Educational Engine

A Technical Report submitted to the Department of Mechanical and Aerospace Engineering

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

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Spring, 2025
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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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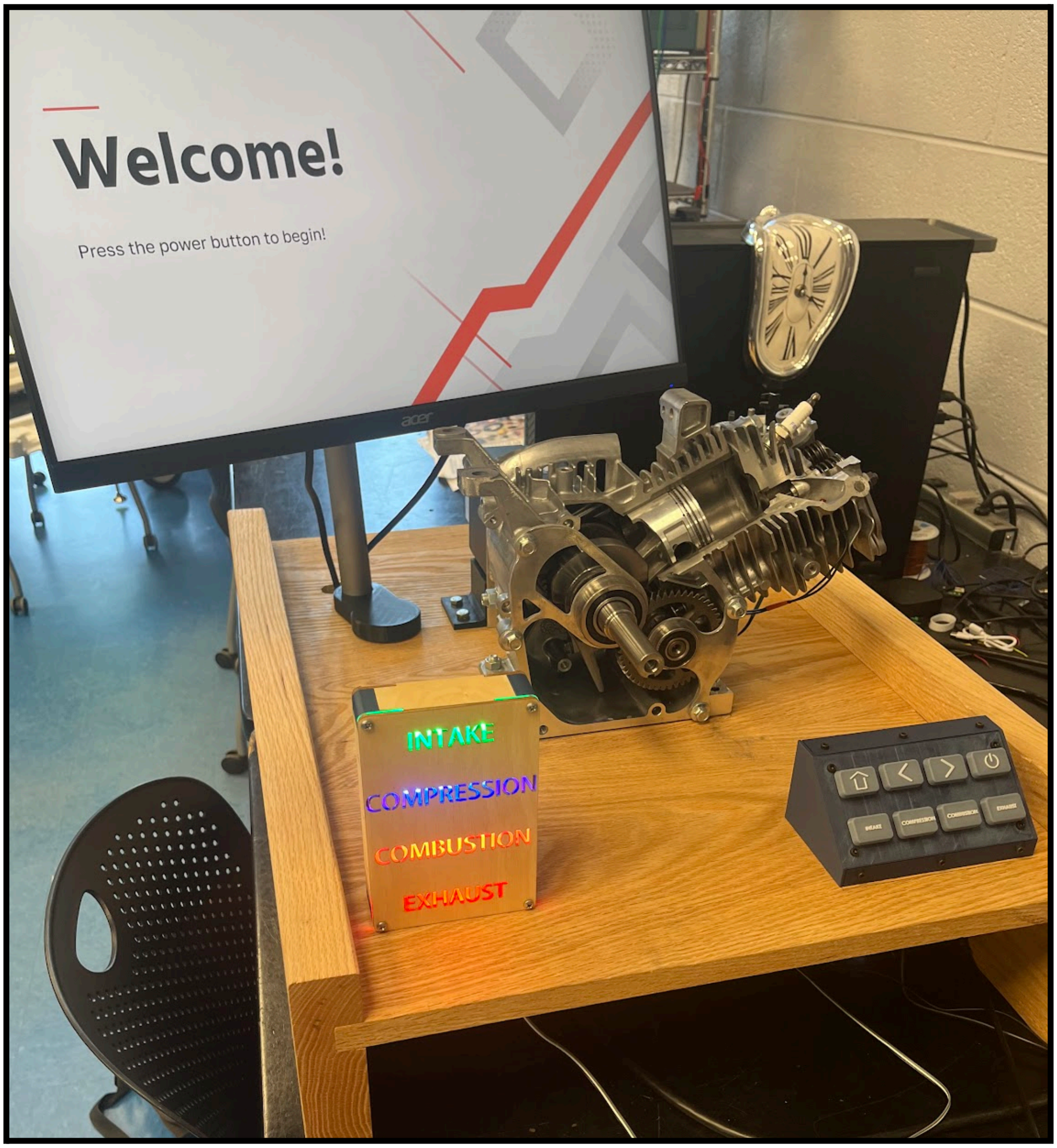
Educational Engine



Problem Statement

Over the course of the 2024-25 academic year, the group worked to address the problem of making engineering education more accessible. This is important so that the next generation of engineers is inspired and prepared to handle the technical challenges of the future. The problem was addressed by designing an interactive model of a four-stroke internal combustion engine. The model was built with the intention that anyone who interacts with it will be able to understand the information presented, making engineering knowledge more available to all. Within the University of Virginia (UVA) community, learning about the internal combustion engine in a hands-on fashion will allow mechanical and aerospace engineers to apply the knowledge they have gained to a widely used engineering technology. Not only will engineers have access to this unique interactive model, but it can also spark conversations about the pros and cons of the technology. The deliverables for this project include a four-stroke engine cutaway model for display and a 3D printed prototype that will be published online.

Background Research

Internal Combustion Engine (ICE) Basics

ICEs use a thermodynamic process called the *Otto Cycle* on an air and fuel mixture to power the engine. While the actual process has energy losses and generates entropy, it is easiest to imagine the cycle in terms of its ideal configuration. The first stage is an isentropic and adiabatic (fully-insulated) compression of the gas. Next, the gas is combusted at a constant volume, which then triggers an isentropic and adiabatic expansion. Finally, heat is released at a constant volume and the cycle repeats itself (Proctor, 2001). See Figure 1 for more details.

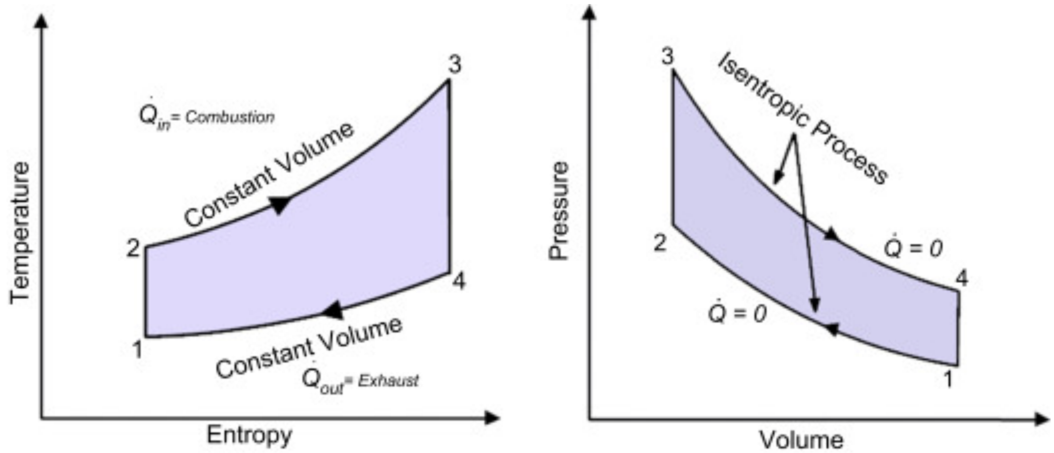


Figure 1: Ideal Otto Cycle (*Science Direct*)

Internal combustion engines either make use of a two-stroke cycle or a four-stroke cycle (with a few exceptions). The four-stroke variety was developed in the 1870s by Nicholas Otto (Wang, 2020) to improve on the two-stroke mechanism from the 1860s (Harvey, 2018). There are a variety of differences between the four-stroke and two-strokes, both technically and performance-wise. The main technical difference is the absence of valves in two-stroke engines, which eliminates the need for a camshaft, making the two-stroke lighter and consisting of fewer parts. In this setup, air and fuel travel from the intake port, to the combustion chamber, and then out of the exhaust port. See Figure 2 below for an example of a two-stroke engine model (Harvey, 2018).

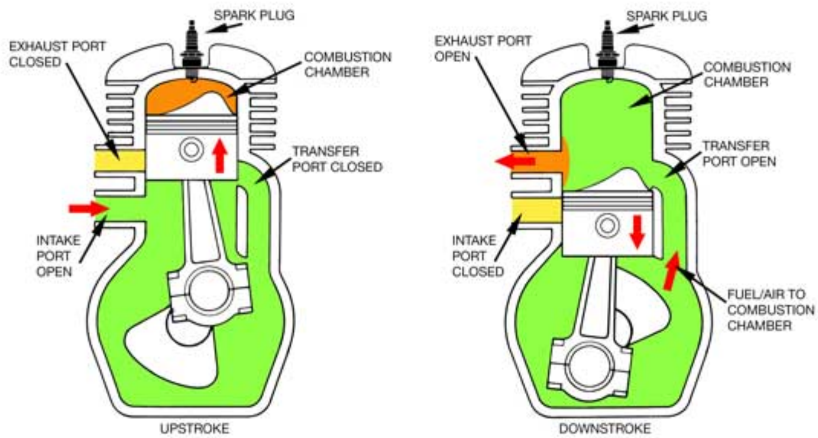


Figure 2: Two-stroke engine Model (*Gas Engine Magazine*)

Each respective model could be optimal for use in different situations, but the four-stroke is the more widely used ICE model. This is for a variety of reasons, but the primary advantage of the four-stroke model is the improved fuel efficiency of its operation. The inherent efficiency of the four-stroke engine is because the power stroke only occurs on every other stroke. This means that a four-stroke engine can ideally use about half as much fuel at the same rotational speed as the equivalent two-stroke engine (Hilgendorf, 2022).

The four-stroke engine cycle consists of two rotations of the piston-crank system over the course of one cycle (Basshuysen, 2016). Each rotation is broken down into two stages for a total of four stages. The first stage is the intake stroke. In this stage, the combustion chamber expands and the air intake valve opens in order to suck in the air for combustion (Basshuysen, 2016). During the next stage, compression, the piston compresses the air in the system, maximizing the potential energy to be released during combustion (Basshuysen, 2016). It is during this stage that fuel is introduced into the system. In the third stage, the power stroke, the fuel-air mixture is ignited and the energy released does work on the piston. The work done is what rotates the crankshaft throughout all four stages of the cycle. Finally, the exhaust valve is opened and the spent product is released (Basshuysen, 2016). A visualization of this cycle is shown in Figure 3.

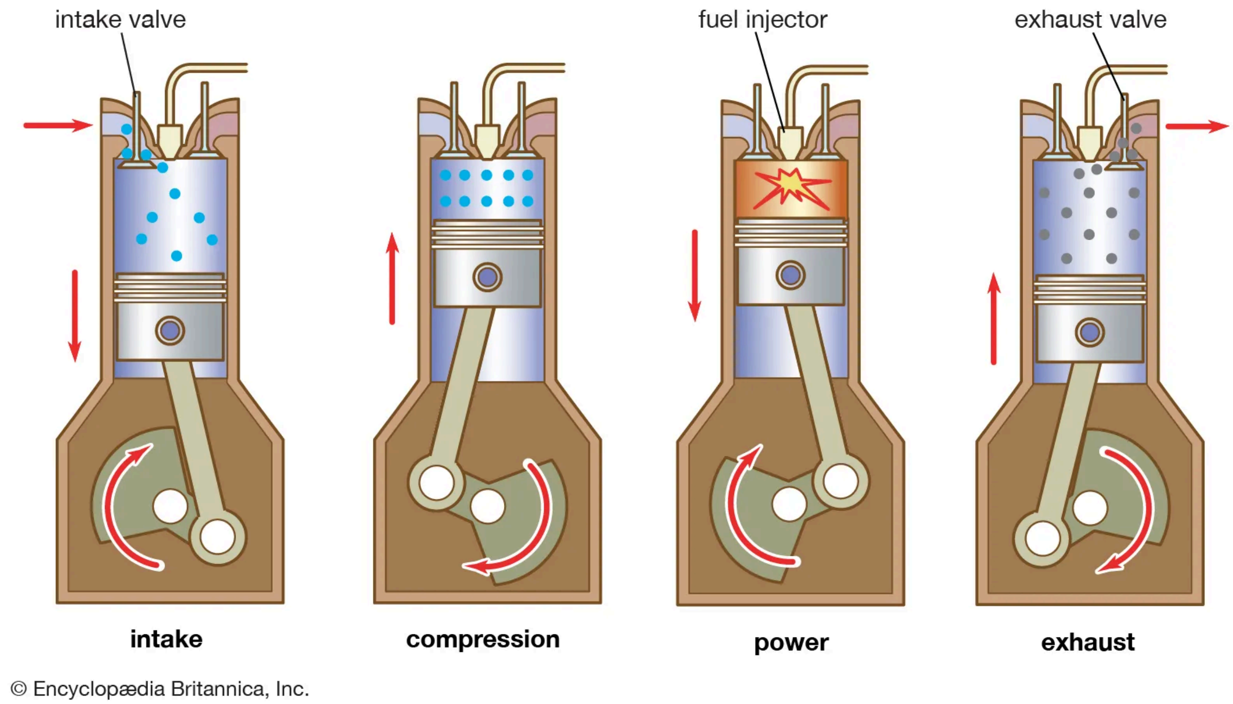


Figure 3: 4-Stroke Engine Cycle visual (*Encyclopedia Britannica*)

One standard version of these engines controls the intake and exhaust valves using a camshaft connecting to the output crankshaft by a timing belt. This design was pioneered by Ford in the 1930s (Ford, 1935). With precise engineering, this allows the valve openings to be perfectly timed by the output shaft rotation. See Figure 4 below for an example of this.

Figure 4: Multi-cylinder engine with timing belt (*Aumet*)

Useful 3D Printing Background

Another part of the research consisted of looking online for similar ICE models that were either 3D printed or made of other materials (such as acrylic). This process was not an exact science; it was not necessary to look for academic and scientific sources to improve on the design. Rather, the goal was to study previous projects to both determine which engine components made sense to include in a more preliminary model and also to see how others have managed to integrate the necessary mechanisms of the engine with the limited material configurations available.

The technical advisor for this project provided the group with two resources to use as a starting point. The first resource was a video of a single-piston model made entirely of laser-cut acrylic. This gave the group an idea of what the final result could look like, as well as demonstrated that 3D printing was not the only option; other materials could be considered. The second was an entirely 3D printed 4-stroke engine model. Looking at this model as an example allowed the group to get an idea of what a fully 3D printed model would look like, as well as take a look at specific part files and look into certain parts in more detail.

Using these examples as a starting point, the group also conducted their own research, finding other examples of 3D printed engine models designed by others. Utilizing Printables, a community database website for 3D printer users, the group was able to find a variety of different examples, and studied the different design decisions and aspects, such as flathead vs. overhead cam models or single cylinder vs. v-twin engines. See Figure 5 below for a couple images of some of the models the group studied.

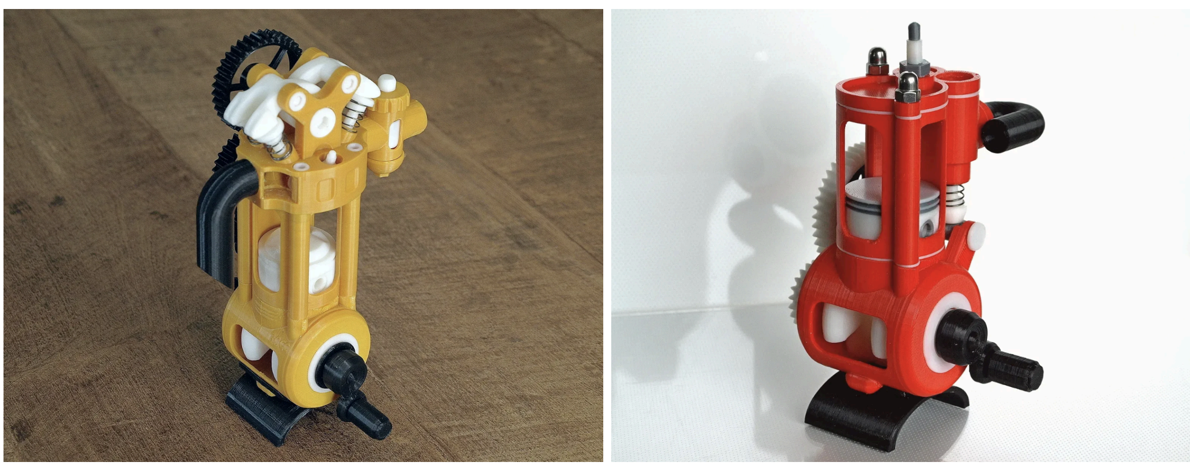


Figure 5: 3D Printed Engine Model Examples (Bootjevarrder Printables)

Completing this research prior to starting the design process was helpful because it helped the group consider certain design aspects that may have been neglected. It was also useful for the group to look at other designs to consider their shortcomings and strengths when carrying out the group's design process.

Ideation

The ideation process began with each individual group member considering the general product description, and generating ten ideas related to the product design. They then developed a sketch and description for each. The scope of the ideas developed by the group members ranged from the overall design of the product to recommendation on specific components.

Ideas pertaining to the general design of the product were useful because it allowed the group to consider a wide range of possible directions to take. To generate ideas that sufficiently fulfilled the objective of the product, the group members had to have a good understanding of the purpose, the target audience, and other important information. Group members also had to utilize their creativity to come up with a variety of significantly differing ideas. At this stage in the design process, quantity was prioritized over quality to encourage the extensive production of ideas, even if a few of the concepts were a bit far-fetched. These overarching concept based ideas ranged from fully virtual software-based designs, to hybrid combinations of electronic and mechanical components, all the way to personally ignitable engine models. In this phase of the process, the most important consideration was the ability of the product to solve the project problem statement, with other contingencies such as feasibility, safety, and other important criteria to be considered later. Some examples of ideas in this category can be seen below in Figures 6, 7, and 8.

Design 4: In-line two-cylinder, 3-dimensional four stroke engine cycle model. Powered using wall outlet w/ servo motor, timing controlled using microcontrollers. LED's and other visual components used to show phases, as well as timing differences between cylinders.

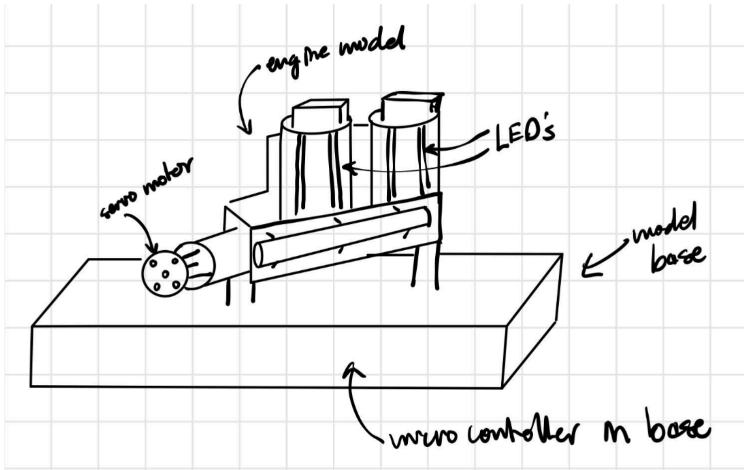


Figure 6: In-line 2-Cylinder Engine Model Idea

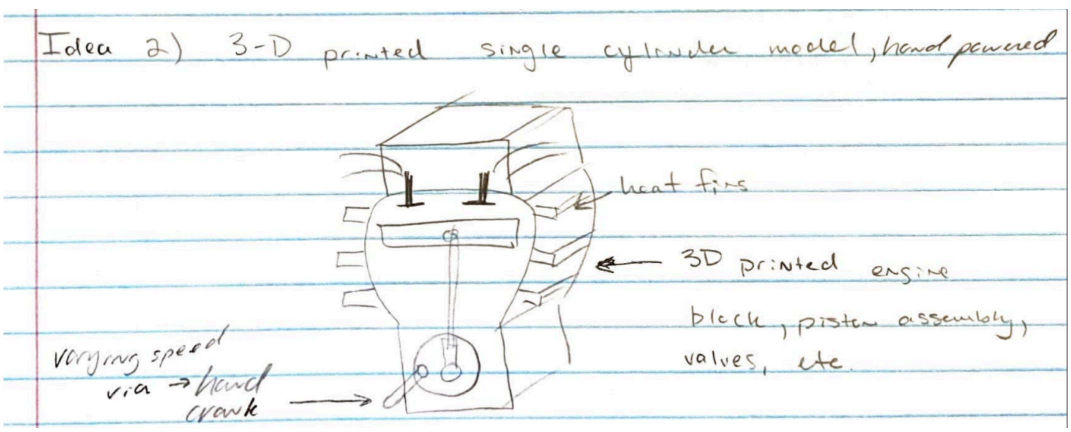


Figure 7: 3D Printed Single Cylinder Hand-Powered Model

Design 7: Cutaway V-twin ICE model. Motion driven by stepper motor, timing controlled using microcontrollers & LED’s to show phases, powered by wall outlet. Display screen showing important information.

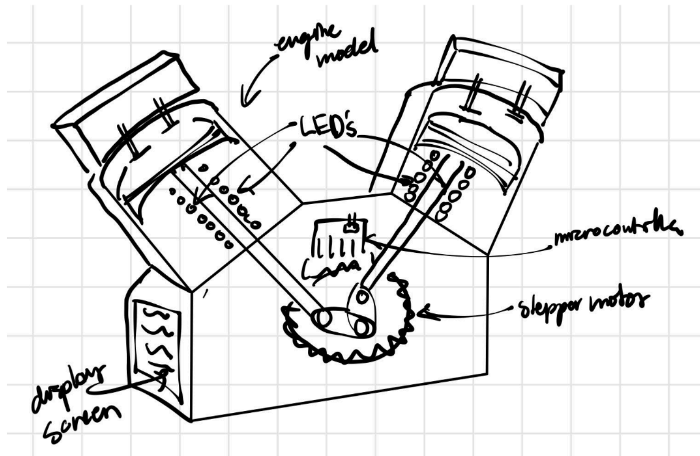


Figure 8: V-Twin Cutaway Model Idea

Developing these concepts was an important part of the ideation process. The development of such a wide range of diverse ideas allowed for the group to observe patterns and connections between designs, discover approaches from certain designs that could be applied to others, and set the foundation for a more robust final design.

Some of the ideas produced by the group did not concern the overall design, but rather specific components. Ideas that fit into this category were also useful to the group because the application of these ideas could be considered on different overall concepts. Addressing the objective for the product at this scale also allowed the group to consider areas of importance which may have been overlooked when considering the design as a whole. See Figures 9 and 10 below for a few examples of ideas that fit this description.

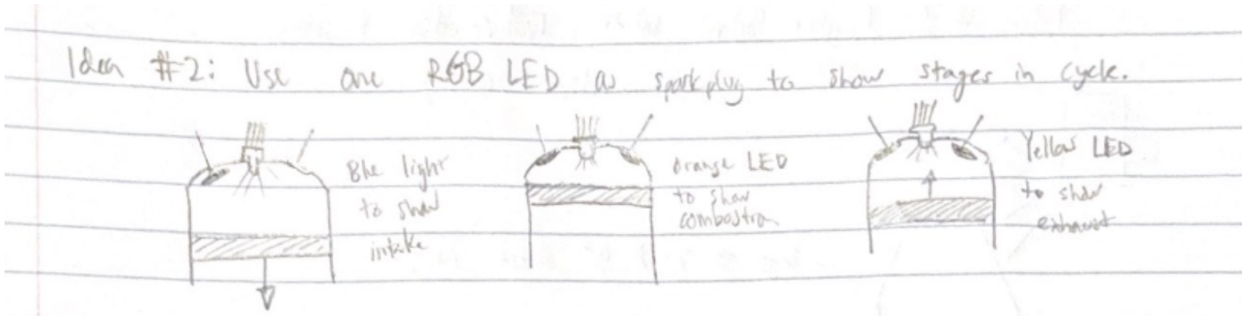


Figure 9: RGB LED Spark Plug Idea

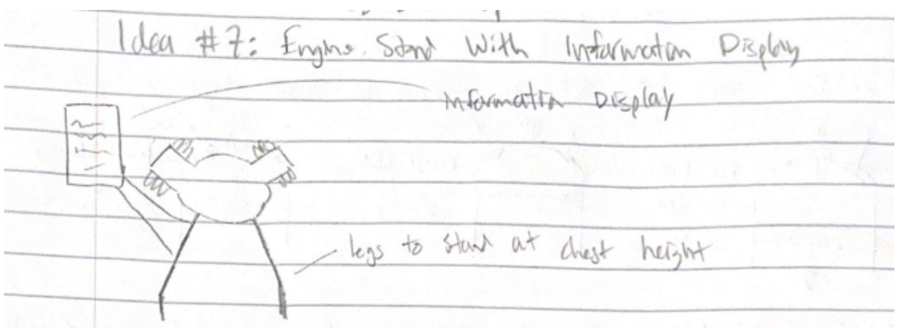


Figure 10: Engine Stand and Display Screen Idea

Each of the group members taking their own method to the ideation phase allowed the group to approach the objective from multiple angles, generating a wide range of ideas and solutions for consideration in the selection and screening phase. Each group member's ideation process and documentation in full can be found in Appendix A.

Selection and Screening

Selection and Screening Process

The group implemented a two-tiered screening criteria to assess all of the alternative ideas generated by the group members. This system was specifically designed to keep the idea generation phase and the screening phase more integrated with one another. The first round of screening involved coming up with several screening criteria (shown below in Description of Criteria), that may have been neglected in the initial idea generation, but were nonetheless of paramount importance in the design. These criteria were initially weighted equally to determine which of the initial concepts were fulfilling a sufficient variety of the criteria. The original 40 ideas generated by the group in the ideation phase were then scored collaboratively by the group members, using said criteria. See Figure 11 below for the spreadsheet used to screen the ideas at the individual and group level. The group then considered the highest ranking ideas. Taking the best components from these ideas, the group created seven hybrid finalized designs that seemed to fulfill the design criteria most adequately. Effectively, the group narrowed down the design concept from the initial 40 ideas to seven final design concepts.

	Criterion (Scored on a scale of 1 (lowest) to 10 (best))									
Design Idea	Creativity	Interaction	Aesthetic	Longevity	Ease-of-use	Repairability	Communication of Info	Quantity of Info	Total Score	Moving For
Virtual interactable engine model	3	2	4	9	6	9	7	10	6.25	YES
2-D tabletop educational model	4	5	8	4	7	6	3	3	5	NO
3-D Single-cylinder battery powered mode	4	6	4	5	6	5	1	2	4.125	YES
3-D In-line two-cylinder four stroke engine	4	7	6	5	6	4	2	3	4.625	NO
Cutaway single-cylinder engine model	5	7	7	6	7	7	5	4	6	NO
Full in-line two-cylinder engine model w/ p	5	7	8	6	7	8	6	4	6.375	NO
Cutaway V-twin ICE engine model	5	5	8	6	7	7	6	4	6	NO
V-twin ICE engine model w/ plexiglass win	5	6	9	6	7	7	7	5	6.5	NO
Taxidermy engine model cutaway	8	9	9	9	9	8	7	5	8	YES
Taxidermy cutaway engine model w/ 3-D p	9	9	10	10	9	9	10	10	9.5	YES

Figure 11: Partial View of the Initial Screening Chart

In the second round of screening, the criteria already selected were weighted based on the relative importance decided by the team. Using these new designs and weighted scores, a new matrix was developed, and similar to the first round of screening, the hybrid finalized designs were then collaboratively scored by the group against the newly weighted criteria. See Figure 12 below for the matrix from the aforementioned second round of screening. The team elected to move forward with the design that scored the highest, which would have involved replacing much of the internal engine machinery with 3D printed parts to reduce internal forces and potentially improve visibility. However, the design was modified slightly throughout the fall as specification requirements favored keeping the engine more intact than planned (see Specifications).

	Criterion (scored on a scale of 1 (worst) to 10 (best))									Total Score
	Creativity	Interaction	Aesthetic	Longevity	Ease-of-use	Repairability	Communication of Info	Physical Engagement	Quantity of Info	
Weight	0.05	0.1	0.15	0.15	0.1	0.1	0.2	0.05	0.1	1
Fully 3D Printed, Cutaway, Electrically Powered, V-Twin Model	5	8	7	6	7	6	7	10	7	6.9
Fully 3D Printed Model, Electrified, Cutaway, with Information Display	7	9	7	6	7	6	7	10	9	7.3
Fully Digital Model on TV Screen	3	3	4	9	6	9	4	1	10	5.75
2D Model with Laser Cut Acrylic and Information Display	6	6	5	6	5	8	5	10	6	5.95
OEM Engine, Cutaway, Electrified, Information Display	5	3	8	4	5	3	7	5	7	5.5
3D printed engine "kit" with interchangable components	8	8	8	4	2	3	8	10	10	6.6
OEM Engine with 3D Printed Parts (Weight Reduction), Cutaway, Electrified, Information Display	10	9	9	6	7	4	9	10	9	7.95

Figure 12: Final Selection criteria chart

Description of Criteria

- Creativity (5%)
  - Need to have some creative innovations to keep the model engaging
  - *Weight:* While having some creative innovations will help set the project apart, its low weight is because more practical considerations need to take precedence
- Interaction (10%)
  - Need for an interactive model so that students can control the pace and content of their learning
  - *Weight:* This consideration was determined to be about equal in value to the other major considerations, but is scored lower because a slightly less interactive design is less detrimental to the design than failure or poor information quality
- Aesthetic (15%)

    - Model should be sleek and visually appealing
    - *Weight:* By designing a visually attractive model, the design will better set up as a display piece and may encourage more students to interact with the model
- Longevity (15%)
    - Model should be built to last a long time (minimum 10 years) to be useful to many groups of students over time
    - *Weight:* This is incredibly important because education is an ongoing process and the longer the design lasts, the more people will be able to interact with and learn from the model.
- Ease-of-use/Accessibility (10%)
    - Model use should be self-explanatory so that almost everyone can benefit from the display without prior knowledge
    - *Weight:* Accessibility is important so that all who wish to interact with the model can do so, but there are also limited variations that can be implemented (that are not under consideration to meet other specs), keeping the scoring at 10%.
- Repairability (10%)
    - The model and any auxiliary components should be easy to repair in the future so that whoever maintains the model can fix it without intimate knowledge of the design
    - *Weight:* While this attribute is not important initially, a bad failure could render the model useless if not repaired. The potential to use over-engineered OEM or easily re-printed parts in the model makes this less of an issue, explaining the score.

- Communication of information (20%)
    - Engine information in all forms should be clearly expressed and engaging in all forms of communication (physical, visual/auditory, text, etc.)
    - *Weight:* The educational aspect of the model is most in line with the initial problem statement; if the information is not well-communicated, then it loses its use as an educational tool, especially to non-engineering students
- Physical Engagement (5%)
    - Similar to interaction, physical engagement will also help students interact with the model
    - *Weight:* Further discussion rendered this criteria as more of a “nice-to-have” attribute rather than a necessary component, but its great potential benefit if the requirement was fulfilled kept the spec in consideration.
- Quantity of Information (10%)
    - Need for a comprehensive discussion on engine mechanics, variation, use, and climate impact
    - *Weight:* The educational aspect of the model is most in line with the initial problem statement. It is important to be comprehensive in information discussed, but some extra information may be expendable, lowering the importance of this category

Final Choice

Ultimately, after the ideation, selection, and screening processes, there were two alternatives selected. A final model featuring a purchased engine was selected based on the selection and screening process. Additionally, a 3D printed model was also selected as a secondary project to refine the team's design skills, expand the reach of the model, and streamline the development of the final product. The group elected to move forward with both of the aforementioned ideas because it was determined that these ideas in tandem would best accomplish the overarching goal of making engineering education more accessible.

The first deliverable of the physical project was the 3D printed prototype model. By working on a 3D printed prototype in the first semester, the group was able to cheaply and easily iterate through designs. This enabled the group to develop a deeper understanding of how the different components of the engine interact with each other mechanically, to determine which engine information to display in the final product, and evaluate the potential design obstacles in the final model. This part of the project also allowed the group to become familiar with CAD and engineering design.

For the second part of the project, a Predator 6.5HP 4-stroke engine was cut open and transformed into a display model. This was selected to be cut open and developed into a more permanent display. The Predator engine was chosen because it was small and easier to take apart compared to other proposed models such as a v-twin. It was also the more economically sound decision, in comparison with the other engines under consideration The single-cylinder design will also improve visibility compared to a multi-cylinder setup. The alternative selected included electronically controlled lights (and possibly sounds) controlled by a Propeller 2 microcontroller chip. Furthermore, it was decided that a display screen and a mobile cart setup would be the best way to display information and to transport the display. These designs changed as the final design and construction process occurred.

As seen in the screening section, the initial design called for replacing many of the engine components with 3D printed replicas to allow more control over design, reduce internal forces, and to make parts easier to replace. However, after the engine was purchased, it was found that the parts as purchased remain in good condition, so preserving those parts instead will not only create a more realistic simulation of the engine's operation, but also should remain in good condition for a much longer period of time than the 3D printed alternatives initially selected (see Specifications for more details).

Specifications, Technical Analysis, and Prototype Development

This section is the most robust section of the report, aside from the technical drawings. It involves a summary of the design of the final display and the associated technical analysis. This section also discusses in depth the 3D printed prototype created in Fall 2024 to help the team gain a better understanding of the engine technology and cheaply practice iterative design.

Initial Specifications

During the early phases of the project, the group worked to develop specifications for the cutaway model. Areas of consideration included physical design and upkeep, display of information, user safety, electrical engineering requirements, and reliability. To keep options open, many of the specifications were more broad and could be looked at as more "customer needs" than engineering specifications.

Physically, there were a couple of major engineering considerations that resulted in the development of specifications. In order for people to be able to view the engine as it rotates, it needed to spin at sufficiently slow speeds (determined by the group to be somewhere between 45-180 RPM) with a desired ability for the speed to be controlled and changed by the user. The electric motor must also have the torque capability to hold and rotate the engine. Both of those specifications required a gear reduced motor, as spinning that slowly and handling that much torque are not things most motors in the desired cost range can do. There was also a large emphasis on safety and durability. It was necessary for the engine to have both physical protection and an emergency shut-off to ensure that no one would get hurt getting close to the engine and touching a moving component. Finally, the whole display was to be portable enough to ensure that it could be moved from one area in the MAE building to another as needed.

Another set of specifications considered longevity: the project should have a minimum ten year design life (with five years minimum maintenance), and that repairs could be made by UVA engineering students with the mechatronics experience to understand the wiring, should something fall into disrepair. Working to meet these requirements would include developing operation and installation documentation, careful part ordering, and fatigue life calculations for some of the engine parts. For cleanliness, it was also desired to keep lubrication to a minimum and only used where absolutely necessary.

Electrically, it was desired to have a microcontroller to run the electric motor and other electronic components. This would allow for the supplemental use of screen or visual aids to display information, control over the engine speed, and ability to make modifications to the design later on. After doing some preliminary estimations, the group decided that a minimum of 20 inputs/outputs would be needed to facilitate this. Microcontroller and circuitry assembly design would take this into account going forward.

Another area where specifications needed to be designed concerned the display of information. The group desired to demonstrate the four-stroke cycle physically through the model, but there are other facts and considerations regarding engine design that the group believed were necessary to discuss, including extra components that are commonly used in the engine, environmental impact, and other considerations. It was decided the best way to do this would be to have a display screen to relay through the extra information that the team wished to display. LED lights would also be incorporated into the design to highlight elements of the cycle as they run as a visual aid.

Other considerations included a cost constraint of $800 and navigating limited time and resources of the group members who are working on building the project. The project group was smaller than most other Capstone projects, so this was not a trivial consideration.

While the specifications compiled into the initial list mentioned above, changes during the design and construction process led to some changes in the final result. These include both managing new constraints and changes to the design goals of the project. In the "Components Description and Final Design Specifications" section below, the changes can be viewed.

In this section, it is also important to note that the 3D printed prototype was a major part of the work schedule in Fall 2024, so specification analysis was performed for that device as well. However, specifications for the prototype were more limited. The major constraint was that the device had to be built and fastened entirely out of PLA, and no part was to have any "print supports". This meant that design for manufacturing was critical in the design to ensure that all pieces fit together, and that each component could be printed as-is with no support material to cut away. These challenges made part geometry very specific. The device had to be hand-cranked and demonstrate the valve movements in coordination with the stroke. Initially, electric motor and LED interfaces were considered, but they were ultimately scrapped to focus on the mechanisms of the prototype and the design of the cutaway model.

3D Printed Prototype and Iteration - Fall 2024

The team spent the majority of time in Fall 2024 dedicated to designing the 3D printed model, and iterating on our designs for improvement. The overarching goal was to design a four-stroke engine model that could be 3D printed with any standard Fused Deposition Modeling (FDM) printer. Ideally, this model would be uploaded to maker websites like Thingiverse or Printables with UVA branding such that anyone with access to a 3D printer could easily download and make their own copy.

Consumer 3D printing has limitations, some of these limitations include long print times, layer lines causing anisotropy, and overhangs less than 45° from the horizontal (3D Printing.com, 2024). Skilled engineers can get around these limitations through various means. For instance, one might print in a different orientation to get around steep overhangs, however doing so may orient the layer lines parallel to major forces, leading to shear. Another solution is to print with support material below the overhang, however this will increase material usage, increase print time, and may lead to imperfections in the surface texture. As a result of these challenges and the desired outcome, the team decided to choose some design priorities:

1. Sacrifice Realism As Needed

The team decided that the model need not be an exact replica of an existing engine. The model ought to show the core functionality of a four-stroke engine, but auxiliary components of the engine (such as the carburetor, heat fins, etc.) may be thrown to the wayside to enhance the visual appeal of the model, shorten the design cycle, or support the other design priorities.

2. Avoid Support Material

Support material enables users to print practically any shape. However, support material has its own downsides. Support material adds to the total material usage, and thus cost and print time, of a part. It can be difficult to remove depending on settings used, material, or brand of printer. It can also lead to imperfections in surface quality. In the worst case, the weak support material may fail and cause a failed print. To avoid these problems, the team decided to challenge itself to avoid all use of support material in design. This is achieved by only using overhangs at or below 45° from the vertical (maybe a few degrees more if completely necessary). Small bridges between gaps can successfully be printed without support. In some cases, circles can also be vertically printed but will not be perfectly round (Protolabs, 2024).

3. Assembly and Disassembly

The group wanted the model to be easily assembled and disassembled. This would cause users less stress/difficulty and would mean that replacement parts can be easily printed at the user's discretion. The ideal scenario would be that all interfaces and fasteners would be 3D printed as a part of the design to make functionality as accessible as possible for anyone with a printer and access to drawings.

4. Limit Required Materials

Many makers in the 3D printing community use external hardware such as bolts/screws, threaded inserts, glue, or even plastic welding to join parts together. These may be easy for some users, and may lead to higher strength joints, but present their own issues. Firstly, glue and plastic welding aren't able to be disassembled, going against our third design principle. Secondly, users may be discouraged to print the model if they don't already have this hardware on hand. Small volumes of hardware can be difficult to acquire and represent an additional cost, so the group also decided to limit the tools required by the user to a 3D printer, plastic filament, and a flathead screwdriver. As a side note, the group was also aware that Polylactic Acid (PLA) is typically the cheapest and the most commonly used 3D printer filament, so the model would also need to be designed to function with this type of plastic.

With a drawing that can be edited on CAD relatively easily and with proper access to materials, 3D printing is easy to enable rapid prototyping. After all, the time it takes to iterate new designs is only dependent on the time it takes to print. Nearly every part was printed throughout different stages in the design process. In some cases, it was only necessary to print one small section of a part to test its functionality and save time/material. This iterative design/test process helped the team decide what features worked well and which ones did not. This experience was incredibly valuable both to the success of the model and the success of the team as engineers.

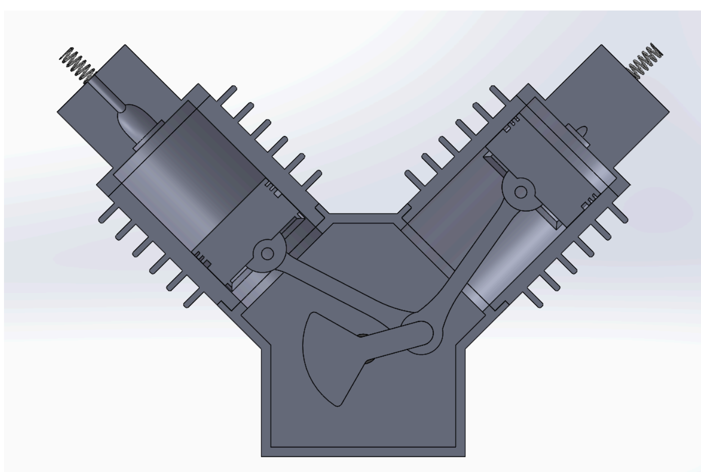


Figure 13: Initial V-twin Configuration SOLIDWORKS Model

The first design of the 3D printed model was a two cylinder, V-twin model. See Figure 13 above for an initial V-twin configuration that was designed, but never printed. This configuration was first chosen because a dual cylinder configuration would show users how the combustion strokes are offset to create a smoother power profile. With the first V-twin configuration, the team designed the engine block, cylinders, crank-shaft mechanism, and pistons. Heat fins were incorporated on the outside of the cylinders to incorporate more realism into the model. A cylinder head was then added to the model with two valves, an intake port, and an exhaust port; an integrated camshaft was also incorporated to ensure proper valve timing. However, after further discussion, the team decided to switch to a single, vertical cylinder. The main reason behind this decision was simplicity. The single cylinder model would not overcomplicate the 3D printed model, and would ensure that only the basic components and mechanisms were included. At this point, the team decided to shift to a single cylinder 3D printed model.

The first single cylinder model had an angled cylinder. See Figure 14 below for a cross-section of this design iteration. Sides of the engine block and cylinder were exposed to allow for easy viewing of the internal mechanisms within the engine model. After 3D printing these components, a few problems were encountered. The main problem was that the offset centroid of the angled cylinder made the model vulnerable to instability and falling over. In order to combat this problem, the model was altered to have a vertical cylinder.

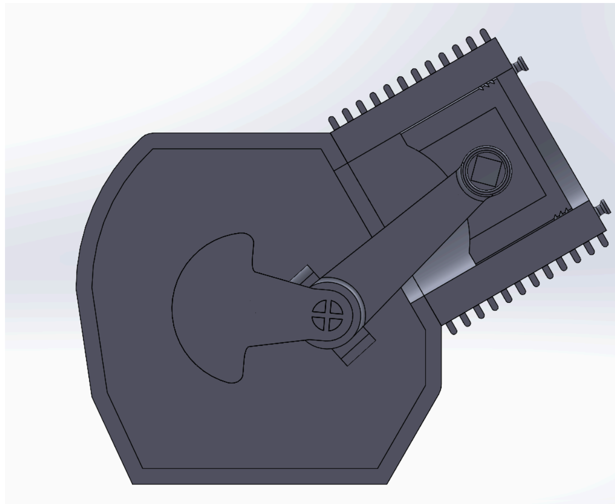


Figure 14: Initial Angled Single Cylinder Configuration SOLIDWORKS Model

After switching to a vertical cylinder design, the team started to focus on some of the more specific components within the 3D printed model. After the engine block, cylinder, and piston assembly were designed, a pushrod valve train was designed to mimic an Overhead Valve (OHV) engine. This stage of development required numerous components and the most detail, involving a cylinder head, valves, pushrods, rocker arms, and a timing system.

The four stroke cycle necessitates that each of the valves opens only once per two rotations of the crankshaft (once in intake, and once in exhaust). To time these valve openings with the crankshaft, a camshaft design was implemented and connected to the crankshaft via a 2:1 spur gear ratio, ensuring that the piston will oscillate twice per one cycle of the valve openings. This gear interface is located on the back of the engine block to maintain visibility of the internals and keep the engine at a reasonable size (Figure 15). The camshaft was designed to have a maximum displacement of 0.15” between the lowest and highest points on the cam lobes. With a 1:1 rocker arm ratio, the valves and pushrods have equal displacement, meaning the valves would also have a maximum displacement of 0.15”. Knowing this displacement allowed the team to do simple geometric calculations to determine the length of the pushrod so that the valve traveled properly and the follower end was always in contact with the camshaft.

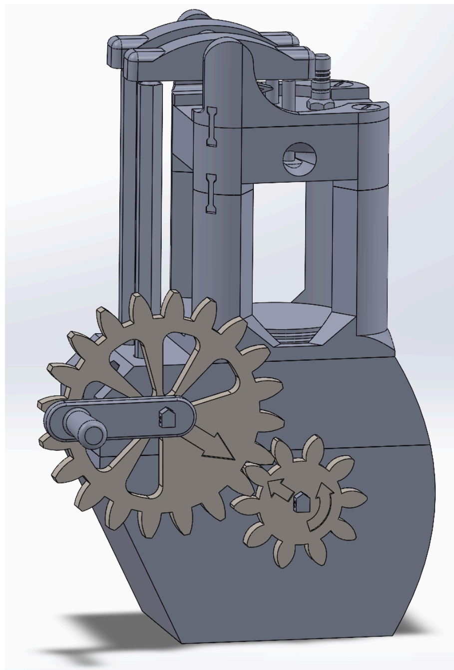


Figure 15: Gear Train on Back of 3D Printed Model

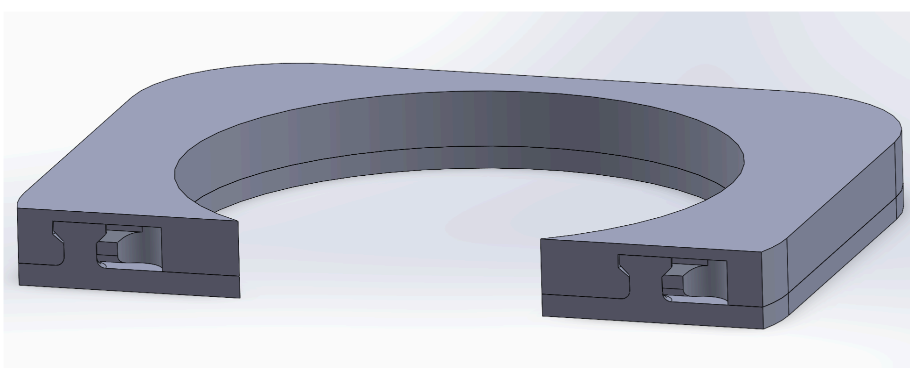
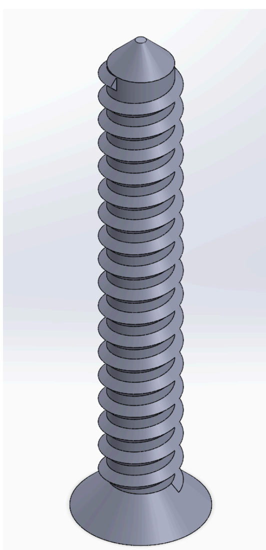


Figure 16: Cross-Section Solidworks View of Sliding Snap Fit

Up until this point, the group had been using sliding snap fits to connect large pieces such as the engine block halves, cylinder, and cylinder head all together (see Figure 16). Though iterations were test printed and the fits generally worked, the connection wasn't consistent enough to use as user printers have varying tolerances and uncertainties. Additionally, the sliding mechanism needed to be printed in a way that was parallel to the layer lines, meaning that there was a high likelihood of shear failure. The group switched most of the connections to a threaded hole and screw when possible. To make this easily printable, the group designed their own threads with a coarse pitch (0.10") and a low overhang angle thread shape. Unfortunately, these 3D printed screws will easily shear at the base if overtightened, so their print settings were modified to maximize strength and, through testing, it was determined that the assembler must tighten to finger tight plus a one-eighth rotation (Figure 17). These screws are used to secure the cylinder to the top half of the engine block; assemble the crankshaft and camshaft pieces; install the spark plug; and secure the rocker supports, cylinder head, and cylinder together.



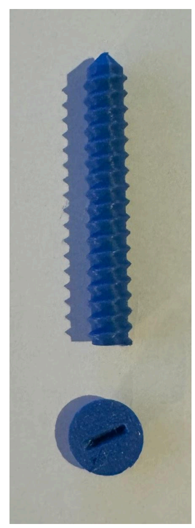


Figure 17: Custom Bolt Design in Solidworks and Over Tightened Print

In addition to the screws, there were a few joining methods used in the last iteration of the model to hold it together. Firstly, the valve stems and pushrods connect to the rocker arm via a ball snap joint. The wrist pin–which connects the piston head to the connecting rod–is an open ring which can be elastically compressed to slide it into the piston head. Then, when it is in place in the middle of the piston head and through the connecting rod, it has enough room to expand back and hold the pieces together. This is one place in the model which is not easily disassembled. On two of the corners, the rocker support blocks a screw from being able to secure the support, cylinder head, and cylinder together. So, these two corners use an “I” shaped piece to slide into the surface on the edge of the pieces and hold them together in the vertical direction (similar to a “biscuit” joint in woodworking). The two halves of the engine block slide together, and are held together by a small snap joint caused by an interfering cylinder that fits into a hole at the end of the sliding motion. Strength isn’t a concern here, as the gears for the crank and cam shafts also hold the two halves together. Lastly, the gears are held onto the shafts with a key (shaped like a pentagon with two right triangles) and secured laterally with a 3D printing optimized cotter pin with a square profile (Figure 18).

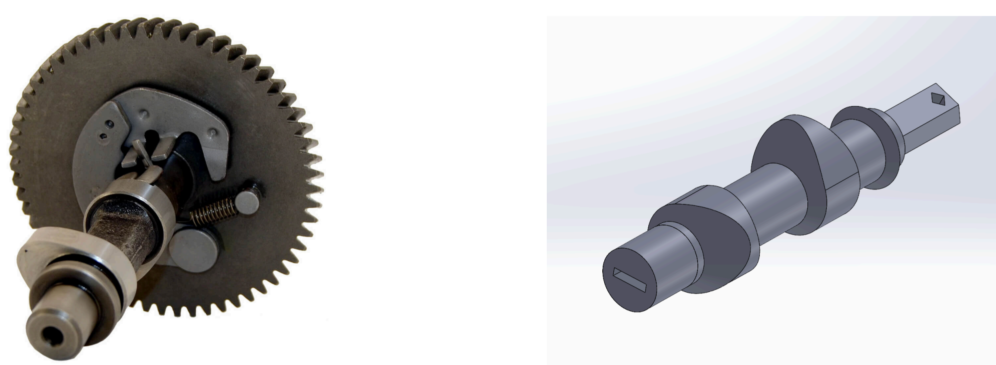


Figure 18: Comparison to Real Camshaft for a Comparable Engine and 3D Printable Camshaft (HOT265 Camshaft from gopowersports.com)

Much like that cotter pin, it is noticeable that many of the pieces differ slightly from their real world counterparts. This is because these parts were optimized to be 3D printed. As an example, the lobes on the camshaft are not perpendicular to the shaft they are on (how they would be in the real world. Instead, the lobes slope at a 45° angle to the shaft. For a comparison, see Figure 18. Although this differs to the trained eye, the model's version of a camshaft is functionally the same and doesn't require any supports, one of the main design principles of this project. The technical drawings for all of the 3D printable model parts can be found in Appendix C.

Initially, the group had hoped to integrate some electronic functionality into the 3D printed model. Potential additions included an electric motor to power the printed model and/or integrating LEDs to illuminate the engine cycle, much like in the final model. However, these electrical integration attempts were not moved forward for a couple of reasons. Firstly, the timeline to develop the final prototype was longer than initially anticipated so unrelated electronic design work took a back seat to the more pressing project needs. Furthermore, integration of electrical parts would decrease accessibility and wouldn't follow the PLA-only design specification. The group decided that it was more in line with the project goals to create a model that was more accessible to anyone online with a 3D printer than to design a more technically advanced model that would be harder to assemble.

Technical Analysis and Calculations

Electric Motor

One major component that required further analysis was the electric motor. There were two main considerations the team needed to work out: the necessary power of the motor to operate the machinery, and the motor operating speed. Upon doing preliminary calculations and physical testing in November 2024, it was determined that the motor purchased would need to provide about 1 ft-lb of torque to overcome gravity in moving the piston head (See Appendix

B-1), friction from the O-rings, and moving the camshaft that controls the valves. It was also assumed that the holding torque to keep the piston in place was a similar value.

This was then backed up by calculations. Rotational torque was calculated by calculating the height change of the piston center of mass, O-ring friction was calculated using an online resource (Parker), and the camshaft was accounted for using a safety factor. After determining the amount of energy/torque was necessary (which was also about one ft-lb), power at different speed settings were evaluated to get final specifications for the motor. Based on planned operating conditions, this requires an engine with a minimum of 78 W power output. All calculations can be found in Appendix B-1, but final power results are listed in table 1 below.

Table 1: Power Specifications at different model operating speeds

Angular speed, ω		Torque Values		Power Calcs		
RPM	rad/s	Torque (ft*lb)	Safety Factor	ft*lb/s	HP	W
10	1.047	0.923	2	1.933	$3.514*10^{-3}$	2.62
30	3.141	0.923	2	5.798	$1.054*10^{-2}$	7.86
100	10.47	0.923	2	19.33	$3.514*10^{-2}$	26.2
300	31.41	0.923	2	57.98	0.1054	78.6

The final step to working out the motor specifications was to find a motor with a gear reducer that would allow a minimum speed of no more than 45 RPM, to be able to interface with electronic speed control, and provide the necessary holding torque to work properly.

The final motor was selected from Stepper Online, and it is a DC brushless motor operating at 24 V. This allowed for a standard electrical power supply to be used and an engine setup that requires less maintenance than a traditional brushed motor. The motor has a built-in gearbox to reduce speeds, with the operating range being less than 150 RPM. The torque output is over 2 ft-lbs but the power is only 60 W. The team responded to these technical limitations by slowing the planned rotational speed to lower the power, and by removing the flywheel of the engine, which reduced the inertia of the shaft and lowered needed torque input.

Fatigue Life

In order to ensure that the device would meet reliability requirements and maintain operation with minimal maintenance, it was necessary to estimate the fatigue life of the crankshaft, which was to be subjected to the largest forces, even in the display model.

After doing the calculations, the internal forces were lower than anticipated. The OEM machinery, being built for more strenuous operating conditions, is expected to have exceptional fatigue life (see Appendix B-2 for calculations). Therefore, the final design was modified to preserve more of the engine machinery. Going forward, it was decided that 3D printed modifications would only be used for support pieces. See Table 1 below for a more comprehensive showing of expected power requirements at some of the projected operating speeds.

In context, the final results of the fatigue calculations make sense. The engine shafts were designed for significantly higher loads, faster operating speeds, and more harsh environmental conditions than what the display will require of them. Therefore, the life of these critical parts are not a concern.

Gear Cutaways and Mechanical Analysis

In order to provide a better view of the engine mechanisms, many parts of the engine had to be cut away. The biggest area of concern from an engineering perspective were the gears on the camshaft and crankshaft. This is because those two pieces will be experiencing forces and moving during operation. While it was determined not to move forward with cutting the crankshaft gear due to geometric constraints, the camshaft gear still had to be analyzed to ensure that it could handle the loads without deforming or incurring excessive stress.

The gear teeth would not be analyzed because no changes would be made to the gear at that location. The forces applied to the helical gear were broken down into its component parts, and the stresses were analyzed. It was determined that the maximum stress would be on the outside of the gear circle, with a shear stress applied from the power transmission torque, shear stress from the helical angle acting on the gear tooth area, and normal stress from the vertical force component acting on the projected gear tooth area. To err on the side of caution, a safety factor of 2 was applied, and the distortion energy method was used to determine the equivalent stress. From these calculations, a minimum polar moment of inertia was calculated, which resulted in a value of $9.6 * 10^{-10}$ m^4.

When designing the gear cutaway, the moment of inertia of the gear was compared to the calculated minimum value to ensure compliance. The moment of inertia was calculated by estimating that each section to be cut out was an arc of a specific angle (based on the thickness of the remaining gear at the middle diameter of the cut) and subtracting those arcs from the total moment of inertia. The final result was a gear with a polar moment of inertia of $3 * 10^{-6}$ m^4. This is well over the minimum order of magnitude, and the safety factor makes sense because gear failure would normally occur in the teeth (to which the group made no modifications). See Appendix B-3 for all calculations.

<u>Supports and FEA</u>

In order to hold the crank and camshaft in place while cutting away the front supports for engine visibility, support brackets had to be designed. This also included a support bracket on the back that connected the camshaft to the encoder. The primary design challenge involved minimizing material so as to not limit visibility while also building the supports robust enough to hold mechanically, and making sure the brackets were in good alignment with the internal threads on the engine body for installation. It was decided to use 6061-T6 Aluminum due to its low cost, easy machinability, and decent material properties. Bearings were also installed surrounding the shafts to reduce dynamic load on the supports and wear on the system. Initially, mock-ups were made in CAD to meet the geometric requirements, but more substantial analysis was needed.

Due to the complexity of the shape and loading on the supports, it was determined to not do calculations by hand and simply do finite element analysis (FEA) simulations to determine the stresses in the support brackets. It was only necessary to model the supports; as the aluminum supports would be much more likely to fail than the steel. After doing the FEA, it was determined that the material and design were more than sufficient to handle the weights of the shafts, with stresses remaining below 15 MPa in all of the brackets, well below the alumnium's yield strength of roughly 200 MPa. See pictures of the FEA results in Appendix B4.

The fourth and final support made for the biggest engineering challenge. Originally, the group planned to make a large circular support bracket that would support the weight of the electric motor and affix it to the engine through some of the bolts already being used to affix the encoder. However, this presented many design challenges. The geometry and alignment of all the engine components would be difficult to protect from shear and torque. Due to the engineering and time constraints, the team opted to sacrifice the aesthetic considerations and move to a different bracket. This bracket had two parts, a 3D printed rest for the motor to bear the weight, thread and an aluminum fastening bracket, which bears no weight but keeps everything in place. The design prevents the motor supports from being a major failure point.

Design of Couplings

Two couplings had to be made to connect the electrical components to the motor. The first coupling involved connecting the electric motor to the crankshaft to power the cutaway display. The second involved attaching the encoder to the camshaft to provide position data to the microcontroller.

To affix the encoder to the camshaft, a dual-section coupler was designed. For ease of assembly, external threads were machined in the coupler. A threaded hole was also placed on the inside of the camshaft to allow for mating between the two components. This was an easy to design part that was easy to assemble and disassemble. The encoder was not threaded, so set screws were used to affix the encoder shaft to the other end of the coupler. Aluminum was chosen for this coupler due to aesthetics and ease of machining. The specification for the threads in the application were ⅜" - 24 (⅜" nominal diameter and 24 threads per inch). The ⅜" size was the largest basic size thread that could be tapped into the camshaft, and the larger pitch enabled more thread engagement and more precise alignment than coarser options considered.

The crankshaft coupler was designed similarly, but on a larger scale than the camshaft. The design was more robust because this coupler supports more weight. Additionally, the coupler had an internal thread to connect to the crankshaft, because it was already threaded. In addition, to ensure more reliable connection between the motor shaft and coupler, three set screws were employed. M14 - 1.5 (14 millimeter nominal diameter and 1.5 threads per millimeter) threads were used for this coupler because the external threads for the crankshaft already existed. This coupler was made of 464 naval brass.

During this stage, it was also determined to only operate the engine in the original spinning direction instead of the planned bi-directional operation. By spinning the motor in the standard operating directions, the right-handed threads on both couples would be under a condition where they would be self-tightening. However, running it the other way would potentially loosen the threads and cause some slipping from the limitations of the set screw tightness. The loss of that functionality to utilize threads as the fastening mechanism was deemed to be a worthy trade-off.

Wiring

In order to make the electronics work and interface with the mechanical components, extensive circuitry needed to be developed. The circuitry was centered around using the P2 microcontroller's input/output pins and ensuring that the electrical components were wired according to specifications.

The circuits are turned on by the P2 microcontroller. Each pushbutton (8 total) has a pull-down resistor to ground to ensure that it is reading on and off correctly (without a current sink to lower the output to 0V, the pins may still read an "on" signal even when the button is not pressed). Two pins receive the rotary encoder speed and direction data. The encoder signals usually read as "on", but when the encoder passes through a certain checkpoint, it sends an "off" signal to one of the output pins. The time between signals are used to calculate speed, and the sequence of the A channel and B channel signals determines the direction of rotation. This means that the A and B channels require pull-up resistors to protect signal quality. The LED channels (6 each), are each wired to a P2 pin (to turn them on) and ground, and they have 100 ohm resistors to protect the pins and diodes from excessive current.

The electric motor, inductive proximity sensor, and Sprite 4K are wired in accordance with their respective wiring diagrams. The Sprite 4K uses a special two way serial communication protocol – the P2 transmitter sends an addressed message to the Sprite 4K which plays the proper video. This protocol makes it easier to code than other alternatives.

There are two main circuits at work powering the machine. There is a 24V, high power circuit powering the motor and inductive proximity sensors, and a 5V circuit sharing a ground powering everything else working off of the P2 microcontroller. As a result, the group is using optical isolator integrated circuit (IC) chips to isolate these two circuits from one another. These IC chips will allow the 24V and 5V circuits to communicate with each other while also preventing noise from the power circuit from interfering with the signal circuit. The two power supplies use separate grounds in the wiring configuration. This communication is done by using infrared (IR) sensors/diode emitters to signal information from one circuit to another. When the signal passes through, the chip turns on a diode which activates the power circuit, much like a transistor or relay.

All of the wiring diagrams are displayed in Appendix B6.

Components Description and Final Design Specifications

The main piece of the engine model is the Predator 150cc 6HP engine. This engine design was selected for a couple of reasons. The combination of sizing and the single cylinder model made it a good base for displaying all of the features desired. The use of real engine parts that are over designed for the forces and operating conditions of the model satisfy the groups specifications on fatigue life, operability, and limited need for maintenance.

To power the model, a 24V, 60W brushless DC motor from Stepper Online was selected. This motor provides several operational advantages: its reduction gearbox gives it a high holding torque and will allow it to operate in the 50-150 RPM range that is desired by the group. Also, because it is brushless, the service life should be much better than their brushed counterparts. Power for the motor and signals come from 24V, 480W and 5V power supplies that are electronically isolated to prevent signal noise.

In order to connect the electronics to the engine block, an extensive system of supports and couplings were created. These couplings make the needed connections between the motor and engine shafts, supports for the shafts, and rests for the engine block and motor. These couplings do not serve to meet specification requirements, but they do keep the setup together and were extensively engineered to prevent physical failure. Additionally, 3D printed mounts were built to connect the inductive proximity sensor to the engine, a mount for the electric motor, and the control panel for people to control the display.

For the final mechanical consideration, a mount was cut and constructed out of wood to serve as a base for the entire engine display and house electronics. Components that were at risk of moving were bolted into the wood piece to secure them. The oak wood was chosen for aesthetics and structural considerations. An H-beam was machined in the wood shop, and then the team mounted components by drilling holes in the board to fasten the bolts and screws into. This design was able to balance both the prominence of the display while also keeping it portable to move it to an optimal display location.

A perfboard was soldered with all the necessary components to facilitate the electronic controls. Electronic control is facilitated by the Propeller 2 microcontroller chip. This complex chip has 64 input/output pins to control the wide variety of circuits needed to make the design work. There are two main circuit operations built out in the project. The first circuit setup controls the engine speed and motion. This is facilitated by using an Uxcell SN04-N inductive proximity sensor to locate cam position and a Taiss E38-6-360-24G rotary encoder to determine the speed and direction of the engine rotation (via the camshaft). With this information being fed to the microcontroller, the controller can process this information and change the motion of the engine as needed according to the software. This satisfies the motion control requirements. While speed control was initially planned, during the design phase it was deemed to be an unnecessary part of operation. However, the capabilities of all of the components allow for this to be incorporated in the future.

The other circuitry controls the LEDs and information display. The LEDs are programmed to come on when certain stages of the engine cycle are reached, improving the information delivery of the model. The display screen gave the group much more freedom to be creative with the engine information, easily satisfying the education requirements initially set out by the group.The information was displayed on an 1080p, 180Hz, Acer 23.5” XF243Y monitor. This enabled the group to present extra information with facts, figures, and text. This provided a “museum-style display” feel to the project where it did not already exist. By using a MedeaWiz DV-S4 Sprite 4K, the group was able to save the information slides as videos and display them on the monitor using the Sprite.

With the components provided, the display model (while not completely meeting every design requirement initially scoped in October) fulfills the primary design objectives of the project. The electronic and mechanical components safely operate in the ranges they were designed to handle, and are over-engineered for longevity purposes. By using the Propeller 2 chip, electronics can be fixed and modified using a system that all UVA mechanical engineers learn in their mechatronics course. The size of the display board provides a balance of stability and portability that would be hard to match with something larger. The LED lights and the display screen will enable the robust information delivery and create the exhibit feel. During the course of the project, the group learned to adjust the success benchmarks in order to keep designing a successful project in line with the problem statement.

All drawings can be found in Appendix C.

Assembly and Testing

Assembly of Display

Development of the assembly began in late Fall of 2024, when the engine was purchased and work began to take it apart and clean it out. Extensive machining was done in the winter of 2025 to enhance the visibility of the display and to cut holes for the various supports and couplings needed to attach the electronic components. This involved cutting out viewports in the engine for the process to be illustrated, taking holes and tapping threads in the back for the attachment of electronic equipment, and cutting out the carburetor for an auxiliary display.

The supports were first designed in CAD and then water jetted out of aluminum plate. Couplings were made by machining stock pieces of aluminum and brass. A laser cutter was used for the acrylic stroke indicator control panel and the wood box that contains the stroke indicator. By the middle of Spring 2025, all of the physical parts were created and ready for assembly.

Once the parts and couplers were made, the assembly process began. The process was fairly straightforward. The first step involved the fastening of the support brackets around the shafts and onto the engine, and the installing the connections of the motor and encoder to the engine. There was some iteration to ensure that all of the components were properly aligned at this time, and testing of the basic functionality of the electric motor and associated couplings was completed in this stage.

As the newly machined components were being re-attached to the engine, the wiring and electrical work began. First, the wiring diagram was completed and all of the circuits were able to be tested on a breadboard. Next, electronics began to be integrated into the physical setup. This involved the installation of LEDs within the machine, assembly of the user interface, and proper wiring of the motor and microcontroller. The display screen was picked out and wired into the setup with an HDMI cord. The different circuits were tested on a breadboard for general functionality and edge cases before being soldered onto a perfboard in their final configuration.

Independently, the display to showcase the engine was built. There was not much to consider from an engineering standpoint, so aesthetics, accessibility and durability were prominent. The display also had to house the 24 V and 5 V power supplies that run the display. The display was made out of wood (creating a wide H-beam), and the cutting was done by using a table saw to cut notches out of the wood block. The different pieces were then glued together to form the display board. The different components were then mounted and then the bolt holes were drilled into the wood block for proper fastening.

The completion of the mounts and component fastening was done in parallel with the perfboard soldering so that the electronic and physical configuration were completed with a few days to spare for final testing. Testing occurred in the last few days before project completion.

After bench testing of the electronics and final iteration of the mechanical components were completed, the final wiring configuration was completed. This helped to clean up the connections between the electronic components and the perfboard, and moved the power strip from the workbench to the display itself. Punch-list items such as a safety warning were also installed after final testing, which brought the project to completion.

Testing of Functionality

Testing of the physical and electrical components were necessary to ensure proper system performance. While engineering analysis was done for most components, that alone was not sufficient to ensure no unexpected issues arose.

Testing of the physical components was fairly straightforward during the initial assembly. Most parts, including the supports and all but one of the couplings functioned as intended immediately. However, the coupler that connected the crankshaft to the electric motor had two problems: an unintentional chamfer in the machining meant the motor shaft could not slide all the way in, and the set screws were too long, creating slippage potential and an eyesore. This was fixed by machining the extra bit of material out, and adding new set screws with a much better fit. There were also iterations of the support bracket geometry to ensure the best alignment with the engine block and to maximize visibility inside the engine.

When the display apparatus was fully built, more problems started to arise. Firstly, the cam followers created a loud squeaking noise while riding on the camshaft. This was solved by adding a dry lubricant to the cams. Another problem was that the mounts for the monitor and motor were too weak to hold up the components. The monitor mount was fixed by ensuring that the back of the motor was clamped to the wooden base. The motor mount's clamping and bolt tightening were made stronger to mitigate the motion to a passable level, but replacing the mount with a stiffer material is still needed.

These tests reinforced the necessity of the iterative nature of design. The calculations and drawings did not take into account these potential pitfalls (and in the case of the noise, the analysis would have been prohibitive to do). It took building the apparatus and working out the remaining problems one by one to bring the mechanical components to functionality. However, the group's understanding of fundamental mechanical engineering principles was what allowed these problems to be easily found and mitigated using scientific analysis.

There were issues with the electronic components too. The main problem was that the encoder was officially rated to run off of 5-24 volts (this was also specified on its label), so the group initially wired the encoder at 5 volts. However, it was later found that, because the encoder had a 5 Volt linear regulator in its internal circuitry, an extra 2 volts (7 volt minimum) was needed to enable proper functionality. So the technical datasheet for this encoder was wrong! The group had to implement a boost converter to boost to 8V, which was sufficient for the encoder to operate consistently.

One lesson learned here was dealing with OEM component sourcing. It was highly unusual that both the manufacturer datasheet and product label would provide the wrong information about the operating range of the devices. However, voltage regulators and how they work are concepts within the scope of mechanical engineering. The group's understanding of the necessity of voltage boosting should have superseded the OEM recommendations. Component sourcing involves just as much engineering as design at times. Additionally, every time the wiring was redone, the code functioned slightly differently, mandating rewrites even when the code worked perfectly at a given wiring configuration. In order to ensure this instability did not short or damage components, fuses were installed next to the most critical electronics.

The software testing was the most challenging part of the testing process. The encoder was continuing to provide problems even after the wiring was complete because it would not reset. This was fixed by putting the encoder control on a single method and calling the method when necessary, instead of dividing the encoder control into different places in the software. The P2 chip also had issues with its parallel processing capability. While all eight parallel processors are supposed to be capable of functioning equally, only one “cog” (processor) would actually actuate the lights and motor. It is unclear if these issues resulted from problems in the hardware or issues benign triggered by other code in the algorithm. Regardless, a workaround was still needed to allow the system to function with what was working. This required creative programming because independent components could not be controlled using independent timing. This was solved by using multiple processors to time and track the encoder and screen cycle, and using the primary cog to actuate all components. This method also involved optimizing the wait times in the code to ensure that the cycle did not rush itself but also did not lag due to dead time. Solving this issue showed how a creative mechanical engineer with mechatronics knowledge can use software to solve electronics problems.

Finally, the team resolved issues with the user interface. It took interaction and outside input to resolve issues with the button pressing and the redundancy between the power and home buttons. It was decided that the power button would stop the machine and the home button would spin it. Here it was necessary to engage with potential users and get the necessary user input to finalize that good design.

All of these issues revolve around the challenges of software development came down to issues surrounding algorithm design. When writing code it is important to test the code piece by piece and comment on what each line of code is supposed to do. This allows debugging to be done piece by piece. It is also important to use pseudocode effectively to design algorithms that can be understood by the programmers. This allows errors in the code to be resolved more quickly and more programming to be done more efficiently. Learning the coding language used inside and out will also allow the programmer to understand the nuances of the code and how seemingly meaningless syntax can cause or mitigate massive errors.

Summary and Conclusions

Fall 2024

The work completed in this semester involved two main objectives being completed: the initial design and selection of the engine cutaway display, and the development of the 3D printed prototype.

By completing the ideation, screening and selection, specifications, and technical analysis assignments, the group was able to determine the necessary design considerations for the cutaway model. Speed requirements, fatigue capabilities, electronic control standards, and display of information were the primary design concerns addressed by the early part of the work. The primary accomplishment of the semester was the identification and purchase of the Predator engine, whose four-stroke operation and geometric layout made it the ideal choice for the project.

The other driver of work was the prototype, whose development worked in parallel with the cutaway model. The group worked through the iterative design and settled on a single cylinder engine with a gear-timed rocker shaft to control the valves. By taking the time to build out the engine mechanisms, the group gained a better understanding of how the mechanisms actually work and how best to display the engine operation on the cutaway model. It provided a cheap template for experimentation that provided focus for the work in the spring on the cutaway model. See Figure 19 for the completed prototype.

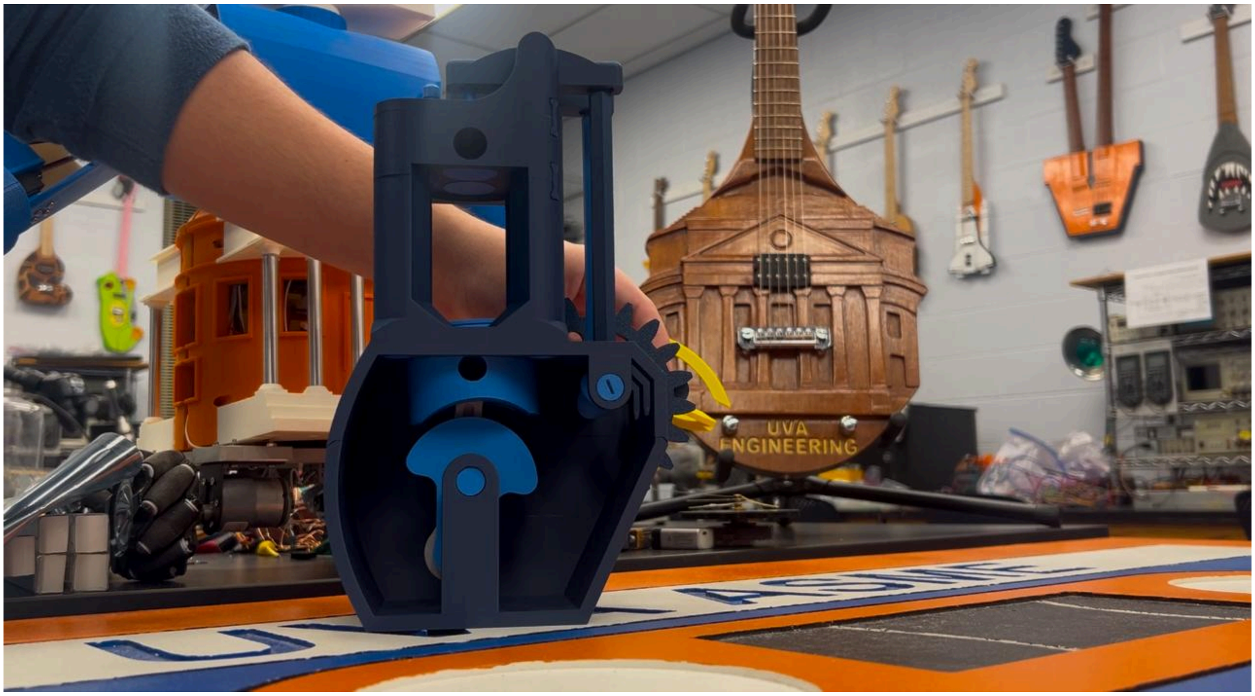


Figure 19: Final 3D Printed Model

Spring 2025

To finalize the prototype from the fall, the 3D printable design was published online at the start of the semester on Makerworld.com, Printables.com, and Thingiverse.com, which can be found in the References. An instructional video and written instructions were also produced to allow for easy assembly. The model was engaged by users online and others were able to make the engine model on their own, which satisfied the original purpose of the fall project.

In the early part of the semester, the group worked on many of the most important physical items. The necessary cuts into the engine were machined over the course of a few weeks, and further technical analysis was done to determine the necessary specifications of the other components (mostly the supports and brackets). At this time, the motor and encoder system as well as the microcontroller that would run the engine were selected and purchased. This combination of P2 chip, inductive proximity sensor, and quadrature encoder allowed the motion of the motor to be controlled by software.

As the machining wrapped up in the early spring, designs for supports and connections were completed and machined. These included couplers for the electric motor and sensors, and supports that allowed the engine shafts to stay in place even though material was removed from the engine. At this point in time, some of the electronics were tested to ensure the design was meeting all intended specifications; power supplies were acquired and bench testing began. Physical designs of mounting pieces and the informational slides to be displayed on the monitor were also completed at this stage.

At the end of the project, the components were mounted on the wooden display platform, and the electronics in the engine were installed. This enabled the soldering of the final electronic configuration and the testing of the encoder and software (which required everything to be in its proper place). Testing was extensive and involved working out bugs in the software, configuring the encoder data, and syncing the lights and display software to the motion of the engine.

Finally, the model was completed and ready for display, and the final reporting was wrapped up. This stage involved optimizing wiring and electronic control, and downloading the program to the P2 chip's flash memory so that the program could be continuously run while no power was provided to the P2 chip. See figure 20 for the final model.

Figure 20: Final Model

Future Work

There are several areas in which work on the project could be expanded upon. These include both areas that the group considered but chose not to include in the final project scope, as well as other ideas that make for logical extensions of the work completed here. The real beauty in this project is that room was left for lots of add-ons. Our group tried to capture what we believed would be the most important features of the four-stroke engine, but there was still room left for other features to be added.

Two areas of design that were unfinished could be initial avenues for future work. Firstly, speed control of the motor rotation was a desired feature that was never implemented. Adding a potentiometer that controls motor speed would be a useful addition. Another feature that was not finished was the mechanical supports. The initial supports for the monitor and the motor were not supposed to handle any load, but the dynamics of the motor and weight of the monitor put excessive stress on the mounts. Effective stopgaps were made, but replacing the PLA with stiffer material like aluminum could serve as a more effective long term solution. There was also some motion between the motor and the engine, so a flexible coupler or universal joint may be necessary for mechanical compliance and to prevent excessive stress. Another alternative could be to reduce the tolerances for the shaft fit to eliminate eccentricity.

Pivoting into natural expansion areas, one area that could see future work is the expansion of safety features on the model. People coming into contact with the model by touching it can be dangerous to both the people and the machine, especially if the engine is on and spinning. The current systems can be improved upon to make them smarter and prevent the worst case scenario of touching the spinning engine. One way this could be achieved is by adding an infrared sensor whose signal would be disrupted by someone putting their hand near the engine. This could trigger an "emergency stop" of sorts to stop the engine from moving, preventing some of the more dangerous collisions.

Another area could be the inclusion of more types of information display. This could be achieved in several ways. Additional machining or 3D printing could be done to showcase more of the auxiliary components in the engine. Additional audio or screens could be added to enhance information delivery beyond what has already been accomplished. Furthermore, the 3D printed prototype could be retrofitted to house electronics, allowing for that more widespread device to gain some of the capabilities of the permanent model.

One more external solution that would further address the questions the project tried to tackle would be to figure out what other machines may be good fits to build future models on.

These models could be built in a similar method to the processes developed by the group over the course of the school year. Learning about other systems such as drivetrains and electromechanical devices could benefit that hands-on experience.

References

Basshuysen, R. V., & Schäferf. (2016). *Internal Combustion Engine Handbook: Basics, Components, Systems, and Perspectives*. SAE International.

Bootjevarder. (2023, November 12). 4 Stroke 4 Valves Over Head Camshaft Engine. Printables. https://www.printables.com/model/212625-4-stroke-4-valves-over-head-camshaft-engine

Bootjevarder. (2023b, November 15). 4 Stroke Flathead Engine v1.0. Printables. https://www.printables.com/model/135305-4-stroke-flathead-engine-v10

Cicatko, J. J., & Faberman, S. H., & Hartless, S. L., & Wallace, H. J. (2025, February 6). Four Stroke Engine Model - No Glue, No Supports. Printables. https://www.printables.com/model/1170209-four-stroke-engine-model-no-glue-no-supports

Cicatko, J. J., & Faberman, S. H., & Hartless, S. L., & Wallace, H. J. (2025, February 7). Four Stroke Engine Model - No Glue, No Supports. MakerWorld. https://makerworld.com/en/models/1083421-four-stroke-engine-model-no-glue-no-supports#profileId-1075752

Cicatko, J. J., & Faberman, S. H., & Hartless, S. L., & Wallace, H. J. (2025, February 8). Four Stroke Engine Model - No Glue, No Supports. Thingiverse. https://www.thingiverse.com/thing:6941301

Ford, H. (1935, March 12). Internal Combustion Engine.

Harvey, P. (2018, November 14). *The 2-stroke cycle*. Gas Engine Magazine - Preserving the History of Internal Combustion Engines. https://www.gasenginemagazine.com/gas-engines/2-stroke-cycle-zm0z19djzhur

Hilgendorf, D. (2022, August 24). *Two-Stroke vs. Four-Stroke Differences*. AMSOIL. https://blog.amsoil.com/two-stroke-vs-four-stroke/

Proctor, C. L. (2001). Chapter III. In *Encyclopedia of Physical Science and Technology* (Third). essay, RamTech, Inc.

Wang, Z., Pan, X., Zhang, W., Zhao, Y., Li, H., & Liu, P. (2020). The development trend of internal combustion engine. *Journal of Physics: Conference Series*, *1626*(1), 012139. https://doi.org/10.1088/1742-6596/1626/1/012139

What are supports in 3D printing? When and why do you need them?. (n.d.). Protolabs Network. https://www.hubs.com/knowledge-base/supports-3d-printing-technology-overview/

What is 3D printing? How does a 3D printer work? Learn 3D printing. 3D Printing. (2024, October 9). https://3dprinting.com/what-is-3d-printing/

ZockZock. (2020, January 3). 4 Stroke Engine Model Complete 3D Printed. Thingiverse. https://www.thingiverse.com/thing:4082307

Appendix A: Ideation Documents

*Begins on next page

Ideation Assignment → 10 concepts

Goal: Build a pedagogical engine model for use in MAE dept.

Big Questions:

- What parts and processes are worth showing?

- Visibility control: safety and part integration trade-offs

- What parts to use: OEM engine, ordered, 3D print, acrylic? others?

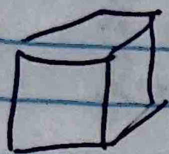
- Mechatronic integration: how much? Lights, engine control?

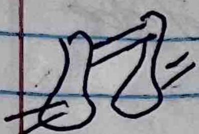
- Dissemination of information, audio/visual in display vs separate screens?

- Safety standards?

- Ease of construction vs visual ease of perceptions vs accuracy (ie, should values be extra large for demonstration?)

Concept Drawing Guide

 → motor

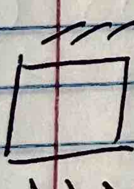
 → crank shaft

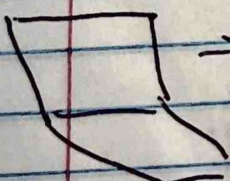
 → piston/cylinder

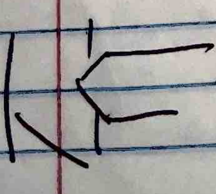
 → timing belt

▫ → microcontroller

o → push button

 → display screen

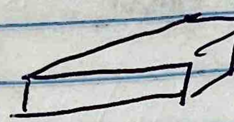
 → computer

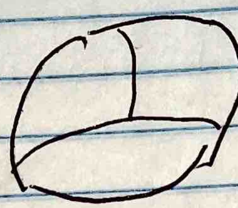
 → carburator

 → Camshaft

 → value set-up

 → Spark plug

 → table/flat surface

 → engine body

List of concepts

1) 360° open 1-cylinder design

2) Digital/virtual Model(s)

3) Constant step motor, separate information screen

4) Homeade Engine Parts in OEM engine body

5) Acrylic/3D print model w/ DC motor & encoder

6) Miniature model with bought parts

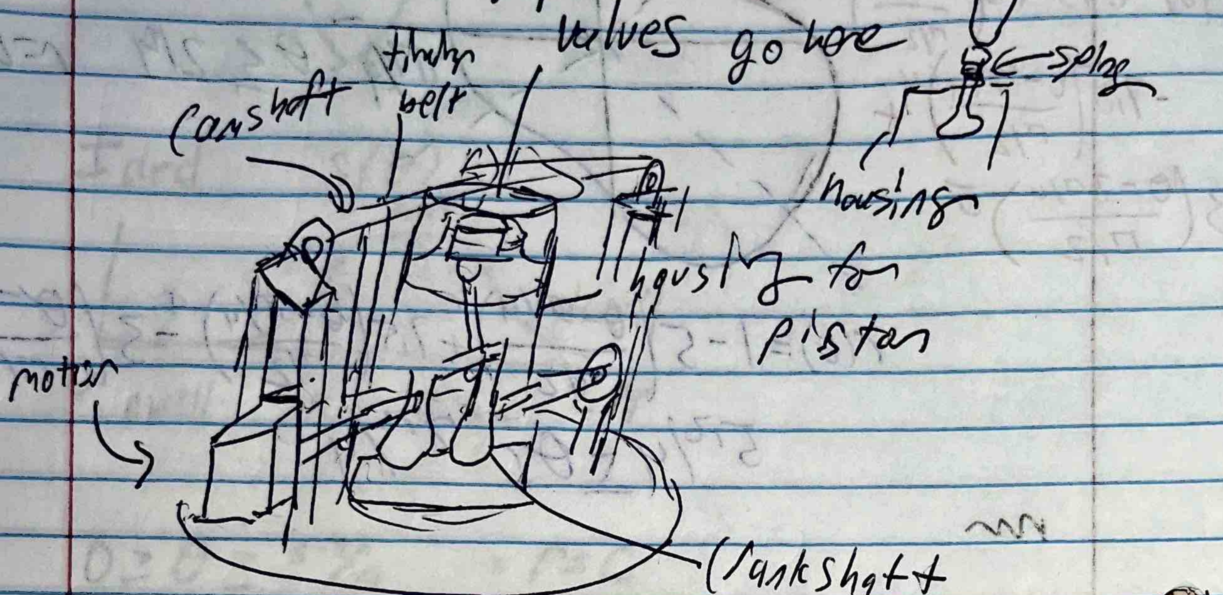
7) Computer-operated acrylic/3D print engine

8) Constent, low-intelligence motor using reclaimed engine pieces

9) Isolated mechanisms all on display

10) 2D model board

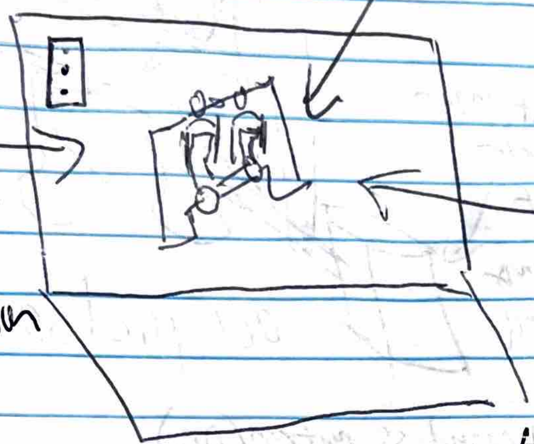
Concept #1 - 360° Open cylinder design
→ No OEM parts
→ max visibility



This model is designed for a full range of visibility from all sides.

the housing is complete, with many parts
→ table with slit for crank
→ raised platform for camshaft
→ cylindrical piston outline, inner cylinder to restrict piston motion
→ valve housing / roof
- Motor: stepper motor with propeller 2 control
- Shafts supported by roller bearings
- Timing belt to control camshaft
→ except belt, bearings all materials acrylic, 3-D printed, glass
→ will need to print many different pieces

Concept #2 → Digital Model/
Virtual Rendering

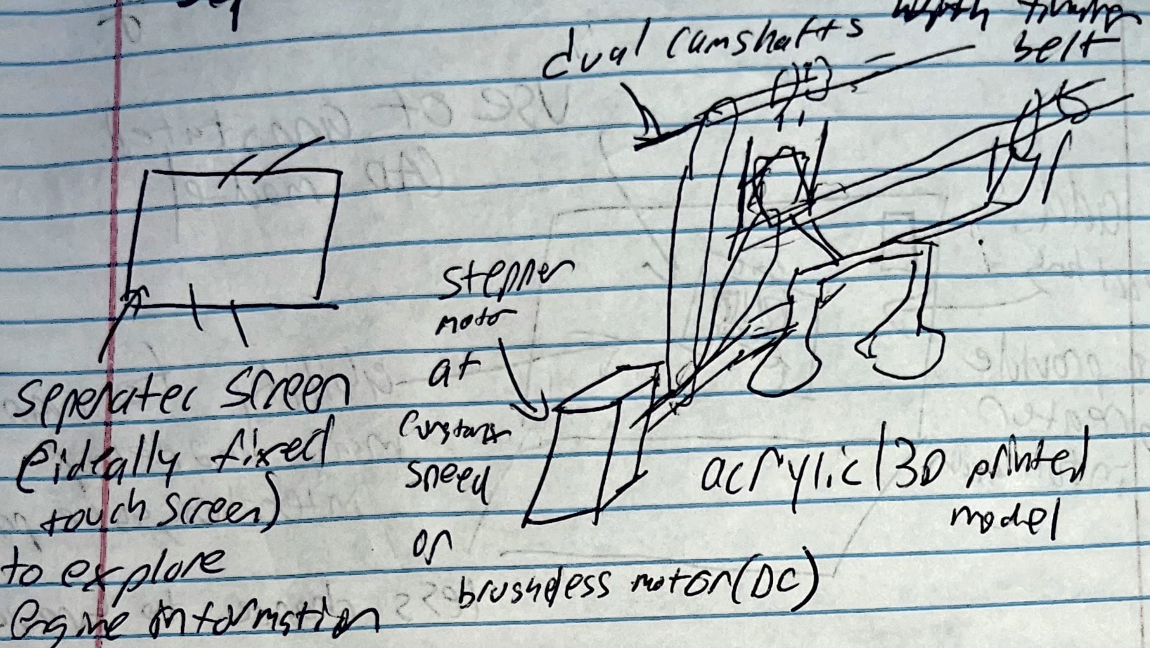


- Engine model would be completely digitized
- Create a web program with interactive CAD files
- Create push buttons to explain concepts
- Provides more illustrative examples and 3-D interaction

→ Design system at physical scale
→ add audio clips and pop-up text

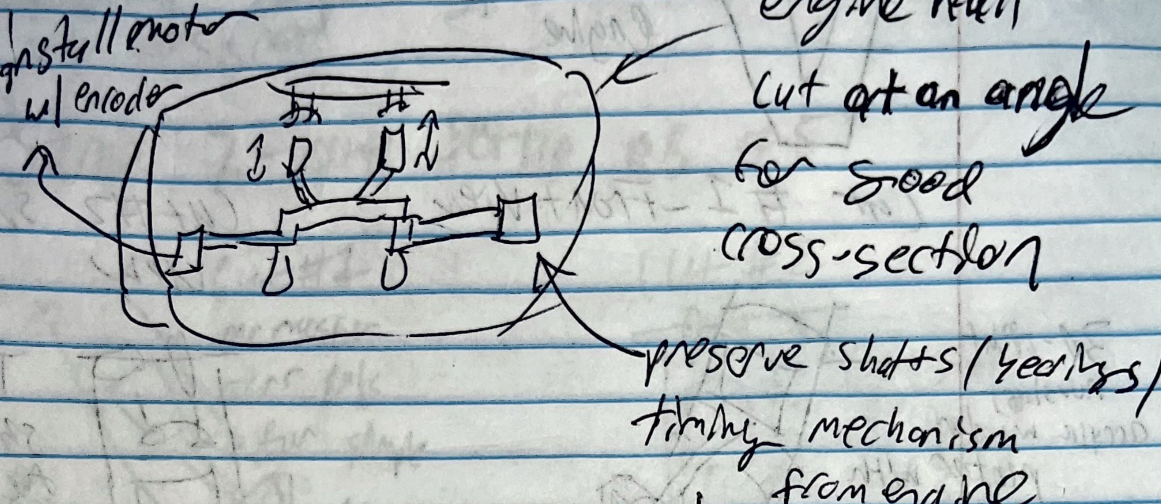
NOT physical construction, major con

Concept #3, constant stepper motor, seperate information screen



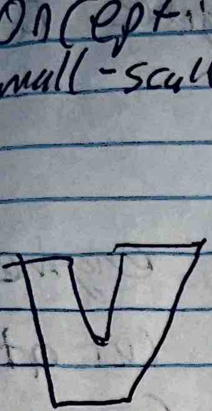
-> This design minimizes OEM parts and electrical/software complexity
-> similar design to concept #1, uses twin cylinder setup
-> DC brushless motor would eliminate programming, only on/off
-> LEDS could be added optionally
-> power shaft & camshaft connected by timing belt
-> relies on screen supplement for educational heavy lifting
-> print most parts and assemble
-> avoid gluing, use screws, interlocking

Concept #4 Engine Body, me-made parts



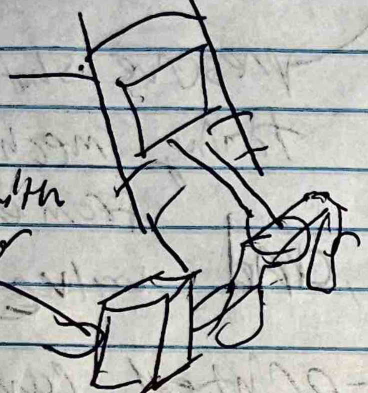
→ replace pistons, and valves with lighter 3D-printed components to lower load on engine
→ add programmable LEDs for visual aid
→ would allow best of both worlds, proper scale with less stressed conditions
→ could reverse engineer components, design will be lighter
→ can keep carburetor/fuel injector

Concept #5 - Acrylic / 3D printed small-scale model with DC motor / encoder



V-twin cylinder engine

Cut #1 - Front View



3D-print housings

acrylic window

motor with encoder for speed control.

Cut #2 side view

This cut showcases the valve assembly

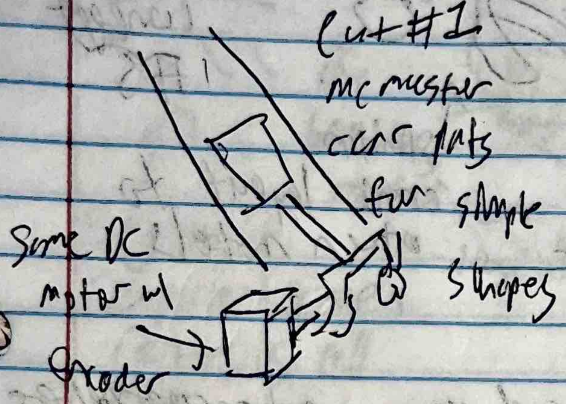
Use springs / cams to govern valve motion

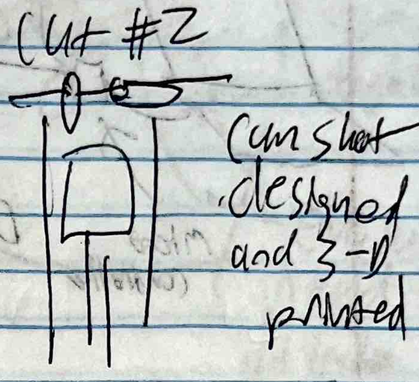
-> 2 90° cuts to see different views
-> camshaft connected via timing belt
-> mostly 3D printed
-> LED lights added for demonstrative purposes
- crankshaft designed with correct counter-weight
- use CAD to design most parts, consider mcmaster-carr
- LEDs for gas flow
- use I2C chip to control electronics

Concept #8: Miniature model with pre-purchased parts

Similar to concept #5, but with many structural components pre-purchased and not designed

- Same 2-cut setup as #5





- consider separately timed motors or timing belts

→ add LED lights as in previous concepts, consider push buttons for pre-recorded info

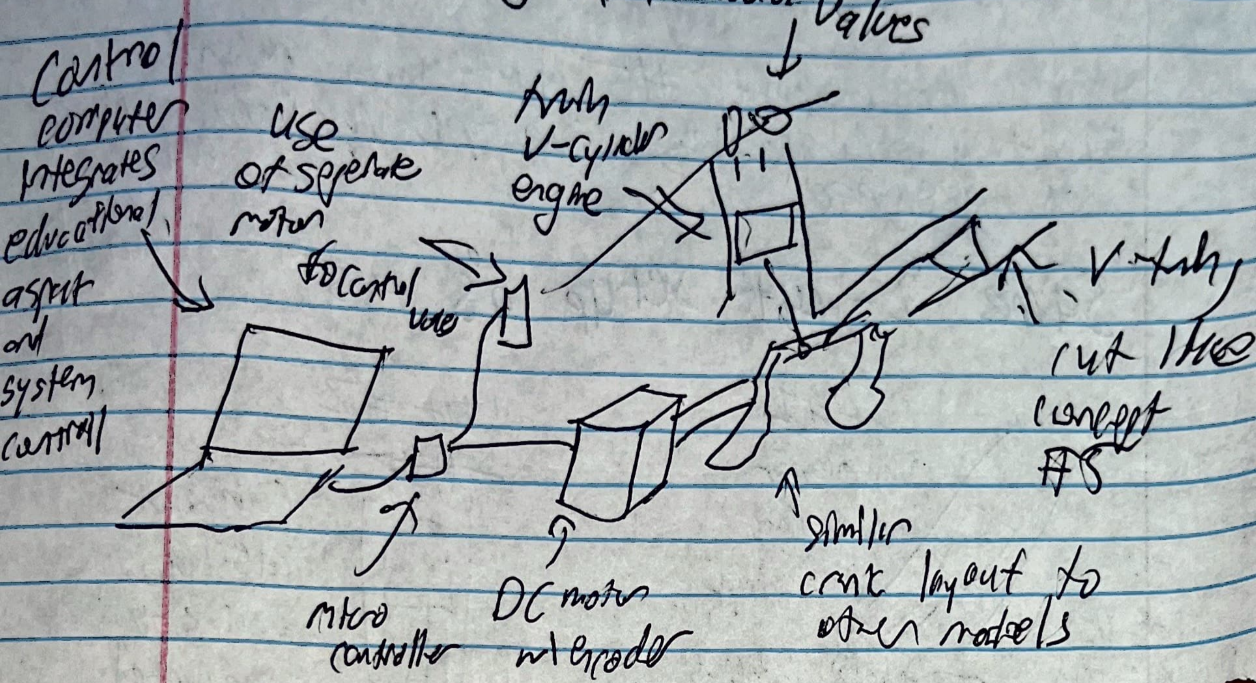
→ consider cost of McMaster parts, cut viewing window ourselves

→ Ensure torque specs on motor are sufficient

→ realistic scaling or exaggeration for visuals sake?

→ consider a carburetor attachment

Concept #7 Computer-oriented acrylic engine model



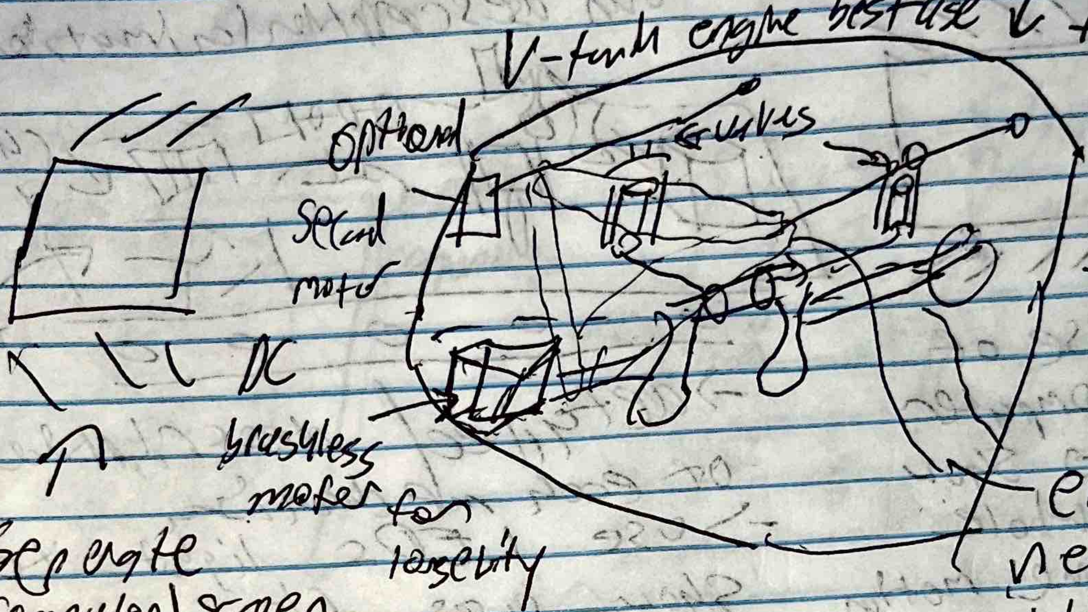
→ Use of computer and many microcontrollers will allow for better integration of controlled components/LEDs/etc
→ education/info dump and engine operation correlated

→ valve timing electronic, not manual
→ large, complex housing to set up different motors

→ V-twin built and cut similar to concept #5
→ 3D print/acrylic parts

→ major con: reliant on software, could be a liability

Concept #8 → Constant running motor (like concept 3, but from reclaimed engine parts (2-motor system)



cut out from engine, use parts from engine

evaluate need for a timing belt

Separate computer/screen controls all educational aspects of the system (explanations etc)

→ LED lights on a constant cycle, powered by a single micro controller

→ replace fatigued parts like OEM bearings if needed

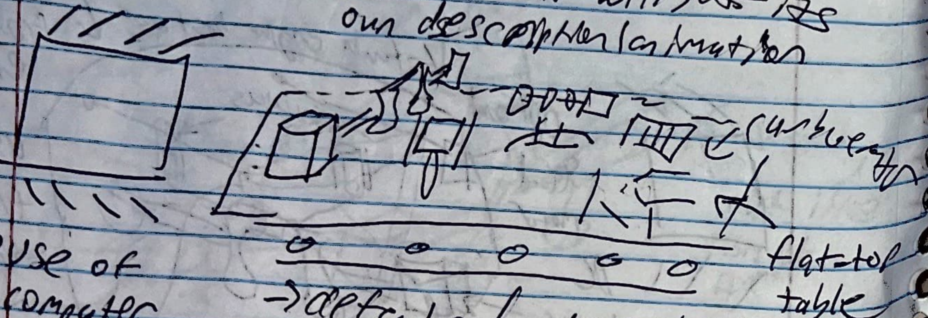
→ inspect valve assembly

→ consider a second motor to run and time valves instead of a timing belt

→ try to keep carburetor intact, see how it can be integrated into design

Concept #9 → Mechanism-based display, no integration

Each component will get its own description/animation



→ Use of computer to show the whole engine motion

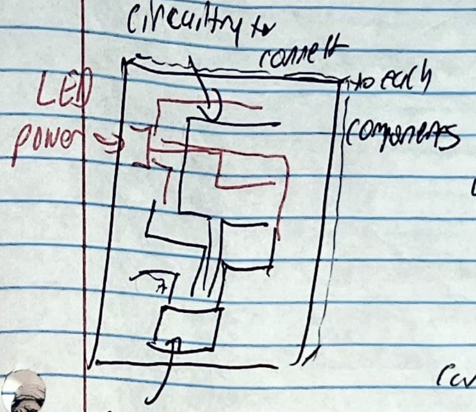
→ detailed description of each mechanism

→ use LEDs lights to show gas flow

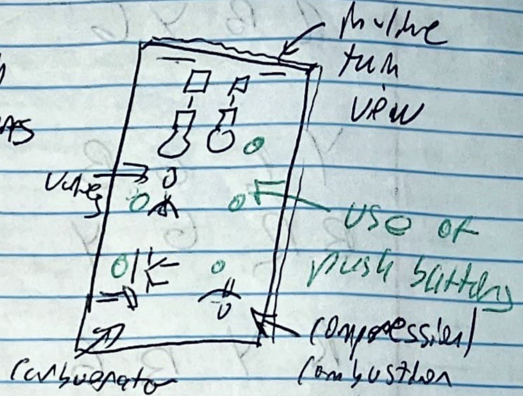
→ will require several motors to run each mechanism independently
→ combination of physical & digital components
→ less interlocking, major mechanical errors than a full-build engine
→ use push-buttons to activate each component
→ consider voice recordings for each part
→ use 3D print or OEM parts to model components
→ may not develop full engine understanding with no interaction between components

Concept #10 → 2-D model board

Use 2-D and acrylic to model engine components and integration



1 motor



In-depth piece-based physical demonstrations

→ parts made from acrylic or 3D printed
→ can use advanced circuitry to interconnect components
→ each model activated with pushbuttons
→ use text plaques and audio
→ can have a full-system model at the top, timing belt in the back to control speed of rotation
- LEDs can highlight model gas flow, and show directions
→ able to be wheeled around

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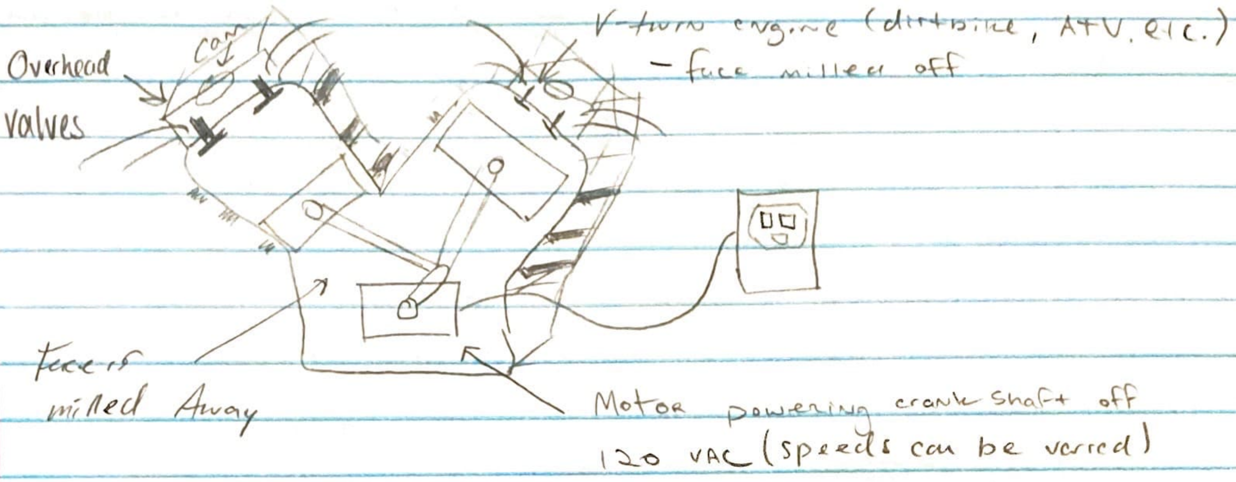
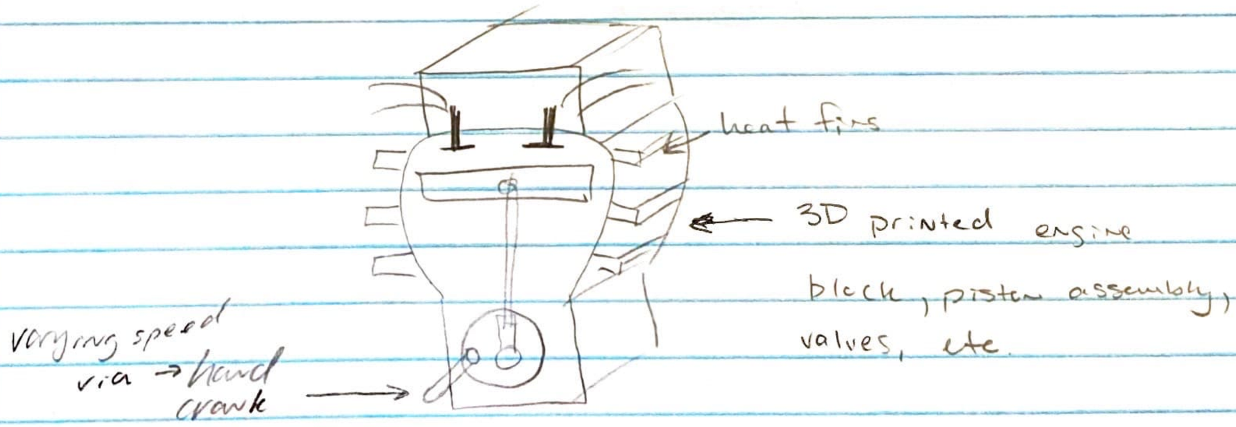
HW # 3: Ideation

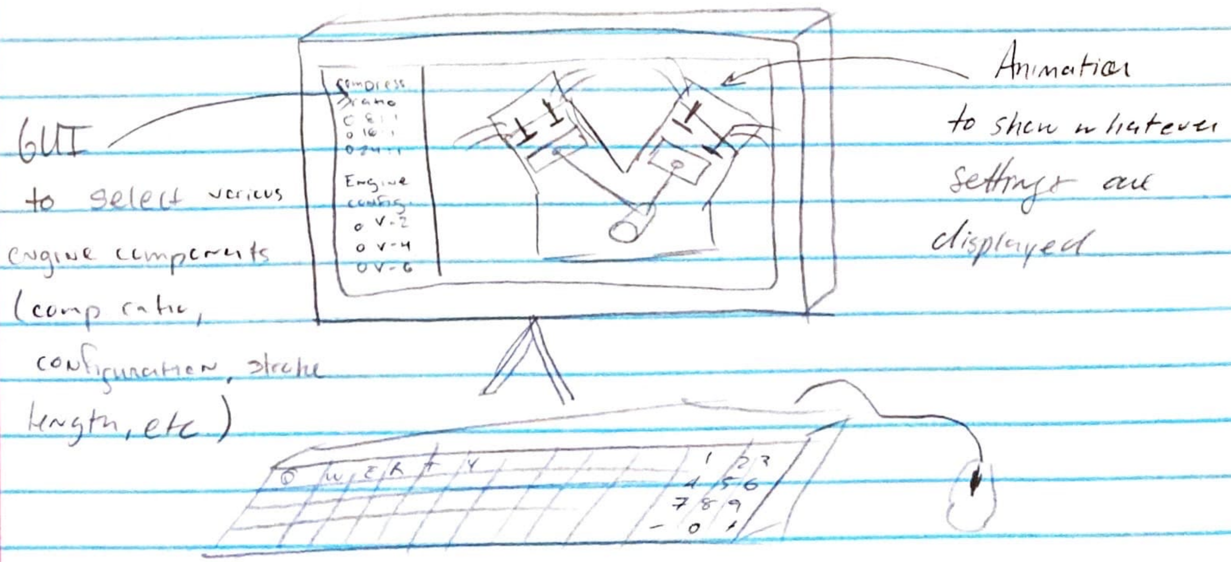
Idea 1) Full-scale, cut-away, electrically powered model



Idea 2) 3-D printed single cylinder model, hand powered



Idea 3) Engine model GUI



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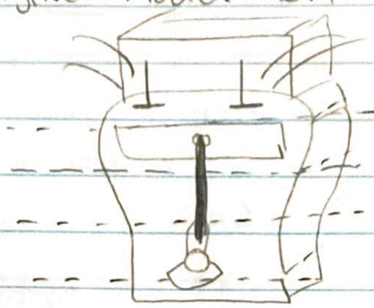
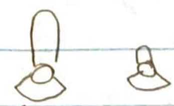
Idea 4) Engine Model Kit



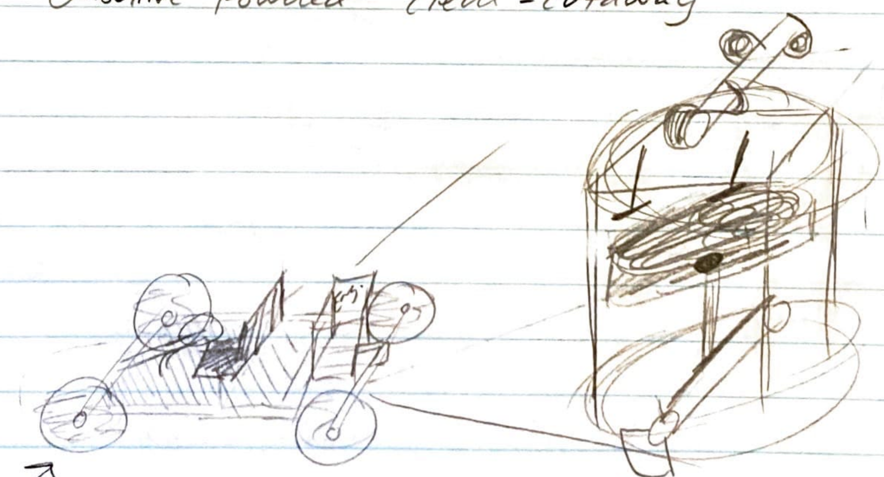
block comes in multiple pieces to be added/taken to change compression ratio, etc



↳ different crank sizes to be swapped out and show different stroke lengths

~~A~~ other parts can be swapped to show different aspects of the engine. Will also come in different configurations (Inline, boxer, V-2, V-4, ...)

Idea 5) Gasoline Powered Clear-cutaway



Go cart / Golf cart / etc. can be used as normal (w/ fuel), however now the transparent engine casing will allow for engine mechanics to be shown during operation.

Engine with some sort of clear casing (internals) can be seen without cutting into engine.

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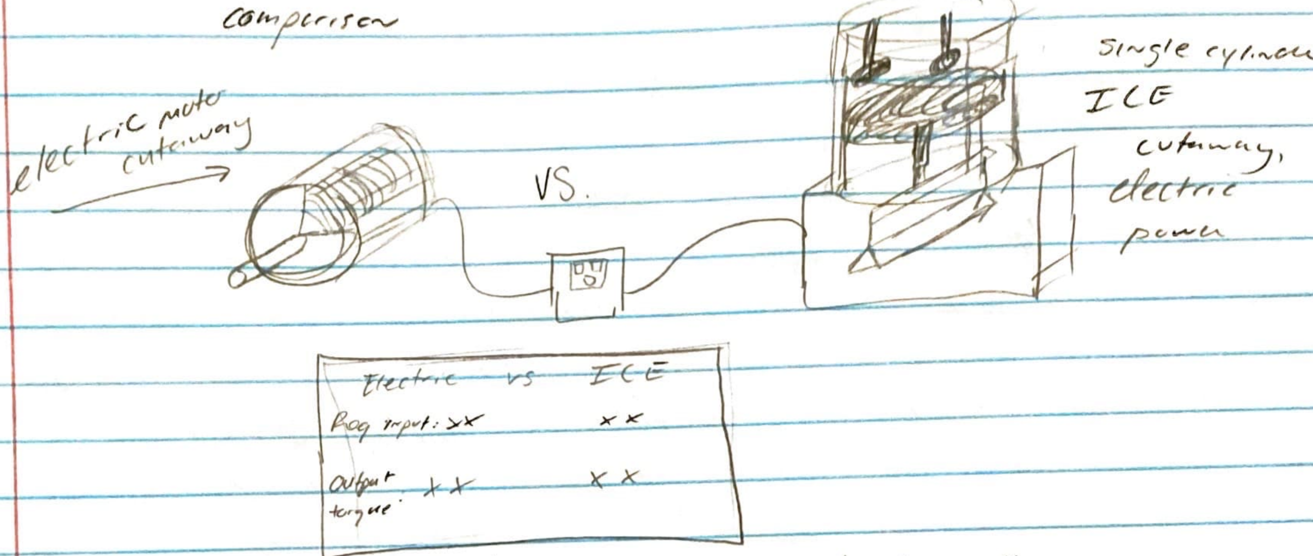
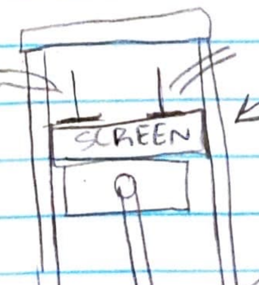
HW #3 Ideation

Idea 6) Electric Motor vs ICE motor side by side comparison



↳ output/video screen that will compare various factors/inputs into each engine/motor type, and show the outputs (similar metrics b/t the 2).
↳ Allows for users to form opinions on which is better.

Idea 7) 2D Acrylic Model with backlit screen
☆ Inspired by Prof. Garner's Modern Mechanisms board.



video screen can animate display videos during 4 strokes. For example, a blue screen showing air for suction stroke/stage

acrylic-cut block outline, piston head, rod, etc.

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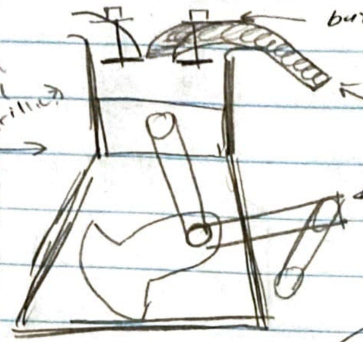
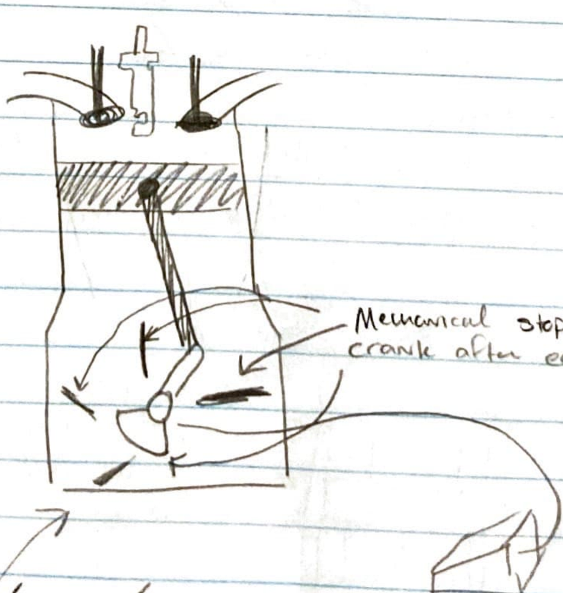
Idea 8) Redneck engineered Model



This works by manually introducing components in the combustion chamber. The intake valve can be opened to introduce air. The valves will seal, and the hand crank can be turned for compression. A flammable liquid will be inserted, and a lighter can then be used to introduced spark/fire, causing expansion to occur. The exhaust valve can then be opened to complete the cycle.

Idea 9) Foot Powered Model



Foot pedal is used to advance the crank through 1 stroke. Foot pedal converts linear to rotary motion (crank).

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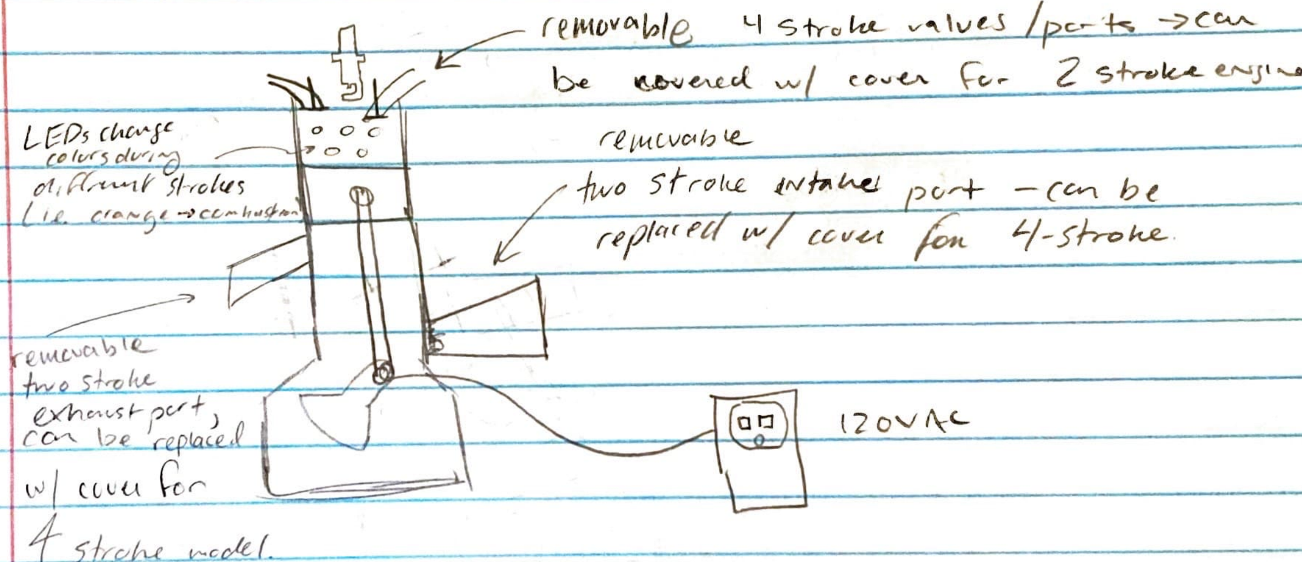
HW# 3 Ideation

Idea 10) 2 Stroke vs. 4 Stroke Interchangable Model

Similar to Idea 4, this model will come w/ interchangable parts to make both a 2 & 4 stroke model and allow for others to compare the two. It will be powered by a electric motor and have LEDs to enhance visuals



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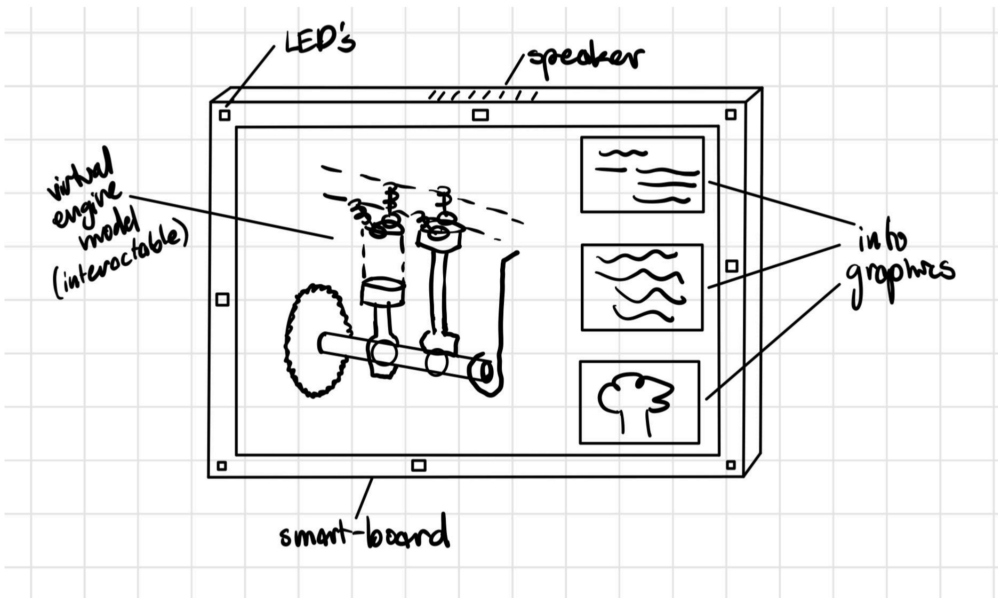
09/12/2024

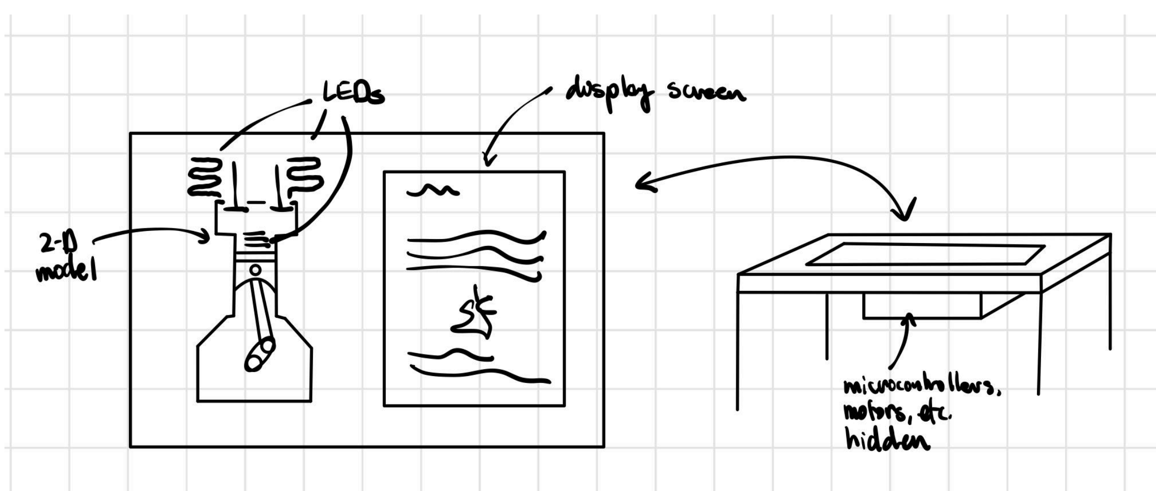
Homework #3: Ideation

General Product Description: Dynamic and interactable educational model of a four stroke internal combustion engine with both mechatronic and mechanical components.

Design 1: Virtual interactable engine model. Displayed on an interactive smartboard with multiple screens, LEDs, speakers, and other augments to the educational experience.



Design 2: 2-dimensional “tabletop” engine model. Components made of acrylic or 3-D printed, driven by stepper motors & controlled by microcontrollers. LED lights and other augments to the educational experience also included.



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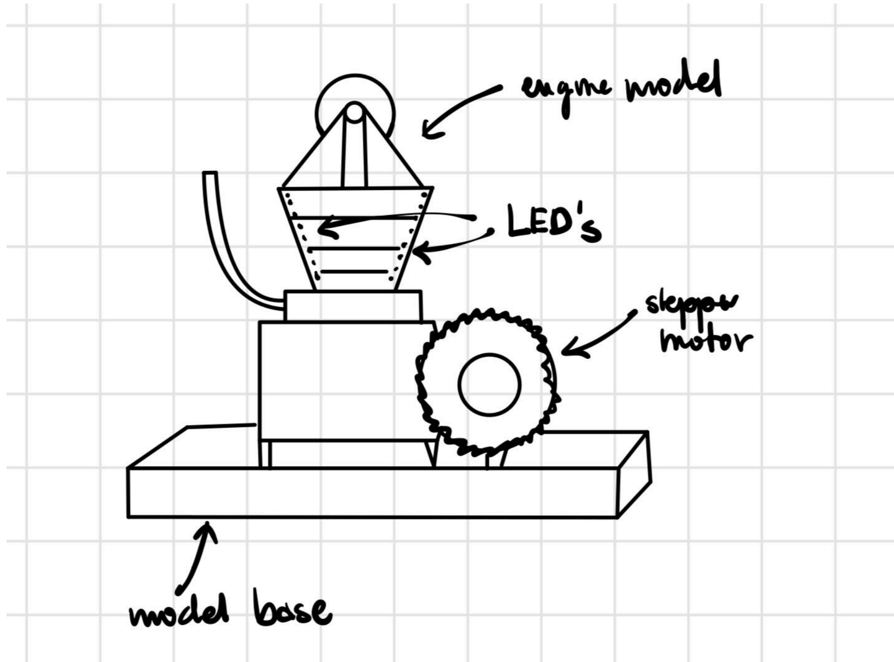
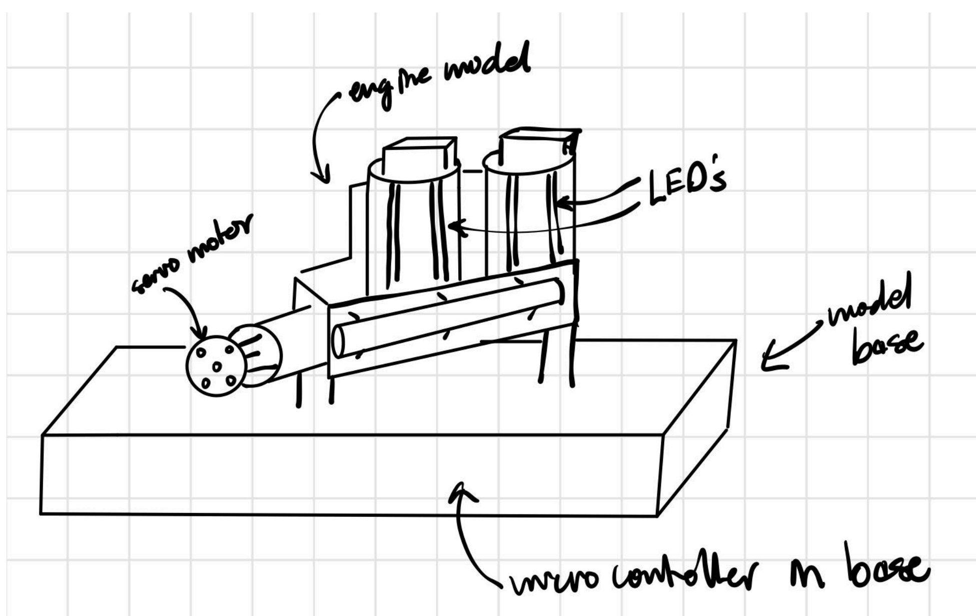
09/12/2024

Design 3: Single-cylinder, 3-dimensional battery powered four stroke engine cycle model. Powered by stepper motors w/ LED's and other components to highlight each phase.



Design 4: In-line two-cylinder, 3-dimensional four stroke engine cycle model. Powered using wall outlet w/ servo motor, timing controlled using microcontrollers. LED's and other visual components used to show phases, as well as timing differences between cylinders.



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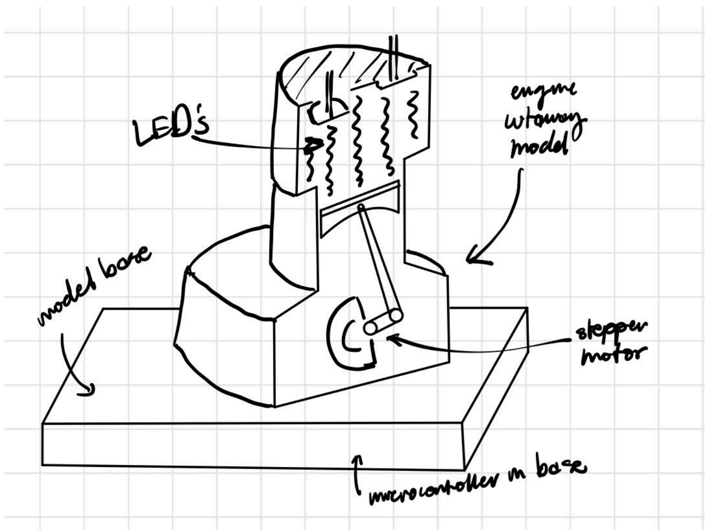
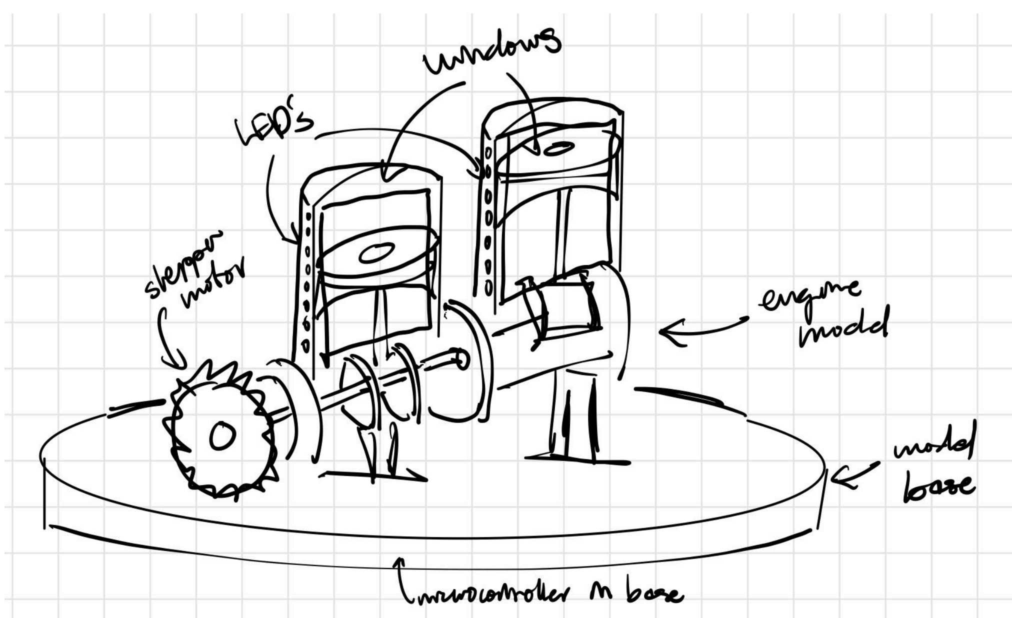
09/12/2024

Design 5: Cutaway internal combustion engine model. Full engine block w/ crankshaft, piston, single cylinder, etc. for full engine viewing experience. Crankshaft rotation driven by stepper motor, other moving components controlled using microcontrollers. LEDs used to show intake, exhaust, etc. phases. All powered using a wall outlet.

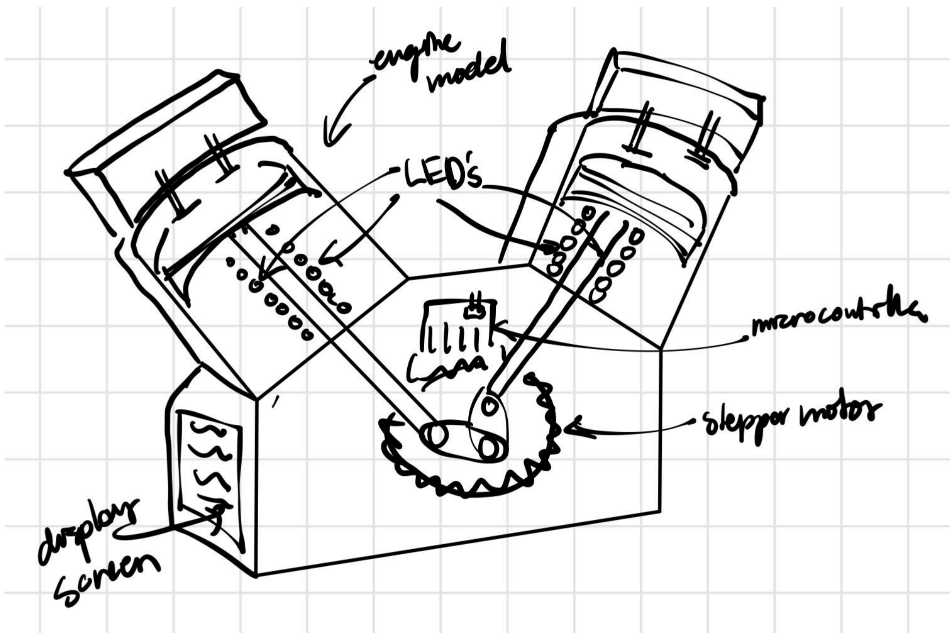


Design 6: Full inline ICE model, complete engine block w/ crankshaft, double cylinder, pistons, etc. Walls in the engine block & cylinder housings drilled out and replaced w/ acrylic or plexiglass to allow for viewing of the internal components. LEDs to show phases. Powered using a wall outlet.

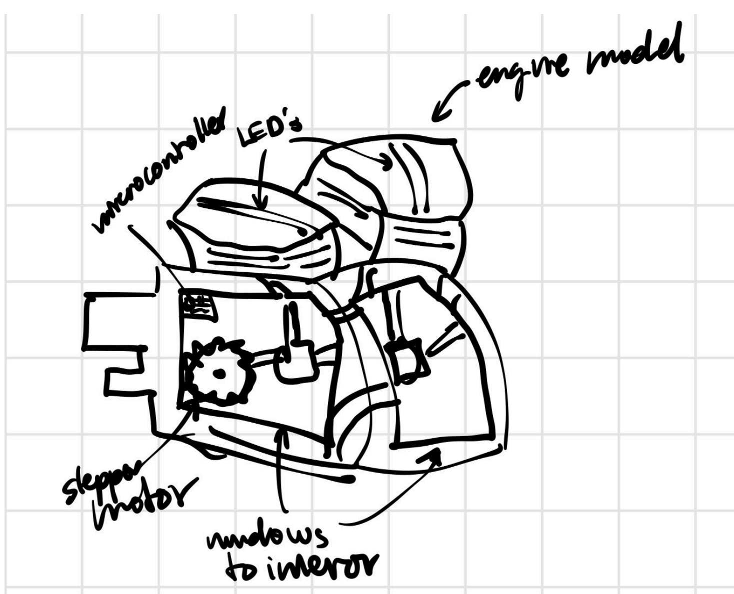


Jonah Cicatko
MAE 4610
09/12/2024

Design 7: Cutaway V-twin ICE model. Motion driven by stepper motor, timing controlled using microcontrollers & LED's to show phases, powered by wall outlet. Display screen showing important information.

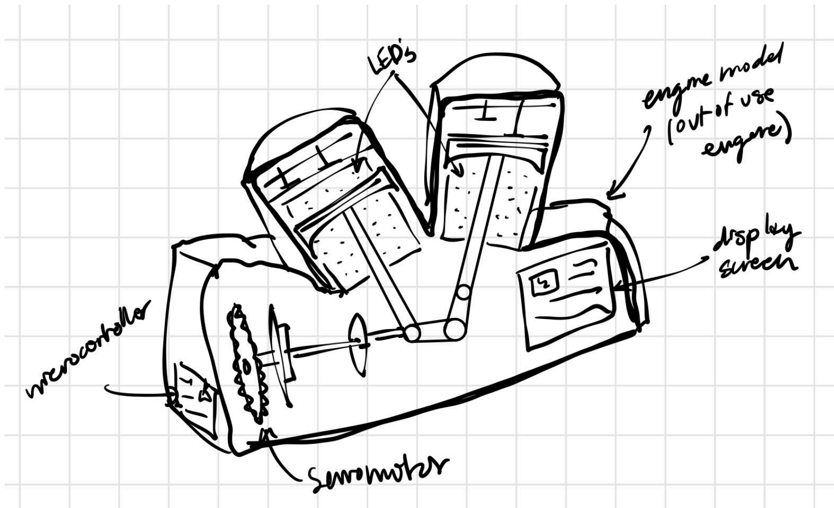


Design 8: V-twin ICE model, crankshaft rotation driven by a stepper motor w/ microcontrollers & LED's used to augment presentation and show stroke phases. Wall cut out and replaced w/ plexiglass/acrylic for internal component viewing.

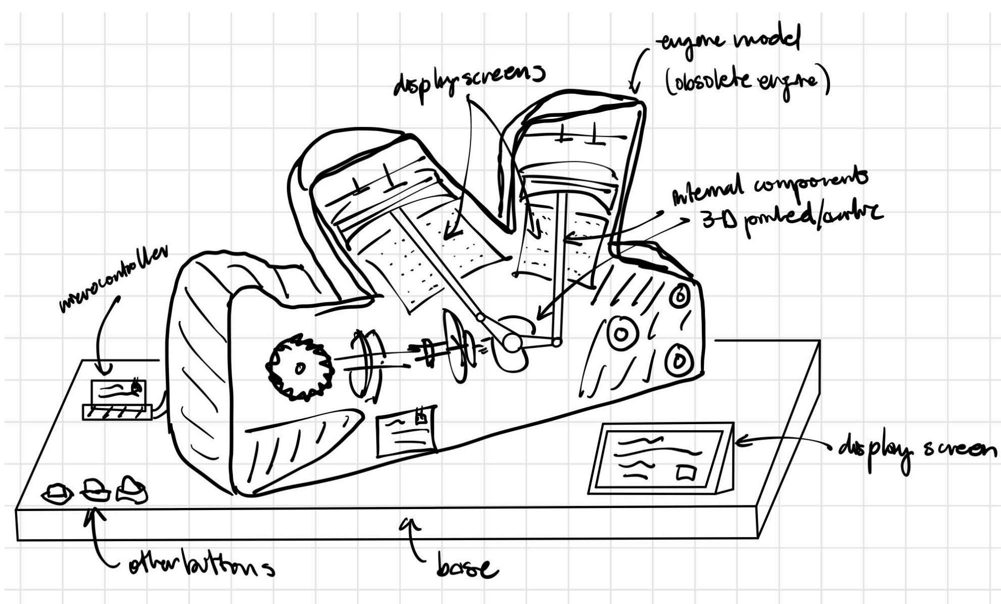


Jonah Cicatko
MAE 4610
09/12/2024

Design 9: Taxidermy cutaway engine model. Out of use engine taken and re-purposed as an educational model, motion driven by a servo motor powered by a wall outlet. LEDs used to display different strokes, microcontrollers used to control timings. Display screen w/ important information to augment educational experience.



Design 10: Taxidermy cutaway engine model, w/ 3-D printed components. Obsolete engine taken and block/housing used, along w/ 3-D printed pistons, crankshaft, etc. Rotation of crankshaft powered by wall outlet. Miniature display screens w/ animations showing intake, exhaust, etc. phases, microcontrollers to control timing. Display screen w/ important information, as well as callable information on different components.

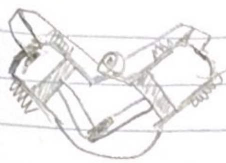


Henry Wallace | Due: 9/26/2024 | Educational Engine

ME Design I - HW #3: IDEATION

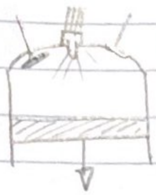
Idea #1: Take V-twin engine, chop up/clean for display

Front View:

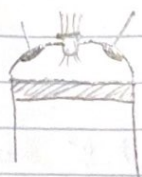


Window in front to show components

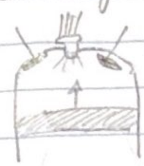
Idea #2: Use one RGB LED as sparkplug to show stages in cycle.



Blue light to show intake

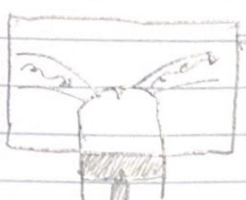


Orange LED to show combustion



Yellow LED to show exhaust

Idea #3: Screen in cylinders to show animations for exhaust/combustion/intake



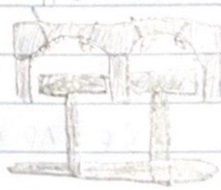
Screen in cylinder plane shows animations with intake, combustion, exhaust.

Idea #4: Overhead Cams

- Use engine with overhead cams instead of pushrods & rockers

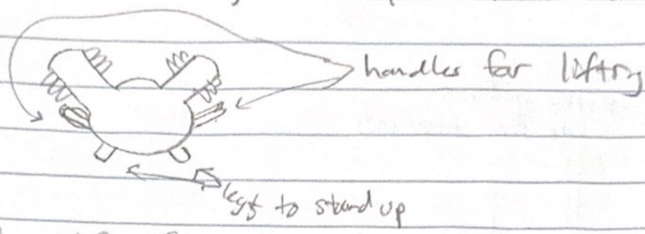
overhead cams

Idea #5: Inline Cylinder Engine

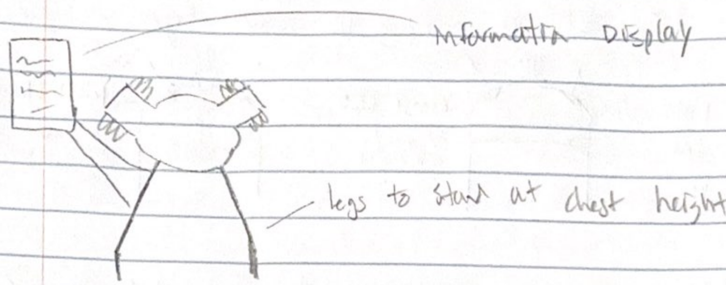


Can see valves well, but not crankshaft

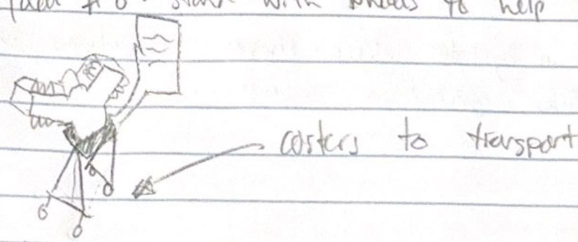
Idea #6: Lightweight 3D Printed Model
- Design in CAD
- Easy to transport to/from classrooms



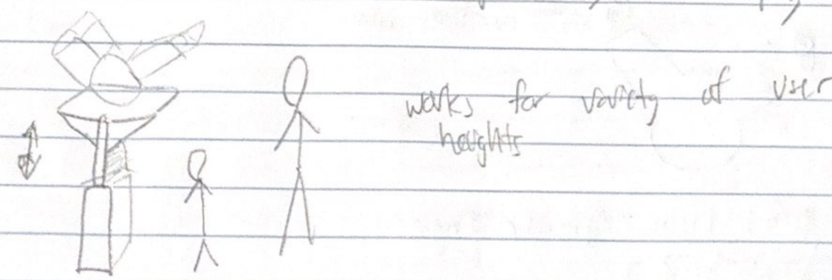
Idea #7: Engine Stand With Information Display



Idea #8: Stand With Wheels to help transport



Idea #9: Linear Actuator to Adjust height of Display



Idea #10: Large Touch Screen Playing Educational Program

waist height display for interactive 3D/CAD model education

Appendix B: Technical Analysis

B1: Engine Power Output

CoM: Piston Road & Head

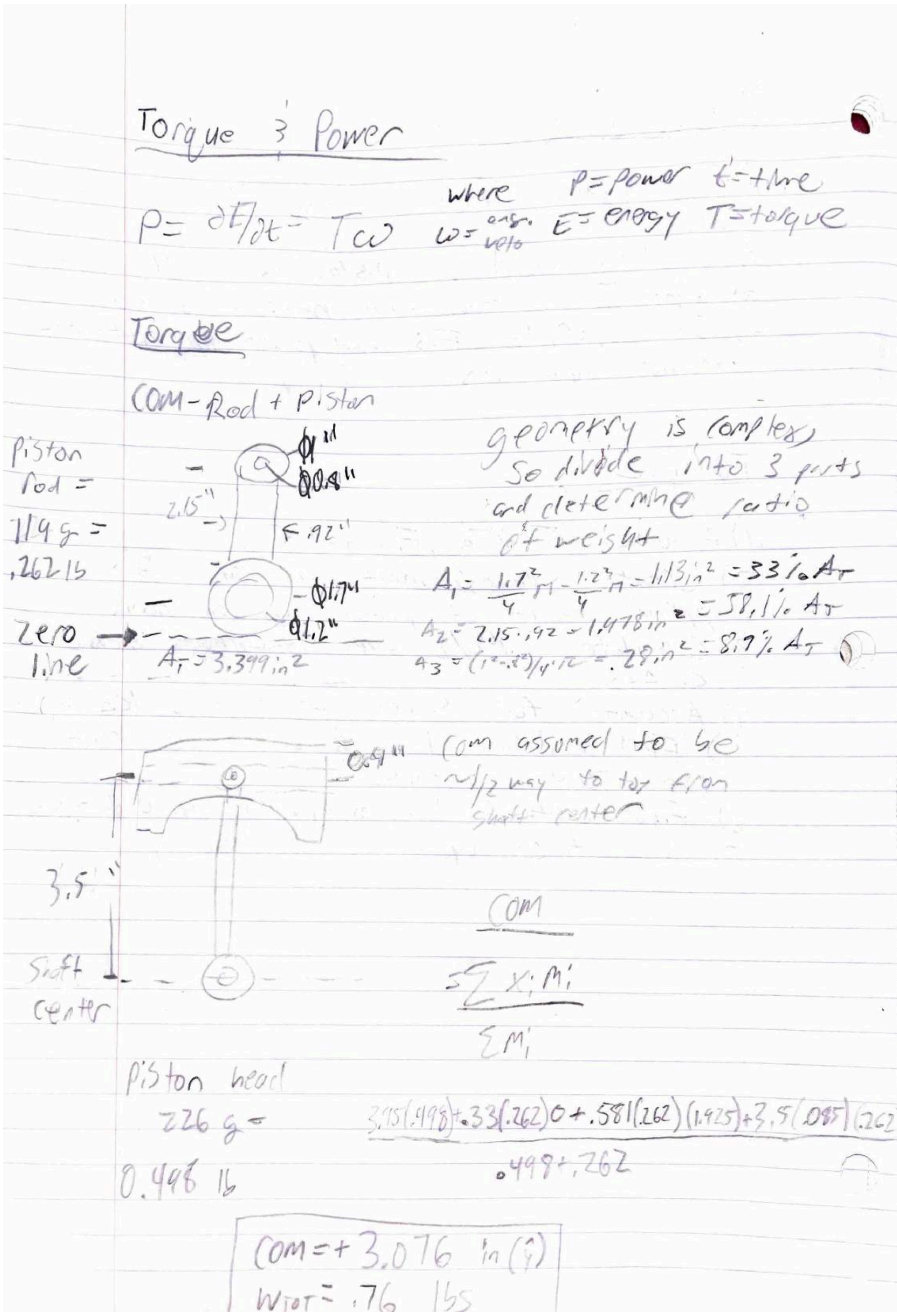


Figure B-1: Center of mass of the Piston

Center of mass (from bottom of piston rod): + 3.076 in ($\hat{y}$)
Weight: 0.76 lbs (measured)
CoM - Crankshaft

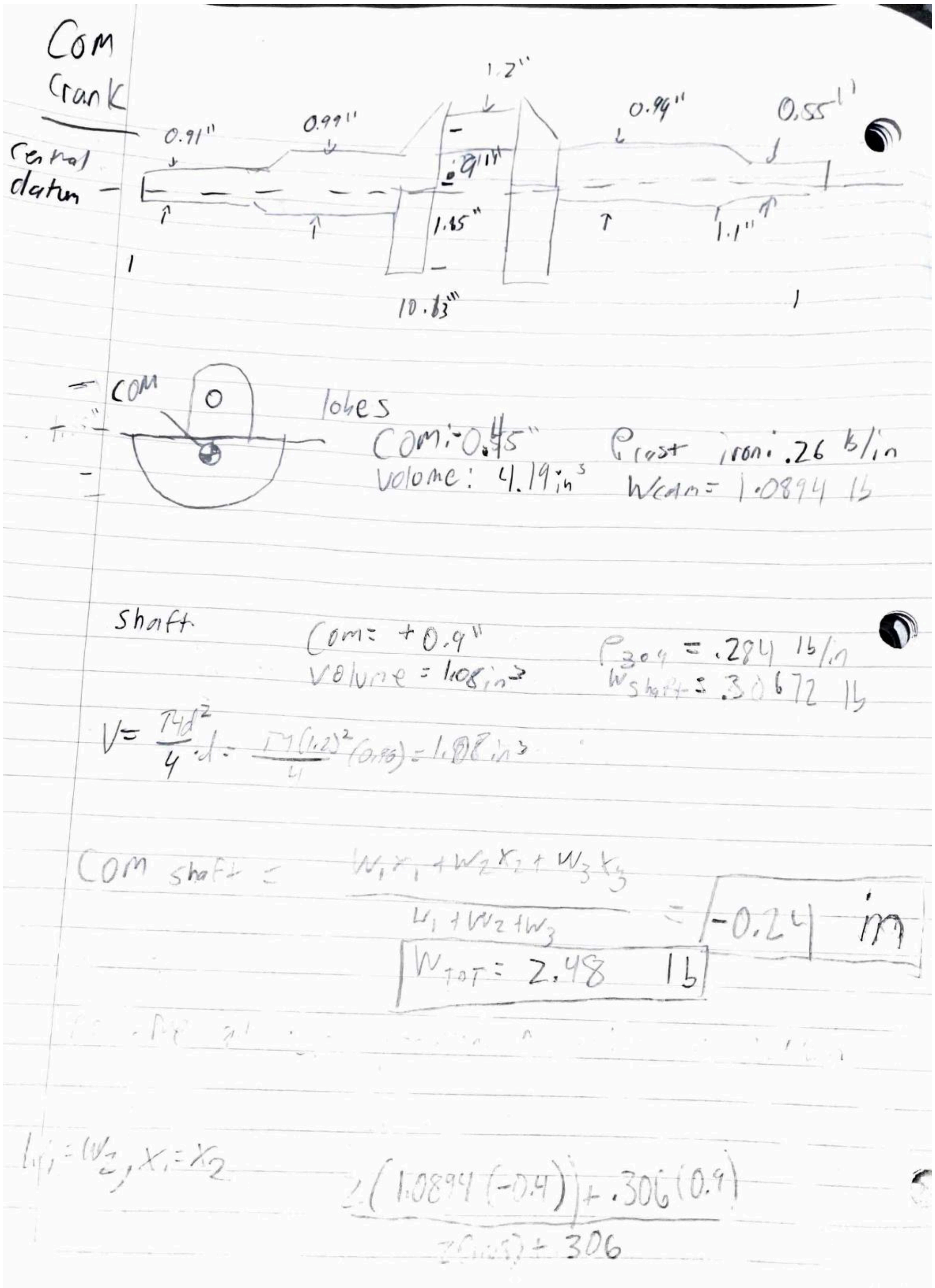
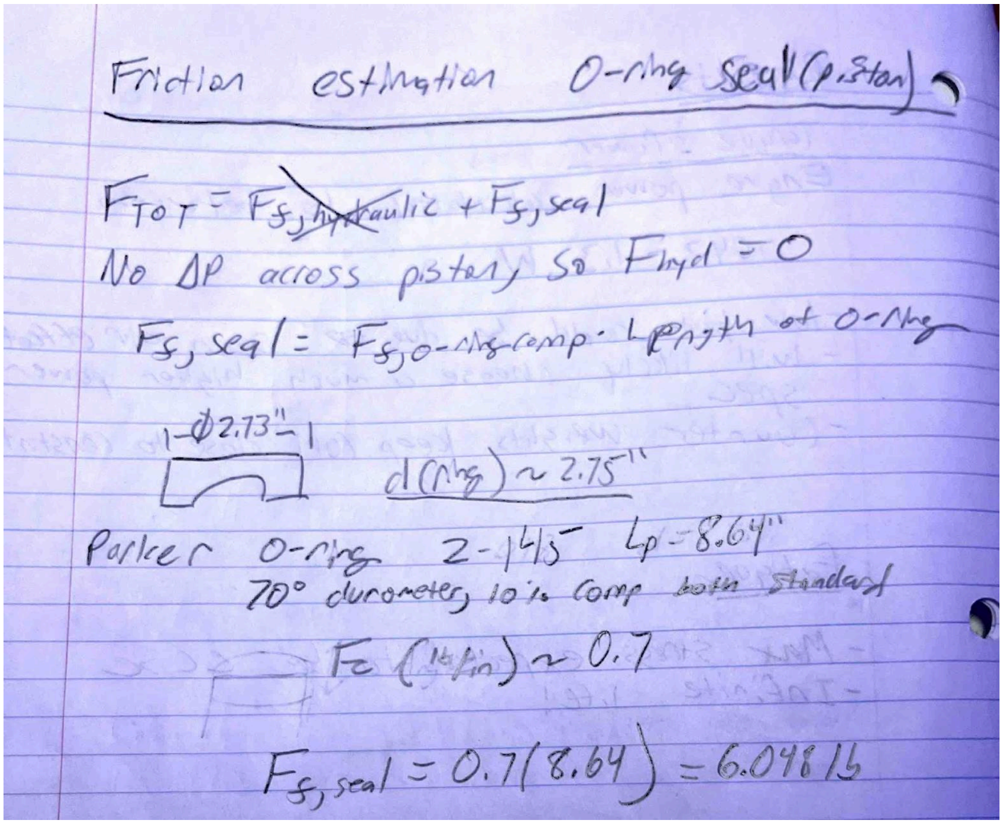


Figure B-2: Center of mass of the crankshaft

Center of mass (from axis of rotation): - 0.24 in ($\widehat{y}$)
Weight: 2.48 lbs
Static Friction of O-ring (from Parker)


Friction estimation O-ring seal (piston)

$F_{TOT} = \cancel{F_{s,hydraulic}} + F_{s,seal}$

No ΔP across piston, so $F_{hyd} = 0$

$F_{s,seal} = F_{s,o\text{-}ring\ comp} \cdot$ Length of O-ring

|—ϕ2.73"—|

d(ring) ~ 2.75"

Parker O-ring 2-145 L_p = 8.64"

70° durometer, 10% comp both standard

F_c (lb/in) ~ 0.7

$F_{s,seal} = 0.7(8.64) = 6.048$ lb

Figure B-3: Friction of the O-ring seal

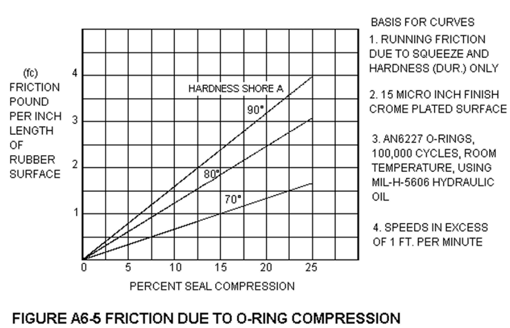


Fig B-4: Chart to determine f_c (Parker US)

Piston seal friction (static) = 6.048 lbs

Final Torque and Power Calculation

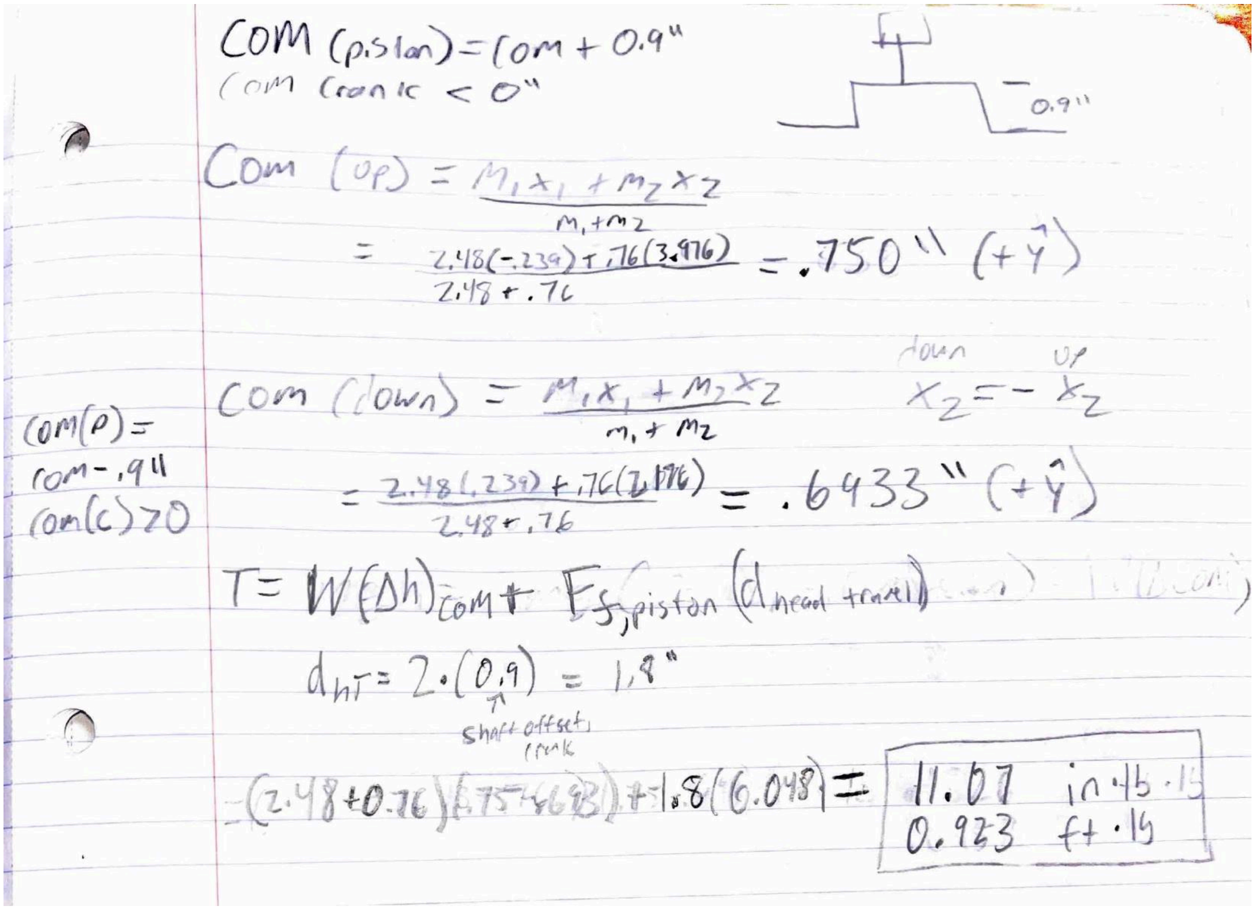


Figure B-5: Calculation of necessary torque

Table B-1: Results of Power Spec

Angular speed, ω		Torque Values		Power Calcs		
RPM	rad/s	Torque (ft*lb)	Safety Factor	ft*lb/s	HP	W
10	1.047	0.923	2	1.933	$3.514*10^{-3}$	2.62
30	3.141	0.923	2	5.798	$1.054*10^{-2}$	7.86
100	10.47	0.923	2	19.33	$3.514*10^{-2}$	26.2
300	31.41	0.923	2	57.98	0.1054	78.6

B2: Fatigue Life

Shear, Moment, and Bending Stress

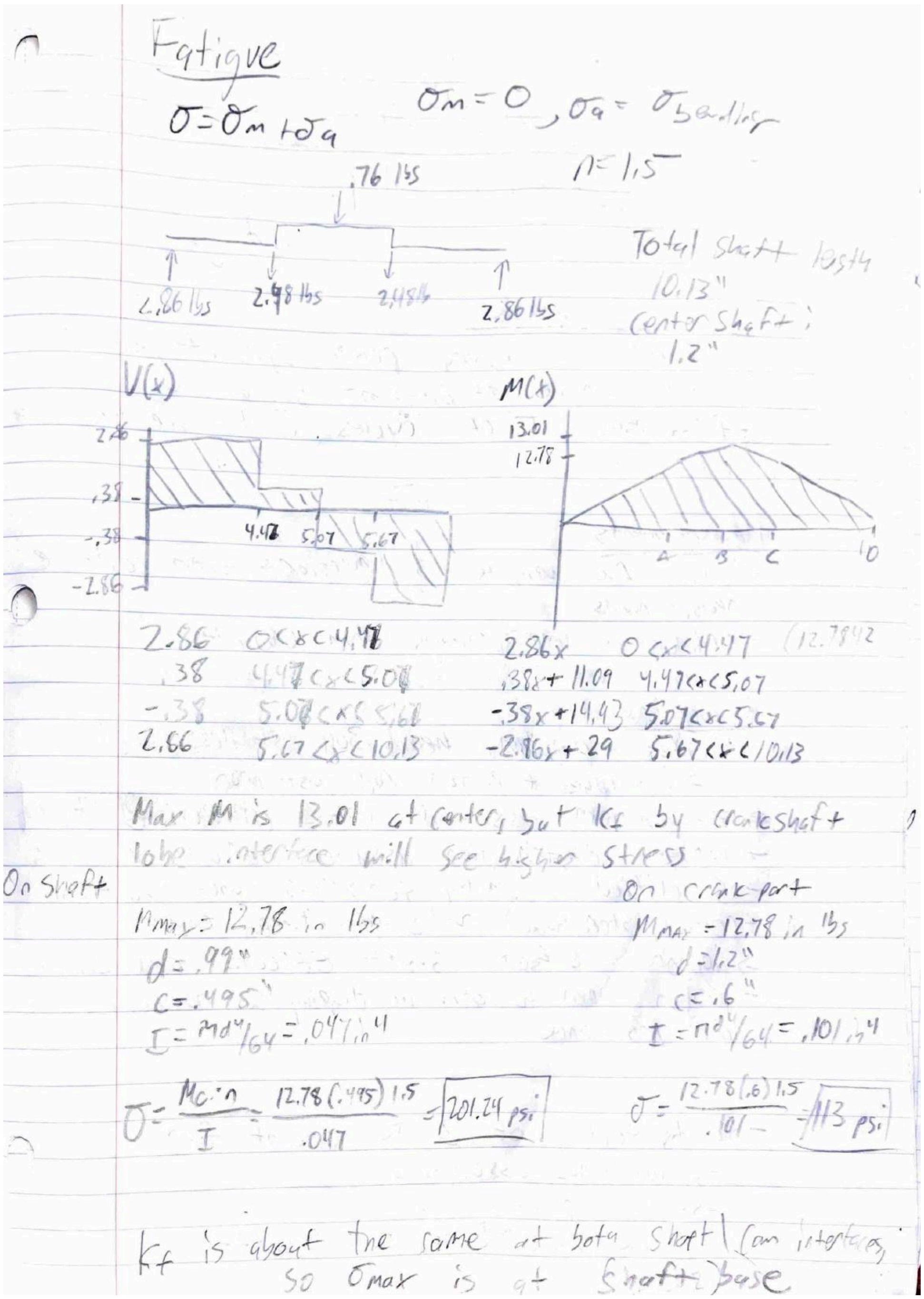
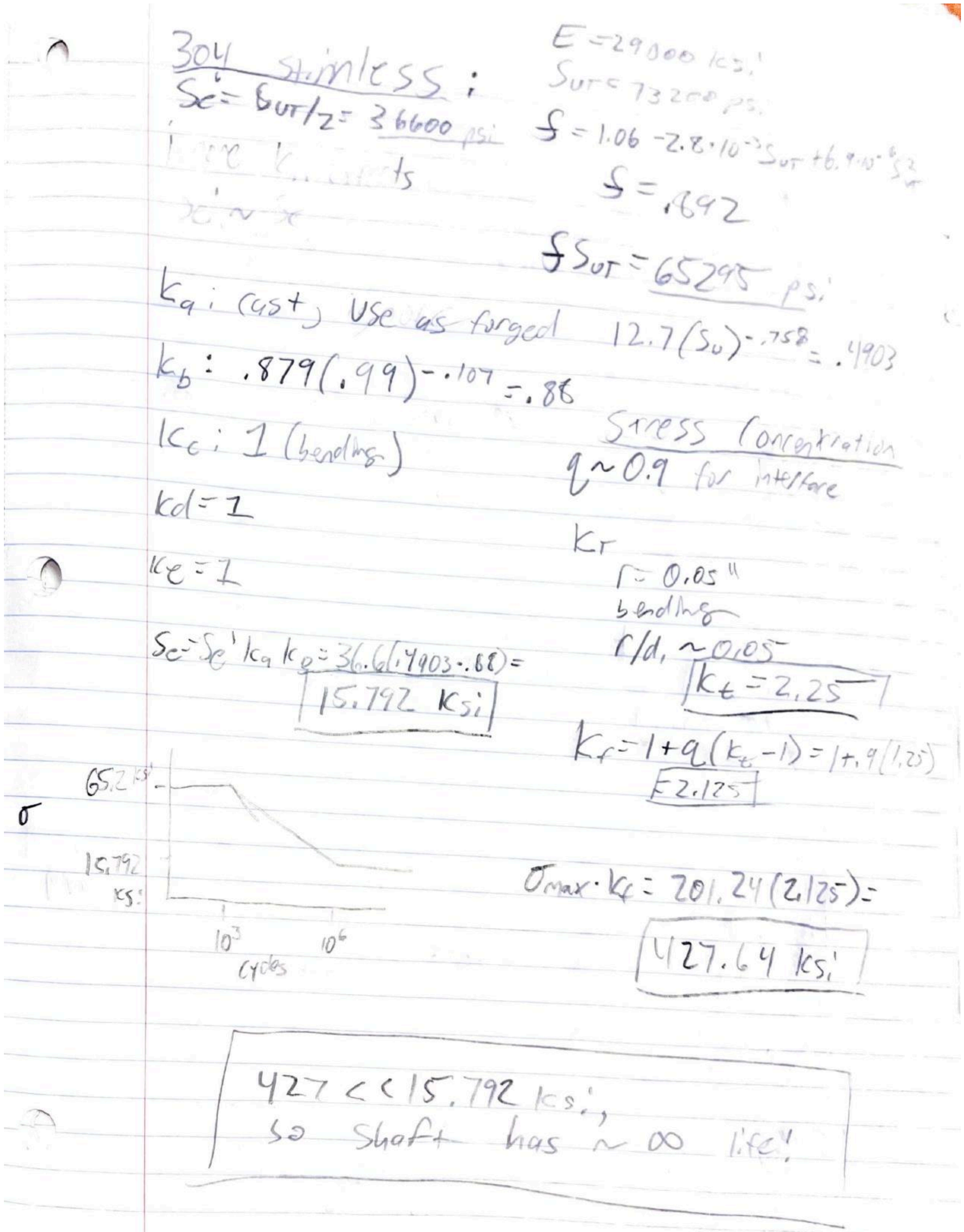


Figure B-6: Determination of shear stress and bending moment on shaft

$\sigma_{MAX} = 201.24\ psi$ (at interface between main shaft and lobe)

Stainless Steel Properties and Fatigue estimation



304 stainless:

$S_e' = S_{UT}/2 = 36600$ psi

$E = 29000$ ksi

$S_{UT} = 73200$ psi

$f = 1.06 - 2.8 \cdot 10^{-3} S_{UT} + 6.9 \cdot 10^{-6} S_{UT}^2$

$f = .892$

$f S_{UT} = 65295$ psi

k_a: cast, use as forged $12.7(S_u)^{-.758} = .4903$

k_b: $.879(.99)^{-.107} = .88$

k_c: 1 (bending)

$k_d = 1$

$k_e = 1$

$S_e = S_e' k_a k_b = 36.6(.4903 \cdot .88) =$ $\boxed{15.792\ ksi}$

Stress Concentration

$q \sim 0.9$ for interface

K_T

$r = 0.05''$

bending

$r/d, \sim 0.05$

$\boxed{K_t = 2.25}$

$K_f = 1 + q(K_t - 1) = 1 + .9(1.25)$

$\boxed{= 2.125}$

$\sigma_{max} \cdot K_f = 201.24(2.125) =$

$\boxed{427.64\ ksi}$

$\boxed{427 << 15.792\ ksi, \text{ so Shaft has} \sim \infty \text{ life!}}$

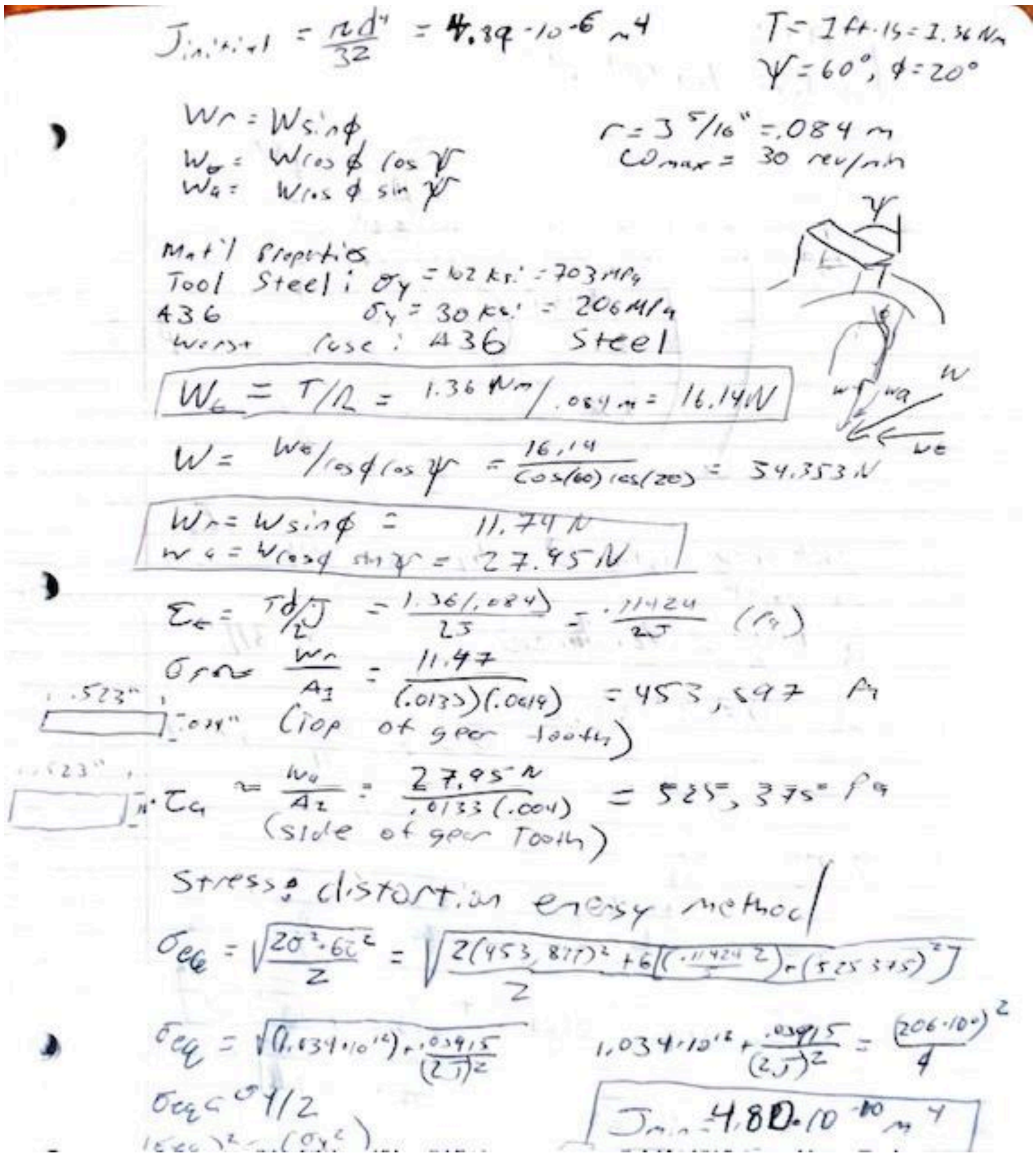
Figure B-7: Fatigue Life Calculations of Shaft

$\sigma_{MAX, Kf} = 427\ psi$

$S_{e,\, approx} = 15,792\ psi$

This discrepancy suggests infinite life

B3: Gear Cutaway



$J_{initial} = \frac{\pi d^4}{32} = 4.39 \cdot 10^{-6}\ m^4$

$T = 1\ ft \cdot lb = 1.36\ Nm$

$\psi = 60^\circ,\ \phi = 20^\circ$

$W_r = W \sin\phi$

$W_t = W \cos\phi \cos\psi$

$W_a = W \cos\phi \sin\psi$

$r = 3\ 5/16" = .084\ m$

$\omega_{max} = 30\ rev/min$

Mat'l Properties

Tool Steel: $\sigma_y = 102\ ksi = 703\ MPa$

436 $\sigma_y = 30\ ksi = 206\ MPa$

Worst case: 436 Steel

$\boxed{W_t = T/R = 1.36\ Nm / .084\ m = 16.14\ N}$

$W = W_t / \cos\phi \cos\psi = \frac{16.14}{\cos(60)\cos(20)} = 34.353\ N$

$\boxed{\begin{array}{l} W_r = W \sin\phi = 11.74\ N \\ W_a = W \cos\phi \sin\psi = 27.95\ N \end{array}}$

$\tau_t = \frac{T d/2}{J} = \frac{1.36(.084)}{2J} = \frac{.11424}{2J}\ (Pa)$

$\sigma_{r} = \frac{W_r}{A_1} = \frac{11.47}{(.0133)(.0019)} = 453,897\ Pa$

.523" .074" (top of gear tooth)

.523" $\tau_a \approx \frac{W_a}{A_2} = \frac{27.95\ N}{.0133(.004)} = 525,375\ Pa$

(side of gear tooth)

Stress: distortion energy method

$\sigma_{eq} = \sqrt{\frac{2\sigma^2 + 6\tau^2}{2}} = \sqrt{\frac{2(453,877)^2 + 6\left[\left(\frac{.11424}{2J}\right) + (525,375)^2\right]}{2}}$

$\sigma_{eq} = \sqrt{(1.034 \cdot 10^{12}) + \frac{.03915}{(2J)^2}}$

$1.034 \cdot 10^{12} + \frac{.03915}{(2J)^2} = \frac{(206 \cdot 10^6)^2}{4}$

$\sigma_{eq} < \sigma_y/2$

$\boxed{J_{min} = 4.80 \cdot 10^{-10}\ m^4}$

Figure B-8: Minimum Gear Moment of Inertia

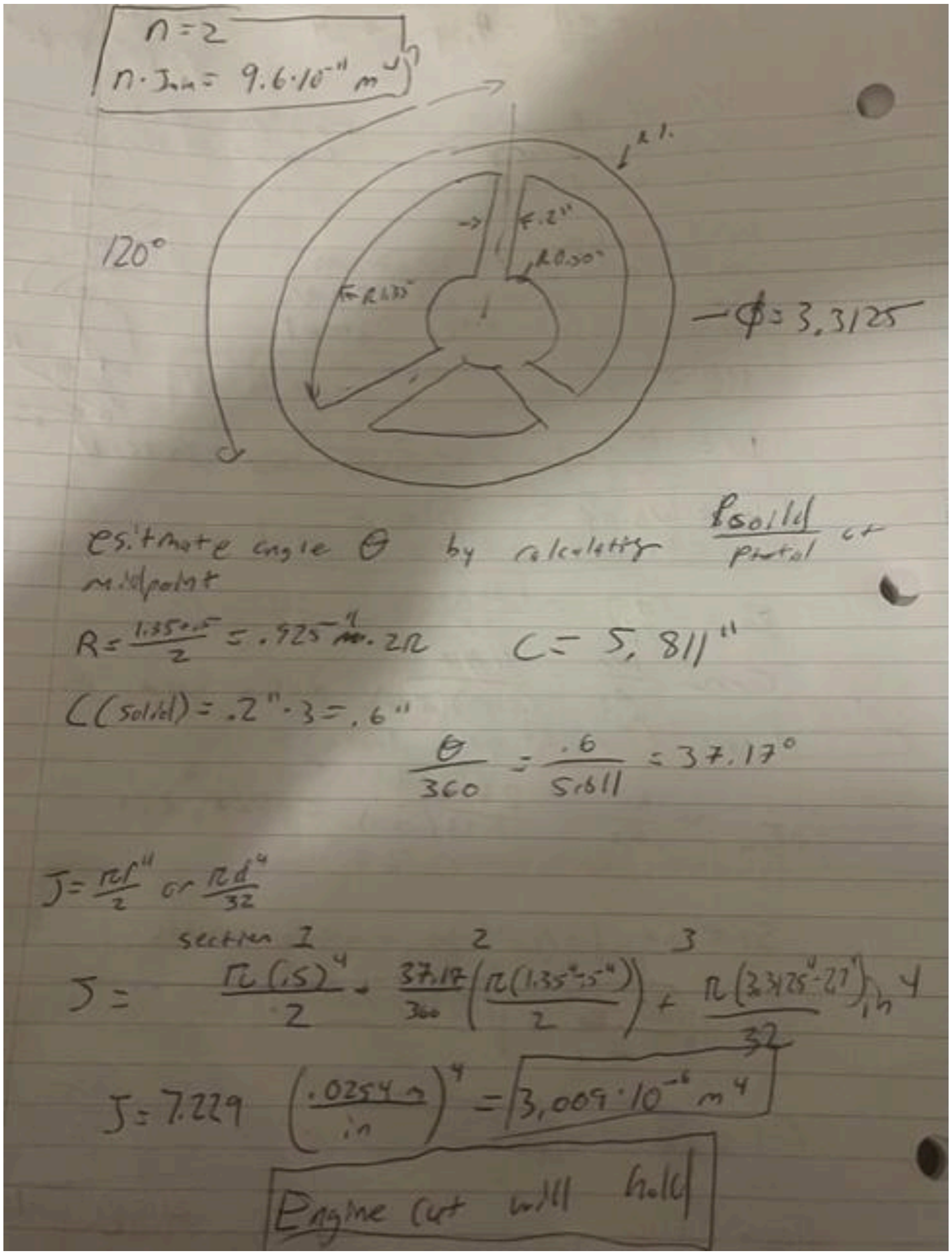


Figure B-9: Moment of Inertia of proposed cut gear

B4: Support Brackets

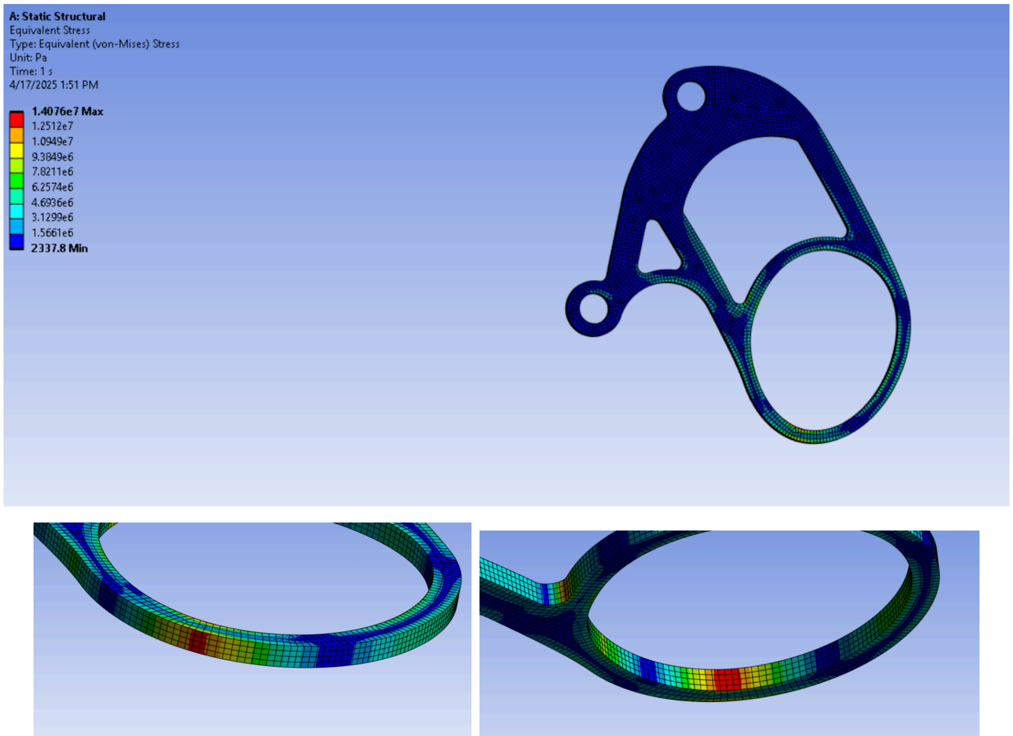


Figure B-10: Crankshaft Mount FEA

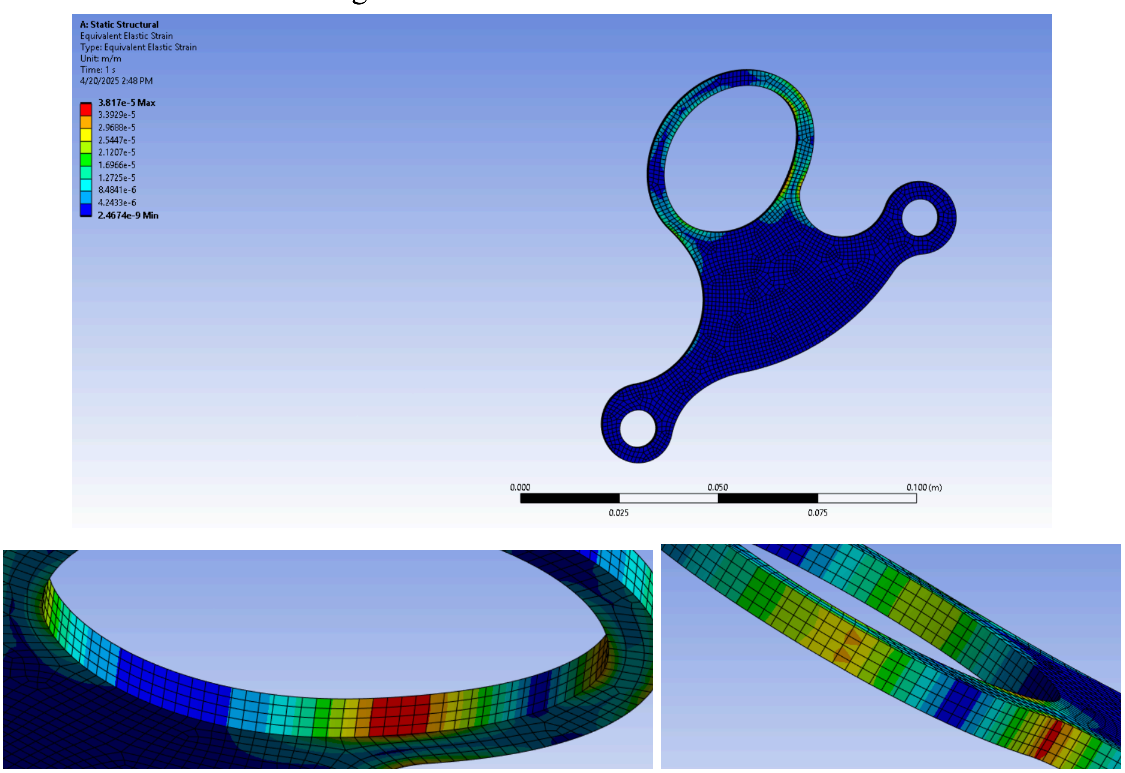


Figure B-11: Camshaft Mount FEA

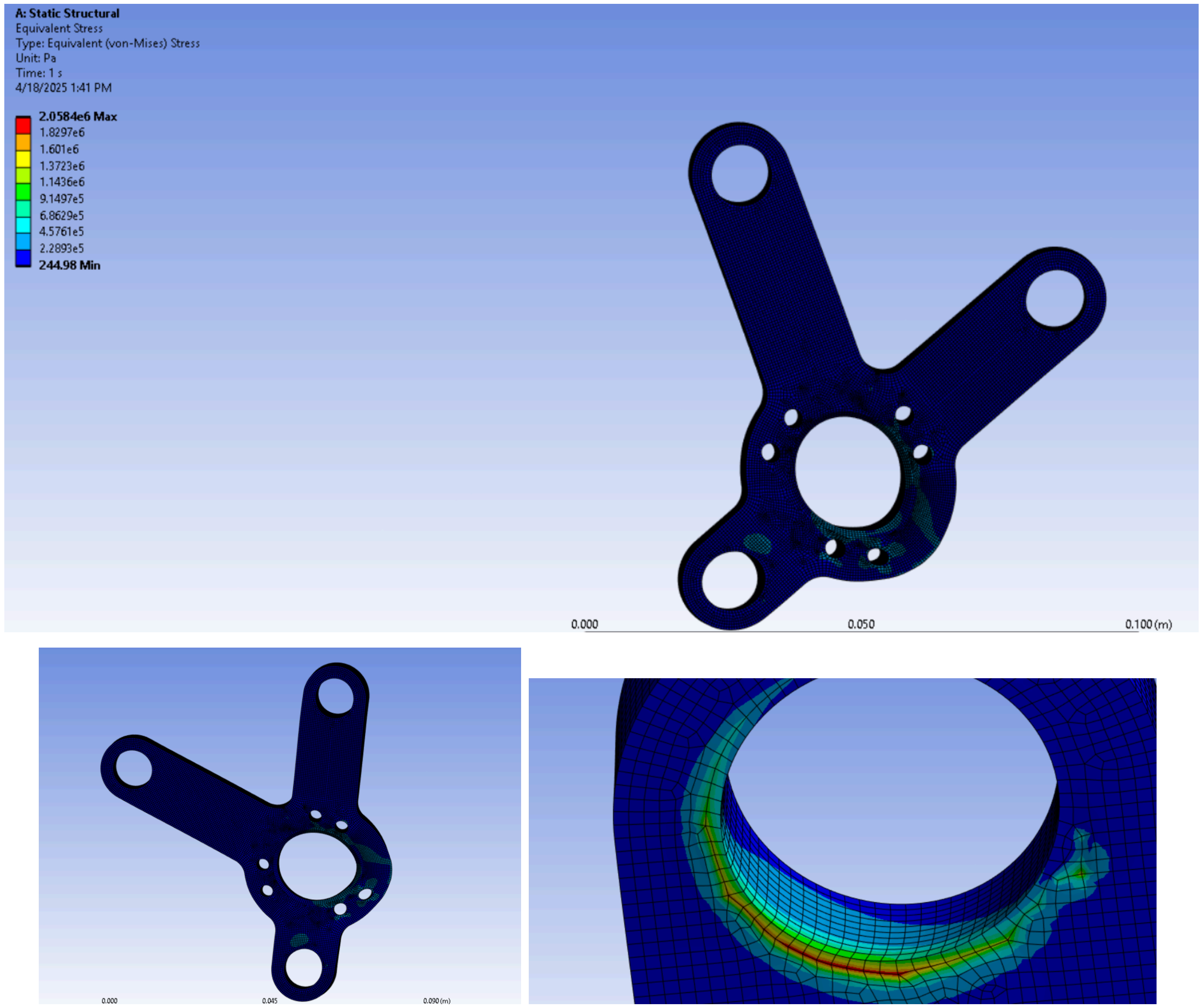


Figure B-12: Encoder Mount FEA

B5: Coupler Design

There were no additional calculations done for the couplers in this section. This appendix was kept for consistency. See Appendix C for the CAD Drawings of the couplers.

B6: Wiring Diagrams

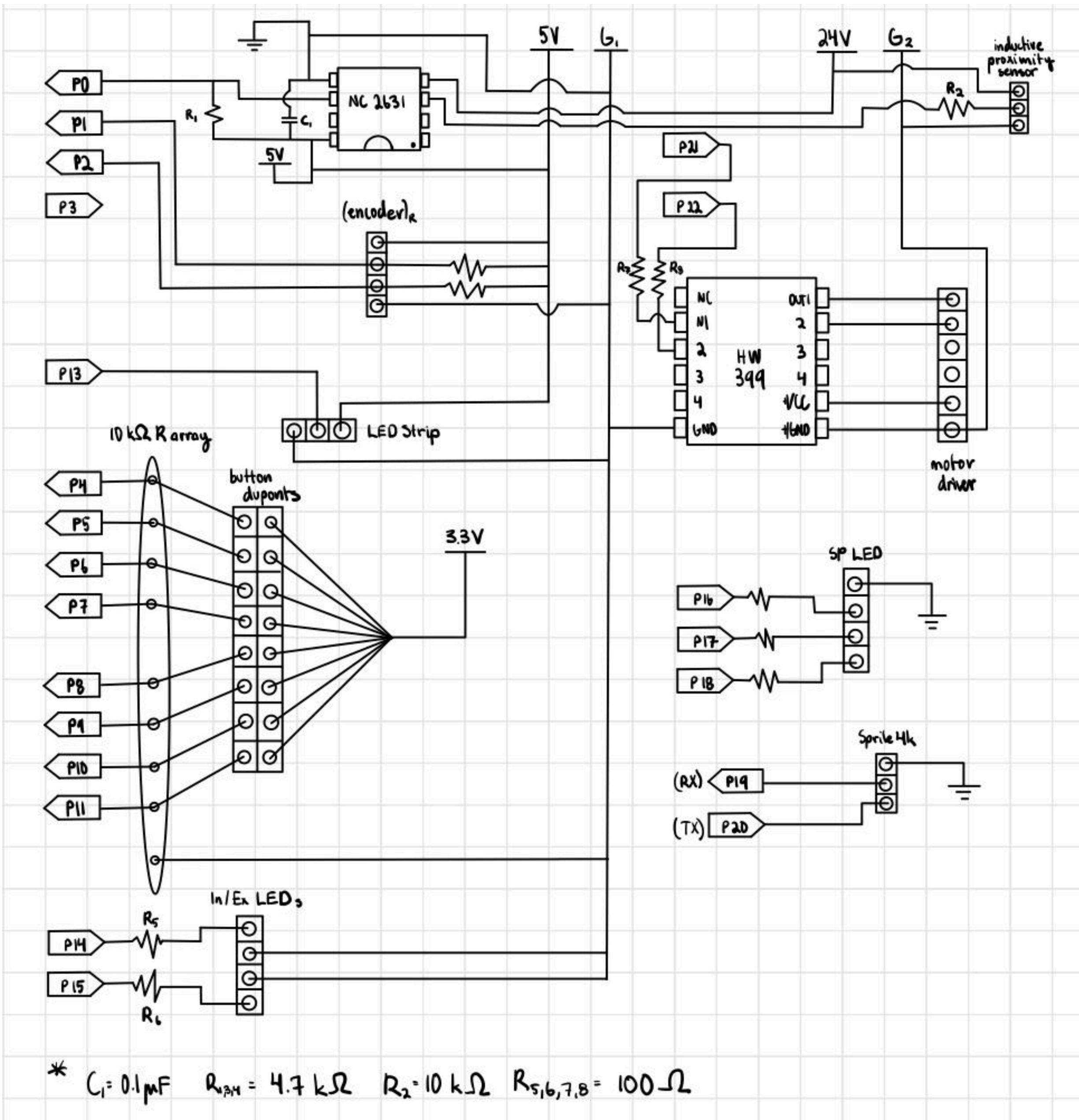


Figure B-13: Perfboard Wiring

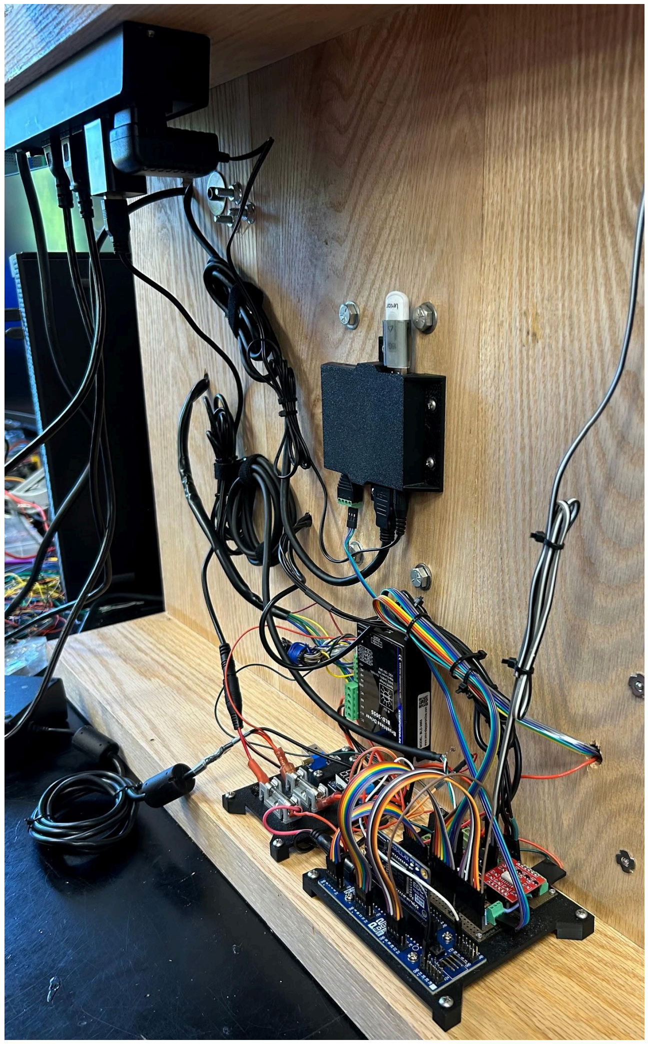
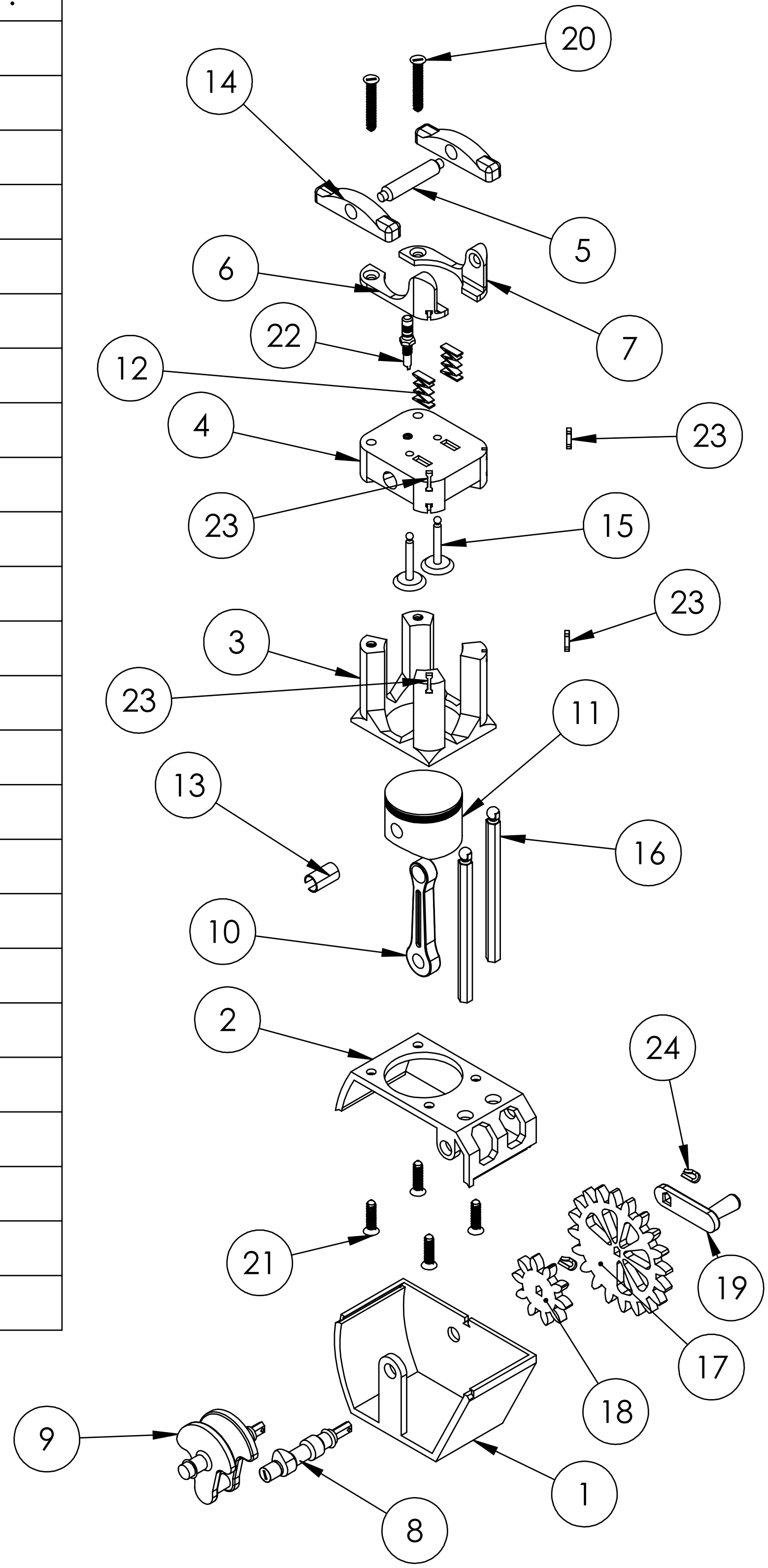


Figure B-14: Final Wiring

Appendix C: Drawings - 3D Printable Model

*Begins on next page

ITEM NO.	PART NUMBER	QTY.
1	Block-Bottom	1
2	Block-Top	1
3	Cylinder	1
4	CylinderHead	1
5	RockerShaft	1
6	RockerSupport-1	1
7	RockerSupport-2	1
8	Assembly-Camshaft	1
9	Assembly-Crankshaft	1
10	ConnectingRod	1
11	PistonHead	1
12	Spring	2
13	WristPinTest	1
14	Rocker	2
15	Valve	2
16	Pushrod	2
17	CamGear	1
18	CrankGear	1
19	HandCrank	1
20	Bolt-Large	2
21	Bolt-Medium	4
22	SparkPlug	1
23	IJoint	4
24	Shaft-Pin	2



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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: ±0.1°
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.005

MATERIAL
PLA Plastic

FINISH

DO NOT SCALE DRAWING

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DRAWN	SL Hartless	12/12/24
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

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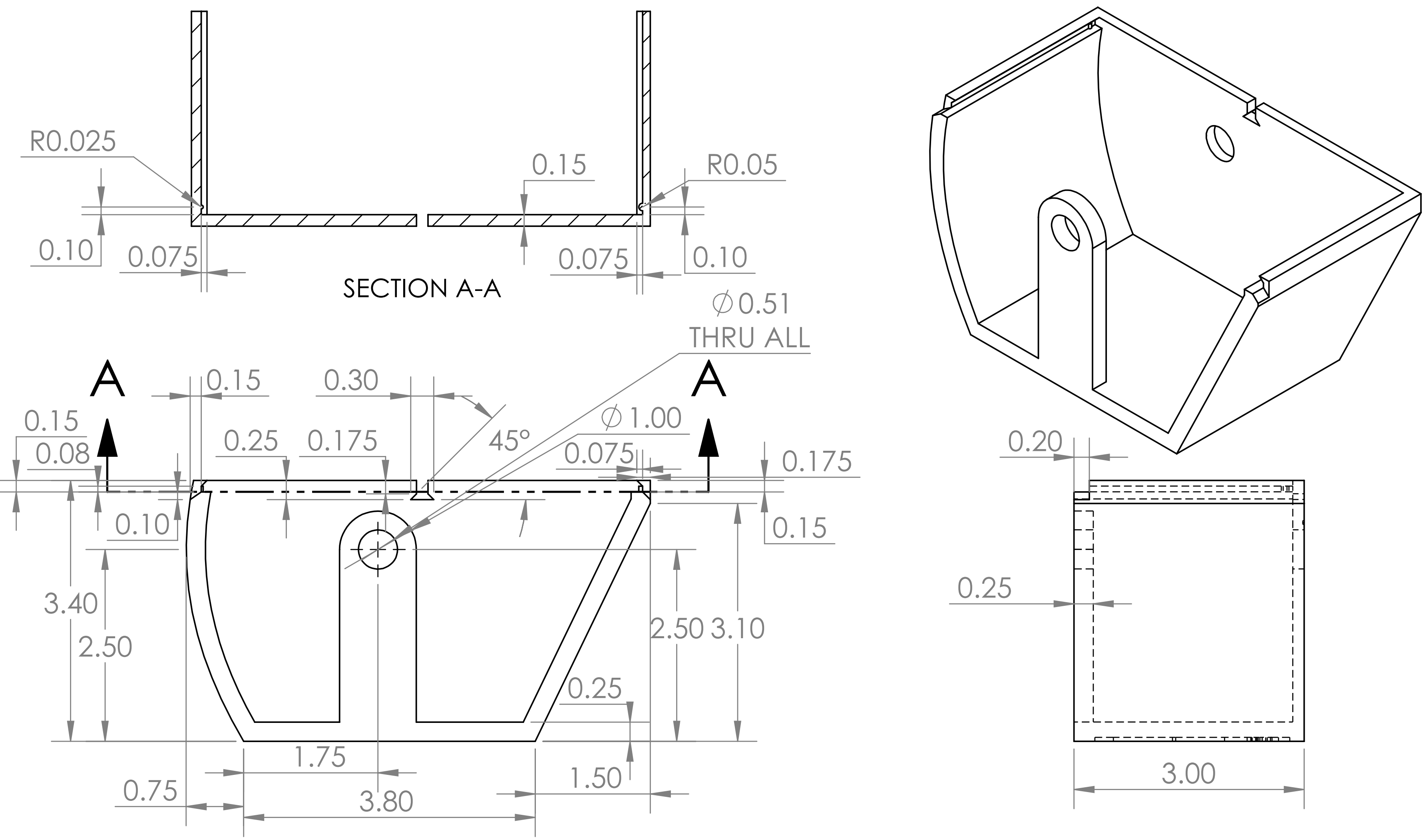

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		MATERIAL Polylactic Acid	COMMENTS:		
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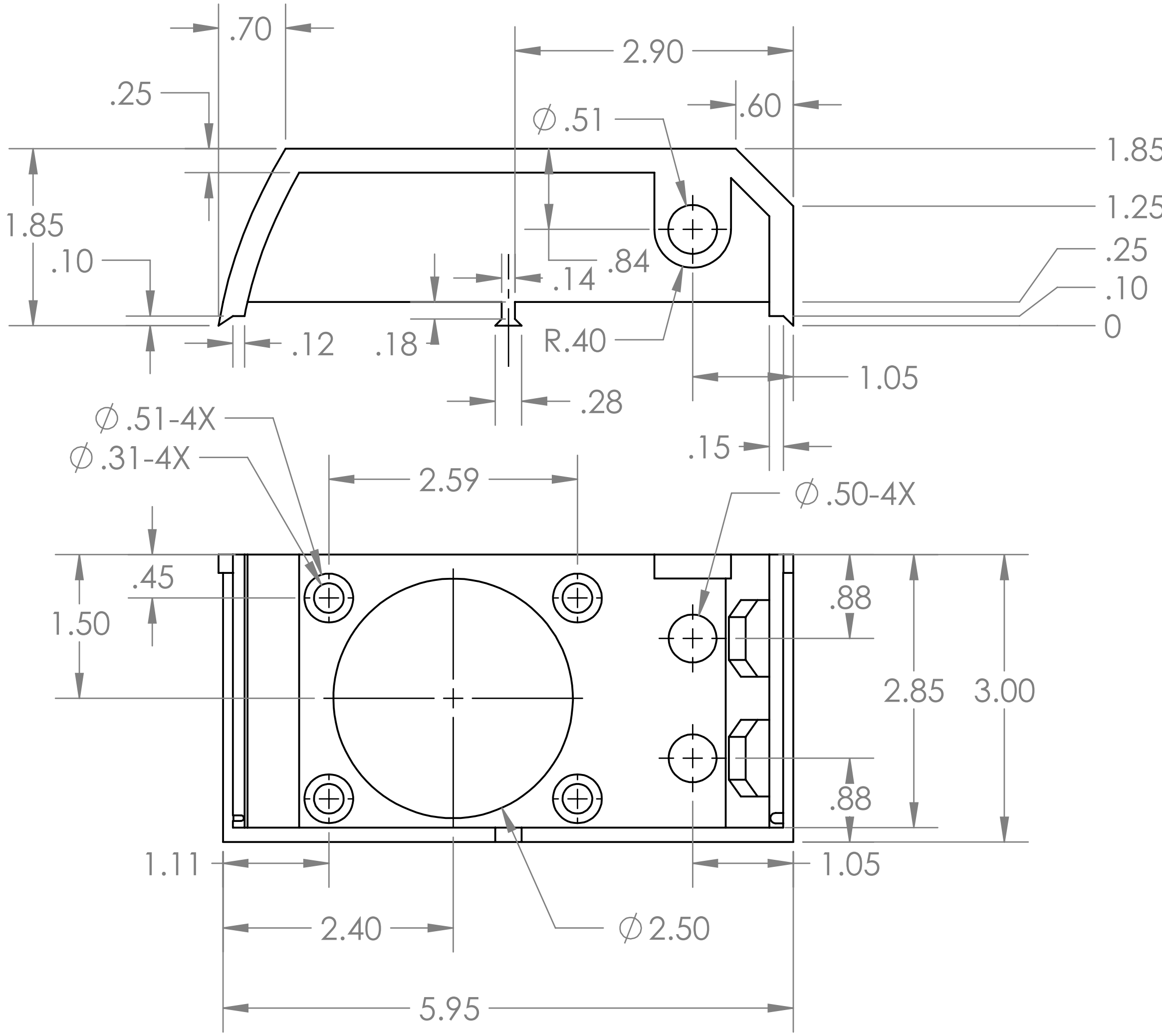
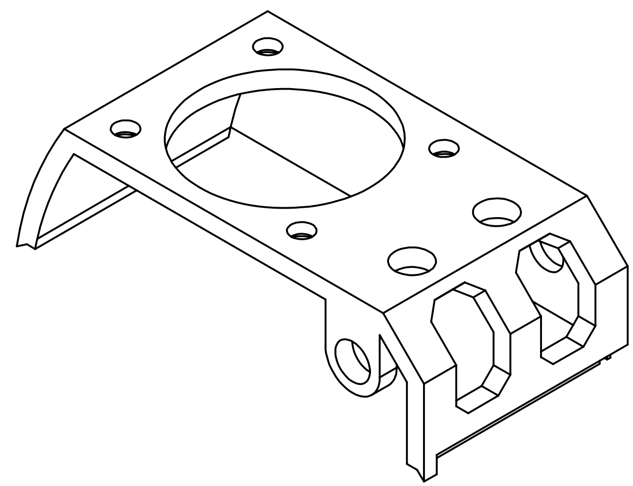


NOTE: All circular holes seen on SHEET 1 are THRU ALL.



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			MFG APPR.		
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		MATERIAL Polylactic Acid	COMMENTS:		
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TITLE:

SIZE **A** DWG. NO. **Block-Top** REV

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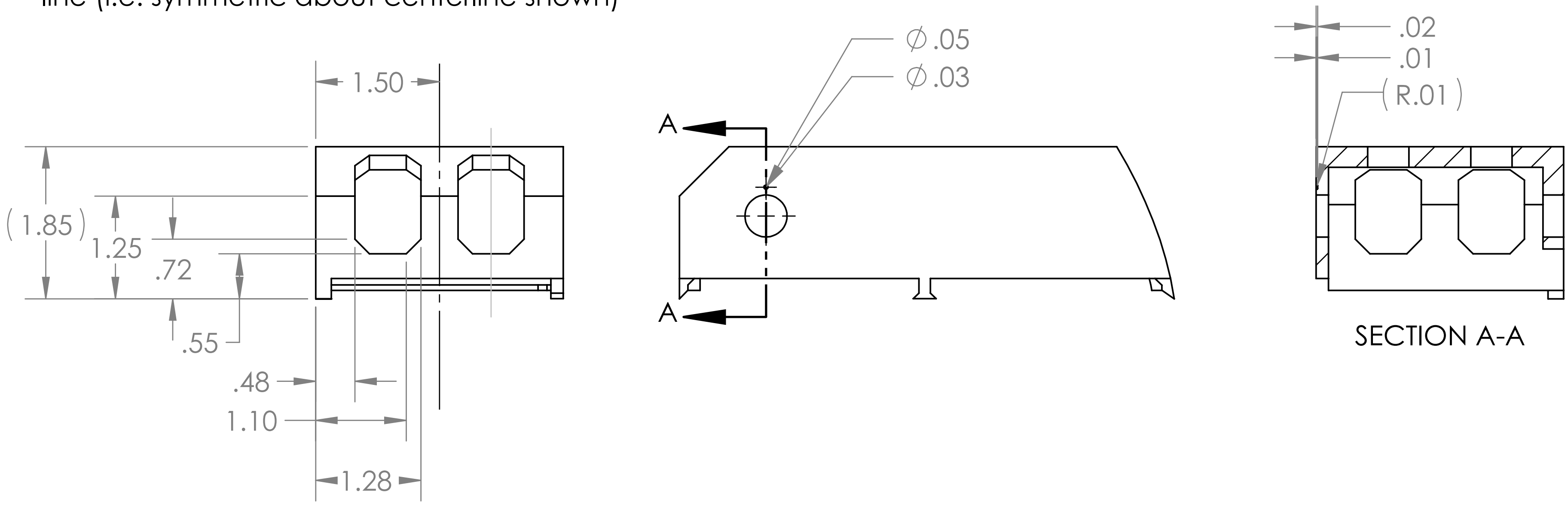
2 1

B B

NOTE: Dimensions for left octagon cutout are same for right octagon cutout about center line (i.e. symmetric about centerline shown)



SECTION A-A

A A

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MATERIAL
Polylactic Acid

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MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

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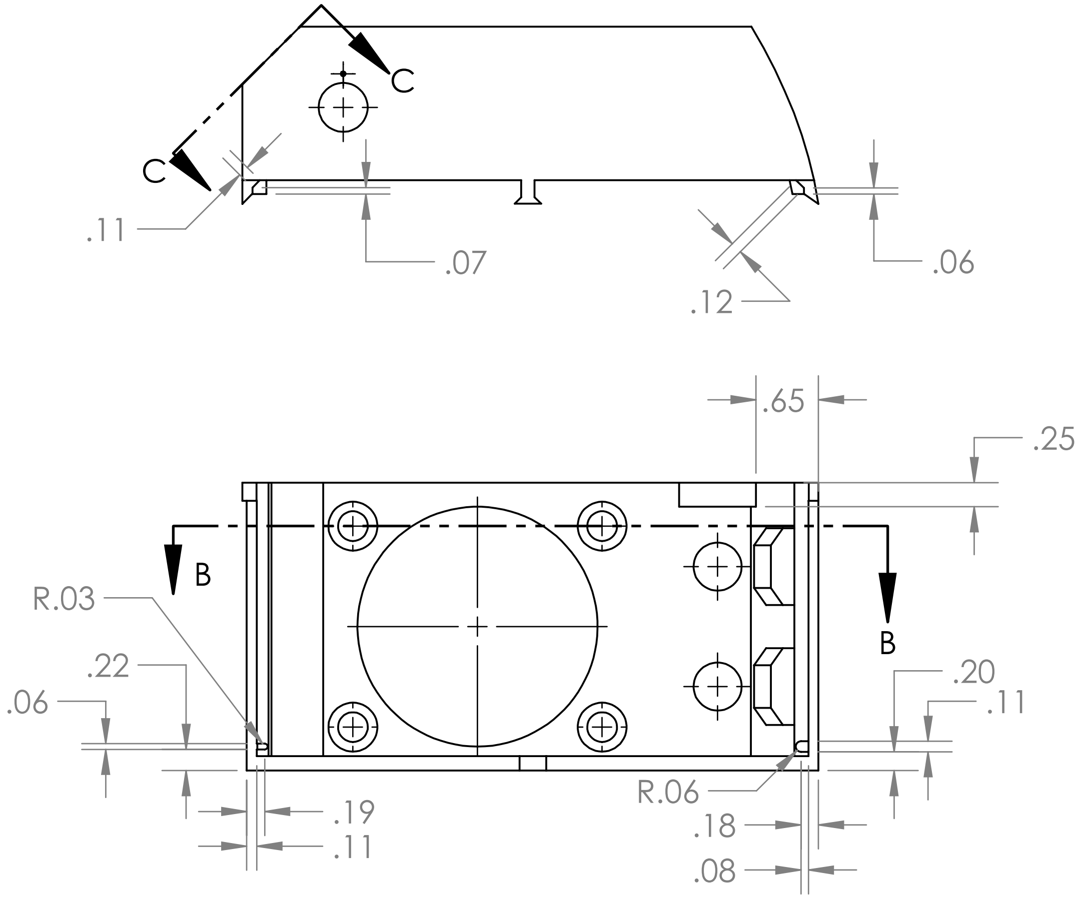
2 1



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TOLERANCES:
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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polylactic Acid

FINISH

DO NOT SCALE DRAWING

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CHECKED	HJW	12/12/24
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

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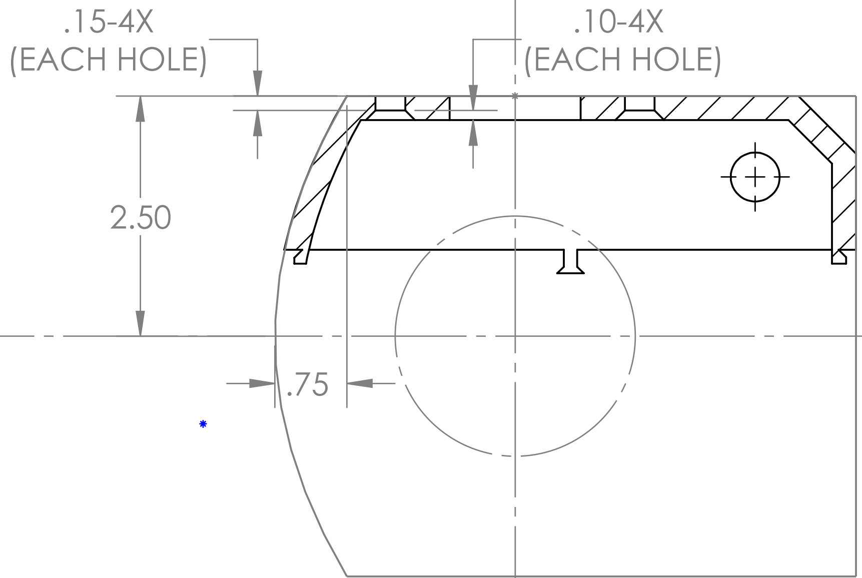
A	Block-Top	

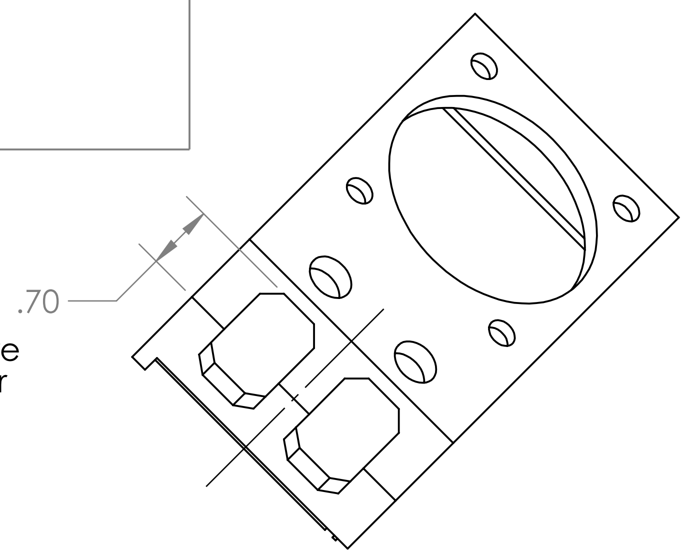
SCALE: 1:2 WEIGHT: SHEET 3 OF 4



SECTION B-B

NOTE: Outer sketch is visible to show dimensioning of outside face curve/spline.

NOTE: Dimensions for left octagon cutout are same for right octagon cutout about center line (i.e. symmetric about centerline shown)



SECTION C-C

	NAME	DATE	
DRAWN	SL Hartless	12/11/24	
CHECKED	HJW	12/12/24	TITLE:
ENG APPR.			
MFG APPR.			
Q.A.			
COMMENTS:			

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polylactic Acid

FINISH

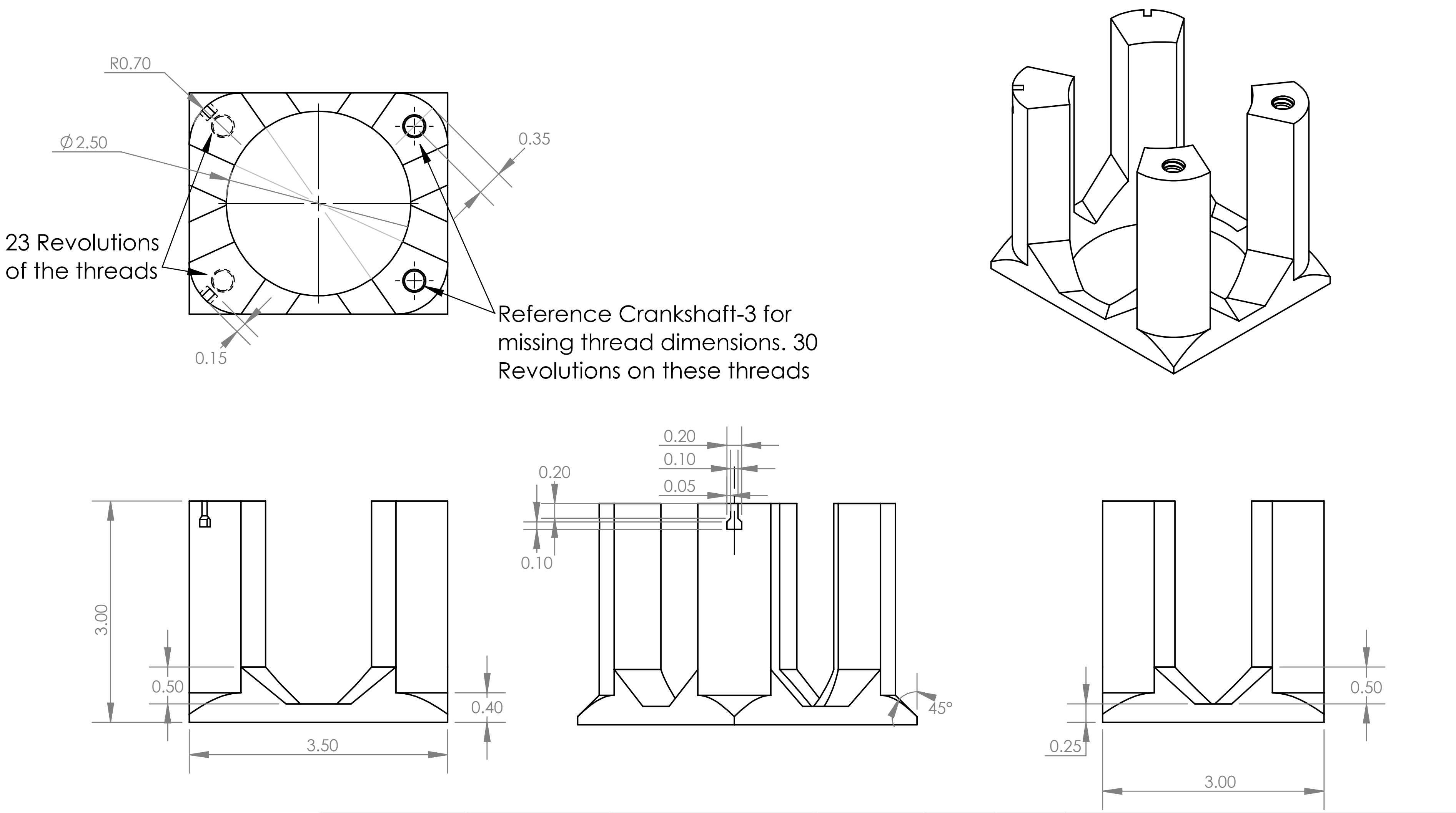
NEXT ASSY | USED ON

APPLICATION

DO NOT SCALE DRAWING

SIZE A | DWG. NO. Block-Top | REV

SCALE: 1:2 | WEIGHT: |



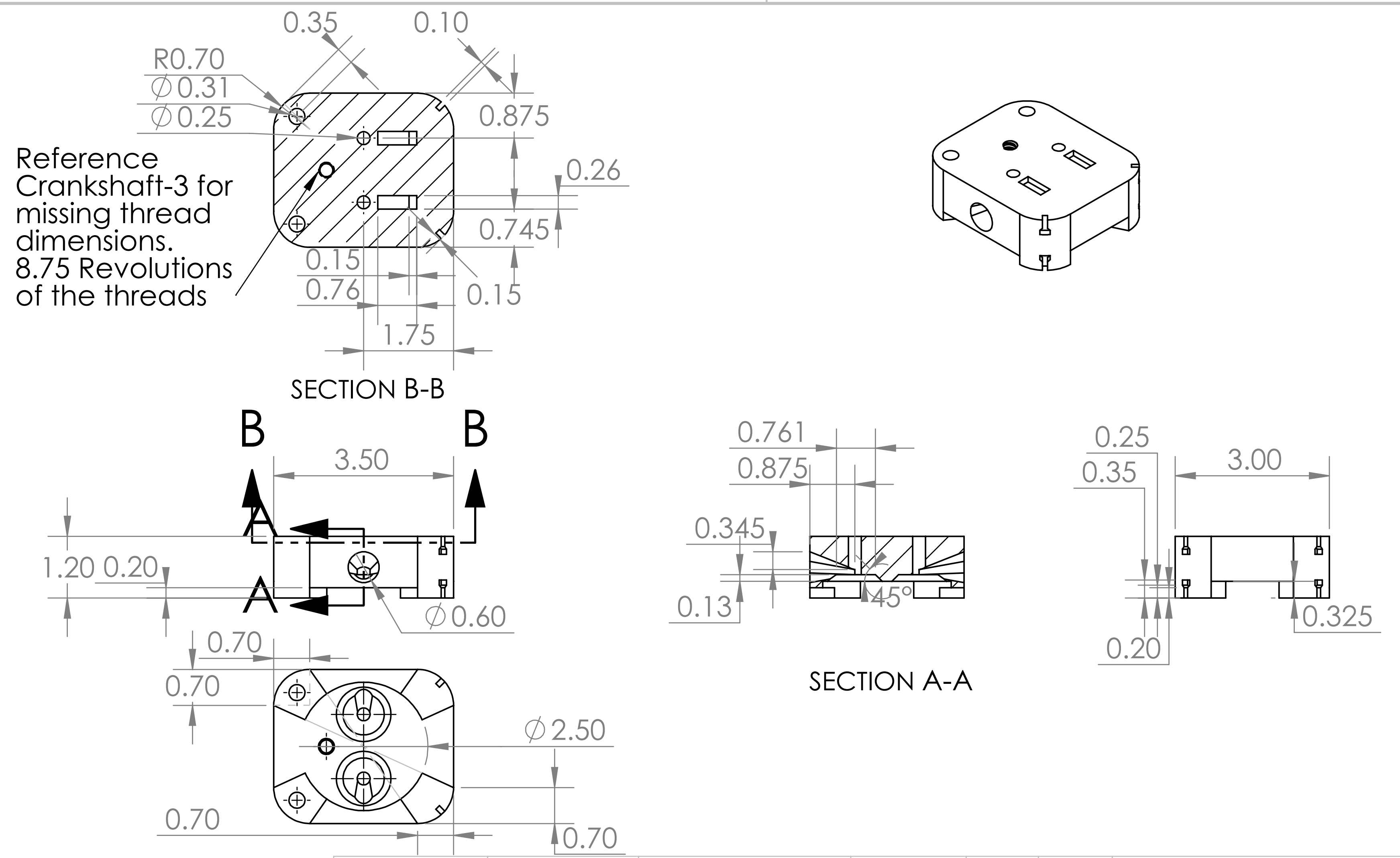
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ±0.1° TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.005	DRAWN	HJW	12/11/24
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL Polylactic Acid	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

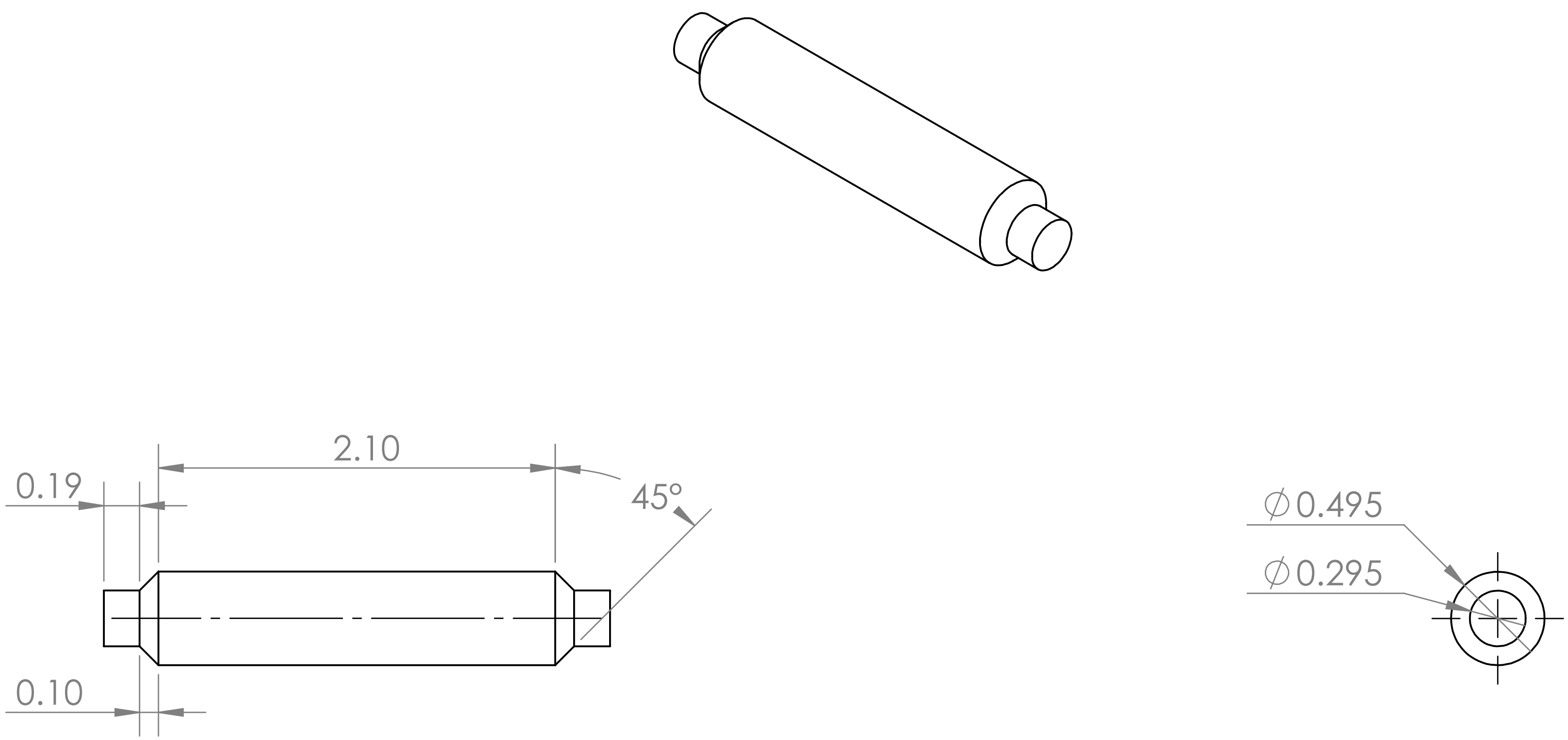
Cylinder

SIZE	DWG. NO.	REV
A		

SCALE: 1:2 WEIGHT: SHEET 1 OF 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ±0.1° TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.005	DRAWN	HJW	12/11/24	
			CHECKED			TITLE:
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			CylinderHead
		MATERIAL Polylactic Acid	COMMENTS:			SIZE A DWG. NO. REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:3 WEIGHT: SHEET 1 OF 1



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NEXT ASSY	USED ON
APPLICATION	

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: ± 0.1°
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polylactic Acid

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HJW	12/10/24
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

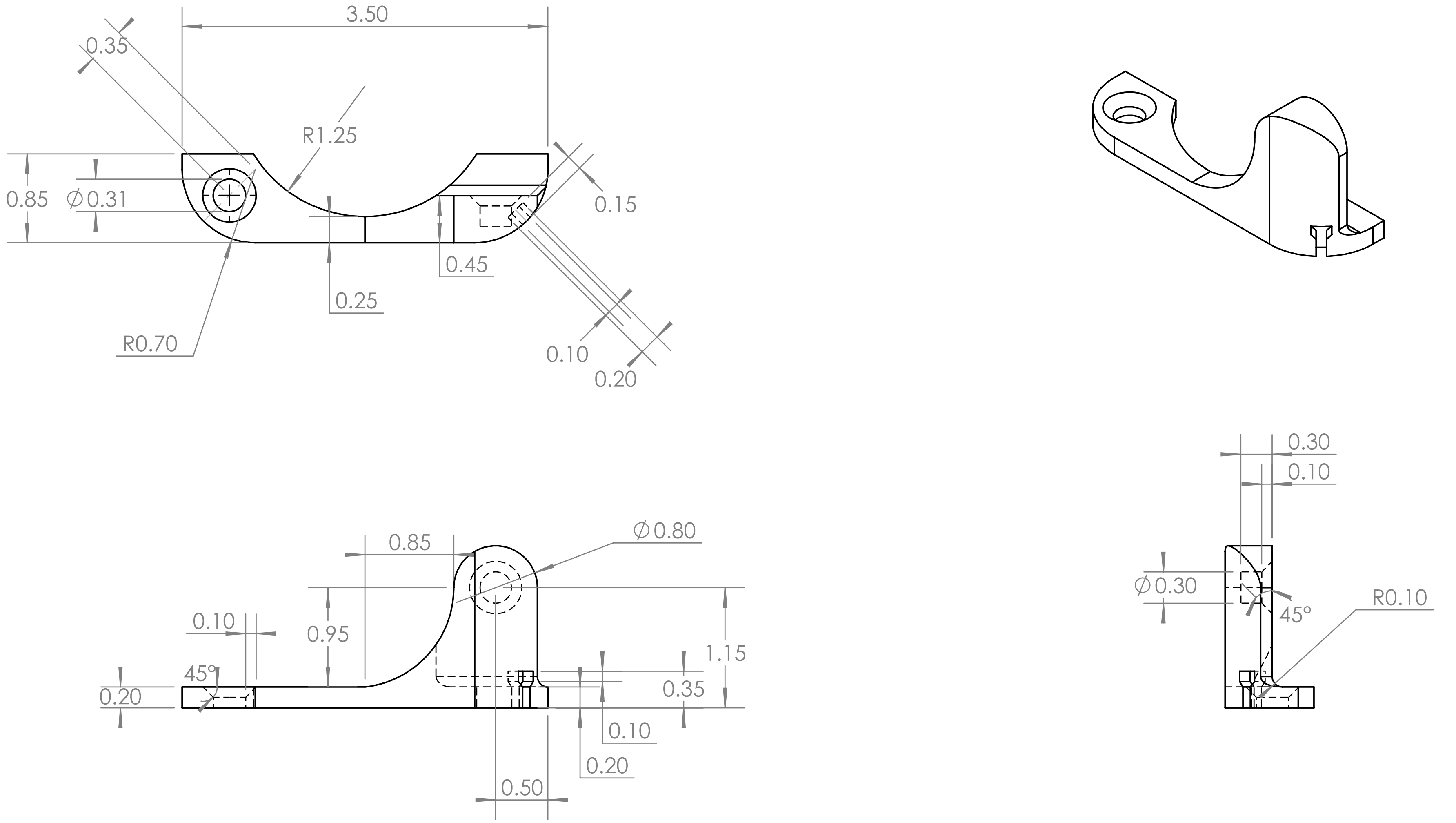
COMMENTS:

TITLE:

RockerShaft

SIZE	DWG. NO.	REV
A		

SCALE: 1:1 WEIGHT: SHEET 1 OF 1



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: ±0.1°
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polylactic Acid

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HJW	12/10/24
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

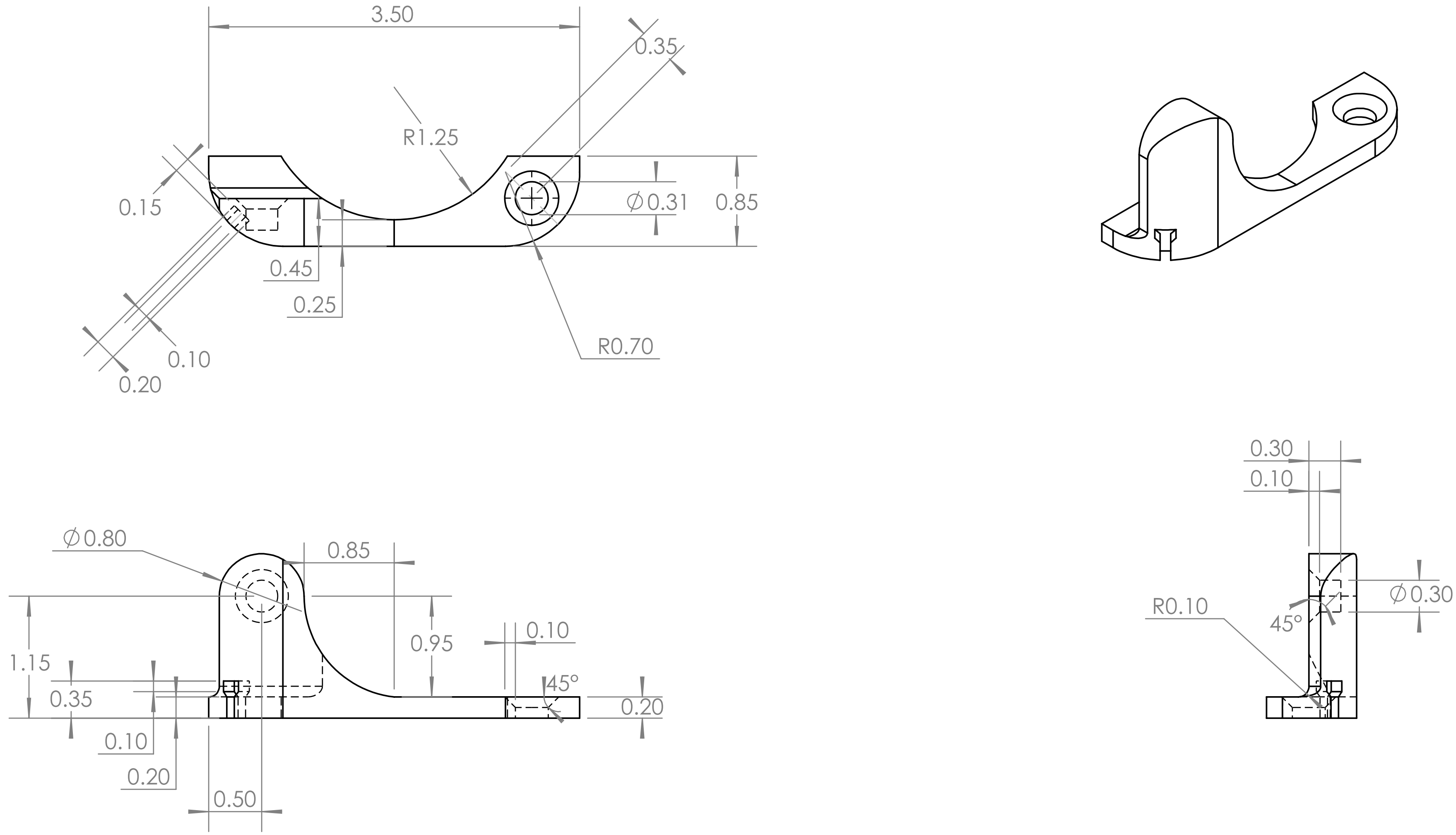
COMMENTS:

TITLE:

RockerSupport-1

SIZE	DWG. NO.	REV
A		

SCALE: 1:1	WEIGHT:	SHEET 1 OF 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: ±0.1°
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polylactic Acid

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HJW	12/10/24
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

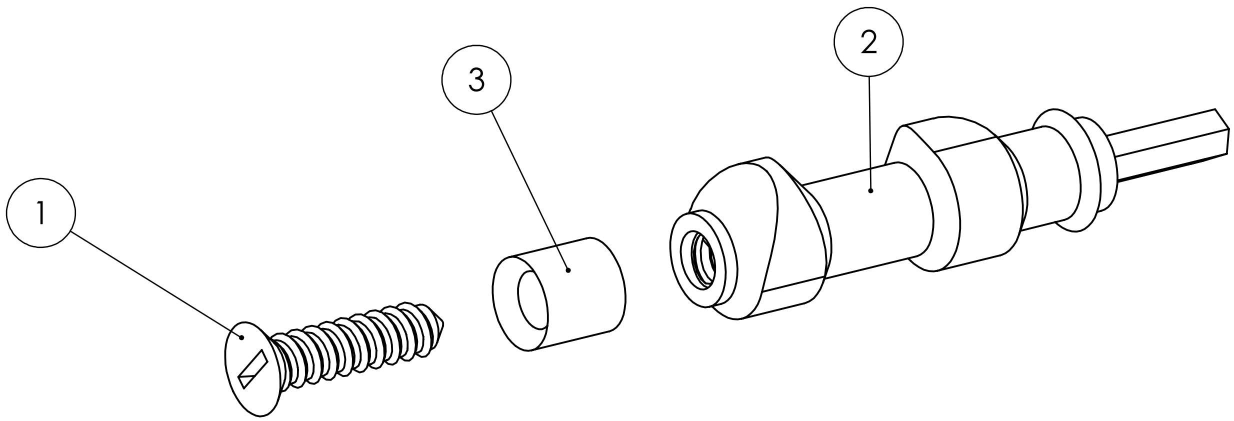
TITLE:

RockerSupport-2

SIZE	DWG. NO.	REV
A		

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

ITEM NO.	PART NUMBER	QTY.
1	Bolt-Medium	1
2	Camshaft-1	1
3	Camshaft-2	1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	SL Hartless	12/9/24	
	CHECKED			TITLE:
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL PLA Plastic	COMMENTS:			SIZE A — DWG. NO. Assembly-Camshaft — REV
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:1 — WEIGHT: — SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

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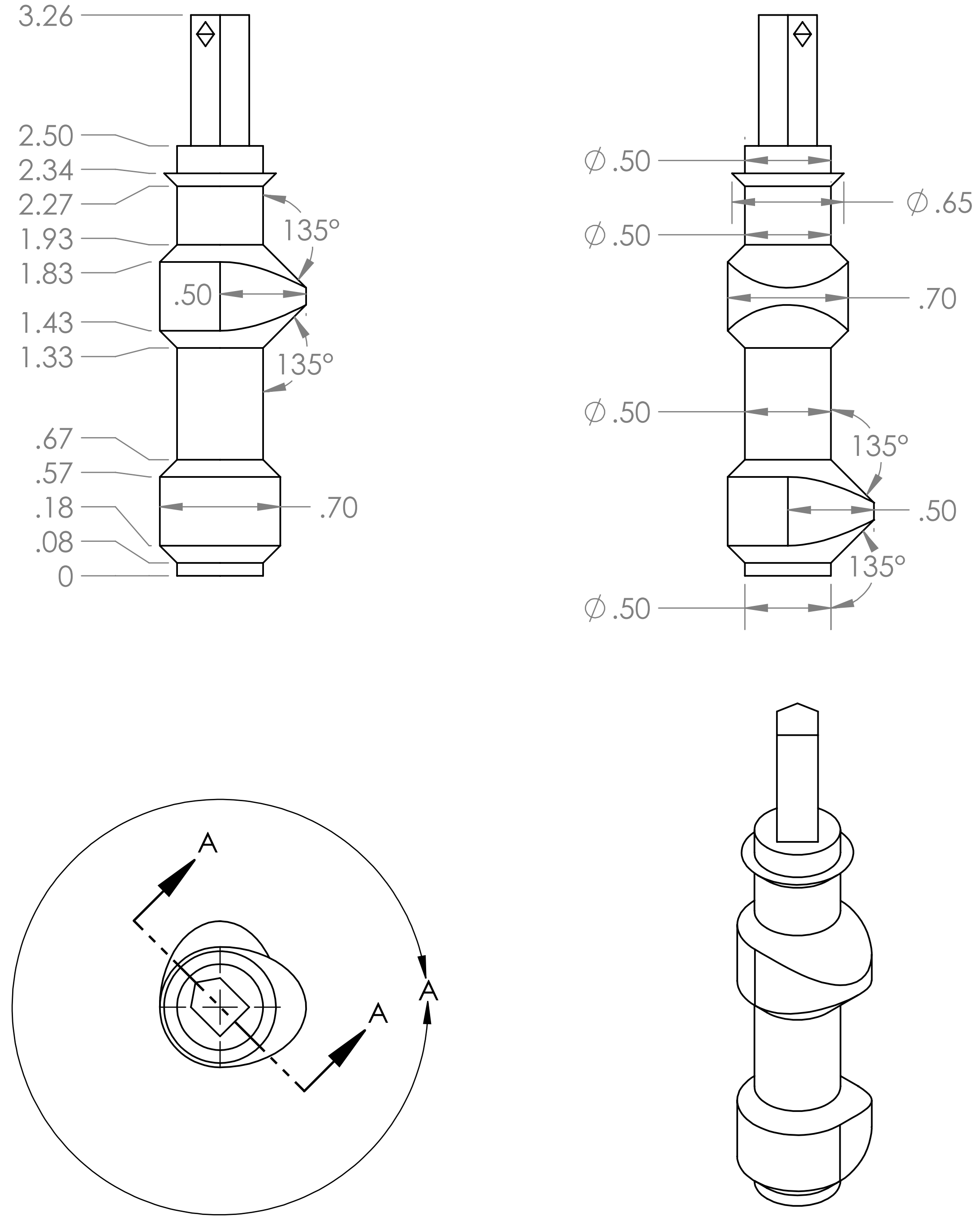
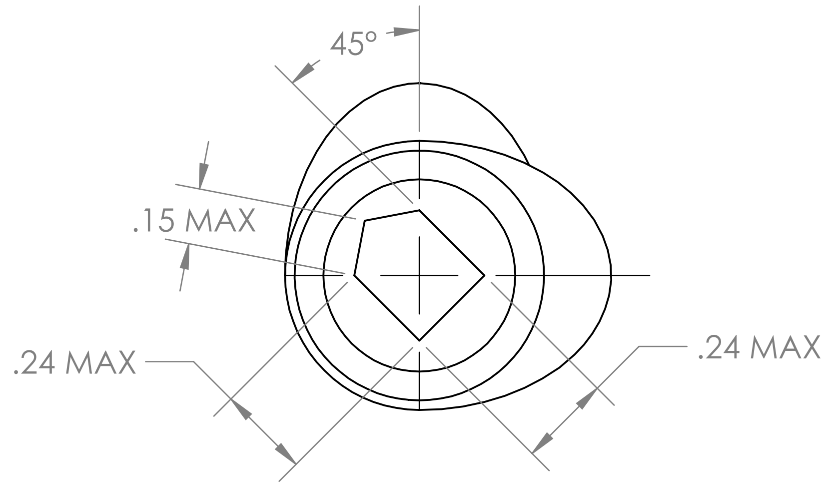


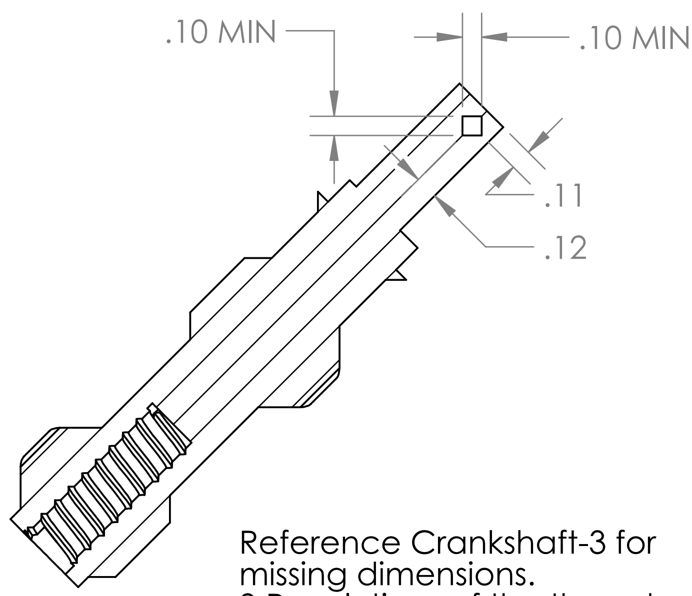
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ±0.1° TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ±		NAME	DATE
			DRAWN	SL Hartless	12/9/24
			CHECKED	HJW	12/12/24
			ENG APPR.		
			MFG APPR.		
		MATERIAL Polylactic Acid	Q.A.		
NEXT ASSY	USED ON	FINISH	COMMENTS:		
APPLICATION		DO NOT SCALE DRAWING			

SIZE	DWG. NO.	REV.
A	Camshaft-1	

SCALE:1:1 | WEIGHT: | SHEET 1 OF 2



DETAIL A
SCALE 2 : 1



Reference Crankshaft-3 for missing dimensions.
9 Revolutions of the threads.

SECTION A-A

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NEXT ASSY	USED ON
APPLICATION	

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: ± 0.1°
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ±

MATERIAL
Polylactic Acid
FINISH

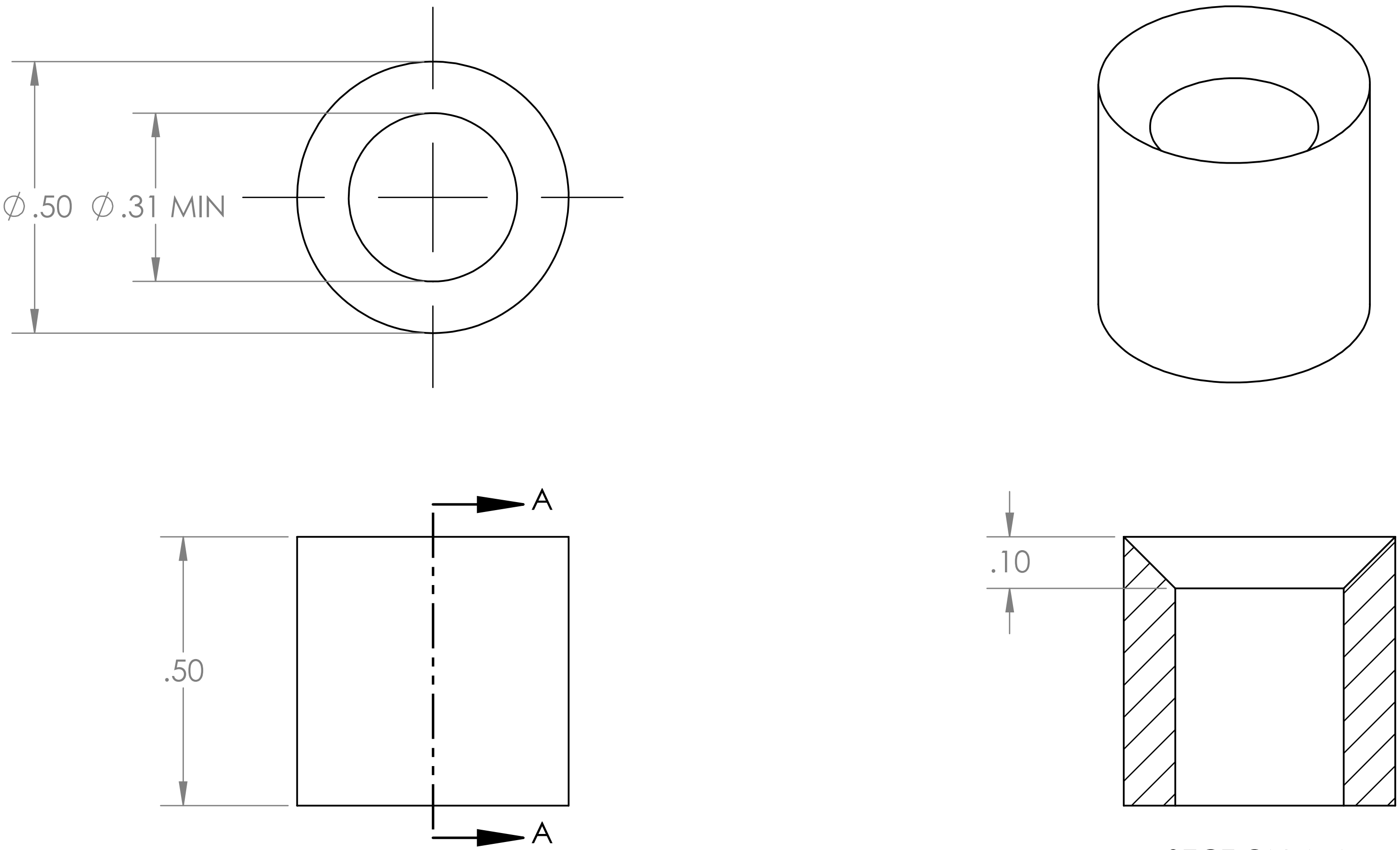
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	SL Hartless	12/9/24
CHECKED	HJW	12/12/24
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

SIZE	DWG. NO.	REV.
A	Camshaft-1	

SCALE:1:1 WEIGHT: SHEET 2 OF 2



SECTION A-A
SCALE 3 : 1

UNLESS OTHERWISE SPECIFIED:	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ±	
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL	Polylactic Acid
FINISH	
DO NOT SCALE DRAWING	

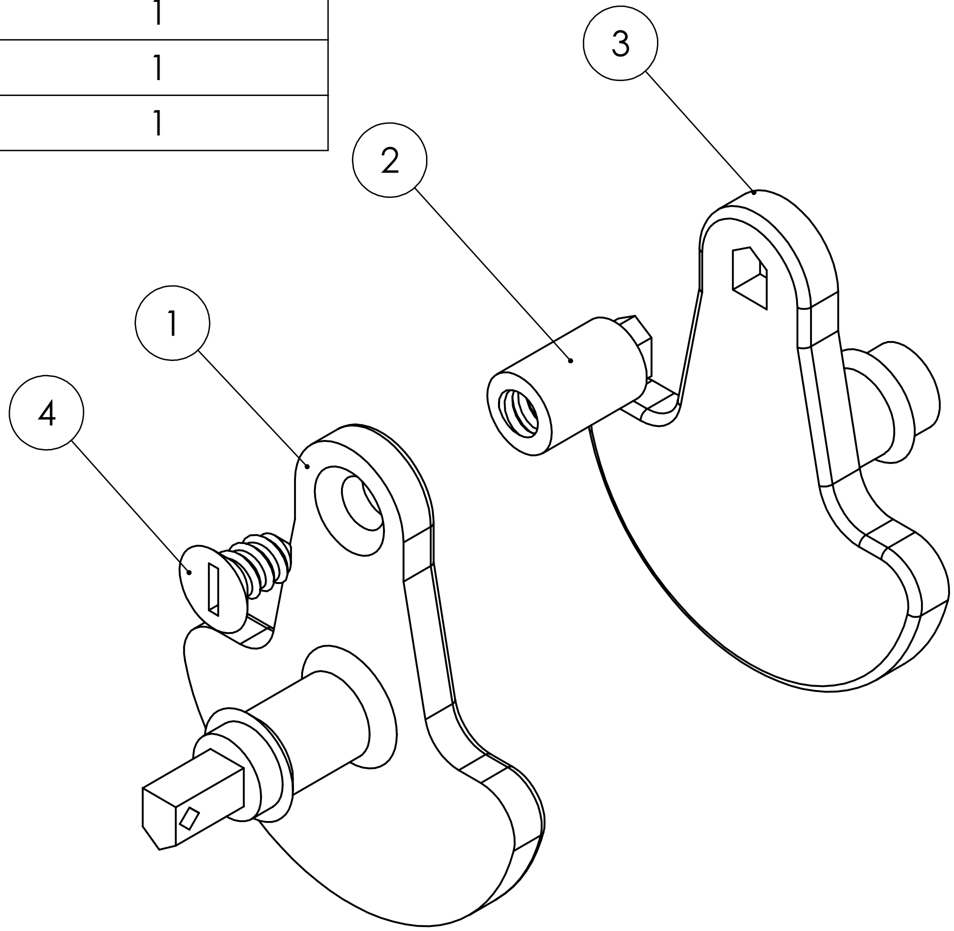
	NAME	DATE
DRAWN	SL Hartless	12/9/24
CHECKED	HJW	12/12/24
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

NEXT ASSY	USED ON
APPLICATION	

TITLE:

SIZE	DWG. NO.	REV
A	Camshaft-2	
SCALE: 4:1	WEIGHT:	SHEET 1 OF 1

ITEM NO.	PART NUMBER	QTY.
1	Crankshaft-2	1
2	Crankshaft-3	1
3	Crankshaft-1	1
4	Bolt-Small	1



NEXT ASSY	USED ON	
APPLICATION		DO NOT SCALE DRAWING

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polylactic Acid

FINISH

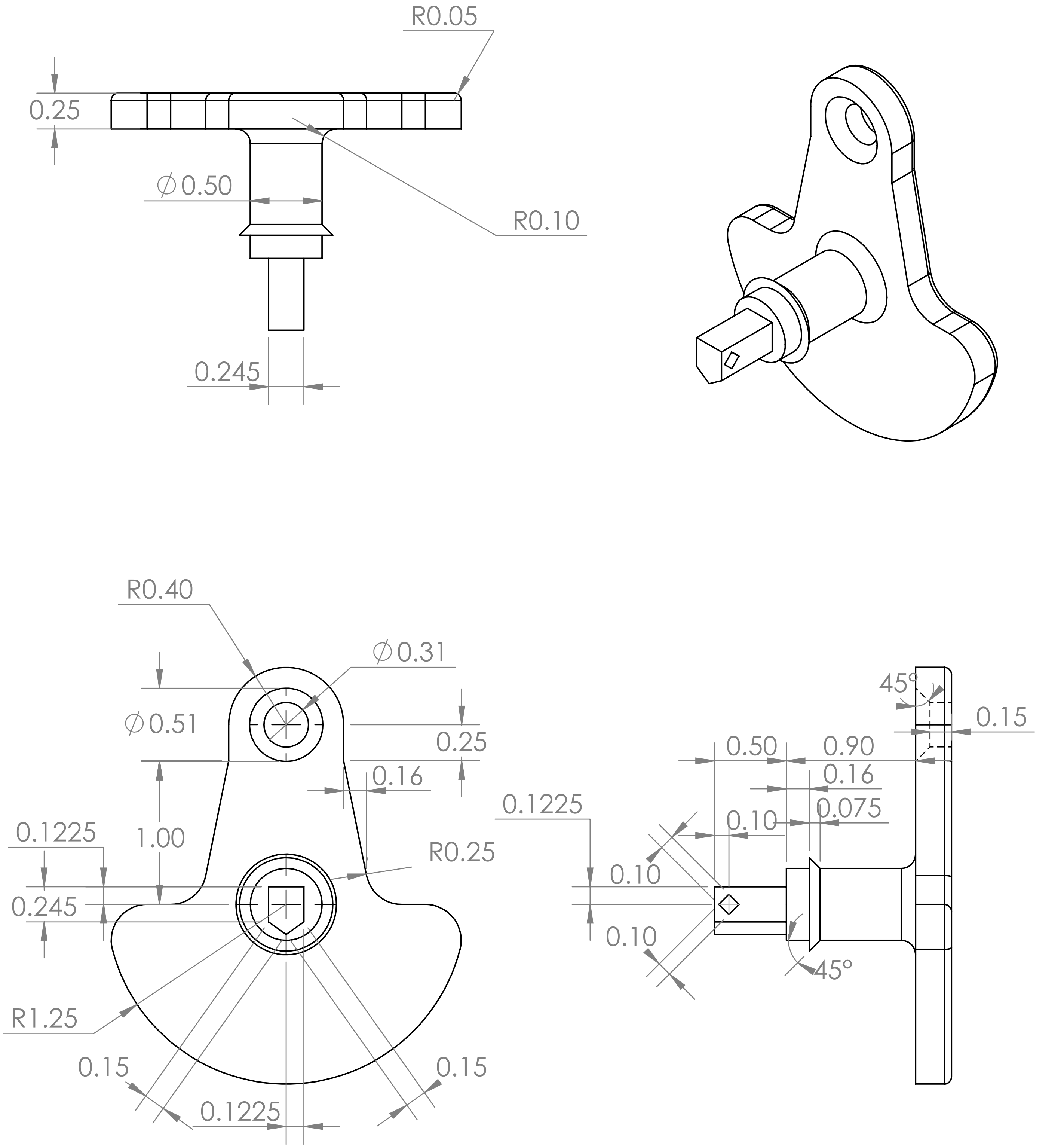
	NAME	DATE
DRAWN	HJW	12/11/24
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE	DWG. NO.	REV
A	Assembly-Crankshaft	

SCALE: 1:1 WEIGHT: SHEET 1 OF 1



PROPRIETARY AND CONFIDENTIAL		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ±0.1° TWO PLACE DECIMAL ±0.01 THREE PLACE DECIMAL ±0.005		NAME	DATE
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <COMPANY NAME >. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <COMPANY NAME> IS PROHIBITED.			DRAWN	HJW	12/10/24
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		MATERIAL Polylactic Acid	Q.A.		
NEXT ASSY	USED ON	FINISH	COMMENTS:		
APPLICATION		DO NOT SCALE DRAWING			

Crankshaft-2

SIZE	DWG. NO.	REV.
A		

SCALE:1:1	WEIGHT:	SHEET 1 OF 1

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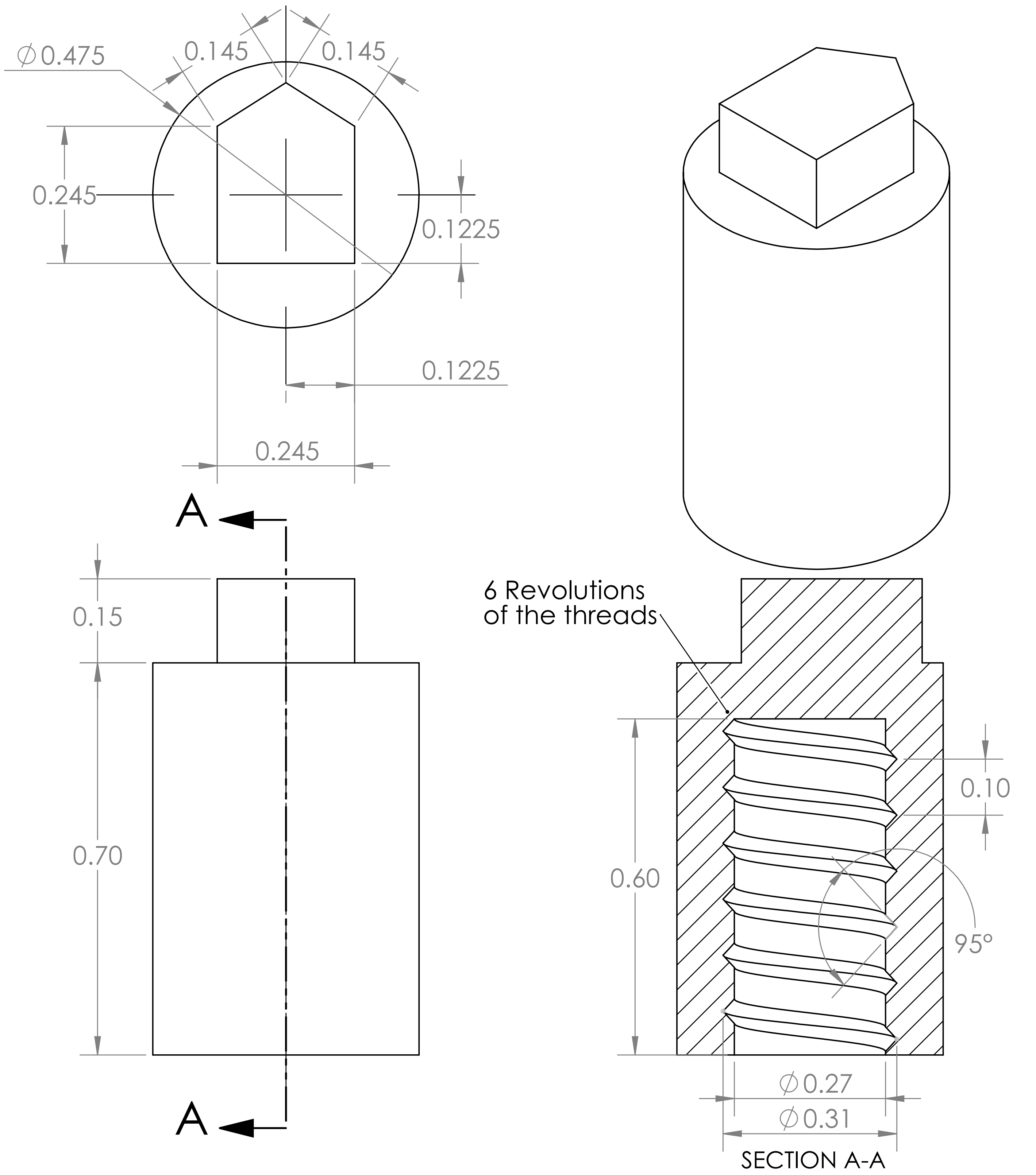
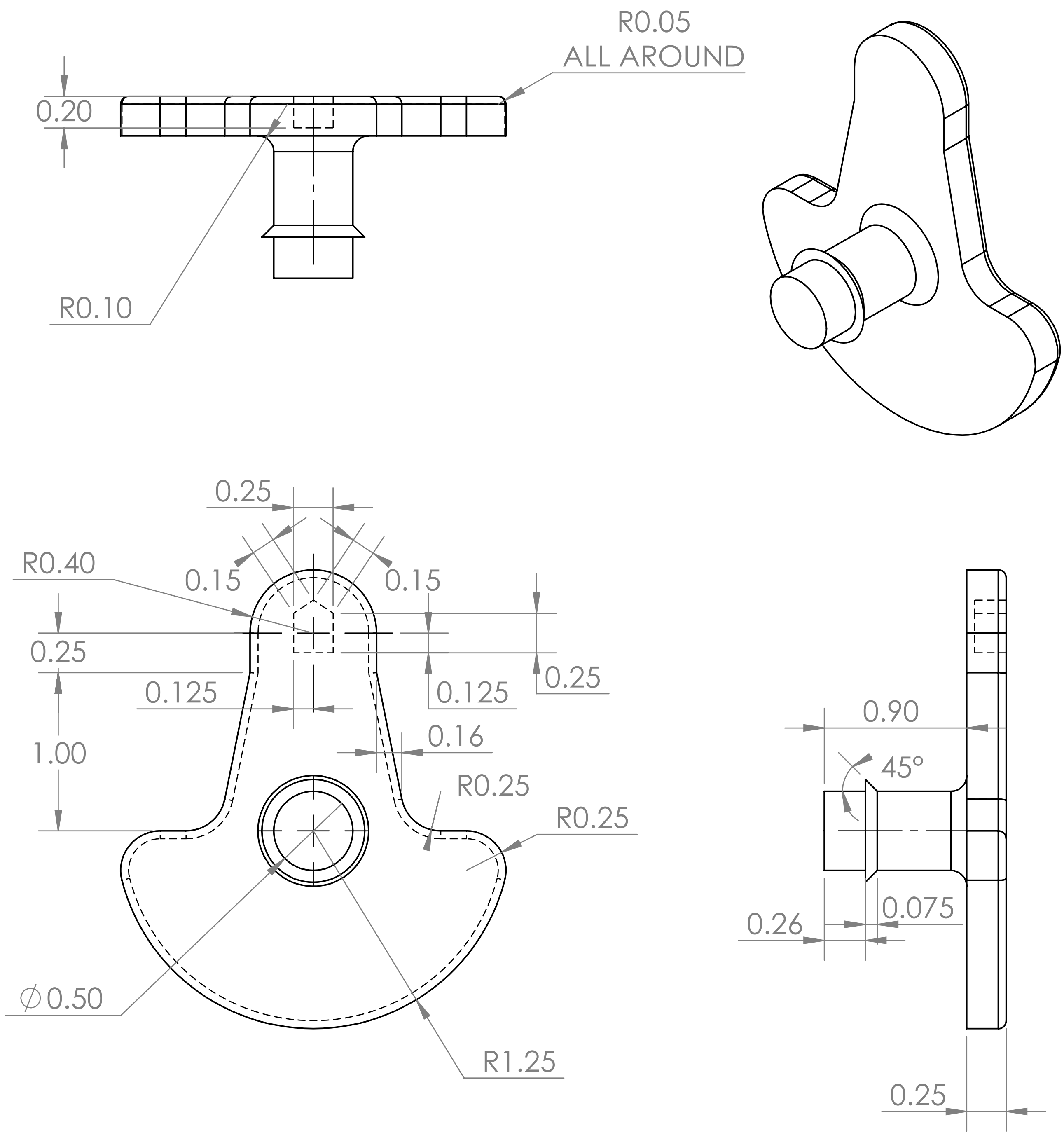
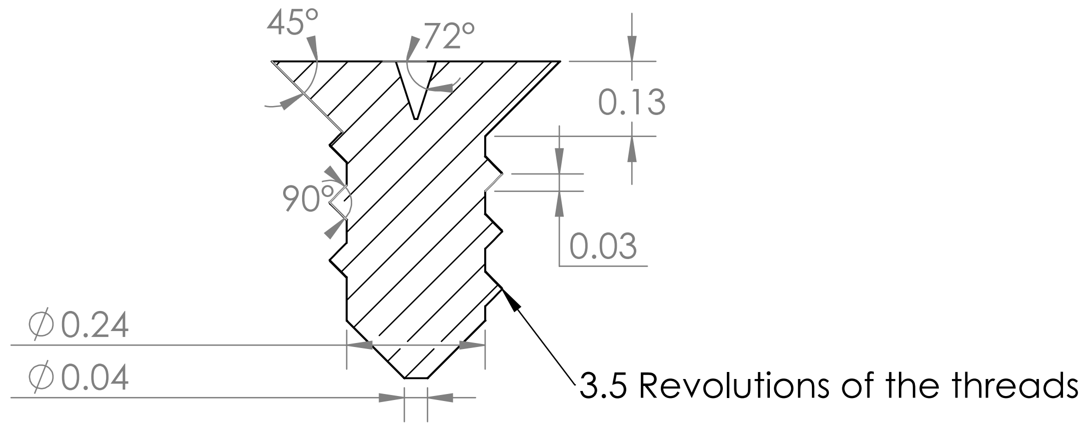


DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ±0.1° TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.005		NAME	DATE		
	DRAWN	HJW	12/10/24		
	CHECKED				
	ENG APPR.				
	MFG APPR.				
	Q.A.				
MATERIAL Polylactic Acid	COMMENTS:			Crankshaft-3	
FINISH				SIZE A	DWG. NO.	REV.
DO NOT SCALE DRAWING				SCALE:4:1	WEIGHT:	SHEET 1 OF 1

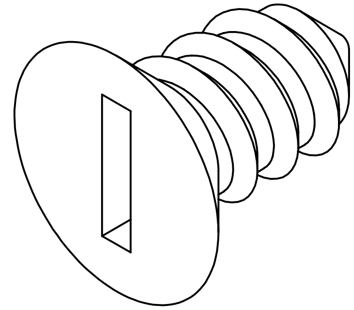
NEXT ASSY	USED ON
APPLICATION	

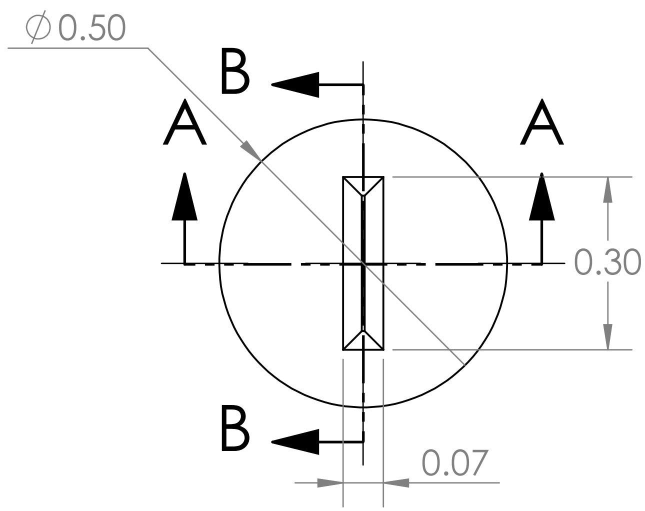


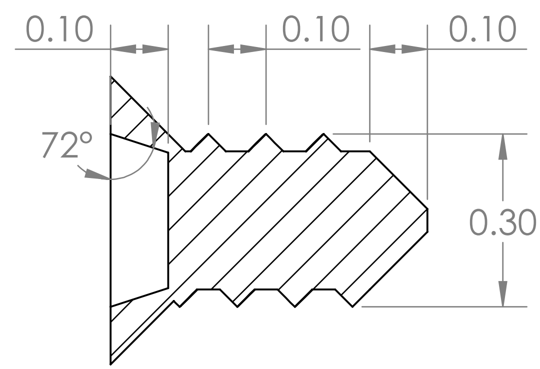
				NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ± 0.1° TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.005	DRAWN	HJW	12/10/24	
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		MATERIAL Polylactic Acid	Q.A.			
		FINISH	COMMENTS:			Crankshaft-1
NEXT ASSY	USED ON					SIZE A · DWG. NO. · REV.
APPLICATION		DO NOT SCALE DRAWING				SCALE:1:1 · WEIGHT: · SHEET 1 OF 1



SECTION A-A







SECTION B-B

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: ±0.1°
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polylactic Acid

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HJW	12/11/24
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

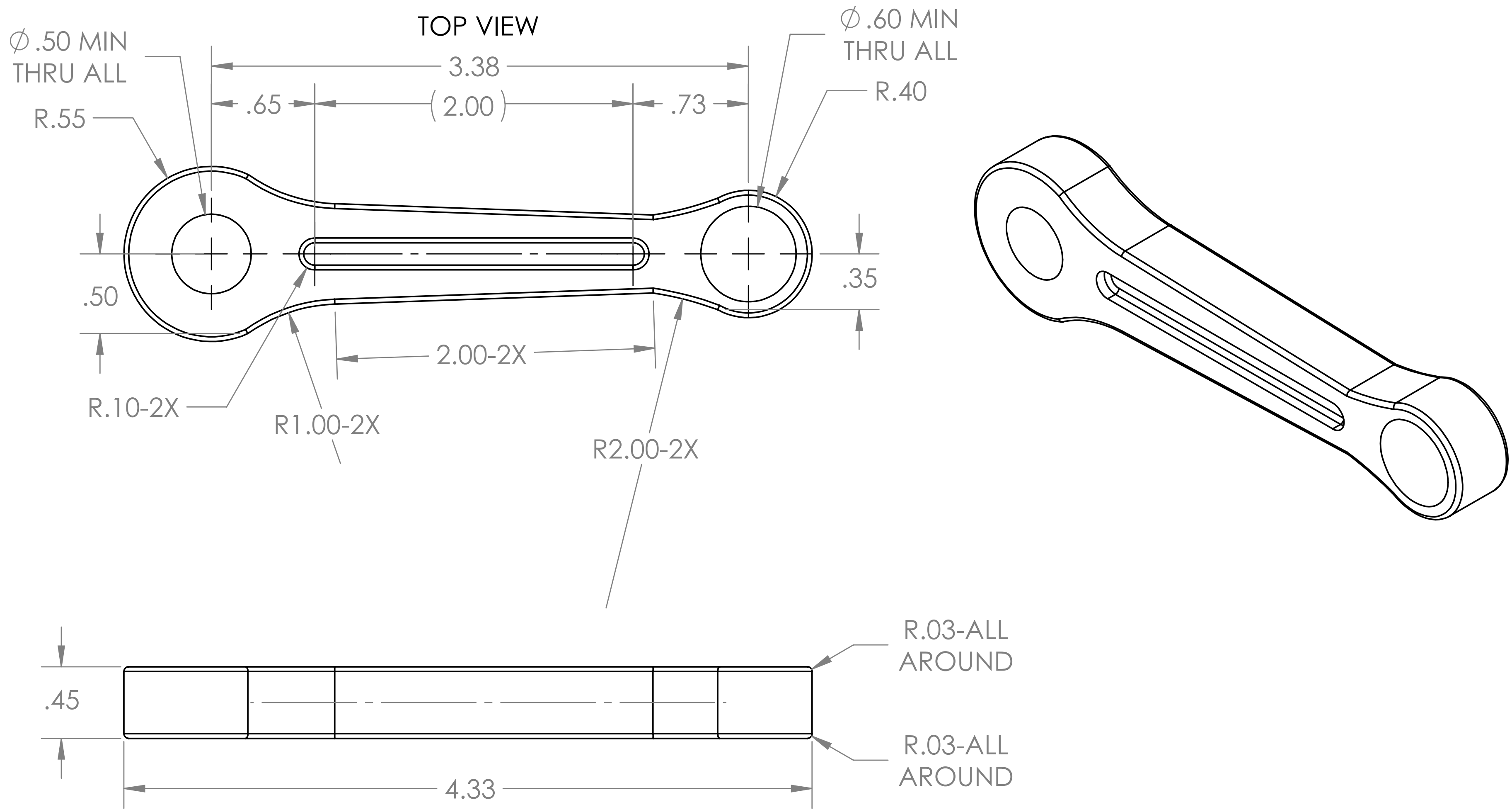
COMMENTS:

TITLE:

Bolt-Small

SIZE **A** DWG. NO. REV

SCALE: 3:1 WEIGHT: SHEET 1 OF 1



	NAME	DATE
DRAWN	SL Hartless	12/10/24
CHECKED	HJW	12/12/24
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polylactic Acid

FINISH

DO NOT SCALE DRAWING

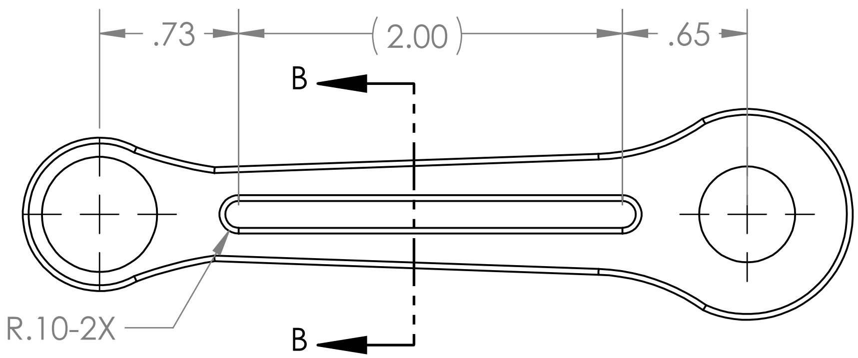
NEXT ASSY	USED ON
APPLICATION	

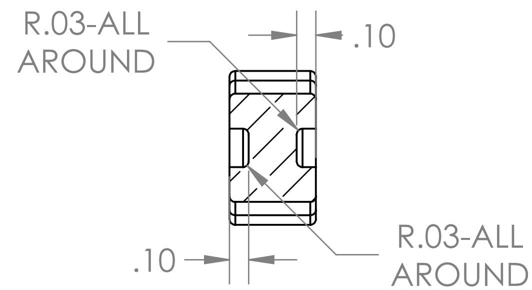
TITLE:

SIZE	DWG. NO.	REV
A	ConnectingRod	

SCALE: 1:1	WEIGHT:	SHEET 1 OF 2

BOTTOM VIEW





SECTION B-B

NOTE: This center slot feature in BOTTOM VIEW is equivalent to that in TOP VIEW. The slot feature is mirrored on each side.

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polylactic Acid

FINISH

DO NOT SCALE DRAWING

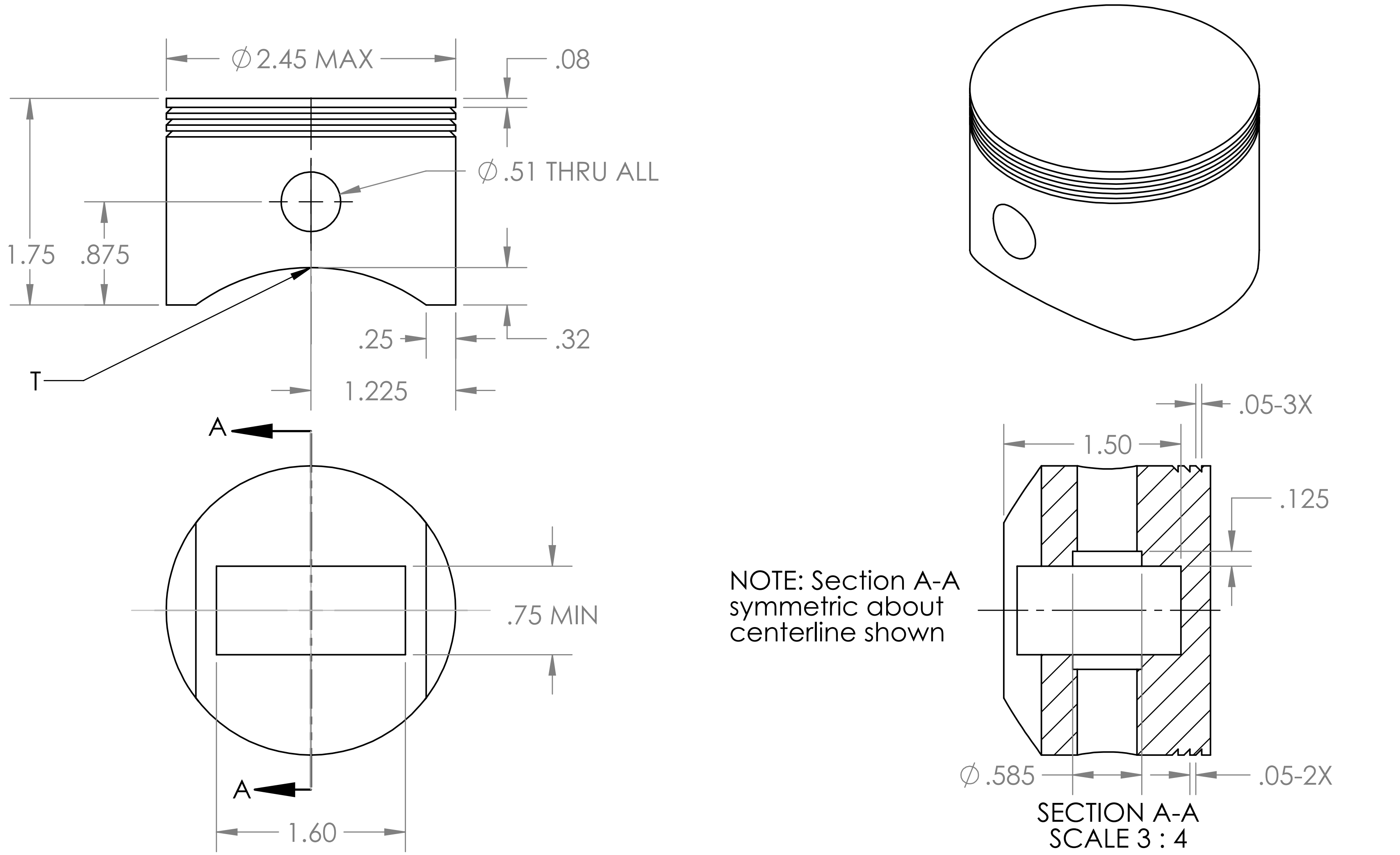
	NAME	DATE
DRAWN	SL Hartless	12/10/24
CHECKED	HJW	12/12/24
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE	DWG. NO.	REV
A	ConnectingRod	

SCALE: 1:1 WEIGHT: SHEET 2 OF 2

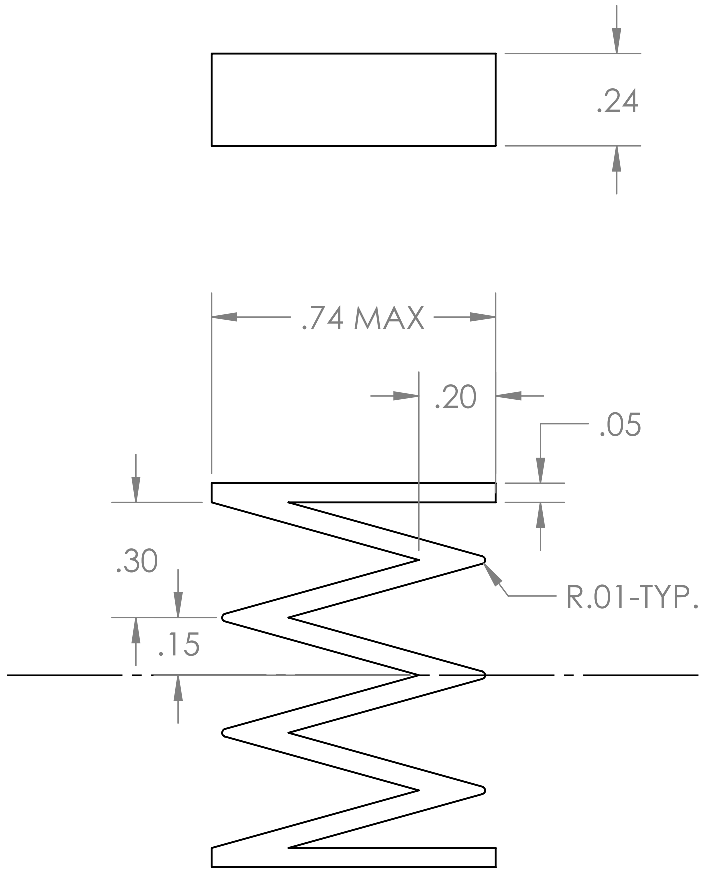


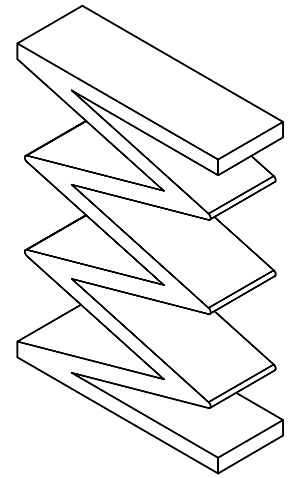
			NAME	DATE
UNLESS OTHERWISE SPECIFIED:				
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.005		DRAWN	SL Hartless	12/9/24
		CHECKED	HJW	12/12/24
		ENG APPR.		
		MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:		Q.A.		
MATERIAL Polylactic Acid		COMMENTS:		
FINISH				
NEXT ASSY	USED ON			
APPLICATION		DO NOT SCALE DRAWING		

TITLE:

SIZE **A** DWG. NO. **PistonHead** REV

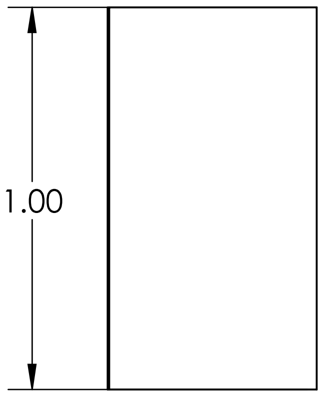
SCALE: 3:4 WEIGHT: SHEET 1 OF 1

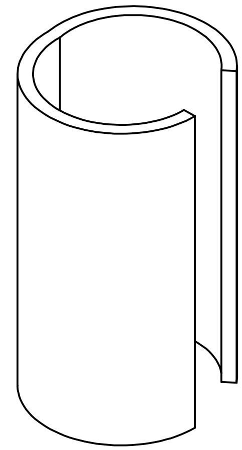


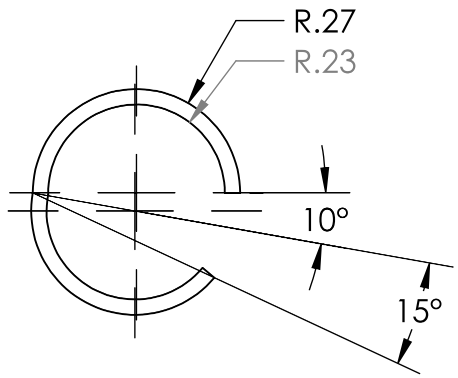


NOTE: Spring is symmetric about centerline shown.

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ±	DRAWN	SL Hartless	12/9/24	
			CHECKED	HJW	12/12/24	TITLE:
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Polylactic Acid	COMMENTS:			SIZE A · DWG. NO. Spring · REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 2:1 · WEIGHT: · SHEET 1 OF 1







		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ± 0.1° TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.005	DRAWN	SL Hartless	12/9/24	
			CHECKED	HJW	12/11/24	TITLE:
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Polylactic Acid	COMMENTS:			SIZE **A** DWG. NO. WristPin REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 2:1 WEIGHT: SHEET 1 OF 1

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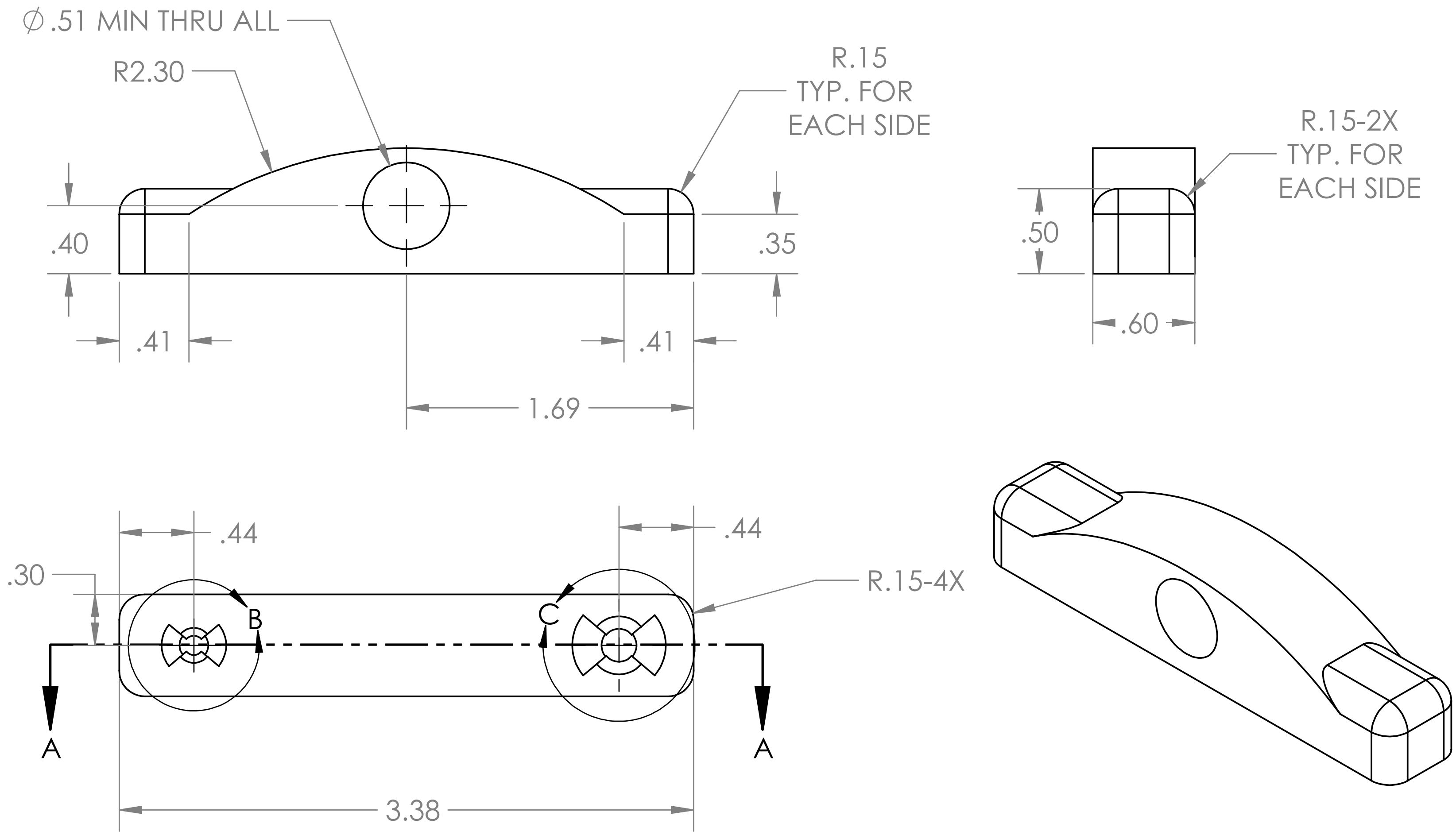
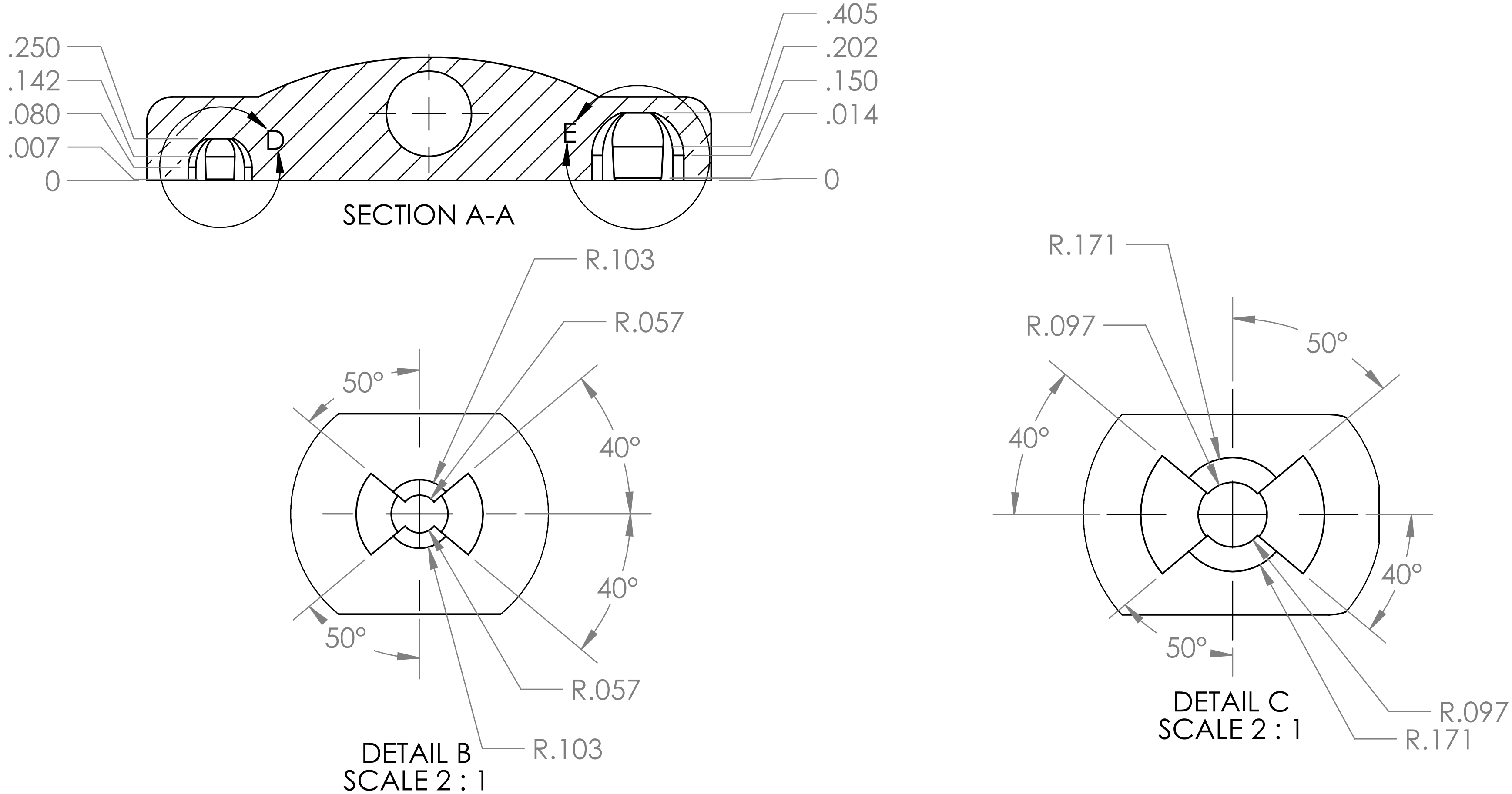


		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ± 0.1° TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.005	DRAWN	SL Hartless	12/10/24	
			CHECKED	HJW	12/12/24	TITLE:
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Polylactic Acid	COMMENTS:			SIZE A · DWG. NO. Rocker · REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1 · WEIGHT: · SHEET 1 OF 4



PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: ±0.1°
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polylactic Acid

FINISH

DO NOT SCALE DRAWING

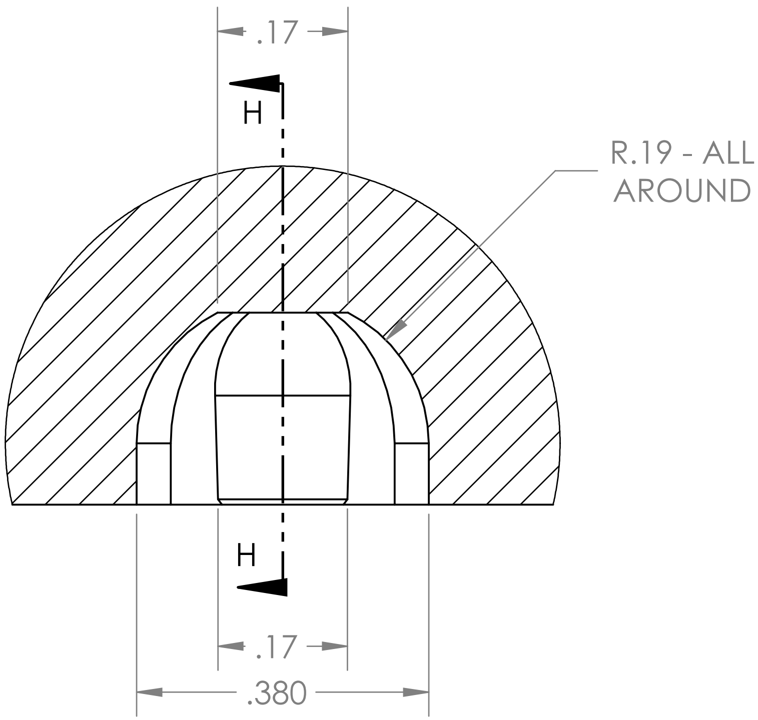
	NAME	DATE
DRAWN	SL Hartless	12/10/24
CHECKED	HJW	12/12/24
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

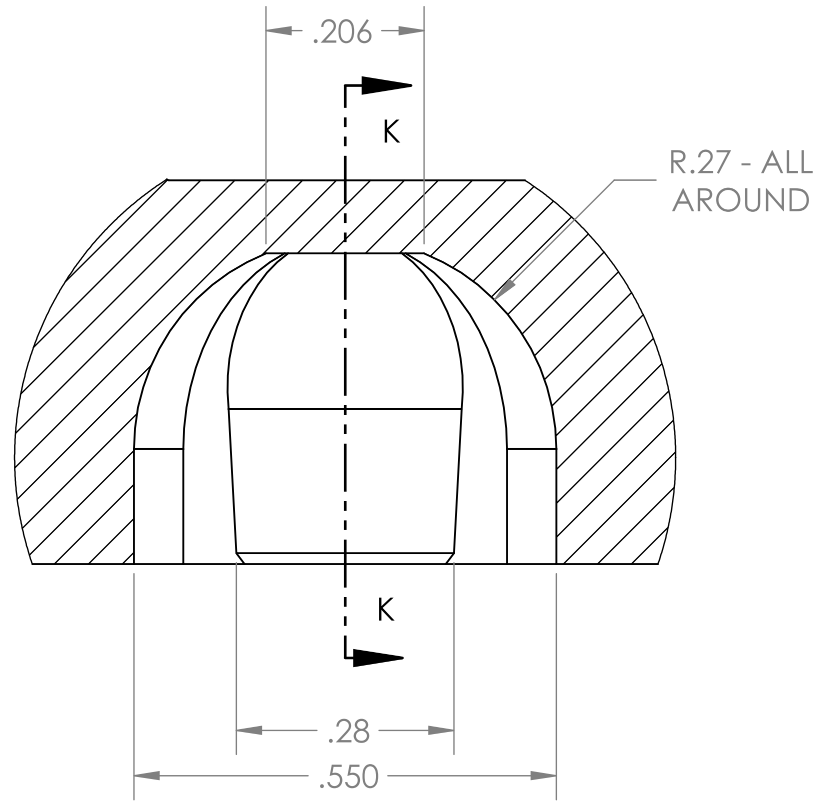
TITLE:

SIZE	DWG. NO.	REV
A	Rocker	

SCALE: 1:1 WEIGHT: SHEET 2 OF 4



DETAIL D
SCALE 4 : 1



DETAIL E
SCALE 4 : 1

PROPRIETARY AND CONFIDENTIAL

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: ± 0.1°
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polylactic Acid

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	SL Hartless	12/10/24
CHECKED	HJW	12/12/24
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

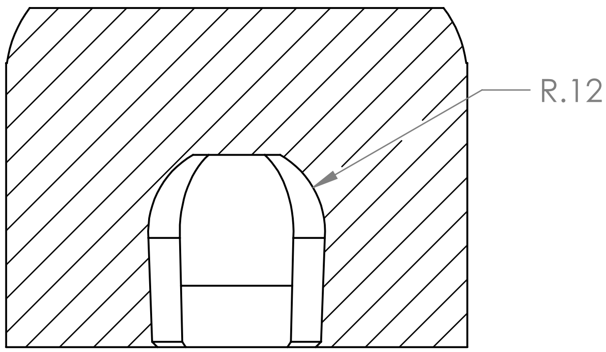
TITLE:

SIZE	DWG. NO.	REV
A	Rocker	

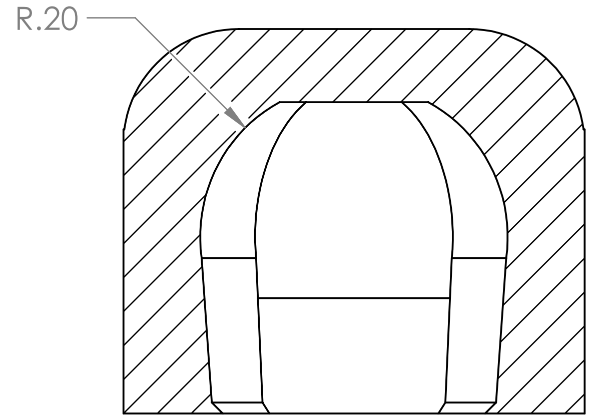
SCALE: 1:1 WEIGHT: SHEET 3 OF 4

2 1

B B



SECTION H-H
SCALE 4 : 1



SECTION K-K
SCALE 4 : 1

A A

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ±0.1° TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.005	DRAWN	SL Hartless	12/11/24
	CHECKED	HJW	12/12/24
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL Polylactic Acid	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

PROPRIETARY AND CONFIDENTIAL

TITLE:

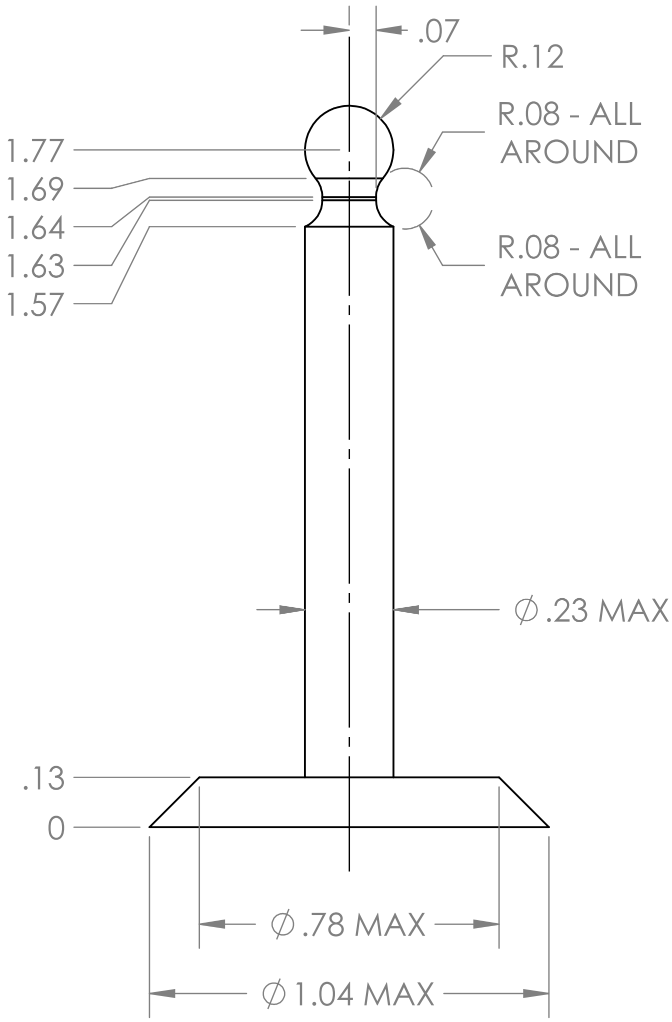
SIZE A | DWG. NO. Rocker | REV

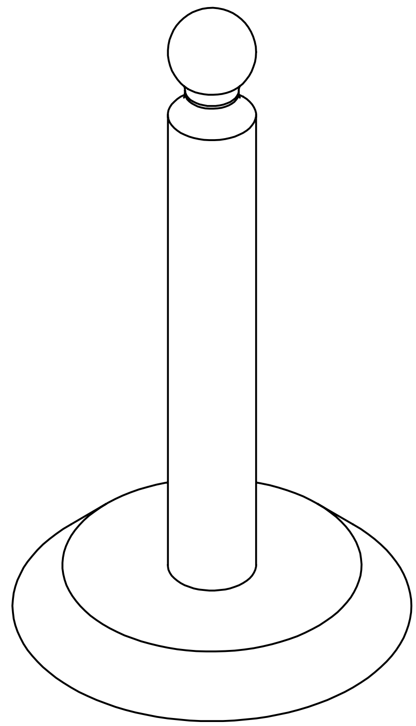
SCALE: 1:1 | WEIGHT: | SHEET 4 OF 4

2 1

2 1

NOTE: Symmetric about centerline shown





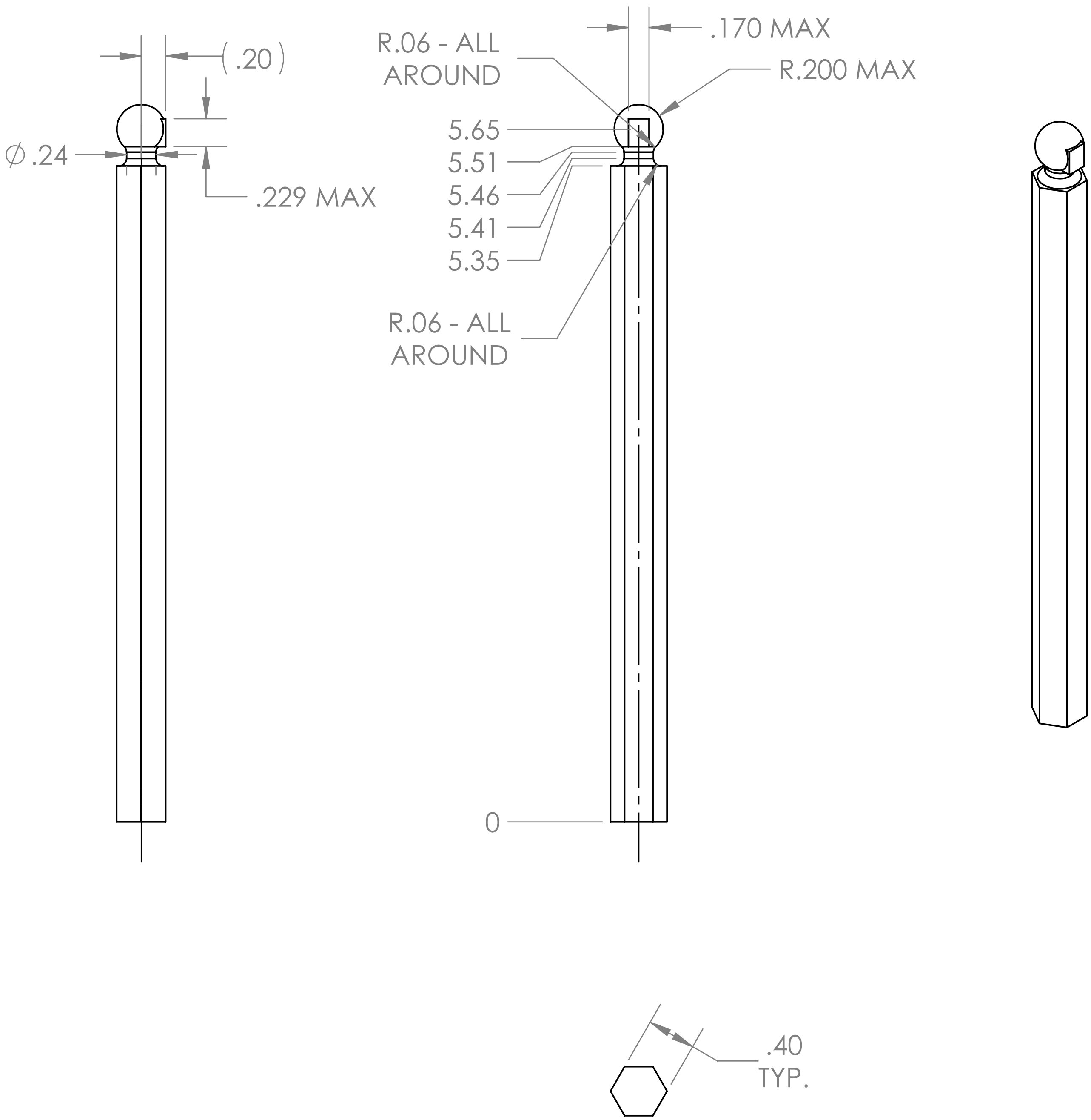
B B

A A

PROPRIETARY AND CONFIDENTIAL		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ±		NAME	DATE
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <COMPANY NAME >. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <COMPANY NAME> IS PROHIBITED.			DRAWN	SL Hartless	12/9/24
			CHECKED	HJW	12/12/24
			ENG APPR.		
			MFG APPR.		
		MATERIAL Polylactic Acid	Q.A.		
	NEXT ASSY / USED ON	FINISH	COMMENTS:		
	APPLICATION	DO NOT SCALE DRAWING			

SIZE	DWG. NO.	REV.
A	Valve	
SCALE:2:1	WEIGHT:	SHEET 1 OF 1

2 1



PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <COMPANY NAME>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <COMPANY NAME> IS PROHIBITED.

NEXT ASSY	USED ON
APPLICATION	

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.005

MATERIAL
Polylactic Acid

FINISH

DO NOT SCALE DRAWING

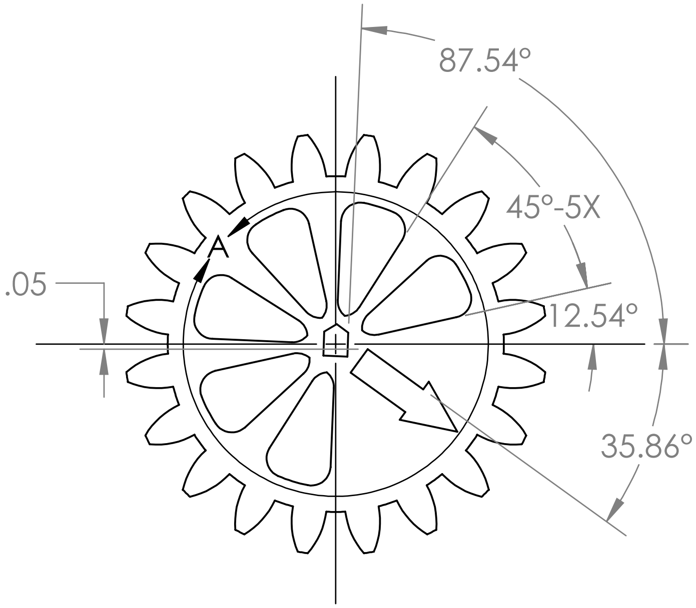
	NAME	DATE
DRAWN	SL Hartless	12/9/24
CHECKED	HJW	12/12/24
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

SIZE	DWG. NO.	REV.
A	Pushrod	

SCALE: 3:4	WEIGHT:	SHEET 1 OF 1

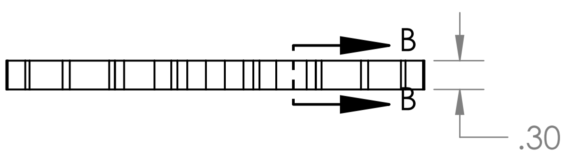
2 1

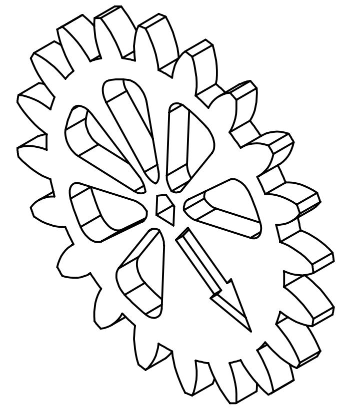


SPUR GEAR PROPERTIES	
Diametral Pitch	5 teeth/inch
Pressure Angle	20 degrees
Number of Teeth	20 teeth

NOTE: All profiles except for arrow are THRU ALL. See SECTION B-B.

B B





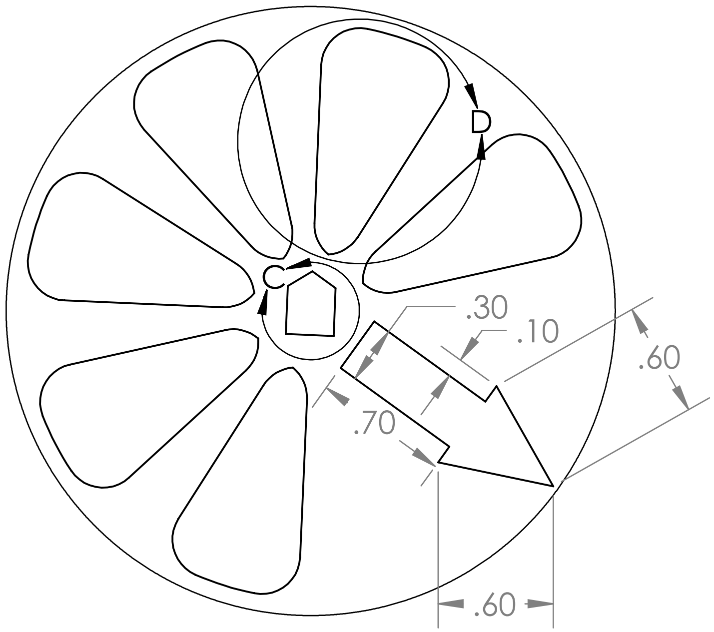
A A

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ± 0.1° TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.005	DRAWN	SL Hartless	12/11/24	
			CHECKED	HJW	12/12/24	TITLE:
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Polylactic Acid	COMMENTS:			SIZE A DWG. NO. CamGear REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:2 WEIGHT: SHEET 1 OF 3

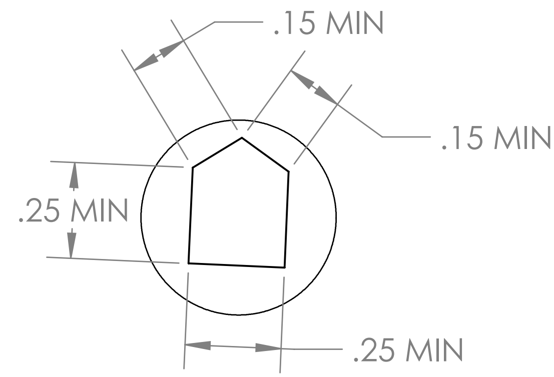
2 1

2 1

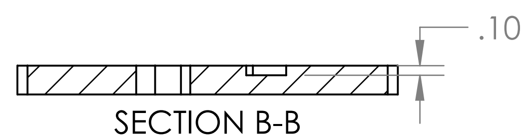
B B



DETAIL A
SCALE 1 : 1



DETAIL C
SCALE 2 : 1



SECTION B-B

A A

		UNLESS OTHERWISE SPECIFIED:
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ±0.1° TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.005
		INTERPRET GEOMETRIC TOLERANCING PER:
		MATERIAL Polylactic Acid
NEXT ASSY	USED ON	FINISH
APPLICATION		DO NOT SCALE DRAWING

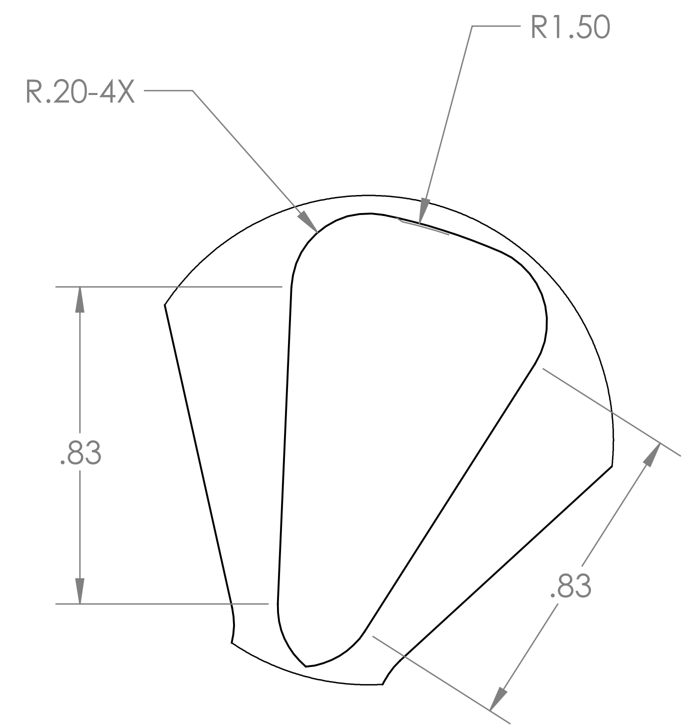
	NAME	DATE
DRAWN	SL Hartless	12/11/24
CHECKED	HJW	12/12/24
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE:

SIZE	DWG. NO.	REV
A	CamGear	

SCALE: 1:2 WEIGHT: SHEET 2 OF 3

2 1



NOTE: The dimensions as shown in DETAIL D are TYP. for each instance of this profile (6X). Each profile is 45° apart as shown on SHEET 1.

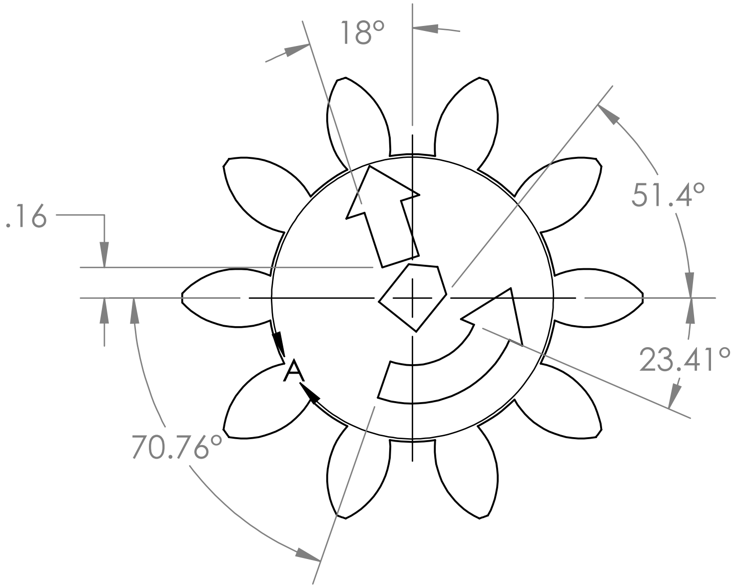
DETAIL D
SCALE 2 : 1

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ± 0.1° TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.005	DRAWN	SL Hartless	12/11/24
	CHECKED	HJW	12/12/24
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL Polylactic Acid	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

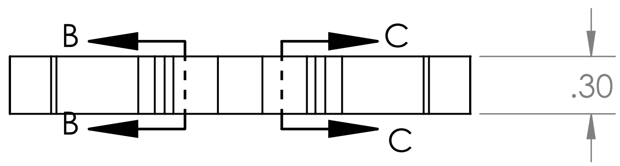
TITLE:

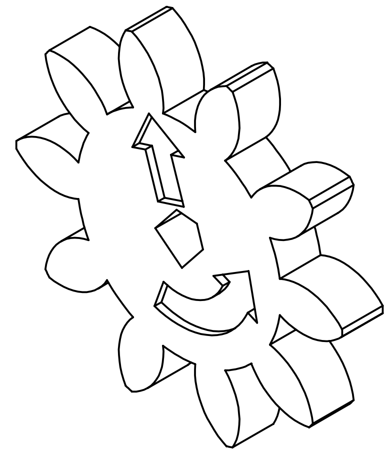
SIZE	DWG. NO.	REV
A	CamGear	
SCALE: 1:2	WEIGHT:	SHEET 3 OF 3



SPUR GEAR PROPERTIES	
Diametral Pitch	5 teeth/inch
Pressure Angle	20 degrees
Number of Teeth	10 teeth

NOTE: Center hole is THRU ALL. Two arrow profiles are cut to depth as shown in SECTION B-B and SECTION C-C





NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: ± 0.01°
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polylactic Acid

FINISH

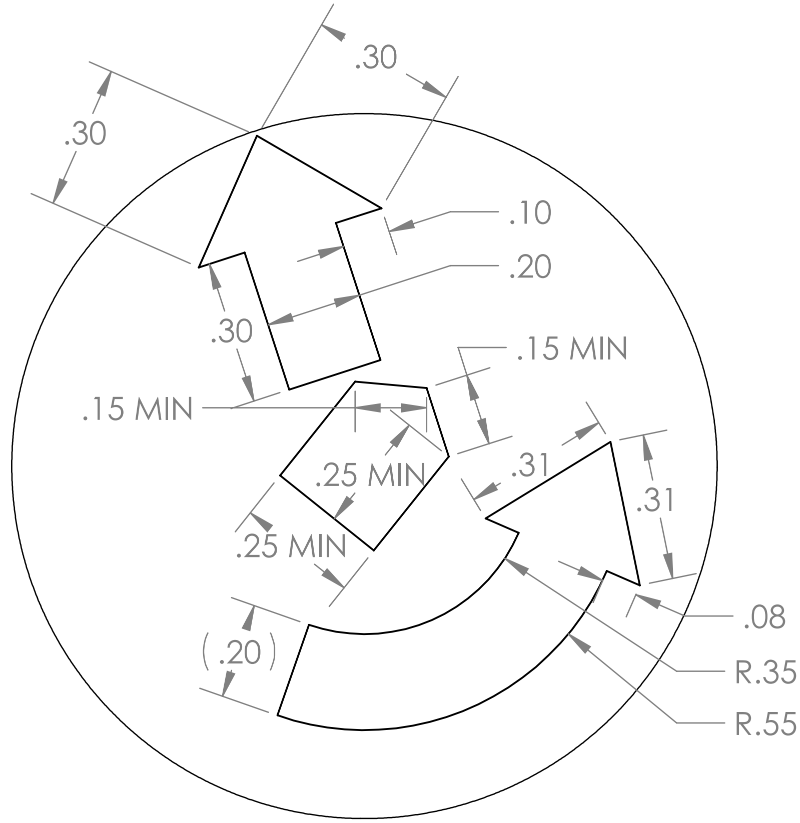
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	SL Hartless	12/10/24
CHECKED	HJW	12/12/24
ENG APPR.		
MFG APPR.		
Q.A.		

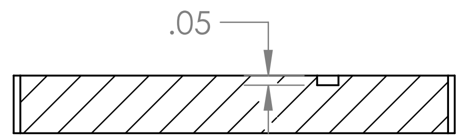
COMMENTS:

TITLE:

SIZE	DWG. NO.	REV
A	CrankGear	
SCALE: 1:1	WEIGHT:	SHEET 1 OF 2

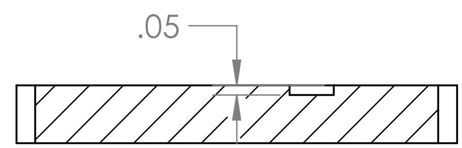


DETAIL A
SCALE 5 : 2



SECTION B-B

Depth of Straight Arrow



SECTION C-C

Depth of Curved Arrow

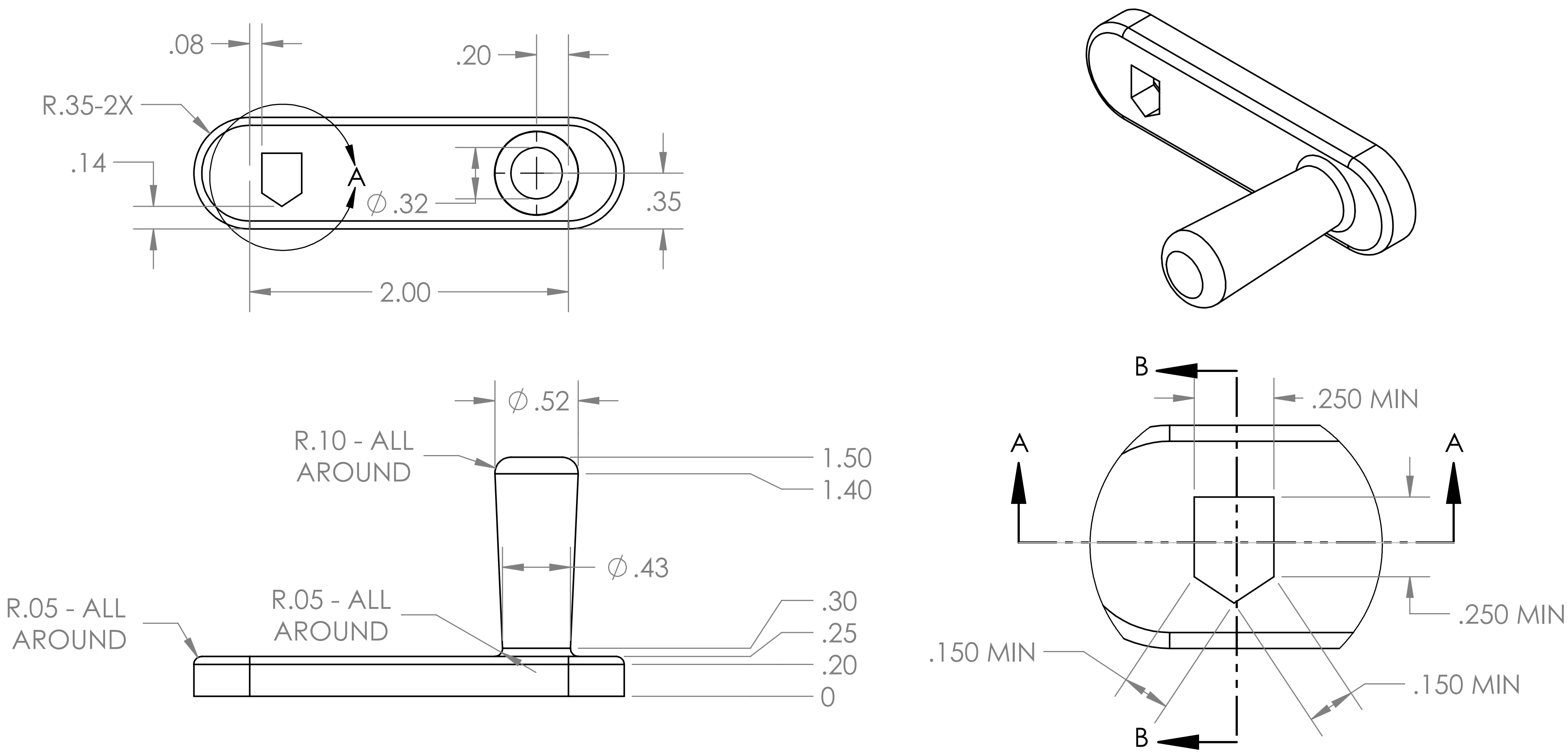
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ±0.1° TWO PLACE DECIMAL ±0.01 THREE PLACE DECIMAL ±0.005	DRAWN	SL Hartless	12/10/24
	CHECKED	HJW	12/12/24
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL Polylactic Acid	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

TITLE:

SIZE A | DWG. NO. CrankGear | REV

SCALE: 1:1 | WEIGHT: | SHEET 2 OF 2



DETAIL A
SCALE 2 : 1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polylactic Acid

FINISH

DO NOT SCALE DRAWING

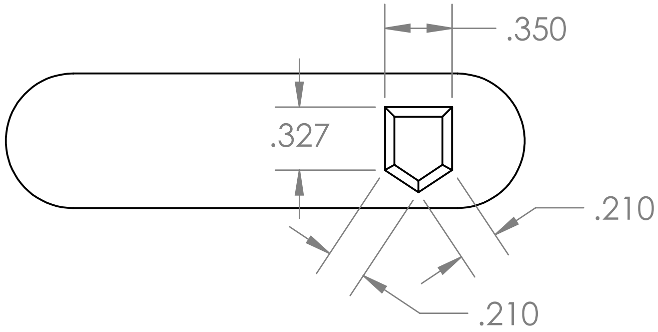
	NAME	DATE
DRAWN	SL Hartless	12/10/24
CHECKED	HJW	12/12/24
ENG APPR.		
MFG APPR.		
Q.A.		

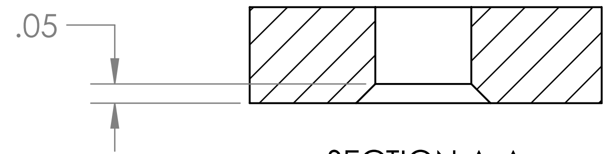
COMMENTS:

NEXT ASSY	USED ON
APPLICATION	

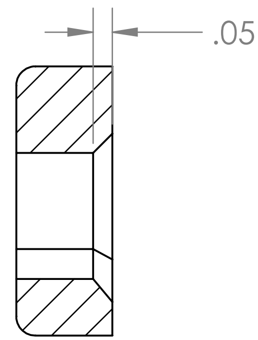
TITLE:

SIZE	DWG. NO.	REV
A	HandCrank	
SCALE: 1:1	WEIGHT:	SHEET 1 OF 2





SECTION A-A
SCALE 2 : 1



SECTION B-B
SCALE 2 : 1

	NAME	DATE
DRAWN	SL Hartless	12/10/24
CHECKED	HJW	12/12/24
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polylactic Acid

FINISH

DO NOT SCALE DRAWING

NEXT ASSY	USED ON
APPLICATION	

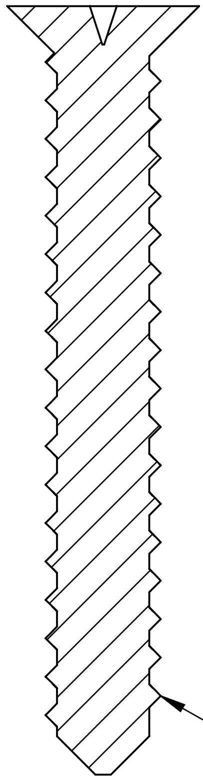
TITLE:

SIZE **A** DWG. NO. HandCrank REV

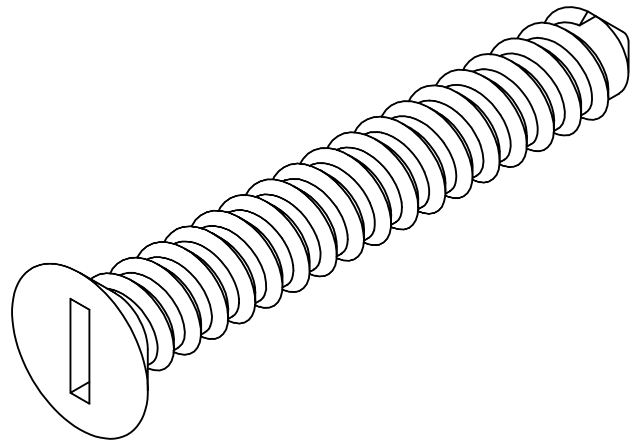
SCALE: 1:1 WEIGHT: SHEET 2 OF 2

2 1

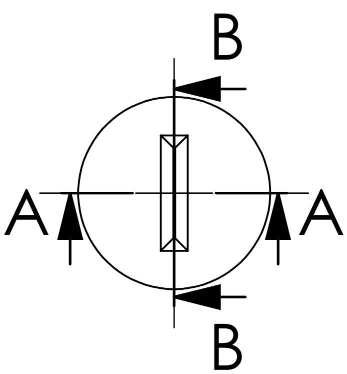
B B

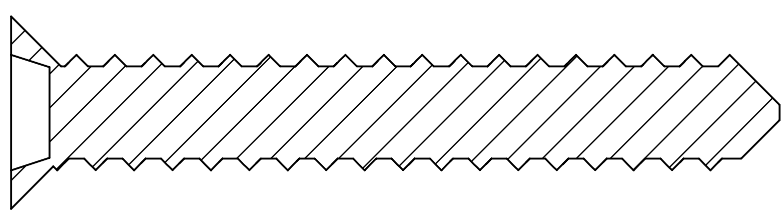


SECTION A-A



Reference Bolt-Small for missing dimensions. 18 Revolutions of the threads





SECTION B-B

A A

				NAME	DATE	
			DRAWN	HJW	12/11/24	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: ±0.1° TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.005	CHECKED			
			ENG APPR.			
PROPRIETARY AND CONFIDENTIAL			MFG APPR.			
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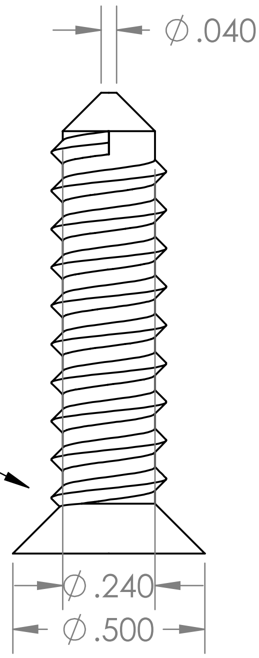
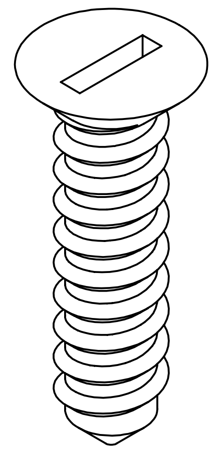
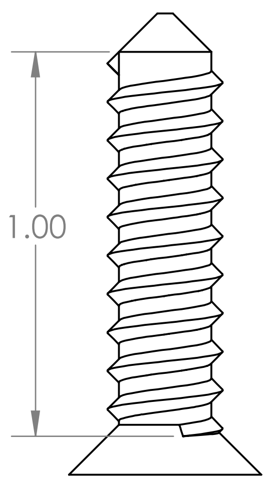
	NEXT ASSY / USED ON	FINISH	COMMENTS:			Bolt-Large
	APPLICATION	DO NOT SCALE DRAWING				SIZE A / DWG. NO. / REV.
						SCALE:2:1 / WEIGHT: / SHEET 1 OF 1

2 1

Reference Bolt-Small for missing dimensions. 10 Revolutions of the threads.







	NAME	DATE	
DRAWN	SL Hartless	12/9/24	
CHECKED	HJW	12/12/24	
ENG APPR.			
MFG APPR.			
Q.A.			
COMMENTS:			

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.005

MATERIAL
PLA Acid
FINISH

NEXT ASSY	USED ON
APPLICATION	

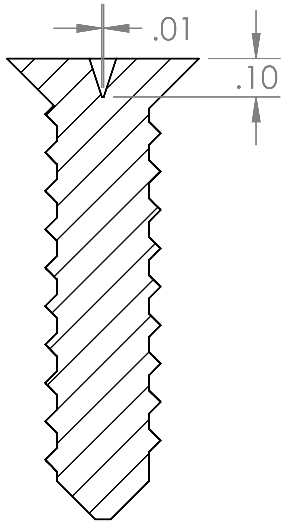
DO NOT SCALE DRAWING

SIZE A | DWG. NO. Bolt-Medium | REV.

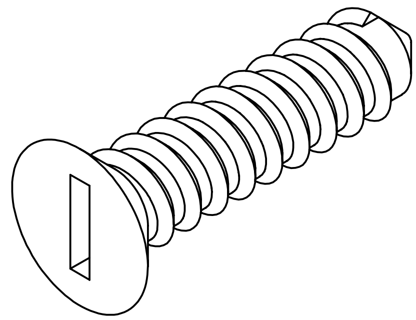
SCALE:2:1 | WEIGHT: | SHEET 1 OF 2

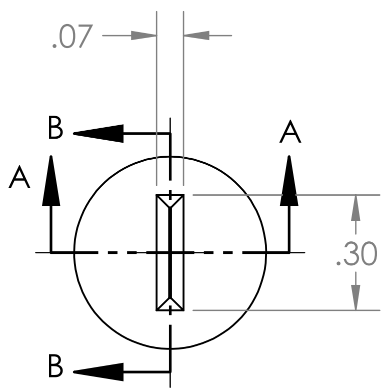
2 1

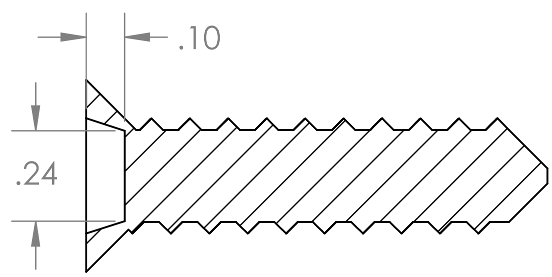
B B



SECTION A-A







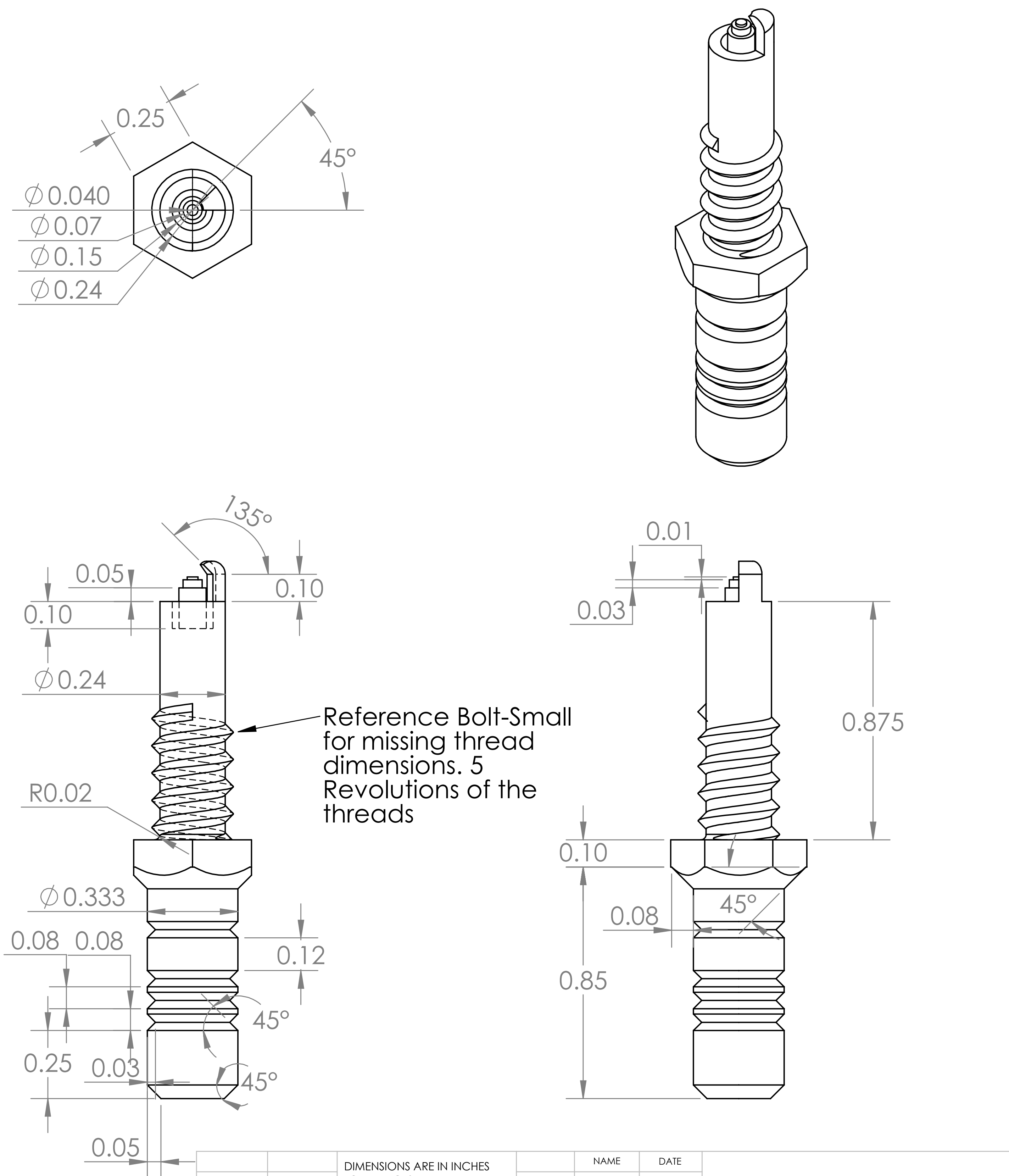
SECTION B-B

A A

		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.005		NAME	DATE
			DRAWN	SL Hartless	12/9/24
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		MATERIAL PLA Plastic	Q.A.		
NEXT ASSY	USED ON	FINISH	COMMENTS:		
APPLICATION		DO NOT SCALE DRAWING			

SIZE	DWG. NO.	REV.
A	Bolt-Medium	
SCALE:2:1	WEIGHT:	SHEET 2 OF 2

2 1



PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL
Polyactic Acid

FINISH

DO NOT SCALE DRAWING

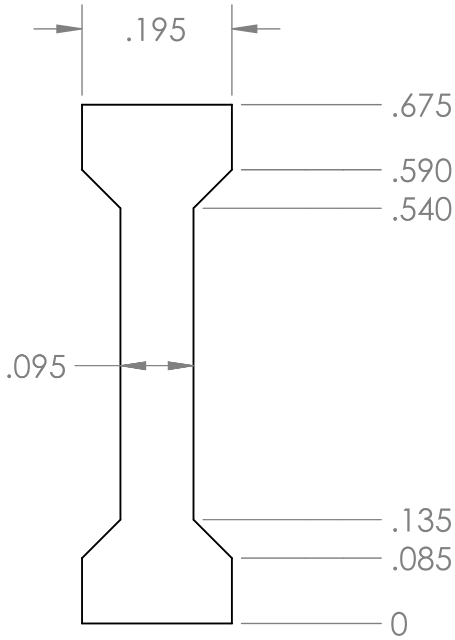
	NAME	DATE
DRAWN	HJW	12/10/24
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

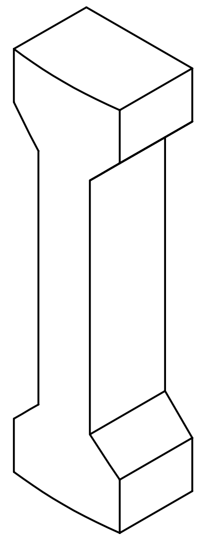
COMMENTS:

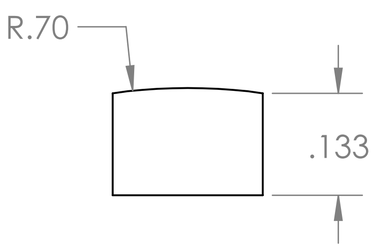
SparkPlug

SIZE	DWG. NO.	REV.
A		

SCALE:2:1 WEIGHT: SHEET 1 OF 1







PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.005

MATERIAL
PLA Plastic

FINISH

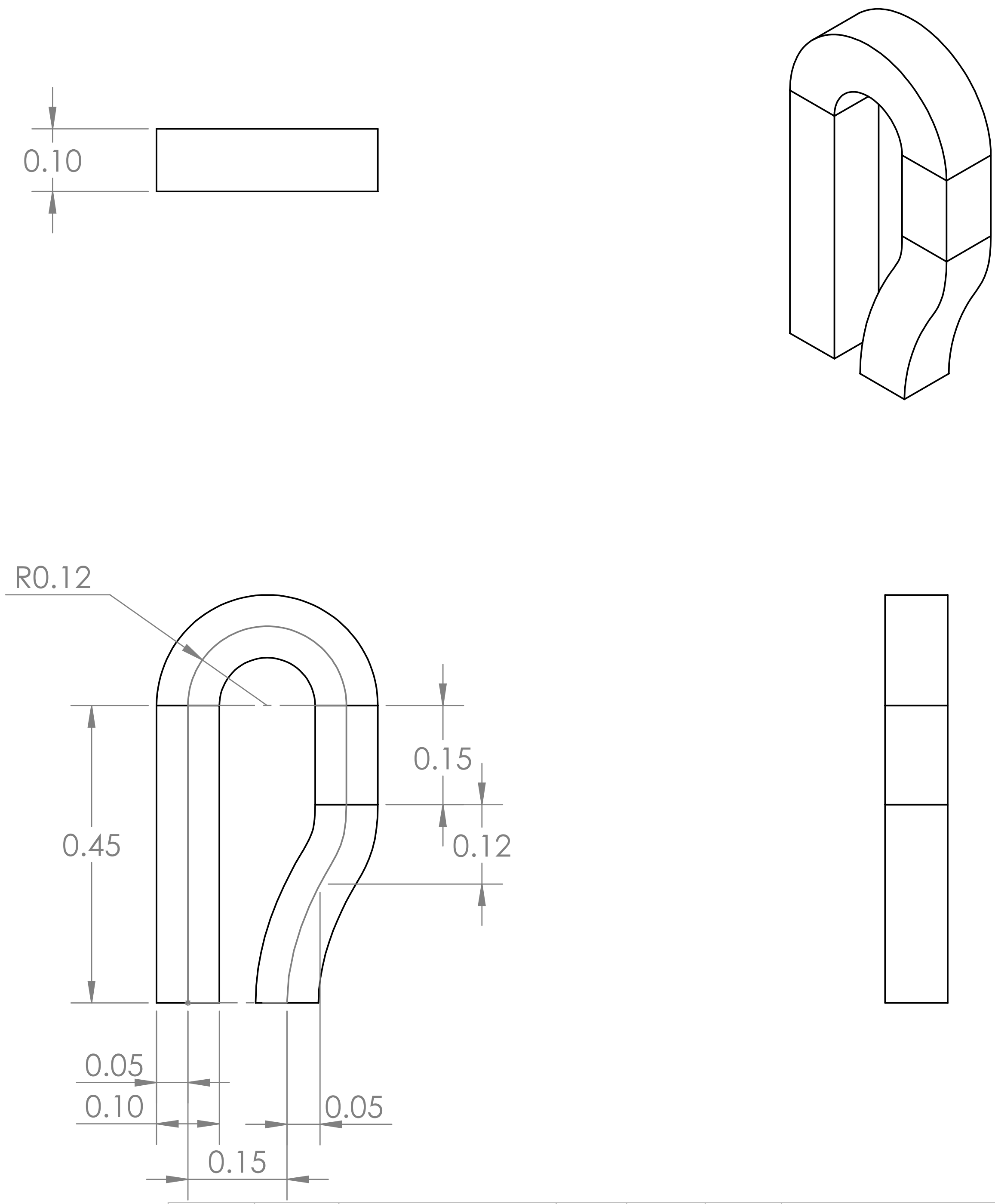
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	SL Hartless	12/10/24
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

SIZE	DWG. NO.	REV.
A	IJoint	

SCALE:4:1 WEIGHT: SHEET 1 OF 1



		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: ±0.1° TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.005		NAME	DATE	
			DRAWN	HJW	12/10/24	
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		MATERIAL Polylactic Acid	Q.A.			
			COMMENTS:			Shaft-Pin
NEXT ASSY	USED ON	FINISH				SIZE A DWG. NO. REV.
APPLICATION		DO NOT SCALE DRAWING				SCALE:4:1 WEIGHT: SHEET 1 OF 1

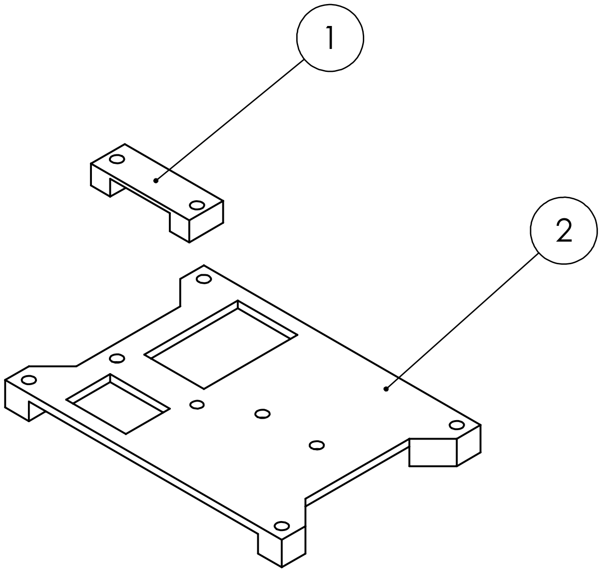
Appendix D: Drawings - Final Engine Model

*Begins on next page

2 1

ITEM NO.	PART NUMBER	QTY.
1	8VStrap	1
2	FusesMount	1

B B

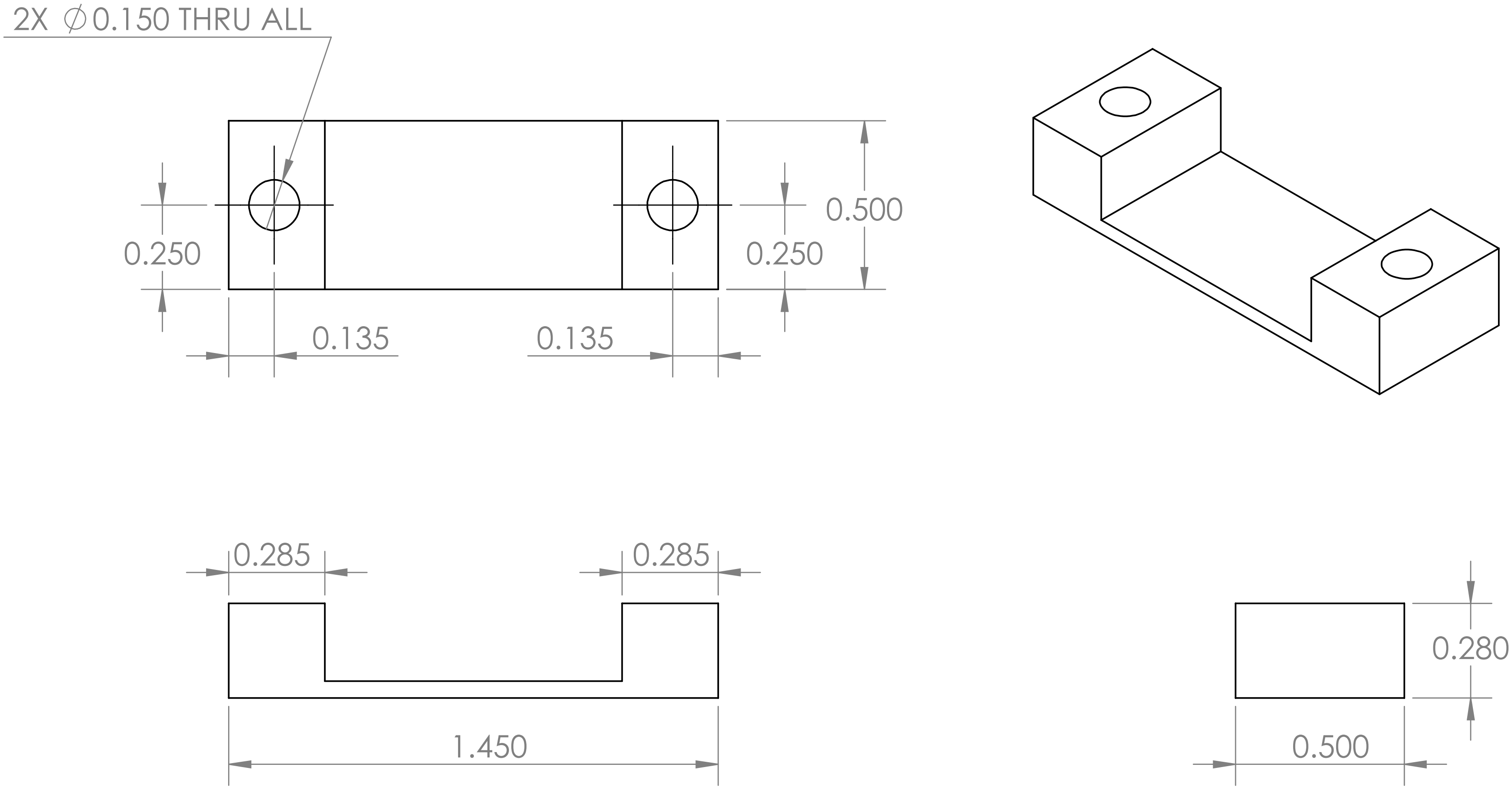


A A

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	SL HARTLESS	5/2/25	
	CHECKED			TITLE:
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL ABS PLASTIC	COMMENTS:			SIZE A DWG. NO. Fuse Mount 8V Strap Assy_Dra REV
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:2 WEIGHT: SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
ABS Plastic

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HJW	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

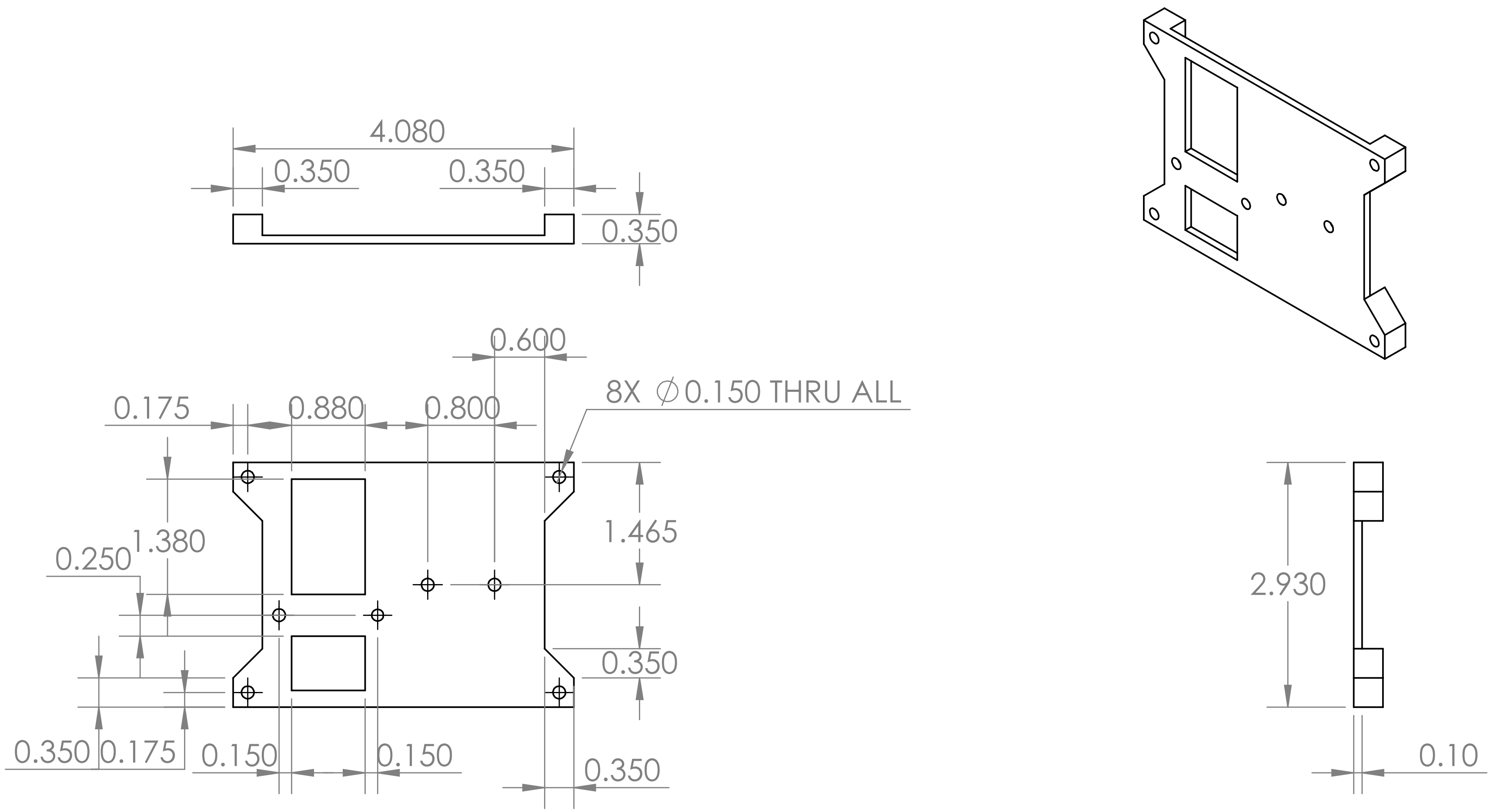
COMMENTS:

TITLE:

8VStrap

SIZE	DWG. NO.	REV
A		

SCALE: 2:1 WEIGHT: SHEET 1 OF 1



NEXT ASSY	USED ON
APPLICATION	

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
ABS Plastic

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HJW	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

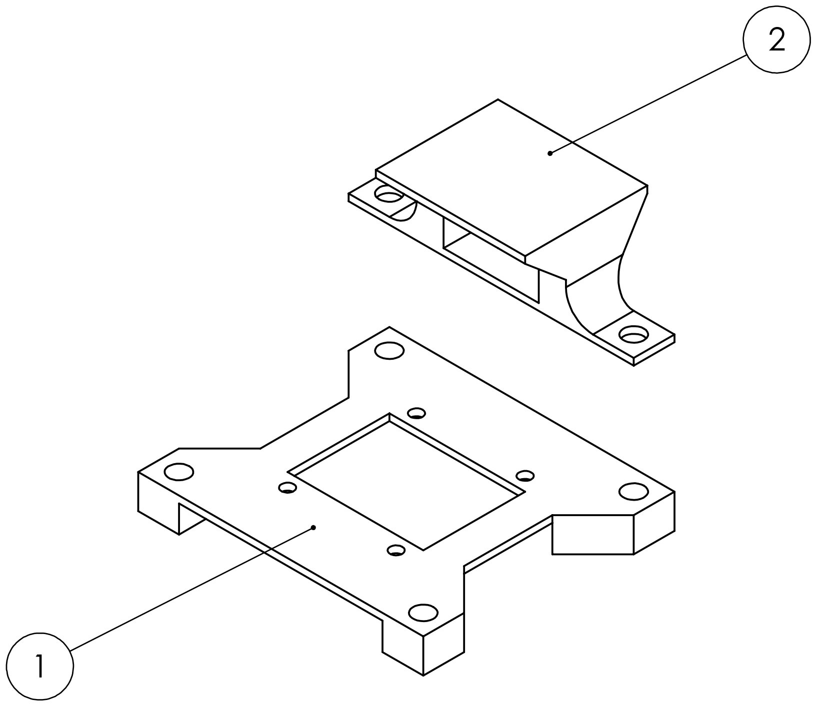
TITLE:

Fuses Mount

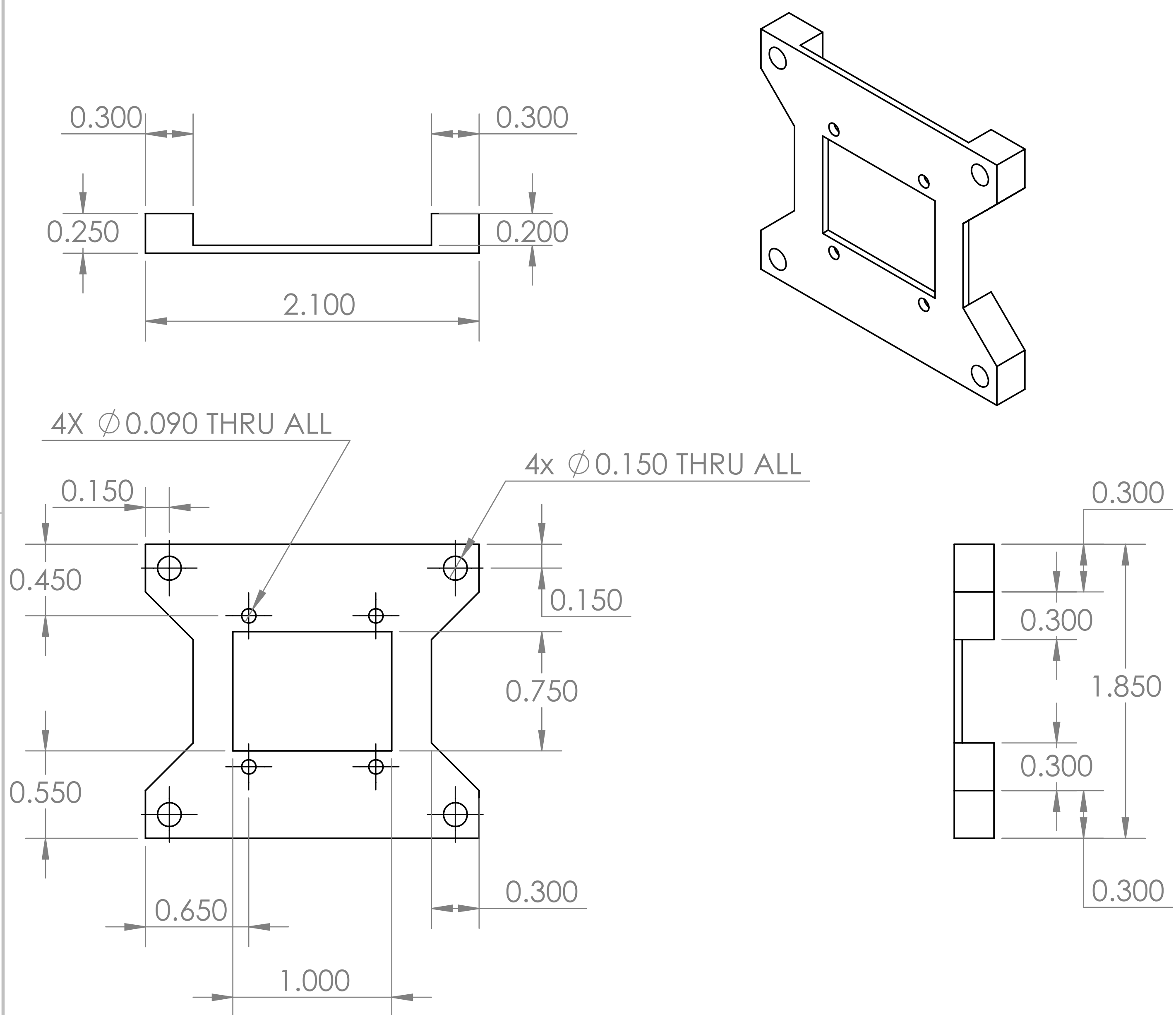
SIZE	DWG. NO.	REV
A		

SCALE: 1:2 WEIGHT: SHEET 1 OF 1

ITEM NO.	PART NUMBER	QTY.
1	RelayMount-1	1
2	RelayMount-2	1

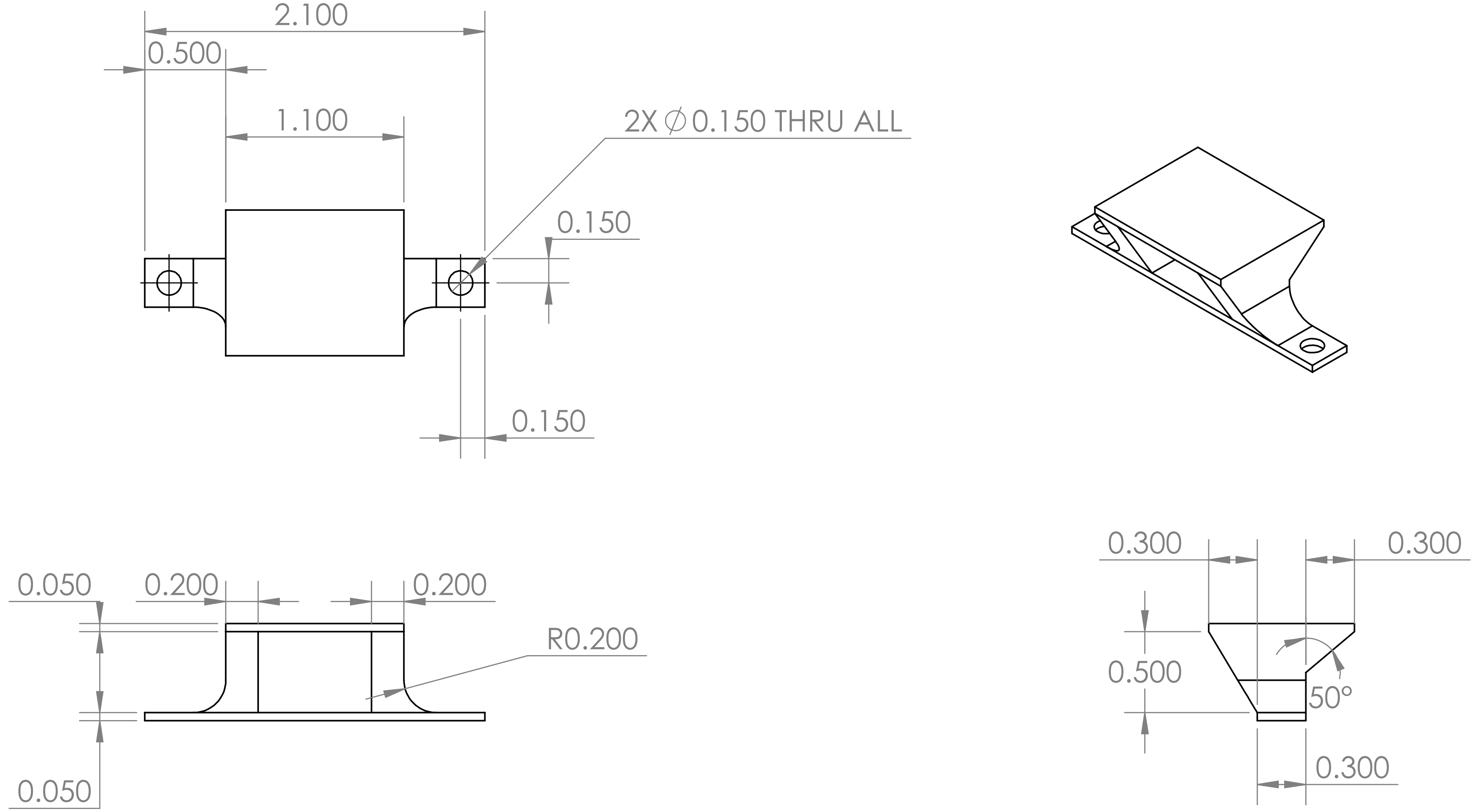


		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	SL HARTLESS	5/2/25	
			CHECKED			TITLE:
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL ABS PLASTIC	COMMENTS:			SIZE A · DWG. NO. Relay Mount Assembly_Drawing · REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1 · WEIGHT: · SHEET 1 OF 1



DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.01 THREE PLACE DECIMAL ±0.005		NAME	DATE	
	DRAWN	HJW		
	CHECKED			
	ENG APPR.			
	MFG APPR.			
MATERIAL ABS Plastic	Q.A.			
FINISH	COMMENTS:			RelayMount-1
DO NOT SCALE DRAWING				SIZE A DWG. NO. REV.
				SCALE:1:1 WEIGHT: SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	



PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
ABS Plastic

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HJW	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

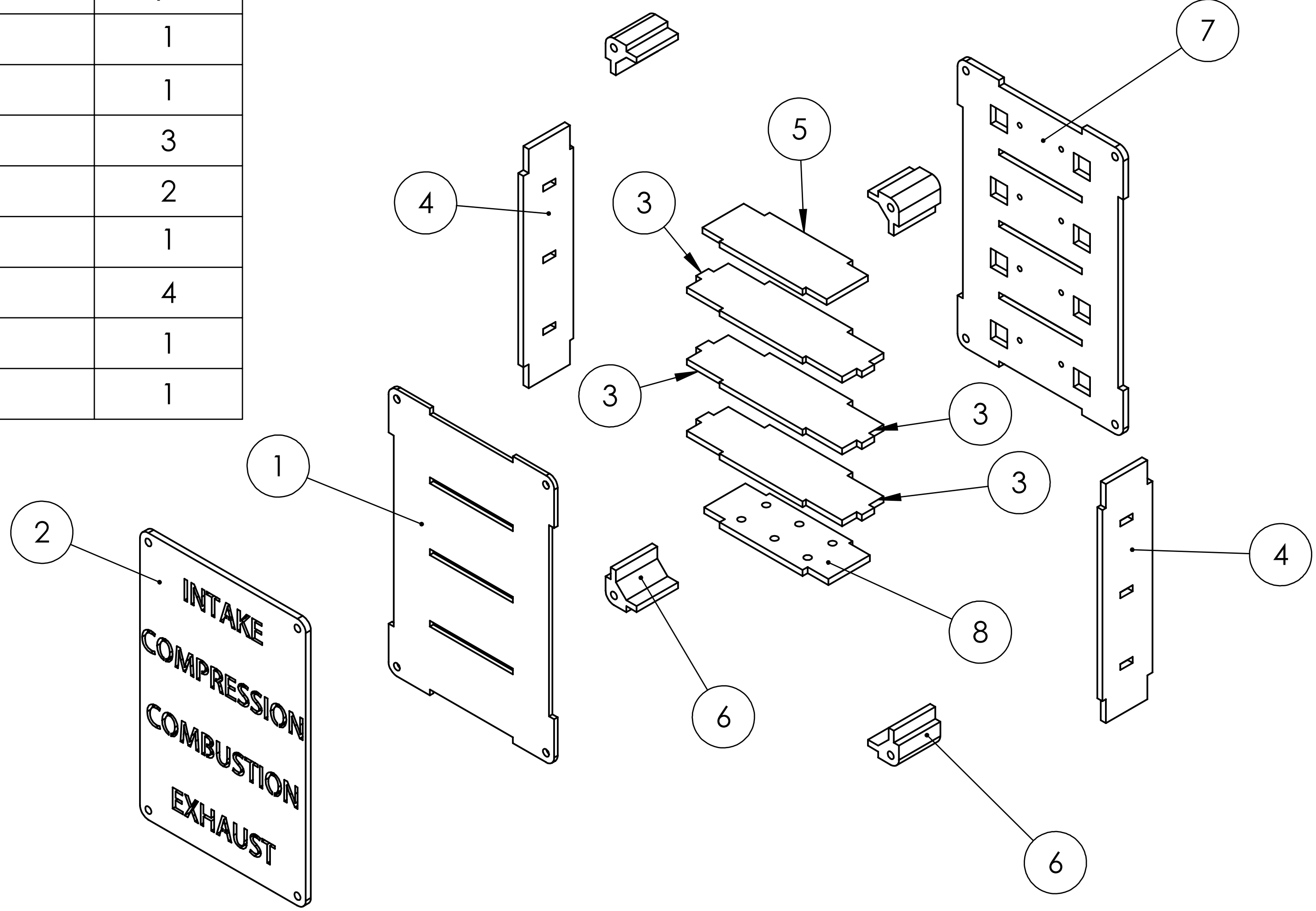
TITLE:

RelayMount-2

SIZE **A** DWG. NO. REV

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

ITEM NO.	PART NUMBER	QTY.
1	AcrylicPanel	1
2	NamePlate	1
3	Shelf	3
4	SidePlate	2
5	TopPlate	1
6	Corner	4
7	BackPlate	1
8	BottomPlate	1



UNLESS OTHERWISE SPECIFIED:		
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±		
INTERPRET GEOMETRIC TOLERANCING PER:		
MATERIAL MISC.		
FINISH		
DO NOT SCALE DRAWING		

	NAME	DATE
DRAWN	SL HARTLESS	5/2/25
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

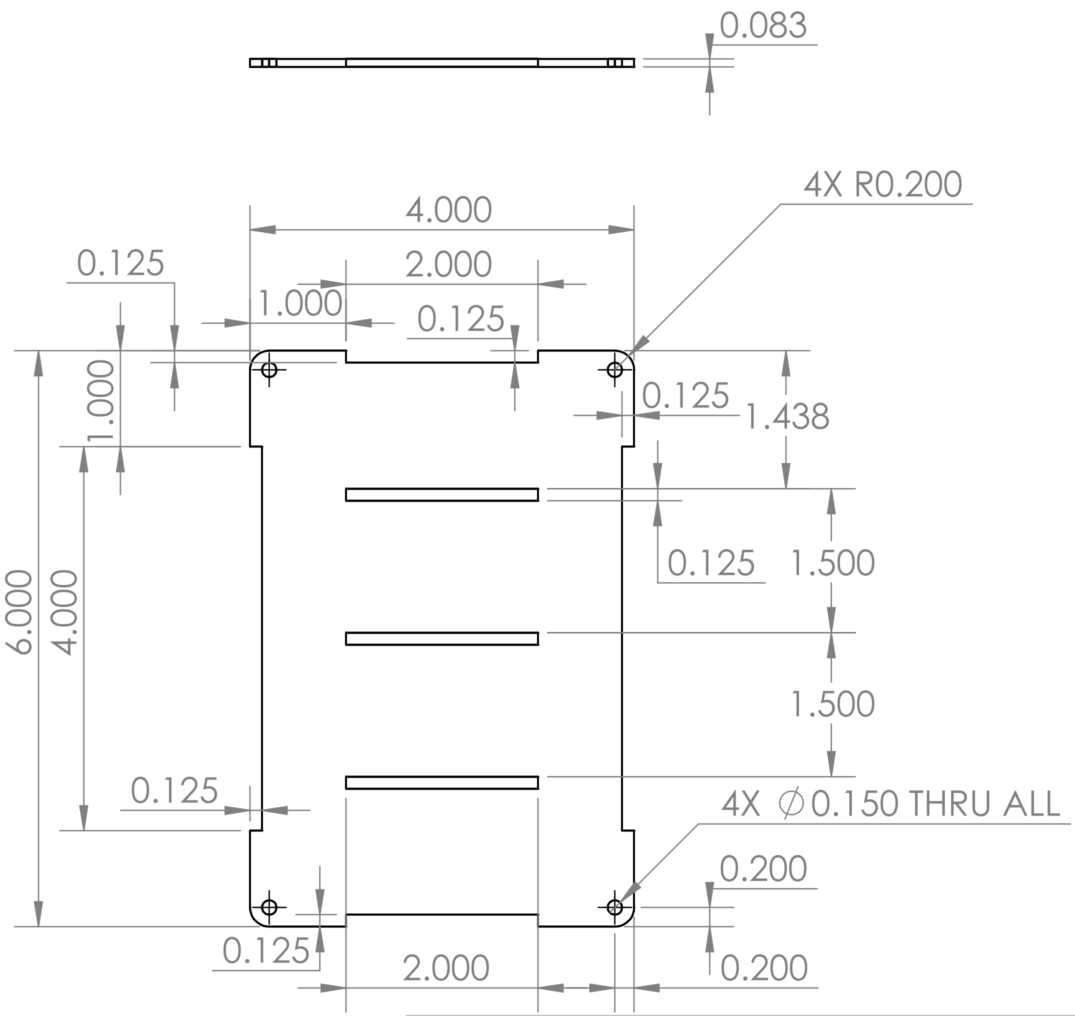
NEXT ASSY	USED ON
APPLICATION	

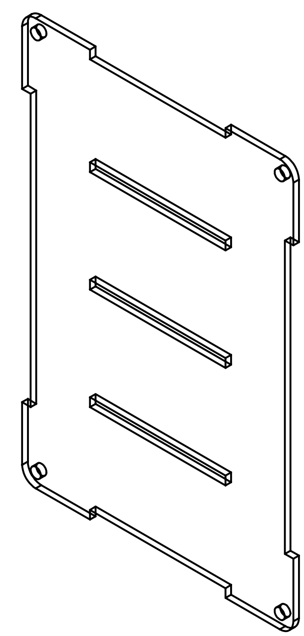
PROPRIETARY AND CONFIDENTIAL

TITLE:

SIZE A DWG. NO. LED Box Assy_ Drawing REV

SCALE: 1:8 WEIGHT: SHEET 1 OF 1





	NAME	DATE
DRAWN	HJW	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Acrylic

FINISH

DO NOT SCALE DRAWING

NEXT ASSY	USED ON
APPLICATION	

PROPRIETARY AND CONFIDENTIAL

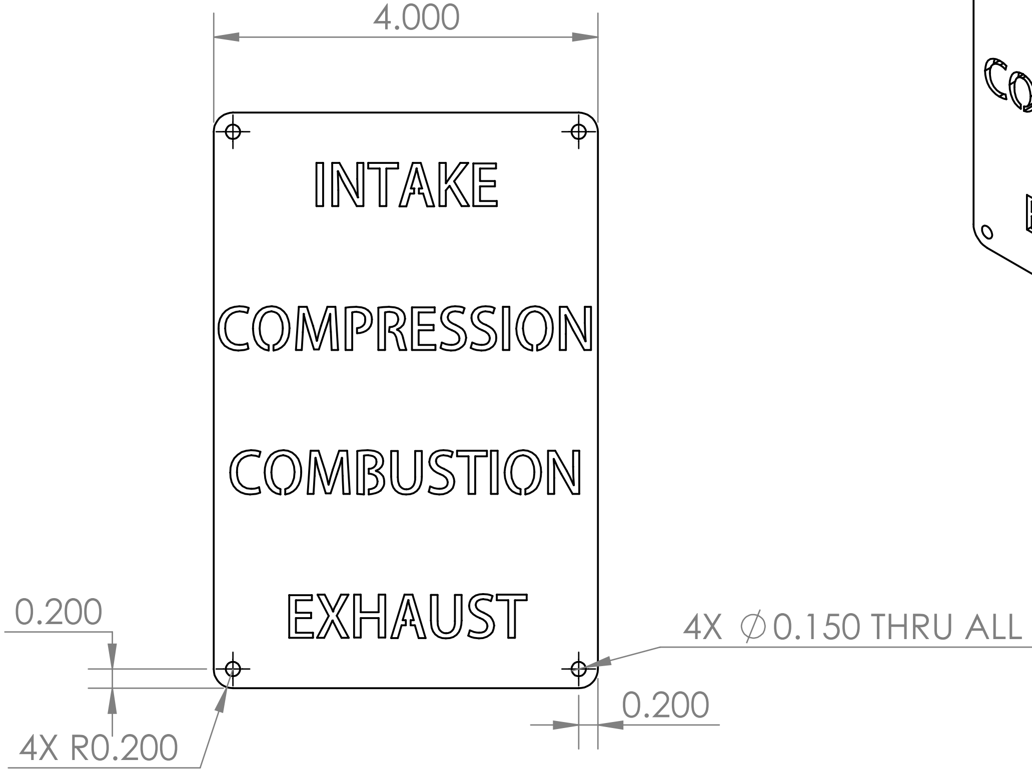
TITLE:

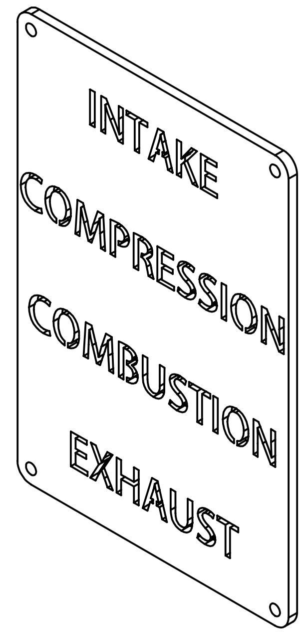
AcrylicPanel

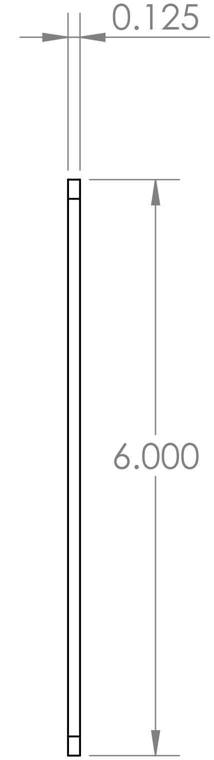
SIZE	DWG. NO.	REV
A		

SCALE: 1:2 WEIGHT: SHEET 1 OF 1

NOTE: ALL TEXT CENTURY GOTHIC, 0.45" HEIGHT,
1.5" SPACING, CENTERED

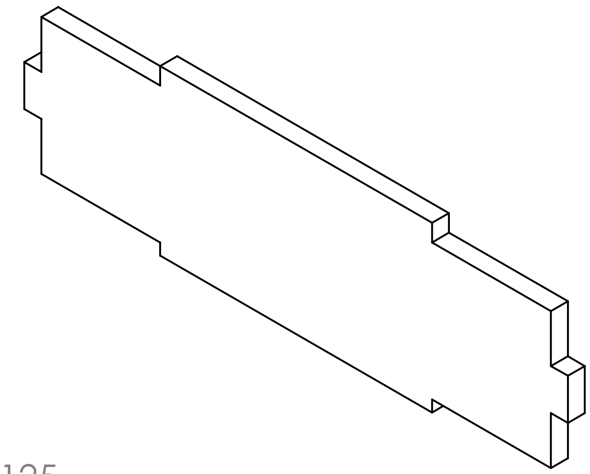


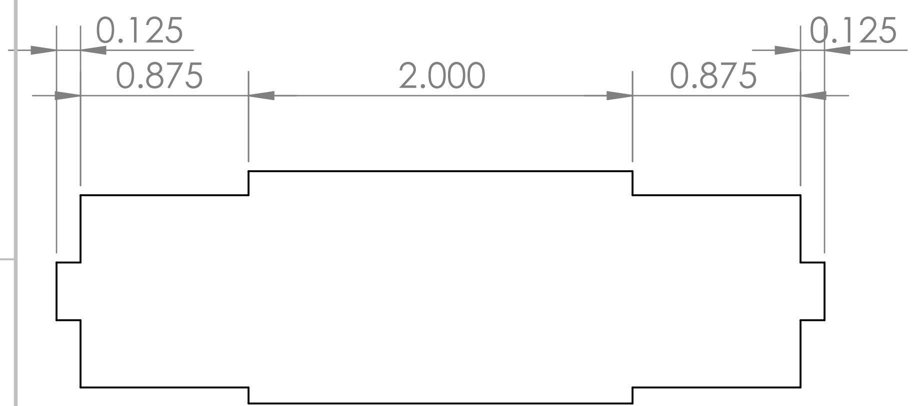


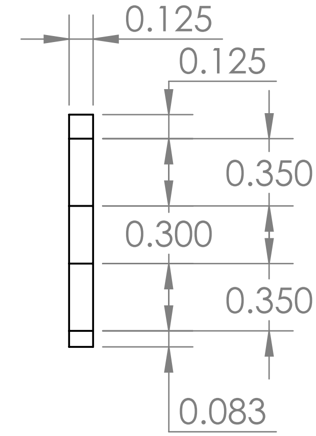


		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.01 THREE PLACE DECIMAL ±0.005	DRAWN	HJW		TITLE:
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			NamePlate
		MATERIAL PLYWOOD	COMMENTS:			SIZE A / DWG. NO. / REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:2 / WEIGHT: / SHEET 1 OF 1

2 1 B A







B B

A A

		UNLESS OTHERWISE SPECIFIED:
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.01 THREE PLACE DECIMAL ±0.005
		INTERPRET GEOMETRIC TOLERANCING PER:
		MATERIAL Plywood
NEXT ASSY	USED ON	FINISH
APPLICATION		DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HJW	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE:

Shelf

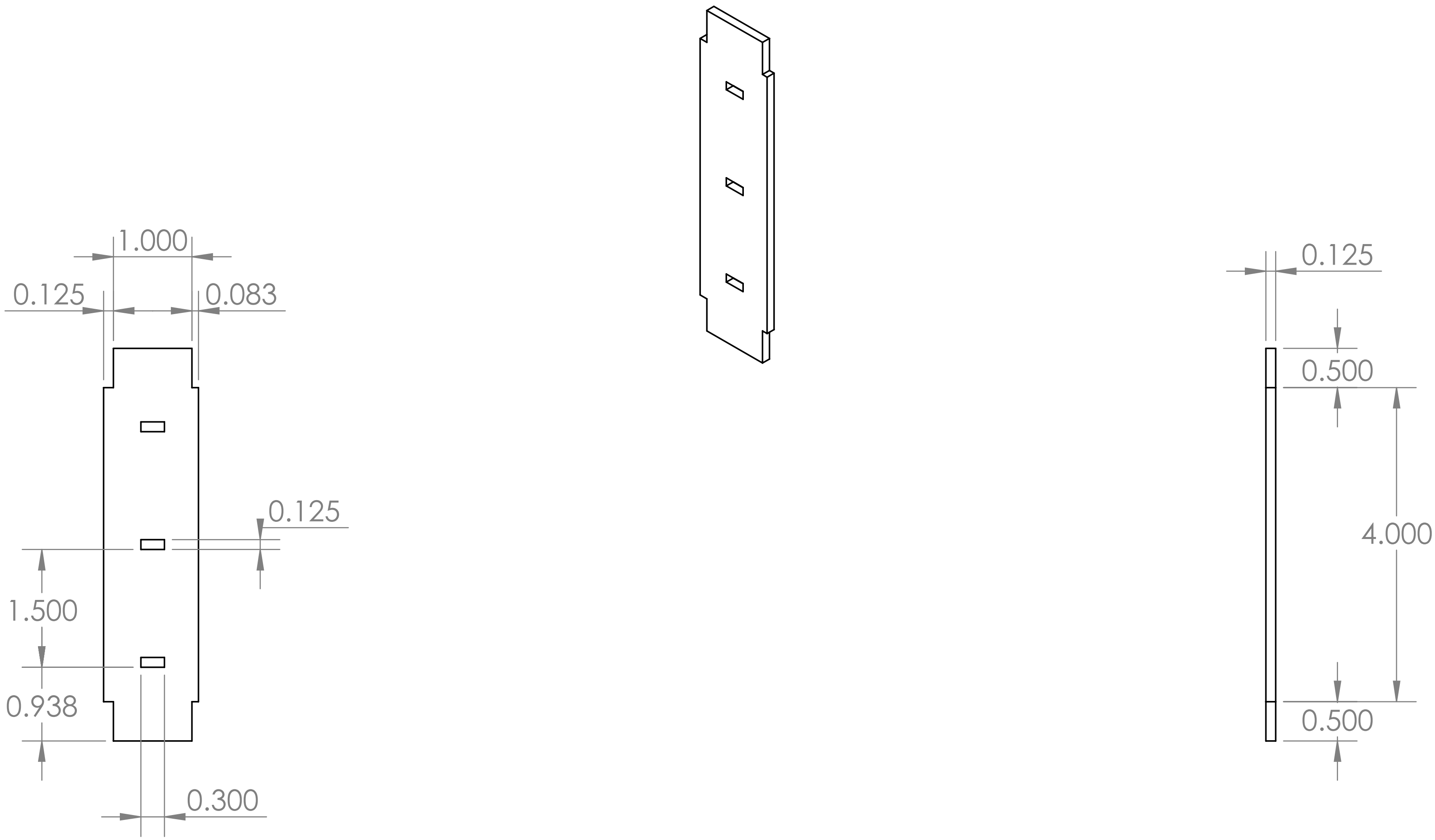
SIZE	DWG. NO.	REV
A		

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

2 1

B B

A A



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Plywood

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HJW	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

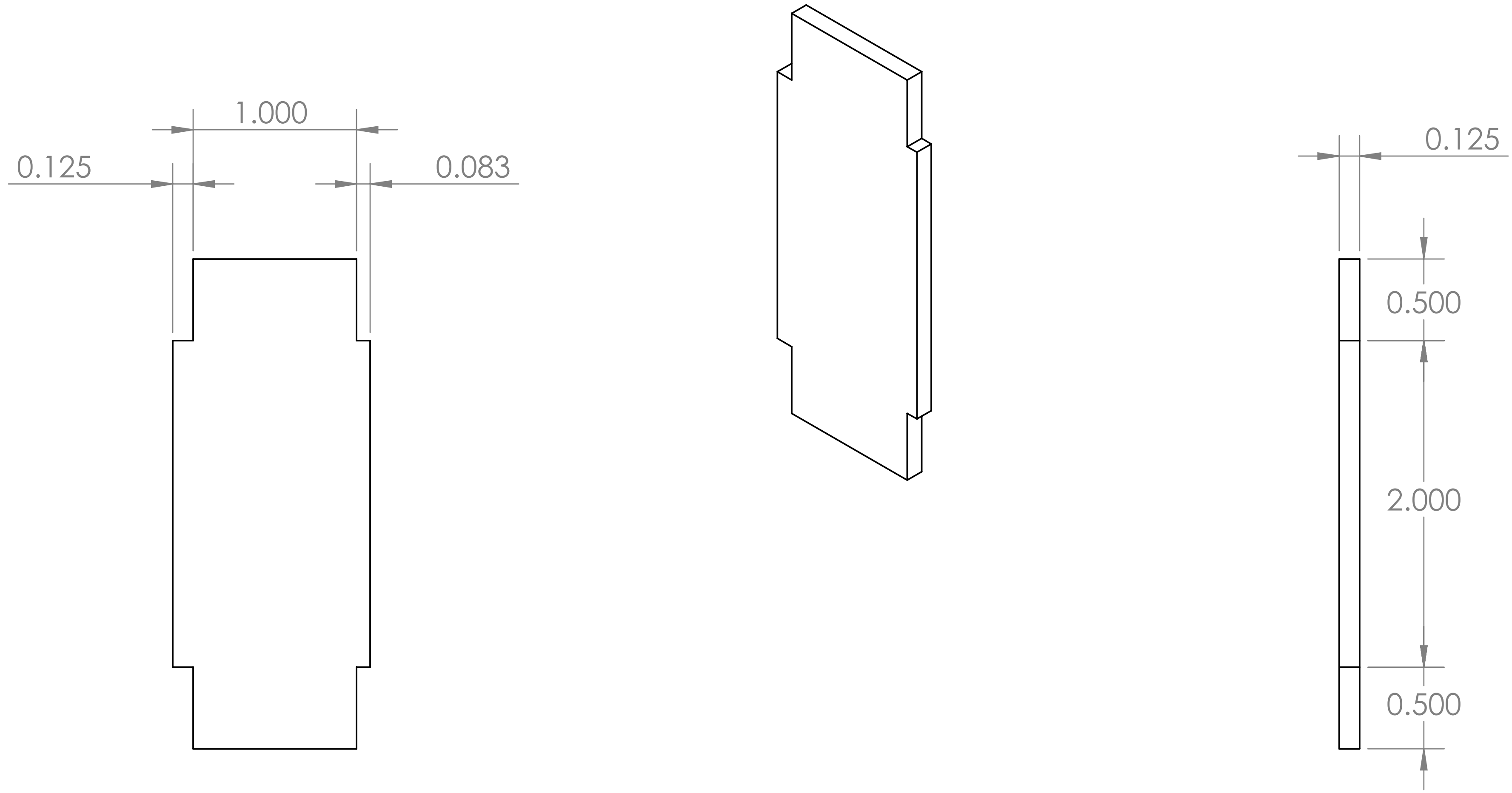
TITLE:

SidePlate

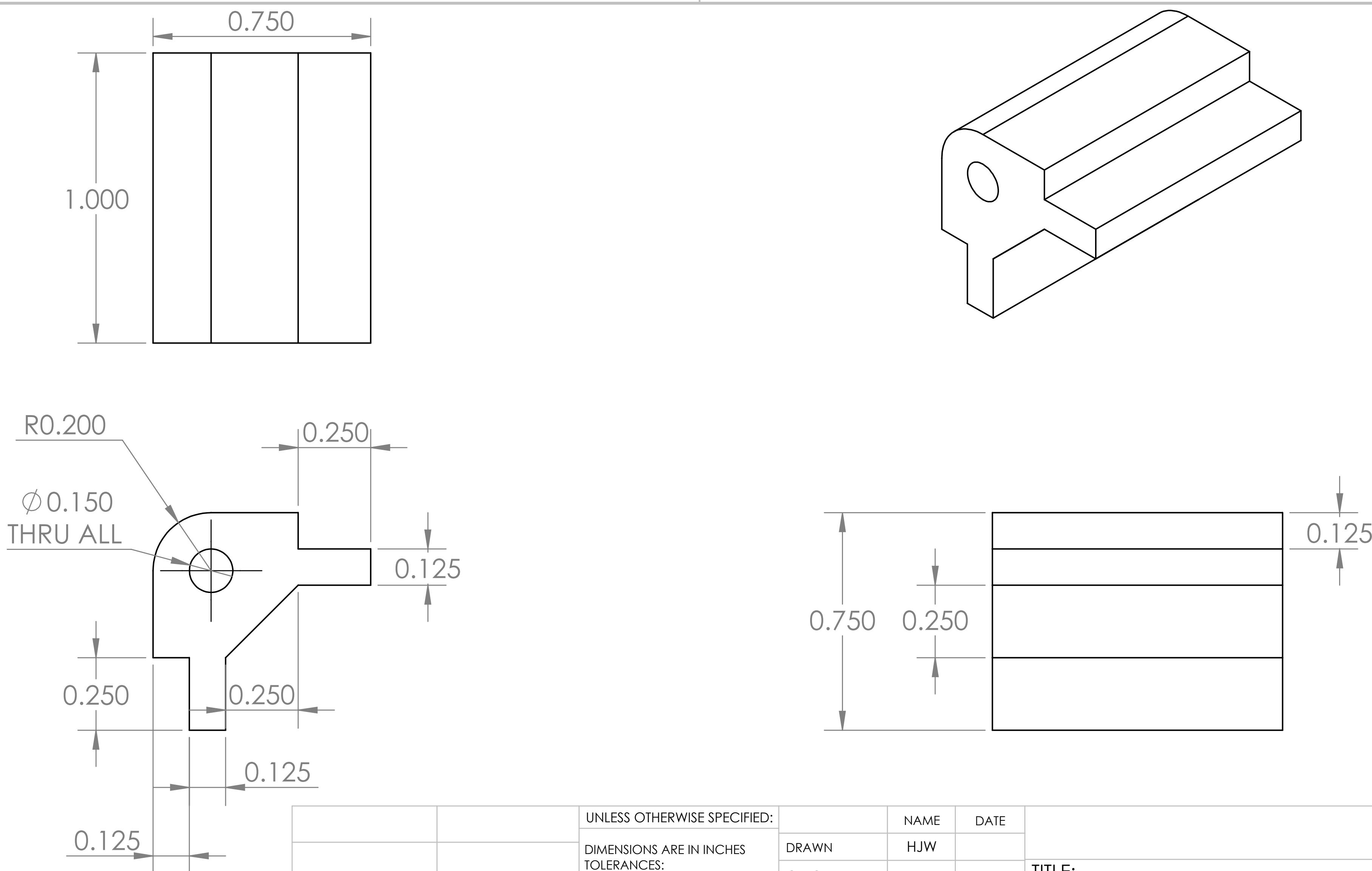
SIZE **A** DWG. NO. REV

SCALE: 1:2 WEIGHT: SHEET 1 OF 1

2 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.01 THREE PLACE DECIMAL ±0.005	DRAWN	HJW		TITLE:
			CHECKED			
			ENG APPR.			
			MFG APPR.			TopPlate
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Plywood	COMMENTS:			SIZE A | DWG. NO. | REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1 | WEIGHT: | SHEET 1 OF 1



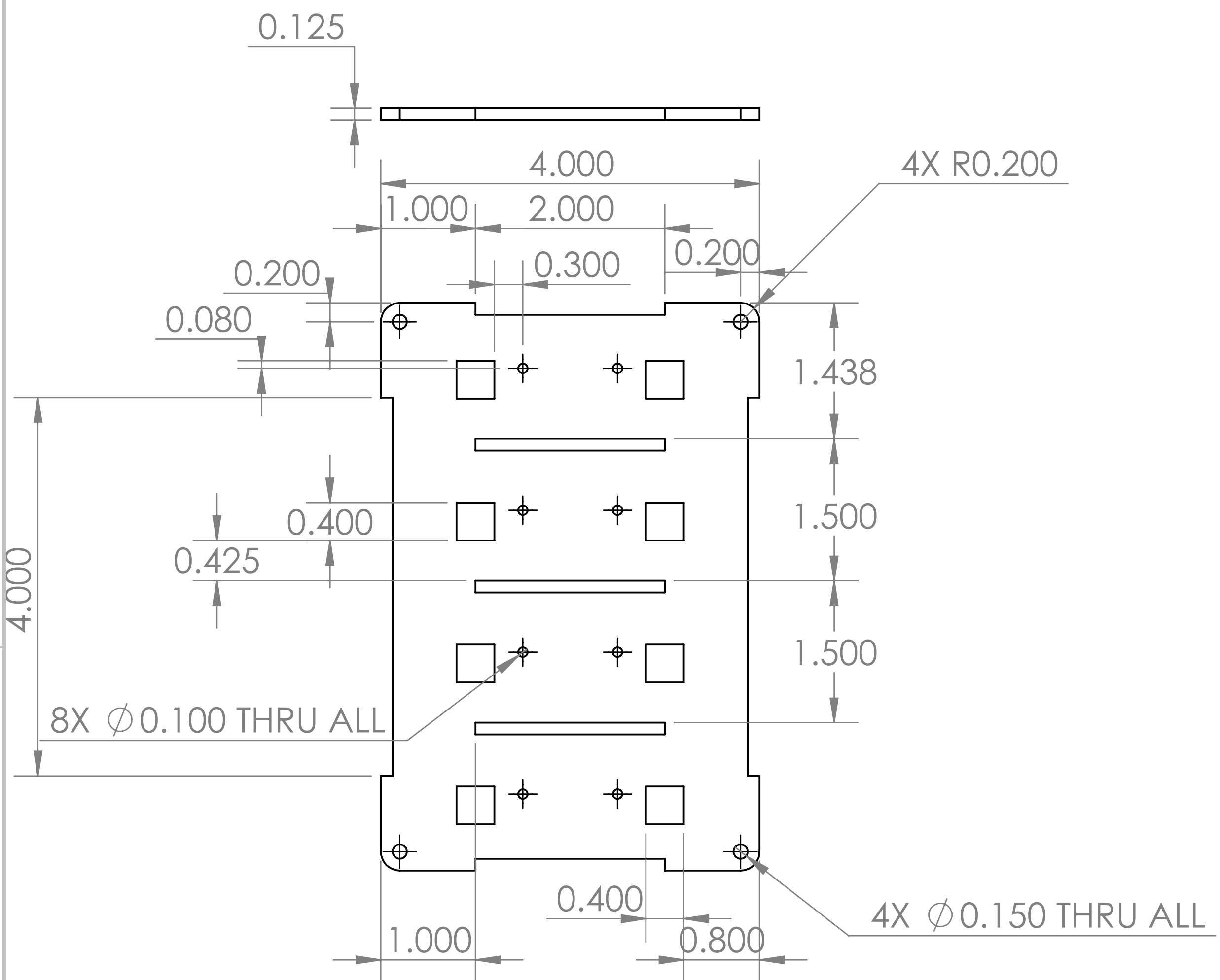
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.01 THREE PLACE DECIMAL ±0.005	DRAWN	HJW	
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL Polylactic Acid	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

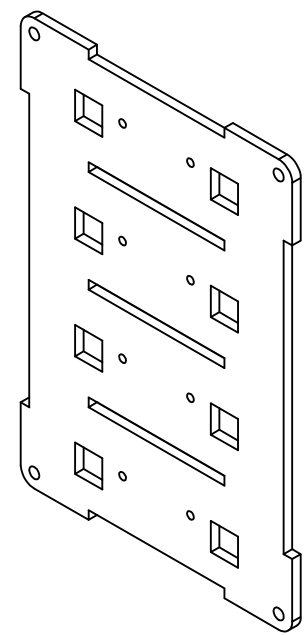
TITLE:

Corner

SIZE	DWG. NO.	REV
A		

SCALE: 2:1	WEIGHT:	SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.01 THREE PLACE DECIMAL ±0.005	DRAWN	HJW	
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL Plywood	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

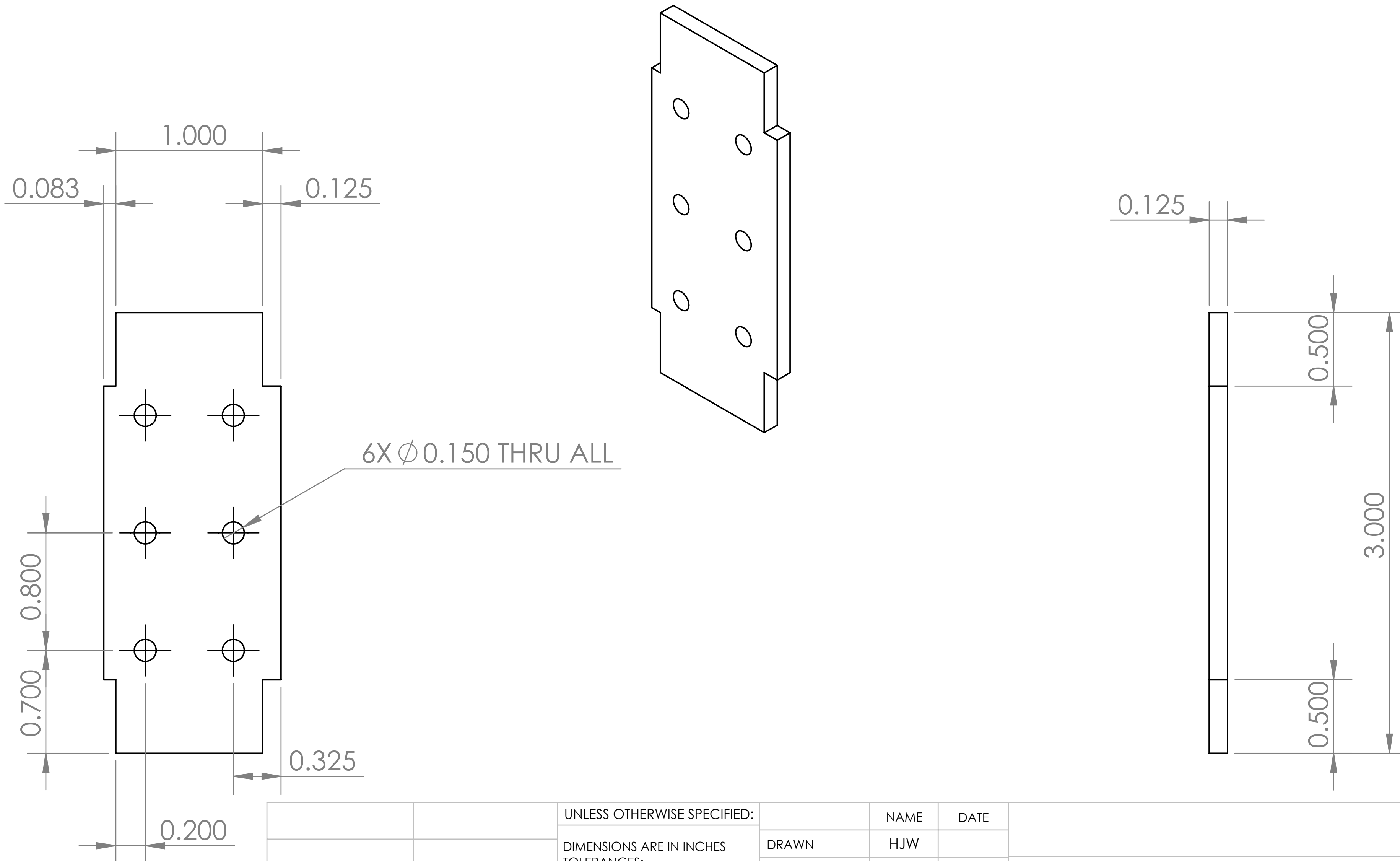
TITLE:

BackPlate

SIZE	DWG. NO.	REV
A		
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

2 1

B B



A A

NEXT ASSY	USED ON
APPLICATION	

PROPRIETARY AND CONFIDENTIAL

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Plywood

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HJW	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

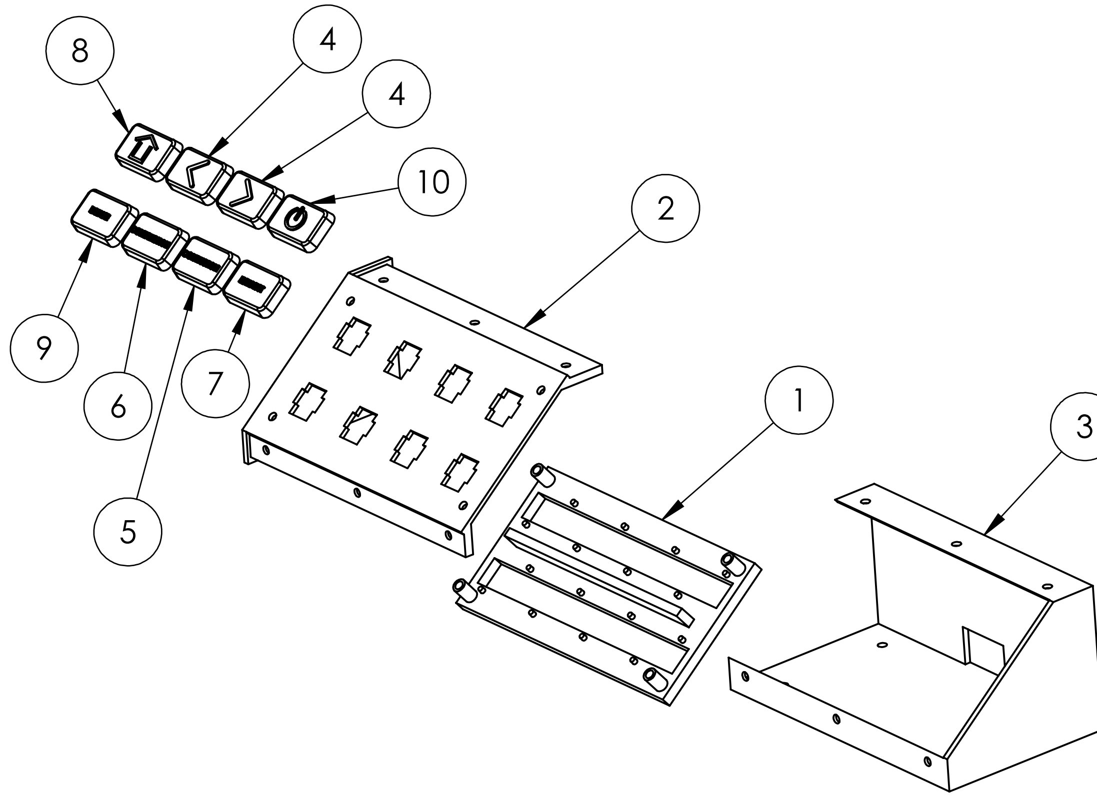
BottomPlate

SIZE	DWG. NO.	REV
A		

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

2 1

ITEM NO.	PART NUMBER	QTY.
1	KeyHolder	1
2	SheathBox	1
3	SlipCover	1
4	ArrowCap	2
5	CombustionCap	1
6	CompressionCap	1
7	ExhaustCap	1
8	HomeCap	1
9	IntakeCap	1
10	OnOffCap	1
11	Cherry MX Blue Switch	8
12	SparkFun Electronics Cherry MX Switch Breakout	8



NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
PLA PLASTIC

FINISH

DO NOT SCALE DRAWING

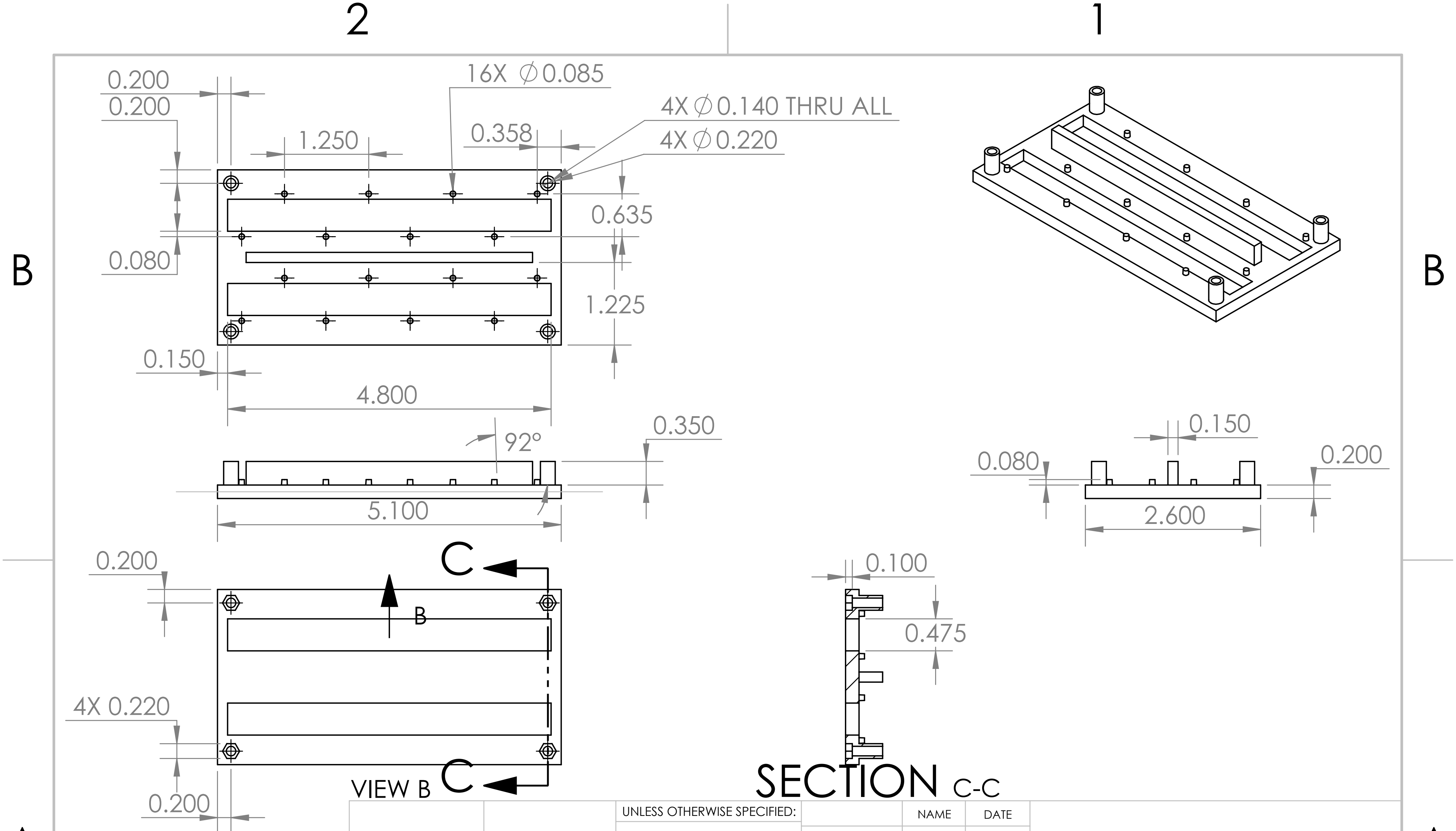
	NAME	DATE
DRAWN	SL HARTLESS	5/2/25
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE A | DWG. NO. Keyboard Assembly_Drawin | REV

SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1



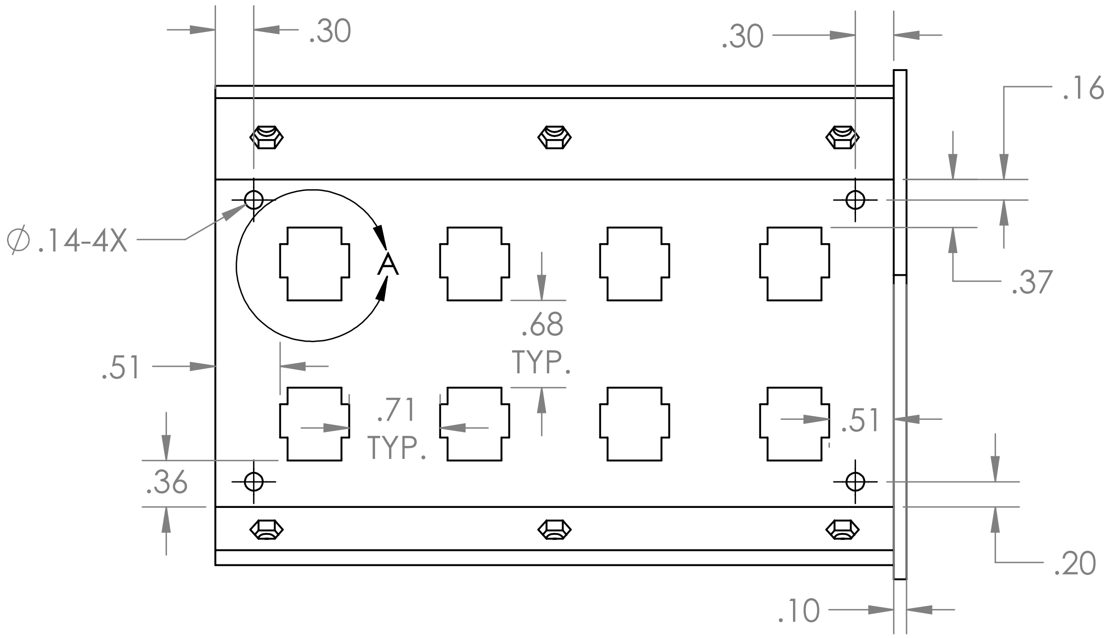
				NAME	DATE
		UNLESS OTHERWISE SPECIFIED:	DRAWN	HJW	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.01 THREE PLACE DECIMAL ±0.005	CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL Polylactic Acid	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

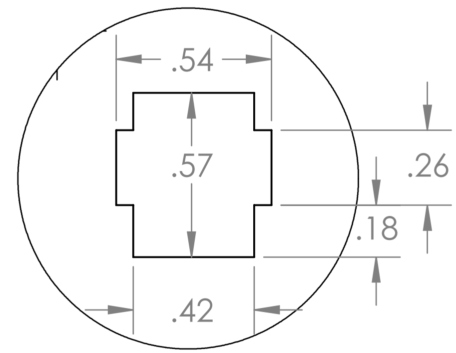
KeyHolder

SIZE	DWG. NO.	REV
A		

SCALE: 1:2 WEIGHT: SHEET 1 OF 1



DIMENSIONS ARE TYPICAL
FOR ALL 8 INSTANCES



DETAIL A
SCALE 3 : 2

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: ± 0.1°
TWO PLACE DECIMAL ±0.01"
THREE PLACE DECIMAL ±0.005"

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
PLA PLASTIC

FINISH

DO NOT SCALE DRAWING

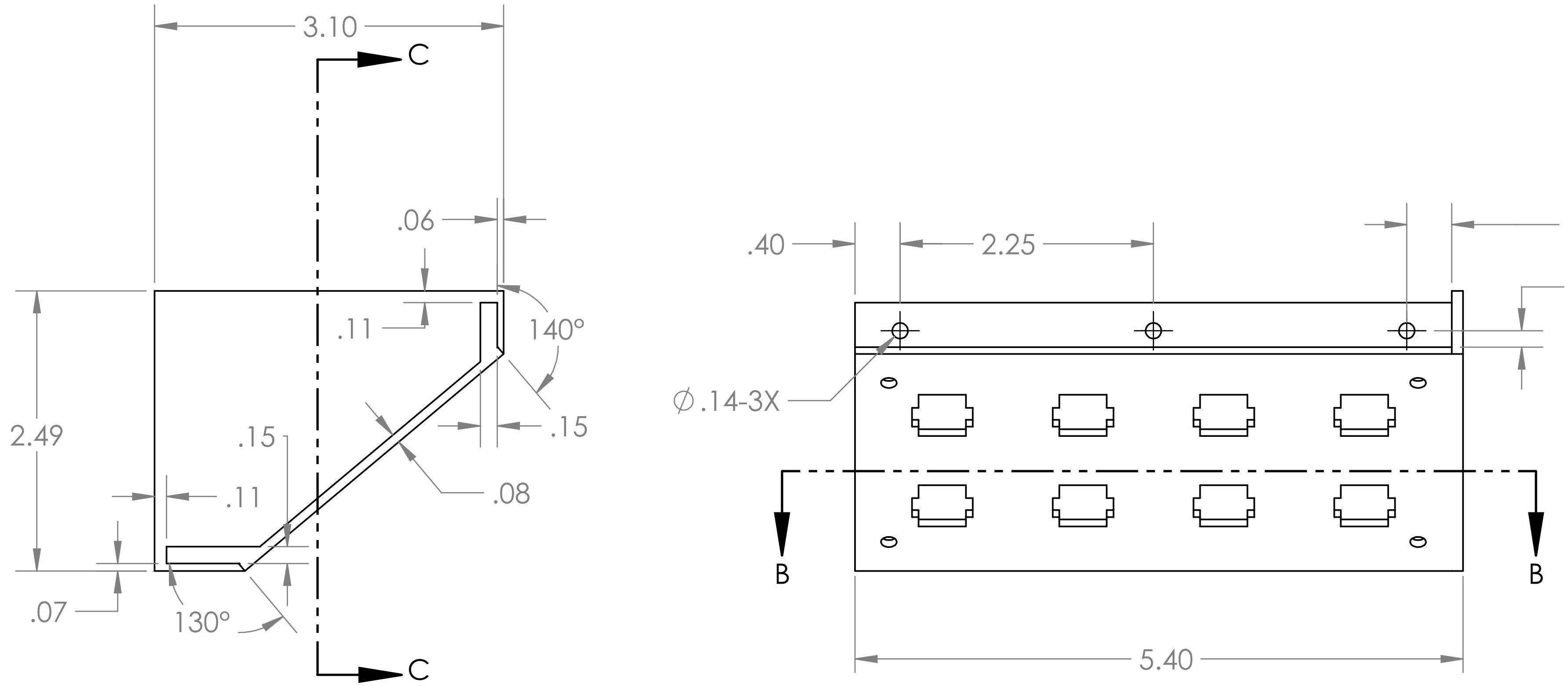
	NAME	DATE
DRAWN	SL HARTLESS	5/2/25
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE	DWG. NO.	REV
A	Keyboard Sheathbox_Drawi	

SCALE: 2:3	WEIGHT:	SHEET 1 OF 4



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ±0.1° TWO PLACE DECIMAL ±0.01" THREE PLACE DECIMAL ±0.005"	DRAWN	SL HARTLESS	5/2/25
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL PLA PLASTIC	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

PROPRIETARY AND CONFIDENTIAL

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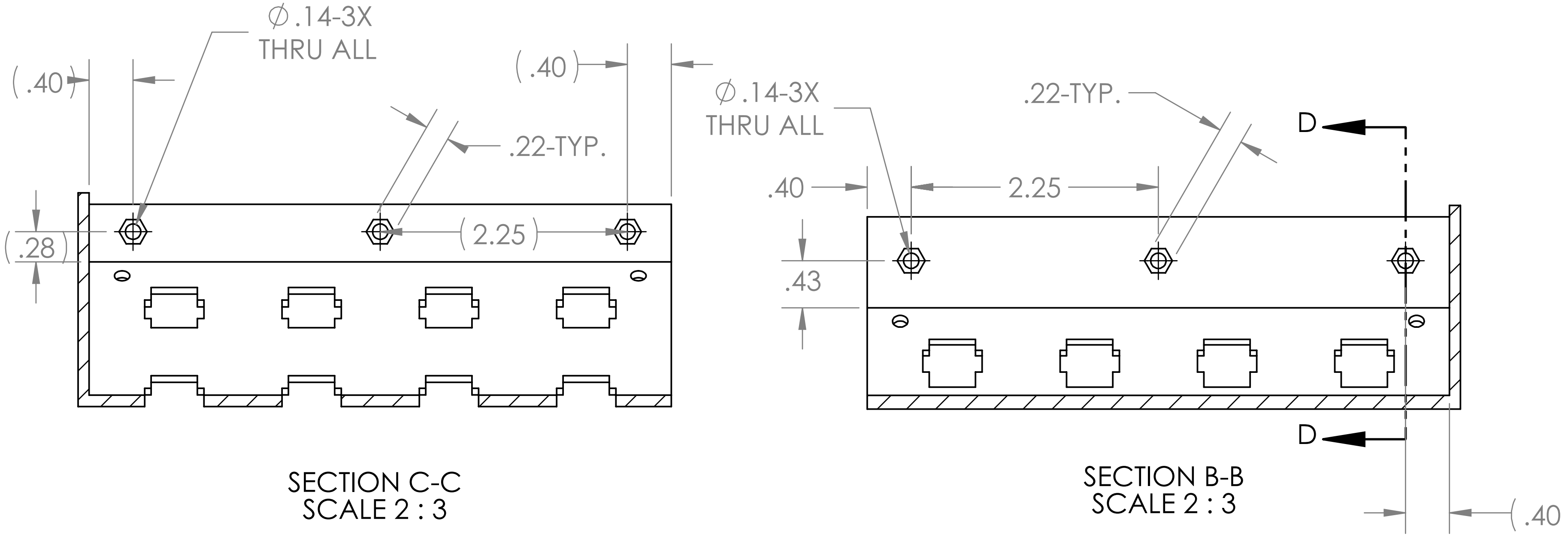
TITLE:

SIZE A DWG. NO. Keyboard Sheathbox_Drawi REV

SCALE: 2:3 WEIGHT: SHEET 2 OF 4

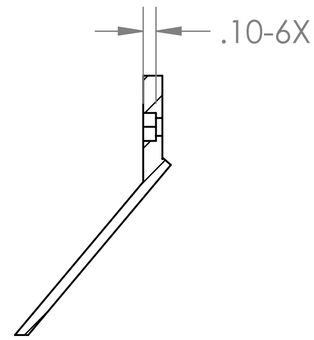


SECTION C-C
SCALE 2 : 3

SECTION B-B
SCALE 2 : 3

UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ±0.1° TWO PLACE DECIMAL ±0.01" THREE PLACE DECIMAL ±0.005"	DRAWN	SL HARTLESS	5/2/25	TITLE:	
	CHECKED				
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL PLA PLASTIC	COMMENTS:			SIZE A	DWG. NO. Keyboard Sheathbox_Drawi	REV
FINISH					
DO NOT SCALE DRAWING				SCALE: 2:3	WEIGHT:	SHEET 3 OF 4

NEXT ASSY	USED ON
APPLICATION	



SECTION D-D
SCALE 2 : 3

NOTE: 0.1" DEPTH IS TYP.
FOR ALL 6 HEX INSTANCES

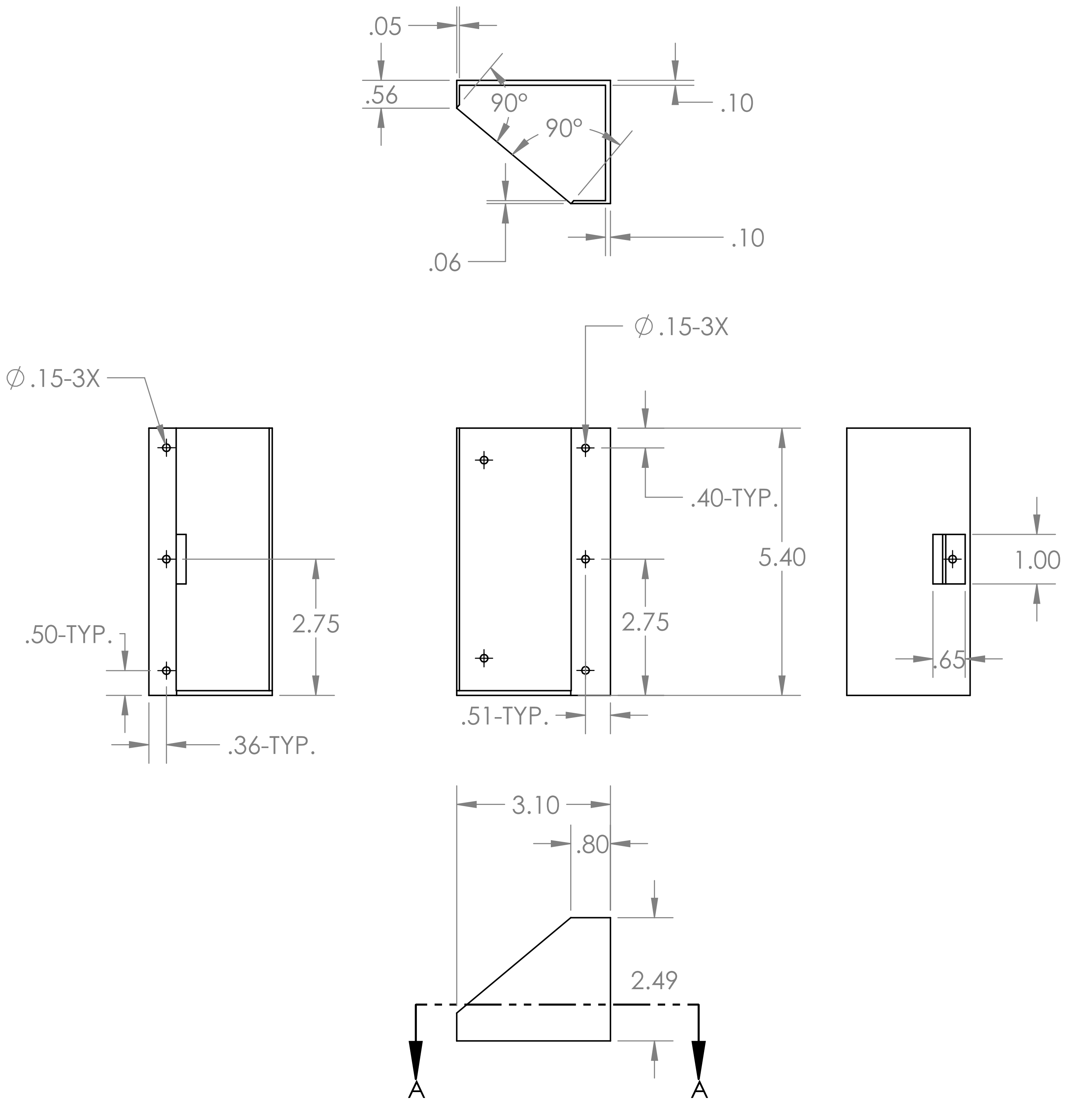
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ±0.1° TWO PLACE DECIMAL ±0.01" THREE PLACE DECIMAL ±0.005"	DRAWN	SL HARTLESS	5/2/25
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL PLA PLASTIC	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

TITLE:

SIZE A DWG. NO. Keyboard Sheathbox_Drawi REV

SCALE: 2:3 WEIGHT: SHEET 4 OF 4



	NAME	DATE	
DRAWN	SL HARTLESS	5/2/25	
CHECKED			
ENG APPR.			
MFG APPR.			
Q.A.			
COMMENTS:			

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: ±0.1°
TWO PLACE DECIMAL ± 0.01"
THREE PLACE DECIMAL ±0.005"

MATERIAL
PLA PLASTIC

FINISH

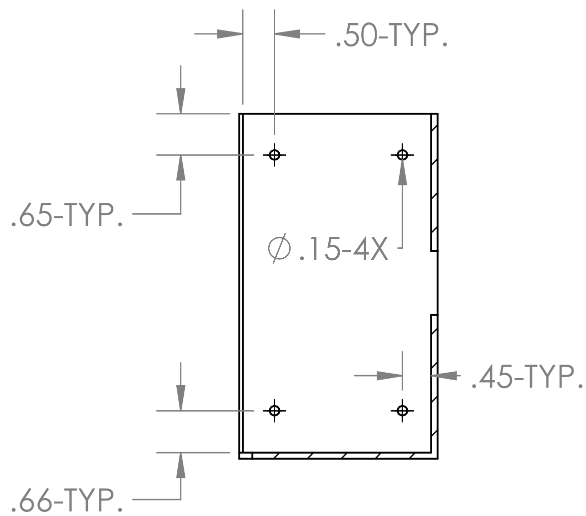
DO NOT SCALE DRAWING

NEXT ASSY | USED ON
APPLICATION

SIZE A | DWG. NO. Keyboard SlipCover_Drawing | REV.

SCALE:1:4 | WEIGHT: | SHEET 1 OF 2

B B



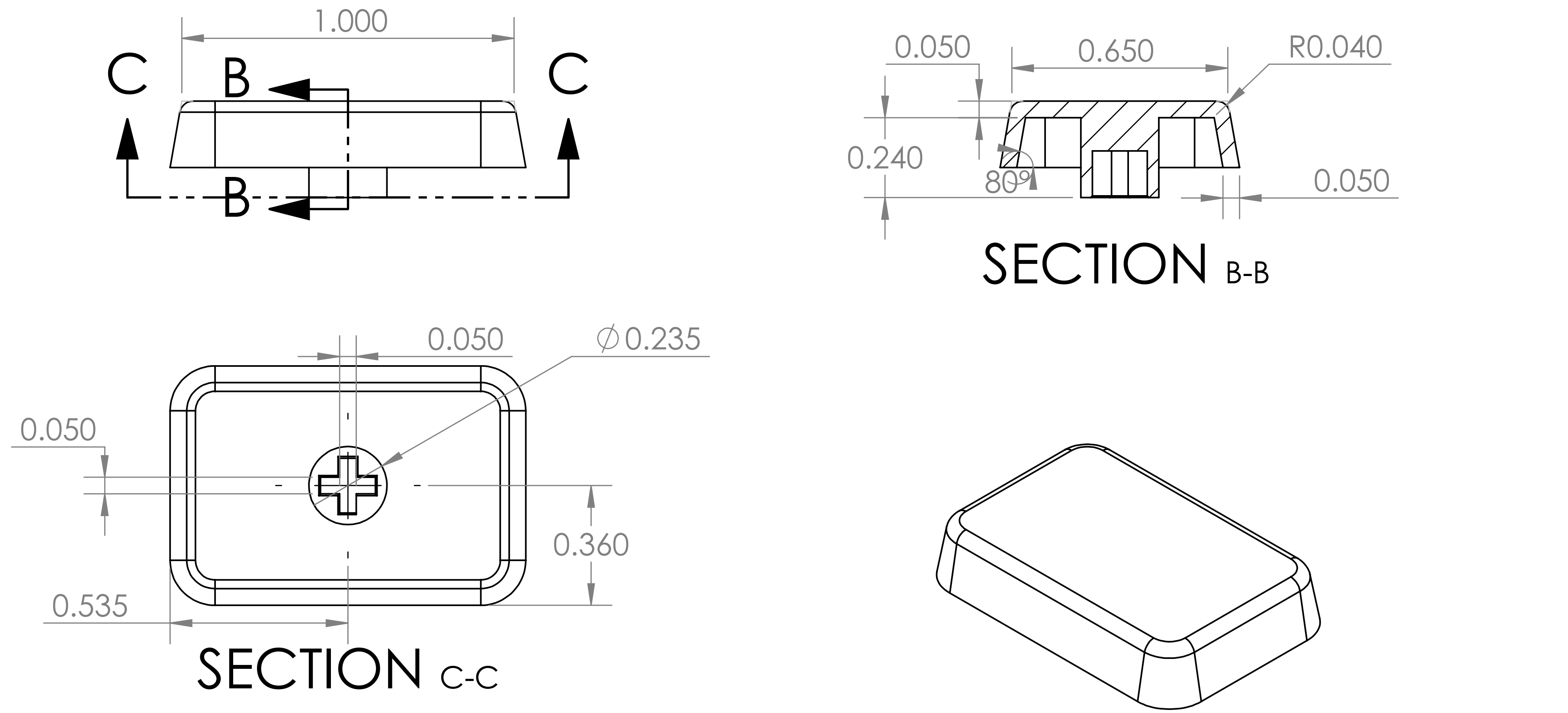
SECTION A-A
SCALE 1 : 3

A A

		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: ±0.1° TWO PLACE DECIMAL ±0.01" THREE PLACE DECIMAL ±0.005"		NAME	DATE
			DRAWN	SL HARTLESS	5/2/25
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		MATERIAL	Q.A.		
NEXT ASSY	USED ON	FINISH PLA PLASTIC	COMMENTS:		
APPLICATION		DO NOT SCALE DRAWING			

PROPRIETARY AND CONFIDENTIAL

SIZE	DWG. NO.		REV.
A	Keyboard SlipCover_Drawing		
SCALE:1:4	WEIGHT:	SHEET 2 OF 2	



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polylactic Acid

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HJW	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

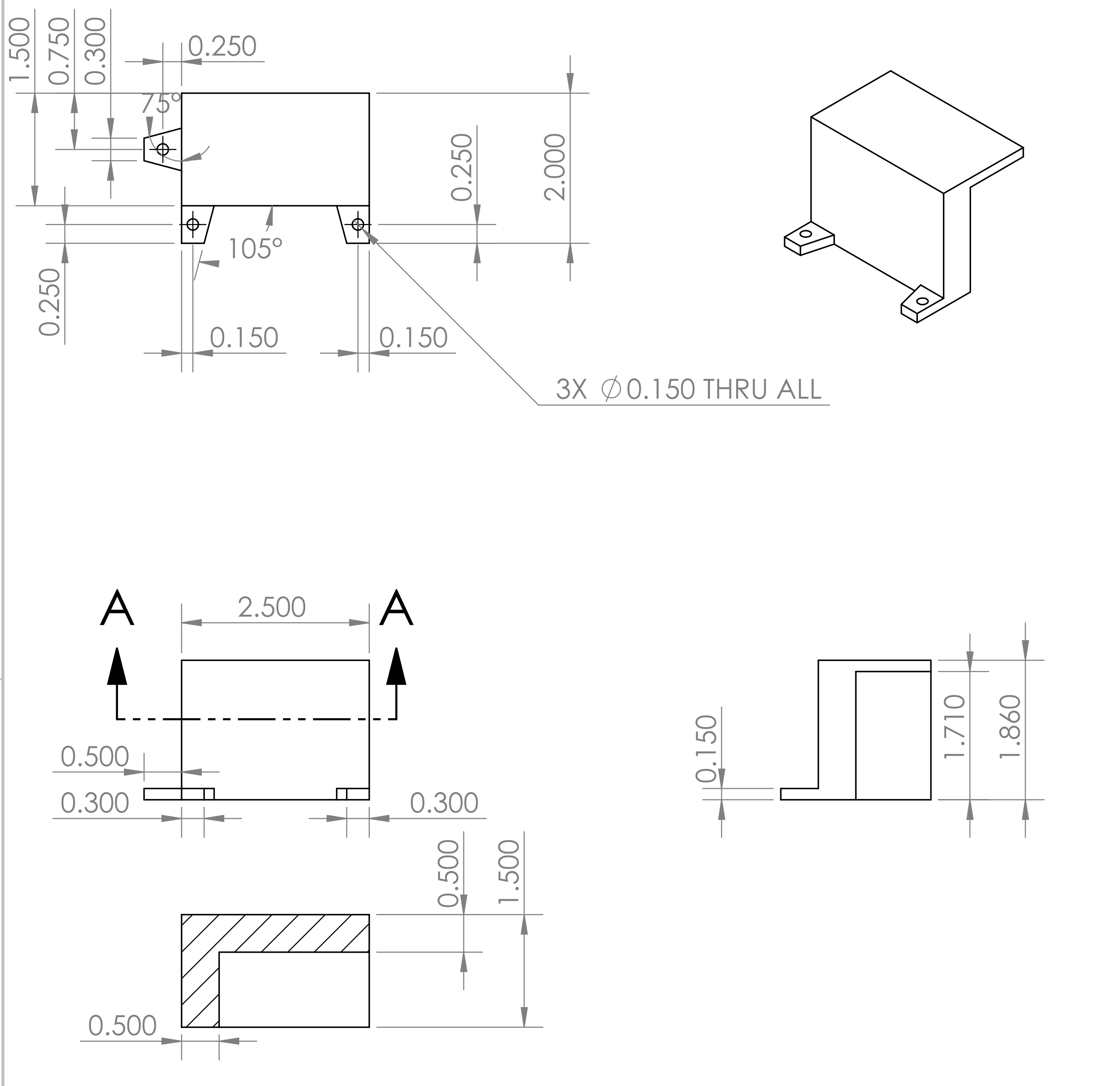
COMMENTS:

TITLE:

BlankKey

SIZE **A** DWG. NO. REV

SCALE: 2:1 WEIGHT: SHEET 1 OF 1



SECTION A-A

PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005

MATERIAL
ABS Plastic

FINISH

DO NOT SCALE DRAWING

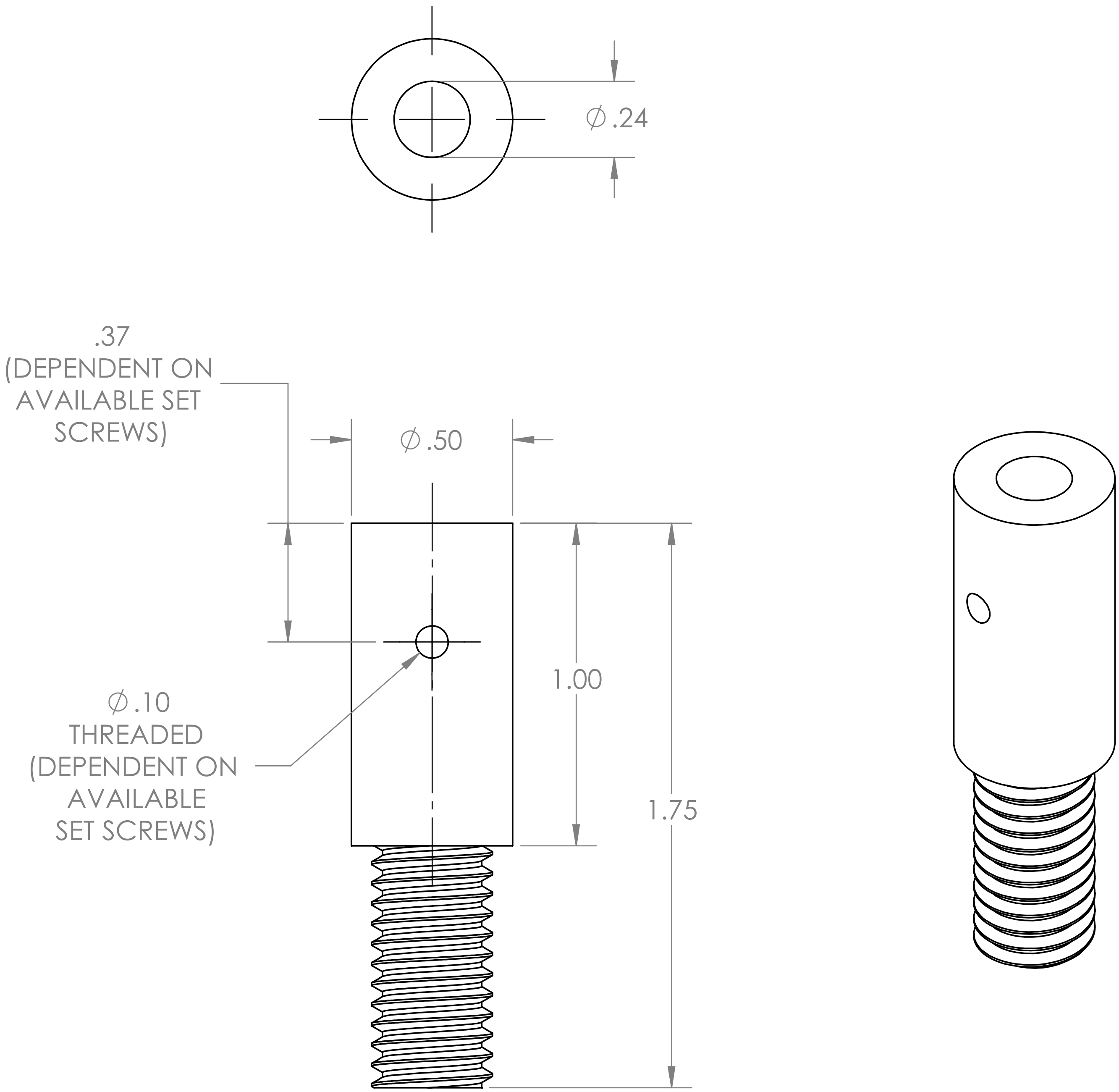
	NAME	DATE
DRAWN	HJW	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

24VSupport

SIZE	DWG. NO.	REV.
A		

SCALE: 1:2 WEIGHT: SHEET 1 OF 1



NEXT ASSY	USED ON		
APPLICATION			

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.1"
THREE PLACE DECIMAL ±

MATERIAL
6061 T6 ALUMINUM

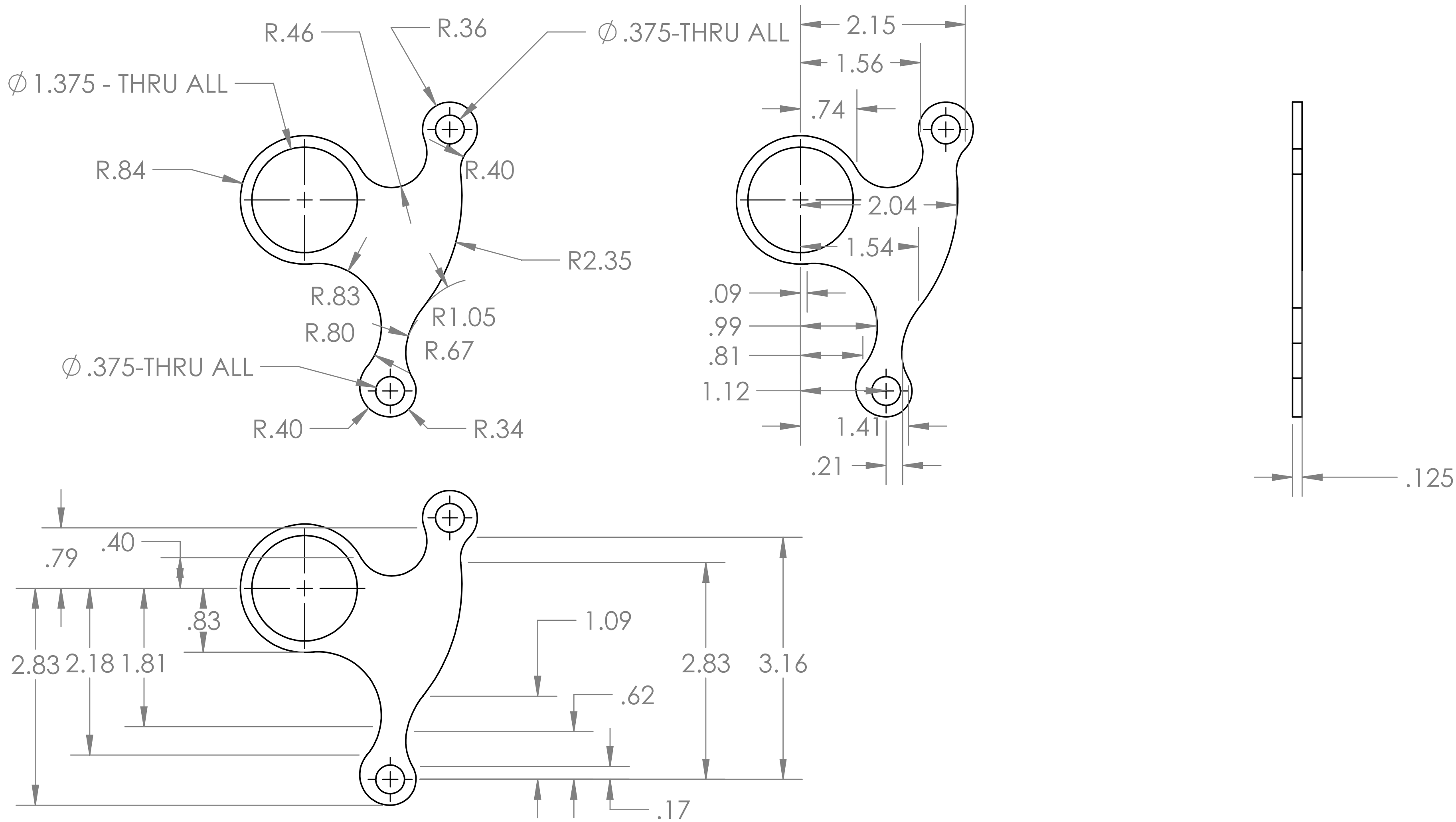
FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	SL HARTLESS	5/2/25
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

SIZE	DWG. NO.	REV.
A	Camshaft Coupler_Drawing	
SCALE:2:1	WEIGHT:	SHEET 1 OF 1



NEXT ASSY	USED ON	
APPLICATION		

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.01"
THREE PLACE DECIMAL ± 0.005"

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6061 T6 ALUMINUM

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	SL HARTLESS	5/2/25
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

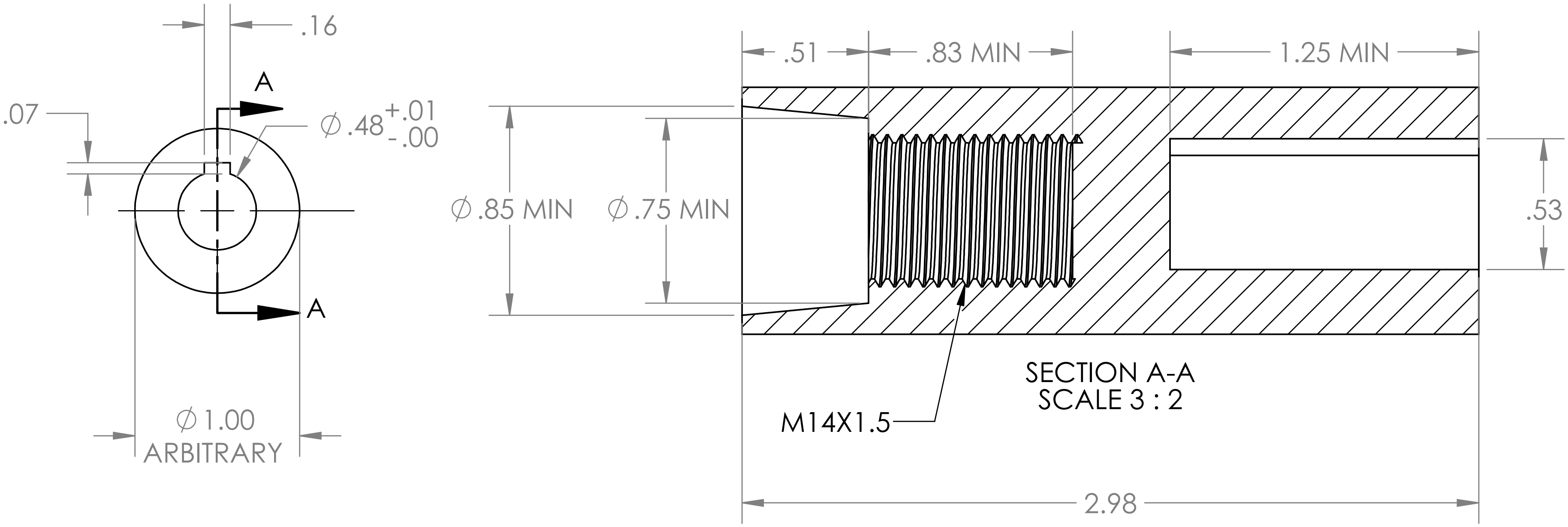
TITLE:

SIZE	DWG. NO.	REV
A	CamshaftSupport_Drawing	

SCALE: 1:2 WEIGHT: SHEET 1 OF 1

2 1

B B



SECTION A-A
SCALE 3 : 2

A A

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± 0.01"
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
464 NAVAL BRASS & ALUMINUM

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	SL HARTLESS	3/20/25
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

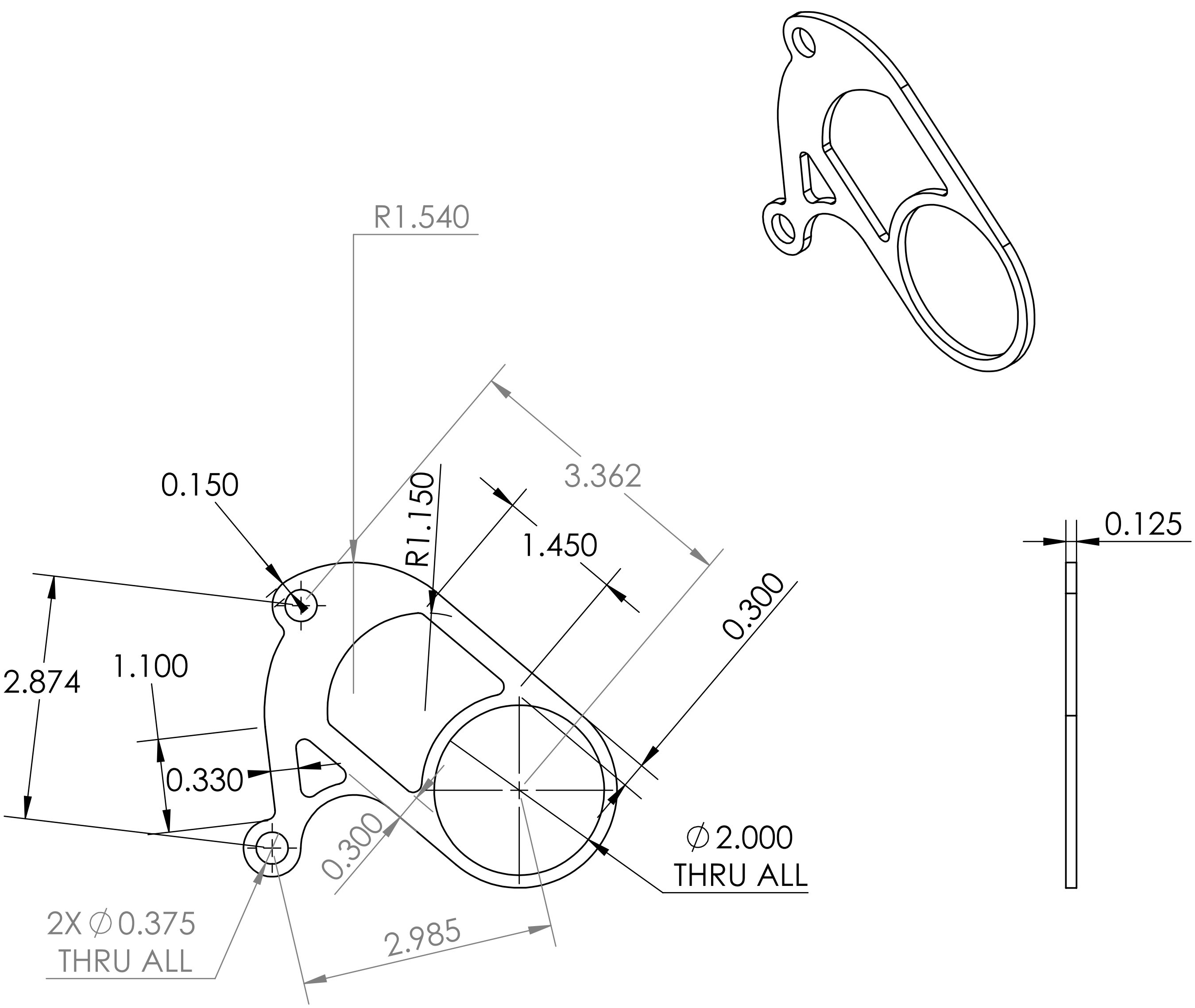
SIZE	DWG. NO.	REV
A	Crankshaft Coupler_Drawin	

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

2 1

2 1

Notes:
- All fillets are 0.100" unless otherwise noted.
- Member width 0.150" unless otherwise noted.
- Part was made using measurements and tracing an orthogonal picture of the Predator 212 open crankcase, so dimensions may not be comprehensive.



		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.01 THREE PLACE DECIMAL ±0.005		NAME / DATE
			DRAWN	HJW
			CHECKED	
			ENG APPR.	
			MFG APPR.	
		MATERIAL 1/8" Thick Aluminum Sheet	Q.A.	
NEXT ASSY	USED ON	FINISH	COMMENTS:	
APPLICATION		DO NOT SCALE DRAWING		

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Crank Support

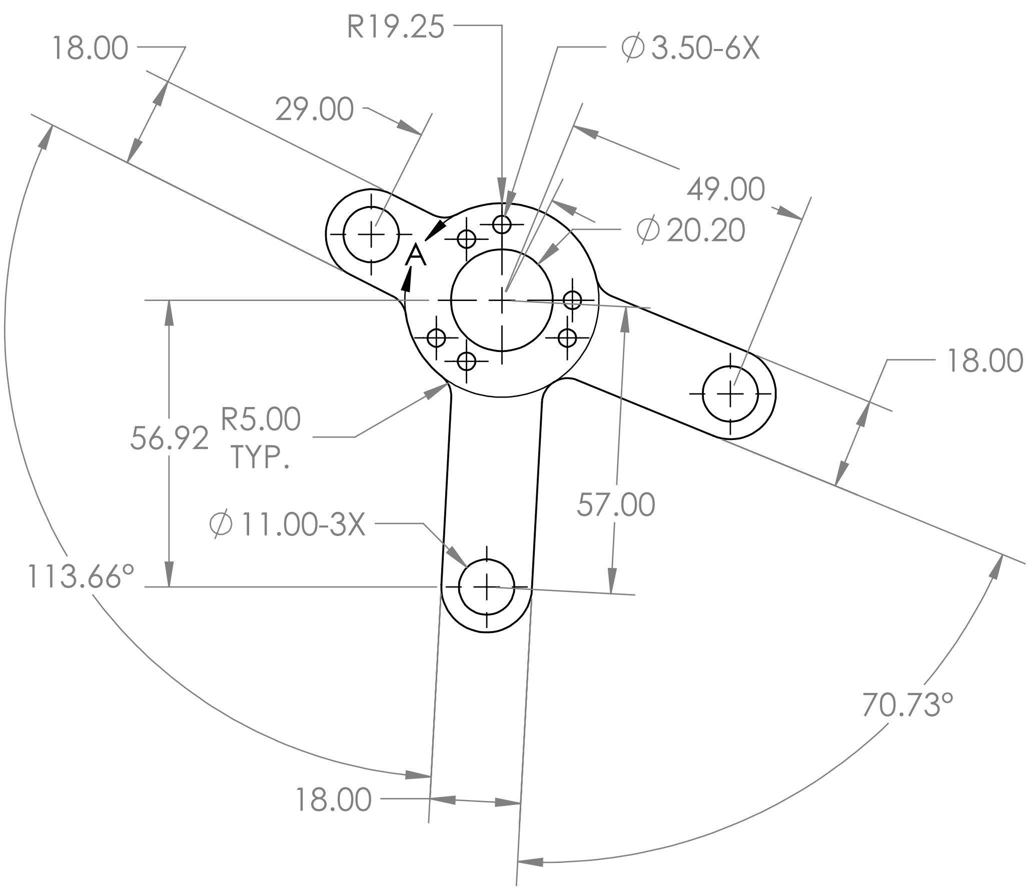
SIZE A | DWG. NO. | REV.

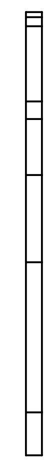
SCALE:1:2 | WEIGHT: | SHEET 1 OF 1

2 1

B B

NOTE: ALL HOLES ARE THRU ALL





A A

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN MILLIMETERS TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.25MM THREE PLACE DECIMAL ±0.125MM	DRAWN	SL HARTLESS	5/2/25
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL 6061 T6 ALUMINUM	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

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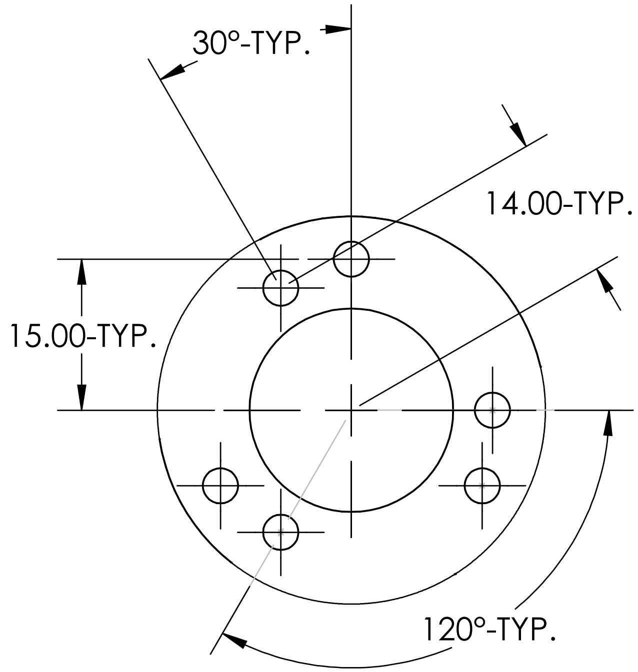
TITLE:

SIZE A DWG. NO. Encoder Bracket_Drawing REV

SCALE: 2:3 WEIGHT: SHEET 1 OF 2

2 1



DETAIL A
SCALE 4 : 3

NOTE: PATTERN REPEATS
EVERY 120 DEGREES.

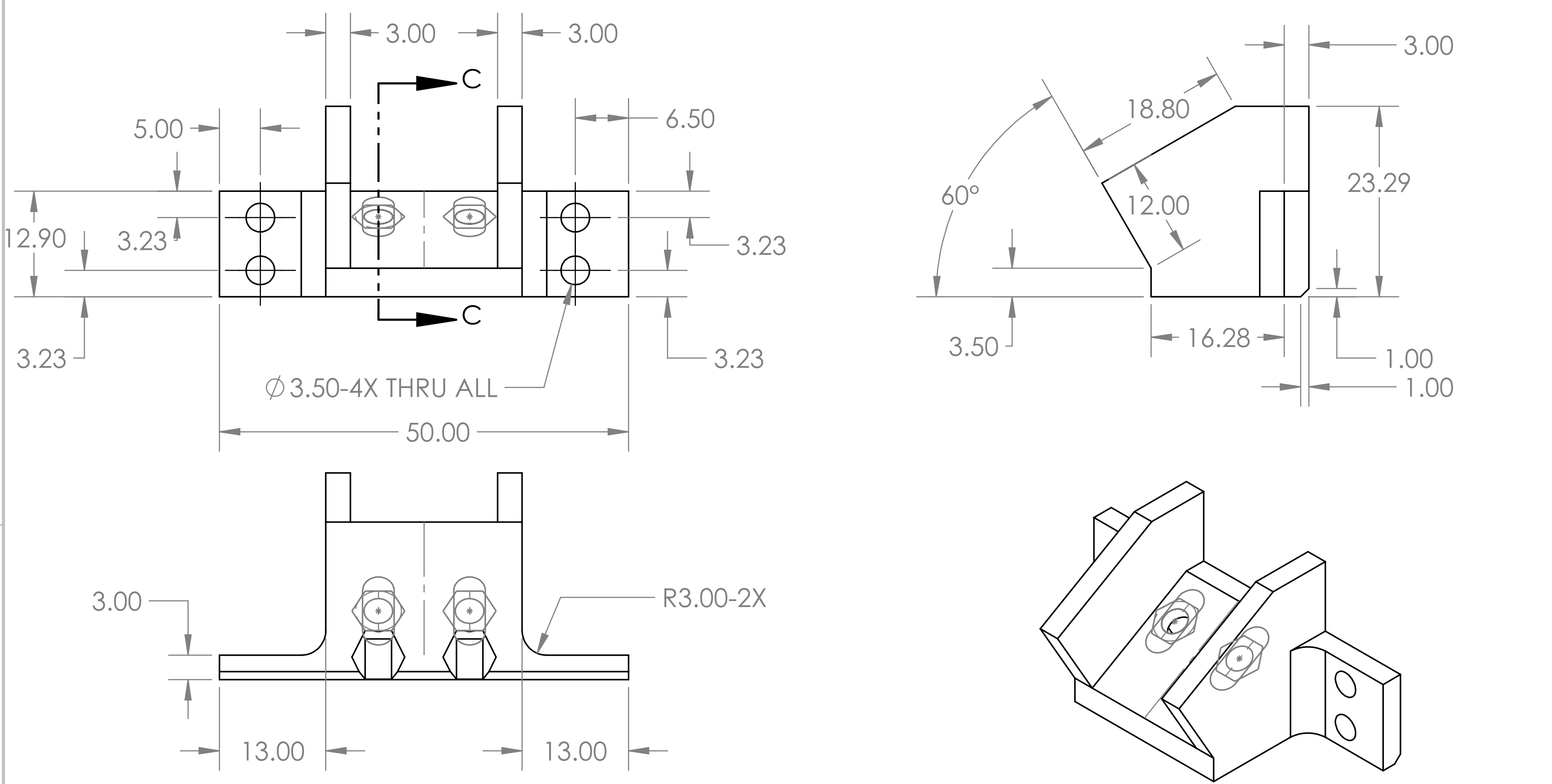
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN MILLIMETERS TOLERANCES: FRACTIONAL ± ANGULAR: ±0.1° TWO PLACE DECIMAL ±0.25MM THREE PLACE DECIMAL ±0.125MM	DRAWN	SL HARTLESS	5/2/25
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL 6061 T6 ALUMINUM	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

TITLE:

SIZE	DWG. NO.	REV
A	Encoder Bracket_Drawing	

SCALE: 1:2	WEIGHT:	SHEET 2 OF 2



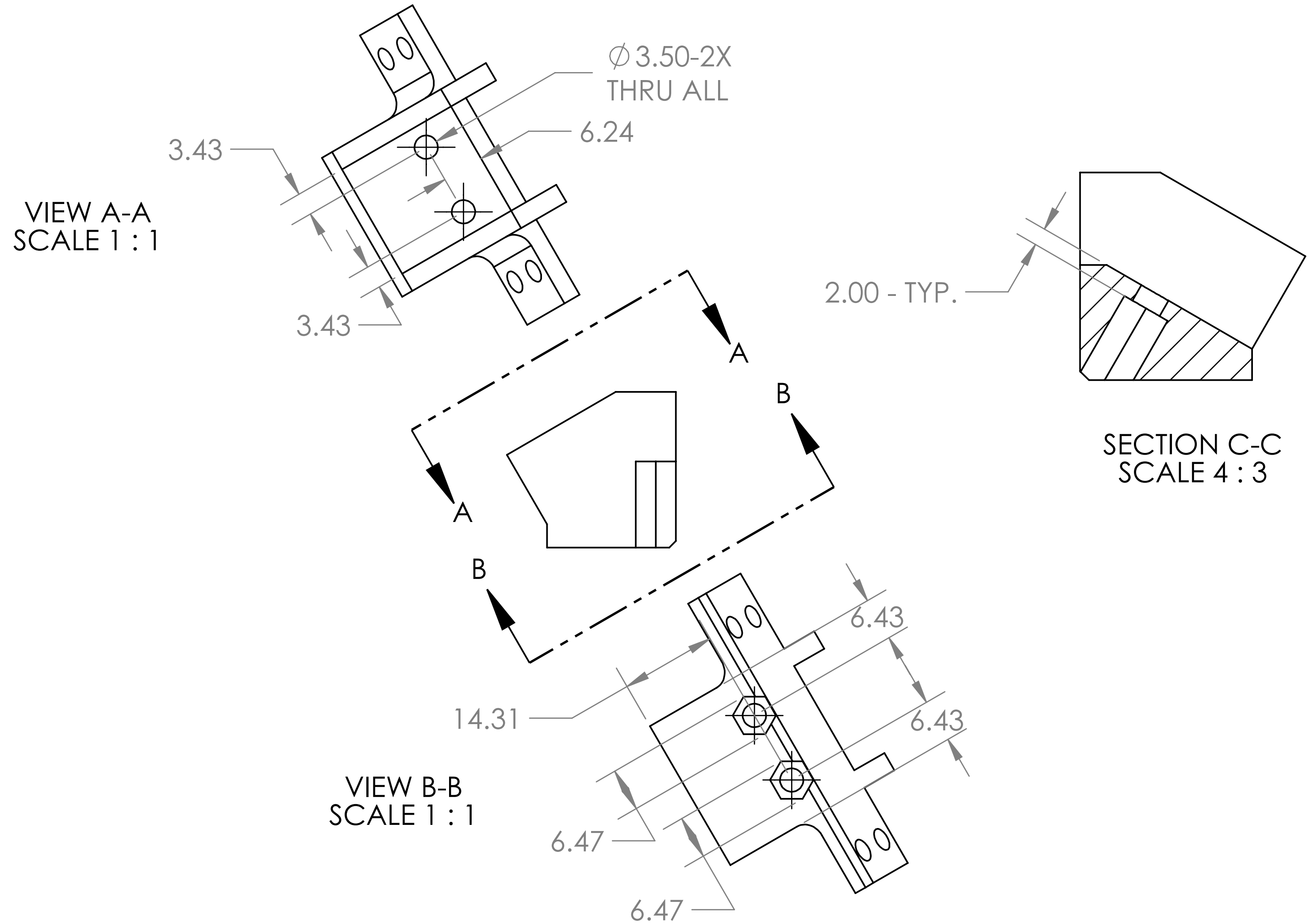
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN MILLIMETERS TOLERANCES: FRACTIONAL ± ANGULAR: ± 0.1° TWO PLACE DECIMAL ±0.25MM THREE PLACE DECIMAL ±0.125MM	DRAWN	SL HARLTESS	5/2/25
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

SIZE A | DWG. NO. Inductive Proximity Sensor Mount_ | REV

SCALE: 4:3 | WEIGHT: | SHEET 1 OF 2

PROPRIETARY AND CONFIDENTIAL



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL ±
ANGULAR: ±0.1°
TWO PLACE DECIMAL ± 0.25MM
THREE PLACE DECIMAL ±0.125MM

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
ABS PLASTIC

FINISH

DO NOT SCALE DRAWING

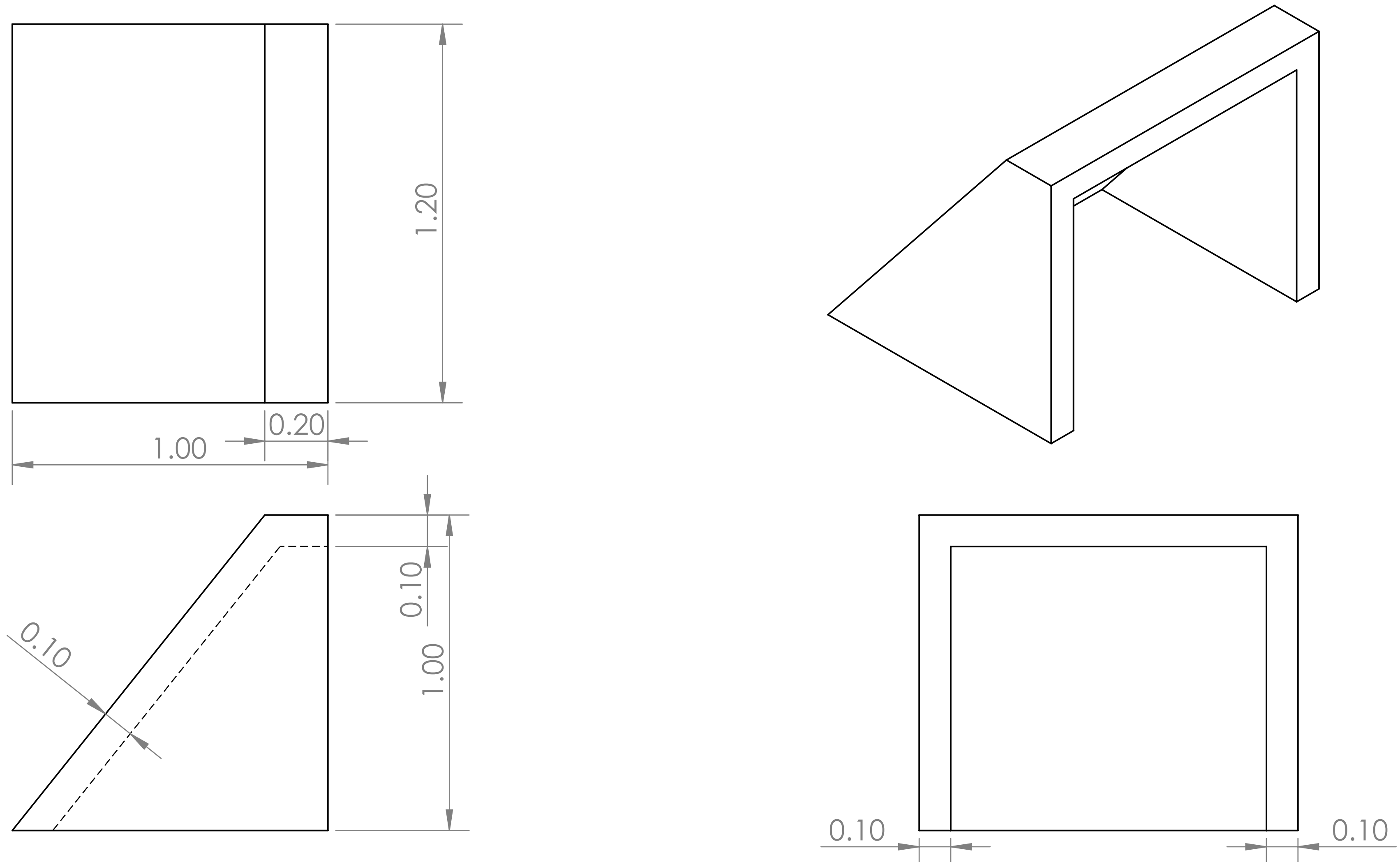
	NAME	DATE
DRAWN	SL HARLTESS	5/2/25
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE A | DWG. NO. Inductive Proximity Sensor Mount_ | REV

SCALE: 1:1 | WEIGHT: | SHEET 2 OF 2



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
ABS Plastic

FINISH

DO NOT SCALE DRAWING

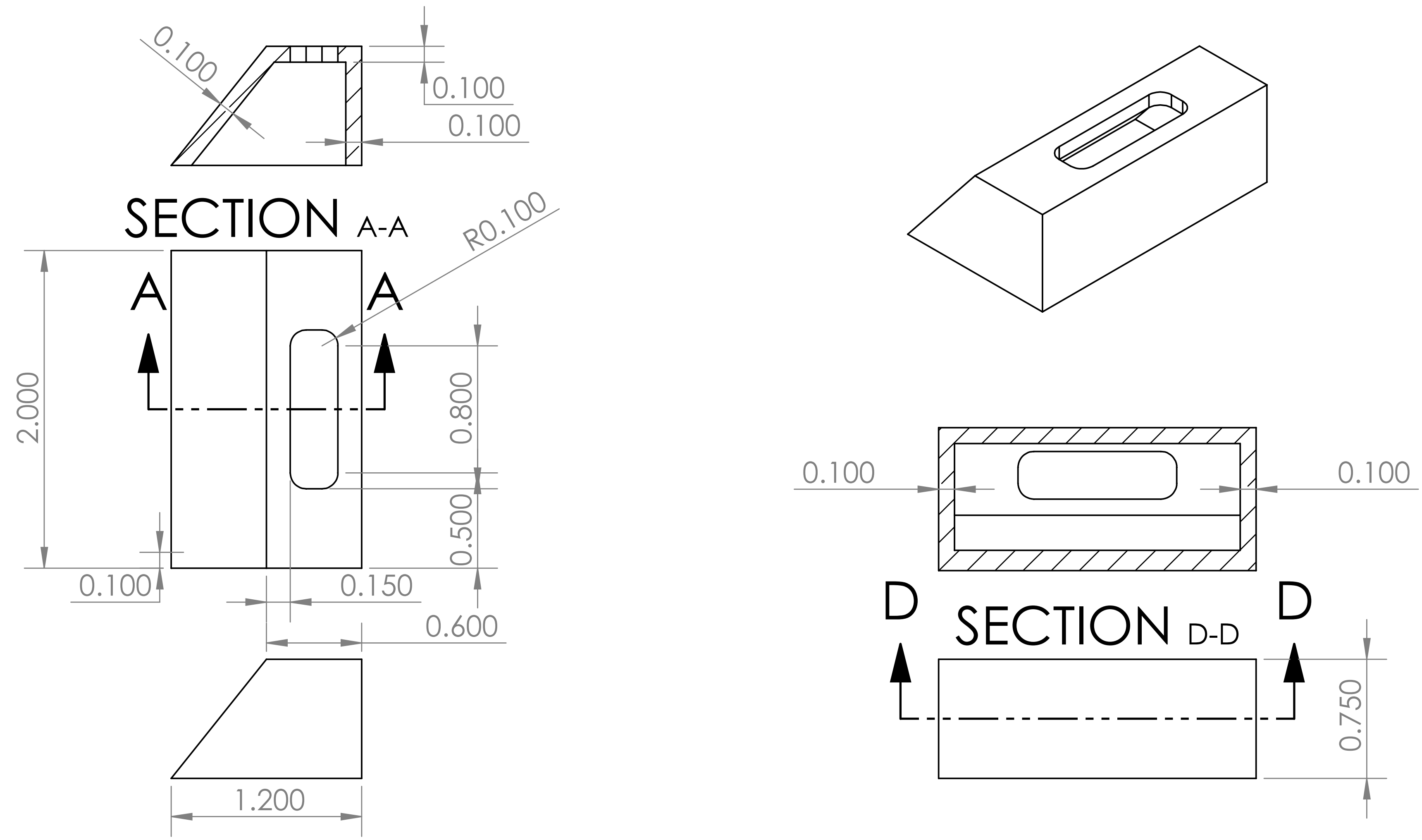
	NAME	DATE
DRAWN	HJW	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

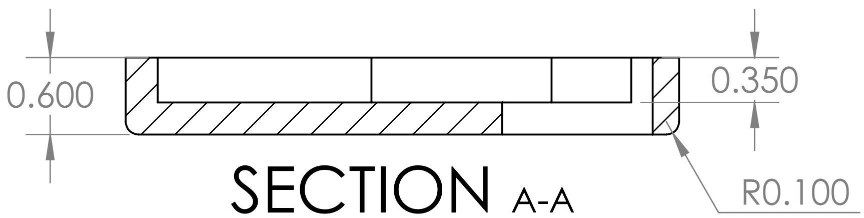
TITLE:
Keyboard Wire Cover

SIZE	DWG. NO.	REV
A		

SCALE: 2:1 | WEIGHT: | SHEET 1 OF 1

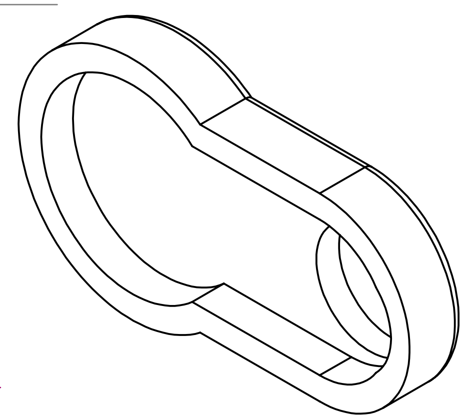


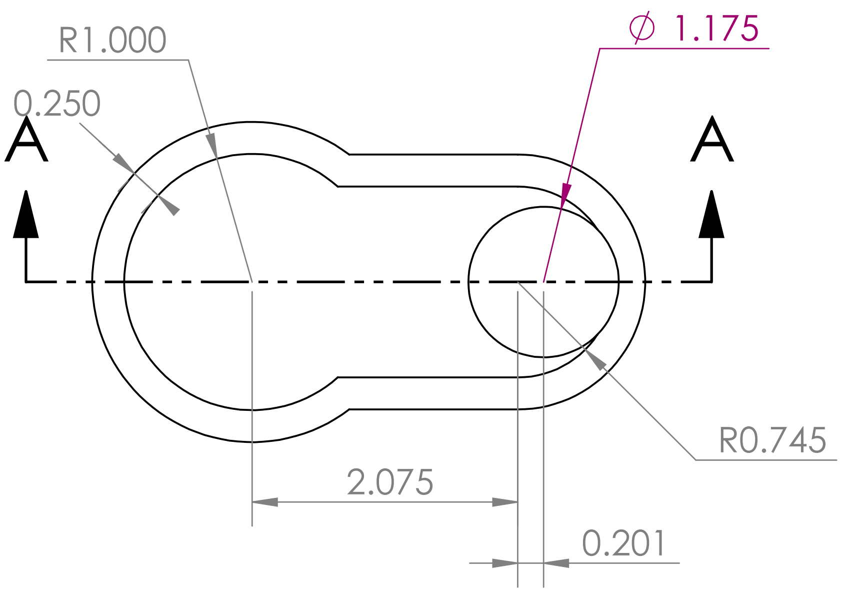
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.01 THREE PLACE DECIMAL ±0.005	DRAWN	HJW		TITLE: LED Wire Cover
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL ABS Plastic	COMMENTS:			SIZE A | DWG. NO. | REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1 | WEIGHT: | SHEET 1 OF 1



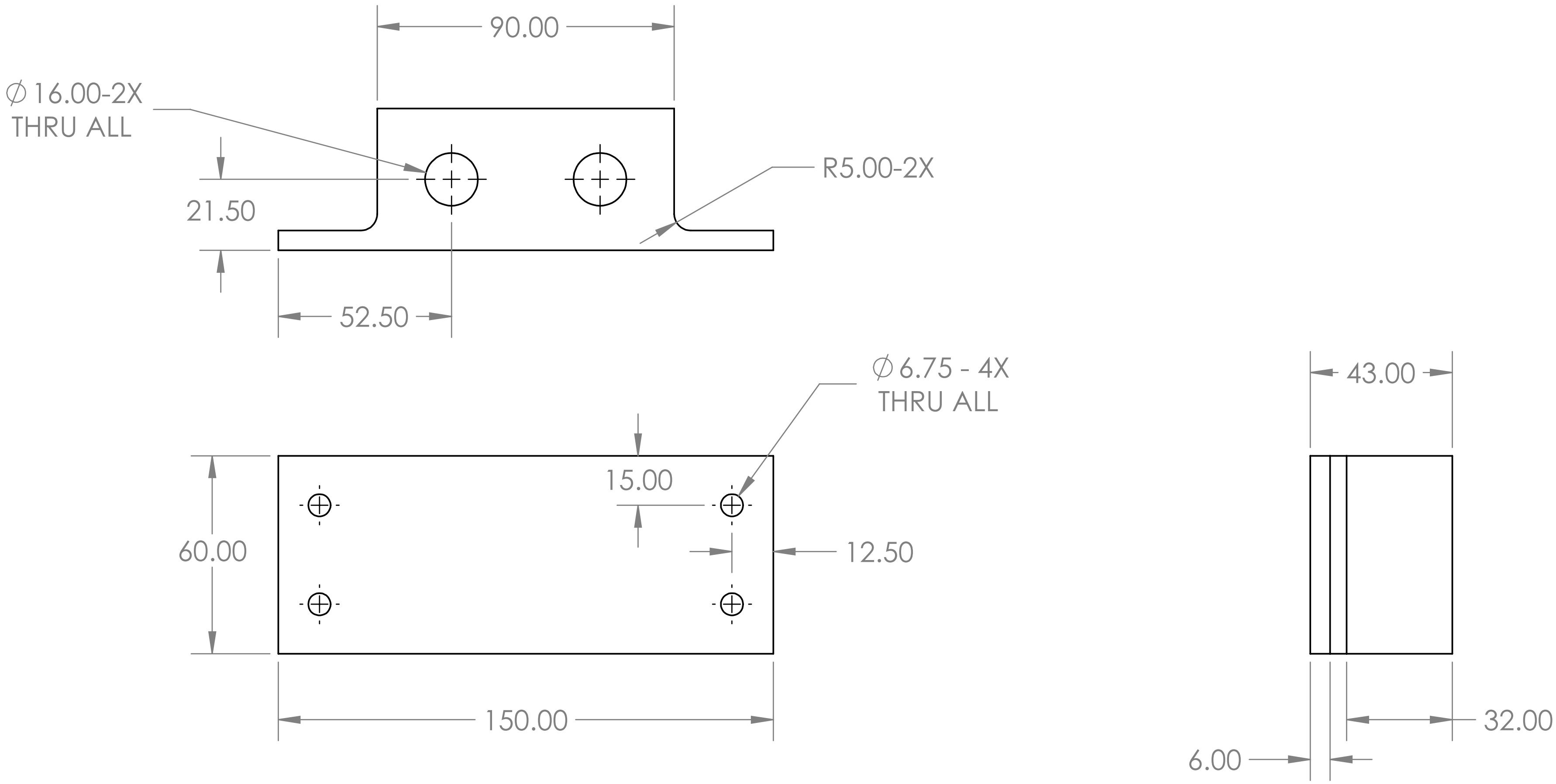
SECTION A-A

SCALE 2 : 3





		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.01 THREE PLACE DECIMAL ±0.005		NAME	DATE	
			DRAWN	HJW		
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		MATERIAL ABS Plastic	Q.A.			
NEXT ASSY	USED ON	FINISH	COMMENTS:			MonitorBaseCover
APPLICATION		DO NOT SCALE DRAWING				SIZE A · DWG. NO. · REV.
						SCALE: 2:3 · WEIGHT: · SHEET 1 OF 1



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL ±
ANGULAR: ± 0.1°
TWO PLACE DECIMAL ± .25MM
THREE PLACE DECIMAL ± .125MM

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL
ABS PLASTIC

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	SL HARTLESS	5/2/25
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE	DWG. NO.	REV
A	Motor Mount Block_Drawin	

SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

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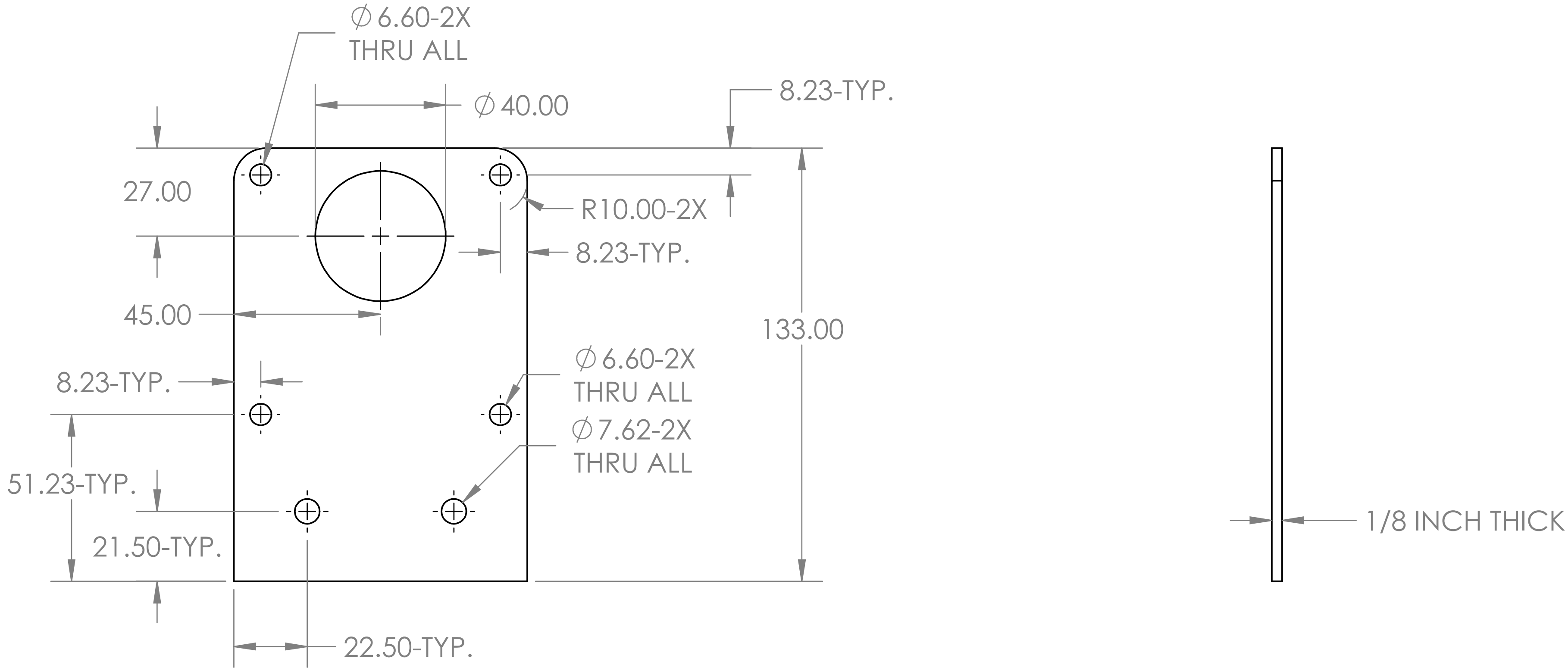
2 1

B B



A A

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.25MM
THREE PLACE DECIMAL ±0.125MM

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6061 T6 ALUMINUM

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	SL HARTLESS	5/2/25
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

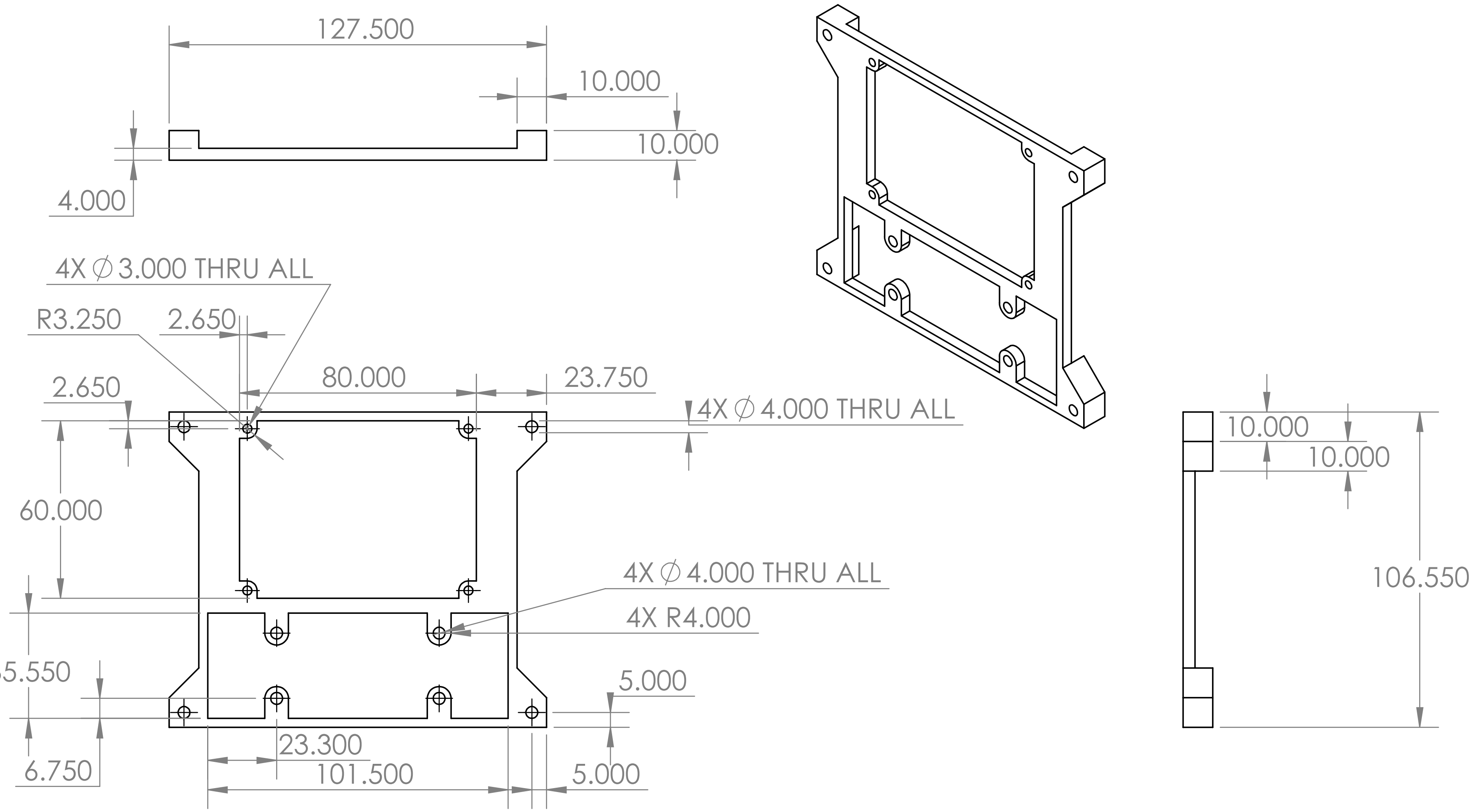
SIZE	DWG. NO.	REV
A	Motor Mount Plate_Drawin	

SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

2 1

2 1

B B



A A

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.25
THREE PLACE DECIMAL ±0.125

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
ABS Plastic

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HJW	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

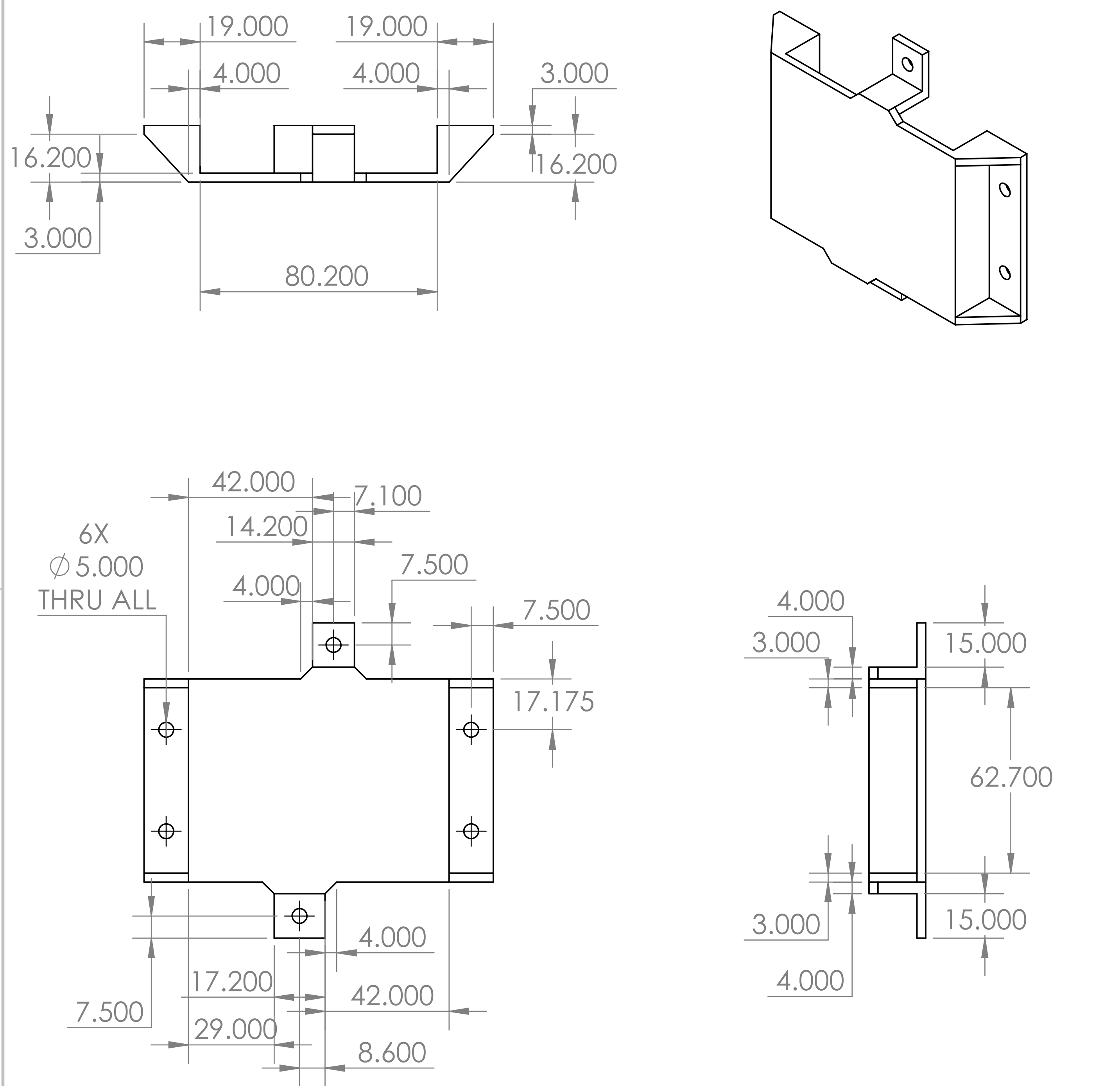
COMMENTS:

TITLE:
PCB Mounting Plate

SIZE	DWG. NO.	REV
A		

SCALE: 1:2 WEIGHT: SHEET 1 OF 1

2 1



NEXT ASSY	USED ON
APPLICATION	

DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.25
THREE PLACE DECIMAL ±0.125

MATERIAL
ABS Plastic

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	HJW	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

SpriteBracket

SIZE	DWG. NO.	REV.
A		

SCALE:1:2 WEIGHT: SHEET 1 OF 1

Appendix E: Bill of Materials

Assembly Part No.	Item	Description	Quantity	Cost
1	**PREDATOR 6.5 HP (212cc) OHV Horizontal Shaft Gas Engine**	This engine is cheap and hopefully easy to take apart, allowing for ease of use and whose components will be easy to reintegrate into the electric model	1	$150.00
2	**MedeaWiz 4K Sprite**	Allows the group to play the video on the screen and control it with the Propeller2 Chip	1	$168.99
3	**Bambu Lab PLA Basic (1.75mm, 1kg)**	Used to 3D print replacement components and connection interfaces as necessary	1	$27.99
4	**Electronic Motor and Controller**	Will power the engine model and the controller enables control over speed and direction	1	$80.00
5	**6061 Aluminum 3/4", 1' bar stock**	Used to machine couplings for	1	$5.40

		camshaft mount		
6	**6061 Aluminum 1/2", 6' stock**	Planned to use for to machining couplings for motor mount, 6' order instead of 6" which we chose to count against the budget	1	$11.21
7	**McMaster Carr 9/16" ID Bearing, 7/16" width**	Provides support for camshaft turning and reduces friction	2	$21.97
8	**McMaster Carr 1" ID Bearing, 1/2" width**	Provides support for crankshaft turning and reduces friction	1	$13.73
9	**Acer - Nitro 27" IPS LED 180Hz 0.5ms FreeSync Gaming Monitor (DisplayPort, HDMI) - Black**	Displays information independent of engine cycle motion	1	$199.99
10	**ProjectSource 10-ft Workshop Power Strip- 15A**	Power strip for all plugins	1	$16.98
Total Cost		**$718.23**		

Many of the materials were sourced with extra mechatronics components that were unused, allowing for the budget to focus on more critical items. Items taken from the unused mechatronics components were a quadrature encoder, power supplies, LEDs, IC chips, and wiring components. In the future, replacement parts dedicated to the project could be purchased for future upkeep.