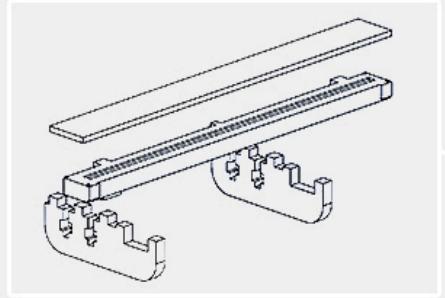
# Front Infeed Assembly



1



# Front Infeed Assembly

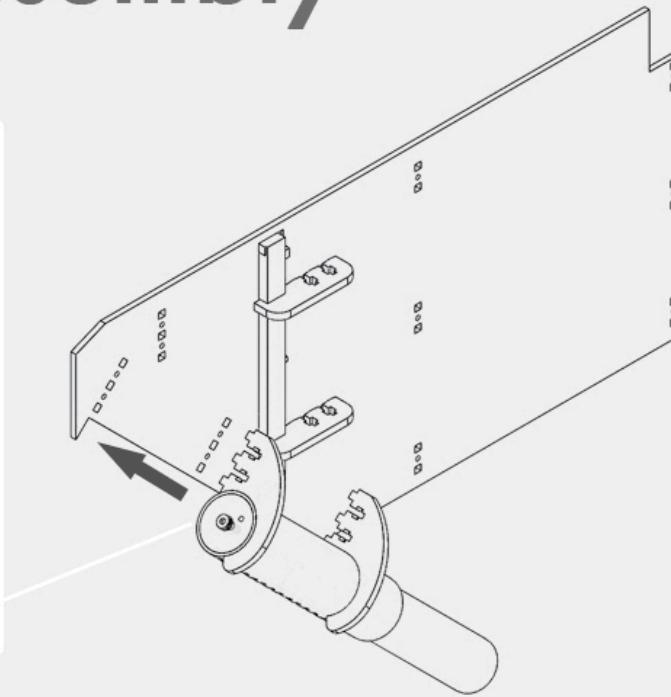
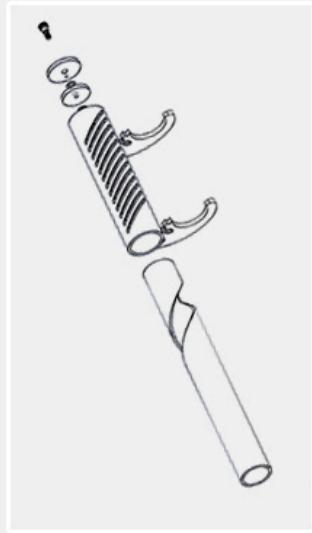


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# Front Infeed Assembly

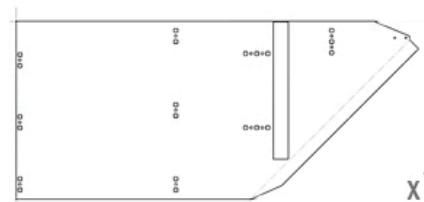
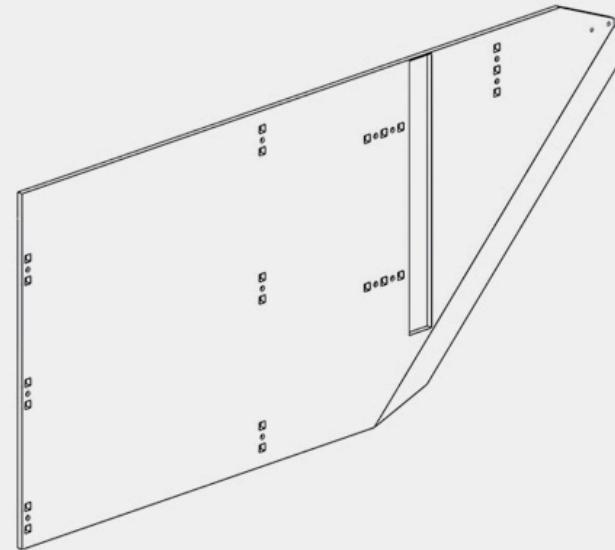
3



x2

# Front Outfeed Assembly

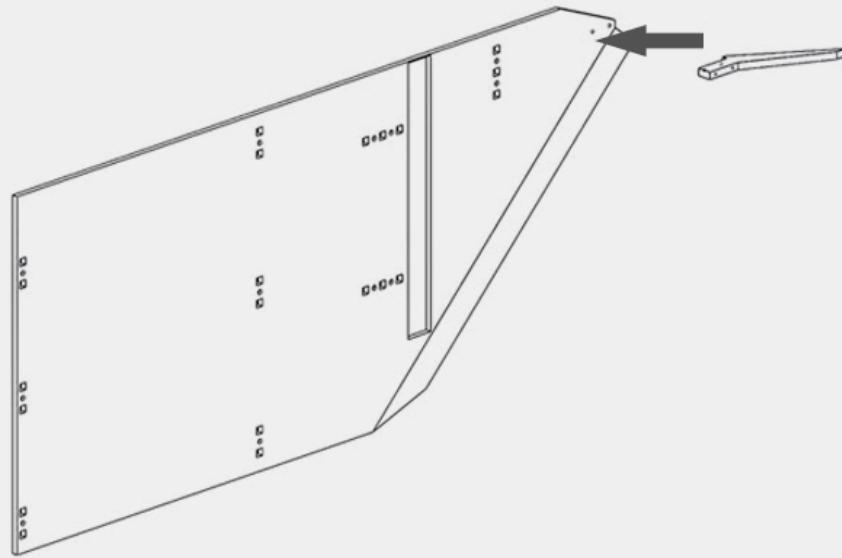
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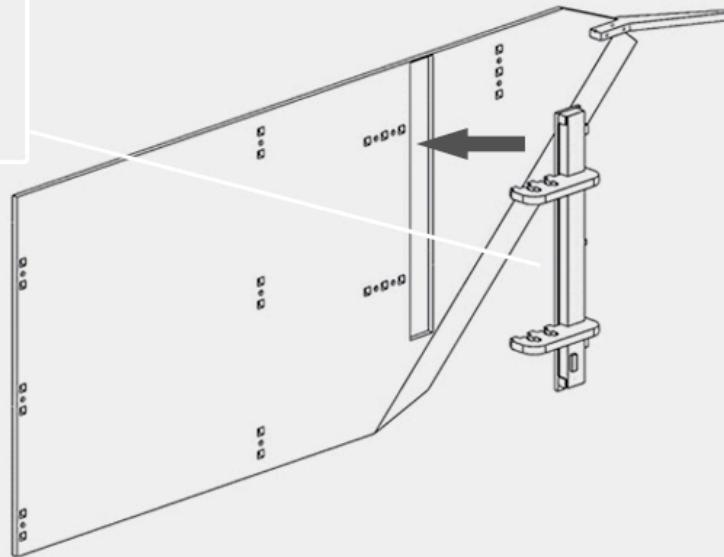
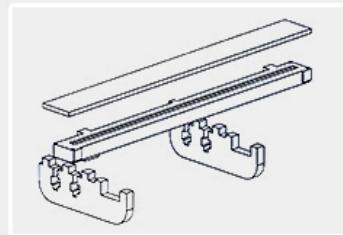
# Front Outfeed Assembly

2

x1



# Front Outfeed Assembly



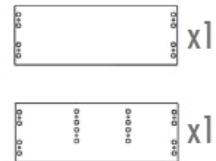
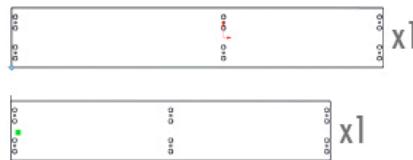
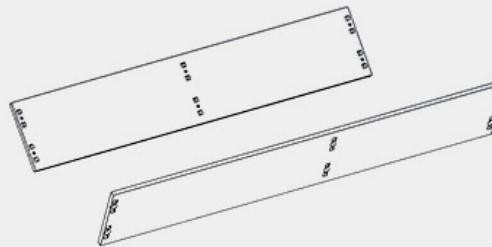
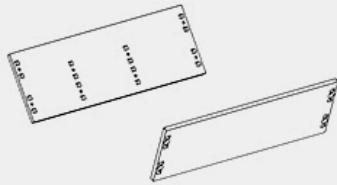
3



x2

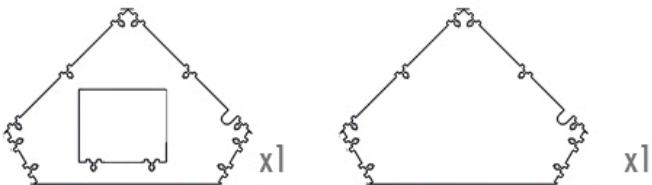
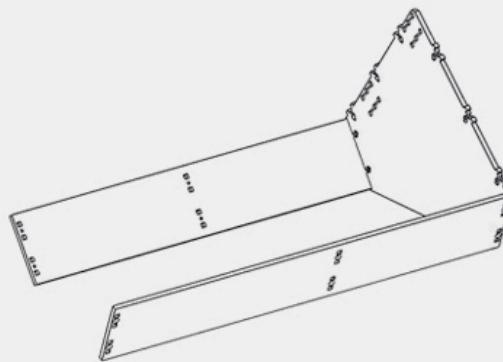
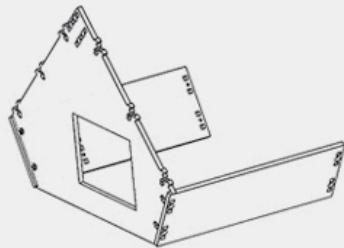
# Base Assembly

1

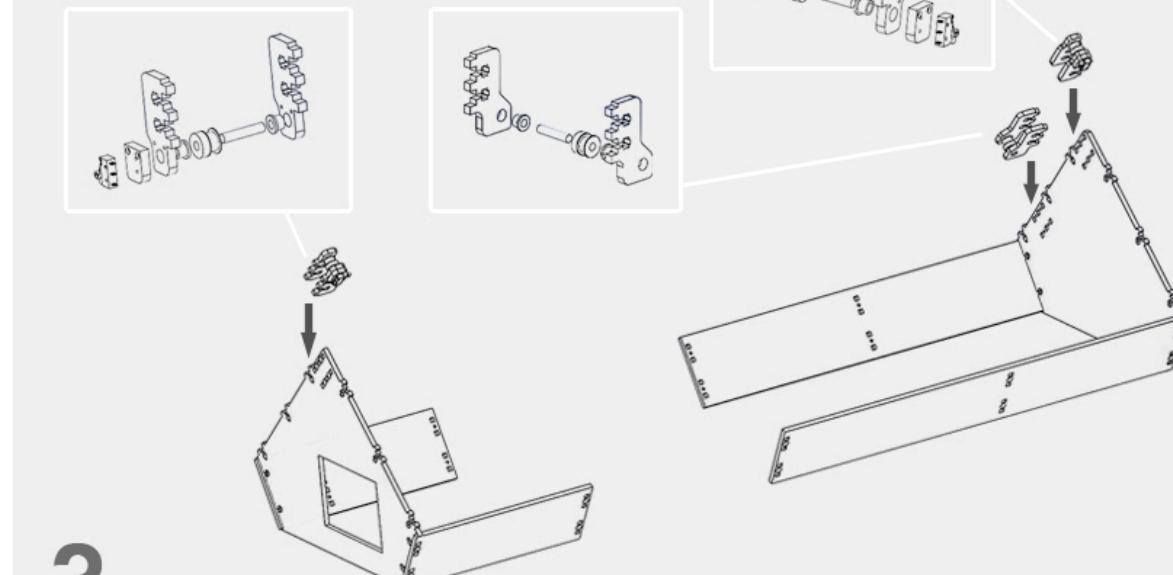


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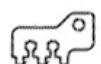


# Base Assembly



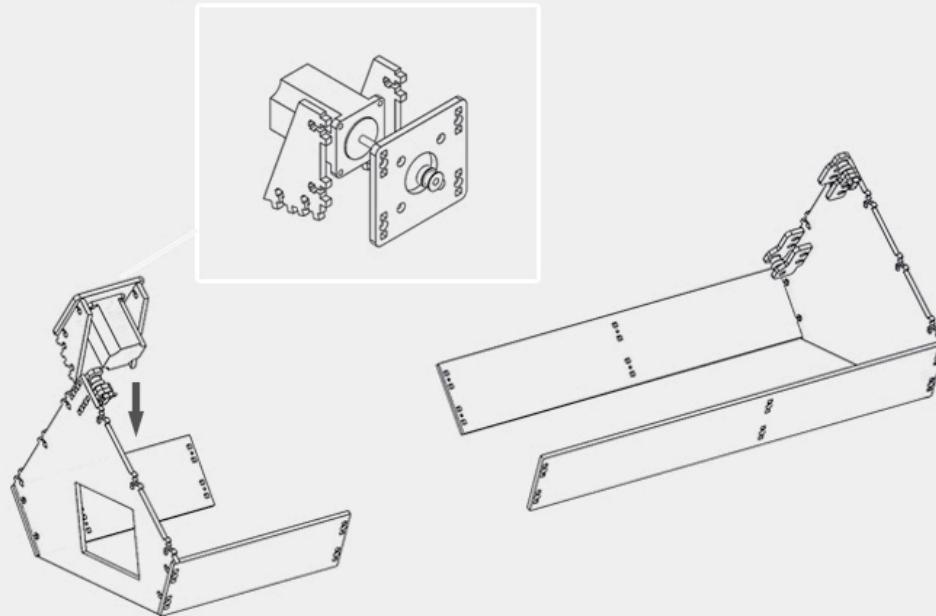
 x4

 x2

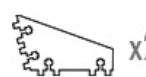
 x2

# Base Assembly

4



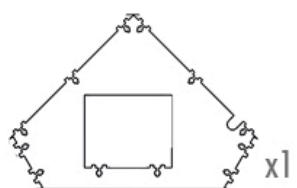
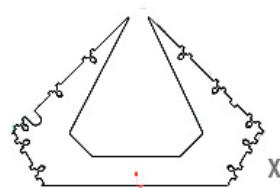
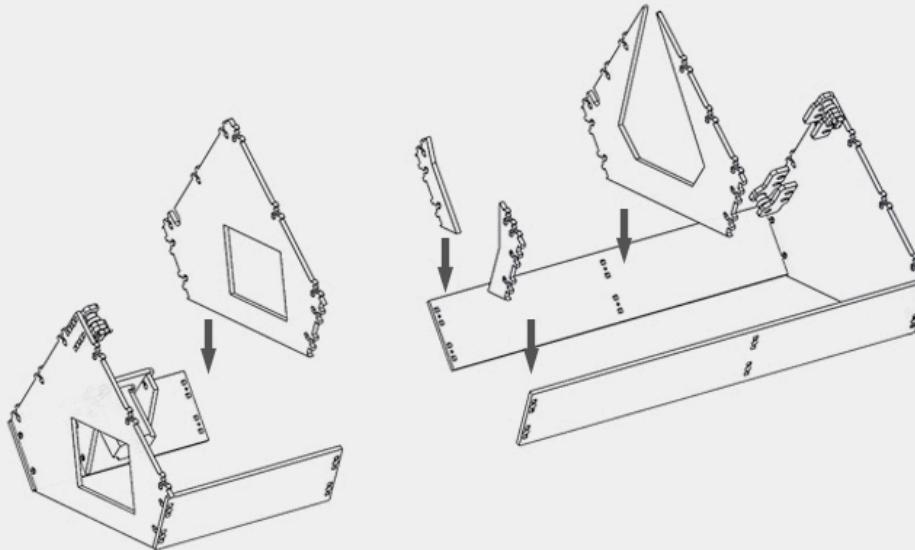
x1



x2

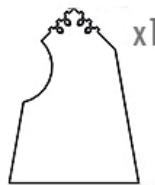
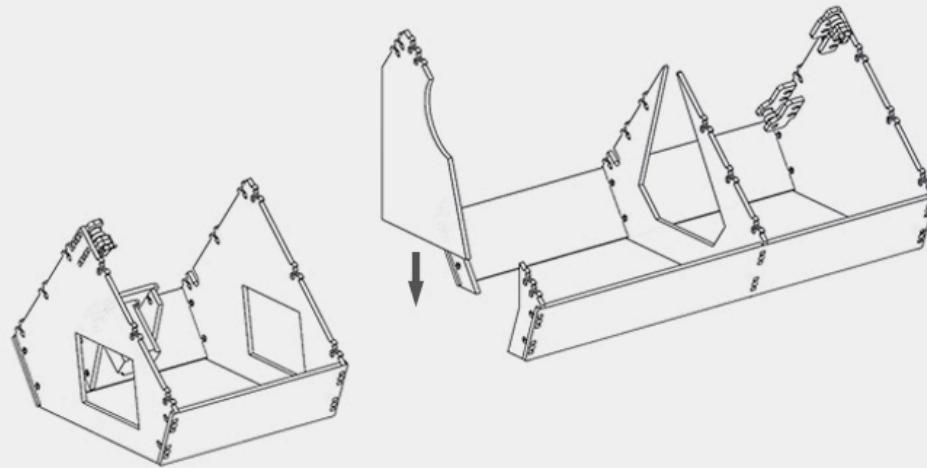
# Base Assembly

5



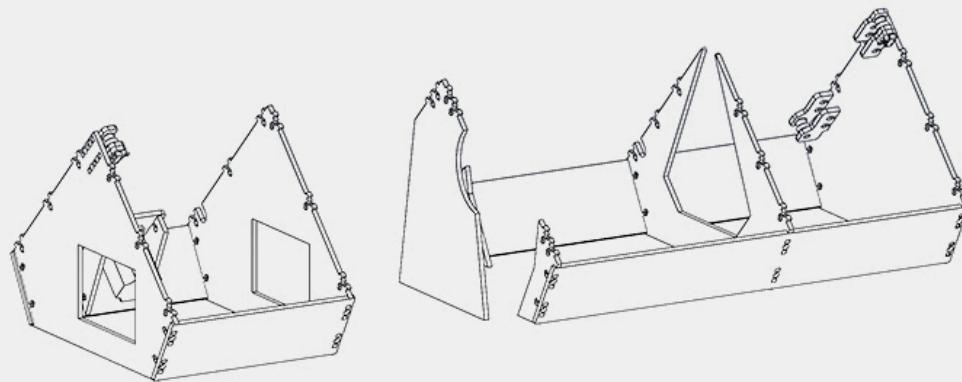
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5



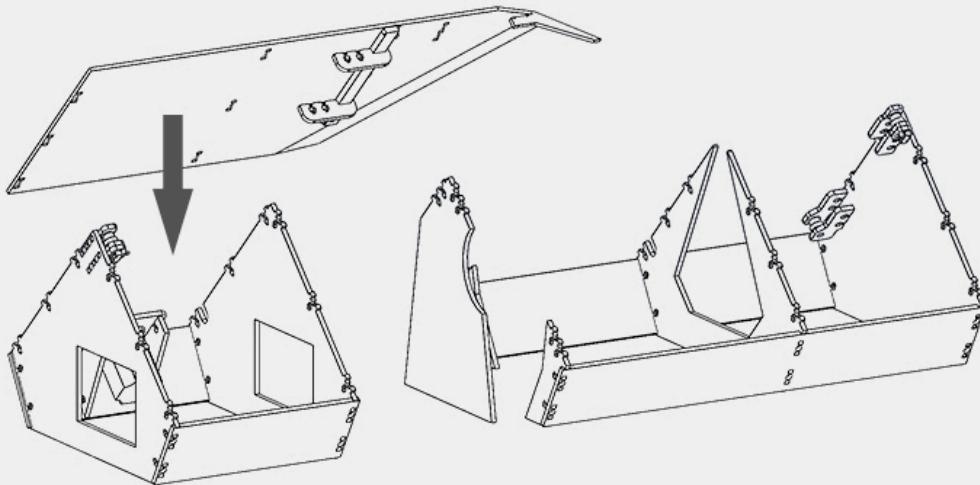
# Final Assembly

1



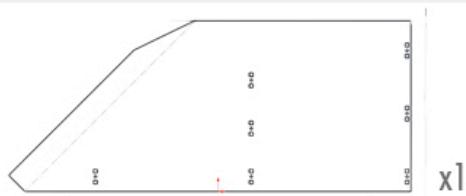
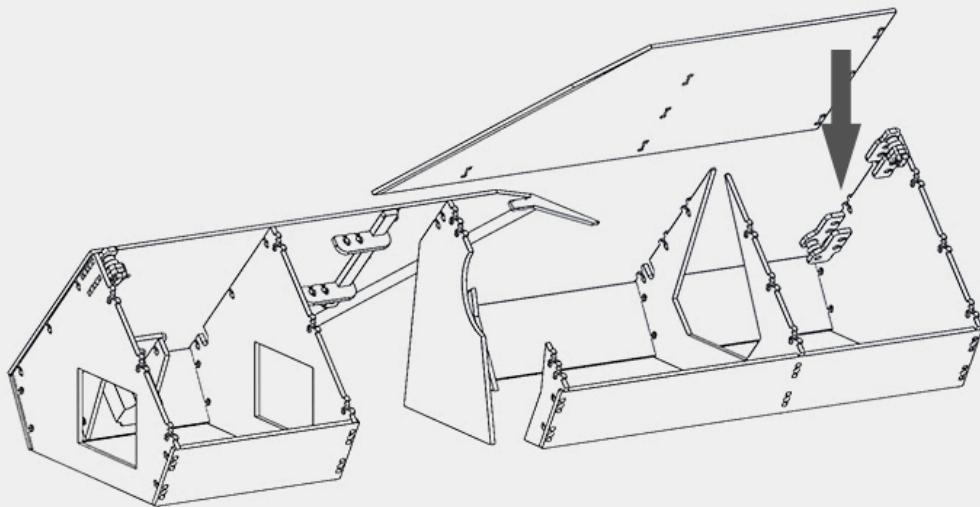
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2



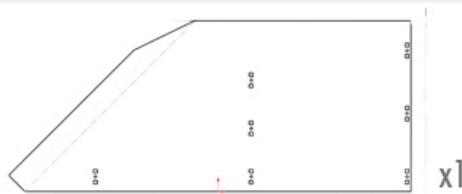
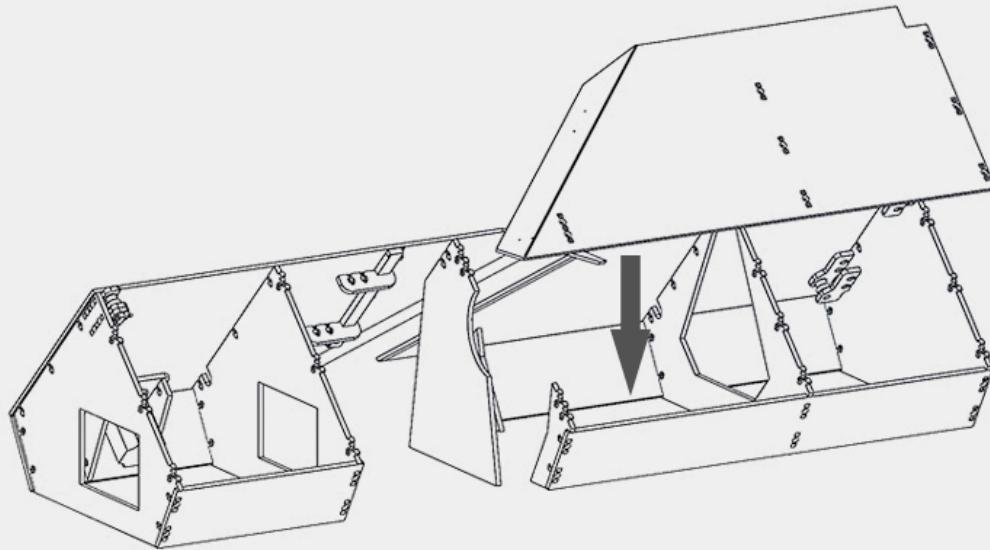
# Final Assembly

3



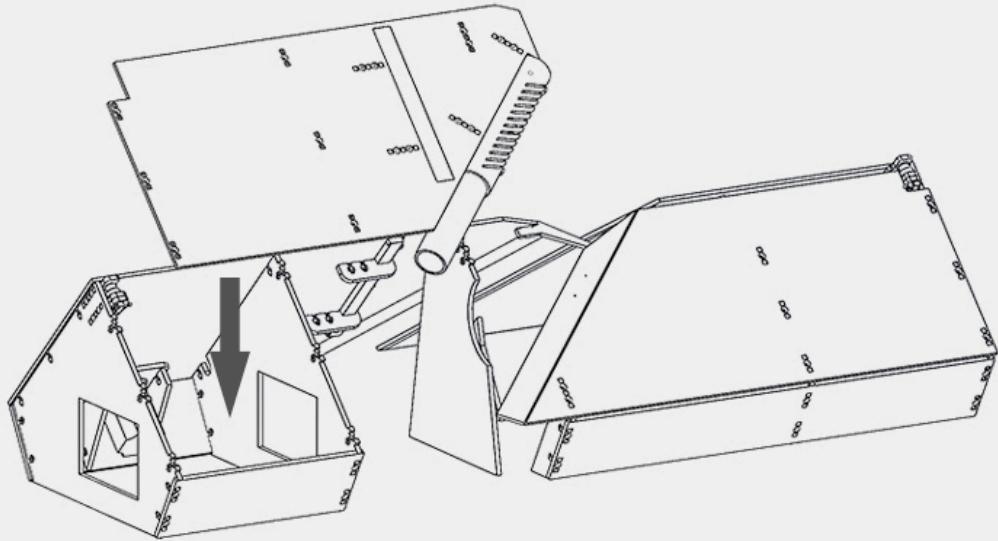
# Final Assembly

4



# Final Assembly

5



## VALIDATION RESULTS

In order to systematically demonstrate that the engineering specifications for our linear book scanner have been met, we conducted the following empirical tests after finalizing the design of our prototype.

### Scanning Rate and Failure Rate

In order to validate our pages per hour and failures per hour requirements, we first determined the speeds for our scanning cycle. We determined the necessary saddle speed for scanner operation to be about 1.5 in/second – this is dictated by the scans pixel density. We therefore ran the saddle at 1.5 in/second for the first 12 inches of the stroke to scan the length of the page. After completing scanning, we ran the saddle at 6 in/second for 18 inches to finish the forward stroke. On the return stroke we used a speed of about 7.5 in/second for a total of 30 inches distance. This left us with a stroke time of about 15 seconds. These speeds are shown in Figure 43.

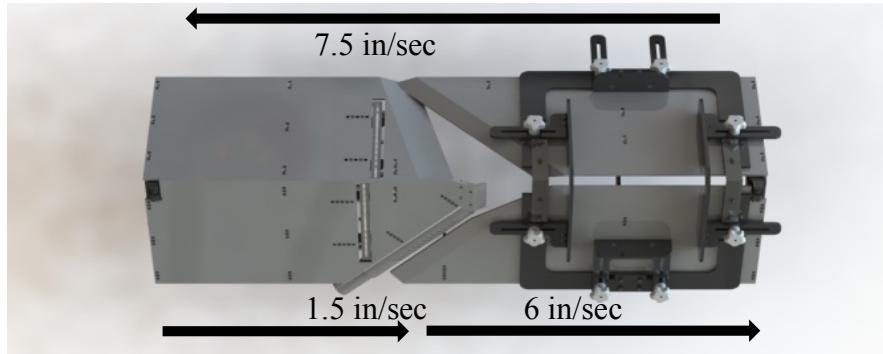


Figure 43: Saddle speeds during a page scan cycle.

We then ran the scanner cycle for seven different books, these are shown in Table 13. These books are labeled and with the prototype for any future testing.

Table 13: Seven books used for testing showing a wide range of book style.

Book #	Description
1	thin paper, good quality, hard cover, standard size
2	thick paper, rough paper, relatively small book
3	thick paper, glossy finish, largest size book
4	normal paper, standard size pages, thick book
5	thin paper, heavy book, non uniform page edge (dictionary)
6	good quality paper, worn down pages, standard size
7	average size book, thicker paper, 200 pages
8	small soft cover book

After each cycle we checked to see if a page entered the channel successfully and then if any pages in the channel exited successfully. A failure was defined as any time the scanner failed to draw one page into the channel or as any time a page (or pages) exited the channel with damage. We tested books 2, 3, 5, and 7 extensively collecting data from the first, middle, and last thirds of the book (as this variable impacts page turning success) and then collected less complete data from books 4, 6, and 8. Book 1 was not tested. The “first third” of a book is defined as having most of the pages on the infeed side of the scanner, the

“middle third” of a book is defined as having an equal amount of pages on each side of the scanner and the “final third” of a book is defined as having most of the pages on the outfeed side of the scanner. The summary of the validation data can be seen in Table 14.

**Table 14: Success percentages of channel entrance and exit for 7 books.**

Book #	Success Entering Channel			Success Exiting Channel			Total Trials
	First Third	Middle	Last Third	First Third	Middle	Last Third	
2	100%	92%	89%	0%	85%	67%	44
3	100%	67%	100%	100%	100%	100%	24
4	NA	56%	NA	NA	79%	NA	39
5	90%	100%	100%	100%	100%	91%	28
6	75%	100%	NA	75%	100%	NA	10
7	100%	95%	86%	82%	100%	100%	49
8	NA	100%	100%	NA	NA	NA	15
<b>Average</b>	<b>97%</b>	<b>85%</b>	<b>93%</b>	<b>64%</b>	<b>92%</b>	<b>88%</b>	<b>29.9</b>

Using the data above, we found the overall successful entry percentage to be 92%. We also found the overall successful exit percentage to be 81%, although one problem book (book 2) skewed our overall results. To find the number of cycles per hour we used Eq. 9 and 10.

$$\frac{3600 \frac{\text{seconds}}{\text{hour}}}{15 \frac{\text{seconds}}{\text{cycle}}} = 240 \text{ cycles/hour} \quad 2 \frac{\text{pages}}{\text{cycle}} * 240 \frac{\text{cycles}}{\text{hour}} = 560 \text{ pages/hour}$$

**Eq. 9 and 10**

Calculating pages per hour and failures per hour was more difficult because some books had failures only on the entry side, others had failures only on the exit side, and a few had failures on both. For a conservative estimate, we multiplied overall successful entry percentage by overall successful exit percentage to determine pagers per hour to be 417.

$$560 \frac{\text{pages}}{\text{hour}} * 92\% * 81\% = 417 \frac{\text{pages}}{\text{hour}}$$

**Eq. 11**

The failures per hour was 143, this was found by subtracting successful pages per hour from total pages per hour.

**Justification:** We easily surpassed our goal for 200 pages scanned per hour. For failures per hour, we were far from our goal of 0 but this is not necessarily unacceptable. First, when a page failed to be sucked into the channel, we found that increasing the vacuum level could often pull a problem page in. Furthermore, we speculate that multiple pages being drawn into the channel can be detected using an ultrasonic transducer and with our design, allowing the operator to back the saddle up and reattempt to draw just one page (maybe at a lower vacuum setting). We therefore feel both entry failure cases are a result of improper device calibration rather than a device design flaw. We found failures to exit to be isolated to specific books and book portions. For our testing, book 2 was the issue. We hypothesize that adding a top mount to the saddle to hold the book in a better position may assist page exit. For the other books, we found that the greatest number of page exit failures occurred in the “first third” of a book. Because the “final third” of a book had significantly better exit success percentages, we think the exit

problem could be addressed by scanning from the middle of a book to the end, and then rotating it 180 degrees and scanning from the same middle page to the front. Doing this would scan the entire book while scanning the “final third” twice.

### **Book Specifications**

**Maximum Book Weight:** We determined that the weight of a book did not impact the scanner’s ability to successfully turn a page, since we tested various book weights within our limits. Therefore, in order to test the maximum book weight limit of the device, we placed a 6 lb book into the saddle to see if the motor could successfully run the scan cycle and make sure the panels did not deflect in a problematic manner. We determined that the scanner could operate successfully with a 6 lb book, as deflection was minimal and the out feed success was not compromised.

**Minimum and Maximum Book Size:** To test the minimum and maximum book sizes, we included books of minimum and maximum size in the collection of books we used for pages per hour and failures per hour validation. We found both the large and small book could be scanned successfully and fit in our saddle dimensions properly.

### **Lifetime**

We cannot accurately test the lifetime of our scanner. However, after running about 300 cycles overall, we can see some wear to the scanner surfaces. This is the only part of the scanner that seems to have “aged” with operation. As the saddle has moved down and back the length of the scanner, it has created some scoring on the scanner’s Delrin sliding surfaces. These scratches are in the direction of saddle motion and seem to have little impact on page turning or book wear and tear. In fact, they seem to beneficially decrease the friction on the panels, despite the visual wear. It should also be noted that the scoring seemed to occur mostly within the first 100 cycles and has not gotten visibly worse over the last hundred cycles.

### **Device Weight**

We determined the device weight to be 50 lbs. This was well over our goal of 20 lbs. A major reason our weight was so high was the use of a plywood plank to align the two halves of the scanner. Even removing this plank, however, would leave us with a scanner weight of about 35 lbs. We feel that this weight is acceptable because although our scanner does not meet the design specification, it does meet the portability design requirement due to the size of parts we assembled together. We found the scanner to be easily transported using two people while assembled and are convinced it could be easily relocated by one person if each half was moved separately. Each half, individually, weighs less than 20 lbs. Furthermore, due to its reduced length and height, it can easily be transported in a sedan. This is shown in Figure 44. Lastly, because the scanner is made up of nearly entirely flat sheets, it can also be disassembled and then flat-packed into a suitcase for airplane travel.



**Figure 44: Linear book scanner in the trunk of a sedan.**

### **Time to Proficiency**

Our goal for the training time required to operate the scanner was 30 minutes. Using a student tester, we found that an oral walkthrough of scanning procedure had the new operator successfully scanning in just over 6 minutes. When the scanner was fully shut down, the new operator took just under 3 minutes to successfully initialize the scanner, load a book, calibrate the vacuum, and begin scanning.

### **Price**

Our goal for the scanner price was to be under \$1,500. After adding up the cost for the scanner components as well as the extra parts to operate the scanner (i.e. vacuum, monitor, cables), we found our scanner to be just under \$900 as can be seen in the BOM in Appendix A.

### **Noise Level**

Our goal for the scanner noise level was to operate at less than 55 dB. Unfortunately we were unable to find a reliable decibel meter, any smartphone we tried gave unrealistic results. However the vacuum causes the majority of the noise and is being run on the lowest setting whereas before it was run on the second highest setting. During testing we had no issue communicating over the scanners noise; we didn't have to shout to hear each other and the scanner doesn't seem louder than any other office equipment.

## DISCUSSION AND DESIGN CRITQUE

### Frame Geometry

The frame geometry has proved to work well in this design. One added benefit is that the unit is now less than 48" long. This makes it much easier to transport – it can actually fit in the trunk of a sedan with the back seat folded down. However the outfeed geometry could be improved to eliminate the occasional failures.

Because of the cyclical loads the saddle and the book receives, the exact dynamics of a loose sheet of paper passing through the channel is highly unpredictable. Through trial and error, we were able to shape the device in order to direct the pages away from any corners or edges that would cause failures. Unfortunately, it was not possible to devise a permanent solution to this problem due to time constraints, and intensive research to determine the characteristics of the phenomenon is beyond the scope of this project.

### Vacuum Slots

This improved design dramatically improved the vacuum slot draw feature. The helix has worked very well during testing to select where the vacuum goes, and also had the benefit of requiring much less air to suck the page than the initial prototype did. This allows the vacuum to be run at a lower speed, greatly reducing the noise. In future designs, it may be possible to remove the vacuum and replace it with a small fan so that the system is totally self-contained.

### Saddle

The improved saddle is able to support most of the books that are tested fairly well. However, it is unable to provide a uniform loading across the top of the book, which will aid in the suction of pages for light-weighted book. A cover could be added at the top of the saddle to provide the pressure needed. Besides that, the saddle too is unable to support the book when most of the pages are at either the front side of the book or the backside. A spring loaded adjustable support might be able to solve this issue.

### Assembly

The assembly is a highlight for our design and significantly improves upon the previous design efficiency and simplicity. It uses 120+ fasteners with only 10 tapped holes. The whole prototype contains 34 acrylic parts and 6 Delrin parts. This is relatively little parts for a complex machine like the Linear Book Scanner prototype. Besides that, 97% of the assembly is being cut using laser engraver and that enable it to be manufacture within a very short period of time. The operator too does not need to possess any serious milling skills as only 2% of the prototype will be mill. It is possible to assemble the prototype alone but ideally it will need up to 2 people to fully minimize the time required and make assembling it easier.

### Materials

The materials that are being used in the prototype are functioning and performing as expected. The usage of Delrin for both the infeed and outfeed panel does reduces the friction between the surfaces of the book with the outer surface of the prototype. However, due to the cyclic effect of the saddle movement, scorings are now visible on the Delrin surface. The scoring does not affect the movement of the saddle nor does it induce more friction. It only affects the aesthetic of the prototype for the time being. The acrylic on the other hand is able to withstand the average load that is applied onto it due to the weight of the book, the saddle, as well as the outer panels. However it does not perform that well in preventing the flexing of the prototype due to the tension of the belt. Better positioning the acrylic ribs onto a stable supporting structure, could provide a remedy to this problem.

## **RECOMMENDATIONS**

After completing our linear book scanner design, we have a couple of recommendations to improve the design going forward in the future.

First, there still needs to be work done on the outfeed panels to finalize the geometry. Currently we are using a plastic forming material (InstaMorph) to correct the geometry of the front outfeed panel. If more book scanners are to be designed in the future, this geometry would have to be adjusted for that slight modification.

We also recommend developing a frame for the design, in order to replace the wood plank that we currently use. This could be a simple, flat panel with cut outs where material is not needed. Its two function would serve to standardize the special relationship between the two sections and it could support the inner panels for additional support. This design could be easily implemented using our same fastener. This would reduce the weight significantly, increase the portability, standardize placement of the two infeed and outfeed components.

We initially tried to implement a fan on the inside of the page turning channel, with the hopes of blowing the page more towards the outfeed side. We did not use the fan idea because it was challenging to find a correct mounting location could effectively apply a force, on a range of book sizes. While our outfeed success was very high, we recommend trying to install a fan on the inside of the page channel that would assist the page during its outfeed path.

Next, the linear book scanner design can benefit from additional electronic components. An ultrasonic transducer could be added near the infeed slot to help detect multiple pages being drawn into the page turning channel. Also, an IR sensor can be added to detect when there is not a successful entry into the channel. The two limit switches that we have utilized on the ends of our design will have to be added to the current coding parameters.

## **CONCLUSION**

A linear book scanner was created for our sponsors, the University of Michigan Library, so that they may digitize their collection faster and more cost effectively. Care was taken to understand their design requirements and how to best translate those into engineering specifications. Then through testing of the original linear book scanner built by Dany Qumsiyeh and numerous brainstorming sessions we were able to develop several innovative ways to improve the linear book scanner. These include a revised geometry that brings the length of the unit below 48" greatly improving portability. It also includes a helical vacuum slot that allows the vacuum position to be quickly and precisely adjusted. These and numerous other changes allowed our prototype to show significant improvements in scanning rate and failure rate as compared to the initial linear book scanner. Although this book scanner is not yet a mature product, we have been able to make many refinements to the mechanical geometry. Overall this project shows great promise to become a mature technology that can greatly reduce the cost in digitizing books.

## **ACKNOWLEDGEMENTS**

This semester long project would not have gone as smooth as it did without the help and guidance we received from a number of people. We would now like to acknowledge those involved in the project, in no specific order. Our teacher, Dan Johnson, has been vital in both guiding and critiquing our engineering

ideas throughout the design process. All of our sponsors from the UM-library, Kat Hagedorn, Meghan Musolff, Jim Ottaviani, John Weise, were very supportive and clear about their vision for the Linear Book Scanner. Dany Qumsiyeh, who initially spearheaded the original designs, was great at communicating his prior knowledge with us and travelled to Ann Arbor on multiple occasions for project updates. Bob and Mark of the machine shop were very helpful in facilitating the manufacturing of various parts. All of the ME 450 professors, Prof. Chronis, Prof. Sienko, Prof. Kuo, Prof. Kota, were great at evaluating our engineering design throughout the design process. Jeffrey Plott provided us concrete methods to improve our presentation giving skills. We want to say thank you to everyone that made this a wonderful semester and the linear book scanner project a success.

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## APPENDIX A

### Linear Book Scanner Costs

<b>Material</b>	<b>L</b>	<b>W</b>	<b>Thickness</b>	<b>Quantity</b>	<b>Cost</b>	<b>Extended Cost</b>	<b>Source</b>
Acrylic	12	48	0.25	4	37	148	McMaster-Carr
Delrin	12	48	0.2	2	80	160	McMaster-Carr
						<b>Subtotal</b>	<b>308</b>
<b>Fasteners</b>							
92210A113	4-40 Bolt			1	4.86	4.86	McMaster-Carr
90631A005	4-40 Nut			1	2.55	2.55	McMaster-Carr
92210A197	8-32 Bolt			2	6.96	13.92	McMaster-Carr
90631A009	8-32 Nut			2	2.35	4.7	McMaster-Carr
<b>Drive System</b>							
1375K39	Pully			1	10.77	10.77	McMaster-Carr
6338K411	Bronze Bushing			6	0.74	4.44	McMaster-Carr
59625K330	Knobs			8	0.75	6	McMaster-Carr
7658K16	Limit Switch			2	3.21	6.42	McMaster-Carr
1830T279	Outer Tube			1	11.66	11.66	McMaster-Carr
1830T259	Inner Tube			3	12.63	37.89	McMaster-Carr
17715A68	Angle Brackets			2	4.11	8.22	McMaster-Carr
6061K31	1/4 Shaft			1	5.11	5.11	McMaster-Carr
						<b>Subtotal</b>	<b>116.54</b>
<b>Electronics</b>							
Logic Level Converter				1	3.95	3.95	Adafruit
Breadboard				1	15.96	15.96	Adafruit
USB Front				3	3.95	11.85	Adafruit
LED Button				3	1.5	4.5	Adafruit
D-link				1	25.99	25.99	Amazon
RPI				1	40.96	40.96	Amazon
HMDI Cable				1	5.76	5.76	Amazon
SD Card				1	9.99	9.99	Amazon
Canon lide 210				2	69.99	139.98	Amazon
						<b>Subtotal</b>	<b>258.94</b>
						<b>Total</b>	<b>683.48</b>
<b>Supplied</b>							
Vacuum					75	Sponsor	
Display					50	Design Lab	
						<b>Subtotal</b>	<b>125</b>
						<b>Total</b>	<b>808.48</b>

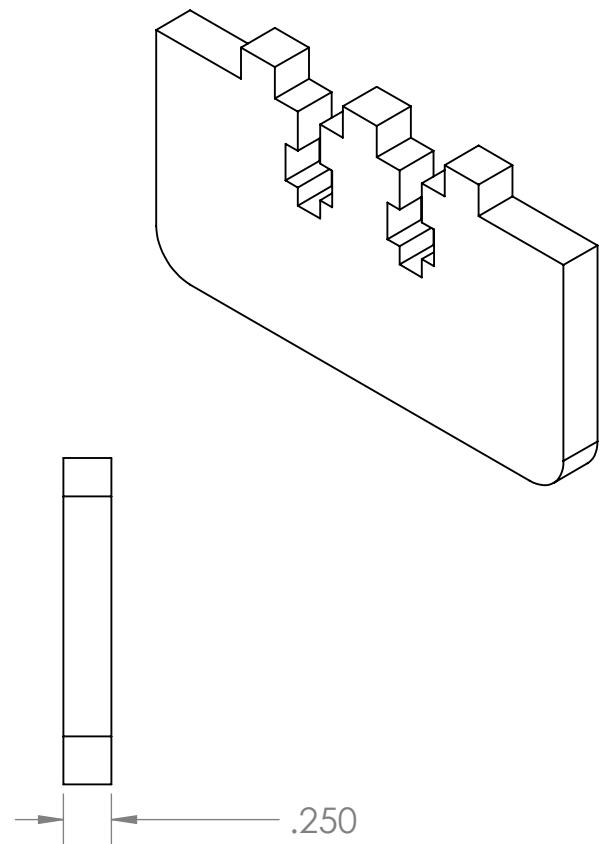
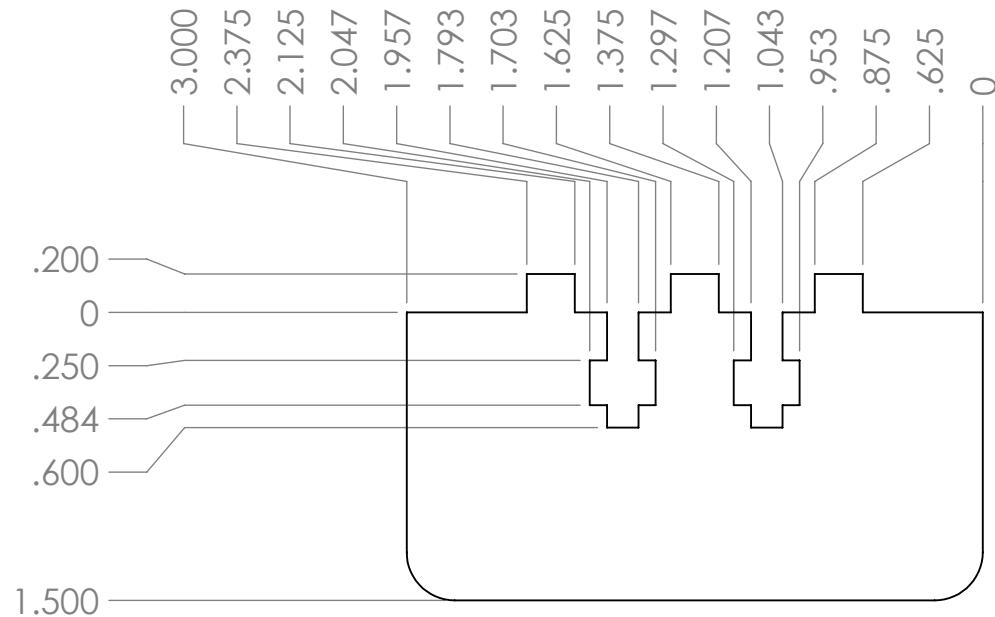
## Linear Book Scanner Parts

#	SUB-ASSEMBLY	PART NAME	DESCRIPTION	MATERIAL	Quantity
1	VACUUM TUBE	INSIDE TUBE CAP		Acrylic	1
2	VACUUM TUBE	OUTSIDE TUBE CAP		Acrylic	1
3	VACUUM TUBE	INSIDE TUBE	1.75 x 10"	Delrin	1
4	VACUUM TUBE	OUTSIDE TUBE	2" od x 10"	Delrin	1
5	VACUUM TUBE	Bolt	1/4"-20	Steel	1
6	VACUUM TUBE	LED	5mm blue	Plastic	1
7	VACUUM TUBE	Nut	1/4"-20 nylock	Steel	1
8	VACUUM TUBE	Washer	1/4"-20 washer	Nylon	1
9	SIDE OUTFEED FRONT	92210A197	8-32 316 Flat Head SHCS	316	4
10	SIDE OUTFEED FRONT	OUTFEED FRONT, SIDE	side panel	Delrin	1
11	SIDE OUTFEED FRONT	SCANNER BAR, OUTFEED		SA	1
12	SIDE OUTFEED FRONT	90631A009	8-32 Nylock Nut	Steel	4
13	SIDE OUTFEED BACK	INFEED BACK, SIDE		Delrin	1
14	SIDE INFEED FRONT	92210A113	4-40 316 Flat Head SHCS	316	4
15	SIDE INFEED FRONT	92210A197	8-32 316 Flat Head SHCS	316	8
16	SIDE INFEED FRONT	HORN MOUNT		Acrylic	1
17	SIDE INFEED FRONT	HORN_1		Acrylic	1
18	SIDE INFEED FRONT	INFEED FRONT, SIDE		Delrin	1
19	SIDE INFEED FRONT	SCANNER BAR, INFEED		SA	1
20	SIDE INFEED FRONT	VACUUM TUBE		SA	1
21	SIDE INFEED FRONT	90631A009	8-32 Nylock Nut	Steel	8
22	SIDE INFEED BACK	INFEED BACK, SIDE		Delrin	1
23	SCANNER BAR, OUTFEED	BRACKET	mounting bracket	Acrylic	2
24	SCANNER BAR, OUTFEED	Glass Cover	9.25 x 1"	Glass	1
25	SCANNER BAR, OUTFEED	Scanner Bar	Canon 220 Scanner Bar	n/a	1
26	SCANNER BAR, INFEED	BRACKET	mounting bracket	Acrylic	2
27	SCANNER BAR, INFEED	Glass Cover	9.25 x 1"	Glass	1
28	SCANNER BAR, INFEED	Scanner Bar	Canon 220 Scanner Bar	n/a	1
29	SADDLE	92210A197	8-32 316 Flat Head SHCS	316	28
30	SADDLE	LINK	links the sides	Acrylic	2
31	SADDLE	LOWER PADDLE		Acrylic	2
32	SADDLE	LOWER PADDLE SLIDE		Acrylic	2
33	SADDLE	SIDE PADDLE		Acrylic	2
34	SADDLE	SIDE PADDLE SLIDE		Acrylic	4
35	SADDLE	SIDE_1	saddle side	Acrylic	2
36	SADDLE	SIDE_2	saddle side	Acrylic	2
37	SADDLE	59625K330	Knob	Plastic	8
38	SADDLE	92210A546	1/4-20 Flat Head SHCS	SS	8
39	SADDLE	17715A68	Bracket link to side	Steel	2
40	SADDLE	90631A009	8-32 Nylock Nut	Steel	28
41	PULLY BLOCK, INFEED	LIMIT SWITCH MOUNT	mounting holes for limit switch	Acrylic	1
42	PULLY BLOCK, INFEED	MOUNT, PULLY	mount	Acrylic	2
43	PULLY BLOCK, INFEED	1375K39	Idel pulley 20 teeth	Aluminum	1
44	PULLY BLOCK, INFEED	6338K411	Bronze bearing with shoulder	Bronze	2
45	PULLY BLOCK, INFEED	SHAFT, PULLEY	1/4" x 1.25" TB&P	Steel	1
46	PULLEY BLOCK, OUTFEED	MOUNT, PULLEY	mount	Acrylic	2
47	PULLEY BLOCK, OUTFEED	1375K39	Idel pulley 20 teeth	Aluminum	1
48	PULLEY BLOCK, OUTFEED	6338K411	Bronze bearing with shoulder	Bronze	2
49	PULLEY BLOCK, OUTFEED	SHAFT, PULLEY	1/4" x 1.25" TB&P	Steel	1
50	PULLEY BLOCK, LOWER OUTFEED MOUNT OFFSET, PULLEY		mount	Acrylic	2

## Linear Book Scanner Parts Cont.

#	SUB-ASSEMBLY	PART NAME	DESCRIPTION	MATERIAL	Quantity
51	PULLEY BLOCK, LOWER OUTFEED	1375K39	Idel pulley 20 teeth	Aluminum	1
52	PULLEY BLOCK, LOWER OUTFEED	6338K411	Bronze bearing with shoulder	Bronze	2
53	PULLEY BLOCK, LOWER OUTFEED SHAFT, PULLEY		1/4" x 1.25" TB&P	Steel	1
54	MOTOR MOUNT	92210A197	8-32 316 Flat Head SHCS	316	8
55	MOTOR MOUNT	FACE	face holes to mount NEMA 23 stepper	Acrylic	1
56	MOTOR MOUNT	SIDE		Acrylic	2
57	MOTOR MOUNT	1375K39	Idel pulley 20 teeth	Aluminum	1
58	MOTOR MOUNT	Stepper	NEMA 23 Stepper	Magnets	1
59	MOTOR MOUNT	90631A009	8-32 Nylock Nut	Steel	8
60	Main Assembly	ELECTRONICS SLIDE		Acrylic	
61	MA	FRAME	Main Scanner Frame	MA	1
62	MA	SADDLE	saddle assembly	SA	1
63	MA	SIDE INFEED BACK	side assembly	SA	1
64	MA	SIDE INFEED FRONT	Infeed w/ vacuum tube and scanner	SA	1
65	MA	SIDE OUTFEED BACK	side assembly	SA	1
66	FRAME	92210A197	8-32 316 Flat Head SHCS	316	43
67	FRAME	LOWER INFEED BACK RIB	Side pannel to increase stiffness	Acrylic	1
68	FRAME	LOWER INFEED FRONT RIB	Side pannel to increase stiffness	Acrylic	1
69	FRAME	LOWER OUTFEED BACK RIB	Side pannel to increase stiffness	Acrylic	1
70	FRAME	LOWER OUTFEED FRONT RIB	Side pannel to increase stiffness	Acrylic	1
71	FRAME	RIB 2	Second rib, has electronics hole	Acrylic	1
72	FRAME	RIB 3	Third Rib, support end of front pannels	Acrylic	1
73	FRAME	RIB 4 INFEED	Stub rib- supports back panel corner	Acrylic	1
74	FRAME	RIB 4 OUTFEED	Stub rib- supports back panel corner	Acrylic	1
75	FRAME	RIB 5	Outfeed Rib	Acrylic	1
76	FRAME	RIB 6	End cap rib, has two bearing blocks	Acrylic	1
77	FRAME	MOTOR MOUNT	mount for stepper motor	SA	1
78	FRAME	PULLY BLOCK, INFEED	Idel pulley assy	SA	1
79	FRAME	PULLY BLOCK, LOWER OUTFEED	Idel pulley assy	SA	1
80	FRAME	PULLY BLOCK, OUTFEED	Idel pulley assy	SA	1
81	FRAME	RIB 1	Front rib, has electronics hole	SA	1
82	FRAME	90631A009	8-32 Nylock Nut	Steel	43
83	ELECTRONICS SLIDE	BASE	electronics base	Acrylic	1
84	ELECTRONICS SLIDE	FRONT		Acrylic	1
85	ELECTRONICS SLIDE	SIDE INFEED		Acrylic	1
86	ELECTRONICS SLIDE	SIDE OUTFEED		Acrylic	1
87	ELECTRONICS SLIDE	SLIDE MOUNT INFEED		Acrylic	1
88	ELECTRONICS SLIDE	SLIDE MOUNT OUTFEED		Acrylic	1

SIZE

**A**

REMOVE BURRS &amp; SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

**BOLT HOLE FOR EXPO**

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

1:1

MATERIAL

WEIGHT

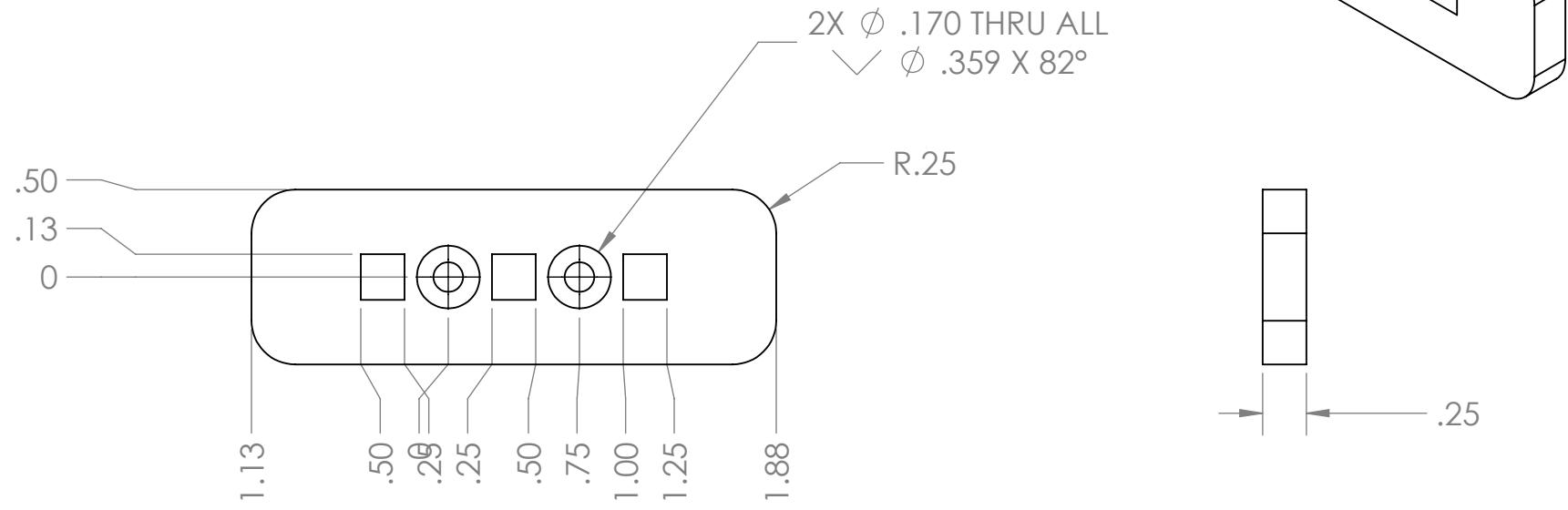
SCALE

REV.

H:\ME\_450\Linear Book Scanner\Fastener Example\

FILE PATH

SIZE  
**A**



REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## NUT HOLE FOR EXPO

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

1:1

MATERIAL

WEIGHT

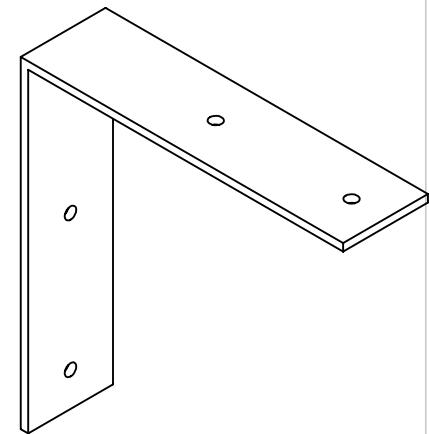
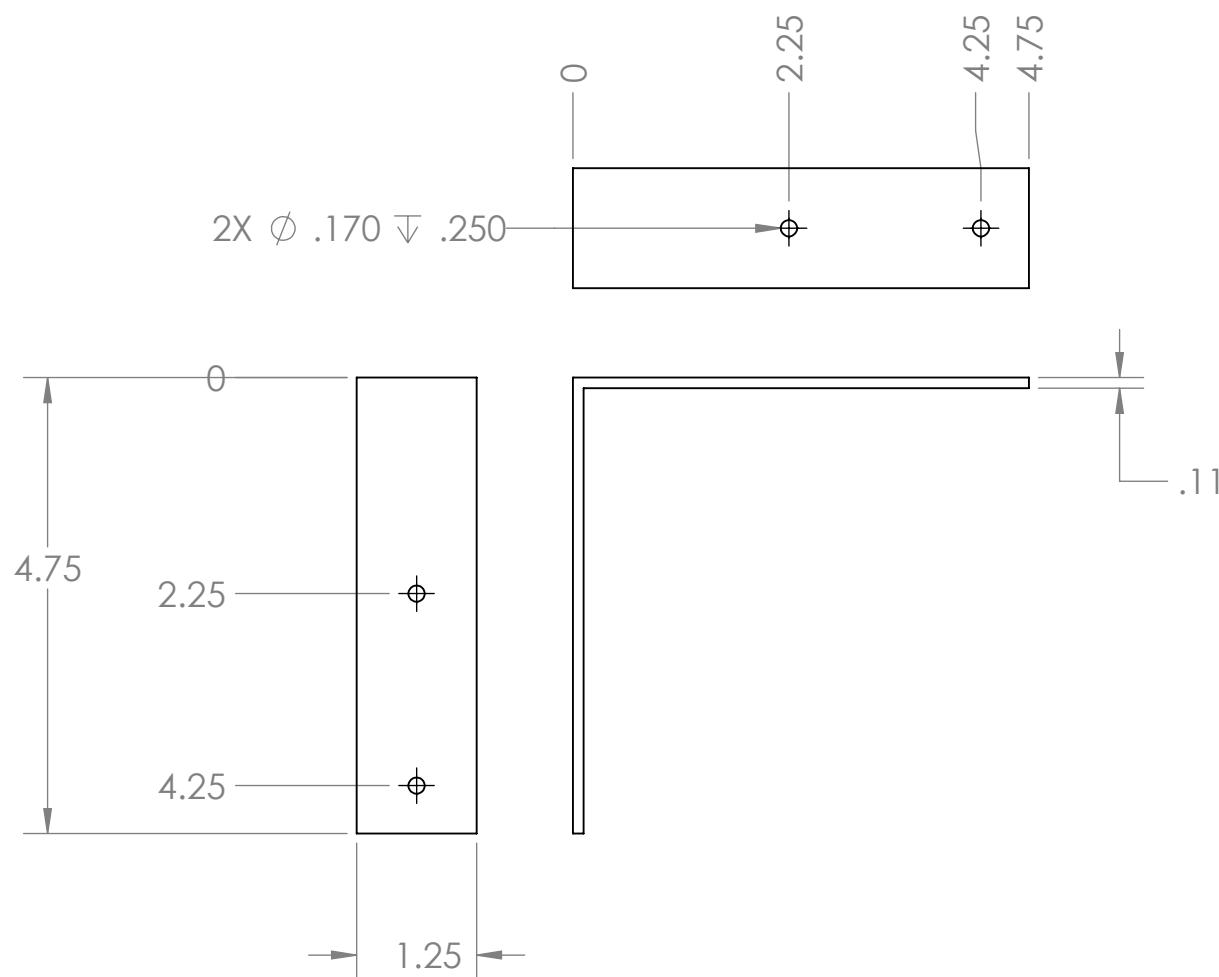
SCALE

REV.

H:\ME\_450\Linear Book Scanner\Fastener Example\

FILE PATH

SIZE  
**A**



REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL:  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

**17715A68**

DESCRIPTION

PART NO.

GROUP

ENGINEER

**SHAWN WRIGHT**

DRAWN BY

DATE

1:2

MATERIAL

WEIGHT

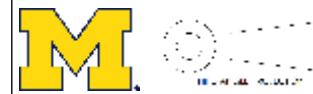
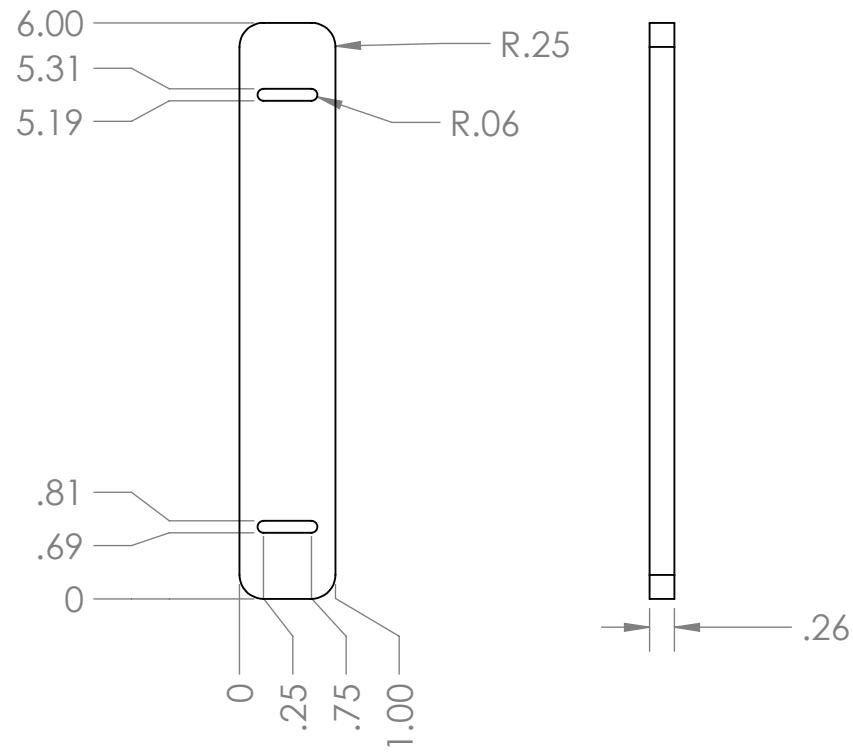
SCALE

REV.

H:\ME\_450\Linear Book Scanner\Saddle\

FILE PATH

SIZE

**A**

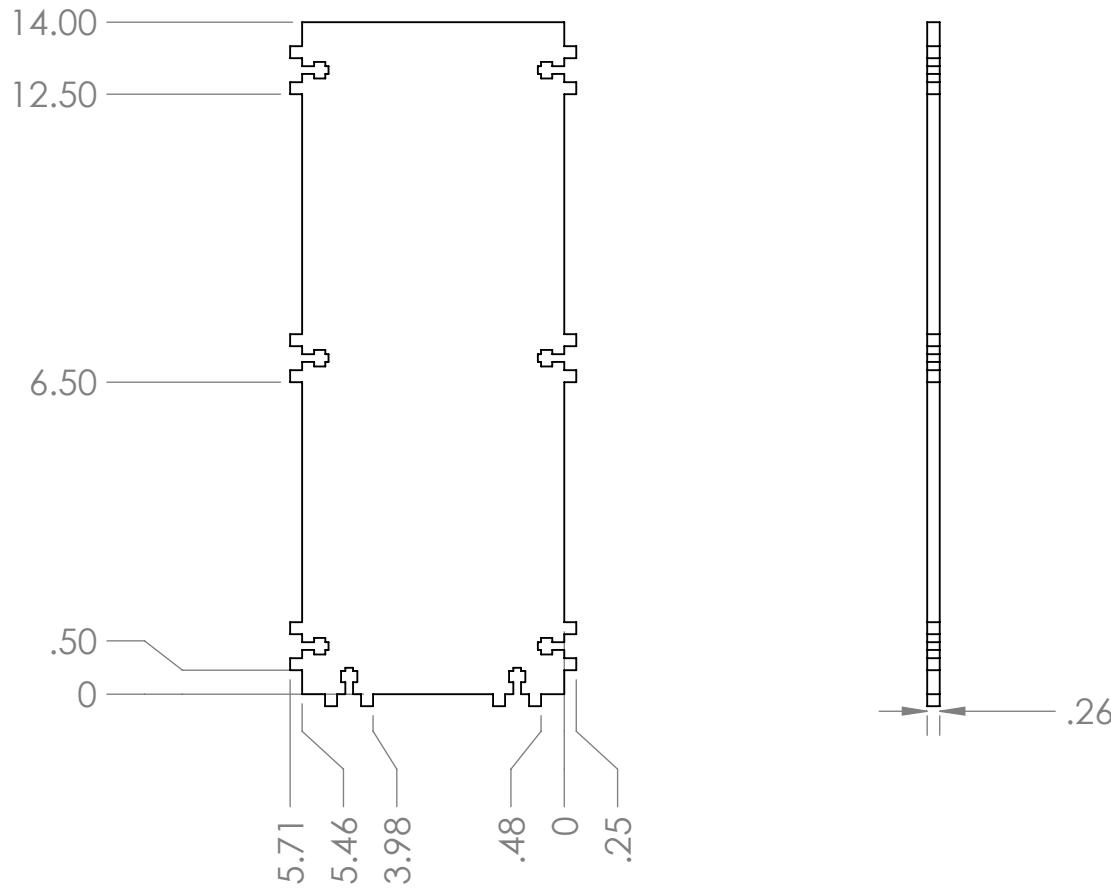
REMOVE BURRS &amp; SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## Base Spacer

DESCRIPTION	
PART NO.	GROUP
ENGINEER	DRAWN BY
MATERIAL	SCALE
H:\ME_450\Linear Book Scanner\Base\	1:2
REV.	
FILE PATH	

SIZE  
**A**



REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## BASE, ELECTRONICS SLIDE

DESCRIPTION

PART NO.

GROUP

SHAWN WRIGHT

DRAWN BY

DATE

ENGINEER

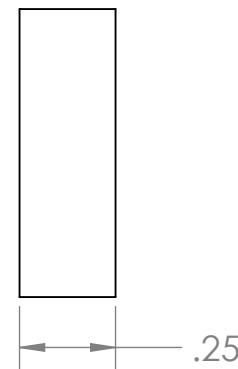
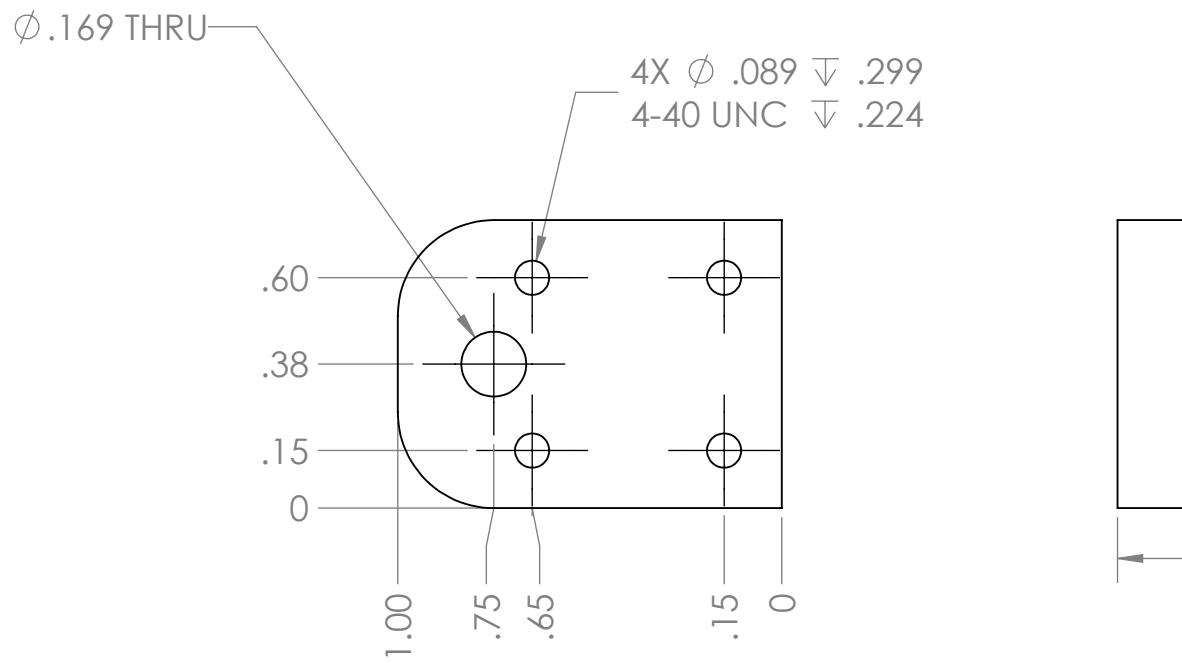
1:4 SCALE

MATERIAL WEIGHT REV.

FILE PATH

H:\ME\_450\Linear Book Scanner\Electronics Slide\

SIZE

**A**

REMOVE BURRS &amp; SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

**BELT MOUNT LOWER, SADDLE**

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

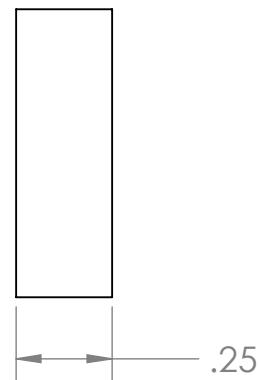
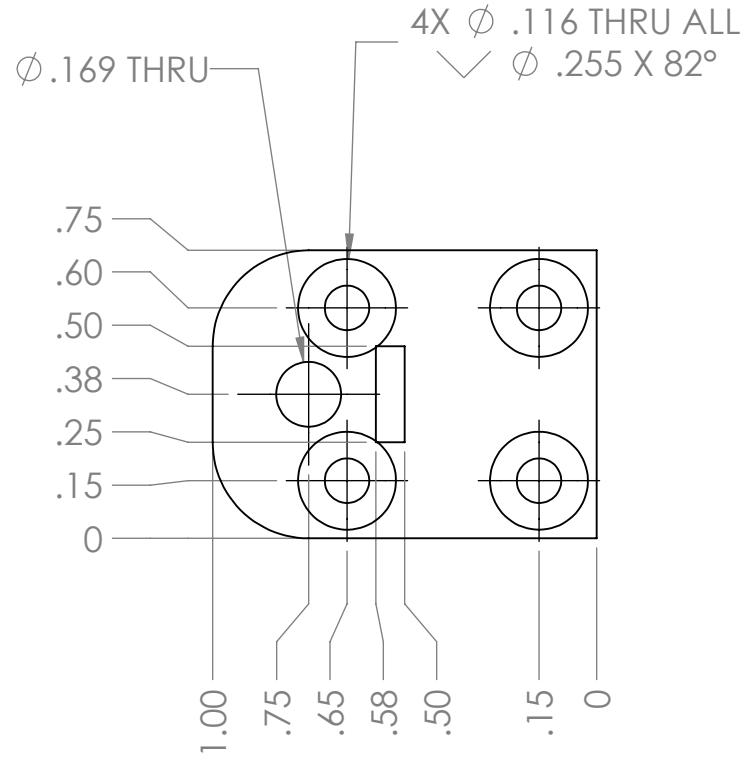
2:1

MATERIAL WEIGHT SCALE REV.

H:\ME\_450\Linear Book Scanner\Saddle\

FILE PATH

SIZE  
**A**



REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## BELT MOUNT UPPER, SADDLE

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

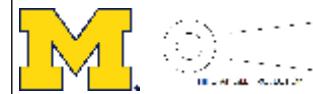
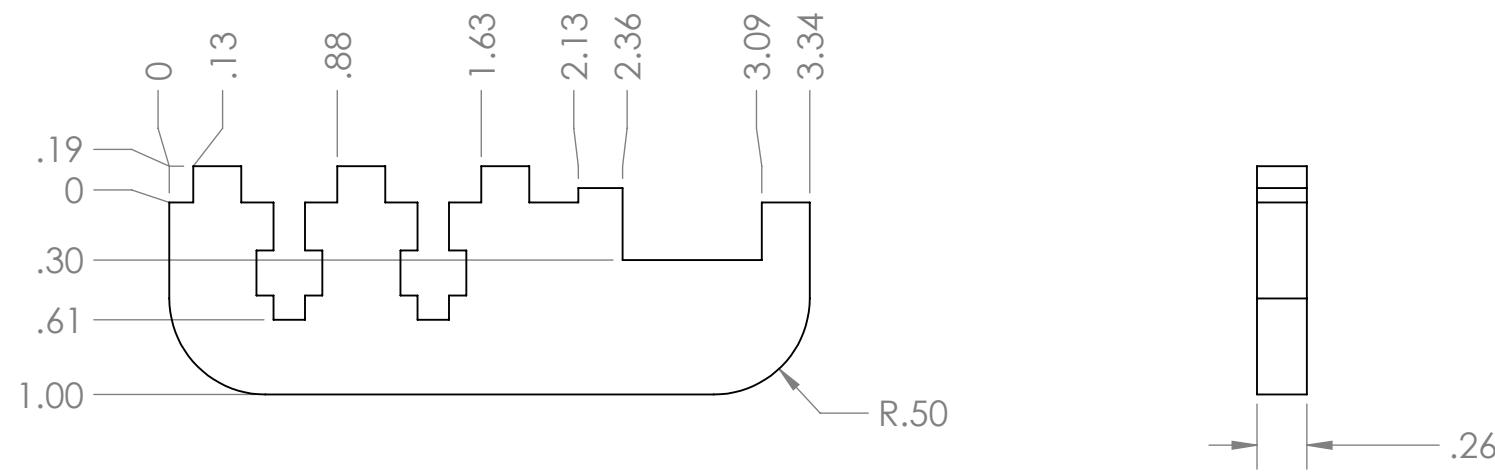
2:1

MATERIAL WEIGHT SCALE REV.

FILE PATH

H:\ME\_450\Linear Book Scanner\Saddle\

SIZE

**A**

REMOVE BURRS &amp; SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

**BRACKET, SCANNER BAR INFEED**

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

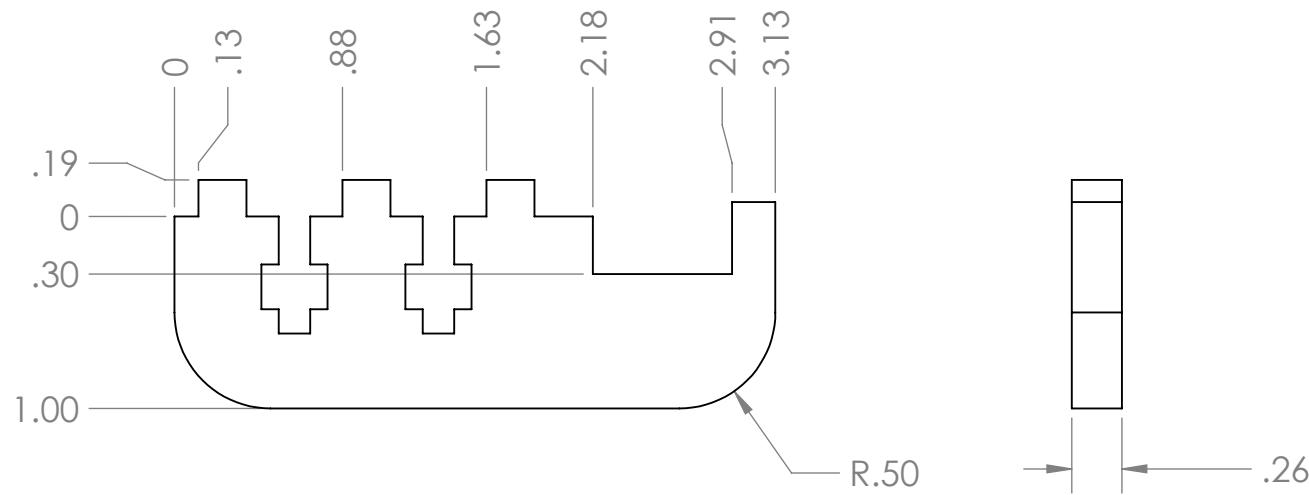
1:1

MATERIAL WEIGHT SCALE REV.

H:\ME\_450\Linear Book Scanner\Scanner Bars\

FILE PATH

SIZE

**A**

REMOVE BURRS &amp; SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

**BRACKET, SCANNER BAR OUTFEED**

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

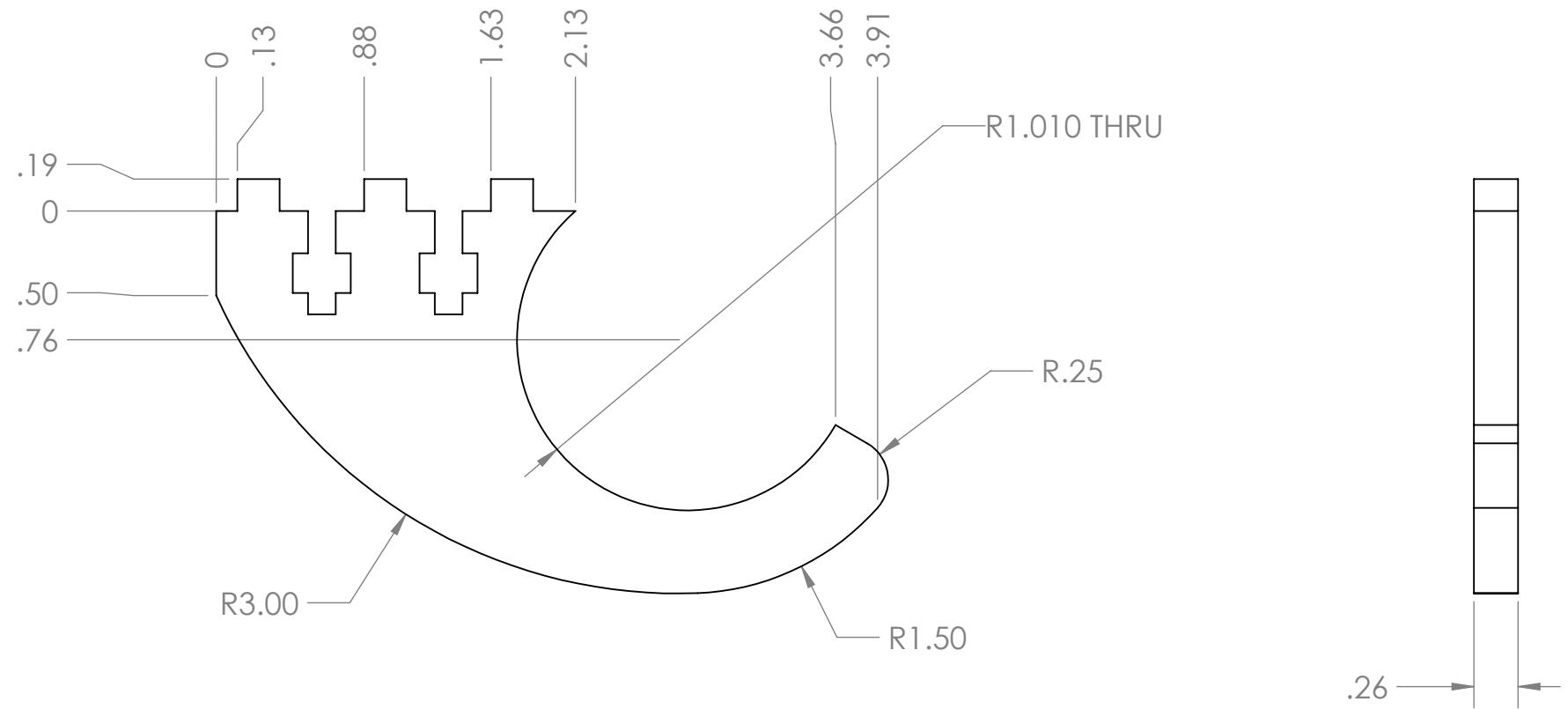
1:1

MATERIAL WEIGHT SCALE REV.

FILE PATH

H:\ME\_450\Linear Book Scanner\Scanner Bars\

SIZE  
**A**



REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL:  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL:  $\pm 0.020"$   
THREE PLACE DECIMAL:  $\pm 0.005"$

## BRACKET, VACUUM TUBE

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

-

DATE

1:1

MATERIAL

WEIGHT

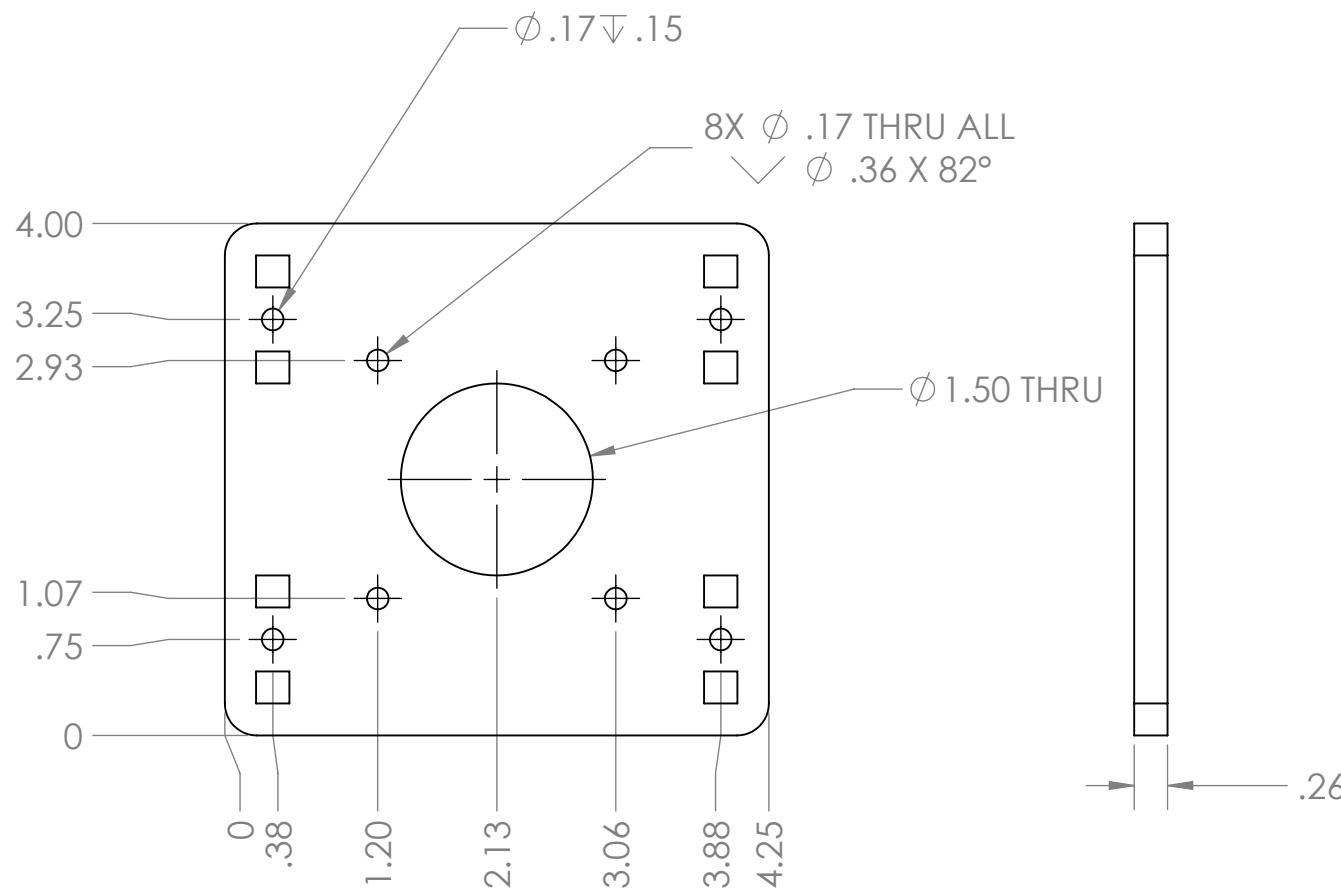
SCALE

REV.

H:\ME\_450\Linear Book Scanner\Vacuum Tube\

FILE PATH

SIZE

**A**

REMOVE BURRS &amp; SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## FACE, MOTOR MOUNT

DESCRIPTION

PART NO.

GROUP

SHAWN WRIGHT

DRAWN BY

DATE

ENGINEER

1:2

MATERIAL

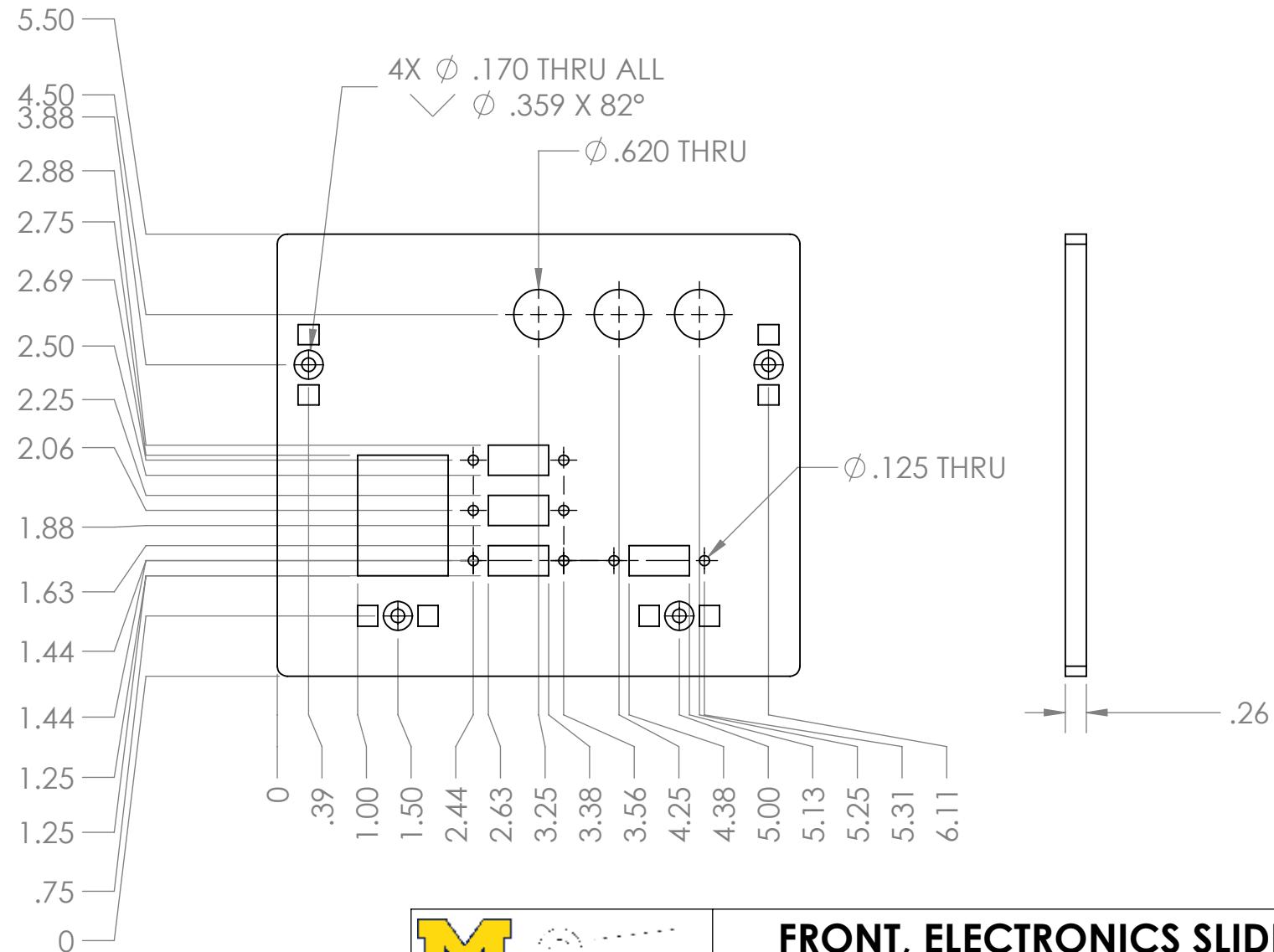
WEIGHT

SCALE

REV.

H:\ME\_450\Linear Book Scanner\Motor Mount\

FILE PATH

SIZE  
**A**

REMOVE BURRS &amp; SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

**FRONT, ELECTRONICS SLIDE**

DESCRIPTION

PART NO.

GROUP

SHAWN WRIGHT

DRAWN BY

DATE

ENGINEER

1:4

MATERIAL WEIGHT

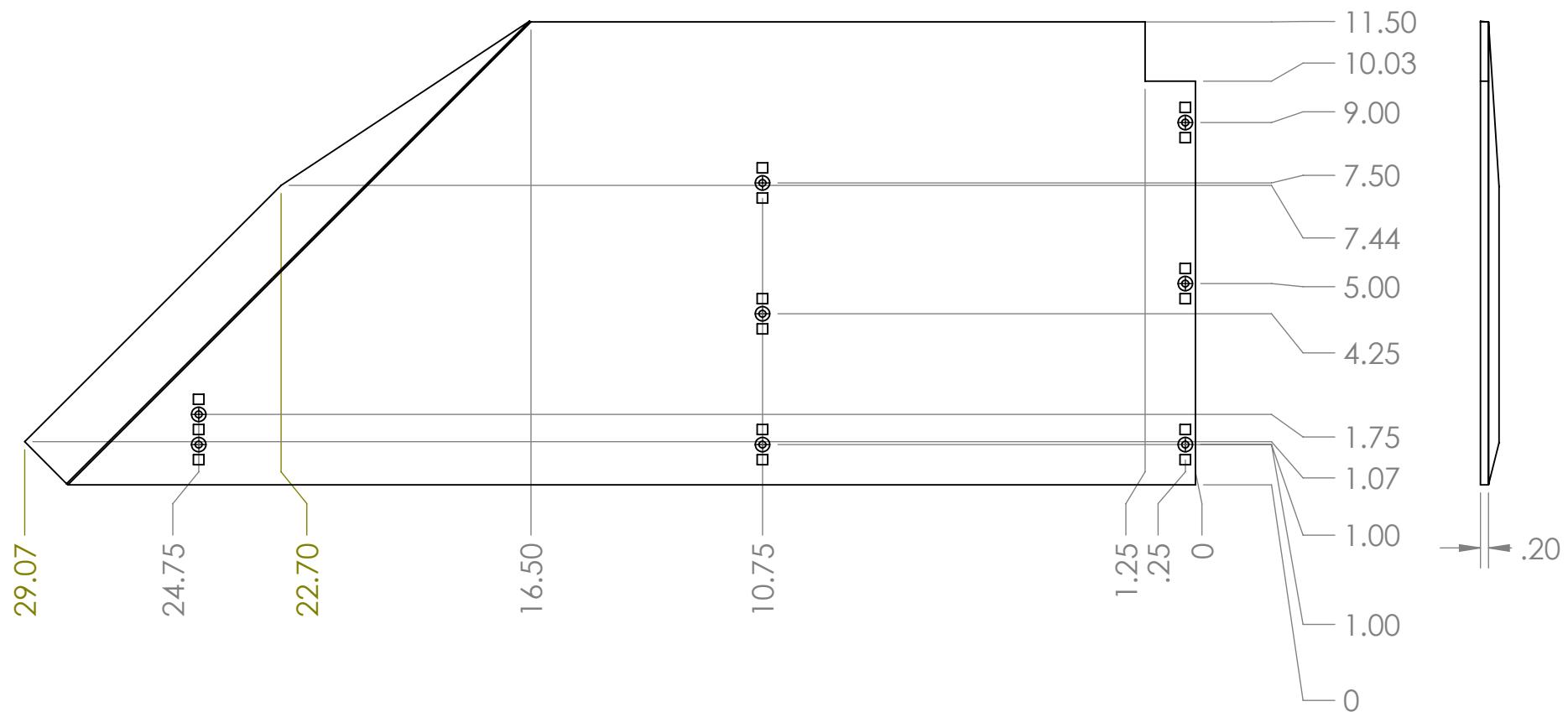
SCALE

REV.

H:\ME\_450\Linear Book Scanner\Electronics Slide\

FILE PATH

SIZE  
**A**



REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## INFEED BACK, SIDE

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

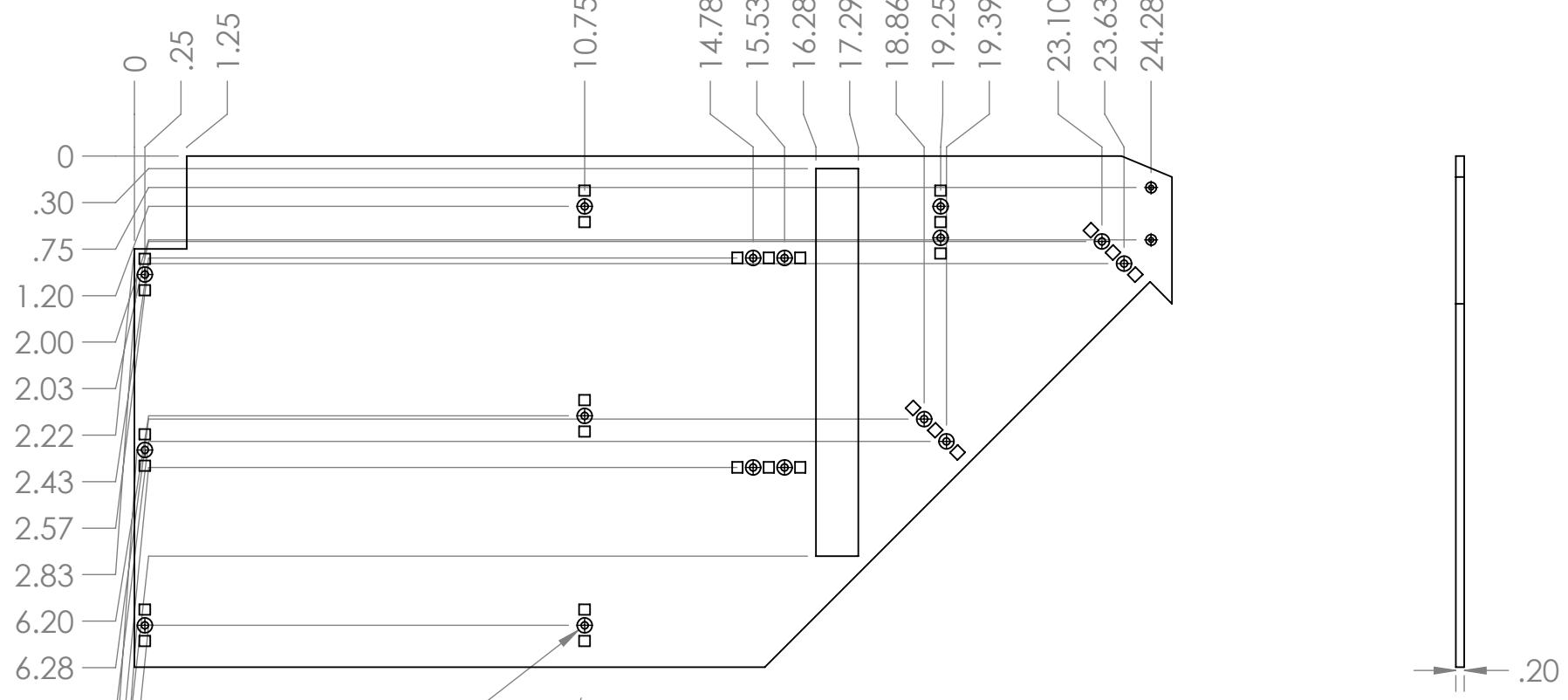
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MATERIAL WEIGHT SCALE REV.

FILE PATH

H:\ME\_450\Linear Book Scanner\Sides\

SIZE  
**A**



REMOVE BURRS & SHARP EDGES

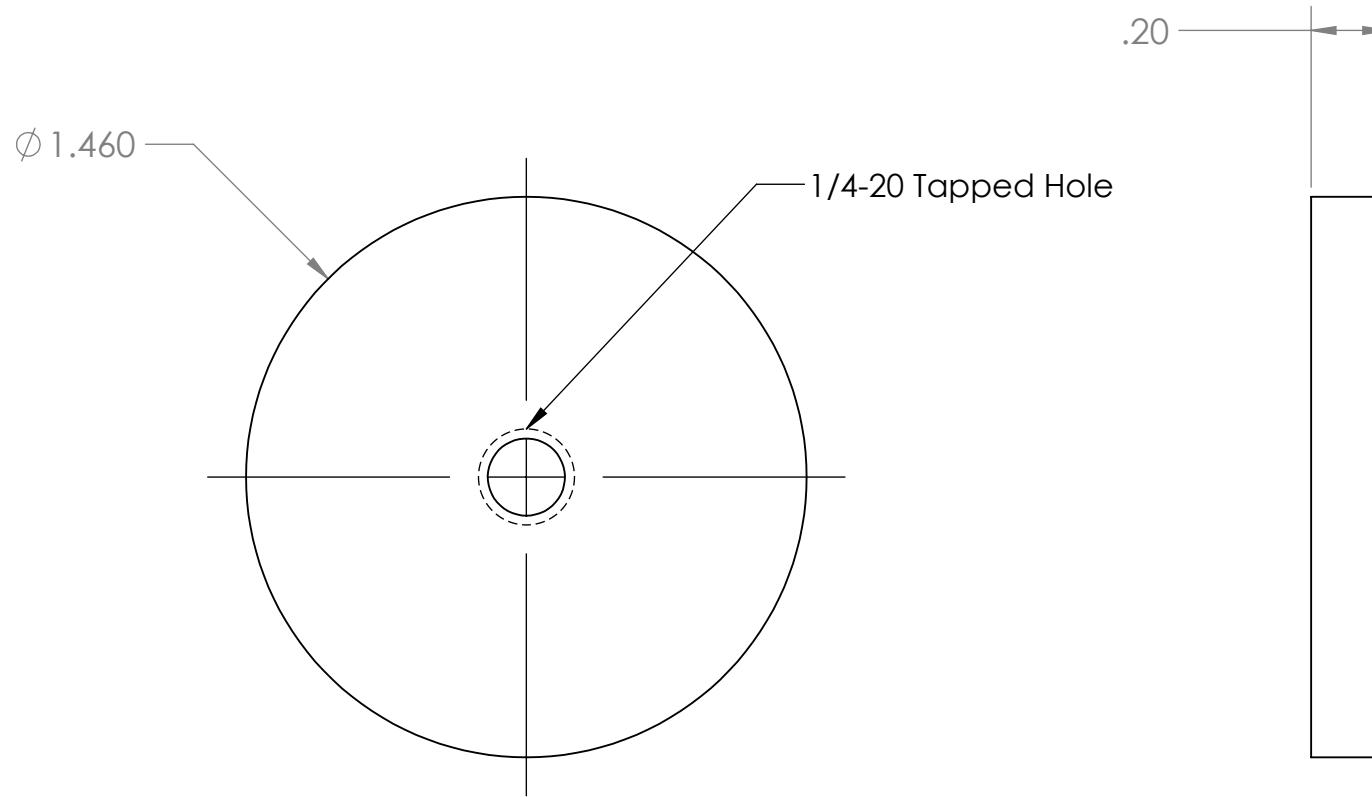
UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## INFEED FRONT, SIDE

DESCRIPTION	
PART NO.	GROUP
ENGINEER	DRAWN BY
SHAWN WRIGHT	
1:8	SCALE
MATERIAL	REV.
FILE PATH	

H:\ME\_450\Linear Book Scanner\Sides\

SIZE  
**A**



REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## INSIDE TUBE CAP, VACUUM TUBE

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

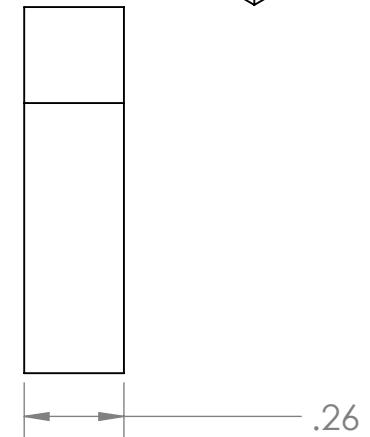
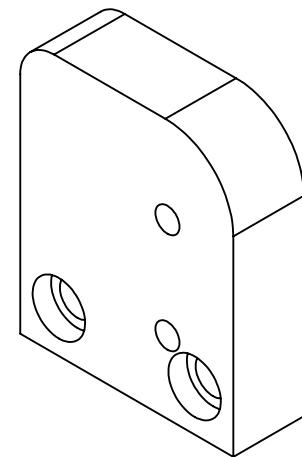
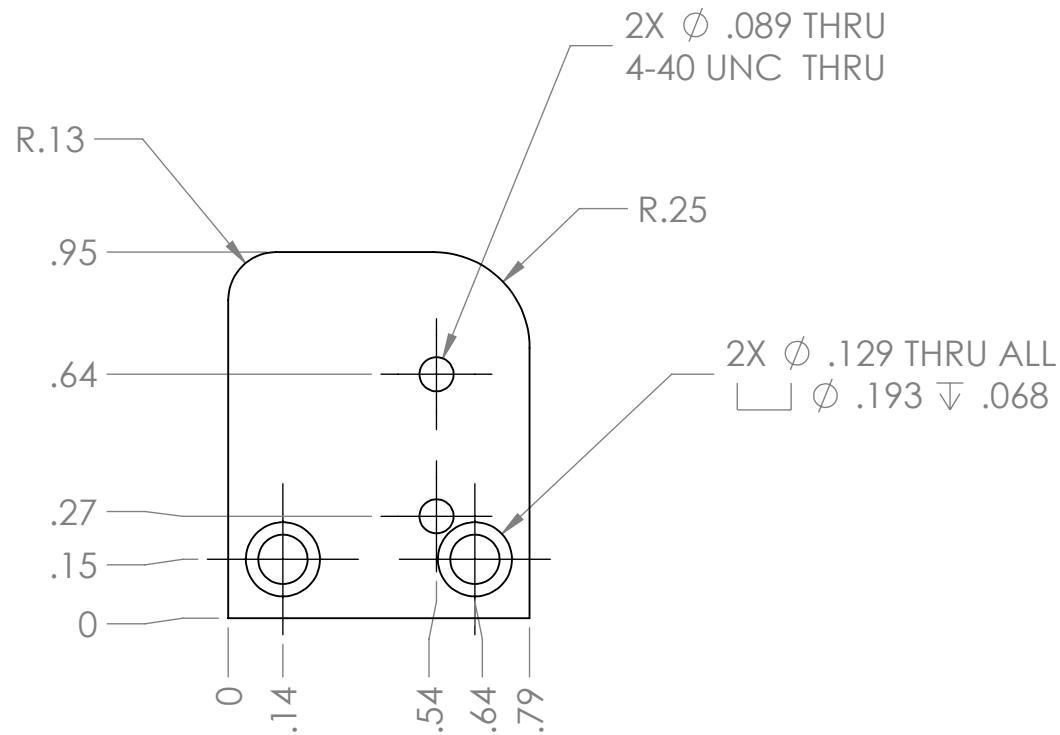
2:1

MATERIAL WEIGHT SCALE REV.

FILE PATH

H:\ME\_450\Linear Book Scanner\Vacuum Tube\

SIZE

**A**

REMOVE BURRS &amp; SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

**LIMIT SWITCH MOUNT, OUTFEED**

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

2:1

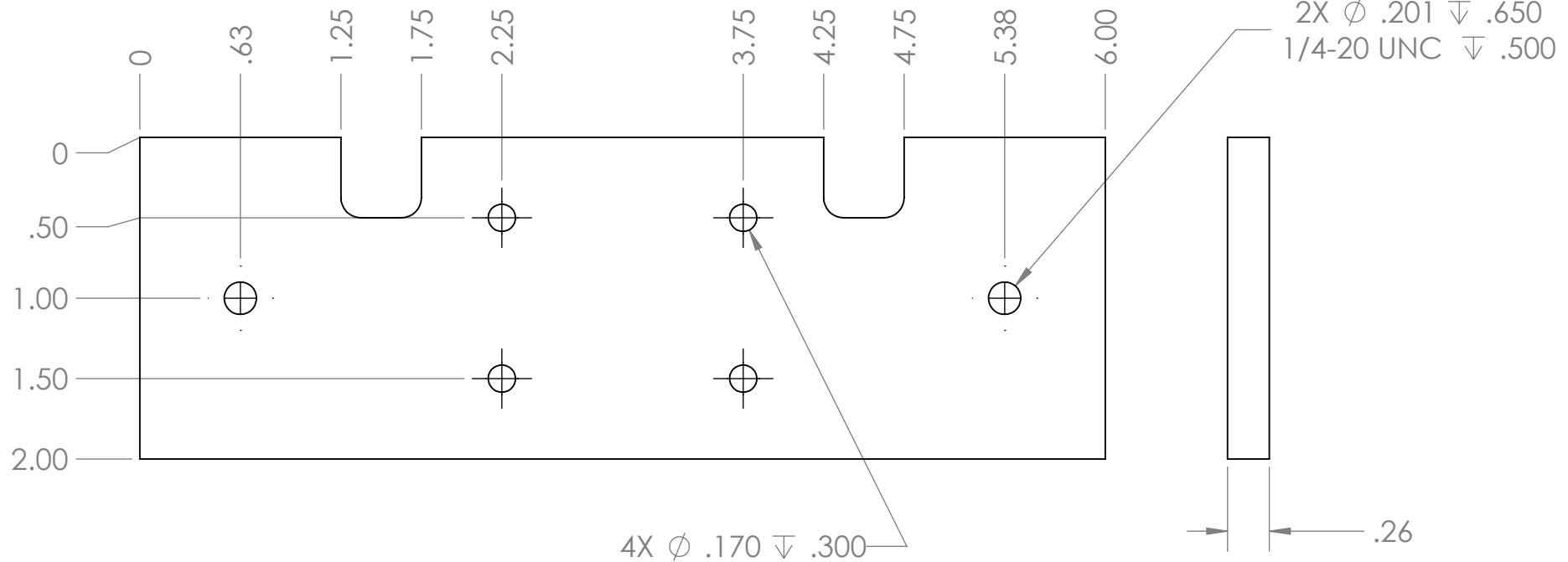
MATERIAL WEIGHT

SCALE REV.

H:\ME\_450\Linear Book Scanner\Pulleys\

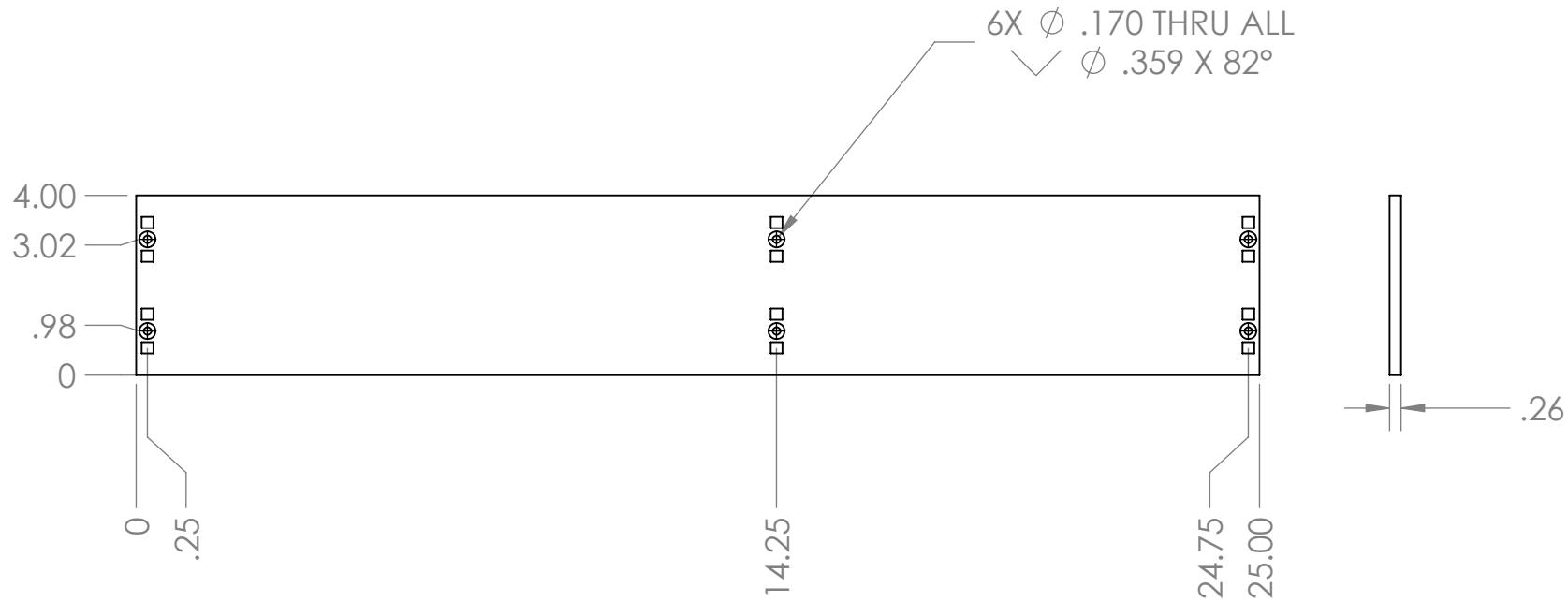
FILE PATH

SIZE  
**A**



  REMOVE BURRS & SHARP EDGES	LINK, SADDLE			
		DESCRIPTION		
	PART NO.	GROUP		
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL $\pm 1/32"$ ANGULAR: MACH $\pm 2^\circ$ BEND: $\pm 1/16"$ TWO PLACE DECIMAL $\pm 0.020"$ THREE PLACE DECIMAL $\pm 0.005"$	SHAWN WRIGHT			
	ENGINEER	DRAWN BY	DATE	
		MATERIAL	WEIGHT	1:2 SCALE REV.
	H:\ME_450\Linear Book Scanner\Saddle\			
	FILE PATH			

SIZE  
**A**



REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## LOWER INFEED BACK RIB, FRAME

DESCRIPTION

PART NO.

GROUP

SHAWN WRIGHT

DRAWN BY

DATE

ENGINEER

1:8

MATERIAL

WEIGHT

SCALE

REV.

H:\ME\_450\Linear Book Scanner\Frame\

FILE PATH

SIZE  
**A**



REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## LOWER INFEED FRONT RIB, FRAME

DESCRIPTION

PART NO.

GROUP

SHAWN WRIGHT

DRAWN BY

DATE

ENGINEER

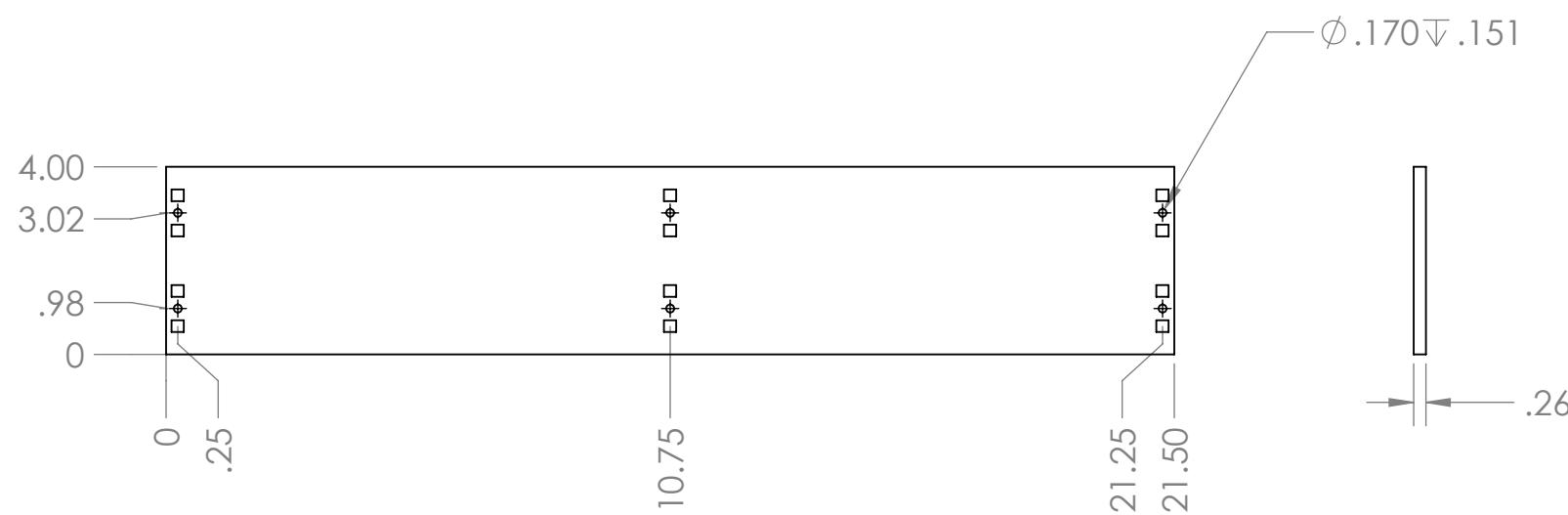
DATE

1:4  
MATERIAL WEIGHT SCALE REV.

FILE PATH

H:\ME\_450\Linear Book Scanner\Frame\

SIZE

**A**

REMOVE BURRS &amp; SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL:  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL:  $\pm 0.020"$   
THREE PLACE DECIMAL:  $\pm 0.005"$

**LOWER OUTFEED BACK RIB, FRAME**

DESCRIPTION

PART NO.

GROUP

SHAWN WRIGHT

DRAWN BY

DATE

ENGINEER

1:8

MATERIAL

WEIGHT

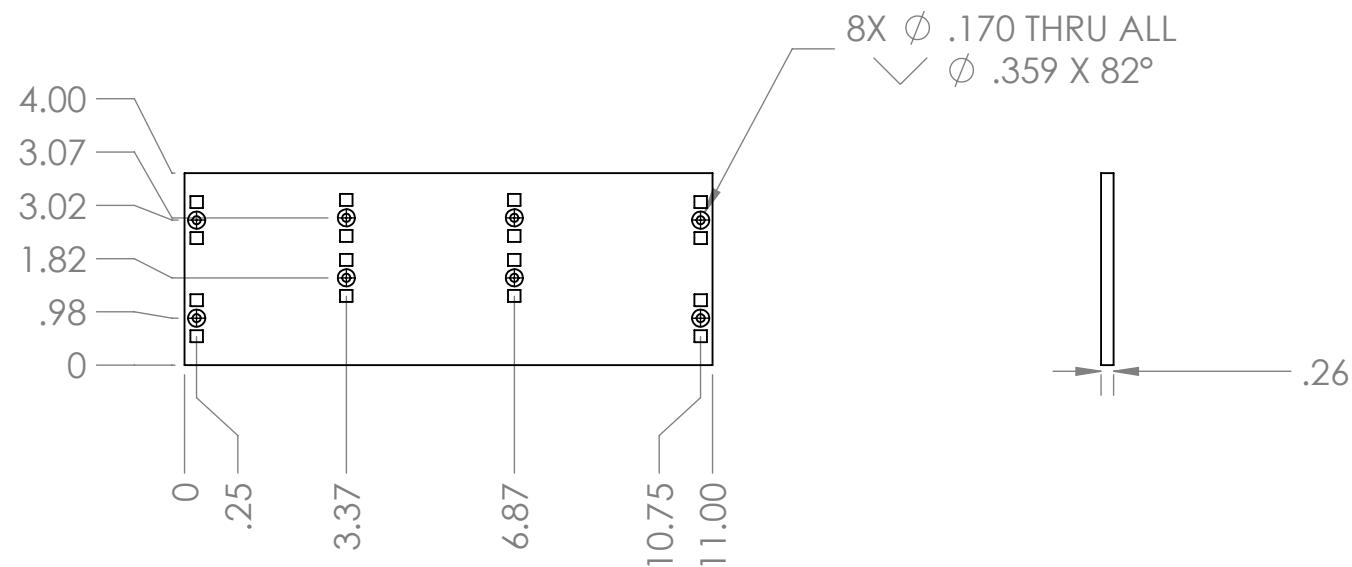
SCALE

REV.

H:\ME\_450\Linear Book Scanner\Frame\

FILE PATH

SIZE

**A**

REMOVE BURRS &amp; SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

**LOWER OUTFEED FRONT RIB, FRAME**

DESCRIPTION

PART NO.

GROUP

SHAWN WRIGHT

DRAWN BY

DATE

ENGINEER

1:4

MATERIAL WEIGHT

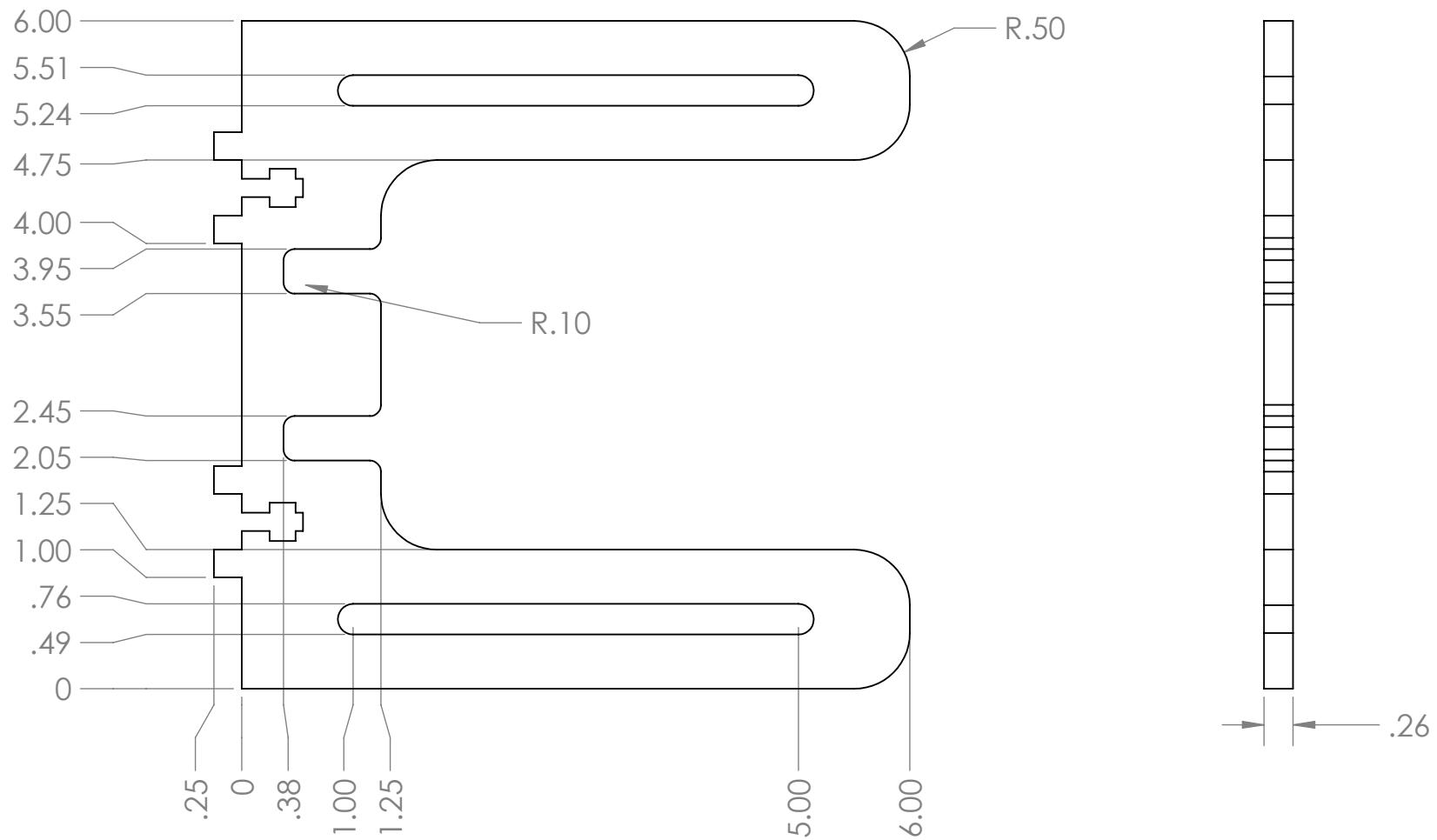
SCALE

REV.

H:\ME\_450\Linear Book Scanner\Frame\

FILE PATH

SIZE  
**A**



REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## LOWER PADDLE SLIDE, SADDLE

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

1:4

MATERIAL

WEIGHT

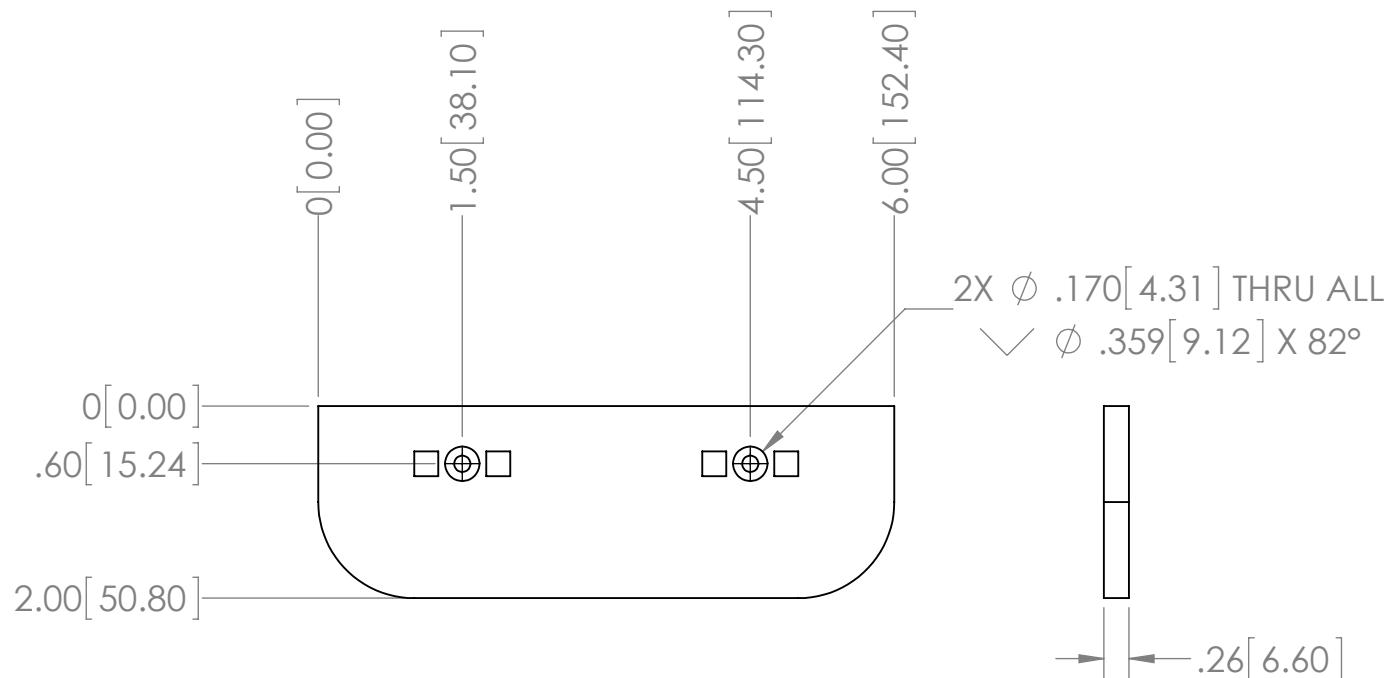
SCALE

REV.

H:\ME\_450\Linear Book Scanner\Saddle\

FILE PATH

SIZE  
**A**



REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## LOWER PADDLE, SADDLE

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

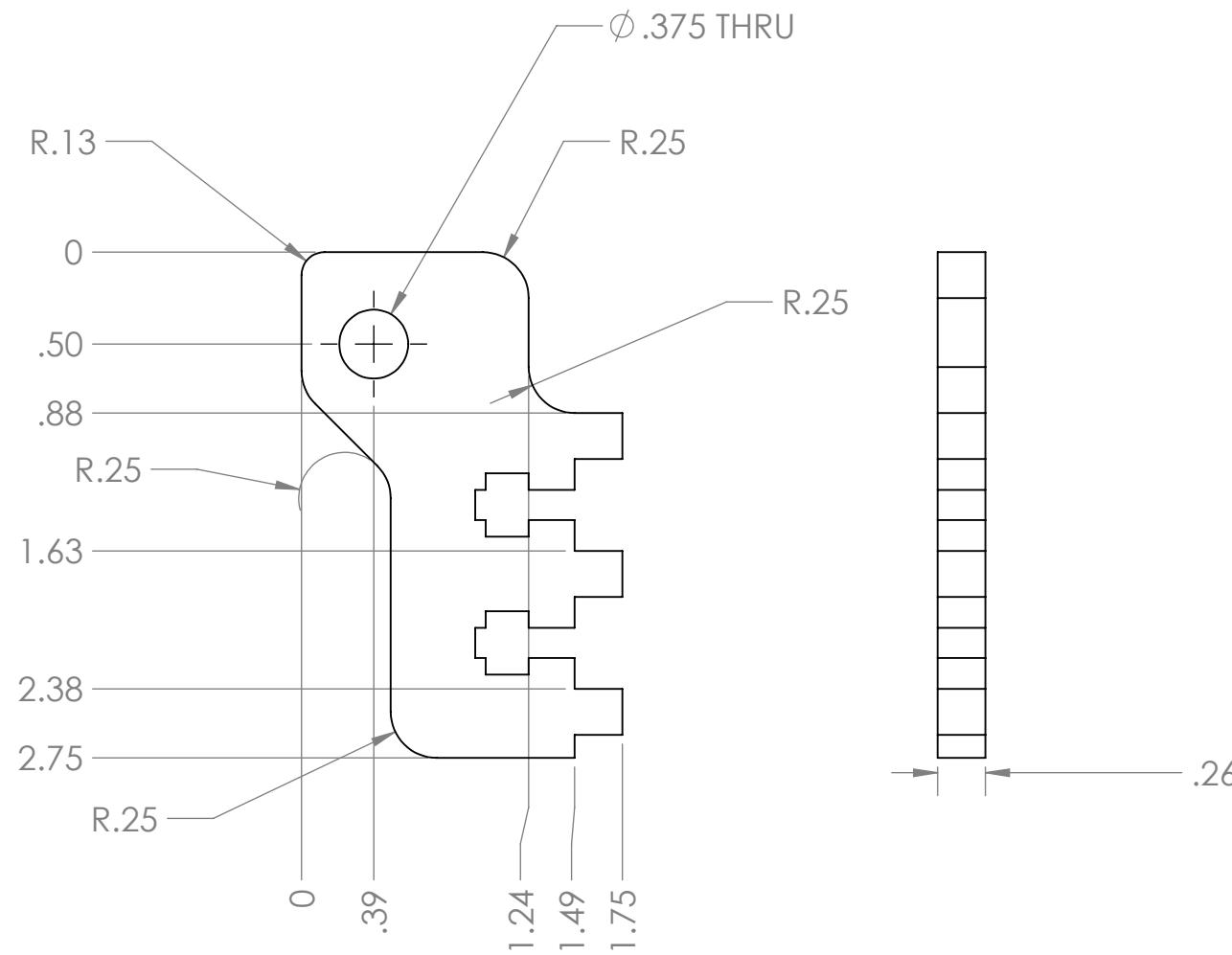
1:2

MATERIAL WEIGHT SCALE REV.

FILE PATH

H:\ME\_450\Linear Book Scanner\Saddle\

SIZE  
**A**



REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## MOUNT OFFSET, PULLY

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

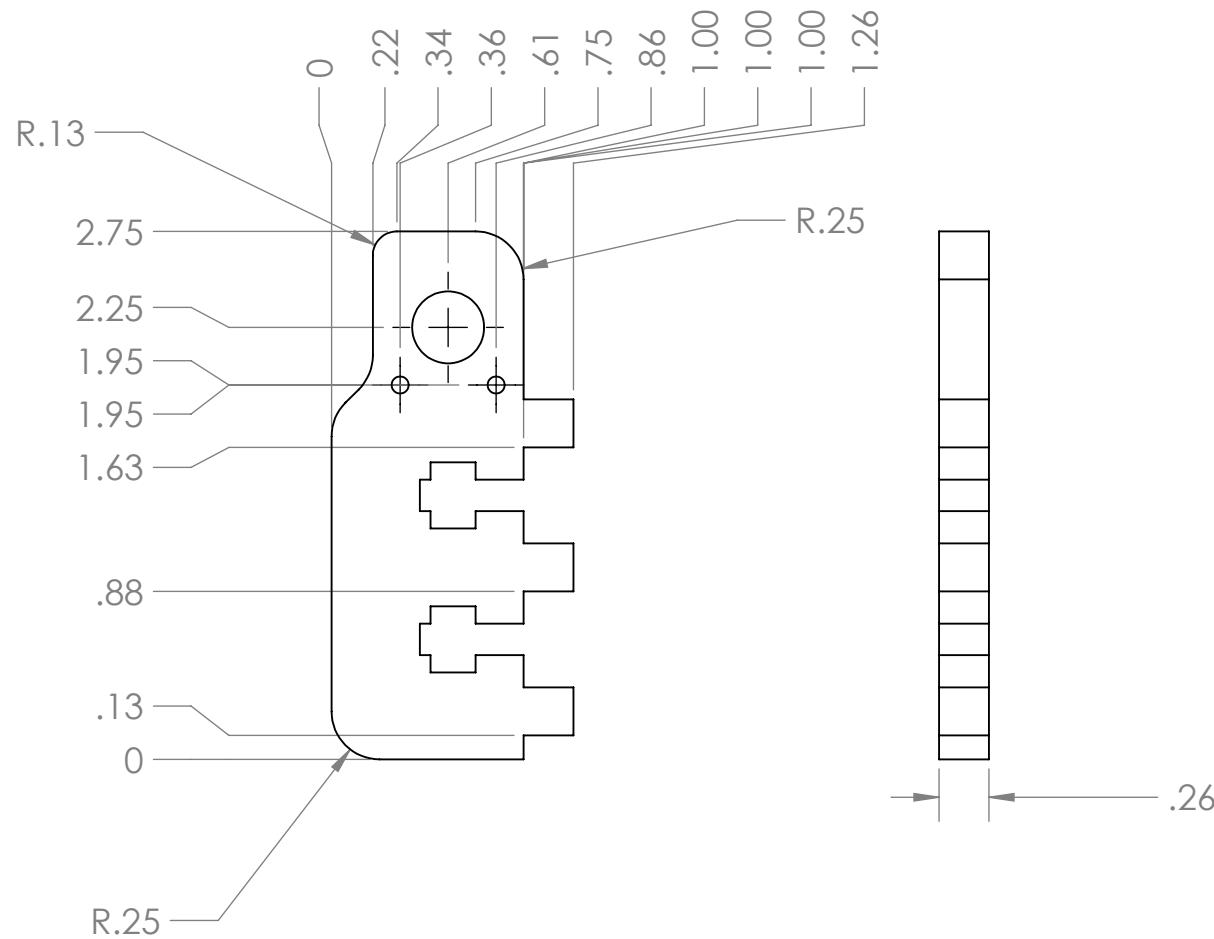
1:1

MATERIAL WEIGHT SCALE REV.

FILE PATH

H:\ME\_450\Linear Book Scanner\Pulleys\

SIZE

**A**

REMOVE BURRS &amp; SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

**MOUNT, PULLY**

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

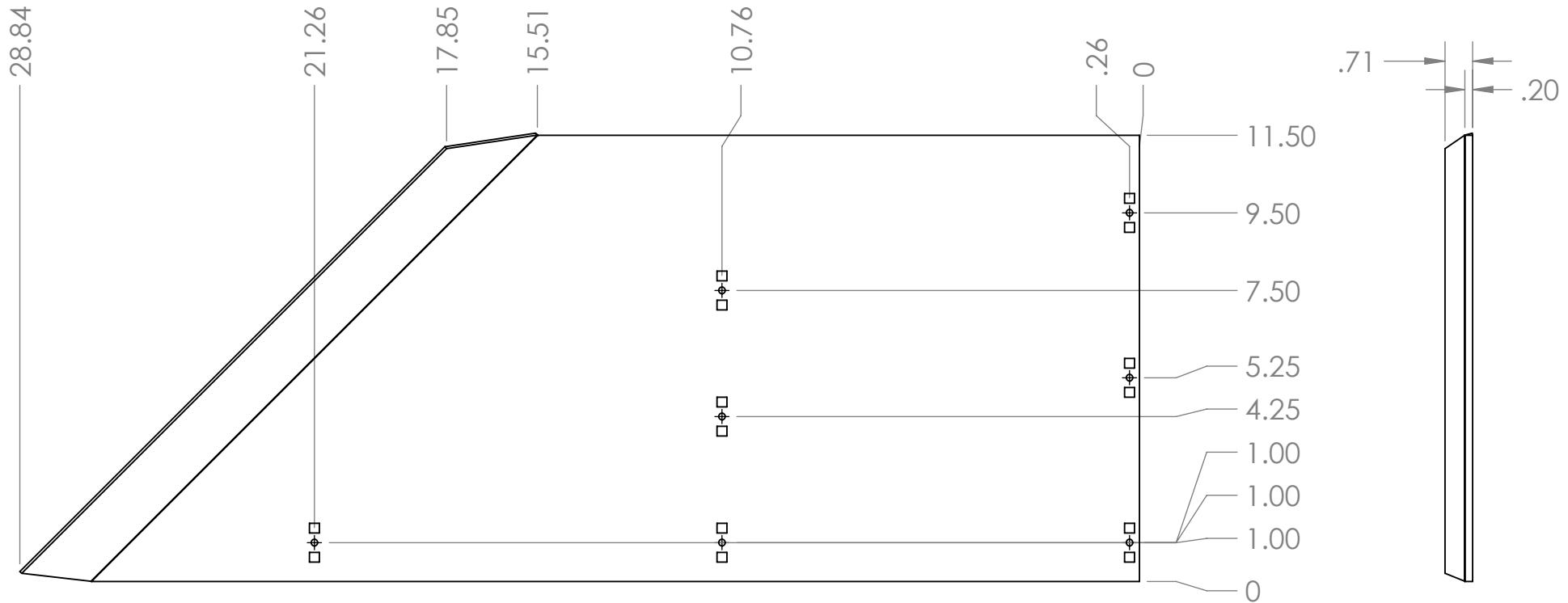
1:1 SCALE

MATERIAL WEIGHT REV.

FILE PATH

H:\ME\_450\Linear Book Scanner\Pulleys\

SIZE  
**A**



REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
FRACTIONAL  $\pm 1/32"$   
ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## OUTFEED BACK, SIDE

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

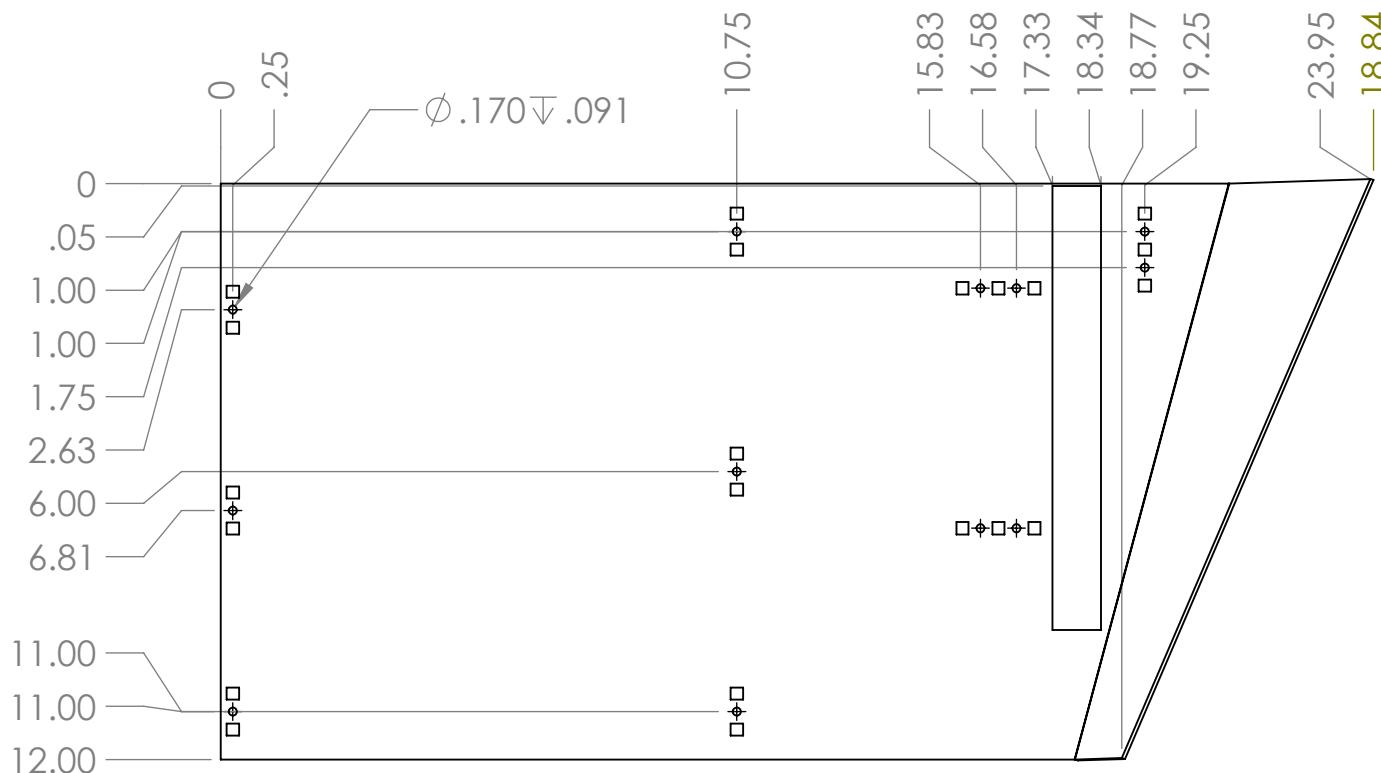
DATE

H:\ME\_450\Linear Book Scanner\Sides\

MATERIAL WEIGHT SCALE REV.

FILE PATH

SIZE

**A**

REMOVE BURRS &amp; SHARP EDGES

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DIMENSIONS ARE IN INCHES  
TOLERANCES:  
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ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

**OUTFEED FRONT, SIDE**

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

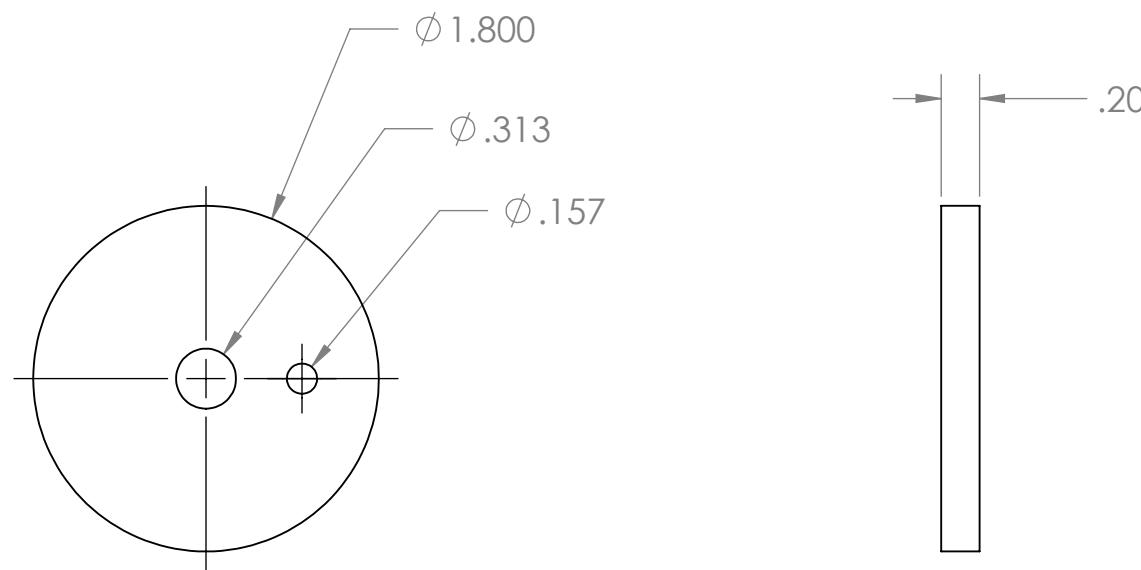
H:\ME\_450\Linear Book Scanner\Sides\

1:8

MATERIAL WEIGHT SCALE REV.

FILE PATH

SIZE  
**A**



REMOVE BURRS & SHARP EDGES

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ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## OUTSIDE TUBE CAP, VACUUM TUBE

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

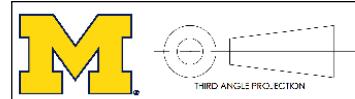
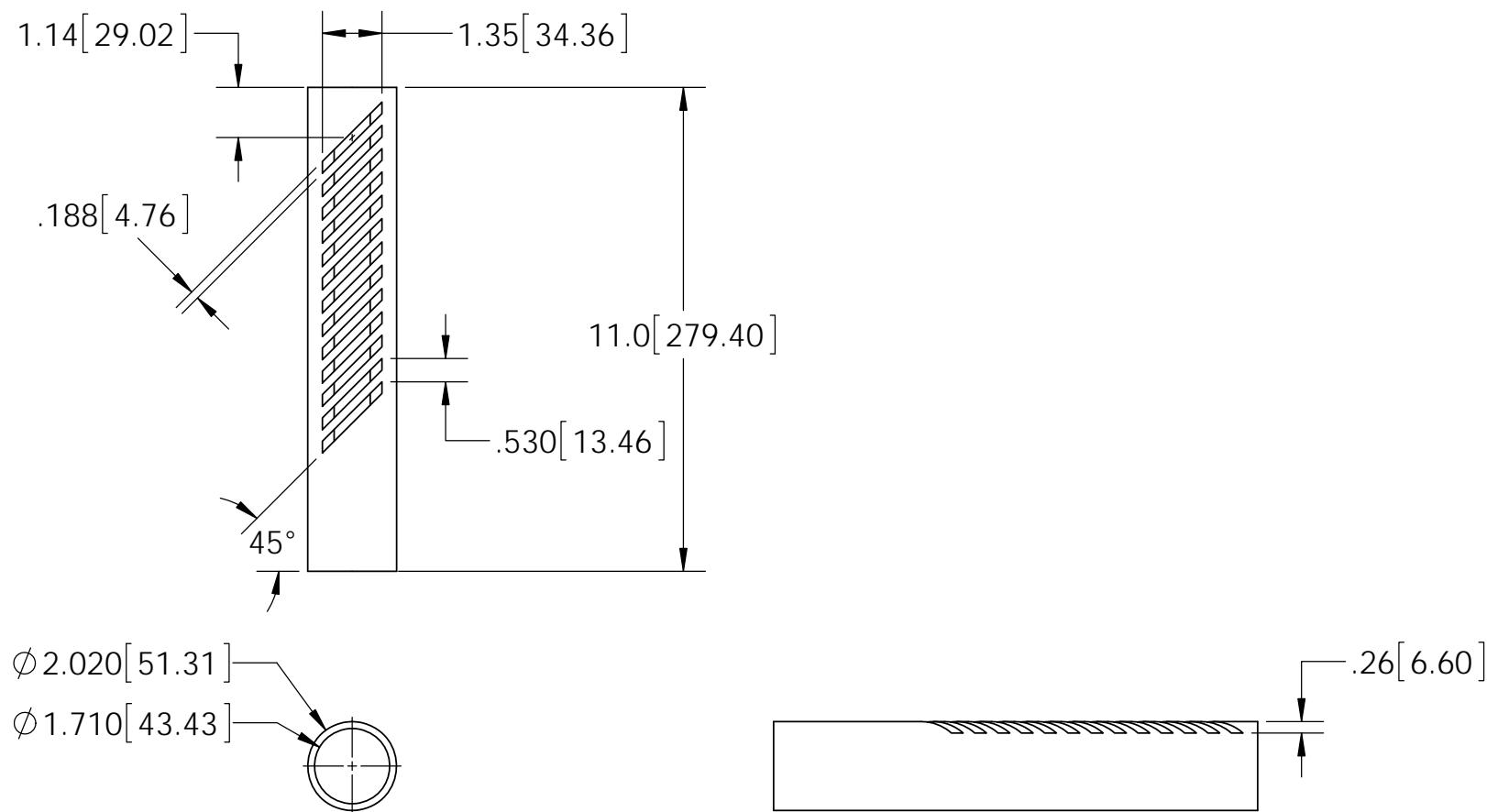
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1:1

MATERIAL WEIGHT SCALE REV.

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SIZE  
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ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

**OUTSIDE TUBE, VACUUM TUBE**

DESCRIPTION

PART NO.

LINEAR BOOK SCANNER

GROUP

ENGINEER

SHAWN WRIGHT

11/5/2013

DATE

DELRIN

MATERIAL

1:4

SCALE

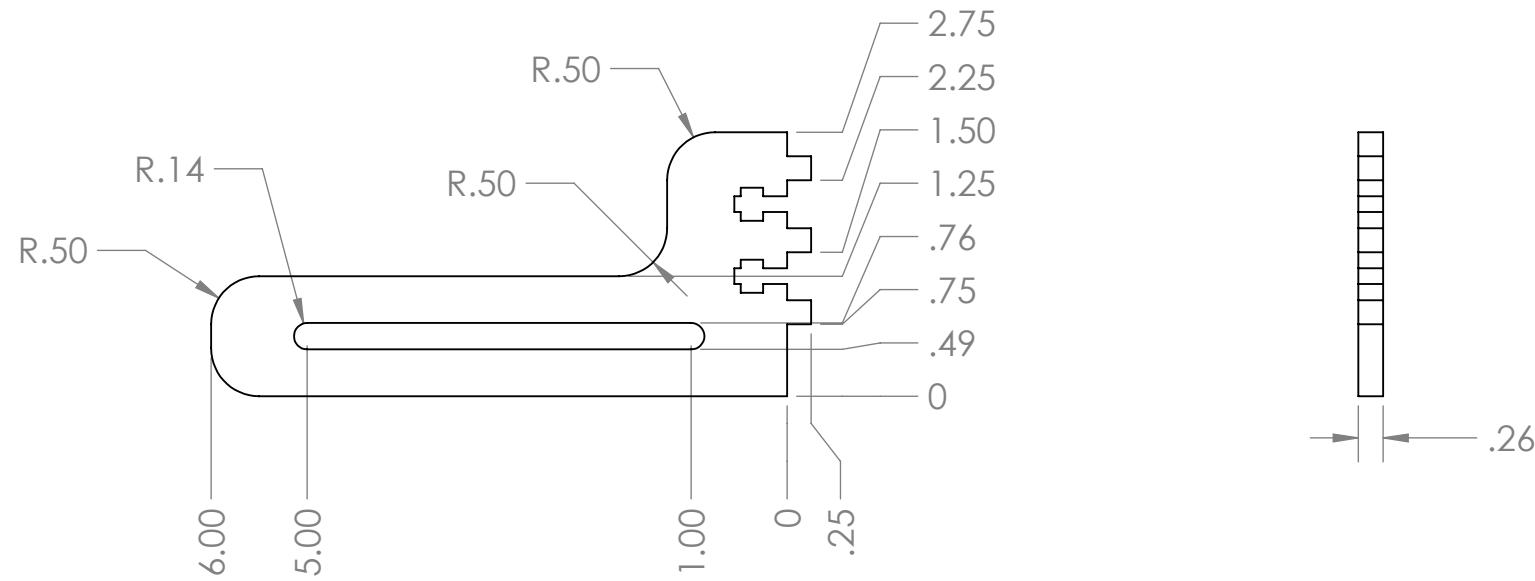
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FILE PATH

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SIZE

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REMOVE BURRS &amp; SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
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ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

**PADDLE SLIDE, SADDLE**

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

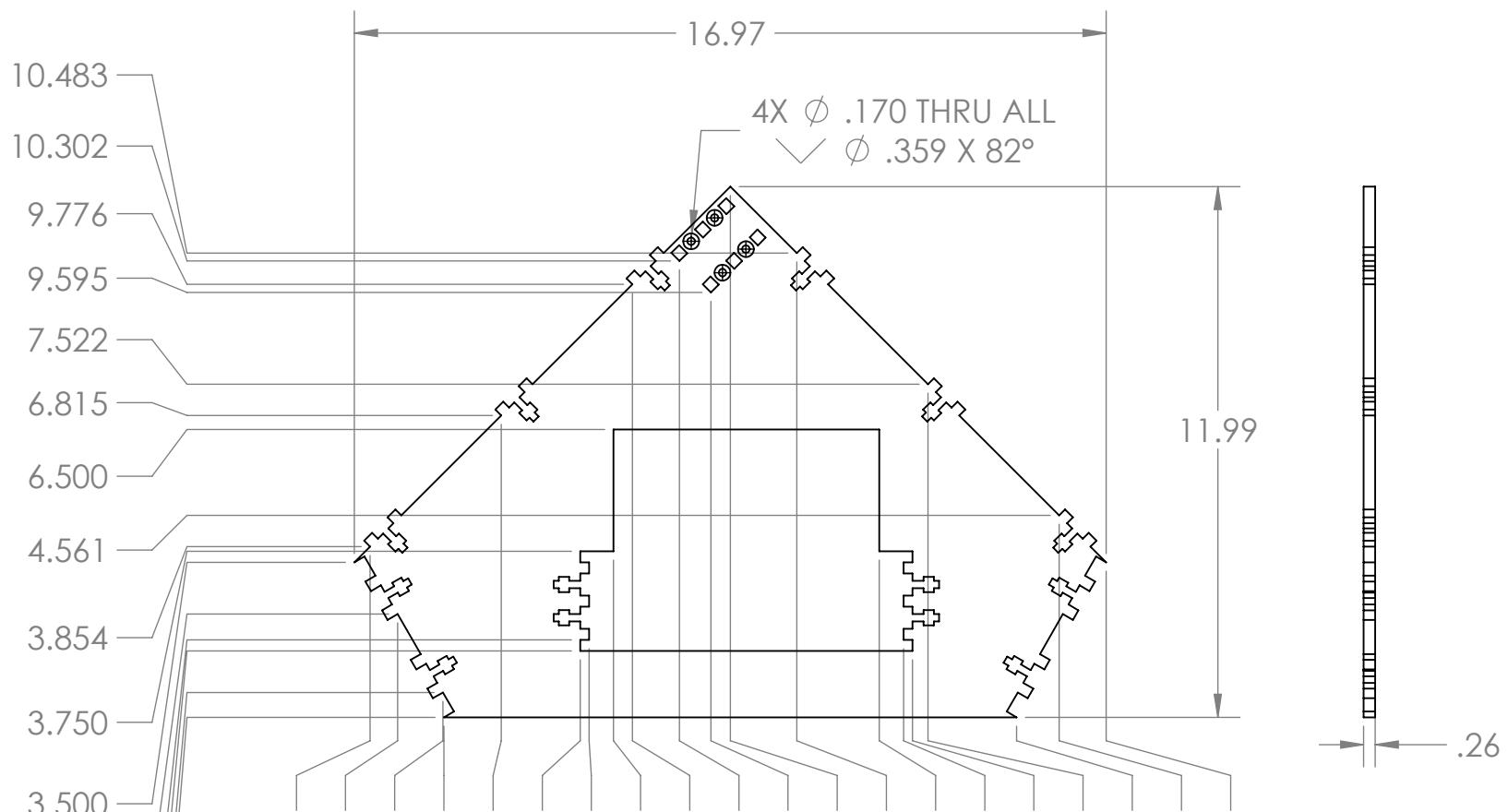
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1:2 SCALE

MATERIAL WEIGHT REV.

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ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
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THREE PLACE DECIMAL  $\pm 0.005"$

**RIB 1, FRAME**

DESCRIPTION

PART NO.

GROUP

SHAWN WRIGHT

12/11/2013 DATE

ENGINEER

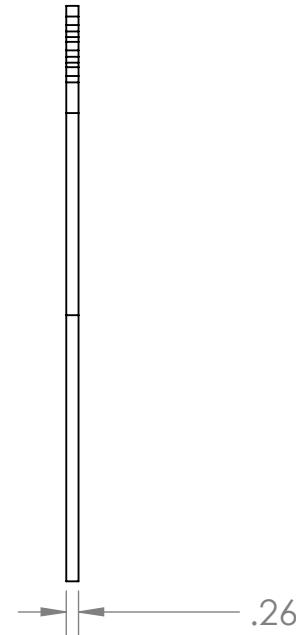
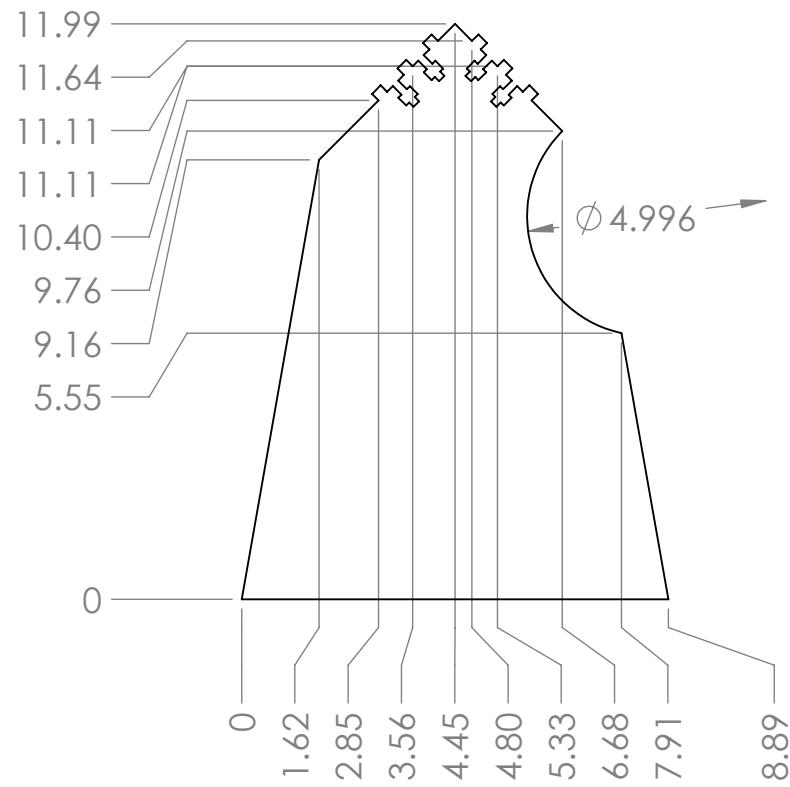
1:4 MATERIAL WEIGHT SCALE REV.

ACRYLIC

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TWO PLACE DECIMAL:  $\pm 0.020"$   
THREE PLACE DECIMAL:  $\pm 0.005"$

**RIB 3, FRAME**

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

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MATERIAL

WEIGHT

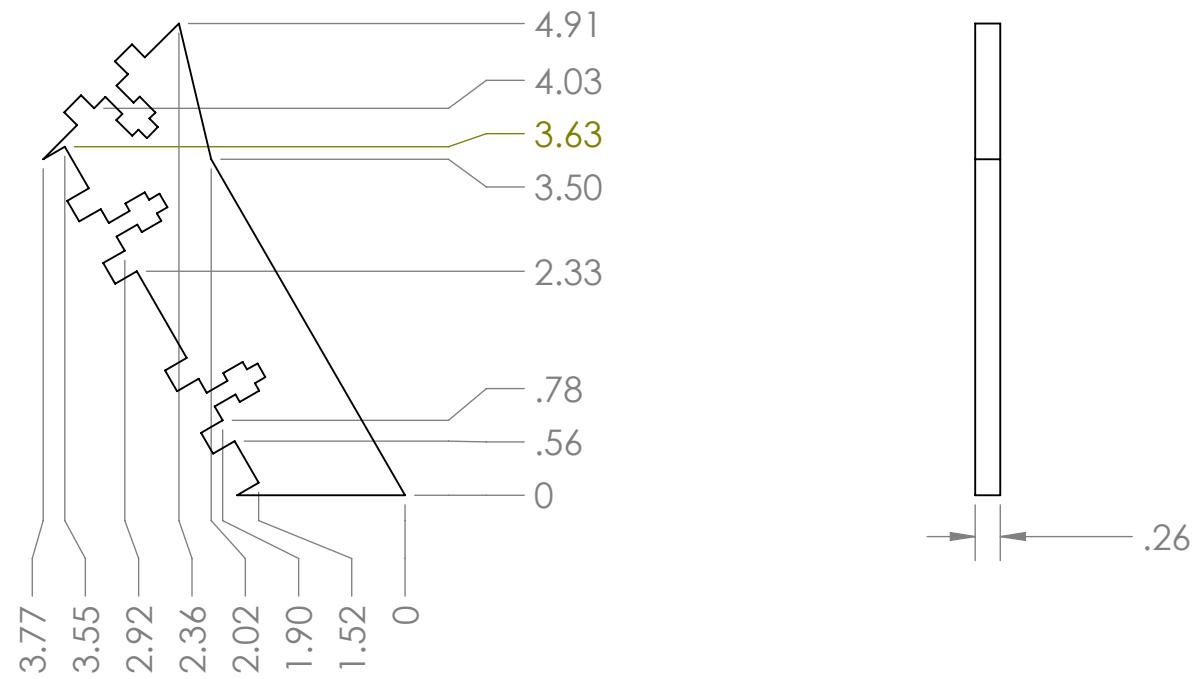
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**A**

REMOVE BURRS &amp; SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
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THREE PLACE DECIMAL  $\pm 0.005"$

## RIB 4 OUTFEED, FRAME

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

1:2

MATERIAL

WEIGHT

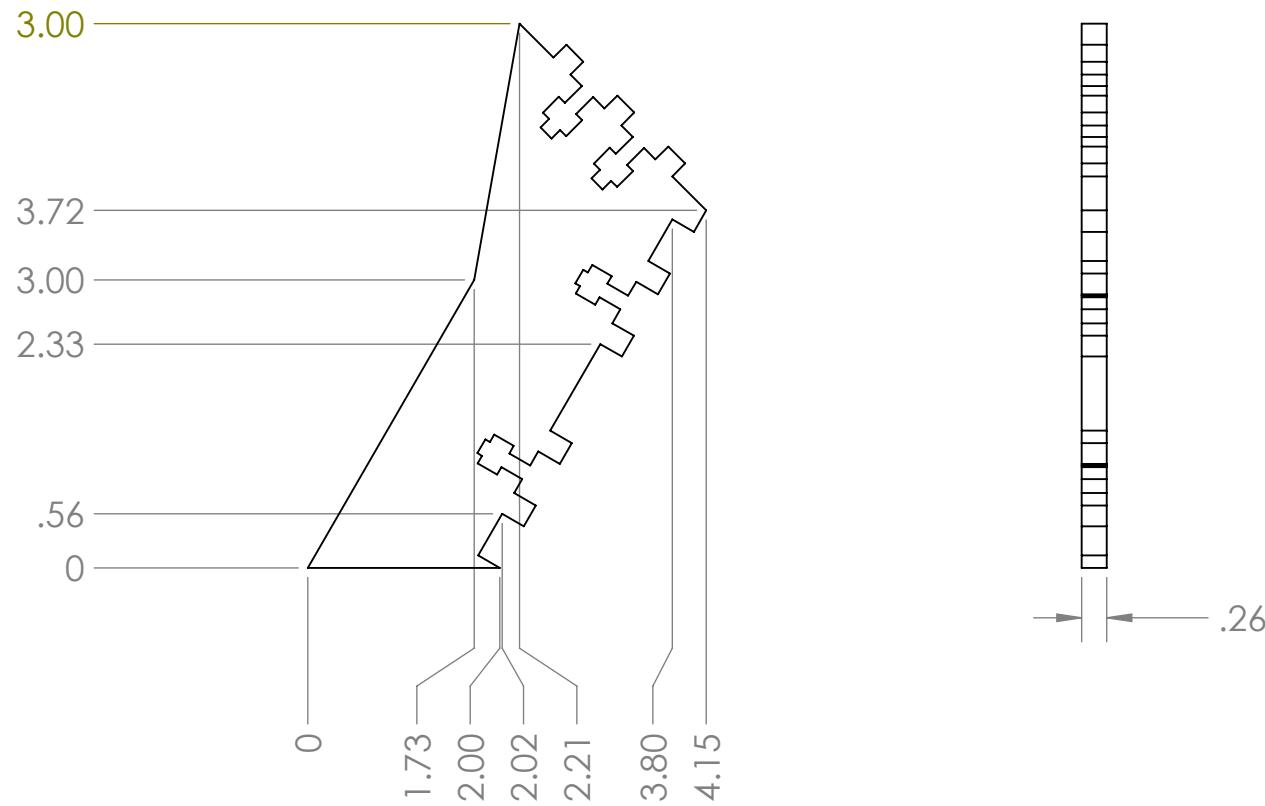
SCALE

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REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
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TOLERANCES:  
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TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## RIB 4, FRAME

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

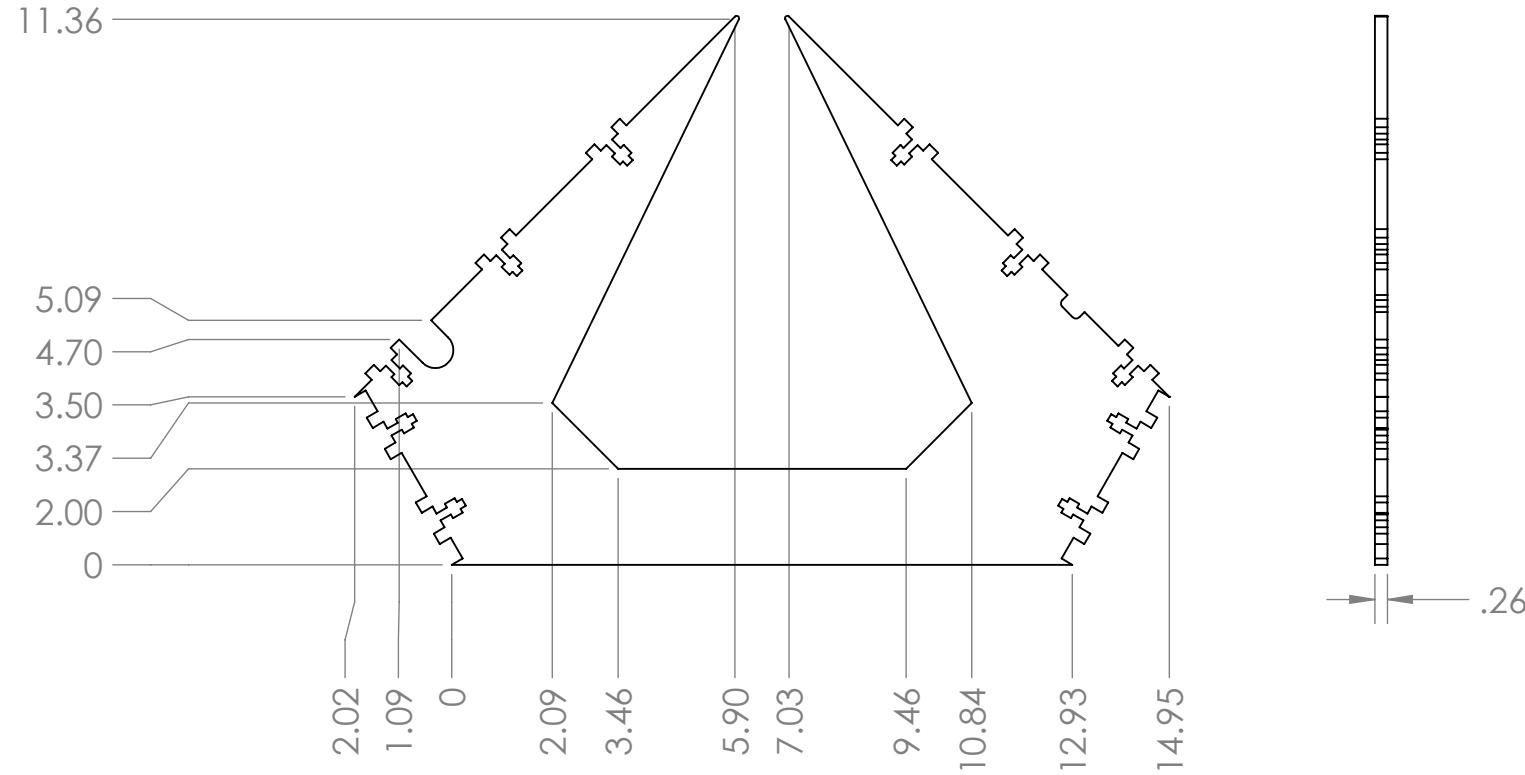
1:2 SCALE

MATERIAL WEIGHT REV.

FILE PATH

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SIZE  
**A**



REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
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TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## RIB 5, FRAME

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

MATERIAL

WEIGHT

SCALE

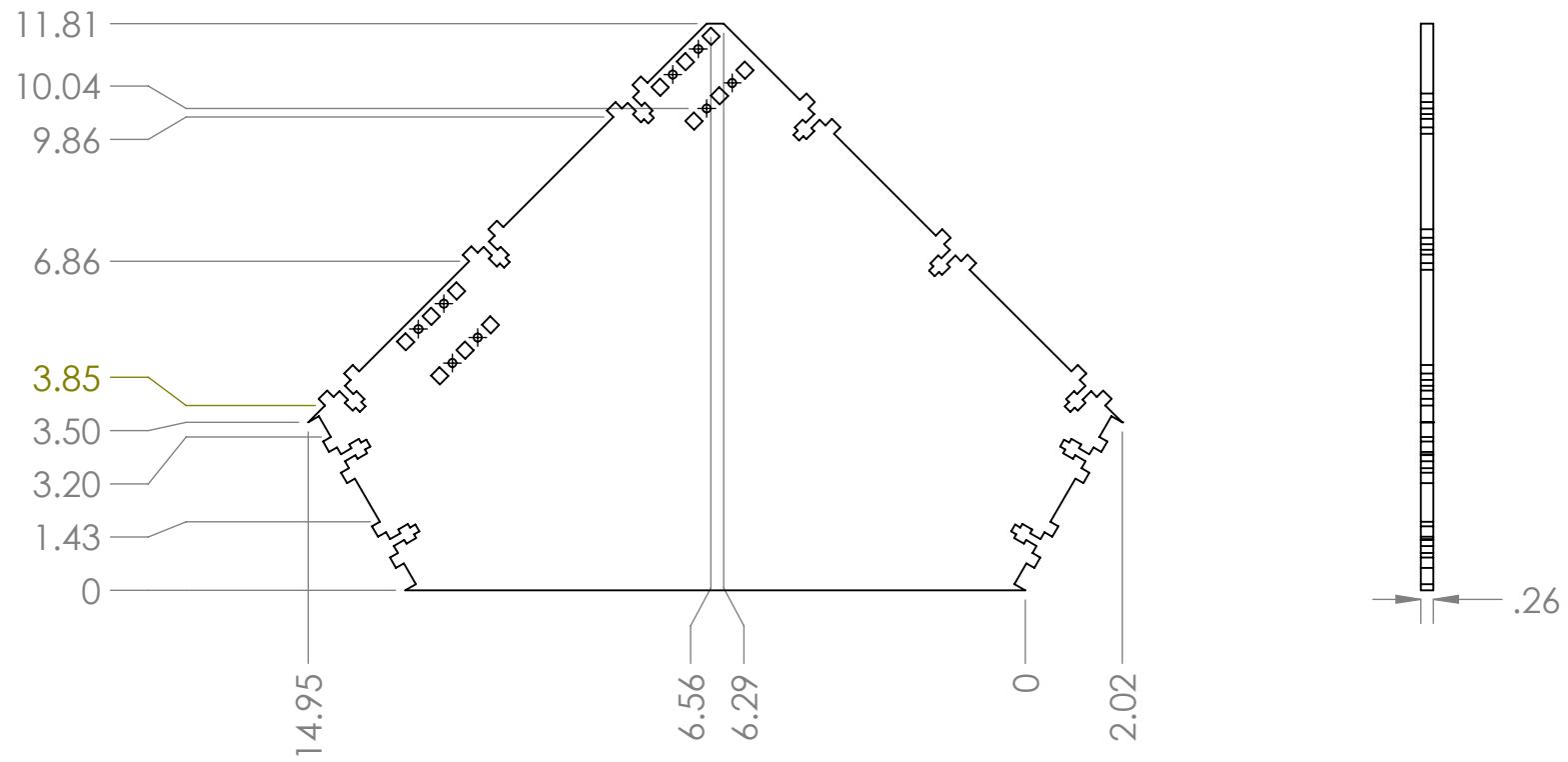
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FILE PATH

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SIZE  
**A**



REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
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ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## RIB 6, FRAME

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

MATERIAL

WEIGHT

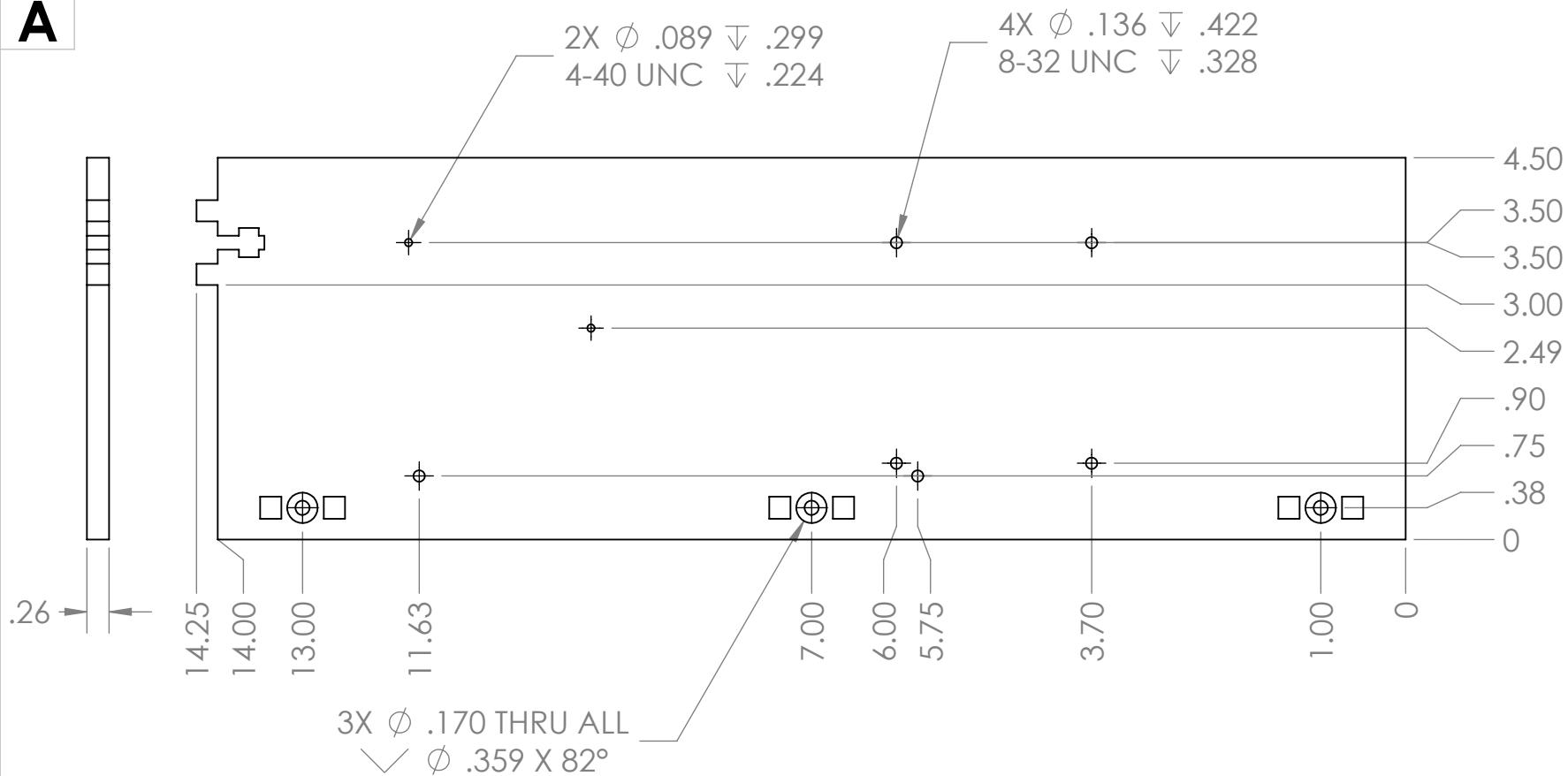
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FILE PATH

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REMOVE BURRS &amp; SHARP EDGES

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TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

**SIDE INFEED, ELECTRONICS SLIDE**

DESCRIPTION

PART NO.

GROUP

SHAWN WRIGHT

DRAWN BY

DATE

ENGINEER

1:8

MATERIAL

WEIGHT

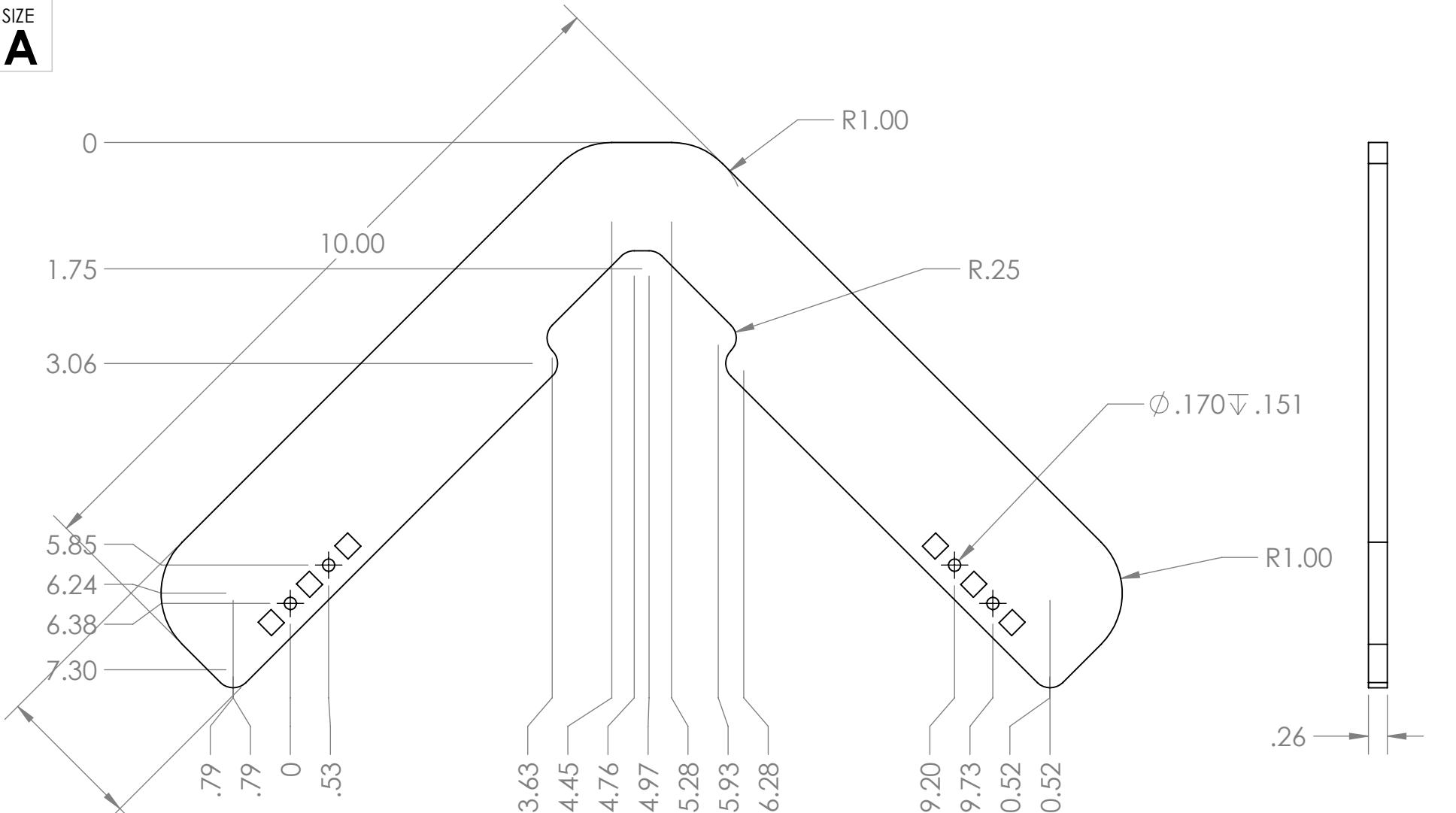
SCALE

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REMOVE BURRS & SHARP EDGES

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ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL:  $\pm 0.020"$   
THREE PLACE DECIMAL:  $\pm 0.005"$

## SIDE PADDLE, SADDLE

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

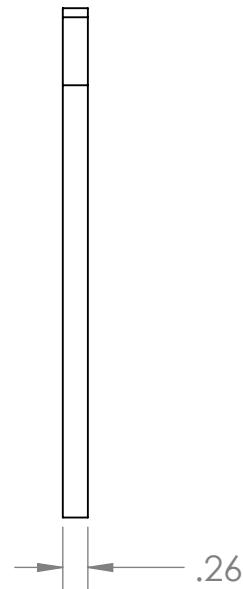
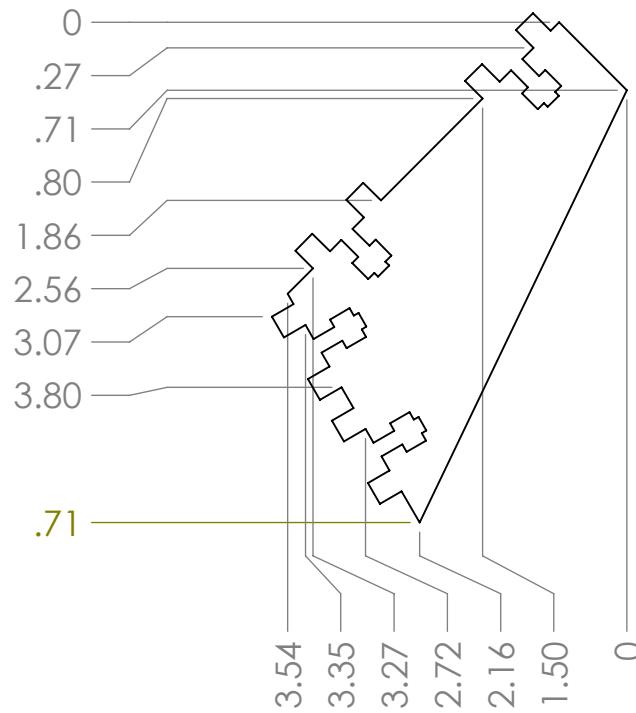
1:4 SCALE

MATERIAL WEIGHT REV.

FILE PATH

H:\ME\_450\Linear Book Scanner\Saddle\

SIZE

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REMOVE BURRS &amp; SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
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ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## SIDE, MOTOR MOUNT

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

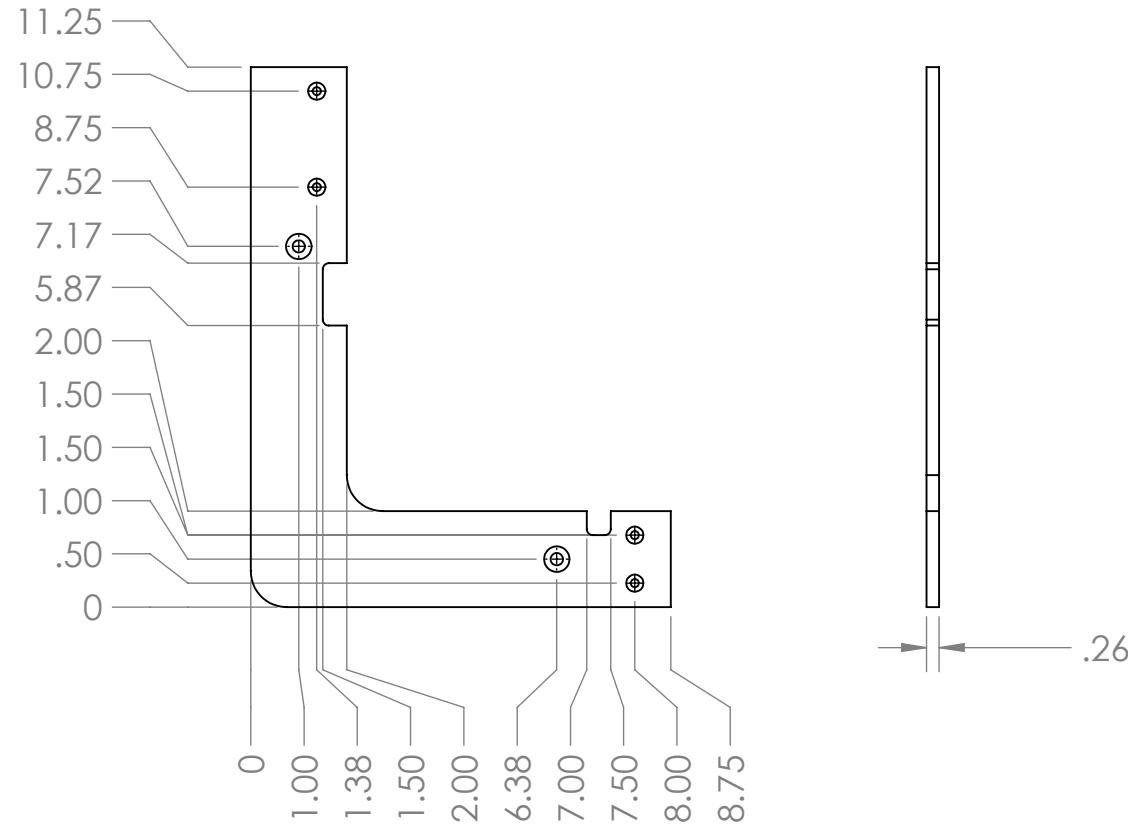
1:2

MATERIAL WEIGHT SCALE REV.

H:\ME\_450\Linear Book Scanner\Motor Mount\

FILE PATH

SIZE  
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REMOVE BURRS & SHARP EDGES

UNLESS OTHERWISE SPECIFIED:  
DIMENSIONS ARE IN INCHES  
TOLERANCES:  
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ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL  $\pm 0.020"$   
THREE PLACE DECIMAL  $\pm 0.005"$

## SIDE\_2, SADDLE

DESCRIPTION

PART NO.

GROUP

ENGINEER

SHAWN WRIGHT

DRAWN BY

DATE

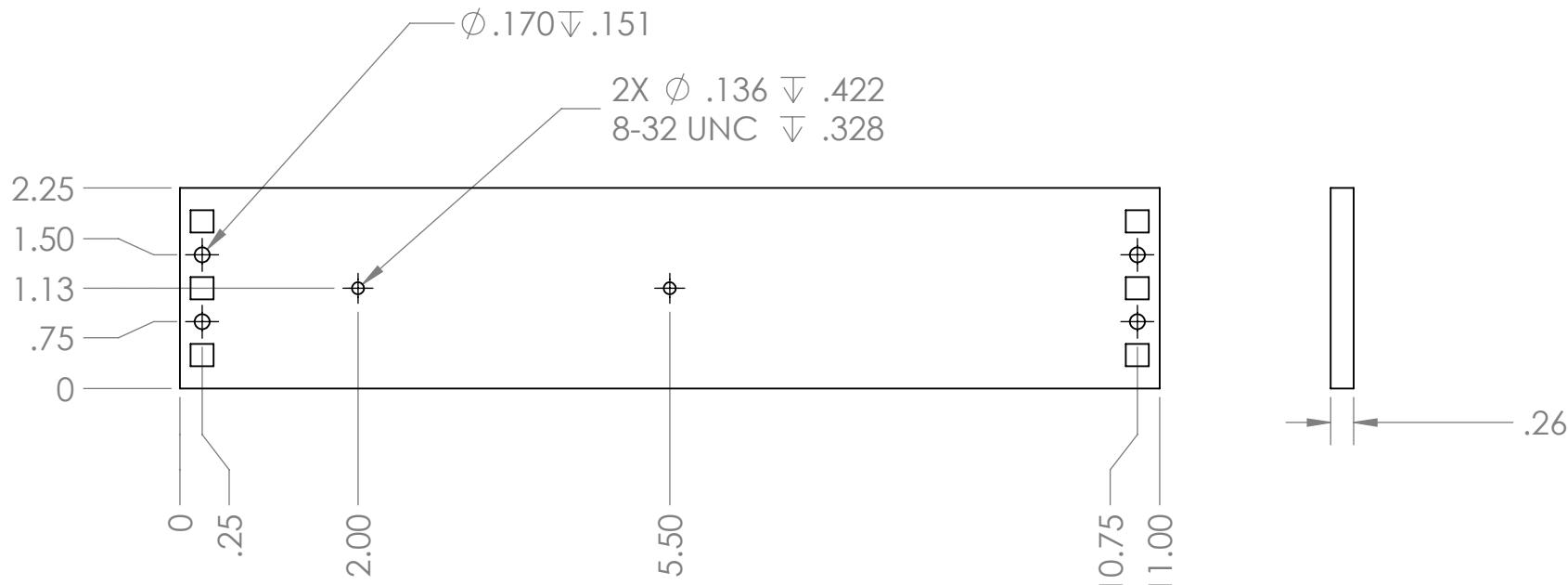
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MATERIAL WEIGHT SCALE REV.

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REMOVE BURRS & SHARP EDGES

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DIMENSIONS ARE IN INCHES  
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ANGULAR: MACH  $\pm 2^\circ$  BEND:  $\pm 1/16"$   
TWO PLACE DECIMAL:  $\pm 0.020"$   
THREE PLACE DECIMAL:  $\pm 0.005"$

## SLIDE MOUNT INFEED, ELECTRONICS SLIDE

DESCRIPTION

PART NO.

GROUP

SHAWN WRIGHT

DRAWN BY

DATE

ENGINEER

1:4 SCALE

MATERIAL

WEIGHT

REV.

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FILE PATH

## APPENDIX B

### Changes made past DR3

**Outfeed plate geometry:** The most challenging design feature after DR3 has been the shape of the outfeed plate. The infeed and vacuum tube is fairly consistent at pulling a page into the page channel, but the page consistently gets snagged on edges on the outfeed plate. Ideally, the page channel could be injection molded into smooth surfaces that guide the page clear of any edges that can catch the page. Unfortunately, given to the money and resources at our disposal, this was impossible. With laser cutting, we were able to create small horn features to attach to the outfeed plate and bend the plate to more smoothly engage the page.

More specifically, we bent the Delrin outfeed plate an additional 30 degrees along the dashed line marked “Old Bend” and an additional 25 degrees along “New Bend” as shown in Figure B1. This change was suitable in engaging the paper more consistently. Then we needed to redirect the paper edge away from any corners or edges of the Delrin plate on its way out of the page channel. Through trial and error, we found that additional smaller attachments were needed to alter the path of the page to avoid the paper folding onto itself as it exists the outfeed, as shown in Figure B2.

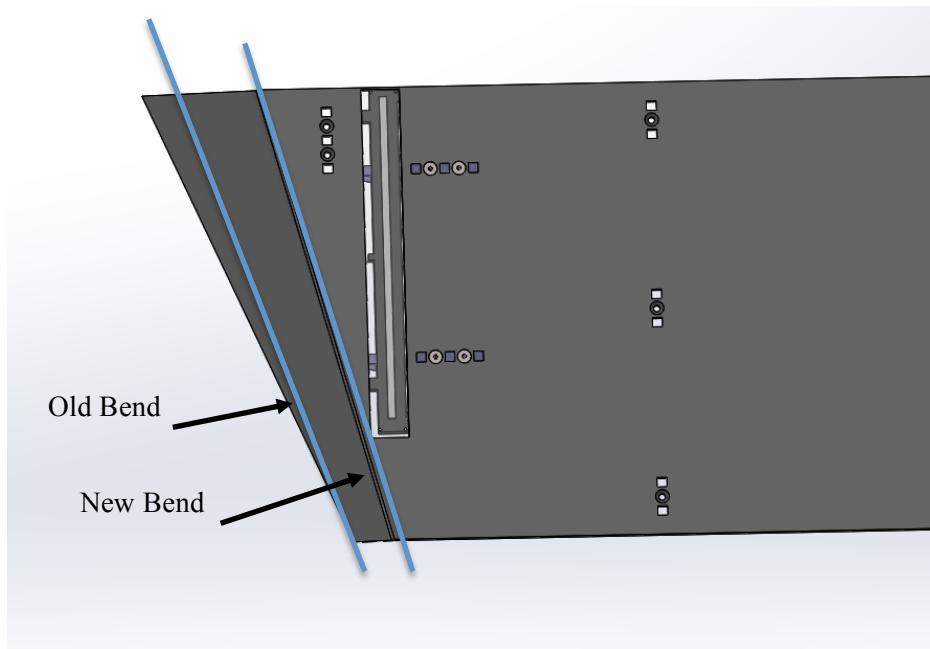


Figure B1: Diagram of outfeed plate bends.

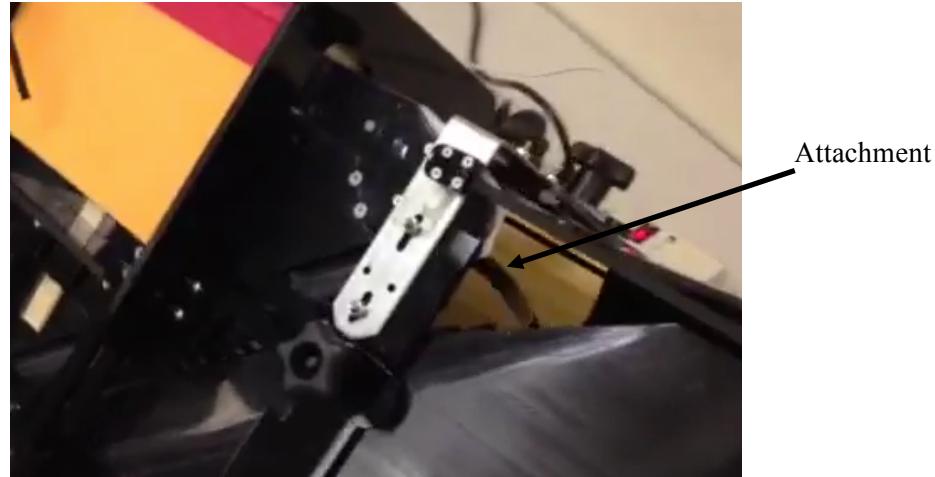


Figure B2: Outfeed geometry attachments.

**Middle rib position:** In order to accommodate the larger bent portion of the outfeed plate, we were forced to reposition the middle rib from its original position to its new position 2.5 inches towards the scanner bars, as shown in Figure B3 by the two sets of rib mounting holes. There were no improvements due just to this change; it is just a byproduct of the previous design change.

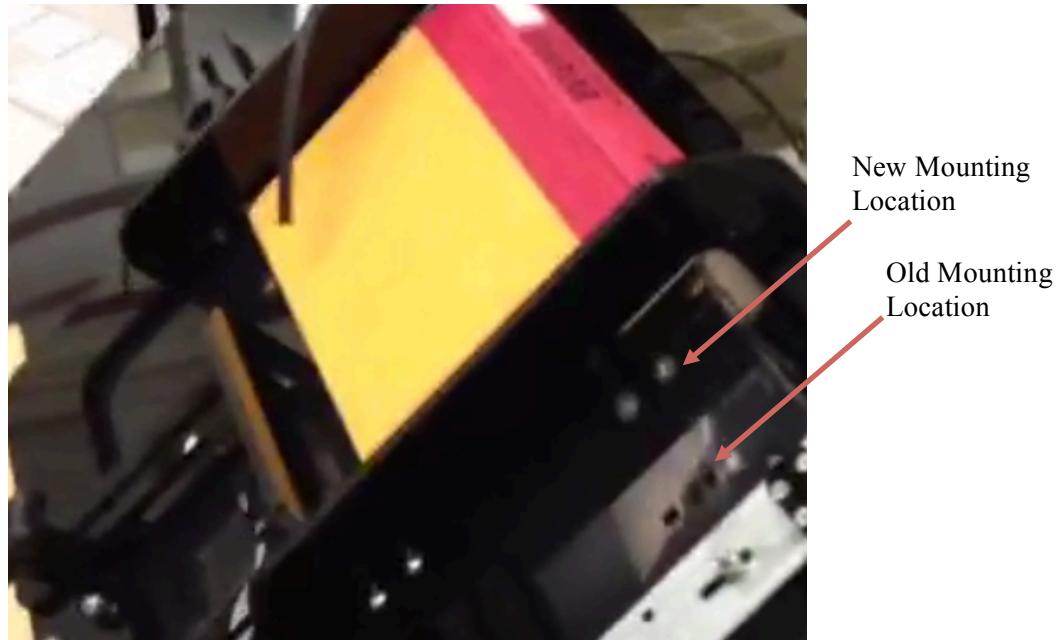


Figure B3: Linear Book Scanner showing change of middle rib position.

**RFID Shielding with Aluminum Foil:** After wiring all of the electronics, we discovered a glitch that happens at random moments during testing. The automatic control stalls occasionally for no explicable reason. Finally, we used aluminum foil to wrap the motor driver and Raspberry Pi, creating a primitive shield for unknown interference that might be causing the noise. We recommend moving the motor driver away from any computers and possibly in its own enclosure in the future.

## APPENDIX C

A major component of our Linear Book Scanner prototype that we choose to analyze are the ribs that will be supporting our prototype. The main function of the ribs are to support both the infeed and outfeed panel as the saddle and the book traverse across it. The ribs have a number of objectives which include: supporting the book and saddle weight, minimizing deflection, lightweight, and low cost (price). We had a couple of constraints for our rib pieces as well.

First, to properly support the weight of the saddle assembly and minimize deflection, we wanted a material with a high young's modulus (E). For our calculations in Eq. C1, we assumed there would be a 10 pound force, length of 8 inches from applied force and corner, a base of 48", and width of 17". We initially said that we wouldn't want our design to deform more than 1mm or 0.001m, due to the weight of the assembly.

$$\delta = \frac{FL^3}{3EI} \quad \text{Eq. C1}$$

In order to achieve our engineering specification of having the prototype weighing around 20 pounds, we ideally wanted a material which possess a density that is low enough that it would not affect much of weight of the prototype as well having a Young's Modulus that is high enough so that it could properly support the weight of the saddle and the book without much deflection. Using Eq. C2, we determined we needed a minimum young's modulus of 0.52 GPa, or  $7.54 * 10^4$  psi. We then assumed that the electronics portion of our design will weigh 5 pound which in turns limit the structural part of our prototype to weigh around 15 pounds or less. We estimated the volume of prototype by calculating the volume of all the pieces that we would need for the assembly of our prototype. For calculations, we had 4 pieces of material at a thickness of 0.25".

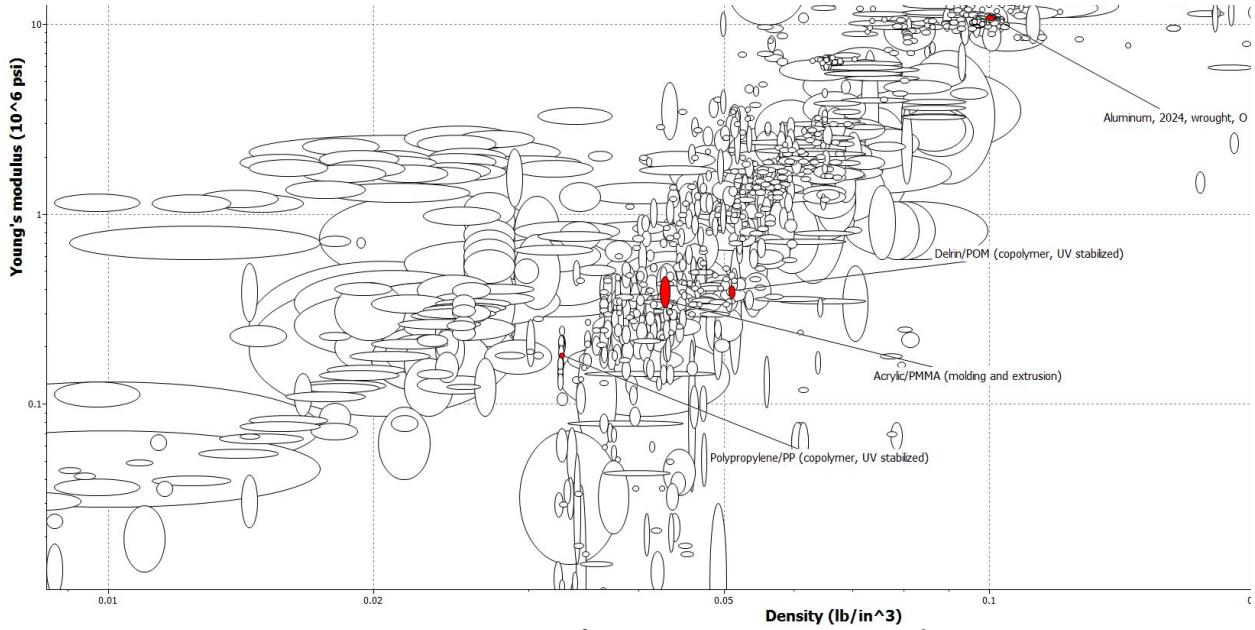
$$\text{Volume (in}^3\text{)} = 12'' \times 48'' \times (\text{number of pieces}) \times (\text{thickness}) \quad \text{Eq. C2}$$

$$\text{Density (pounds/in}^3\text{)} = \text{Mass (pounds)} * \text{Volume (in}^3\text{)} \quad \text{Eq. C3}$$

Using Eq. C3 we were able to calculate the total volume of our prototype at 576 in<sup>3</sup>. To determine the ideal range of density our chosen material should has, we divided 15 pounds by the volume that we calculated. The density we determined was 0.026 (pounds/in<sup>3</sup>). A safety factor of 2 is then included in order to compensate for additional parts that we may have to add to our prototype. Thus we are able to come up with a constraint for the density of the material choice at a value of less than 0.052 (pounds/in<sup>3</sup>).

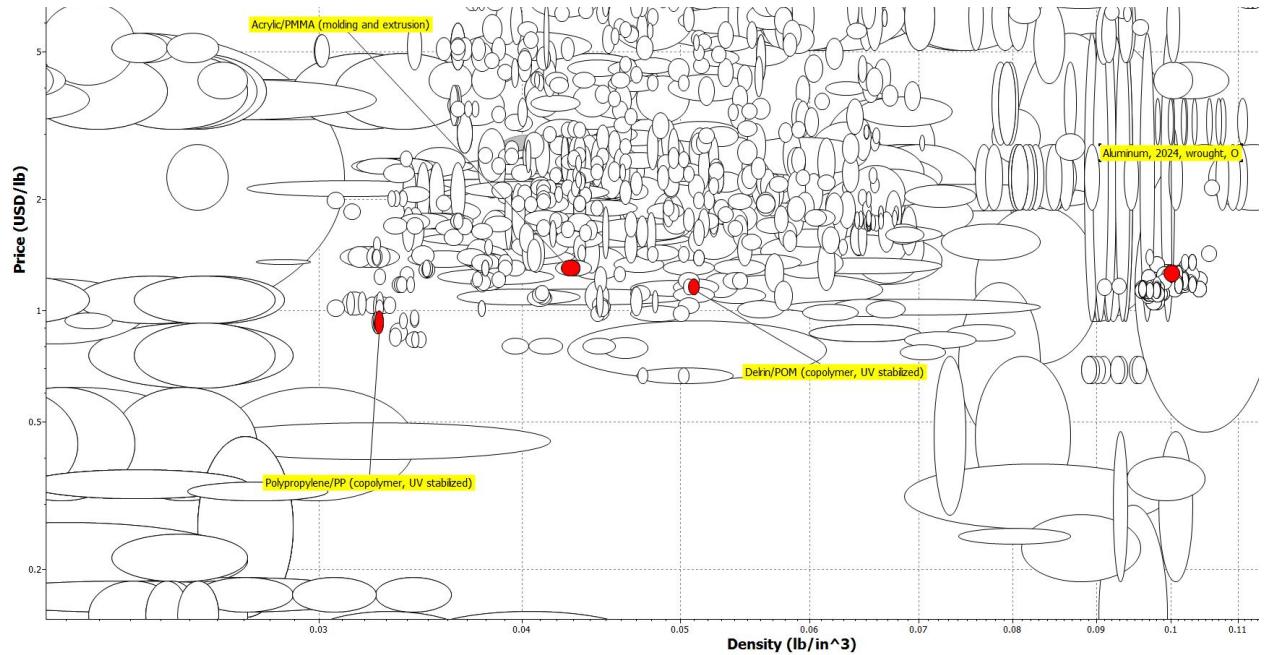
Lastly we didn't have a "hard" constraint on our price since we were still evaluating the parts we would need for our design. Our last constraint was to minimize the cost of the material we chose.

Our top four material choices that we identified to use for our inner ribs were acrylic, Delrin, aluminum, and polypropylene. We choose to analyze aluminum because our project sponsor used that material and it could be helpful since we know how it performs already. We also identified Delrin as a possible material since we already had identified it as the material we would be using for the outer faces of the design. Delrin was chosen for these faces due to its low coefficient of friction and its ability to be laser cut.



**Figure C1: Density ( $\text{lb/in}^3$ ) vs. Young's Modulus ( $10^6 \text{ psi}$ ).**

We were first able to eliminate the aluminum from of material considerations. As shown on graph number C1, it had a density greater than our constraint, and therefore was eliminated from consideration. All three of the other materials passed our young's modulus constraint, so we have to evaluate how we would manufacture the design. Due to the fact that polypropylene could not be laser cut using the available laser-cutting machine, and the fact that around 97% of the assembly of our prototype will be done using laser cutter, we also had to eliminate polypropylene from consideration. Lastly, both acrylic and Delrin satisfied our density and young's modulus constraints. Thus we then tried to evaluate them based on price.

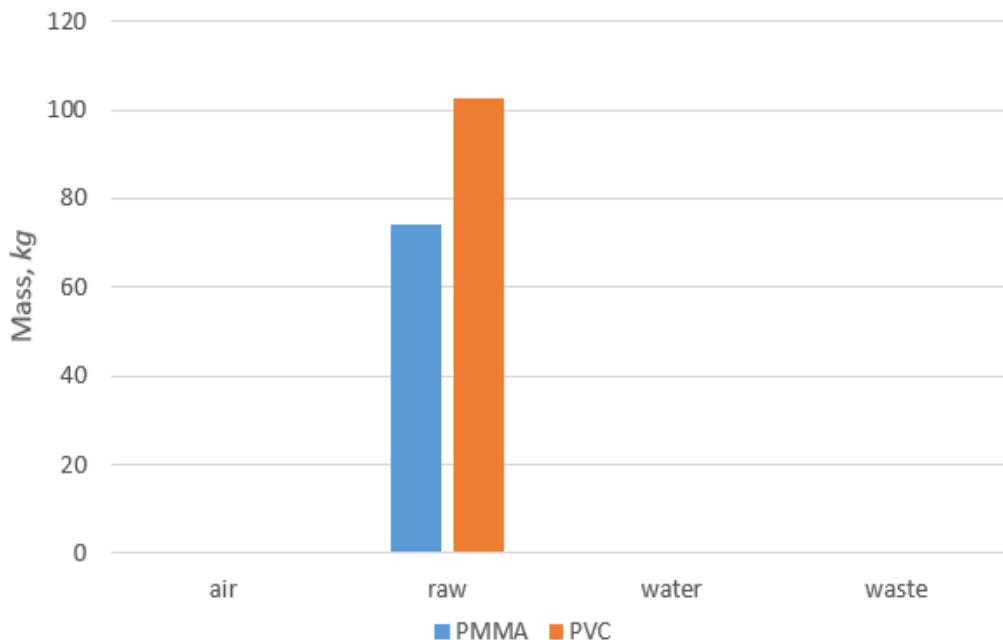


**Figure C2: Density ( $\text{lb/in}^3$ ) vs. Price ( $\text{USD/lb}$ ).**

While Figure C2 illustrates how the acrylic is more expensive than the Delrin, as we checked the price of both acrylic and Delrin through McMaster-Carr online, the acrylic was \$37.60 and the Delrin was \$89.45 for a sheet with a dimension of 48"x12"x1/4". Therefore, to minimize the cost of the prototype without trading off much of its performance and functionality, we decided to use acrylic for our inner ribs of the design and Delrin as both the infeed and outfeed panels.

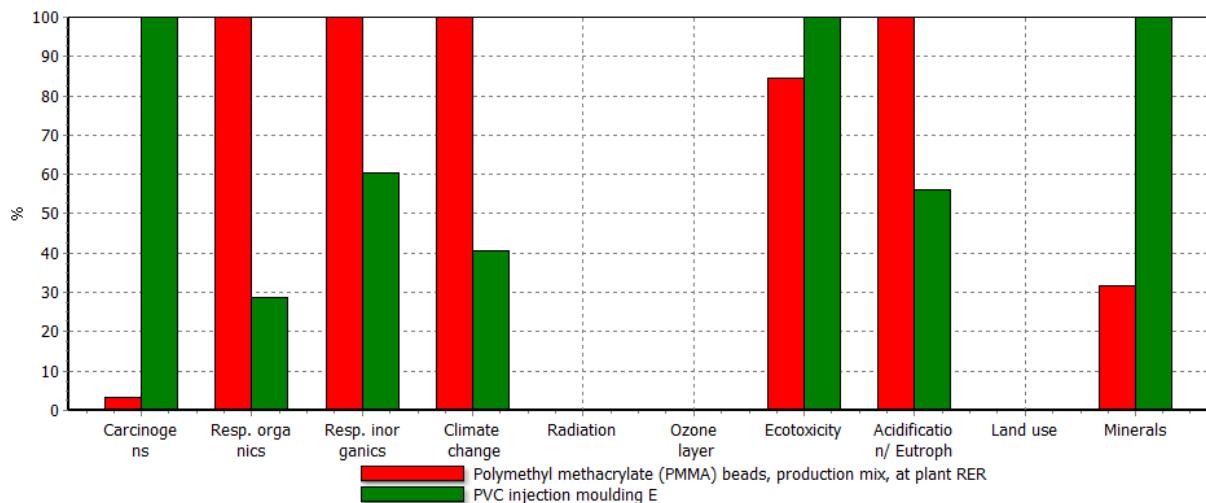
### **Environmental Impact**

For our environmental impact analysis, we will look at acrylic (PMMA) and Delrin (POM). Since the material option for Delrin was not available in SimaPro, we choose PVC instead due to its similar material properties. The mass of acrylic that we used was 200 in<sup>3</sup> and around 8.2 pounds, and the mass of Delrin that was used was 192.4 in<sup>3</sup> and 9.96 pounds.



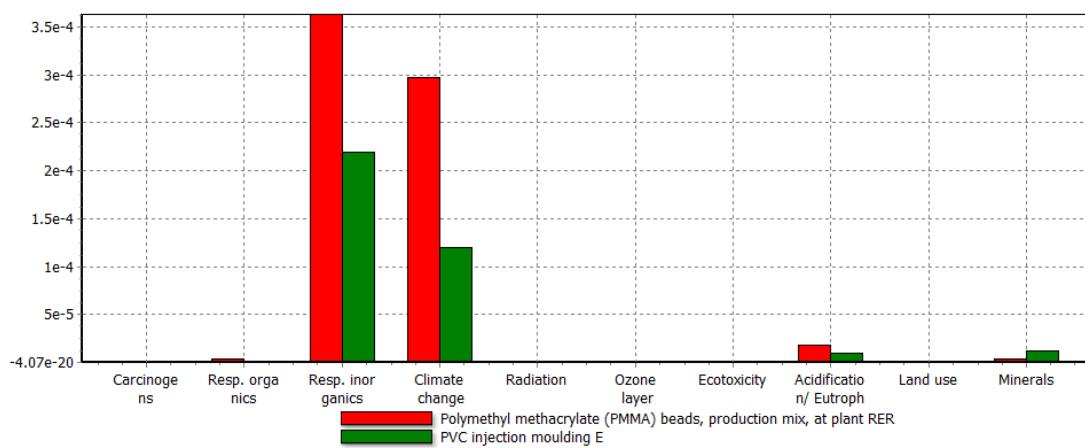
**Figure C3: Mass of components used in the production of the materials.**

In Figure C3, the total mass of PMMA (blue) was 74.56 kg and the total for PVC was 103.24 kg. The majority of the mass for both materials was associated with the use of raw materials component.



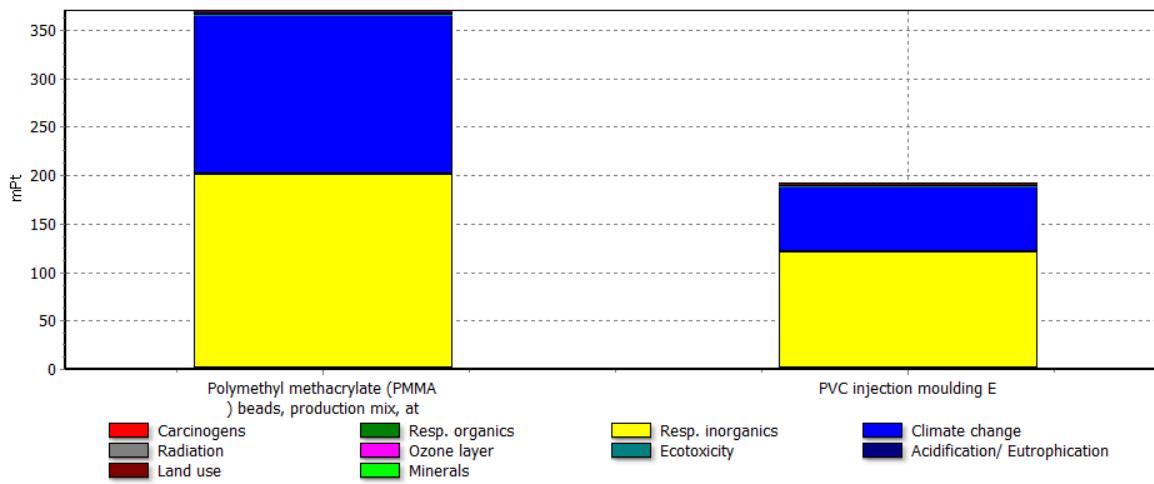
**Figure C4: Impact caused by the materials.**

In the second Figure C5, we compared the relative impacts from PMMA (acrylic) and PVC (Delrin). The PMMA had a greater percentage impact in respiratory organics and inorganics, climate change, as well as acidification. PVC only had greater impacts in three sections, which include carcinogens, eco-toxicity, and minerals. Neither PMMA nor PVC contributed to radiation and ozone layer effects. Figure C5 depicts a normalized score, using 1 kg masses, for human health, eco-toxicity, and resource categories. PMMA was largest in size for respiratory organics, respiratory inorganics, climate change and acidification. PVC had larger sizes in only the materials category.



**Figure C5: Normalized score using 1 kg masses of the materials for human health, eco-toxicity and resource categories.**

Finally, the last Figure C6, summarizes the comparison between the two materials using a single score comparison using “points”. PMMA, shown on the left, contributed more to respiratory inorganics (yellow) and climate change (blue) than the PVC material, shown on the right. This helped to indicate how PMMA (acrylic) has a high point value than the PVC (Delrin) material, and thus acrylic would have a bigger impact when the life cycle of our whole product is considered. Since respiratory inorganics and climate change are the main indicators shown, the “human health” and “ecotoxicity” damage mega categories are going to be more important than the “resources” category.



**Figure C6: Single score comparison of both materials.**

In conclusion, the acrylic has a higher impact on the environment than the delrin material. For the full life cycle of our design, both materials will be important due to their similar size in mass; acrylic at 200 in<sup>3</sup> and Delrin at 192.4 in<sup>3</sup>.

After going through this material analysis, we would possibly change from acrylic to Delrin for some of our materials. Depending on if cost was not a major issue for the product as well as the number of products that are intended on being produced, we may choose to use the delrin instead of acrylic for some of our parts, since their material properties are very similar. Overall, The Delrin (PVC) could help minimize our environmental footprint on climate change and respiratory inorganics released.