ANIMATED OTTO-LANGEN ATMOSPHERIC ENGINE

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Abstract
Based on an existing relationship between Dr. Owen and the Deutsches Museum, Otto-Mated was given the opportunity to collaborate with the two in a year-long senior design project. Otto-Mated has been tasked with modeling and simulating the operation of the Otto-Langen Atmospheric Engine, found in the Deutsches Museum. This modeled simulation acts as an educational tool while preserving the engine from damage and wear that would incur from running the engine. The model is to be created in SolidWorks and animated in Blender, effectively providing the museum with accurate and educational videos demonstrating the engine's function. Within this document are the plans, decisions, and processes used to create our final product for Deutsches Museum.

Introduction
Team Otto-Mated took the opportunity to model the Otto Engine, both virtually and physically, as well as create a simulation of the engine. Our final goal was to provide the Deutsches Museum with an animation and physical model of the essential parts of the engine, which could be placed in an exhibit. Stakeholders in this project include, but are not limited to, the following: The Deutsches Museum and its employees, museum visitors, Dr. Frank Owen, and our team. Dr. Owen has established a working relationship with the Deutsches Museum that allowed us to gain information that may otherwise have been inaccessible. Furthermore, the museum's relationship with its visitors is crucial, and we, as creators of an exhibit, strove to better this relationship by providing an enriching experience. Within this design report, we will cover the background, design requirements and specifications, design development, management plan, results and suggestions for the future.

Additionally, it should be known that the main goal of this project was to educate museum visitors about the Otto Engine. The educational exhibit includes the history behind the engine, what it was used for, the engine components, the way the components work together, and the theory behind the thermodynamics of the engine and its cycle.

Background
The Deutsches Museum is a world-renowned museum specializing in science and technology. Established in 1903, the museum now has 66,000 square meters of floor space dedicated to displaying its unique, original artifacts and explaining the concepts and mechanisms behind them (1). Looking to the future, the museum hopes to enable even more visitors to see its exhibits by sharing them online. The museum also wishes to preserve the integrity of the items in its possession for as long as possible. Many items in the museum's collection are machinery, and by their very nature wear out with use. These parts are irreplaceable due to their antiquity. As such, the museum cannot demonstrate how the machines operate using the original equipment, but must use models and recreations to demonstrate the working principles to their visitors. Recently, the museum has begun using advances in 3D modeling to create virtual models of their specimens. These virtual models are then animated to show how the machine works and moves. This technology allows museum exhibits to run indefinitely without wear, and is an effective, low cost way for the museum to showcase its collection. With the capabilities of the Internet expanding, the museum is also looking to post many of its exhibits online in a web-based museum, where animations would be practical. Knowledge of these machines is vital due to their significance in modern machines, which have taken those principle designs and have continued to evolve over time.

To aid in this effort, the museum has previously recruited senior project teams from Cal Poly, who, under the direction of Dr. Frank Owen, have modeled two different devices: a mechanical calculator and the Frauenkirche clock. For these projects, the students created a SolidWorks model of each component in the devices, based on key measurements and pictures with a scale reference. Once all the components were modeled, the devices were assembled and animated, all within SolidWorks. However, the museum found that the animations from SolidWorks did not always behave as expected and the resolution was not very high. After these projects, Dr. Owen investigated other programs capable of producing the types of animations desired by the museum; through his research, he discovered Blender. His theory was that SolidWorks could be used to create properly sized virtual components, which could then be animated in Blender. The museum supports this process and has given him the task of testing his theory on modeling and animating a new machine: the Otto Langen Atmospheric Engine.

In order to understand the task of animating the Otto Engine, it was necessary to see what currently exists concerning educational animations in exhibits. Fortunately, one of Dr. Owen's acquaintances is a docent at the Computer History Museum located in Mountain View, California as well as an associate of the Deutsches Museum. Our team accepted the opportunity to receive a tour at the Computer History Museum with Dr. Owen's acquaintance. This opportunity allowed us to gain some insight on what we should strive to create. The museum had several educational animations demonstrating the inner workings of clocks and mechanical calculators (Note: These are not the same clock and calculator modeled in previous projects with the Deutsches Museum.). We observed the qualities of these animations, especially in the following areas: level of complexity, method of communication, and method of maintaining viewer interest. Figure 1 is a snapshot of the mechanical calculator animation, which provides a baseline for the qualities mentioned above. This animation simplified the mechanism as much as possible while still conveying its underlying concepts and operations. Furthermore, ideas and descriptions are conveyed through text, which appears on the screen as the action occurs. Occasionally, narration was also used, but never at the same time as a written description. Our team determined that this animation was lacking in its ability to maintain viewer interest, thus creating an area for us to focus on.

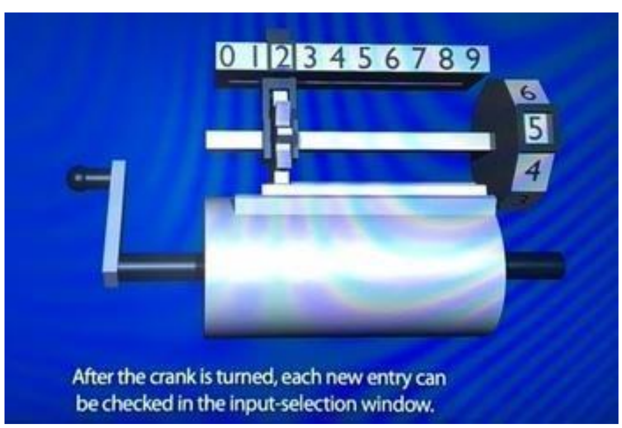


Figure 1. Mechanical calculator animation seen at the Computer History Museum.

Along with observing the quality of animations themselves, we also surveyed the user interface through which these animations played. The museum had several viewing stations, as seen in Figure 2, throughout the exhibits allowing video selection and the ability to listen to narrations without disturbing other museum visitors.

Figure 2. Animation viewing station seen in the Computer History Museum.

The key ideas to take away from this viewing station include: the ease of use, viewer selection, and ease of access. The museum implemented touch screens and "one-way telephones," making the stations intuitive and easy to use. By using touchscreens, the users are given the ability to select from several short animations and videos regarding the mechanism in front of them. Additionally, having several viewing stations throughout the exhibit and two listening devices per station, makes them accessible to multiple viewers at one time without disturbing the other guests. Based on this museum's layout and the positioning of viewing stations, we have deduced that the best way to attract viewers is to make the station easily accessible even with heavy exhibit traffic.

To try and synthesize the best parts of the videos, exhibits, and viewing stations from the Computer History Museum, a Google form was created with six different videos that asked viewers what features (cutaways, narration, written descriptions, arrows, etc.) they found the most useful. Sample questions from the forms are shown in Appendix C. Due to time constraints, a large sample size was not able to be accrued. However, based on preliminary results, a video with narration that shows the engine in operation, but also has cutaway views to see the internal workings, seems to be the most appealing and understandable format for viewers. More data will continue to be taken throughout the project, but this form gives an initial understanding of what has worked well in previous videos and what we should be aiming for.

Along with exploring existing animations and methods of display, we also investigated existing research and models of the Otto Engine. Naturally, the Deutsches museum is not the only group to have interest in explaining the history and function of engines and other mechanical devices. A quick internet search on “how do engines work” or “Otto Engine explained” brings up countless examples of other groups trying to do somewhat of the same thing, ranging from engine enthusiasts (working out of a garage) to multinational engine companies that need advertising and employee training. One such engine enthusiast and historian, expressed interest in working with us. Wayne Grenning, a resident of New York, has done extensive research on the Otto Engine as well as made physical, running models. Even though this model-making is a side business and hobby, the models are based off of extensive research as well as interaction with many of the different surviving engines. Mr. Grenning’s Otto Engine expertise along with his desire to educate others on the engine has become a valuable asset to our team [3]. We have been provided literature with over 70 pages written on the engine, specific to its complex components, such as the engine’s slide valve [5]. Wayne’s book that we utilized can be seen in Appendix J. Wayne has also sent us technical drawings that were used to manufacture the models he produces. Although, the engines he has modeled are not exactly the same as the one located in Deutsches Museum, but the differences have been identified and the engine we are working with shares many of the same dimensions. The parts that differ will be mentioned to the Deutsches Museum, where it is necessary for detailed and scaled pictures of those parts to be obtained.

The Otto engine has extreme significance within the present world since it’s the foundation for the modern internal combustion engine. This engine was among the first viable internal combustion engines and considerably more efficient than its competitors when it was released [5]. During a time when steam was the main power source of large machinery, the internal combustion engine provided a way to turn fuel into mechanical energy via a relatively instantaneous combustion. This bypassed the intermediate step of heating a working fluid before it’s used to produce mechanical energy. Although we have come a long way with increasing the efficiency and power output of a combustion engine, the Otto Engine was the foundation from where it all started.

<u>Design Requirements and Specifications</u>

The first step in the design process was to define our problem statement. Our problem statement has been defined as the following: *The Otto Engine, located at the Deutsches Museum in Munich, Germany, is the basis for the modern internal combustion engine. Due to the Otto Engine’s antiquity and irreplaceability, the museum needs an alternative visual demonstration to show the function of the engine’s components. The demonstration should provide an engaging, educational experience for the museum visitors.*

The next step in the process was defining our requirements for the design. Prior to developing several solutions for the museum, we decided to quantify our requirements with a Quality Function Development (QFD) diagram, which was used to aid and organize our thinking. The QFD chart lists the users and other entities that interact with the product under design, in this case the visual demonstrations for the museum. The QFD also lists all the requirements and concerns these parties have for the product. These requirements go into a “Needs” section on the left-hand side, forming the rows of the diagram. Across the top of the diagram, all the tests that will be used to evaluate the requirements are listed, which form the columns. At the intersection of the requirement rows and specification columns, a rating shows how well the specification tests the requirement row. This allows an easy check to make sure the specifications created test all of the requirements and that no requirements were overlooked. Any requirements that aren't tested are likely to be neglected in the design process making this type of evaluation a key step early on in the process. Additionally, the QFD ensures the final product meets the requirements. The QFD analysis used for this project can be seen in Appendix A. The users considered were museum docents, maintenance personnel and website developers, as well as museum guests. The museum guests considered included elementary school children, tourists, deaf visitors, blind visitors, and automotive engineers.

The QFD analysis for this project included a variation of needs from all these different groups, which are listed below:

- A level of fun and interaction to keep children engaged.
- A high level of mechanical detail for those with an engineering background.
- A written description for the hearing-impaired or an audible version for the visually impaired.
- A good aesthetic appeal for all viewers.
- A standard file format for museum employees.

Additionally, a table of specifications was constructed to summarize our requirements with a description of those requirements and how they will be met, which can be seen in Table 1.

Table 1. Table of specifications of the exhibit. T denotes Testing, M denotes Measurement, and PR denotes Peer Review.

Specification No.	Description	Target	Verification
1	Level of Mechanical Detail	6^{th} Grade to College Level	T
2	Aesthetic Appeal	Viewer Attraction	T
3	Historical Context	Sum of 1-2 pages	M
4	Coding Level	Basic Computer Skills	T
5	Ease of Interaction	Kids Can Interact	T
6	Written Descriptions	Less Than 1 Page per Animation	M
7	Fun Level	People Watch Entire Animation	T
8	Physical Accuracy	Model Tolerances within 15%	M
9	Size	Under 200 ft^2	M
10	Cost	Under $7000	M
11	Accurate Process Description	College Level	M, PR
12	Multilingual	At Least 2 Languages	M
13	Audio	For All Written Descriptions	M

It is expected that throughout the initial steps of the project, we will discover new requirements. The more extensive list is shown in the QFD found in Appendix A, but even this list is not comprehensive, as more needs continued to arise as the project progresses. With these customer needs laid out, it was necessary to devise ways to test that the product is fulfilling these needs. Specifications were created to target values set for these different measures. A ranking of how well each specification tested compliance with the customer needs was also given. This allowed us to check that all customer needs were tested and that any competing or conflicting requirements were revealed. For example, we included all of the engine parts to achieve an accurate physical model and complete mechanical detail; however, this will inevitably drive the size of the model up, potentially making the model too busy and less visually appealing. These sorts of relations are what the QFD analysis highlights.

Design Development

The museum exhibit and Otto Engine animations go hand in hand. With that being said, we needed to know how the museum visitors will be viewing the animations and, therefore, we needed to know the layout of the exhibit. This started our concept generation. The Otto Engine exhibit will exist within a redesigned portion of the Deutsches Museum that is planned to open in 2019, requiring a new exhibit design. Our concept generation focused on the layout of the exhibit and how the animations would appear within the that exhibit. During the concept generation, our team came up with seven concepts, which can be seen in Appendix E. From these concepts, we were able to narrow our decision down to two designs that were based on our specifications in Table 1 and the use of evaluation criteria. The first criteria used in the process was the "Go/No-Go" evaluation. Within this initial evaluation, our group evaluated each concept and assessed whether or not it would meet our acceptance criteria. Based on our assessment, we were able to eliminate the ideas that violated some of our specifications. The second evaluation was the Pugh Matrix, which is discussed below and can also be seen in Appendix F. These evaluations, and our personal analysis, brought us to our final two concepts: the "In-Wall" exhibit and the "Central Display" exhibit.

Pugh Matrix

To narrow down and refine the exhibit layouts, a Pugh matrix was used. The Pugh matrix is a simple comparison tool for design in which one design is picked as a reference, and then all the other designs are rated to be better (+), worse (-), or as good (0) at fulfilling various specifications. After looking at the total number of +, -, and 0's, judgements can be made about which designs are worth further investigation, or what elements should be taken from one design and added to another to make a final design better than both predecessors. For our exhibits, we chose 6 key areas to compare in an effort to balance an exceptional visitor experience with the cost of creating the exhibit. These criteria are listed in Table 2 along with a description for each.

Table 2. The criteria and corresponding descriptions for the museum exhibit.

Criteria	Description
Volume of Guests	The number of guests that an exhibit can engaged by at once. This is based on the number of screens/display areas, and their locations/orientations.
Viewer Experience Time Independence	This criterion is meant to evaluate whether the exhibit is cyclical, so that if a visitor came during the middle of a cycle they would have to wait for the new cycle to start before the information presented made sense.
Amount of Interaction	A function of the number of viewing angles, and any interactive menus or models.
Cost	Setup cost of the exhibit, focused mainly on the materials required, like the number of displays.
Programming Effort	Similar to cost, this criterion tries to estimate how much setup would be required to create the user interface for a given layout.
Space Efficiency	A measure of how much of the floor space occupied is engaging the museum guests, and not just dead space or hidden.

Due to the unweighted, and purely relative, ranking system used in the Pugh matrix, the top scoring design is not always the top design. Scores can be skewed based on the design used as the reference datum. To avoid making design decisions with this bias, a second Pugh matrix was created with a different reference to check for this type of error.

From our Pugh matrix, the Central Display and Middle Room designs were our highest scorers, with nearly the same results for both designs. Given the amount of similarity between these two designs, the Middle Room design has been dropped and we will only be proceeding with Central Display. The Two Menus design scored better than the Central Display when the Central Display was used as the reference, but this was mostly due to the interactive menus. We decided to incorporate these menus into the Central Display's small screens moving forward. We also decided to preserve the layout of the In-Wall Display design because the museum might not have room for the engine exhibit to be in the middle of an open area, which may require an in-wall design. Both exhibits are made from the same basic components, so we can move forward with both designs by doing the detailed design for these components. The two final designs were mocked up in SolidWorks and are described later in the report.

Top Designs

The two layouts chosen use the same basic components, just arranged in different ways. These components consist of the following: the original Otto Engine, the smaller model of the engine, small display screens, and large overhead screens. The components are designed to be modular, so that the final product can be set up quickly in its final arrangement. The small screen displays will present visitors with a menu, similar to a scene selection menu from a DVD. A cross sectional view of the engine will serve as the background, and then the different detail videos would be available for selection as thumbnails along the sides of the screen.

While small screens are presenting the details of the engine to interested visitors, large overhead screens would be continuously running an overview video to introduce the engine and its history to all museum guests. The audio for this video would be played out loud so any visitors passing by could hear. This video would demonstrate how the engine was used, describing its place in history and providing the aesthetic appeal to draw in visitors. For the wall design, two overhead screens are placed on either side of the original engine, which is protected behind a railing and surrounded by the small display screens. The scaled physical model is then placed near the display screens and towards the center of the exhibit, allowing visitors to walk around it. The In-Wall layout can interact with a large volume of guests at once, due to the large overhead screens, numerous small screens, and the physical model allowing plenty of space to walk around. This layout can be seen in Figure 3.

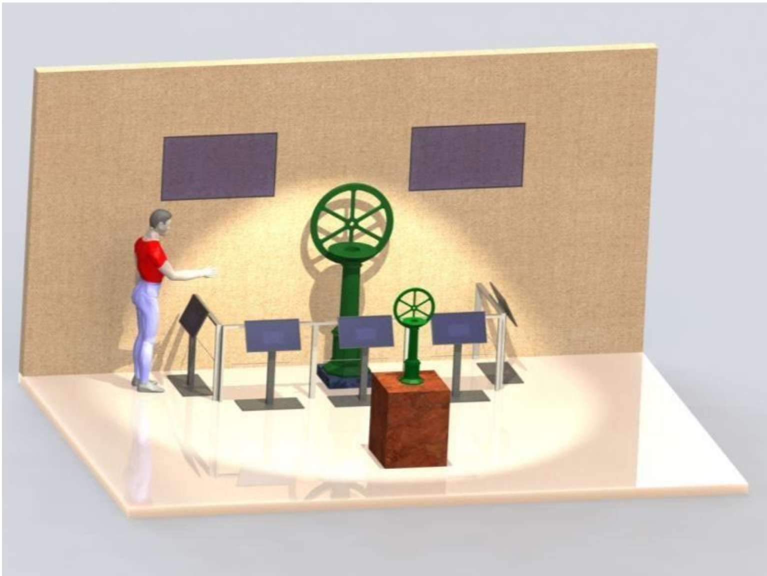


Figure 3. SolidWorks layout of the "In-Wall" exhibit.

The second concept chosen was the central display, where large screens are hung from the ceiling instead of mounted on the wall. These large screens provide the same viewer attraction as seen in the In-Wall design. The protective railing is still in place around the engine, but in this layout, there are additional smaller screens further removed from the railing. The physical model replaces one of the smaller displays in one of the corners. This layout allows 360 degrees of visibility for both the original engine and the model, as shown in Figure 4. Being able to view the engine from all sides increases the interactivity of the exhibit. Furthermore, the amount of viewer traffic this design can handle is easily adjusted by the number of smaller screens placed around the railing.

Figure 4. SolidWorks layout of the “Central Display” exhibit.

The In-Wall and Central Display exhibits meet specifications stated in Table 1 in a similar fashion. Both exhibit layouts have large screens that are meant to provide aesthetic appeal and viewer attraction through visibility at a distance. The Central Display design, however, does have an advantage in this area since its large screens are visible from all directions as opposed to the single direction of visibility in the In-Wall design. The two exhibit designs also share the same level of interaction, ease at which viewers can engage with the screens, and audio capabilities. These shared attributes are due to both exhibit designs using the same viewing interface, which is discussed in the Functional Description section. Ultimately the deciding factor is the architect’s design and the museum’s overall layout. It was revealed that the museum architectural plan called for the exhibit to be along a wall with a layout similar to our proposed In-Wall design; however, as per the museum’s request, we cannot divulge any plans or layouts. Since our main task for the museum is to provide the animation and video experience, we then focused on designing and creating the video sequences used in the In-Wall design.

Functional Description

Animating the engine was the main goal of our project and is a key element in educating the public about the engine and how it functions. The animations help us meet the design specifications not met through the exhibit design alone, which include: being visually appealing, describing the processes of the engine, and showing a high level of mechanical detail. The engine is unique in many different ways and the animations are meant to convey these details in a way that will keep museum goers interested while educating them. A brainstormed storyboard, outlining how we planned to convey all of this information was developed, and can be seen in Appendix D. This was the first rendition of storyboarding and directed us as we began to receive measurements and start drawing parts using SolidWorks. The frames were a general snapshot of the different videos that will run and detail the most important and unique processes or components of the engine. Once the complexity of the parts and the time crunch were better understood, we decided to focus the animations to four videos. The flowchart, used as our layout drawing, of these videos can be seen in Appendix G. These videos include the engine running in its entirety, the engagement and disengagement of the clutch, the functions of the slide valve, and the workings of the main auxiliary components that drive the slide valve.

The main video describing the overall function of the engine wasn't completed. Due to the complexity of some of the individual components such as the slide valve and clutch, time was focused on constructing the videos for these. The overall running of the engine is more easily understood and was left to do last if we had time. Our plans for the video was for it to be an overview video of the entire engine running. This video would be zoomed out so the whole engine can be seen. The uniqueness of the power stroke, driven by the atmosphere, would be noted and mentioned as the piston falls. It would then pan around the engine, highlighting the main components that are described in the other animations. These highlighted components will have text written to identify them as they are highlighted. Brief descriptions of the identified highlighted components were kept for the individual system videos.

The first detail video is that of the clutch. This video starts with everything stationery. Text labels come up to name and describe all the different parts. Once every part has been labeled the rack moves and the outer spur gear is driven backwards. As this happens, labels appear and call out the important motions happening, namely the spur gear rotation, the roller rotation and the stationary core. This is followed by the rack coming back down on the power stroke. Again, text labels appear, calling out the new direction of rotation for the spur gear, how the rollers have been wedged and the core (which is attached to the main shaft) is now being driven. Lastly, the rack slows its descent and the rollers are freed. Text appears to describe how the clutch has now returned to its original state, ready for the cycle to repeat, while the inertia of the flywheel keeps the main shaft spinning.

The slide valve is the next detail video. For clarification, this video starts by disassembling the slide valve and its covers, so that all the parts and ports can be seen, labeled and described by text. With this labeling complete, the slide valve is reassembled against the cylinder base. The slide valve is then put through a full cycle, with a text description of all the opened and closed ports and all other relevant activity occurring at the slide valve, such as intake and combustion. Particle flows and flame effects were planned to be used to further demonstrate where air and fuel are flowing, and where combustion is occurring, however the complexity of blender made this a tough feat to accomplish. This is something that if added would definitely enhance the video quality.

The valve train that controls the valve and fuel flow systems is the last detailed video. This video was not completed due to time constraints. As a recommendation to those that would like to animate it in the future, the planned animation is detailed as follow: This video would start with the auxiliary shaft spinning, and have text appear to describe how the gear on the end is driving the auxiliary shaft off the main shaft. When this is complete, the rack would be lowered enough that it strikes the activation lever, engaging the pawl on the eccentrics that drives their motion. Several processes happen in a very short amount of time, so the video would be played in slow motion, and likely more than once through. Again, text would appear to describe what is happening, and call out the important steps in this sequence. With the pawl engaged, the eccentrics would be allowed to run through their rotation. Text would highlight how the two eccentrics are interlinked. The text would also detail how one eccentric is connected to the pushrod, which controls the slide valve, and how the other lifts the piston for intake with its attached lever. An actual description of how the slide valve works was saved for the slide valve video; however, notes on how the eccentrics control its motion and what occurs at each height would be given. Multiple angles would be used to give a better visualization of all the motions and the connections between them.

In an effort to show our direction in how the animations will be displayed, we developed a mockup of the small screens, which can be seen in Figure 5. These detail videos will cover the topics presented in the storyboard, and would revert back to the home menu after the video ended. To allow for more user interaction, videos will include some video playback control options. The videos were audibly narrated and supported with text.

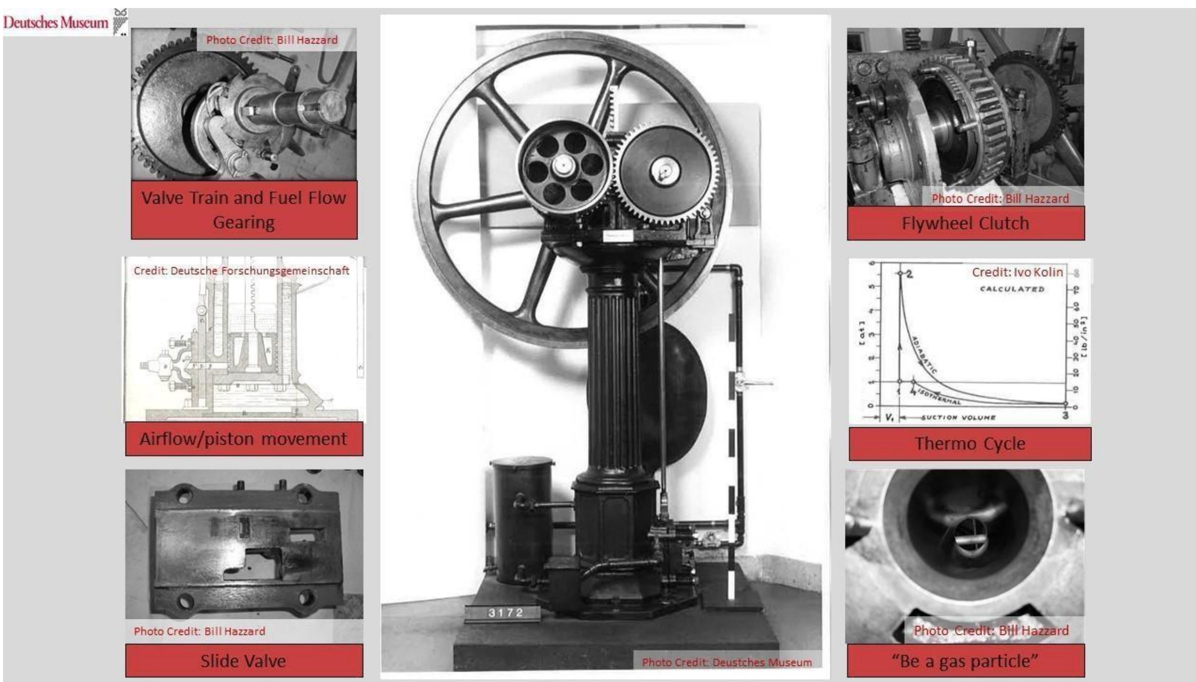


Figure 5. Potential selection screen proposed for the small interactive display screens, using photographs taken of a similar engine [3].

During an analysis of failure modes of the animations (FMEA), seen in Appendix L, we identified certain aspects of the videos that may be problem areas. We kept these known failure modes in mind as we developed the animations to mitigate them and their consequences. A few of them include brightness issues, glitches, legibility, and synchronization issues. These failures may lead to such things as user confusion, inaccurate representation of what's actually happening, and a poor end product that doesn't achieve our set goals. To prove that we met our end goals, we had a wide spread of test subjects view the videos and give their verbal input on the certain failure mode criteria we established.

Supporting Analysis

In anticipation of the final animations, we composed smaller specific scenes to prove our ability to accomplish various movements and effects. Based on the final animations mentioned in the Functional Description, we identified particle motion, fire/smoke, and gear interaction as essential components. Before the final engine assembly was completed, scenes demonstrating each effect were constructed as a form of practice and further understanding Blender's capabilities. During our learning experience with Blender, we utilized a Blender guide, which can be seen in Appendix J.

In order to accurately show the slide valve's operation, we used several views to capture each port's function. Seeing that the geometry and timing involved with this specific part is rather intricate, we developed the idea of following a gas particle as it travels through the valve. Unfortunately, due to time constraints, we were unable to realize this idea, but Figure 6 is a scene used to demonstrate the intended motion.

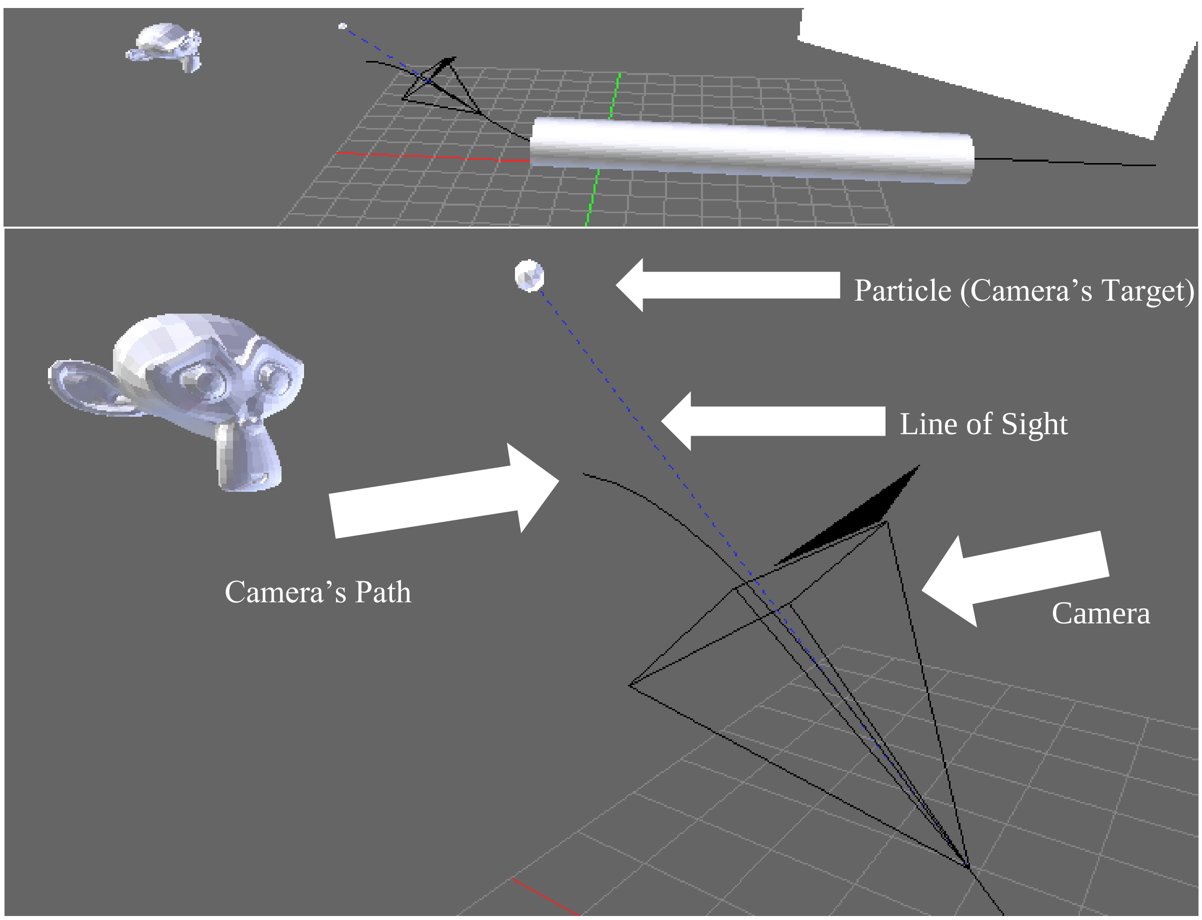


Figure 6. Particle path with trailing camera.

As seen in Figure 6, the camera is attached to a curved path which it will follow at a specified speed. The scene begins with the camera and particle at the rightmost side of the tube. From this starting point, the two travel through the tube until they reach their final destination with the monkey head in the camera's view. This scene could be played out in one of two ways in a slide valve’s animation:

1) The particle shown in Figure 6 can be made visible and the camera can follow along.
2) The particle can be made transparent such that the particle is invisible to the camera, achieving a point of view experience.

The reason the particle must remain in place in both options is that the camera must target an object to follow as it travels along the path. Although the monkey head is the final destination and camera view, it cannot be the camera’s target. If it were made the target, the camera would point in the head’s direction during the entire video. This would result in displaying the top of the tube as opposed to looking down to the next opening. Additionally, the path upon which the camera and particle travel can be manipulated in all directions giving the freedom to travel in any direction necessary.

In addition to using the particle to demonstrate the slide valve, we also considered using a flame feature to simulate the pilot light, but again ran out of time to implement. Blender has an internal feature that can be used to create a smoke/flame effect emitted from an object. In Figure 7, an object is placed in the Blender scene with a "Smoke Domain" added to control the smoke and fire emission. Changing the object's shape or the smoke domain's dimensions will change the direction and behavior of the smoke and fire emission. Furthermore, smoke and flame rates can be adjusted as well as the emission density.

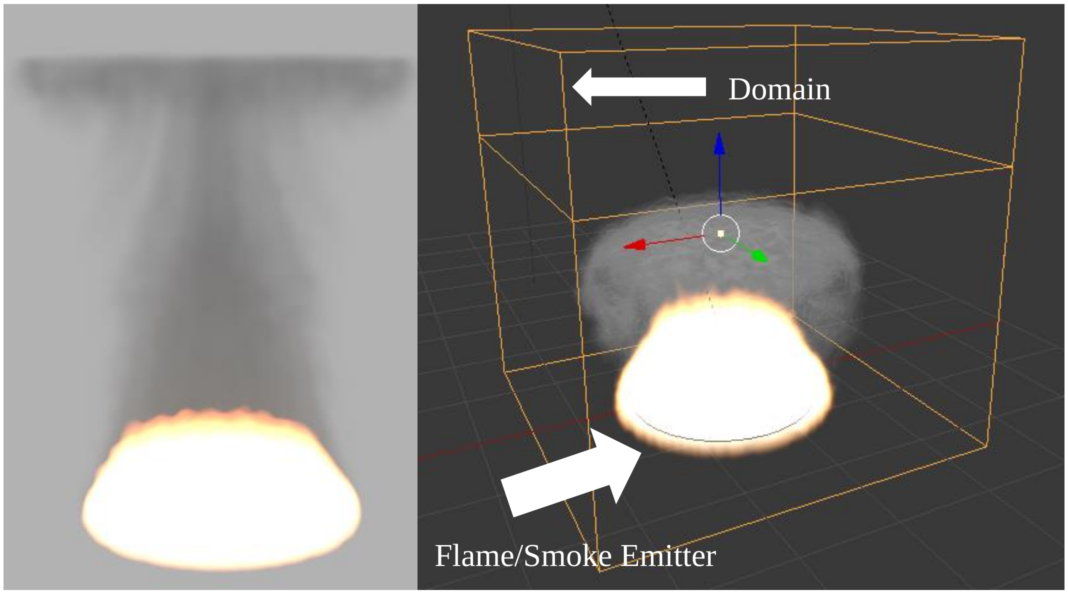


Figure 7. Smoke and flame emission, using an object and domain.

Another important area that we sought to model was the valve train of the engine. The engine is constructed in a way that a larger, main gear drives a smaller, auxiliary gear. The auxiliary gear's attached shaft is the driving component for the valve train. This an important area to analyze within our simulation, as the valve train makes the engine unique. In order to animate the two gears, we used constraints within Blender. There are two constraints that we studied for the gears. The first constraint is called "Copy Rotation," which works best for two gears with an equal number of teeth, or for two gears that begin the motion with the smaller gear driving the larger gear. Copy Rotation links the two gears together by adding the constraint to the driven gear and selecting the driving gear as the target gear. The Blender screen for this process can be seen in Figure 8, where the pink gear (driven) is constrained to the grey gear (driving). There are several other important factors that must be known within this constraint, which all appear in Figure 8. The screen shows all three spatial coordinates, where the z-axis is the only one selected, due to both gears rotating about the z-axis. It is also extremely important to select the "Invert" box, which allows the gears to spin in opposite directions as they should. The final factor of importance is the "Influence." The influence is used to change the amount of rotations the smaller gear goes through within one rotation of the larger gear. As you can see in Figure 8, the influence is set to a value of one, due to both gears having an equal number of teeth. If the driven gear had twice as many teeth as the driving gear, then the influence would be set to one-half, which means that the large gear can only rotate half of a full rotation within a full rotation of the small gear. Essentially, the large gear is rotating at half the speed of the small gear.

The Copy Rotation constraint allows fluid motion and greater accuracy of the gear relationships within the animation; however, this constraint cannot be used for two cases. The first case occurs when a large gear drives a small gear. This case causes the influence, as discussed above, to be greater than one due to the driven gear needing to rotate more than once within one rotation of the driving gear. Blender does not allow the influence to be greater than one, making this constraint impossible for the given circumstance. The second case occurs when the influenced gear has more than twice the number of teeth compared to the driving gear. Blender's influence factor converts fractions to their decimal approximations, such as the fraction ⅓ to 0.333 instead of the actual fraction or repeating decimal. This value is inaccurate and could lead to the simulation becoming out of sync in a longer animation.

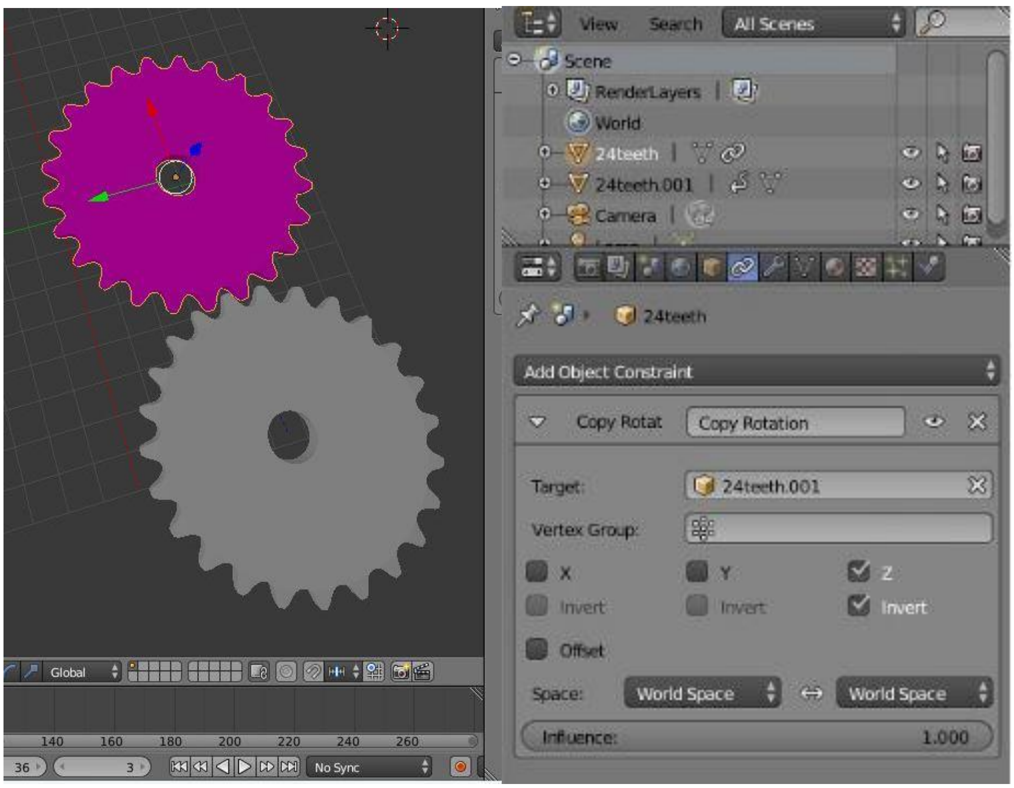


Figure 8. Blender constraint, Copy Rotation, used on gears.

These two cases lead us to study the second constraint, called "Transformation," which can create proper constraints for the gears without these adverse effects causing any problems within the animation. The Blender screen for this constraint can be seen in Figure 9. Similar to the Copy Rotation constraint, the driving gear is selected as the target. Our goal is to take the rotation from the target gear and give it to the driven gear, which is accomplished by assigning the "Source" as rotation ("Rot"). We then have to decide when we want to start taking the rotation from the target which, in our case, is immediately; therefore, under the z-axis the "Min" is set to zero. The "Max" decides when we want the driven gear to stop taking the rotation. In our simulation we never want the driven gear to stop if the driving gear is rotating, so it is set to 360°. This allows a full rotation to continuously occur in the animation. The "Destination" (driven gear) must also be selected as rotation, with the minimum set to zero for the z-axis. The maximum of the z-axis is more complex for gears of different sizes. For our Blender screen in Figure 9, the maximum is set to negative 360°. The negative sign tells the driven gear to spin in the opposite direction of the driving gear, since there is no invert box to be selected. The maximum is set to 360° because the two gears have the same number of teeth, so they will complete one full rotation simultaneously.

As discussed previously, the Copy Rotation constraint does not allow a large gear to drive a small gear, but the Transformation constraint does. In order to allow a large gear to drive a small gear, the maximum value of the z-axis must be a multiple of 360°, depending on how many rotations the driven gear must complete in one revolution of the driving gear. For example, if the driving gear has 16 teeth and the driven gear has 8 teeth, then the maximum would be set to 720° to allow two full rotations of the small gear during one rotation of the large gear. The Transformation constraint also allows greater accuracy with fractions. This is achieved by setting the driven gear's maximum value to the product of the gear ratio multiplied by 360°. For example, if the driving gear has 8 teeth and the driven gear has 24 teeth, we would expect the large gear to rotate one-third of a full rotation for every revolution the small gear undergoes. This calculation would make the maximum value for the z-axis of the destination (driven) 120 degrees. The final noteworthy item within the Transformation constraint is the "Extrapolate" box, which allows the driven gear to constantly take rotation, rather than stopping and taking it at a certain point in time. This box must always be selected to achieve a valid animation.

Since the valve drive gear system in the engine consists of the small gear driving the large gear, we could use either constraint method. However, the driving gear has 50 teeth, while the driven gear has 56 teeth. Although the driven gear does not have more than twice the teeth of the driving gear, the fraction may not be interpreted properly by the influence within the Copy Rotation constraint. For our given system, we are more likely to succeed using the Transformation constraint.

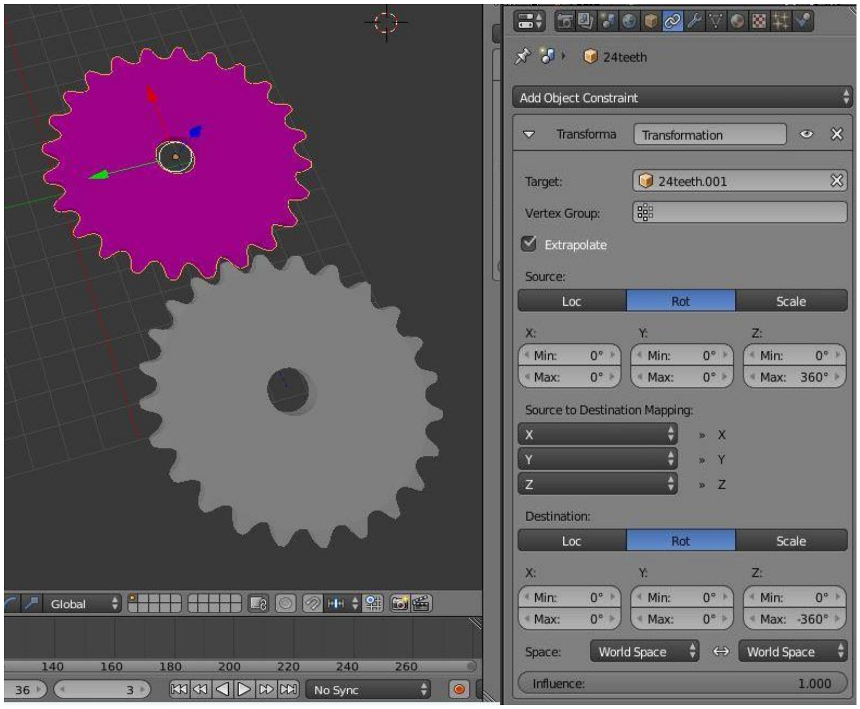


Figure 9. Blender constraint, Transformation, used on gears.

Safety Considerations

Even though this project consists of only virtual animations, safety considerations are always something that need to be examined. A Failure Mode Effects Analysis matrix was constructed to analyze possible failure modes of the product and the effect they would have on the end user. This matrix can be found in Appendix L. As can be seen in the appendix, a safety section was constructed. Although many of the safety considerations only apply to the physical exhibit, there were still some avenues of safety that were considered while developing the animation sequences. These videos are detailed and could require a large amount of computation power. Trying to keep this at a minimum will lessen the power load needed, therefore reducing the heat generated. A more direct avenue of safety concern is with the animation itself. If the animations fail due to glitching and flashing, it may cause a viewer with epilepsy to have a seizure. We designed for this by avoiding unnecessary complexity in the animations to reduce the risk of glitching. The other areas of safety concern seen in the FMEA will be presented to the museum when constructing the exhibit with possible recommendations (i.e. do not run the engine backwards as it could draw in a full stroke of gas and explode). In order to further prove that all safety considerations have been entertained, a safety hazard checklist can be found in Appendix K. During this testing, no seizures occurred.

Explanation and Justification of Material Selection

Much like a physical project has many different materials to choose from, ranging from silly putty to high strength titanium alloys, there are many different software packages that could have been chosen to create the solid models, animations and final videos. Which platforms were chosen was based on price and availability, as well as its abilities. Any 3D modeling program could be used to create the engine parts. However, as mechanical engineering students at Cal Poly, SolidWorks is a free program, and we are very familiar with creating 3D objects via its parametric approach. Blender does have the ability to create 3D objects itself, but in the time it would have taken for the team to learn how to make the complicated geometries of the engine, the entire engine could have been modeled in SolidWorks and imported into Blender. Thus, to save time, SolidWorks was the program chosen to produce the part models.

For animating the engine, again, several options presented themselves. SolidWorks itself has an animation interface, but Dr. Owen's past experiences with other senior project groups working alongside the Deutsches museum indicated other resources should be explored. He had come across Blender as an alternative to explore. Blender is a free, open source graphics software with professional quality, used to produce feature films, video games, and other graphics. As such, we had no doubts that Blender, in the right hands, could be used to create the animations the museum desired. What we needed to verify before we chose to neglect SolidWorks' animation interface was that even in our inexperienced hands Blender could be used to create a high quality, accurate animation in a reasonable amount of time.

The first test of this was to compare the render quality of SolidWorks and Blender. Using parts from a past project animating a clock mechanism, both photo (see Figure 10) and video renderings were made of the regulator mechanism, and compared for quality.

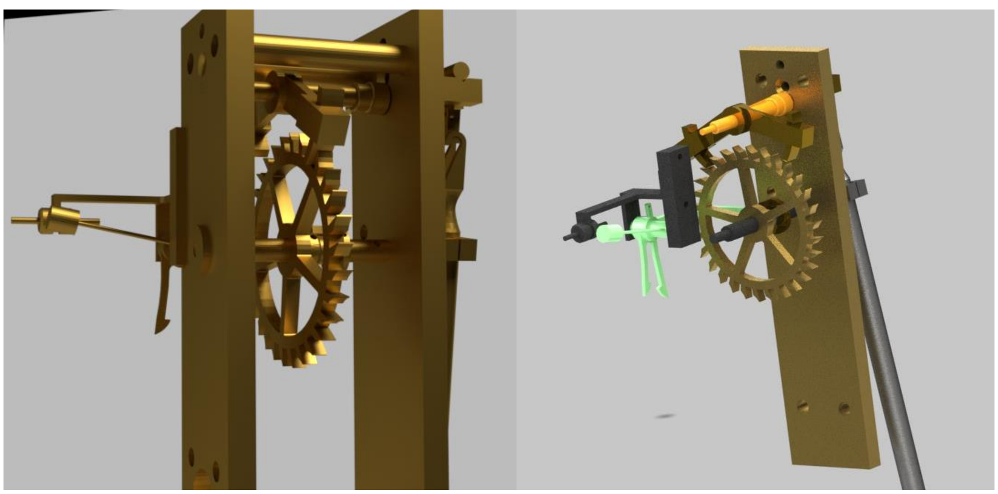


Figure 10. Comparison of renderings produced by Blender and SolidWorks. Blender is on the left; SolidWorks is on the right.

From this comparison, it was determined that Blender produced a higher quality rendering. The SolidWorks rendering was still of passable quality; however, the ease of animation became the determining factor in whether it was worth moving into a new program in order to animate. SolidWorks as an engineering design tool comes equipped with a better set of tools for manipulating mechanical parts and creating their interactions; however, the constraints within Blender can be easily adopted to serve the same functions. Where the two differentiate is in creating more irregular motion. SolidWorks and Blender can both utilize key frames, in which the user specifies a specific object location or orientation at a specific time, and then the computer creates a path between the two points. However, driving repeated motions using key frames is tedious and prone to error. The ways that SolidWorks and Blender allow an animator to get around this differ.

In SolidWorks, keeping with its engineering focus, a motor can be added to a part to drive it. This motor can be set to a constant value for regular motion, controlled by a function, or read data from a time series. This time series can be generated by an outside program, such as MATLAB, and loaded into SolidWorks. While effective, and less tedious than creating key frames, this method of producing irregular motion is not very streamlined. All the different motor functions used to animate the regulator can be seen in Figure 11, and the MATLAB code used to create the motor positions can be found in Appendix M.

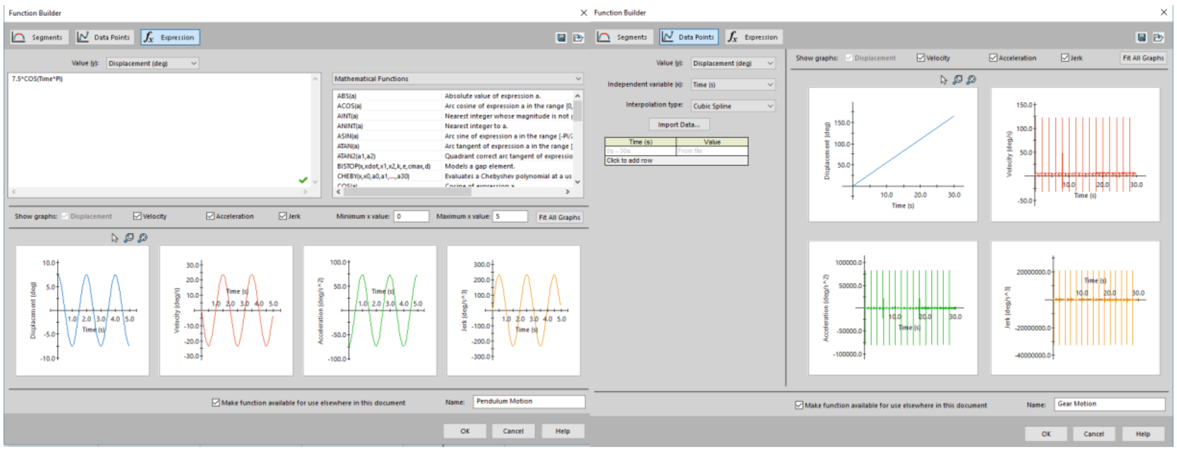


Figure 11. The two motor functions created for the regulator animation. The one on the left is the pendulum motion, created with a simple cosine function within SolidWorks. On the right is the position profile imported from a .csv file created by MATLAB. The code to make this can be seen in Appendix M.

As opposed to the motors in SolidWorks, Blender uses drivers and Python scripts. Blender itself actually runs Python scripts in the background based off the selections made in the Blender interface, and so easily incorporates user created scripts. The easiest way to do this would be to put simple Python functions into the different fields you want to change, creating a driver. This behaves very similar to the two constraints explained earlier. For even more control, an entire script can be written and executed within the text editor of Blender. Within this editor you can call upon any variable in the Blender database, and use any Python command you have loaded in the directory. There are likely many ways to do this, but our current preferred method was taken from the Blender Python web page, which utilizes the frame_change_pre list to create a list of functions to evaluate before each frame change [6]. In this way the results are applied to the upcoming frame, and motion is created. A sample script that recreates the motion of the gears created by the Transformation and Copy Rotation constraints, described in the supporting analysis section, can be seen in Figure 13.

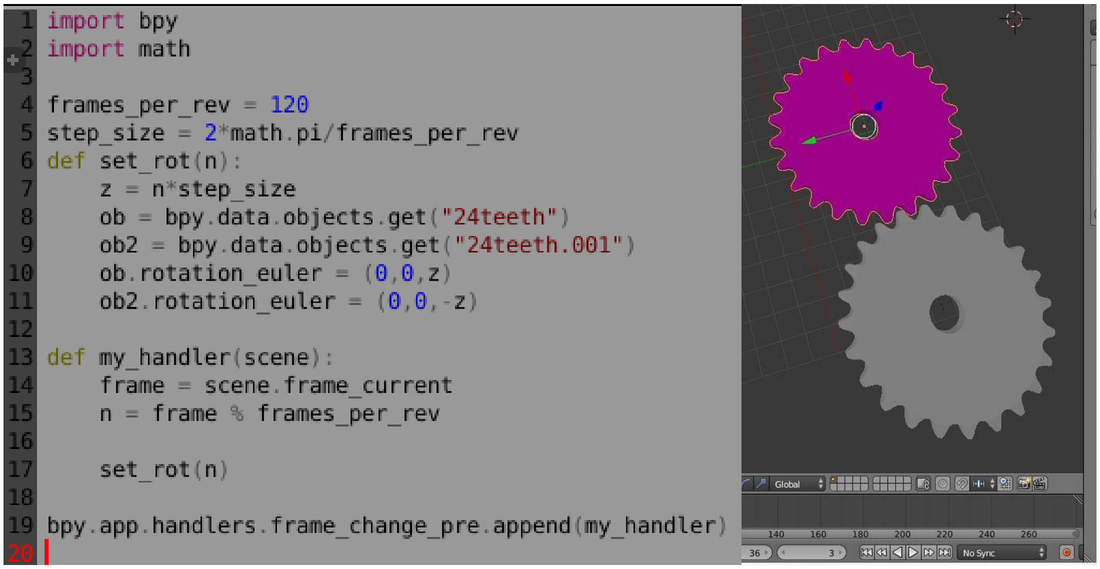


Figure 12. Example Python script written in Blender text editor that drives the two gears.

This ability to control motion via scripts directly in Blender is much more streamlined than writing a script into a separate program and importing the output like SolidWorks requires. This scripting ability, coupled with the improved rendering quality, were reasons why Blender was chosen as the animation engine instead of solely working within SolidWorks.

Fabrication and Assembly Instructions

Due to the heavily digital nature of this project, the fabrication and assembly processes used were not the conventional physical types, but instead methods of creating the digital media necessary for the animation. The first step was transferring the physical parts at the Deutsches Museum into virtual components. To do this, the museum and Dr. Owen provided photographs and hand sketches of the components with dimensions, as shown in Figure 13.

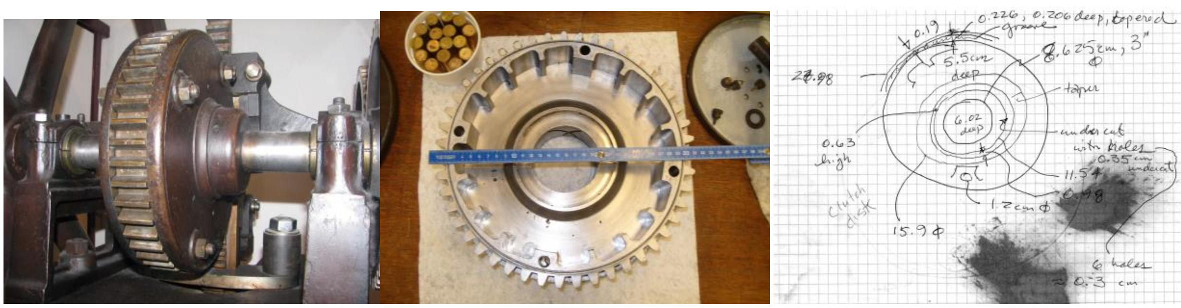


Figure 13. Pictures provided by the Deutsches museum of the clutch, and one of Dr. Owen's sketches of the clutch

These dimensions were then taken into SolidWorks to create a 3D computer model of the physical part. For verification, a 2D drawing very similar to an engineering drawing was created and sent back to the museum to verify that the sketches were interpreted correctly and the solid model closely matched the existing part. Depending on the part, the modeler might also have highlighted areas that they were unsure about to get more information. Dr. Owen then responded with clarifications until the model and part are in agreement. Additionally, parts were organized and cataloged in the Bill of Materials (BOM) after they are constructed, which can be seen in Appendix H. This sequence can be seen in Figure 15, and all the current drawings can be found in Appendix I.

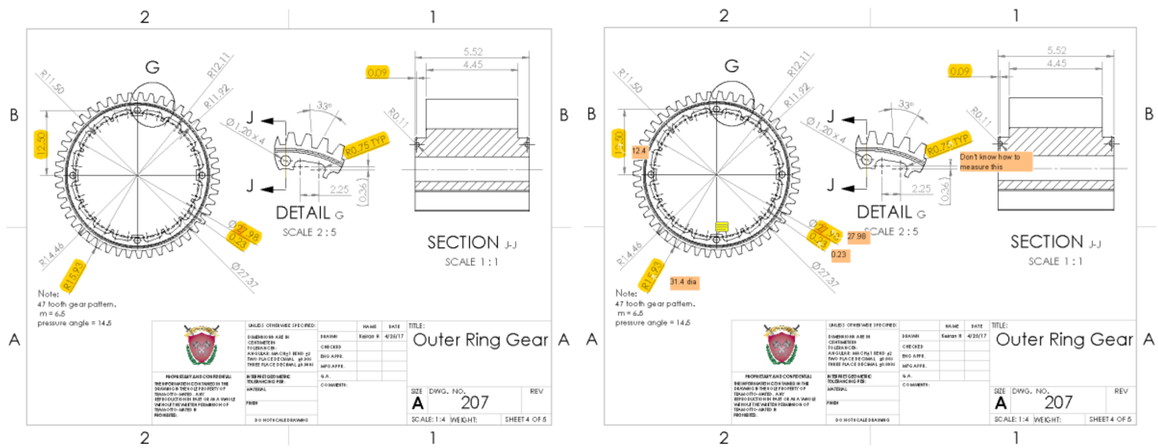


Figure 14. SolidWorks drawing files, where the one on the left was based off Dr. Owen's hand sketch, while the one on the right shows Dr. Owen's comments and necessary corrections.

As another check, once the models were created, they were assembled within SolidWorks. Being based on a real assembly, all of the holes, shafts and gear teeth should match up. When they didn't, the parts were investigated for possible modeling errors, or adjustments were made to the dimensions to bring them in line with the design intent. These assemblies and subassemblies were exported directly into Blender, so it was worth modeling with precision to produce quality animations. Continuing the example given above, the assembled version of the clutch can be seen in Figure 15.

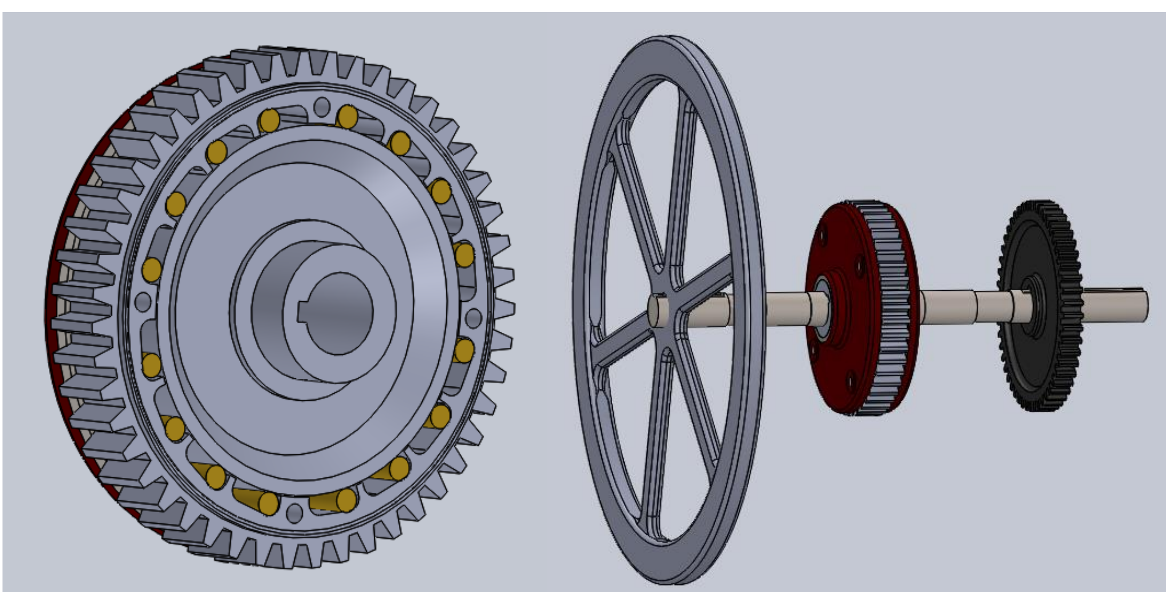


Figure 15. The clutch assembly and main shaft assemblies created in SolidWorks.

Concerning what happens to the parts after their creation in SolidWorks, the parts needed to be saved in a file format that is compatible with Blender. Fortunately, Blender accepts .STL files which are easily created in SolidWorks' "Save As" menu. The most efficient way to import parts into Blender was in their final assembly since geometric and locational mates held during the transfer. After the import, the assembly was oriented appropriately and part origins were reassigned where necessary. The final step before animation was to group subassemblies and set "parent" parts. Creating groups with parented parts makes it possible to move entire subassemblies by animating a single part, or the parent part.

Once the assembly was oriented and the subassemblies grouped, the parts were set into motion. The most basic way to create motion is through the use of key frames. Keyframes allow the user to locate, rotate, and scale parts over a specified amount of times. One of Blender's many perks is its ability to create motion through pre-configured motion curves. The most commonly used motion curve is called the Bezier Curve, which provides smooth acceleration and deceleration between set key frames. In addition to the pre-configured motion curves, each curve can be modified to achieve the desired effect. In Figure 16, Blender's animation window is shown displaying multiple key frames along with an example of a locational key frame being set. Once a keyframe is set at a given frame (i.e. the keyframe at frame 24), the object for which the key frame is being set can be adjusted into its desired orientation. Blender then interpolates between key frames 0 and 24, creating motion between a set initial and final orientation.

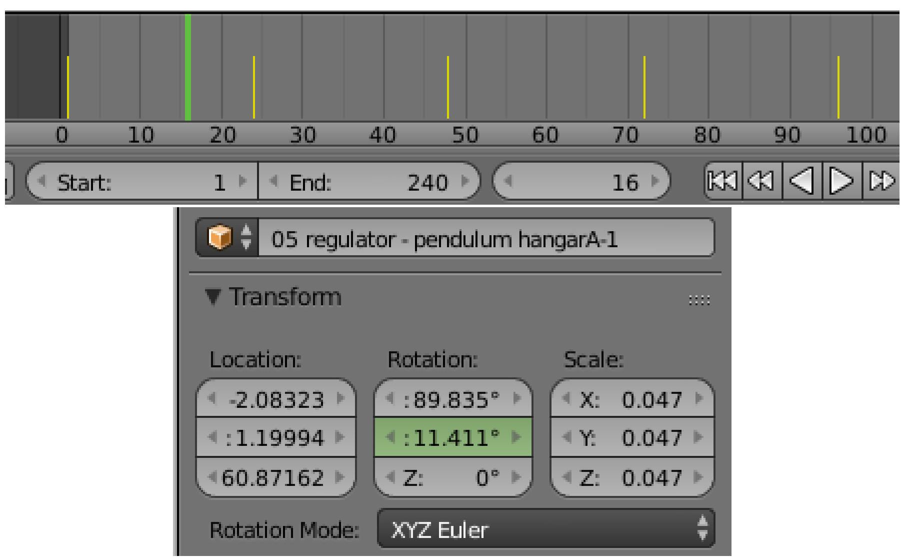


Figure 16. Top: Blender animation window illustrating the use of key frames.
Bottom: Key frame transformation window.

A crucial step within the animation is proper lighting. In order to provide a realistic animation, the objects must have light and cast shadows that differ when the camera view is altered. Blender has many variations when it comes to lighting, but we discovered a light setup within Blender that creates ideal lighting and shadowing. The light setup contains three important components including: a backdrop, sun lamp, and plane. A Blender scene that utilizes these three components can be found in Figure 17. This setup may be referred to as a “three-point lighting” setup, which is commonly used in photography studios and product visualizations. During this setup, “Cycles Render” must be selected at the top of the screen. The first step for the lighting setup is creating a backdrop for the object that requires light, in our case the engine and engine components. A backdrop can be easily created in the Blender screen by adding a plane and extruding the backing, as shown in Figure 17. Once the materials have been adjusted accordingly for the object, we can then add a sun lamp to the scene. The sun lamp is the main source of light and emits light with a constant intensity in a single direction. Its purpose is to emphasize the object and outline the object’s shape, while producing the main shadow. Sun lamps are located outside of the scene and considered to be infinitely far away, where their angle/direction matters instead of their position. Figure 17 shows the sun lamp as the highlighted dotted line going through the clock regulator. Depending on the object and its necessary lighting, the sun lamp can be positioned at varied angles and the size and strength can also be adjusted accordingly. Reducing the lamp size results in sharper shadows, while increasing the size will create softer shadows and shading. Adjusting the strength of the lamp changes the light’s energy and is typically set to a lower value. The final component of the lighting setup is the additional plane. This plane acts as a surface that emits light onto the main object, adding illumination to the unlit areas of the main object and evening out the shadows. This can be achieved by positioning the plane adjacent to the sun lamp and angled towards the main object, as seen in Figure 17. The plane’s material must have an emission shader selected and the size of the plane can also be scaled as necessary to increase or decrease the strength. It is important to note that, while it is an ideal form of lighting, this lighting setup is highly graphics intensive and will cause an exponentially longer rendering process. For simplicity, and a satisfactory outcome, it is also possible to solely use a hemispherical lamp with an angle of 45° from the z-axis.

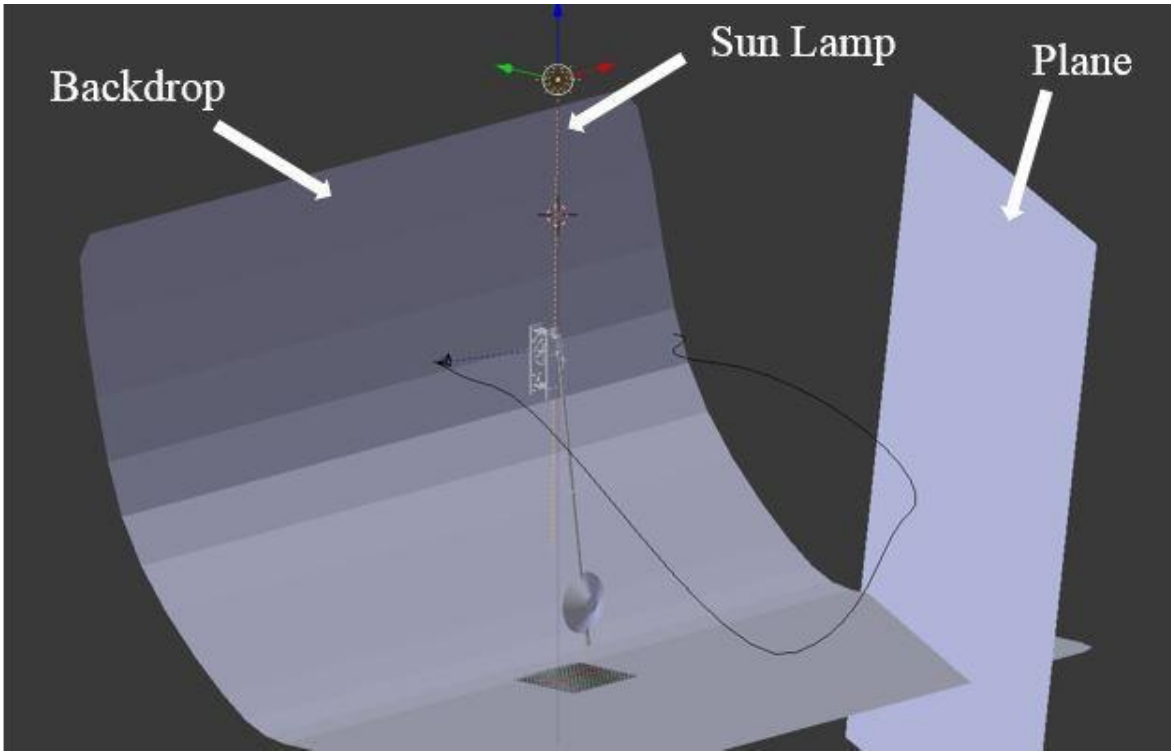


Figure 17. Blender screen, showing the three-point lighting setup.

Concerning the rendering process, it is worth revisiting the topic of Cycles Render. Cycles Render is a relatively new feature to be added to Blender’s arsenal, and is considered to be a major improvement over the already existing internal rendering engine. The new and improved rendering engine excels in creating realistic lighting and shading. Cycles is not only capable of simulating direct lighting, but also reflective lighting while the internal rendering engine cannot. Since reflective lighting is one of the most important factors in creating a realistic scene, the backdrop and light emitting plane become crucial pieces in adding to this realism. Further along the lines of reflective light, Cycles Render has a wide range of adjustment that allow lighting to be tailored to each scene. The most significant adjustment within the lighting options is the amount of path tracing samples. A path tracing sample refers to how many calculations Cycles performs with regard to each ray of direct and reflective light. Cycles default setting is to take 128 samples during rendering; however, we have found that 500 samples provides ideal quality. For the sake of this project's time constraint we used the default number of path tracing samples as opposed to the 500. Just as the lighting setup in Figure 17 increases rendering time, using 500 samples instead of 128 will also exponentially increase rendering time. Additionally, the Cycles rendering engine must be told that shadows, reflective caustics, and refractive caustics are needed in a scene. These settings can be seen in Figure 18. which are located under the render settings in Blender.

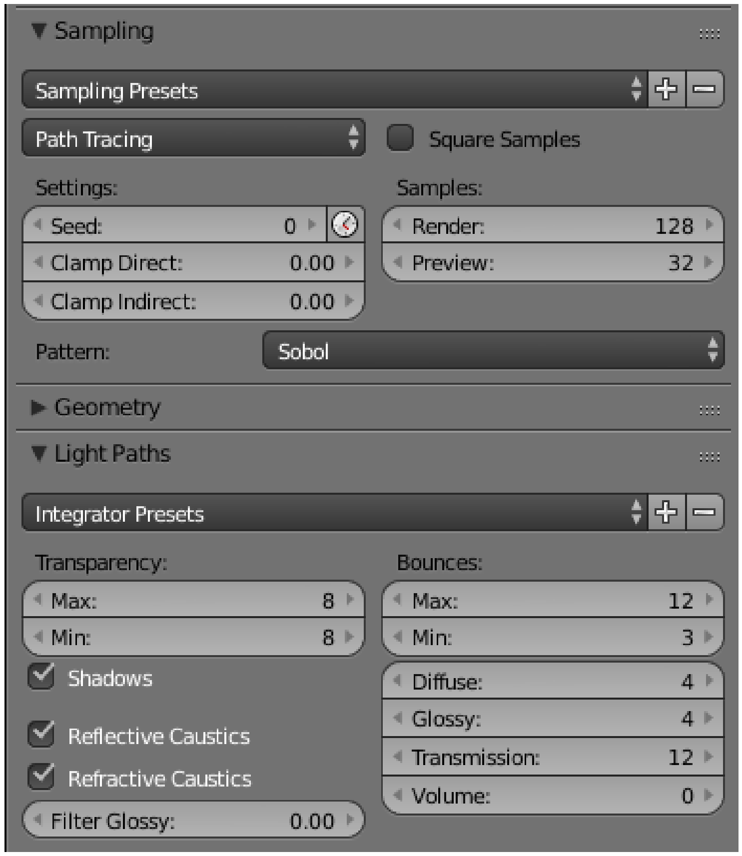


Figure 18. Cycles Render lighting settings found under the render settings tab.

To illustrate the Cycles Render final product, we applied the above settings to the clock regulator mentioned in the Background section. The regulator's final animation utilizes rendered still frames in .PNG format, which are strung together using Blender's ability to interpolate between frames. The still frames are then compiled into a .AVI file for a video output. After animating and rendering the regulator, the final result of a still frame can be seen in Figure 19.

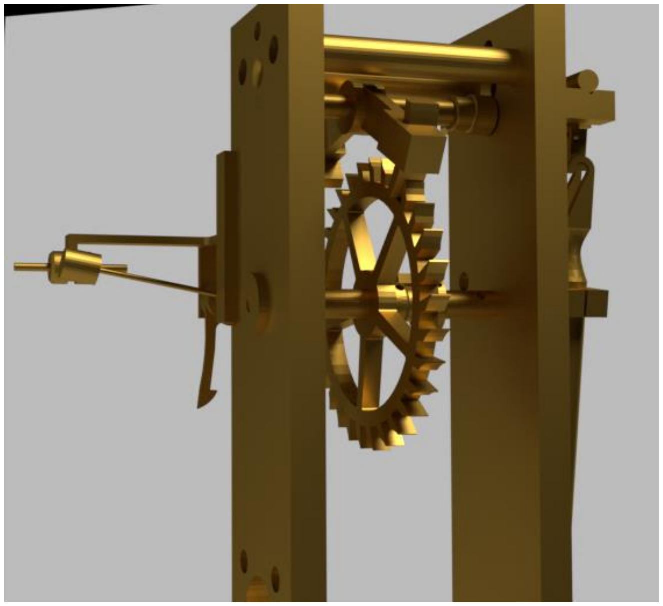


Figure 19. Clock regulator after final lighting and rendering process.

Considering additional rendering and material techniques, Cycles Render offers a materials editing system known as a Node Editor. The Node Editor allows for materials to be key framed and for transitions such as color gradients or transparency. We found the transparency gradient to be especially useful in cleanly removing parts from the engine. In Figure 20, the Blender Node Editor is pictured.

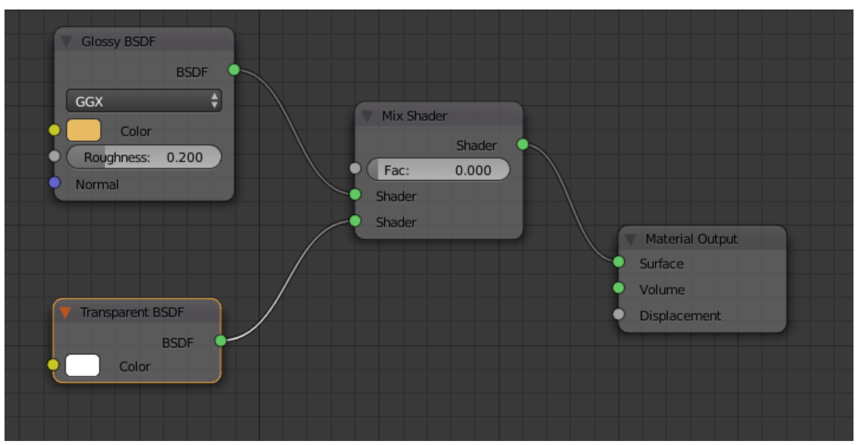


Figure 20. Node Editor available only in Blender's Cycles Render.

Note that the following nodal network includes the follow nodes:

1) Glossy - material surface finish selection with a specified surface roughness
2) Transparent - allows for transition to transparency
3) Mix Shader - takes the input of material surface finish and transparency
4) Material Output - sends input to blender interface

This material transition was specifically on the slide valve cover which is illustrated in Figure 21.

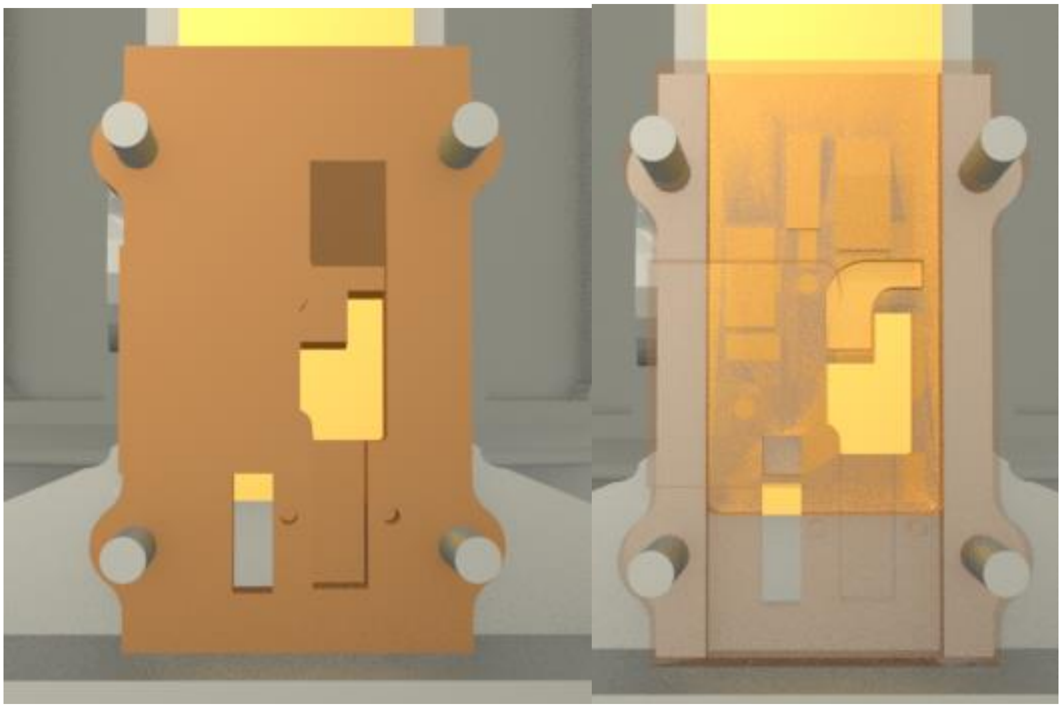


Figure 21. Transparency transition utilized on the Slide Valve Cover.

Initially, we intended to use the same transparency process on the slide valve to show the ports behind it; however, we could not overcome issues with shadowing and other material defects. As an alternative, we found it more effective to insert a still frame of the labeled ports in between videos of the slide valve performing its intended function.

<u>Maintenance and Repair Considerations</u>

An advantage of having a project based in the digital world is that it is not prone to mechanical failure and has minimal maintenance considerations. However, to make this project usable for more than a few years, or upgradeable, an effort was made to allow our project to be brought into any new software or file format used in the future. Given the rapid rate of change in technology, especially in software, file storage, and memory, it is hard to predict what the future holds. However, we attempted to make it easier for our project to be brought up to speed. We have provided the museum with not only the most polished version of the videos we have created, but also all the files used to create it, from SolidWorks models all the way to Blender and AVI video files. Hopefully, with all these files, they will be able to easily recreate our videos even if the video itself cannot be modernized. This would also provide a backup in case the files become corrupted or accidentally wiped.

All technical information of the files, locations, and their interactions were conveyed to Dr. Owen so he could act as a steward of the project and support the museum as the exhibit is constructed since it will not be put into service until 2018. The files were all organized for easy access.

Detailed Cost Analysis

Since our project is unique in comparison to other current projects, we analyzed cost based on time spent creating models and animations. Our time-cost analysis was based on the following categories:

- Parts modeling
- Parts imported into Blender with correct orientation
- Object animation
- Lighting and materials selection
- Rendering
- Video Editing

The time spent simulating the clock regulator can be seen in Table 3. Based on our experience with blender at the time we extrapolated time values for the Otto Engine. Note that times are approximated from initial parts modeling to the final videos. After tallying hours at the end of the project, our estimate was slightly off since actual hours totaled to approximately 325 hours.

Table 3. Time-cost analysis for clock regulator and Otto Engine.

Categories	Clock Regulator (hr)	Otto Engine (hr)
Parts Modeling	N/A	90
Parts Import/Orientation	1	1
Object Animations	45	80
Lighting and Materials	15	10
Rendering	15	60
Video Editing	5	25
Total Time	81	266

Management Plan

Each student had a specific responsibility within the group, but we acted as a team sharing responsibilities whenever necessary. We organized our team responsibilities, which can be seen in Table 4. These responsibilities, per team member, changed over the progression of the project, where some responsibilities were added or some shared with other team members. Although each member had their own responsibilities, there were several roles that the group worked on with equal weight. These roles consist of the following: information gathering/research, documentation of project progress (both the final report and individual logbooks), prototype/physical model testing, and active participation during advisor and sponsor meetings. We also created a Gantt Chart, which can be found in Appendix B, that lists individual responsibilities and project due dates throughout the entire year of senior project.

Table 4. Project responsibilities for each team member.

Team Member	Responsibilities
Chris Splees	· Secretary/recorder · Blender animation · Blender fire simulation · Blender camera path
Rachel Jakob	· Primary point of contact · Time/schedule manager · Blender rendering · Blender lighting · Blender constraints
Keiran Hansen	· Travel/material budget · SolidWorks modeling · SolidWorks animation · Blender scripting · Physical model
Lance Hodgson	· Contact for outside resources · SolidWorks modeling · Bill of materials · Video Narration

3D Printing

Once all the parts were modeled in SolidWorks and were being animated in Blender, team members not directly involved in animating the parts had a little free time. In order to take advantage of this free time and to augment the project presentation at the Senior Expo, it was decided to take advantage of the additive manufacturing options at Cal Poly and 3D print certain parts of the engine, specifically the slide valve. Since the solid models already existed in SolidWorks, all that had to be done in order to create a good model for printing was to copy the parts, scale them down and make minor changes to aid the manufacturing process. These modified, scaled parts were then ready to be exported as .stl files and sent to the Innovation Sandbox on the Cal Poly campus.

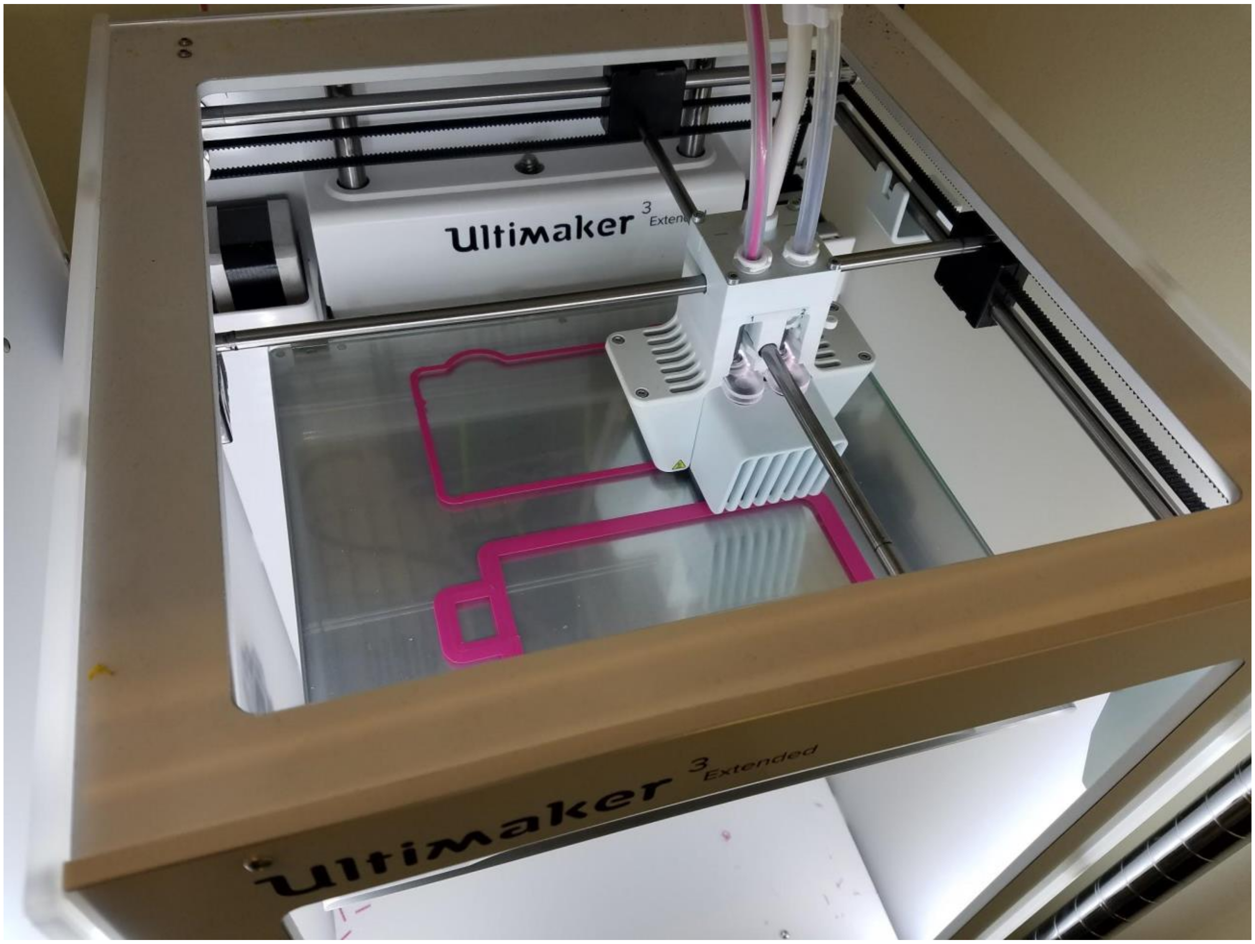


Figure 22: Photo of the slide valve and cover beginning to print at the Innovation Sandbox.

Figure 23: Photo of the completed printed slide valve.

Figure 24: Photo of the slide valve during the painting process.

Once printed, the different recesses within the slide valve were painted to make it clear which recesses were exposed to which ports, and what flowed through that channel. Using these models, we were able to explain the slide valve function in a much more interactive way to visitors at our booth at the Expo, and increase visitor interest. Creating something similar is recommended to the museum and to future projects of a similar nature. Consideration should also be given to making a video using the recreated parts. While not as clean or sophisticated as an animation, walking visitors through the parts and highlighting important interactions among them, and then allowing them to manipulate the parts in their hands seemed very effective at the Expo, and could be recreated by another video to accompany the animations.

Moving Forward

Considering the future of this project, we have designed this project and its documentation to be passed onto Dr. Owen and others who wish to carry on the work. This report entails our methods for animation, desired and executed, that will provide a full understanding of the engine from its combustion to its mechanical function. In order to ensure a clean hand-off, we have compiled all work into a Google Drive which includes: report iterations, video rendering iterations, key engine information, and solid model files. Using the given files in our drive, the project can be carried out beyond the time we were given in our yearlong Senior Project.

Works Cited

[1] Deutsches Museum

D. Museum, “Mission,” *Deutsches Museum: Mission statement*. [Online]. Available: http://www.deutsches-museum.de/en/information/about-us/mission-statement/. [Accessed: 07Feb-2017].

[2] The Complete Guide to Blender Graphics: Computer Modeling & Animation

J. M. Blain, *The Complete Guide to Blender Graphics: Computer Modeling & Animation*. .

[3] Wayne Grenning - Otto Engine Expert

“wgrenning,” *Google Sites*. [Online]. Available: https://sites.google.com/site/wgrenning/home. [Accessed: 07-Feb-2017].

[4] Blender Guru YouTube Tutorials

“Blender Tutorials, Podcasts, Competitions & Products!,” *Blender Guru*. [Online]. Available: http://www.blenderguru.com/. [Accessed: 23-Feb-2017].

[5] Flame Ignition: A Historical Account of Flame Ignition in the Internal Combustion Engine

Wayne S. Grenning, *Flame Ignition: A Historical Account of Flame Ignition in the Internal Combustion Engine*

[6] Blender Python blogspot

Dealgo McArdle. “Python Driven Animation” *Blender Python.* [Online]. Available: http://blenderscripting.blogspot.com/2012/09/python-driven-animaion.html [Accessed: 4-Apr-2017]

<u>**Appendices**</u>

Appendix A. Quality function deployment (QFD)
Appendix B. Gantt chart
Appendix C. Google forms supporting focus group research
Appendix D. Animation storyboard
Appendix E. Initial concept ideas for museum exhibit layout
Appendix F. Pugh matrix
Appendix G. Final animation layout drawing (flow diagram)
Appendix H. Bill of Materials (BOM)
Appendix I. SolidWorks drawings
Appendix J. Product literature
Appendix K. Safety hazard identification checklist
Appendix L. FMEA
Appendix M. MATLAB to create regulator motor profile

ENGINEERING DATA SHEET	Sheet No. A - 1/1	Date: 3/1/17

Appendix A: The Quality Function Development (QFD) matrix.

Relationship Strength: Strong - 5, Medium-3, Weak - 1

Customers and users: Docents, Translator, Elementary Students, Tourists, Engineers, Historians, Maintenance Personnel, Website Interaction, Deaf, Blind, Museum Admin

Company Ratings: Bad 1, 2, 3, 4, 5 Good

Customer Ratings: 1 Bad, 2, 3, 4, 5 Good

Needs: Project requirements and goals (Item No.):
1 Mechanical Detail; 2 Asthetic appeal; 3 History content; 4 coding level; 5 Ease of interaction; 6 Written Description; 7 Fun Level; 8 Physical Accuracy; 9 Size; 10 Cost; 11 Accurate Thermodynamic explanation; 12 Standard, compatible file format; 13 Internet compatible; 14 Multilanguage Compatible; 15

	Specifications: Testing methods	Targets	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Weighted Importance	% Importance
A	Number of Parts	num = num	5	3	4	2	3	2	1	5	3	2	1	1	2	1			
B	Focus Group: Children	60% > Approval	3	4	4	4	4	4	4	2	1	1	2	1	1	1			
C	History Quiz	Avg score >75%, >20% increase	3	2	5	1	1	3	2	2	1	1	1	1	1	1			
D	Visual Appeal Quiz	> 3/5 Stars average	3	5	2	2	4	2	3	2	2	2	1	1	1	1			
E	Function Quiz	Avg score >75%	3	2	3	1	1	5	1	3	1	1	3	1	1	1			
F	Self Check/Analysis	2/4 members evalate/proofread	4	2	3	4	2	3	2	4	4	4	4	2	2	2			
G	Fits in Alotted Space	< dimension given	2	2	1	2	3	2	3	3	5	2	1	1	1	1			
H	Communication w/ Museum	Museum approval	4	4	3	2	2	4	3	5	4	4	3	2	2	4			
I	Thermodynamic Quiz	Avg Score >75% or >30% increase	2	1	2	1	1	3	2	2	2	1	4	1	1	1			
J	Run on Windows, Mac	Test Run on both systems	2	3	2	4	3	1	1	1	1	2	1	5	3	2			
K	Post on YouTube	Post Publicly on YouTube	2	3	1	2	2	1	2	2	3	1	1	4	5	3			
L	Focus group: Engineering students	60% > Approval	4	3	3	2	2	3	3	3	3	1	4	1	1	1			
M	Focus Group: NonEngineer Adults	60% > Approval	3	4	3	1	4	4	3	2	2	1	3	1	1	1			
N																			
O																			
																		0	

ENGINEERING DATA SHEET	Sheet No. B – 1/1	Date: 5/4/17
Appendix B: Gantt Chart		

Quarter:	Winter 2016: January 9th thru March 24							Spring Break
Week	5	6	7	8	9	10	11	0
Task Name	2/6	2/13	2/20	2/27	3/6	3/13	3/20	3/27
Research								
Define Specifications								
Learn/Practice Blender								
Basic Concept Design								
Build Solidworks Parts								
Animate Model								
Physical Model Concept								
Build Physical Model								
Report								

Main Task	**Quarter:**	**Spring 2017: April 3rd thru June 16th**													
	Week	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**0**	**0**
	Subtask	**4/3**	**4/10**	**4/17**	**4/24**	**5/1**	**5/8**	**5/15**	**5/22**	**5/29**	**6/5**	**6/12**	**6/19**	**Summer Break**	
Learn/Practice Blender (Including Clock)	**Interface/Uploading**														
	Detailed Animation														
	Lighting/Camera Angles														
	Materials/Polishing														
Gather Information/Resarch	**Measuremnets**														
	Functions														
Build Solidworks Parts/Assembly	**Slide Valve Components**														
	Clutch and Flywheel														
	Eccentrics														
	Piston and Cylinder														
Animation	**Main Video/Overview**														
	Slide Valve														
	Eccentrics														
	Clutch and Flywheel														
	Rendering														
	Support														
Report															

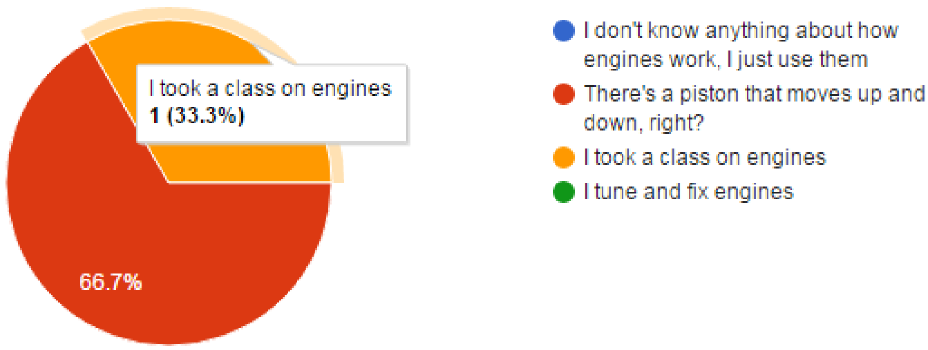
Main Task	Quarter:	Fall 2017: September 14th thru Dec 8th											
	Week	1	2	3	4	5	Break	6	7	8	9	10	11
	Subtask	9/14	9/21	9/28	10/5	10/12	10/19	10/26	11/2	11/9	11/16	11/23	11/30
Build Physical Model													
Animation	Main Video/Overview												
	Slide Valve												
	Eccentrics												
	Clutch and Flywheel												
	Rendering												
	Video Editting												
Report													

Team Member Responsibilities	
Rachel Jakob	(purple)
Chris Splees	(blue)
Lance Hodgson	(green)
Keiran Hansen	(orange)
Entire Team	(gray)

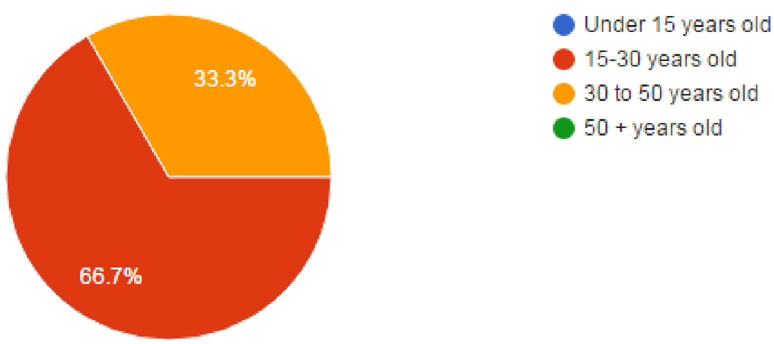
Milestones (Due Dates)		
What	When	Symbol
Project Proposal	2/7/2017	
Preliminary Design Report	3/2/2017	
Final Design Report	5/4/2017	
Final Project Report	11/30/2017	

ENGINEERING DATA SHEET	Sheet No. C – 1/2	Date 3/1/17
Appendix C: Google forms supporting focus group research.		

Which group do you identify with, in terms of engine knowledge (3 responses)



What age range do you fit in? (3 responses)

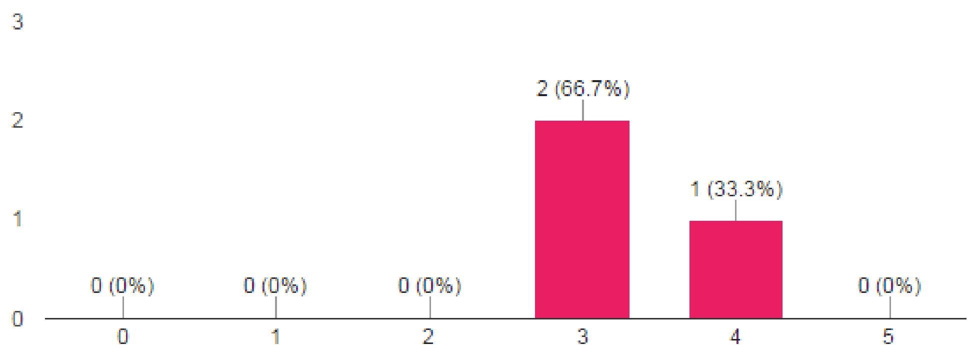


Visit the following link to take the survey:
https://docs.google.com/forms/d/1KRDT1J3ocUJNIszVjBp0snLSOTaktLHJFi69iQqhg3s/edit#responses

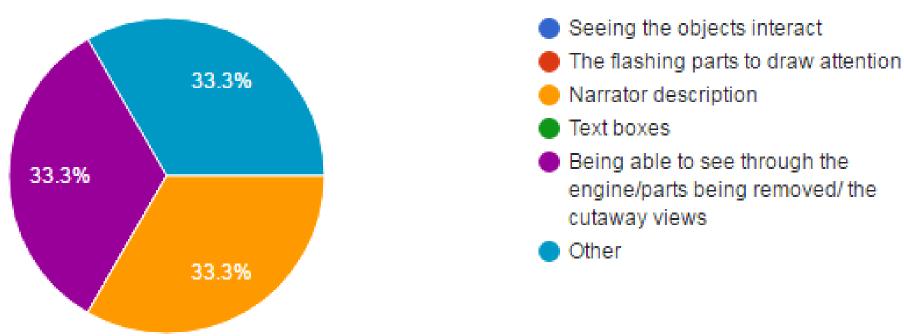
ENGINEERING DATA SHEET	Sheet No. C – 2/2	Date 3/1/17
Appendix C: Google forms supporting focus group research.		

How well did you understand what was happening in this video, on a scale of 0 to 5 ?

(3 responses)

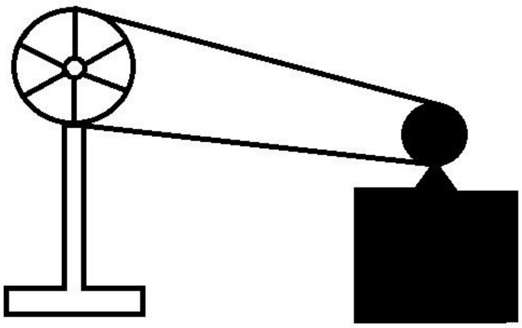


What helped you understand what was happening best? (3 responses)

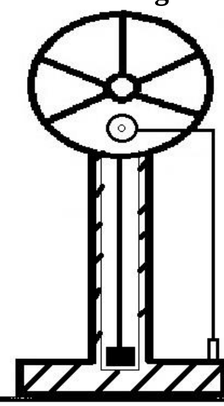


ENGINEERING DATA SHEET	Sheet No. D – 1/2	Date 3/1/17
Appendix D: Animation storyboard.		

1. Overview of the Otto Engine running a device (black box).

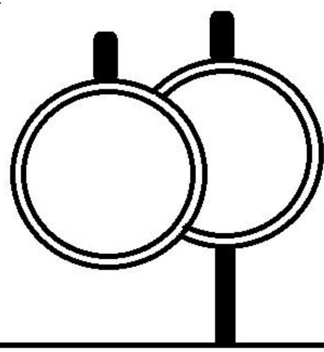


2. Section view of Otto Engine running.



3. Valve train and fuel flow (seen from top half).

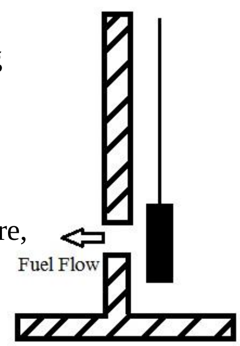
*Visualize gearing that drives gate valve pushrod.



4. Valve train and fuel flow (seen from bottom half).

*Show pushrod driving gate valve.

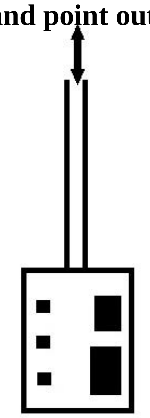
*Show the valve allowing fuel/air mixture, ignition, and exhaust.



5. Focus in on the gate valve and point out key function.

*Show how fuel/exhaust flow through the valve.

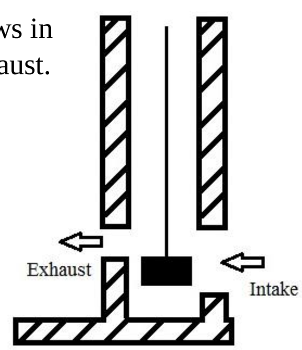
*Fade to valve operating with bottom half of engine.



6. Piston (intake/exhaust)

*Show how piston draws in and forces out fuel/exhaust.

*Include combustion.



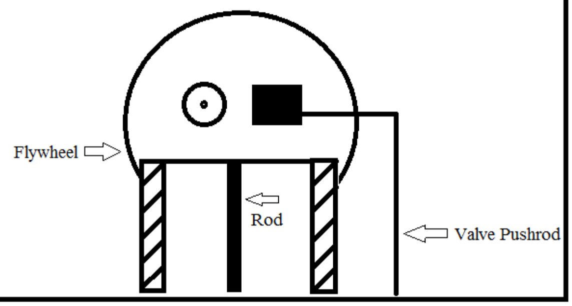
ENGINEERING DATA SHEET

Sheet No.	D – 2/2	Date 3/1/17

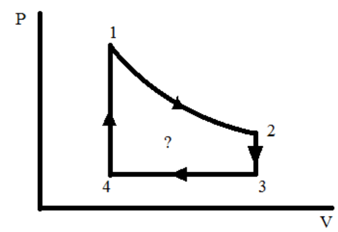
Appendix D: Animation storyboard.

7. Piston rod driving the flywheel.

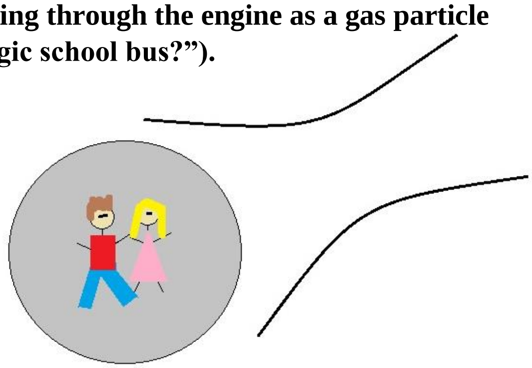
*Order of operation for the gears.



8. Thermodynamics power-cycle.



9. Going through the engine as a gas particle (“magic school bus?”).



ENGINEERING DATA SHEET	Sheet No. E - 1/7	Date: 2/28/17
Appendix E: Initial concept ideas for the museum exhibit layout.		

Concept 1: The "In-Wall" Exhibit

The design of the "In-Wall" Exhibit was based on similar layouts to a "typical" museum exhibit (previous museums that our group has seen throughout our lives). The layout can be seen below in Figure 1. Essentially there would be a large screen behind the actual engine, where animation (1) would be continuously playing. Please see Appendix D for the animation storyboard and corresponding numbers. The actual engine and large screen would remain inside the wall, surrounded by a railing that viewers stand behind. On the railing there would be eight smaller screens that play animations (2-9), as well as a small physical replica of the Otto Engine, which would sit on a rotating pedestal to give the museum visitors a 360° view of the engine. A list of pro's and con's for this concept can be seen below in Table 1.

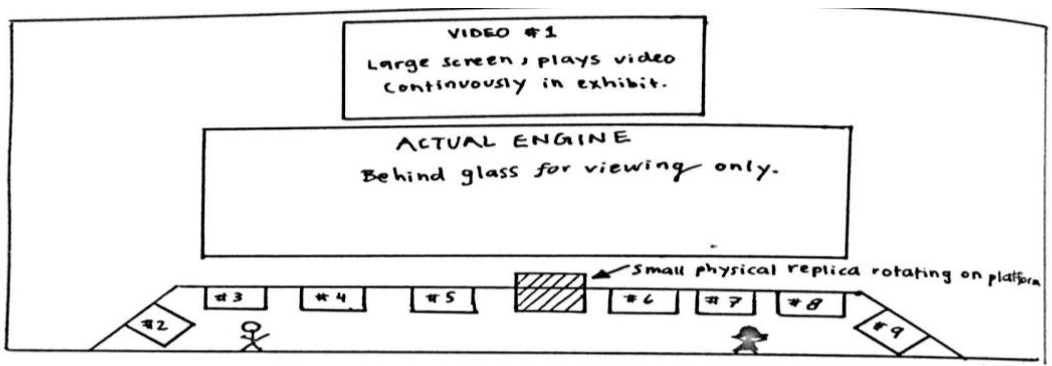


Figure 1. The layout of the "In-Wall" design.

Table 1. Pros and cons for the "In-Wall" design.

Pros	Cons
Keep multiple people engaged	Expensive (many screens)
View exhibit at any time (videos are on loop)	Excess wiring (difficult for setup or fixes)
Small replica is rotating (see entire engine)	Cannot walk around the entire actual engine

ENGINEERING DATA SHEET	Sheet No. E - 2/7	Date: 2/28/17
Appendix E: Initial concept ideas for the museum exhibit layout.		

Concept 2: The “Fun Size” Exhibit

The “Fun Size” Exhibit is an attempt at catering to the younger crowd. This exhibit still includes the engine along with its scaled physical model, but the screens are set lower on the display for children. The exhibit would have a rotating model to show allow for a better view of the parts that make this engine unique. Certain aspects of this design were eliminated right away due to the fact that it caters entirely to one viewer group, but ignores the needs of all other groups. Beneficial aspects of this design include the way it highlights the engine as the centerpiece and the accessibility provided by multiple screens. The layout can be seen below in Figure 2 and a list of pros and cons is also shown below in Table 2.

Figure 2. The layout of the “Fun Size” design.

Table 2. Pros and cons for the “Fun Size” design.

Pros	Cons
Keep multiple people engaged	Expensive (many screens)
View different videos via multiple screens	Screens are too low for adult viewers
Small replica is rotating (see entire engine)	The exhibit is not visible from a distance and will not attract viewers to it

ENGINEERING DATA SHEET	Sheet No. E - 3/7	Date: 2/28/17
Appendix E: Initial concept ideas for the museum exhibit layout.		

Concept 3: The "Central Display" Exhibit

The "Central Display" Exhibit was designed with accessibility, viewer attraction, and engine visibility in mind. As the concept title implies, this exhibit is designed to be in the center of a room with viewing screens available on all sides, which is shown below in Figure 3. While there aren't as many screens available as the "In-Wall" Exhibit, this design still has four viewing screens available for watching specific engine cycles. In addition to the four viewing screens below the engine, there will also be large, jumbo Tron-like screens playing a looping video of the engine performing usable work. This way viewers will always have a video to watch even when the lower viewing screens are occupied. Concerning the engine itself, it will be visible from all angles and accompanied by a scaled physical model. The "Central Display" Exhibit is highlighted by its ability to be seen from all sides and its ability to attract museum goers from a distance. A list of pros and cons can be seen below in Table 3.

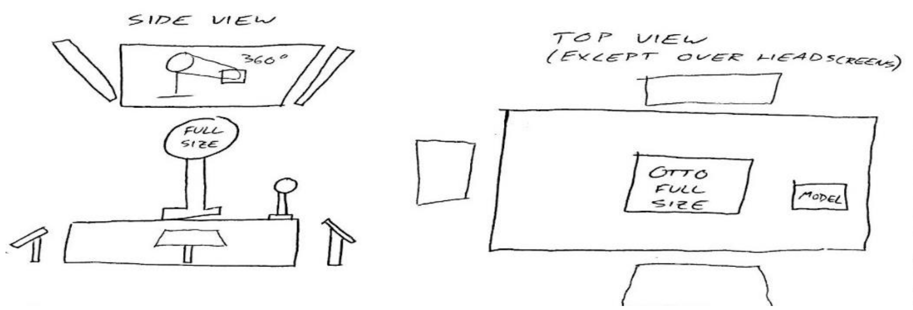


Figure 3. The layout of the "Central Display" design.

Table 3. Pros and cons for the "Central Display" design.

Pros	Cons
Easy to see from all sides	Expensive (many screens)
Suitable for high visitor traffic	Model is relatively less accessible
Engine is well showcased	Top of engine might be too high up

ENGINEERING DATA SHEET	Sheet No. E - 4/7	Date: 2/28/17
Appendix E: Initial concept ideas for the museum exhibit layout.		

Concept 4: The "Corner Display" Exhibit

This concept envisions the exhibit located in the corner of the room, as seen below in Figure 4. Depending on the allotments of space and the layout of the museum, this may be a valuable option to consider. The TV's that will present each individual animation are lined in groups of three in the "interaction area" where a main TV is playing the overview animation on repeat. The engine is found fully backed up to the two corners to save space. The animation will show the entirety of the engine so seeing those back sides will be covered by this. The two walls also contain pictures of the Otto-Langen engine at its famous debut in the Paris exhibition. This concept is good in that it covers a possible design constraint and the viewing area encapsulates the viewers into an "interactive zone" experience. However, not allowing access to two sides of the engine is not ideal. A list of pros and cons for the design is shown below in Table 4.

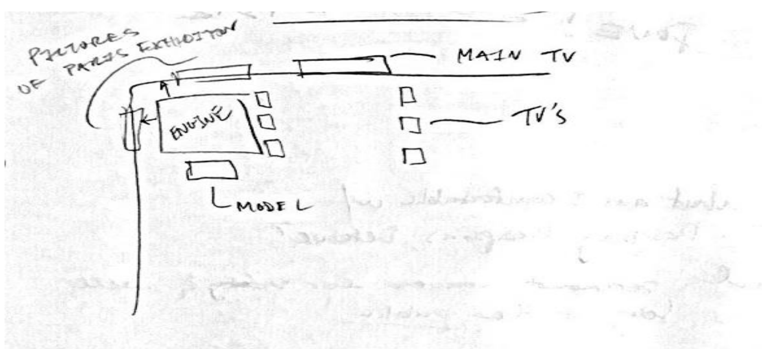


Figure 4. The layout of the "Corner Display" design.

Table 4. Pros and cons for the "Corner Display" design.

Pros	Cons
An engaging "interaction area"	Can't accommodate as many people
Addresses a possible design constraint	Can't see two sides of the actual engine
Power can does not need to be run to middle of room	Can't get close to see pictures since they're posted behind the engine

ENGINEERING DATA SHEET	Sheet No. E - 5/7	Date: 2/28/17
Appendix E: Initial concept ideas for the museum exhibit layout.		

Concept 5: The "Walk-Around" Exhibit

The "Walk-Around" Exhibit sets itself apart from the other exhibit designs by allowing viewers to move around both the engine and its scaled model. A closer view of the engine from all angles enhances the exhibits ability to educate the viewers as well as keeping them interested. Additionally, the engine and model will be surrounded by screens playing a different video on each. This exhibit uses less space than the other exhibit designs while still maintaining the same number of screens due to the compact placement of screens. Unfortunately, a smaller exhibit translates to a lower viewer capacity.

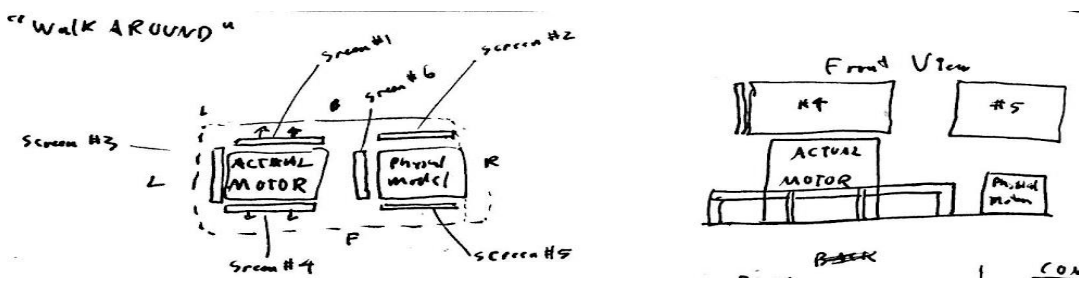


Figure 5. The layout of the "Walk-Around" design.

Table 5. Pros and cons for the "Walk-Around" design.

Pros	Cons
Allows for closer viewing of engine and model	Taller viewers are favored making screens less accessible to shorter viewers
Exhibit takes up less space	Difficult setup for compact design
Maintains about the same number of screens as the other exhibits	Lower viewer capacity due to compact design

ENGINEERING DATA SHEET	Sheet No. E - 6/7	Date: 2/28/17
Appendix E: Initial concept ideas for the museum exhibit layout.		

Concept 6: The "Two Menus" Exhibit

The Two Menus design was created out of the realization that all of the other designs proposed involved a lot of displays, which are not cheap. The goal of this design was to minimize the number of screens without losing content. To do this, only two smaller interactive displays were used, one with a menu with all the videos concerning the valve system and another with a menu of all the other videos. Additionally, only one large display is used to display the overall view, with the model and the actual engine on either side of the large screen. Visitors could then approach the exhibit, watch the overview video, look at the engine and model, and then look at particular detailed videos. The layout can be seen below in Figure 6 and list of pros and cons can be found in Table 6.

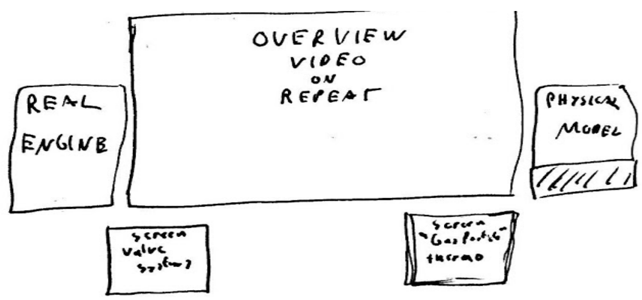


Figure 6. The layout of the "Two Menus" design.

Table 6. Pros and cons for the "Two Menus" design.

Pros	Cons
Allows for closer viewing of engine and model	Less screens means less viewers engaged at once
Exhibit takes up less space	More likely to create lines
Fewer screen and less physical set up	Lower viewer capacity due to compact design

Concept 7: The "Middle Room" Exhibit

The Middle Room exhibit is designed to be placed in the center of a museum's room. The actual engine would sit on the floor and be surrounded by railings that contained several small screens for the viewers to watch the animations and interact with the screens. A layout of the exhibit is shown below in Figure 7. There would be a large screen, "main TV," at one end of the engine that continuously plays an animation of the engine working. The smaller screens would contain the separate animations. On the other end of the engine there would be the smaller physical model of the engine. A list of pro's and con's for this concept can be seen below in Table 7.

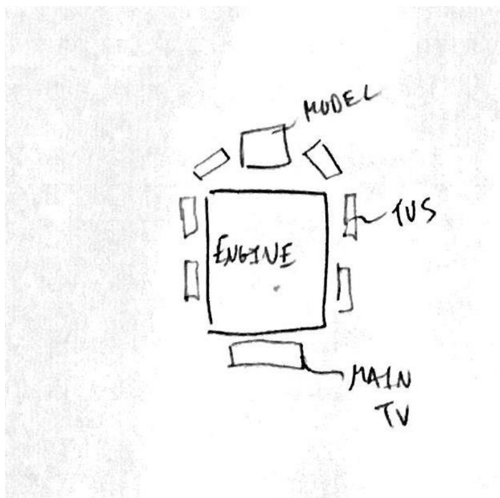


Figure 7. The layout of the "Middle Room" design.

Table 7. Pros and cons for the "Middle Room" design.

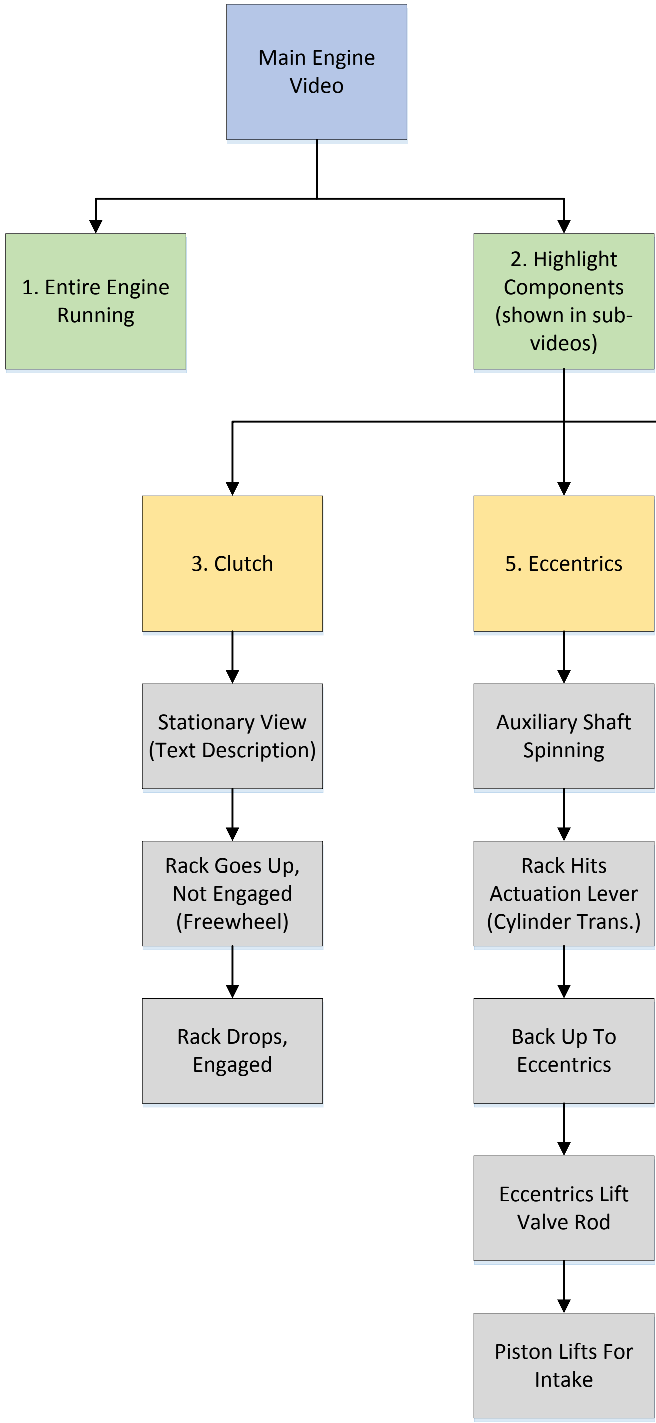
Pros	Cons
Can walk around actual engine (see 360 view)	Only one large screen
Engine is not on a pedestal (top of engine is visible)	Cannot walk around entire model
Many small screens for interaction	Expensive (large screen and small screens)

ENGINEERING DATA SHEET	Sheet No. F - 1/1	Date: 2/28/17
Appendix F: The Pugh matrix for evaluating the museum exhibit concepts.		

Table 1. Pugh matrix for the exhibit design.

Layout / Criteria	Walkaround	2 Menus	Central Display	In Wall Display	Corner Display	Middle Room	Fun Size
Volume of Guests	0	-	0	0	-	0	0
Viewer experience not time dependant	0	+	0	-	0	0	0
Amount of Interaction	+	+	0	-	0	+	-
Cost	0	+	0	0	-	0	-
Programming Effort	0	-	0	0	0	0	0
Space Efficiency	-	0	0	-	-	0	0
# +	1	3	0	0	0	1	0
# -	1	2	0	3	3	0	2
Sum	0	1	0	-3	-3	1	-2

ENGINEERING DATA SHEET	Sheet No. G – 1/2	Date: 4/27/17
Appendix K: Final animation layout drawing (flow diagram).		



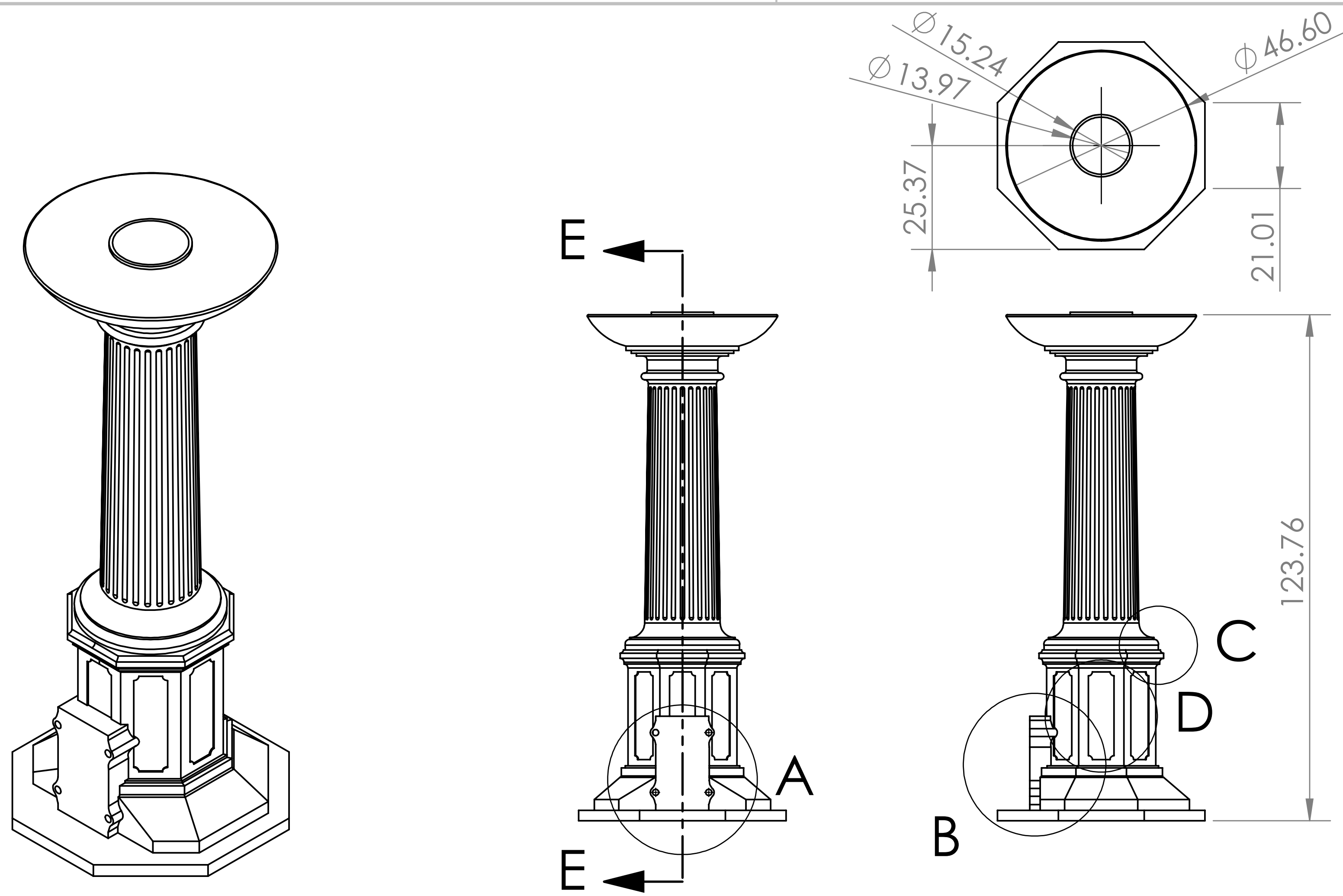
Parts Used in Animation:
1) Ring Gear
2) Clutch (1 side)
3) Rack

Parts Used in Animation:
1) Whole Engine

Parts Used in Animation:
1) Valve
2) Rod
3) Cylinder

ENGINEERING DATA SHEET	Sheet No. H – 1/1	Date: 5/4/17
Appendix H: Bill of Materials		

Category (Animation Story Board)	Otto Mated Part #	Part List	Drawing Inventory (X Denotes Posession)	3D Model Inventory (X Denotes Possesion)	Notes (And File Name)
Piston and Cylinder	101	Column/Cylinder	X	X	Needs editing to match Deutches, see top plate & bottom plate too
	102	Piston	X	X	Aka Piston
	103	Piston Rings			
	104	Piston Pin			
	105	Rack	X	X	Aka Rack Gear, May be different between Wayne/Deutsches
	106	Rack Slide			D
	107	Inlet/Exhaust Geometry	X		See new column full size r5
	110	Gate Valve	X		Aka Governor fuel valve body
	111	Exhaust Piping			
	112	Cross Bracket			D
	113	Piston Spacer		X	
	114	Piston L bracker		X	
Clutch and Flywheel	201	Roller Bearings	X		Aka Clutch Roller, Wayne only
	204	Clutch Rollers		X	Deutsches only
	205	Clutch Core	X	X	"Clutch Core"
	207	Outer Ring Gear	X	X	Aka spur gear new, Deutsches and Wayne have different types,
	208	Sprocket-SideFaceplate	X		Aka Clutch Side Cover
	209	Flywheel-Side Faceplate	X		
	210	Main Shaft	X		
	211	Bearing Pedastal			D
	212	Bearings	X		Ask Wayne but for animation just stick in pedastal
	213	Flywheel	X	X	
	214	Flywheel Key	X		See Main Shaft Drawing
Valve Train	301	Main Gear	X	X	Aka Main and Aux Gear Spec
	302	Auxillary Gear	X	X	Aka Main and Aux Gear Spec
	303	Slide Valve Eccentric	X		Aka Slide Eccentric Body Bottom & Body Top (2Files)
	304	Rack Eccentric	X		Aka rack eccentric
	305	Rack Lifting Arm	X		Aka lifter arm
	306	Rack Lifting Arm Mount	X		
	307	Pawl	X		
	308	Pawl Actuation Lever	X		
	309	Pawl Actuation Lever Leafspring			
	306	Pawl Actuation Lever Mount	X		
	311	Pawl Engagement Spring			
	313	Auxillary Shaft	X		Aka Eccentric Shaft
	314	Bearing Pedastal	X		
	315	Lever Height Stop/Limiter			
	316	Ratchet Gear	X		Aka Ratchet Wheel
	317	Eccentric Pin			
	318	Slide Valve Eccentric Strap			
	319	Rack Eccentric Strap	X		Aka rack eccentric body bottom & top (2 Files)
	320	Slide Valve Lifting Rod	?		Aka guide rod rod???, Possibly easier to just redraw
Slide Valve	401	Slide Valve	X	X	Aka slide valve
	403	Outter SV Mounting Face	X		Aka Cover
	404	SV Bolt Springs			Grab Cad?
	405	Fuel Port Geometry	X		See new column full size r5
	406	SV Nuts	?		Grab Cad?
	407	SV Pin	X		On Slide Valve Drawing
	408	Gate Valve	X		Aka Governor fuel valve body
	409	Slide Valve Stud	X		On Slide Valve Cover Drawing



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	INTERPRET GEOMETRIC TOLERANCING PER:	
	MATERIAL	
	FINISH	
	DO NOT SCALE DRAWING	

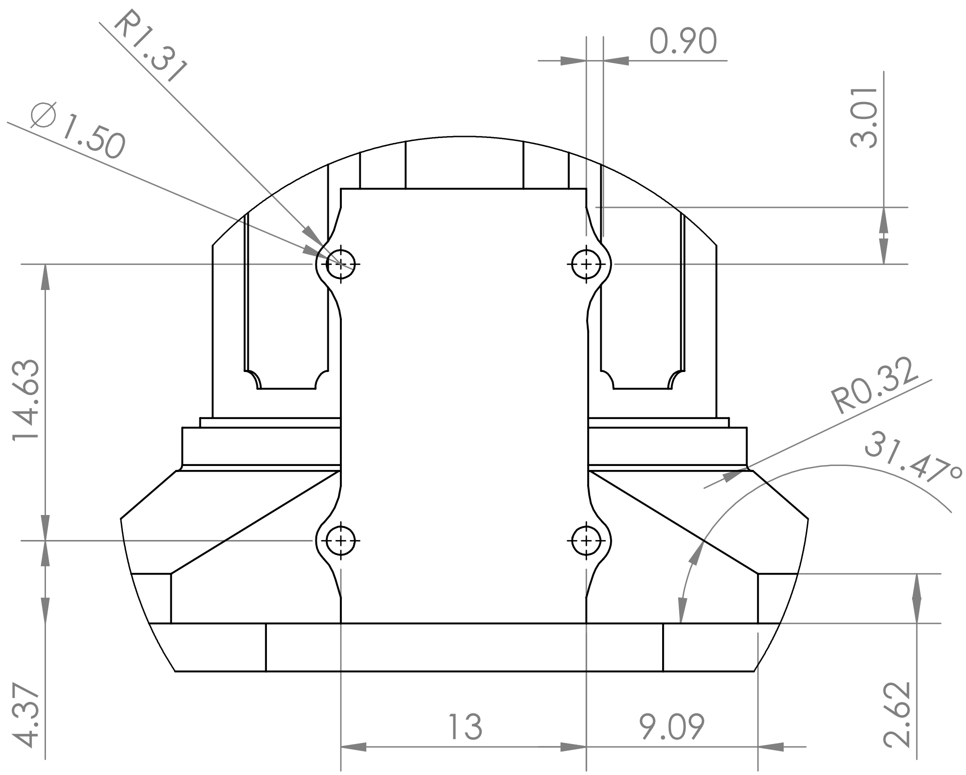
	NAME	DATE
DRAWN	Keiran H	5/1/17
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE:

Cylinder

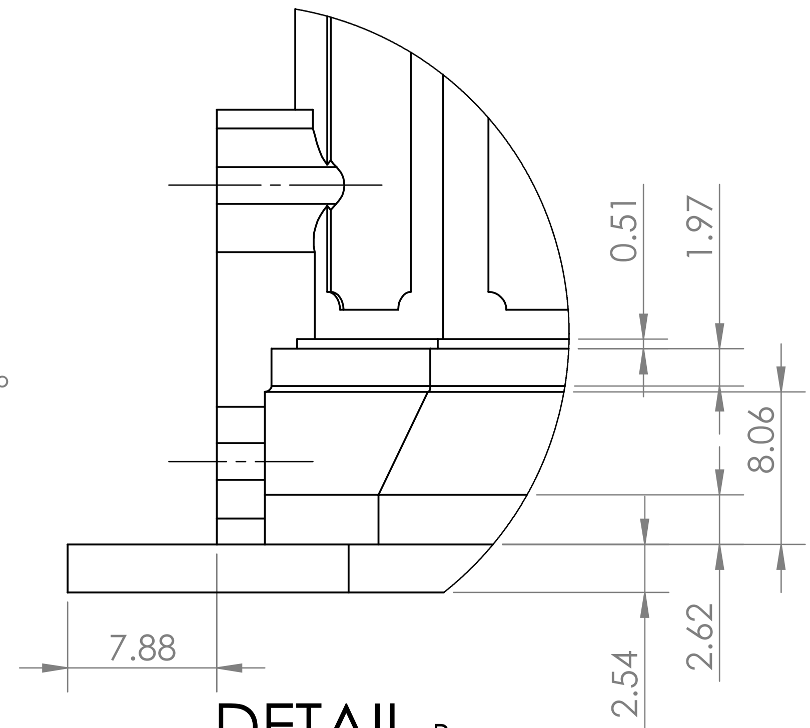
SIZE	DWG. NO.	REV
A	101	

SCALE: 1:16 WEIGHT: SHEET 1 OF 4



DETAIL A

SCALE 1 : 4



DETAIL B

SCALE 1 : 4

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ANGULAR: MACH ±1 BEND ±2
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.0005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

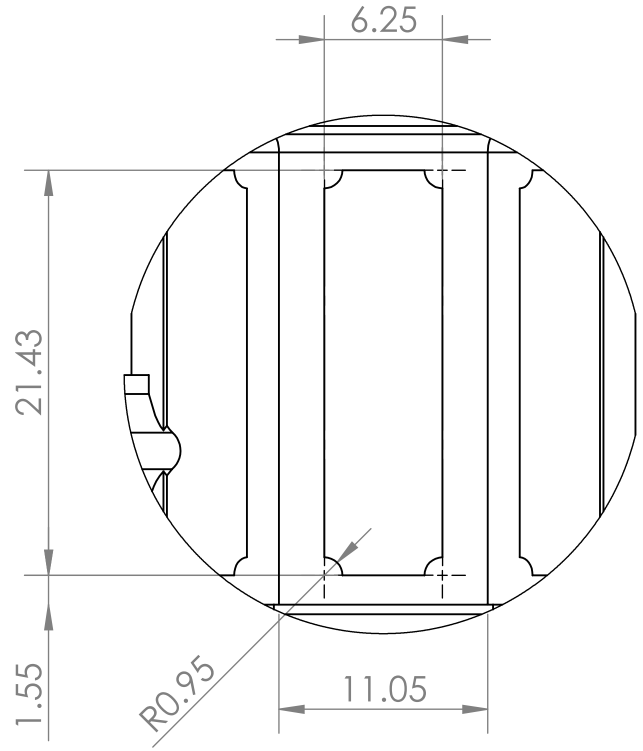
	NAME	DATE
DRAWN	Keiran H	5/1/17
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE: Cylinder

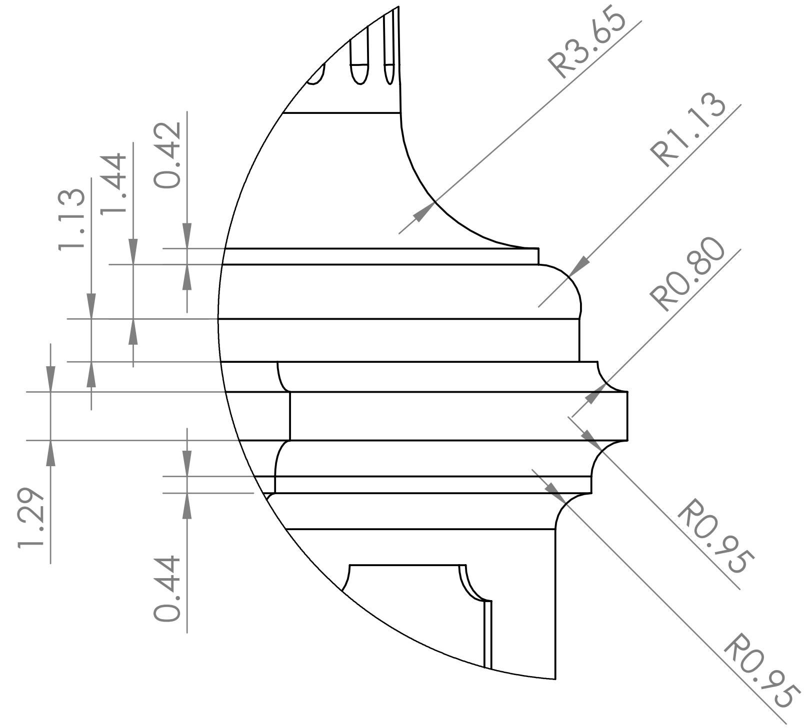
SIZE	DWG. NO.	REV
A	101	

SCALE: 1:4 WEIGHT: SHEET 2 OF 4



DETAIL D

SCALE 1 : 4



DETAIL C

SCALE 1 : 2

PROPRIETARY AND CONFIDENTIAL

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN CENTIMETERS
TOLERANCES:
ANGULAR: MACH ±1 BEND ±2
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.0005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

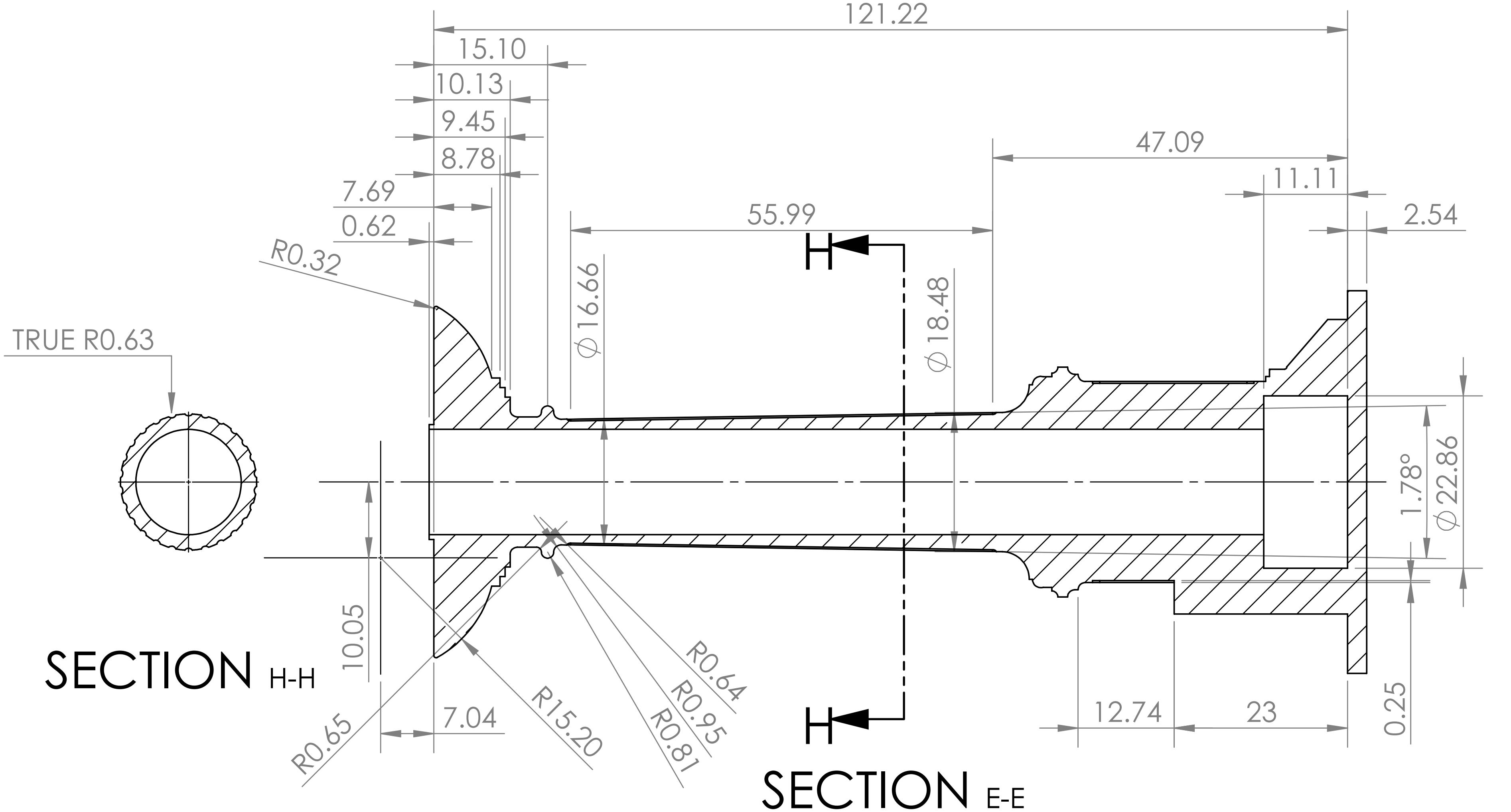
	NAME	DATE
DRAWN	Keiran H	5/1/17
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE: Cylinder

SIZE	DWG. NO.	REV
A	101	

SCALE: 1:16	WEIGHT:	SHEET 3 OF 4



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN CENTIMETERS TOLERANCES: ANGULAR: MACH ±1 BEND ±2 TWO PLACE DECIMAL ±0.005 THREE PLACE DECIMAL ±0.0005	DRAWN	Keiran H	5/1/17
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

PROPRIETARY AND CONFIDENTIAL

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TITLE:

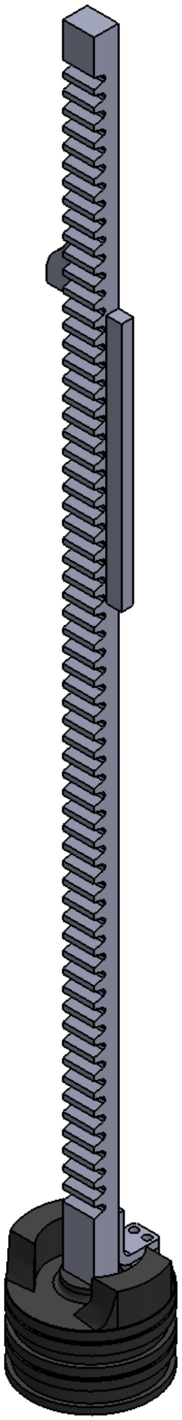
Cylinder: Section View

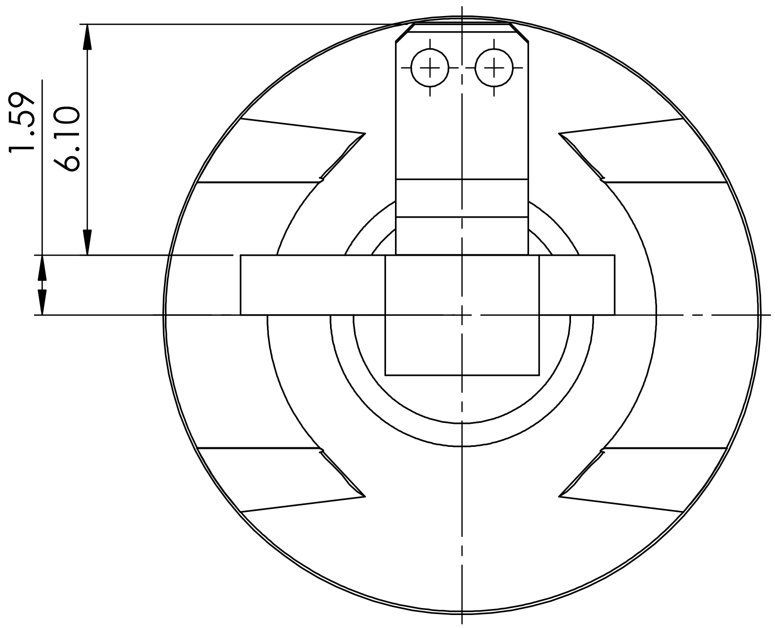
SIZE	DWG. NO.	REV
A	101	

SCALE: 1:8 WEIGHT: SHEET 4 OF 4

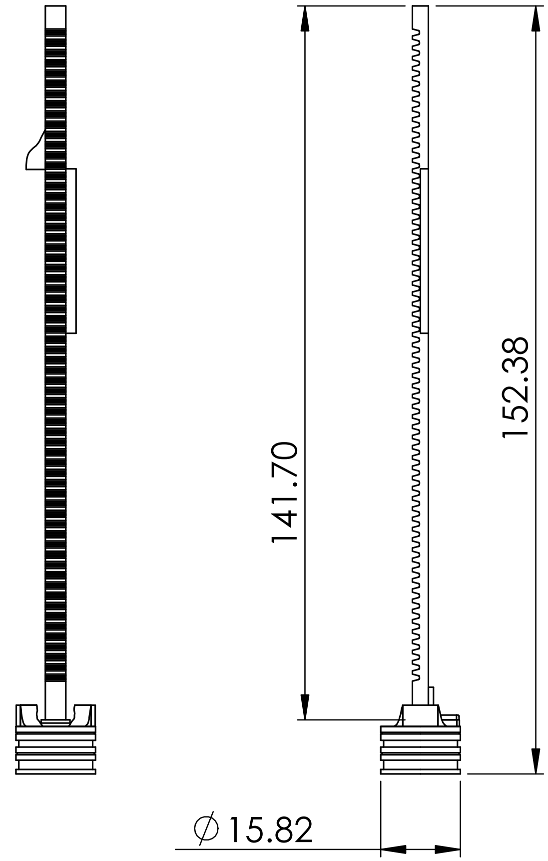
2 | 1

B





Scale: 1:2



A

		NAME	DATE
	DRAWN	Keiran H	4/27/17
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
	COMMENTS:		

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN CENTIMETERS
TOLERANCES:
ANGULAR: MACH ±1 BEND ±2
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.0005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

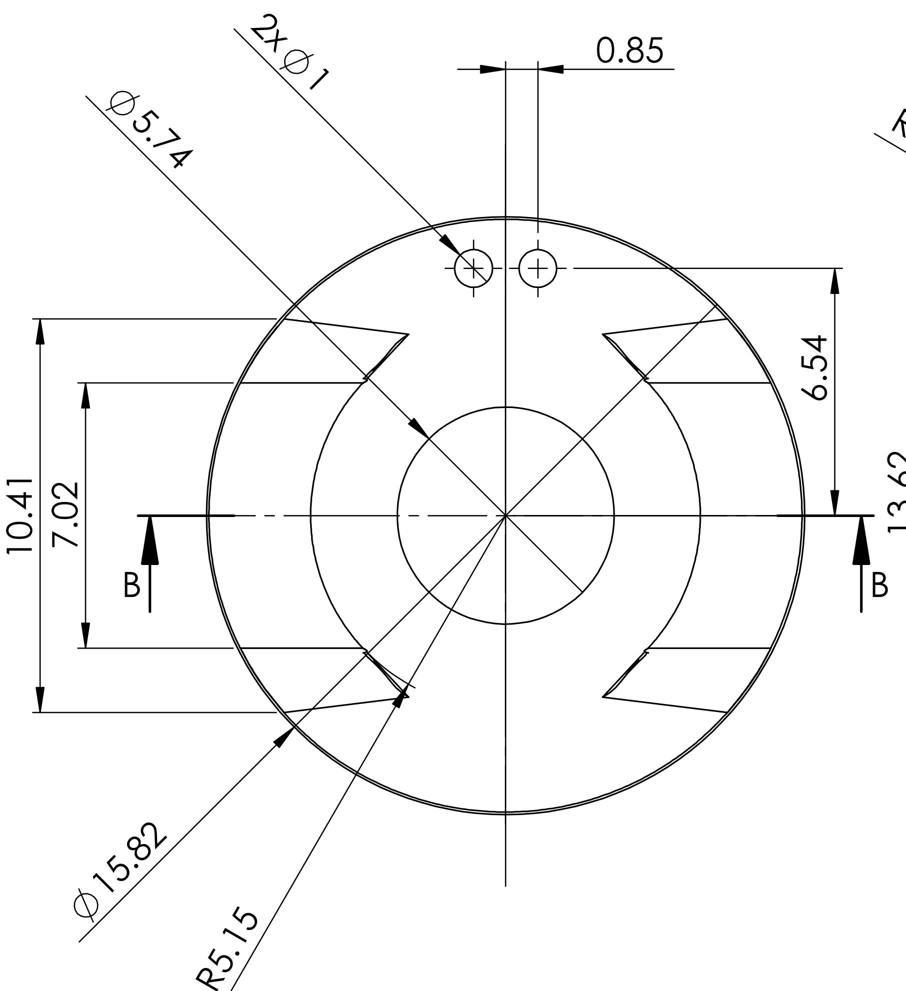
TITLE:

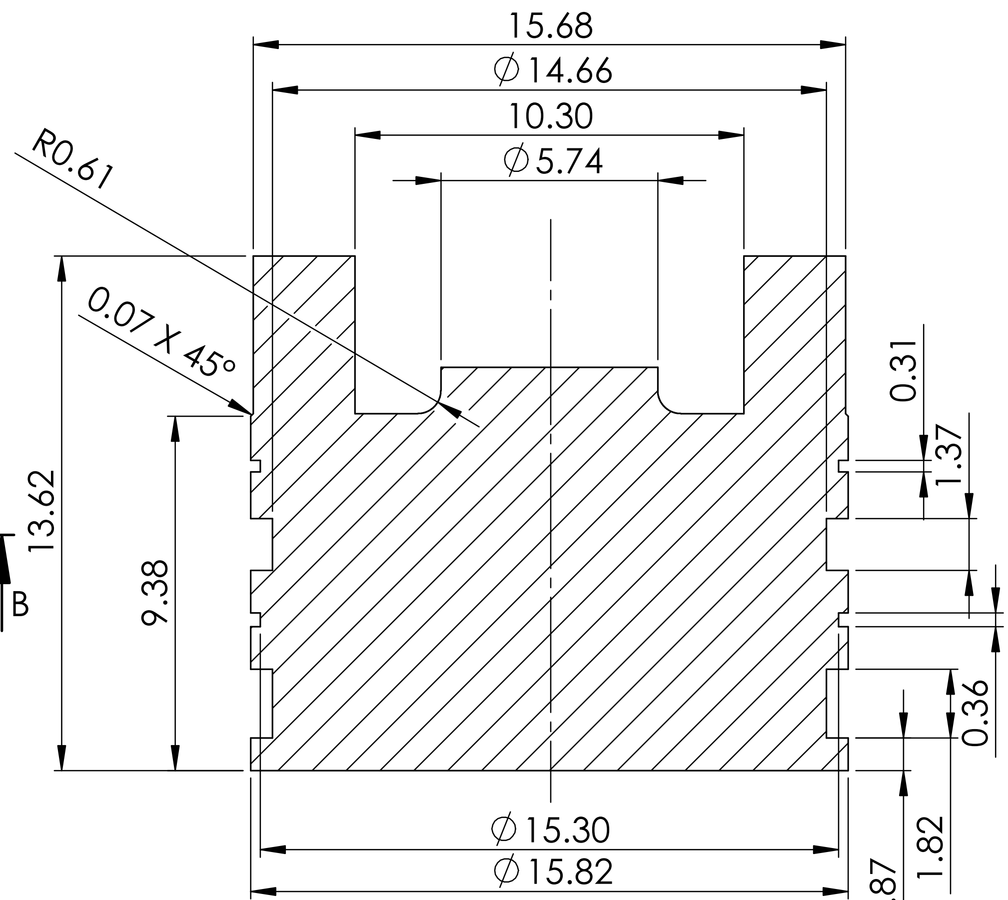
Piston Assembly

SIZE	DWG. NO.	REV
A	100 Series	

SCALE: 1:15 | WEIGHT: | SHEET 1 OF 5

2 | 1





SECTION B-B

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN CENTIMETERS TOLERANCES: ANGULAR: MACH±1 BEND ±2 TWO PLACE DECIMAL ±0.005 THREE PLACE DECIMAL ±0.0005	DRAWN	Keiran H	4/27/17
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

PROPRIETARY AND CONFIDENTIAL

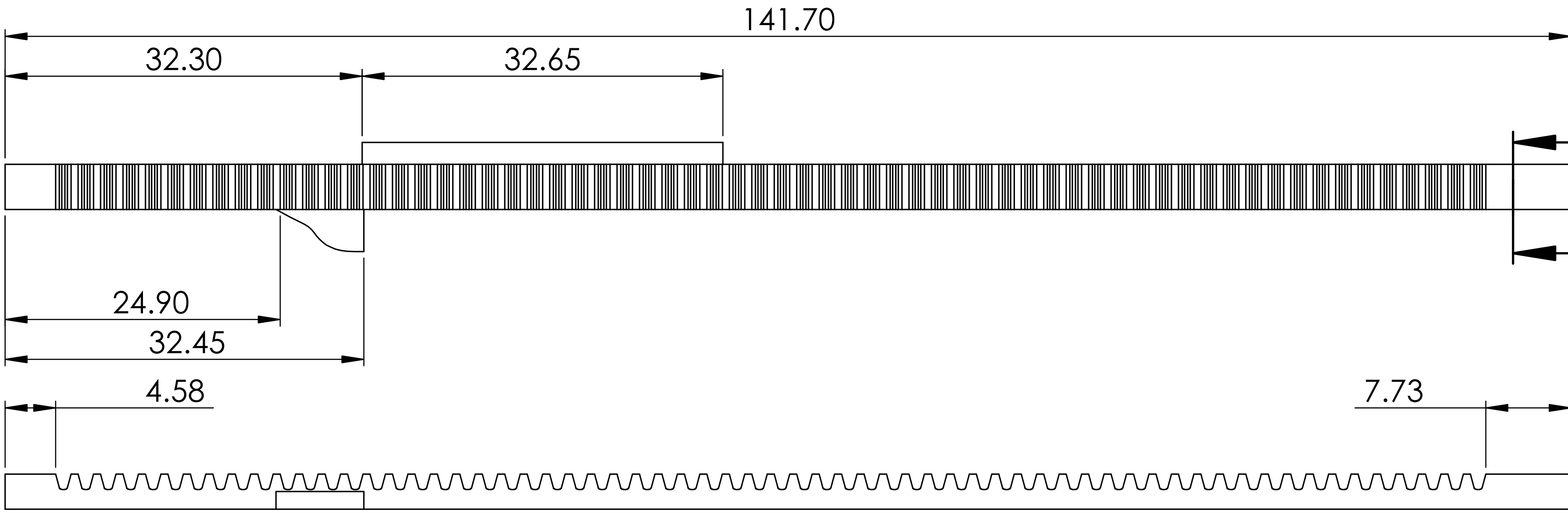
TITLE:

Piston Assembly: Piston

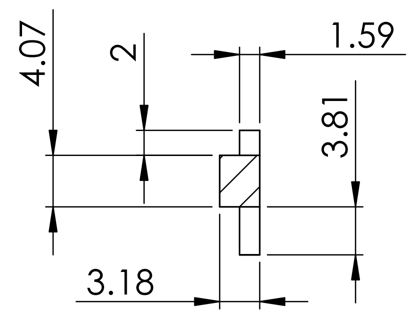
SIZE	DWG. NO.	REV
A	102	

SCALE: 1:2	WEIGHT:	SHEET 2 OF 5

2 | 1



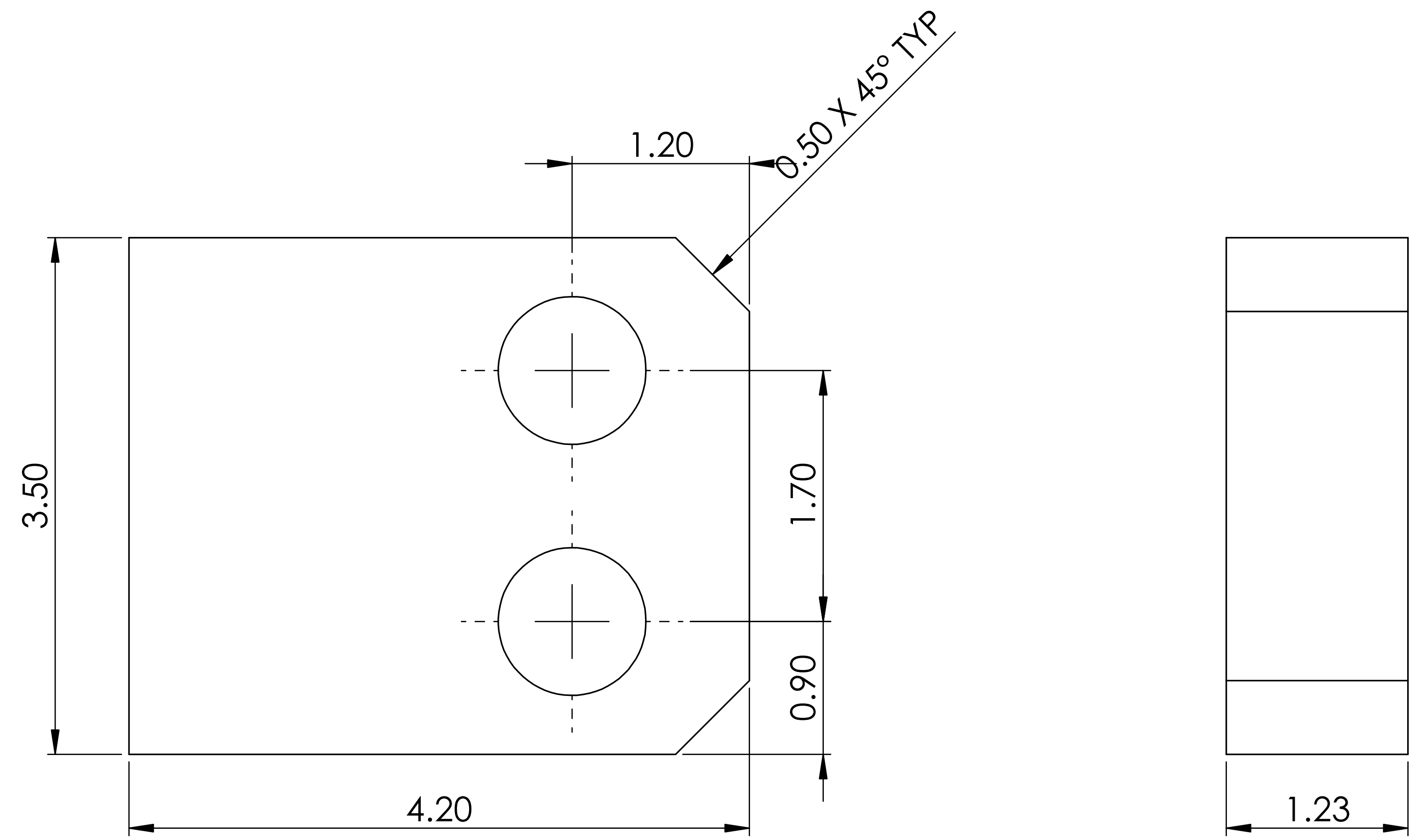
Note:
Rack mates with 6.5 m, 14.5
Pressure angle gear.
64 teeth.



SECTION D-D

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TITLE:
DIMENSIONS ARE IN CENTIMETERS TOLERANCES: ANGULAR: MACH±1 BEND ±2 TWO PLACE DECIMAL ±0.005 THREE PLACE DECIMAL ±0.0005	DRAWN	Keiran H	4/27/17	**Piston Assembly: Rack Gear**
	CHECKED			
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE A — DWG. NO. 105 — REV
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:6 — WEIGHT: — SHEET 3 OF 5

2 | 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN CENTIMETERS TOLERANCES: ANGULAR: MACH ±1 BEND ±2 TWO PLACE DECIMAL ±0.005 THREE PLACE DECIMAL ±0.0005	DRAWN	Keiran H	4/27/17
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

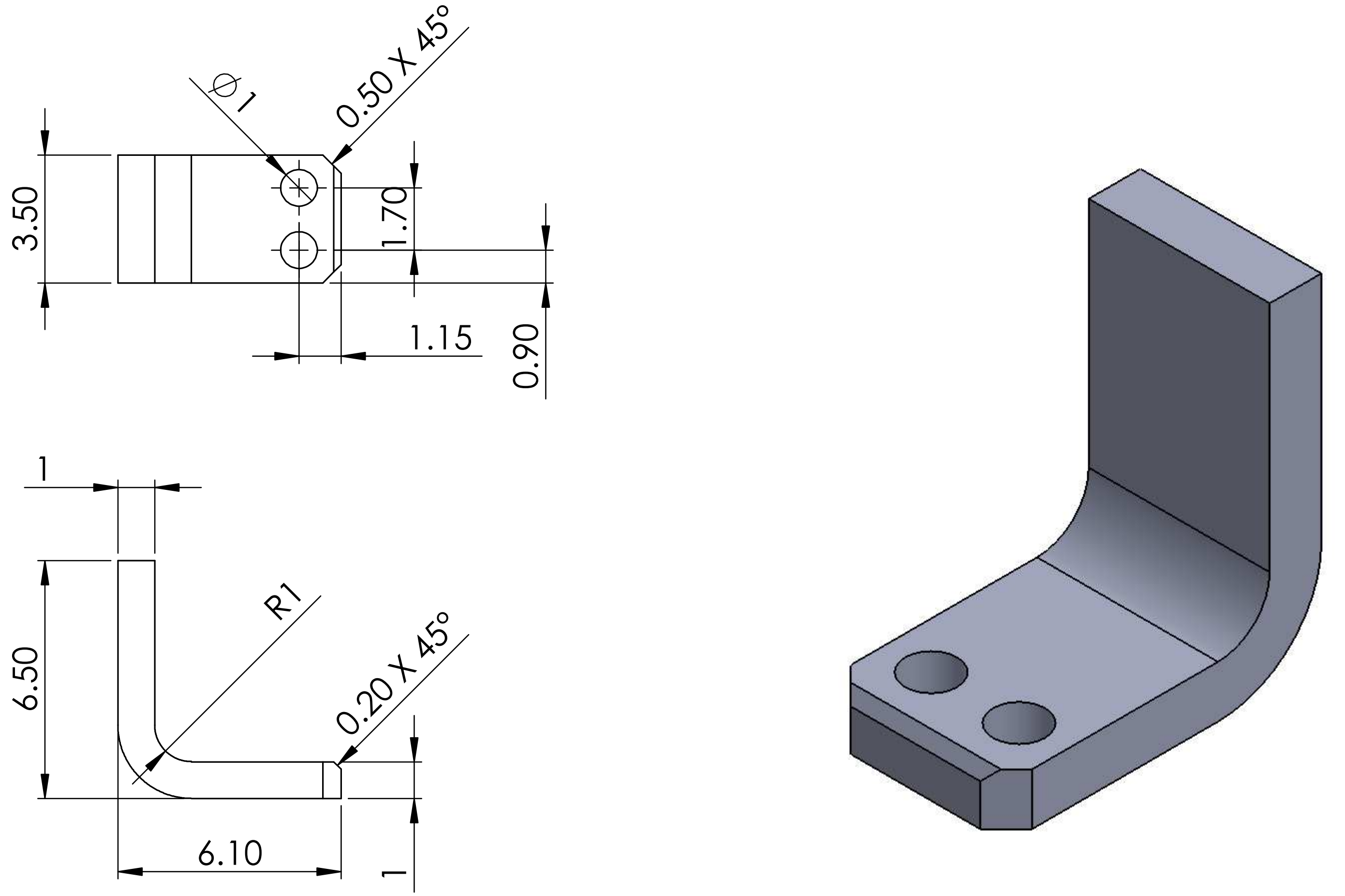
PROPRIETARY AND CONFIDENTIAL

TITLE:

Piston Assembly: Piston Spacer

SIZE	DWG. NO.	REV
A	113	

SCALE: 2:1	WEIGHT:	SHEET 4 OF 5



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UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN CENTIMETERS
TOLERANCES:
ANGULAR: MACH±1 BEND ±2
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.0005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Keiran H	4/27/17
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

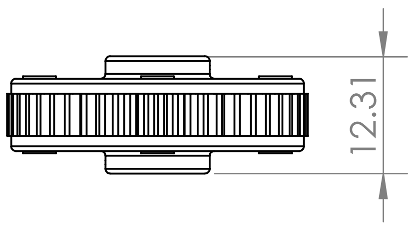
COMMENTS:

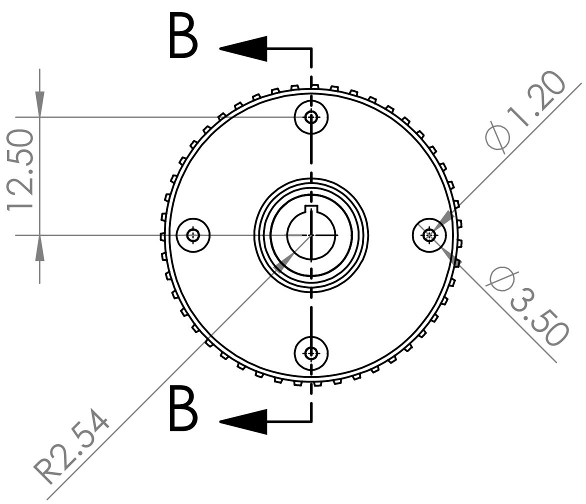
TITLE:

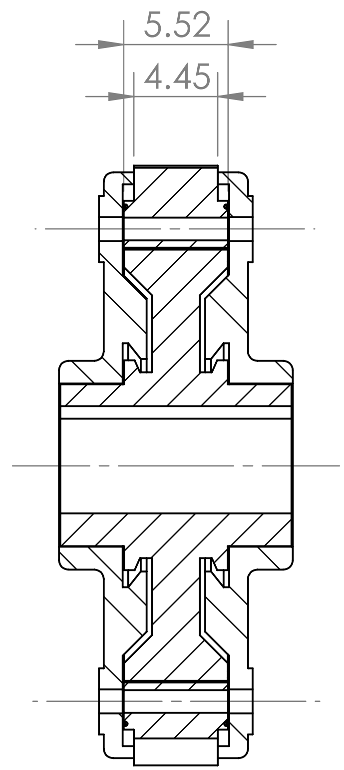
Piston Assembly: Piston L Bracket

SIZE **A** DWG. NO. 114 REV

SCALE: 1:2 WEIGHT: SHEET 5 OF 5

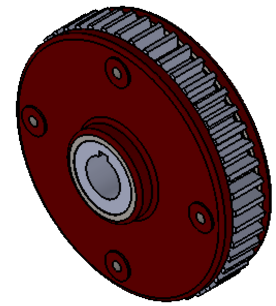






SECTION B-B

SCALE 1 : 4



PROPRIETARY AND CONFIDENTIAL

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN CENTIMETERS
TOLERANCES:
ANGULAR: MACH ±1 BEND ±2
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.0005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

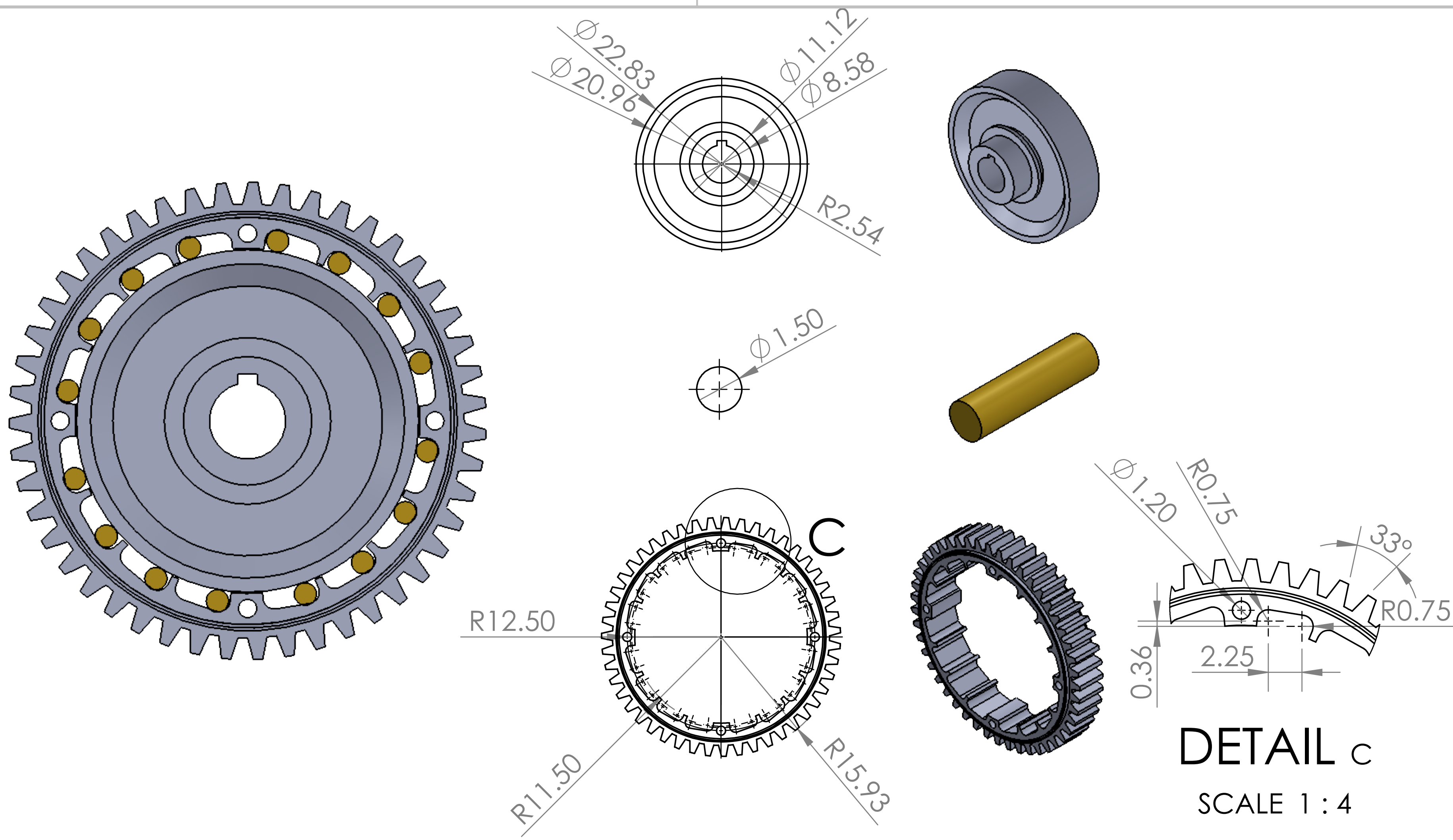
	NAME	DATE
DRAWN	Keiran H	4/25/17
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE: Clutch

SIZE	DWG. NO.	REV
A	200 series	

SCALE: 1:8	WEIGHT:	SHEET 1 OF 5



PROPRIETARY AND CONFIDENTIAL

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UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN CENTIMETERS
TOLERANCES:
ANGULAR: MACH ±1 BEND ±2
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.0005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Keiran H	4/25/17
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

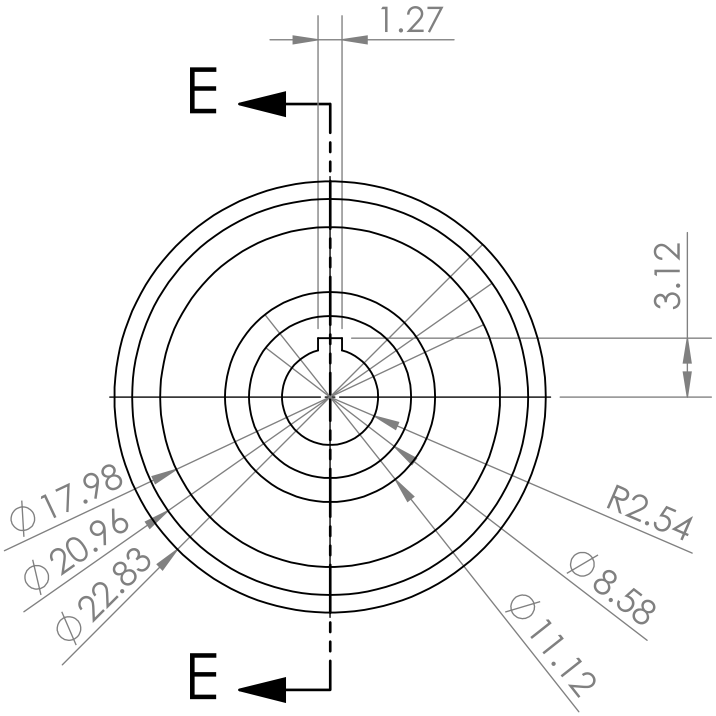
COMMENTS:

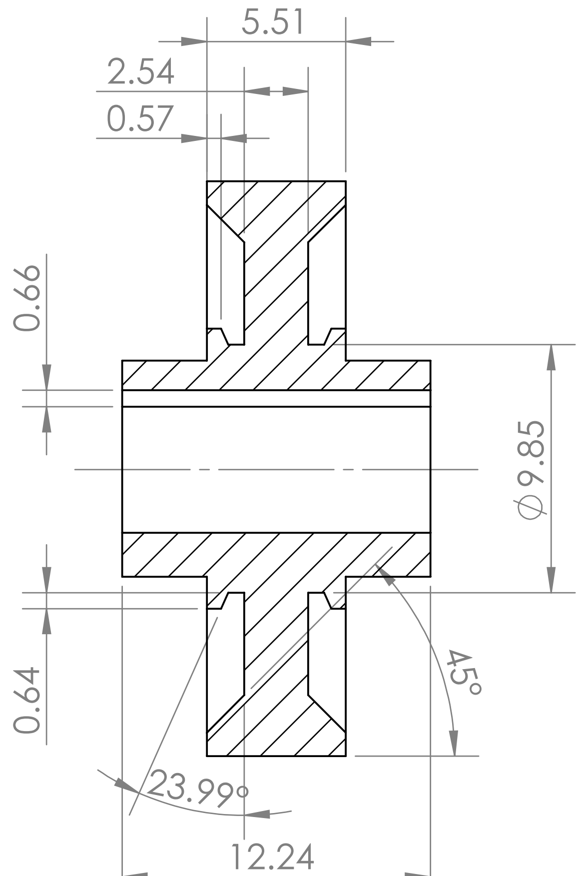
TITLE:

Clutch: Clutch Rollers, Clutch Core, Outer Ring Gear

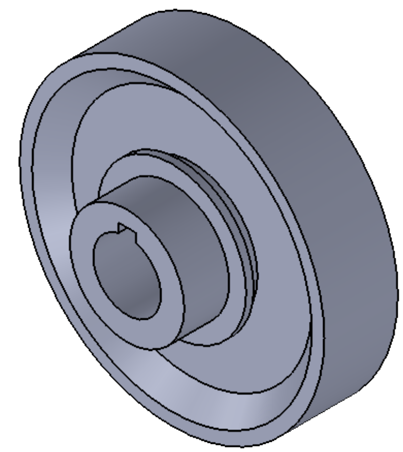
SIZE	DWG. NO.	REV
A	204,205,207	

SCALE: 1:8 | WEIGHT: | SHEET 2 OF 5





SECTION E-E
SCALE 1 : 3



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN CENTIMETERS TOLERANCES: ANGULAR: MACH ±1 BEND ±2 TWO PLACE DECIMAL ±0.005 THREE PLACE DECIMAL ±0.0005	DRAWN	Keiran H	4/25/17
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

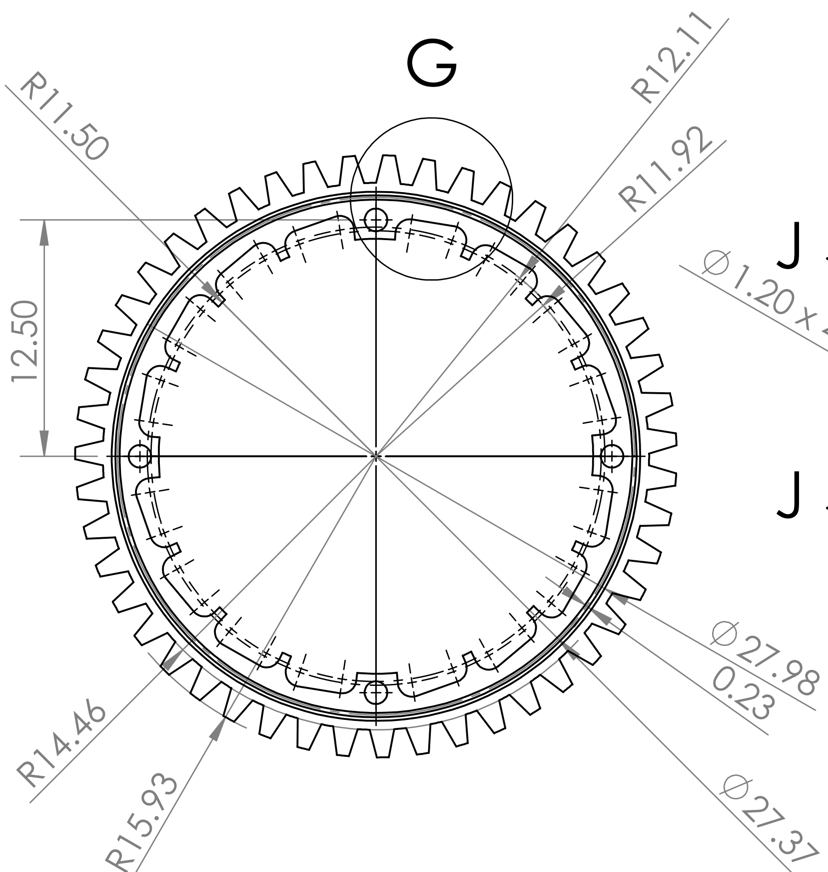
PROPRIETARY AND CONFIDENTIAL

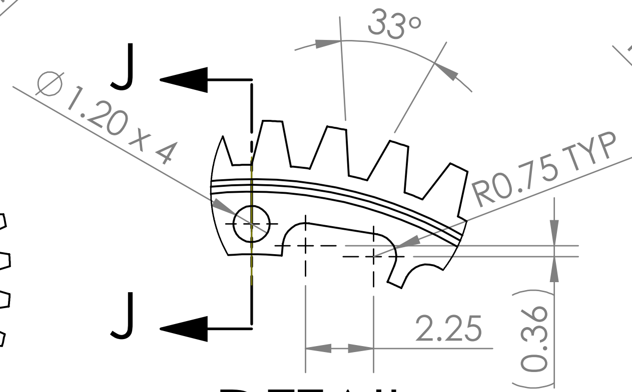
TITLE:

Clutch Core

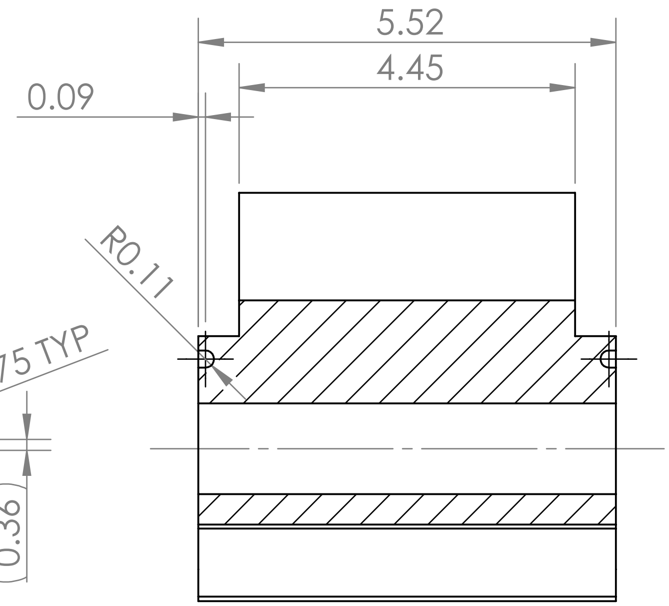
SIZE	DWG. NO.	REV
A	205	

SCALE: 1:5 WEIGHT: SHEET 3 OF 5





DETAIL G
SCALE 2 : 5



SECTION J-J
SCALE 1 : 1

Note:
47 tooth gear pattern.
m = 6.5
pressure angle = 14.5

PROPRIETARY AND CONFIDENTIAL

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN CENTIMETERS
TOLERANCES:
ANGULAR: MACH ±1 BEND ±2
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.0005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Keiran H	4/25/17
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

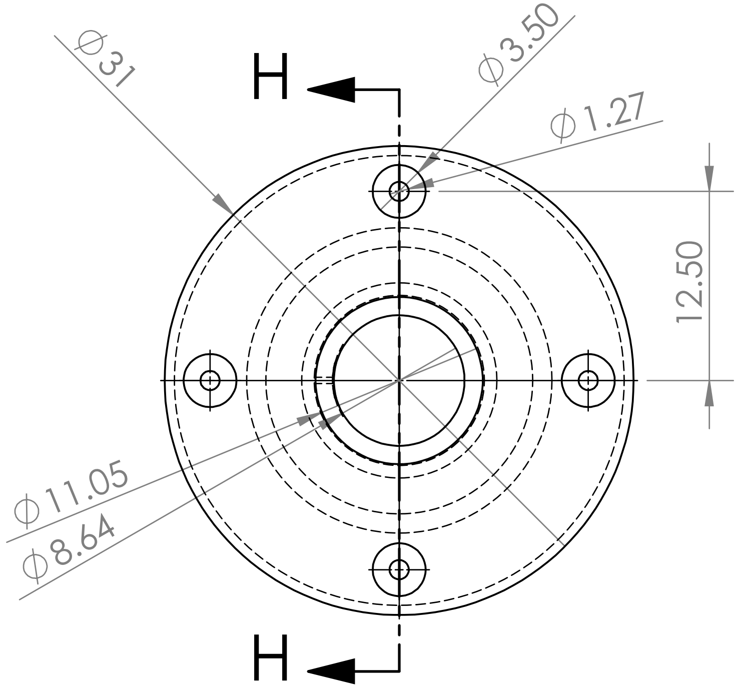
COMMENTS:

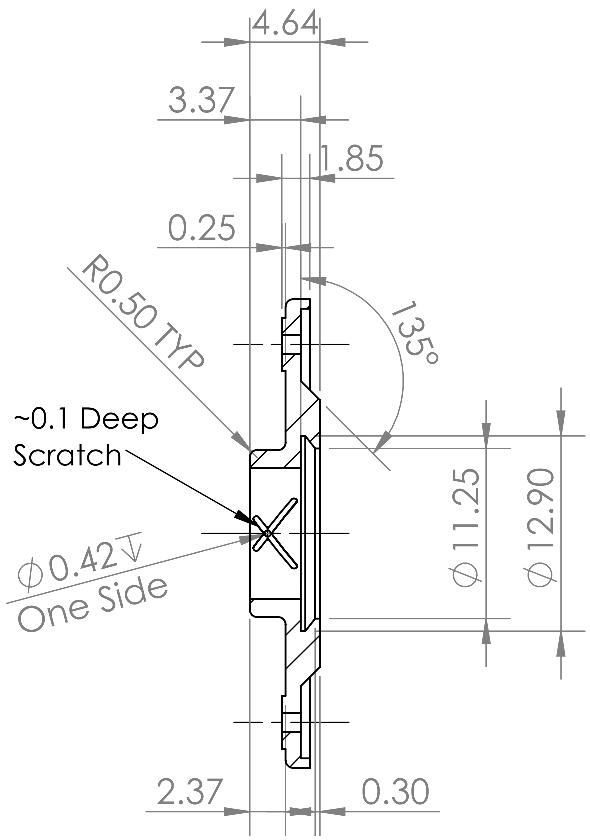
TITLE:

Outer Ring Gear

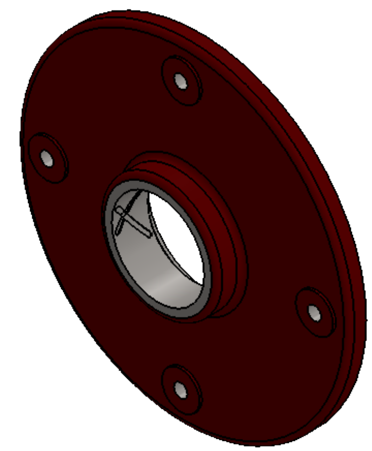
SIZE	DWG. NO.	REV
A	207	

SCALE: 1:4	WEIGHT:	SHEET 4 OF 5





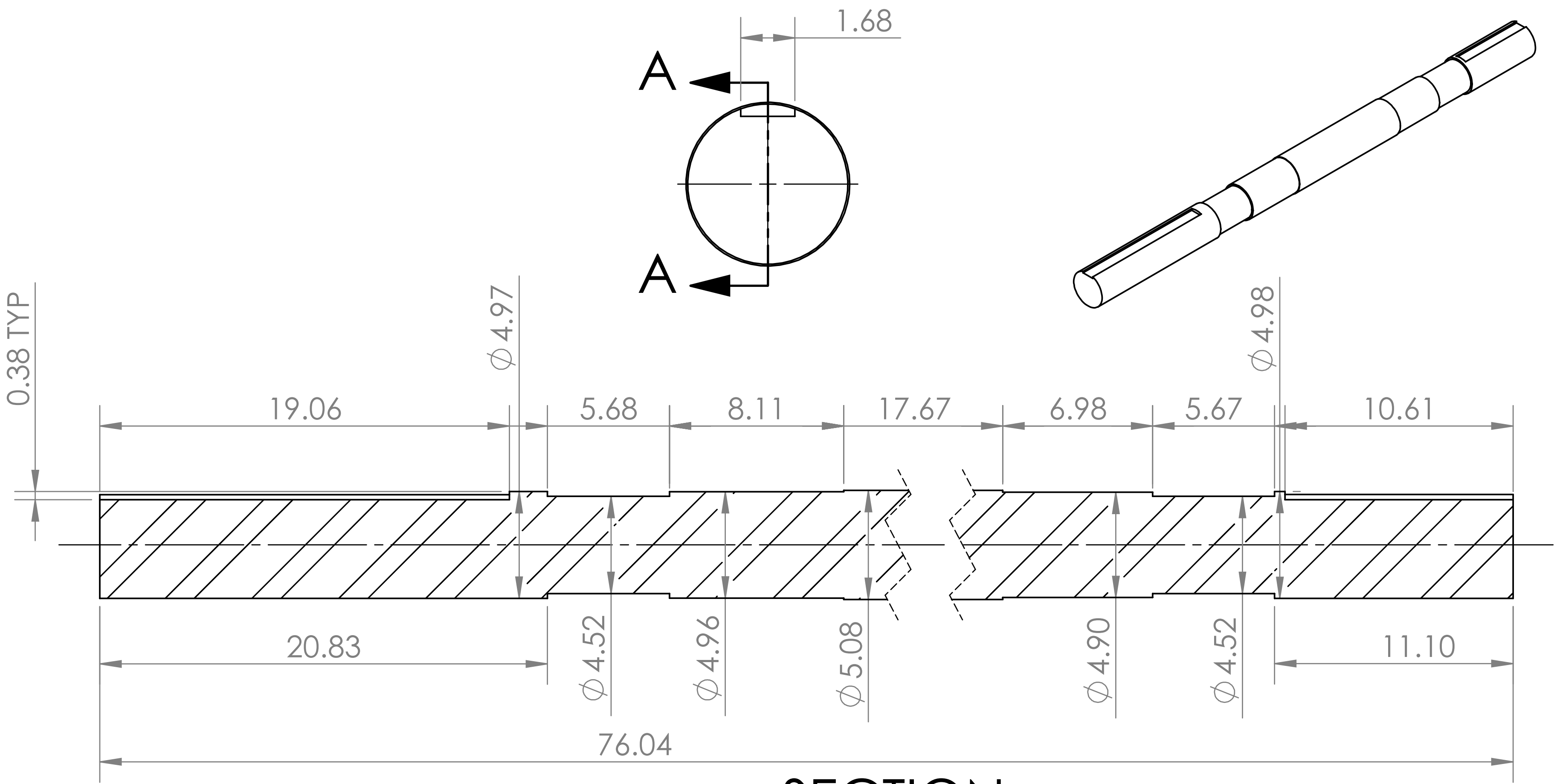
SECTION H-H



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TITLE:	Clutch Side Covers
DIMENSIONS ARE IN CENTIMETERS TOLERANCES: ANGULAR: MACH ±1 BEND ±2 TWO PLACE DECIMAL ±0.005 THREE PLACE DECIMAL ±0.0005	DRAWN	Keiran H	4/26/17		
	CHECKED				
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL	COMMENTS:			SIZE A	DWG. NO. 208 — REV
FINISH					
DO NOT SCALE DRAWING				SCALE: 1:5	WEIGHT: — SHEET 5 OF 5

2 | 1

B | B



SECTION A-A
SCALE: 1:3

A | A

PROPRIETARY AND CONFIDENTIAL

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN CENTIMETERS
TOLERANCES:
ANGULAR: MACH ±1 BEND ±2
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.0005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Keiran H	4/25/17
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

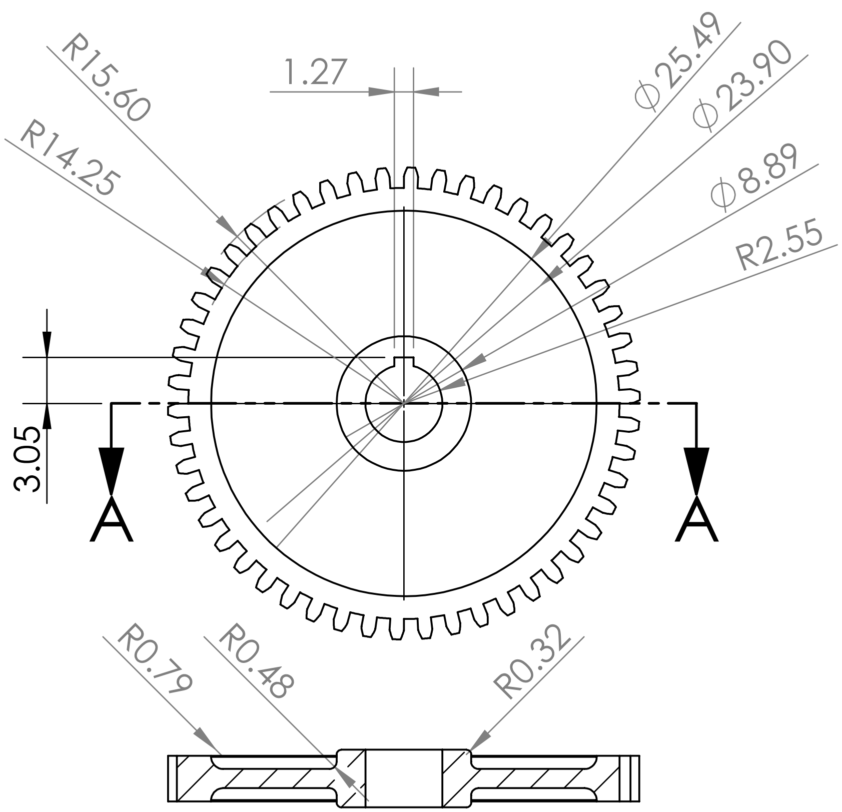
TITLE:

MAIN SHAFT

SIZE	DWG. NO.	REV
A	210	

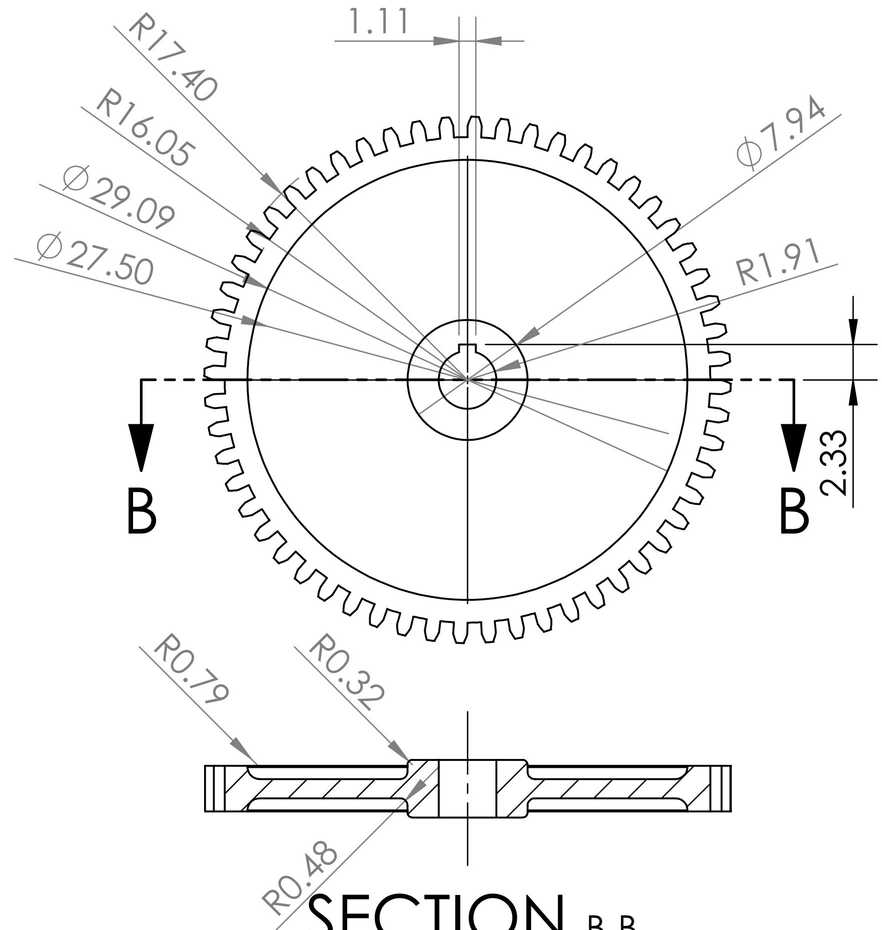
SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1

2 | 1



SECTION A-A

NOTE: MAIN GEAR
m = 6.0 mm, 50 teeth,
14.5 deg Pressure Angle



SECTION B-B

NOTE: AUX GEAR
m = 6.0 mm, 56 teeth,
14.5 deg Pressure Angle

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN CENTIMETERS
TOLERANCES:
ANGULAR: MACH ±1 BEND ±2
TWO PLACE DECIMAL ±0.005
THREE PLACE DECIMAL ±0.0005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Keiran H	4/25/17
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

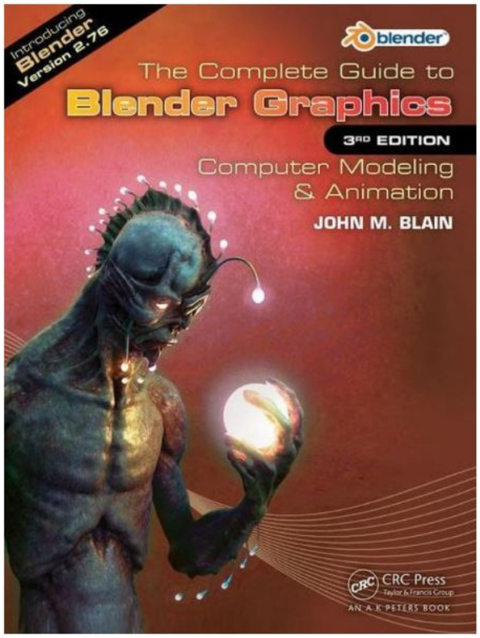
TITLE:
Gears: Main & Aux

SIZE A | DWG. NO. 301, 302 | REV

SCALE: 1:5 | WEIGHT: | SHEET 1 OF 1

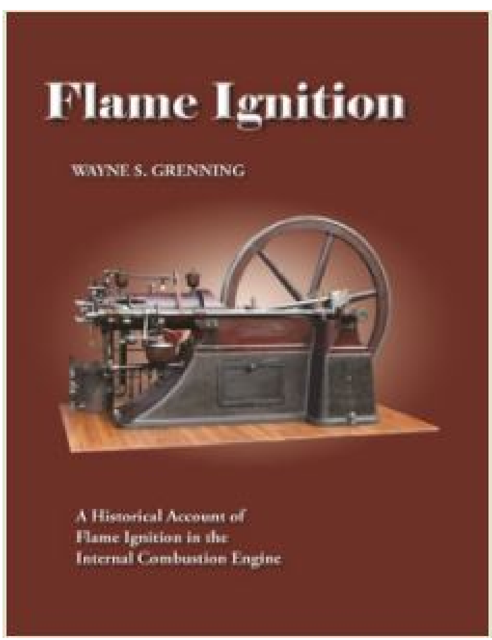
ENGINEERING DATA SHEET	Sheet No. J – 1/2	Date: 4/27/17
Appendix J: Product literature.		

Blender Book



Link to Book: https://www.bookdepository.com/Complete-Guide-Blender-Graphics-John-M-Blain/9781498746458

Engine Book



Link to Book: http://www.coolspringpowermuseum.org/Publications.htm

Blender Links

Fire Simulation:
https://www.youtube.com/watch?v=u-zK7Bu8cAI

Drivers/Constraints:
https://www.youtube.com/watch?v=j1WNbpX7HPo&index=2&list=PLDIkz0D1r1kWdRgnPOn8slLjHAPaAW2uK

https://www.youtube.com/watch?v=q7crYSmn6Dk&index=3&list=PLDIkz0D1r1kWdRgnPOn8slLjHAPaAW2uK

https://www.youtube.com/watch?v=jMoBFzXFAUM&index=1&list=PLDIkz0D1r1kWdRgnPOn8slLjHAPaAW2uK

Transparent Objects:
https://www.youtube.com/watch?v=w9E2RZzhcMM

Camera Follow Path:
https://www.youtube.com/watch?v=SqOso5jgYa4

Lighting:
https://www.3dartistonline.com/news/2015/09/blender-lighting-with-reynante-martinez/

ENGINEERING DATA SHEET	Sheet No. K – 1/2	Date: 4/27/17
Appendix K: Critical design safety hazard identification checklist.		

DESIGN HAZARD CHECKLIST

Team: Otto-Mated Advisor: Ridgely

Y	N	
☐	☑	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☐	☑	2. Can any part of the design undergo high accelerations/decelerations?
☐	☑	3. Will the system have any large moving masses or large forces?
☐	☑	4. Will the system produce a projectile?
☐	☑	5. Would it be possible for the system to fall under gravity creating injury?
☐	☑	6. Will a user be exposed to overhanging weights as part of the design?
☐	☑	7. Will the system have any sharp edges?
☐	☑	8. Will any part of the electrical systems not be grounded?
☐	☑	9. Will there be any large batteries or electrical voltage in the system above 40 V?
☐	☑	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	☑	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
☐	☑	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐	☑	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	☑	14. Can the system generate high levels of noise?
☐	☑	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
☐	☑	16. Is it possible for the system to be used in an unsafe manner?
☑	☐	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

ENGINEERING DATA SHEET	Sheet No. K – 2/2	Date: 4/27/17
Appendix K: Critical design safety hazard identification checklist.		

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
EPILEPSY	AVOID RAPID FRAME CHANGES AND FLASHING LIGHTS	NOV.	ON-GOING

ENGINEERING DATA SHEET	Sheet No. L – 1/2	Date: 5/4/17
Appendix L: FMEA		

									Action Results			
Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) / Mechanism(s) of Failure	Occurence	Criticality	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality
Visually Pleasing	Incompatability and formatting	Aspect ratio is distored and scaling is inaccurate/does not fit on screen	4	Wrong size screen	4	16	Extensive testing on multiple screens and operating systems	Chris Splees November 2017				
				rendering error	4	16						
				Operating system	2	8						
				video format	1	4						
				media player	2	8						
	Animation glitches	Epilepsy, viewer confusion, loss of viewer interest	9	File size/corruption	3	27	Reset/Reboot Option	Rachel Jakob November 2017				
				User Interface bugs	6	54						
				Computer hardware	3	27						
				Wire connections	2	18						
	Brightness issues	Hard to read, glare, eyestrain, lawsuit, headaches	4	Screen Quality	2	8	Testing on multiple screens, test different settings in different	Lance Hodgson November 2017				
				Screen Settings	2	8						
				Low light animation	2	8						
	Synchronization	Confusion, loss of interest, hindered education,	6	video editing error	2	12	Testing, pausing and playing, fast forward, reverse, "scrubbing", running on an overloaded computer	Keiran Hansen November 2017				
				rendering error	1	6						
				excessive file size	1	6						
				Words at wrong pace	1	6						
				equipment malfunction	3	18						
	Legibility	Confusion, loss of interest, hindered education, eyestrain	6	video editing error	2	12	Testing in different lighting condition, trying differnet fonts/backgrounds, test on different screens	Chris Splees and Rachel Jakob November 2017				
				rendering error	1	6						
				Screen Settings	2	12						
				screen size	1	6						
				font size	1	6						
Visitor Safety	Tripping	Visitor injury, damage to exhibit, loss of power, lawsuit	5	rugs	1	5	Design out of exhibit where possible. Use cable trays and conduit.	Keiran Hansen and Lance Hodgson Nov 2017				
				display bases	1	5						
				cords	3	15						
				steps	1	5						
				low barriers	2	10						
	Falling Devices	Visitor injury, lawsuit, damage to exhibit, exhibit closure	7	overhead TV support	2	14	Design out where possible, with redundencies and properly sized restraints	Keiran Hansen and Lance Hodgson November 2017				
				Model restraints fail	2	14						
				Earthquake	1	7						
				Not properly anchored	1	7						
				Corrosion	1	7						

									Action Results			
Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) / Mechanism(s) of Failure	Occurence	Criticality	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality
Visitor Safety	Pinch Points	Visitor injury, lawsuit, equipment failure	5	Get past barriers	2	10	Well designed barriers, docents, maintence, model testing	Keiran Hansen and Lance Hodgson Sept-Nov 2017				
				model design flaw	1	5						
				model failure	1	5						
	Explosion	Visitor injury, lawsuit, museum damage, artifact destruction	1	Gas into engine	2	2	Remote shut off valve, disconnect from gas, prevent backwards rotation, circuit breaker/fuse/surge protector	Keiran Hansen and Lance Hodgson November 2017				
				Engine run backwards	4	4						
				High current/voltage	3	3						
	Excessive Heat	Fire, Visitor injury, exhibit damage	2	Screen heat output	3	6	Check max heat output of displays, combined with max sun intensity, and check the ventilation requirements. Keep computation minimal	Rachel Jakob November 2017				
				High current/voltage	1	6						
				High brightness	1	2						
				High computation load	1	2						
				lack of ventilation	2	2						
				Solar radiation	3	4						
	Sharp edges/corners	Visitor injury, lawsuit	2	Barrier edges	2	4	Source safe barriers, guards over mounts if accesible, fillet or round exposed edges	Keiran Hansen November 2017				
				Model edges	3	6						
				screen edges	1	2						
				screen mounts	3	6						
Copyright Infrignment	Pirating	Lawsuit, loss of creditability, loss of funding, prison	8	Losing track of sources	2	16	Document sources as they are used. Give credit and ask permission	Chris Splees November 2017				
				Bad practices	1	8						
				Negligence	2	16						
	Photo credit	Lawsuit, loss of creditability, loss of	5	Internet sourced	2	10	Put source directly on any images not owned	Lance Hodgson November 2017				
				Negligence	2	10						
	logo use	Lawsuit, fine, prison	5	Negligence	1	5	Avoid logos not created by Deutsches or Team	Rachel Jakob November 2017				
				Bad practices	1	5						
	files/drawings	Lawsuit, fine, prison	5	Internet sourced	1	5	Cite directly on any graphic used	Rachel Jakob November 2017				
				Negligence	1	5						
Teaching	Correct Information	Visitor confusion, miseducation, loss of museum credibility, weakened relationship between Cal Poly and Deutsches	6	Typos	2	12	Extensive editing, and peer review. Seek many sources to verify information presented.	Lance Hodgson October 2017				
				Lack of understanding	1	6						

ENGINEERING DATA SHEET

Sheet No. L – 2/2

Date: 5/4/17

Appendix L: FMEA

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) / Mechanism(s) of Failure	Occurence	Criticality	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Action Results: Severity	Action Results: Occurence	Action Results: Criticality
Teaching	Understandable	Visitor confusion, loss of interest, tarnished museum reputation, weakened relationship between Cal Poly and Deutsches	5	too fast	2	10	Control group testing. Visual explanations where possible to minimize reliance on language. Use simple language/vocabulary.	Keiran Hansen October 2017				
				too small	2	10						
				language barrier	3	15						
				program glitch	1	5						
	Correct Language	Visitor confusion, frustration	4	program glitch	2	8	Testing	Chris Splees November 2017				
				mislabeling	1	4						
User Interface	Stuck in loop or menu	Visitor frustration, exhibit closure	5	Glitch	2	10	Make easily resetable, add a back button, cycle back to home, timer.	Chris Splees and Rachel Jakob November 2017				
				Poor layout	1	5						
	Hacked	Displays incorrect images, files erased, slow running	3	Internet connection	1	3	disconnect exhibit from internet, and disable or cover all usb ports. Save all files in multiple places, and run minimal programs for quick reinstallation.	Chris Splees and Rachel Jakob November 2017				
				usb connection	1	3						
				weak cybersecurity	1	3						

ENGINEERING DATA SHEET	Sheet No. M – 1/3	Date: 5/4/17
Appendix M: MATLAB to create regulator motor profile		

Setting the gear motor profile

Table of Contents

Keiran Hansen Team Otto-Mated

Clean up

```
clc
clear
close
```

Initialize Stuff

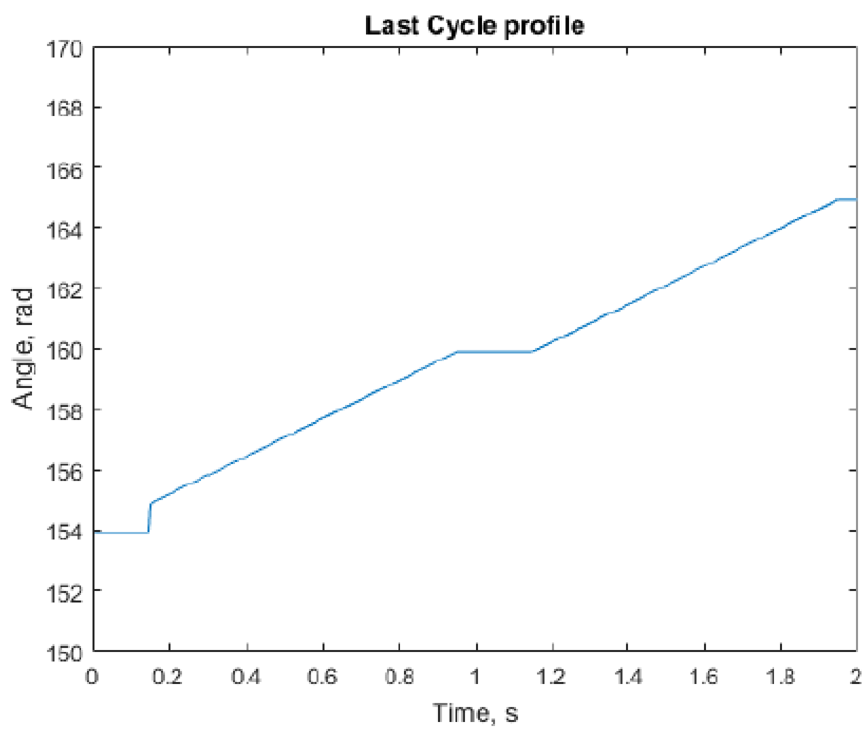
```
Speed = (120)*(1/60)*pi; % rotational speed in radians/sec, input RPM
% time = 0:0.05:30; % Sets the time array
tmax = 30; % length of time
t = 0;
tstep = 0.005;
AbsTime = t:tstep:tmax; % total time array
TotalAngle = zeros(length(AbsTime),2);
TotalAngle(:,1) = AbsTime.';
CycleStart = 0;
counter = 0;
FirstRelease = 0.15;
FirstCatch = 0.95;
SecondRelease = 1.15;
SecondCatch = 1.95;
```

Run

```
tstart = 0;
while t < tmax
    numreltimes = tmax/2;
    reltime= tstart:tstep:2;
    Angle = zeros(size(reltime));
    for i =1:length(reltime)
        Angle(i,1) = CycleStart + Speed*reltime(i)*stepfct(reltime(i)-
FirstRelease)...
            -Speed*(reltime(i)-FirstCatch)*stepfct(reltime(i)-
FirstCatch)...
            +Speed*(reltime(i)-SecondRelease)*stepfct(reltime(i)-
SecondRelease)...
```

ENGINEERING DATA SHEET	Sheet No. M – 2/3	Date: 5/4/17
Appendix M: MATLAB to create regulator motor profile		

```
            -Speed*(reltime(i)-SecondCatch)*stepfct(reltime(i)-
SecondCatch); % gives the angle of the gear
        counter = counter+1;
        TotalAngle(counter,2)= Angle(i,1);
    end
    tstart = tstep;
    CycleStart = max(TotalAngle(:,2));
    t = t + 2;
end
figure(1)
plot(reltime,Angle)
axis([0, 2, 150, 170])
xlabel('Time, s')
ylabel('Angle, rad')
title('Last Cycle profile')
figure(2)
plot(TotalAngle(:,1),TotalAngle(:,2))
xlabel('Time, s')
ylabel('Angle, rad')
title('Total Cycle profile')
ExporttoSolidworks = TotalAngle;
csvwrite('Regulator Gear Angle.csv',ExporttoSolidworks)
```



ENGINEERING DATA SHEET	Sheet No. M – 3/3	Date: 5/4/17
Appendix M: MATLAB to create regulator motor profile