Final Design Report

Schlieren Imaging of Air Assisted Injectors

ME 450 Section 007 (Professor Randy Schwemmin): Fall 2021, Team #25
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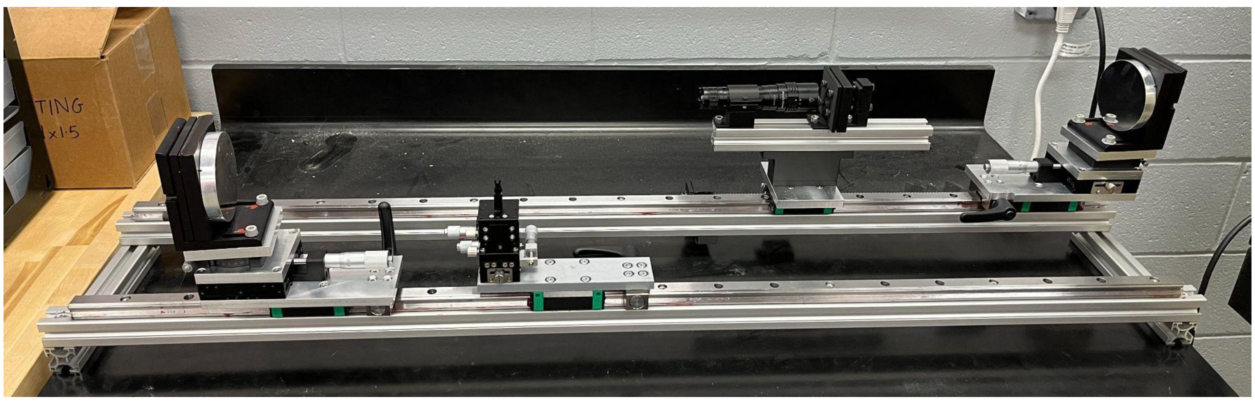

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Revised Abstract

The desired outcome of the project is to research, design, and manufacture a fully functional and ready to use Schlieren imaging system for the purpose of imaging injector sprays and leaks while being comparable to existing Schlieren system quality for a smaller cost. This system will be used to validate computational fluid dynamic models and the formation of Mach diamonds.

Executive Summary

Team 25 was tasked with designing and manufacturing a Schlieren Imaging system to assist Nostrum Energy in validating CFD simulations of injector sprays and leaks. There are currently no off-the-shelf solutions to verify the models given the sponsor's requirements. The stakeholders provided input regarding the requirements of the Schlieren Imaging System and Team 25 developed specifications from them. The key specifications for the system are the following: the system must fit within a 3' by 4' footprint, the system must cost less than $2000, and the system must take less than five minutes to calibrate. This unique combination of requirements is not fulfilled by any commercial Schlieren systems; hence, a custom solution must be developed. The Team used functional decomposition during the concept generation phase. This allowed The Team to focus on individual design challenges. Many design concepts were generated via brainstorming, then narrowed down through discussion and Pugh charts. Once chosen, the final concept was iterated upon while performing budget and other analyses.

A Z-type Schlieren system was chosen for its compactness, relative simplicity, and sufficient distance between the test area and mirrors. The system active components are a single LED flashlight, a condenser lens, a pin hole, two parabolic mirrors, a razor blade, and a DSLR camera. The system is mounted on a frame of Aluminum extrusion, which provides rigidity and a flat surface while being inexpensive and lightweight. The majority of the components are mounted on linear rails which provide collinearity, and adjustability in the x-direction. To lock parts into position, rail brakes are used where fine adjustment is needed and ball screws when rough adjustment is sufficient. For additional adjustment, commercial translational and rotational stages are used. Custom 3D printed and machined hardware was used to fixture stages and active components together. Finally, mounted above the frame is the injector fixture which has Z-direction adjustability and accommodates a variety of injectors. The Final BOM of the system came out to roughly $1850. leaving room for extra parts which were purchased during assembly. The majority of the manufacturing was done on mills in a makerspace and on Nostrum's drill press and 3D printer. Assembly was also performed over the course of two days at Nostrum.

Only a few of the validation tests were performed as the system did not reach full functionality by the end of the semester. The tests that were performed are the following: system compactness, affordability, using supplied mirrors, lens angles, xyz filter adjustability, and camera placement. The system passed all of the tests which were performed. The final system is sufficiently compact, lightweight, simple to calibrate and inexpensive. The system was able to capture Schlieren images, however they were of low quality. This is mainly due to dim images, and an ineffective camera recording method. The Team believes that the system they built is 90% of the way there to becoming the full functioning product that the sponsors have asked for. Many of the major requirements are fulfilled and the system is reliably able to generate Schlieren images.

However, more work is required to run additional experiments and make final changes to the system in order to improve the quality of the images collected.

Project Introduction

Team 25 has been tasked with creating a Schlieren imaging setup that will allow the sponsor, Nostrum Energy, to both validate Computational Fluid Dynamics (CFD) simulations of their injectors and conduct tip leakage testing of various existing fuel injectors. Nostrum Energy currently has CFD simulations of various injectors and an air assisted injection nozzle but currently do not have a way to test if the simulations are representative of how the injectors actually function in the real world. There is no current off-the-shelf solution available in the desired price range for visualizing injector spray and leakage density gradients in both image and video. The injectors that the sponsor wishes to image will potentially be tested with are Viscor, n-heptane, water, and other non-flammable gases. A further outline of the other primary, secondary, and tertiary stakeholders can be seen in Table 1 with their specific project relationships indicated.

Intellectual Property:

Nostrum Energy mandates that any ideas generated by an individual associated with the work being done at Nostrum Energy are the property of Nostrum Energy and may not be used elsewhere per their Non-Disclosure Agreement (NDA). All members of Team 25 agreed to this NDA when they signed on to the project. Therefore, all intellectual property of this project will be retained by Nostrum Energy.

Table 1: Color coded chart of project stakeholders with key

Tier	Stakeholder	Essential?	Contact Name(s)	Specific Role	Noteworthy Contributions
Primary	Nostrum Energy Management/Engineers	Yes	Sam Barros & Lee Markle	Head of R&D and Engineering Consultant, respectively	Provided overview of project, broad requirements, starting recommendations for other stakeholders to contact. Provided important materials/parts for project (refractory mirrors).
	ME 450 Team	Yes	David Johns, Robert Nawara, Carson Koegel, Anthony Mazzola, & Alyssa Orlans	ME 450 Project team members	All design progress on the ME 450 project
	Nostrum Energy Machine Operators	No	Steve Dootz	Operations Engineer	Consulted on requirements for safety and ease of use, and provided recommendations for reducing cycle time
Secondary	Mechanical Engineering Department	Yes	Jon Estrada	Mechanical Engineering Professor	Provided valuable information about imaging techniques and possible light sources as well as resources for research.
	Aerospace Engineering Department	Yes	------------	------------	------------
	Lab Techs	No	Bachir Abeid	Lab Tech within Mechanical Engineering Department	------------
	Holmarc	No	------------	------------	------------
Tertiary	Nostrum Energy's Customers/Associates	Yes	Cameron Tropea	Former Engineer at Delphi Technologies	Provided functional recommendations for schlieren design, different types of knife-edge filters, documentation on suppliers, modular designs, and light sources
	McMaster Carr	No	------------	------------	------------
	Coronavirus/Medical Teams	No	------------	------------	------------
	Valve Manufacturers	No	------------	------------	------------
	ASTM	No	------------	------------	------------
	Thor Labs	No	------------	------------	------------

Key				
Resource Provider	Beneficiaries and Customers	Supporters of the Status Quo	Complementary Organizations/Allies	Affected or Influential Bystanders

Stakeholder Context Assessment:

The main stakeholders that will be positively impacted by this project are the various stakeholders associated with Nostrum Energy including the Management and Engineering teams as well as the lab technicians, and machine operators. This is because our design aims to create a repeatable test asset that will simplify operations and allow the engineering team to validate their designs. A few stakeholders that may be affected negatively by this project are custom machine manufacturers that make very costly test assets in an attempt to solve the problem of visualizing injector tip leakage and validating Computational Fluid Dynamics (CFD) simulations. Similarly, Nostrum Energy's competitors will be negatively impacted by this project as Nostrum will now have an asset that will allow them to create higher quality products that might steal sales from their competitors.

When viewing this design through the lens of public health, safety, and welfare, a key topic comes into focus. Injector tip leakage can lead to poor idle quality and increased fuel consumption for internal combustion engine powered vehicles. By optimizing injectors using the design outlines in the report, the efficiency of internal combustion engines could be improved. This improved efficiency would help to reduce the effects of climate change and all of the resulting negatives that come along with it. Similarly, when looking at potential impacts on the global marketplace, the final design is significantly cheaper than other Schlieren imaging products without sacrificing the required precision needed for a high-quality image. Implementing the design on a large scale would force the price of comparable products down, meaning that more people and companies would have access to this technology. With diverse potential applications in areas such as medicine or aerospace, the design could potentially allow stakeholders to create better solutions to various problems. This, in turn, could have a positive social impact on the quality of life for people affected by the solutions. However, depending on the application, the opposite could be true. Implementing the design in military research could cause a lot of strife and negatively affect those exposed to the resulting technology.

Overall, the final design is more of a “one-off” test asset for Nostrum Energy and doesn’t have far reaching social and economic implications. For this reason, Team 25 used a basic stakeholder map and critical thinking in order to determine the potential societal impacts of the overall design.

The biggest feature of the context affecting the project and how it will be implemented is the location where it will be used. Nostrum Energy has an operations room where all of their test assets are located. It is a brightly lit room with various potentials for vibration and electromagnetic interference. The specific location of the test asset can be seen in Figure 1. All of the test equipment is operated by technicians trained on the specific asset. For this reason, the final design needed to be able to stand up to these conditions and be approachable for a standard Nostrum Energy testing employee to satisfy the design requirements.

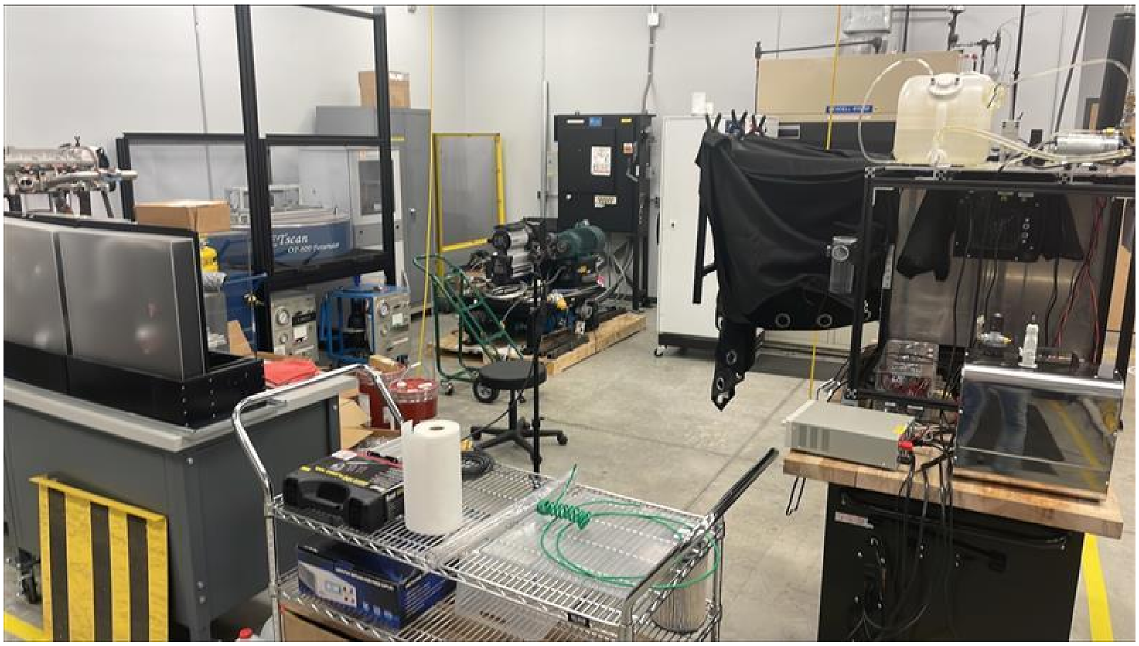


Figure 1: The location in the operations room where the final design will be used.

Library:
Overall, the Team's only engagement with the librarian was through the videos as part of the ME 450 block. Using the information provided in the videos, the team was able to execute searches for articles and standardized procedure documents that allowed them to form a knowledge base around the general principles of Schlieren imaging. An approach that worked well for the team was having each member perform their own search for documentation and adding useful documents directly to the shared Google Drive. This methodology allowed for a larger pool of relevant resources to be formed in a way that ensured all team members to access the same information. This allowed the team to be on the same page when it came to ideas and principles of Schlieren imaging without each member having to laboriously find all of their own articles.

Some challenges the Team encountered when it came to information gathering was the length of some of the supporting documentation around fuel injector testing. The one specific standard created by the Society of Automotive Engineers (SAE) relating to injector testing was SAE

J2715. This standard was roughly 500 pages of extremely dense material which made it difficult to pick out the facts necessary for the project. Another challenge encountered was dealing with conflicting information. Some of the advice gathered from stakeholders contradicted advice from other sources, and it was difficult to choose what sources to listen to.

Inclusion and Equity:

One of the main power dynamics that existed between the Team and their main sponsors at Nostrum Energy, especially at the beginning of the project, was the difference in knowledge between the seasoned professionals and the students. This power dynamic created a rocky start for the Team as they took a lot of the suggestions and technical advice from the sponsors as things they should work very hard to incorporate into the final product. While much of this information needed to be involved in the final design, there were a few key parameters on which the sponsors did not agree. This forced the Team to be the "middle man" as they tried to figure out exactly what the sponsors were looking for in terms of requirements.

There was also a power dynamic that came into play when the Team was talking to experts or other stakeholders with a deep technical knowledge of Schlieren imaging systems. One example of this was when a lab technician told the team that keeping specific components as far apart as they were in the current design would result in inaccuracies in the final Schlieren image the Team was trying to achieve. This forced the Team to spend time discussing new options and a potential redesign before finding out that this information was in fact untrue. The power dynamic present in this example is one of perceived knowledge. The Team believed that this individual knew something that the team did not which ended up with the team wasting time.

The idea of perceived knowledge also affects the power dynamics present between the Team and potential end users of the design. The Team knows how every component of the design is manufactured and how it is supposed to work and be used in the final build. This deep knowledge of the design and the Team member's identities as mechanical engineering students at the University of Michigan could result in the Team overlooking key components of the build that may in fact make it more difficult for the end user to engage with the product than initially intended. While an attempt was made to mitigate this by interviewing specific end users and stakeholders that would be interacting with the product, there is always the possibility of an oversight.

Power dynamics and their various complications were also present within the design Team itself. The main way these power dynamics came to light was through the differing technical knowledge of each team member especially as the Team has had differing levels of hands on experience due to COVID-19. Differences in technical knowledge meant that specific team members were deferred to when it came to the overall design and manufacturability of the final product. Furthermore, some team members had previously worked at Nostrum before the start of this project. Because of this, there was a difference in knowledge of the project context and the sponsor's specific needs. In the early stages of the project, the team members who worked at Nostrum were more prepared to make design decisions than the other members. This effect lessened as the semester progressed and the knowledge levels became more equal.

Despite these power dynamics and the various struggles that came with them, the Team made a conscious effort to try and hear and take into consideration the voices of every different stakeholder and team member when making decisions. Often, this approach meant talking about the concerns and claims of one stakeholder with another. While slow, this approach allowed the team to take multiple views into account before making a decision. Similarly, the Team attempted to listen to every team member’s viewpoint, dissenting or not, before making decisions that would affect the Team itself, the stakeholders, or the final design.

A different aspect of the Team that had its own tradeoffs was the cultural similarities between the team members. Two of the main similarities were that every member of the team was White and from the Midwest. This common thread of culture allowed the team to gel together and start working as an effective unit very quickly. However, the lack of cultural differences within the team meant that they may have missed out on ideas and solutions that could only come from having different cultural perspectives.

The cultural similarities didn’t stop within the team. Our main sponsor at Nostrum Energy, Sam Barros, is also an engineer and has extensive experience in technical fields and the various unspoken rules surrounding design projects. This made it very easy to communicate our ideas with him and make sure that the team and Sam both understood what was being asked and how it would be best to go about creating the final design.

Ethics:

The largest ethical dilemma that the Team faced during their design project was a tradeoff between meeting the sponsors desired budget and creating a high-quality product that the Team could be proud of. Creating a design that performed in a subpar manner was against the personal morals of the Team as they committed to creating a high-quality prototype to aid Nostrum Energy. This dilemma led the Team to create a cost analysis in order to communicate with their sponsor what a high-quality prototype would cost versus what they were able to accomplish at the initial budget. Thankfully, the Team’s sponsor agreed that a higher quality product would satisfy the requirements more completely and raised the budget.

Our product is unlikely to enter the marketplace; However, if it did, the team must be careful of the ethical dilemmas associated with the widespread use of this product. The quality vs. cost dilemma would be increased if the product is mass produced. The Team would not have enough time to produce a large number of low cost, high quality products. Secondly, the team would encounter a common ethical dilemma associated with how the product will be used. It is possible that a consumer will have a use case for the product which is controversial or net detrimental. If so, the team will have to find a balance between being fair, making profits, and the overall social good.

The ethical dilemma with the project's budget boiled down to a matter of honesty and integrity. The Team agreed to create a high-quality product, and they were determined to deliver on that agreement. This moral code of being able to stand by one's word and honest work is one that the Team, as students, are required to uphold at the University of Michigan College of Engineering and will undoubtedly be held to by their future employers.

To complete this project, the Capstone Design process outlined in the ME 450 learning block regarding design processes will be followed. This design process consists of problem definition, concept exploration, and solution development and verification. In the problem definition phase entails conducting interviews with stakeholders and performing library research. Concept exploration first involves divergent thinking, where as many ideas are generated as possible, followed by convergent thinking, where concepts are narrowed down. In solution development, a detained design is formed, manufactured and assembled. Finally, during verification tests are performed to evaluate the performance of the system. Using a systematic design process such as the one described above ensured that the team did not rush towards a final design without fully understanding the problem, or considering all possible solutions. Furthermore, the systematic approach helped the team understand what work still needed to be done and allowed for the creation of an effective project timeline.

At the end of the design process, the sponsor wishes to have a functioning Schlieren imaging system that can be used to test their various injectors with the total cost of parts staying under $2000 ~~$1,500~~ USD excluding the cost of the given camera and parabolic mirrors. Therefore, the Team will need to accelerate the timeline of the class in order to create a functioning test asset by the end of the semester since part ordering will require some lead time.

Team 25 has gathered information on key resources pertaining to Schlieren imaging. A few of these include a paper outlining the parts and processes used to build a Schlieren imaging system on a tight budget put together by a European School [1]. This paper allowed our team to benchmark our proposed system against a similarly priced setup to visualize potential places where our design might have to compromise to stay under the sponsor's budget cap. Another helpful resource was a lecture created by Professor Cameron Tropea that illustrated the mathematical concepts and overall big picture ideas behind what are known as “classical” Schlieren imaging systems [2]. This lecture increased the Team’s understanding of Schlieren imaging and provided it with information about how utilizing different techniques could result in different qualities in the final image. In addition to these written resources, the Team was able to participate in a number of stakeholder meetings that provided additional information about different imaging techniques and helped to further clarify the design requirements and resulting specifications.

A few key stakeholders interviewed by the Team included Sam Barros and Lee Markle, who are the project’s main sponsors and helped to outline its requirements and corresponding specifications. Another helpful stakeholder interview was conducted by the Team with Professor Cameron Tropea. During this interview, Tropea discussed several different important concepts, especially pertaining to the different methods of separating the light of the image and the corresponding effects on the final image. This information expanded the knowledge of Team 25 and will be pivotal in the concept exploration phase of the project. Finally, the Team met with Steve Dootz, an operations technician at Nostrum Energy who would likely be using the final testing asset, and Professor Jon Estrada, a mechanical engineering professor at the University of Michigan conducting Schlieren imaging research, who walked the Team through his lab setup. Steve provided useful feedback about setup times and other expansions of the requirement “easy to use”. Professor Jon Estrada outlined information pertaining to shutter speed and final image quality that Team 25 used to further define realistic imaging requirements for our application.

Currently, there is an information gap relating to the final use of the Schlieren imaging system. One of our sponsors does not expect the system to be able to image an injector spraying n-Heptane testing fluid while the other sponsor does. This miscommunication will need to be resolved before the concept generation gets underway. In order to fill this gap, a meeting will be held with both sponsors in order to clarify the final expectation of the asset’s performance capabilities.

Requirements and Engineering Specifications

Requirements and specifications were generated from conversations with our stakeholders and corresponding background research, and were ranked subjectively based on importance. They are shown in Table 2.

Table 2: Compiled specifications and requirements chart, along with individual and compiled rankings

Req #	Requirements	Specifications	Specification Ranking (1-3)	Requirement Ranking (1-5)	Total Ranking (1-15)

1	Must be compact	Table-top size, ~~3’ by 5~~’ 3’ by 4	3	5	15
~~2~~	~~Must follow SAE J2715~~	~~Image 100 mm x 100mm~~	~~3~~	~~4~~	~~12~~
~~3~~	~~Must capture more focused image of injector~~	~~Image area = 25mm x 25 mm~~	~~3~~	~~3~~	~~9~~
4	Must be simple for operators to use	One button click to operate equipment for data capture	1	3	3
		locating features for repeatable nozzle fixturing with cycle time under 1 minute	2		6
5	Must be rigid	Must not deform when horizontally shock loaded < 220 N to the table	3	2	6
6	Must be lightweight	< 100 lb (not including work table the machine is mounted to)	3	2	6
7	Must be affordable(excluding camera)	Budget of $~~1500~~ $2000	3	4	12
8	Must video and image capture flow pattern of supersonic spray from injectors	Capture images at minimum 60fps or max frame rate of provided camera	3	4	12
~~9~~	~~Must be X-Y adjustable~~	~~X travel: 50 mm~~	~~1.5~~	~~3~~	~~4.5~~
		~~Y travel: 50 mm~~	~~1.5~~		~~4.5~~
10	Must take minimal time to set up/calibrate	< 5 min to calibrate prior to each usage	3	2	6
11	Robust to temp changes	No calibration required 70 +- 10 degrees Fahrenheit	3	3	9
12	Must allow imaging using currently supplied mirrors	Image size 2”x2”	3	4	12
13	Lens positions must not reduce image quality	Lens angle < 10 degrees	3	3	9
14	Extracts air/fluids	Fits shop vac hose	1	4	4
		No droplets visually seen on mirrors	2		8
15	Filter must be X-Y-Z adjustable	X travel ¼”	1	3	3
		Y travel ¼”	1		3
		Z travel ¼”	1		3

16	Camera lens has narrow view	Lens focal length > 100mm	3	1	3
17	Camera can be placed close to filter	Minimum distance between camera and filter is < 1inch	3	3	9
18	Light source must have adjustable intensity	> 5 intensity levels	3	2	6
19	Light on mirror must be uniform	Max brightness < 1.2 * Min brightness	3	3	9
20	Maintain relative flatness across the frame	Maintain 2 thou inch difference in height between ends of frame	3	3	9

Requirements were primarily determined from consultations with project sponsors and related stakeholders; in some cases, the sponsors would directly provide specifications for the requirements. Otherwise, background research and first principle analysis were used to generate specifications. All specifications were checked with at least one of our sponsors.

Requirements 1 and 7 were based on practical constraints provided to the team from the sponsors of the project; more specifically, the size of the machine and the budget available to build it. Requirement 1 was formed based on footprint restrictions present at Nostrum Energy's operations facility. The machine will need to be mounted on top of a work table in a specific location of the room, and must remain within the footprint of that table due to space constraints. The dimensions of the table are 3' by 4'; thus, our specification for the horizontal footprint of our machine is that it must remain within 3' by 4'. A vertical constraint was not given, as extending the machine vertically would not interfere with the operation of the other machines in the work area. Requirement 7 was formed based on budgetary constraints; our sponsor provided a budget of $2000.

Requirements 2, 3, and 8 concern the size, material compatibility, and visibility of the injection area and the corresponding image/video recorded by the system. Requirement 8 was directly provided by the sponsor, along with the corresponding specification, and concerns the ability of the system to document fluids moving at high speeds.

Requirement 4, 9, and 10 originated from the sponsor's need for the Schlieren rig to be repeatable and usable for multiple cycles of different nozzles. Requirement 4 (and the corresponding specifications) were formed after consulting with Steve Dootz, an operations team member at Nostrum. Steve advised us on the functionality that could guide low cycle time and simple machine operation. Requirement 9 followed both conversations with sponsors and a former engineer at Delphi Technologies, Cameron Tropea, who advised that the filter for the system should be adjustable. The specification was directly provided by the sponsors upon consultation. Requirement 10 concerned the overall calibration time and was also provided directly by the sponsors.

Requirements 5, 6, and 11 were based on practical considerations of the background operations around the machine. After discussions with the project sponsors, it was clear that due to foot traffic around the machine's location, the machine might get bumped occasionally by passing team members which might dislocate the filter; in order to reduce maintenance time, requirement 5 was added. The force specification was created based on both the average push force from a human male (220 N) and some first principles analysis of the force that would be transferred from a collision (227 N). Requirement 6 was derived from a stated need for the machine to potentially be moved from its work table to other locations in the operations room; the corresponding 100 lb specification was derived from the max lift capacity of an average human with a safety factor of 2. Finally, Requirement 11 was derived from a conversation with the sponsors of the project, during which it was stated that temperature changes had affected prior Schlieren rigs used in laboratory applications. The corresponding specification was based on the sponsors' estimation of the average temperature of the operations room, along with the variance in temperature that the room experiences.

Requirements 2 and 3 were removed because of new requirements from sponsor communications about using the mirrors provided to the Team. The provided mirrors can't image the dimensions originally desired, hence the requirements had to be removed and revised. The revised version of this requirement can be seen in Requirement 12. Requirement 12 gives a much more achievable image size of 2"x 2" given the parabolic mirror's focal length. Requirement 13 was added after conversations with the sponsor regarding image processing and the quality of the image were addressed. In order to achieve a high-quality image and minimize distortion, each mirror should be at an offset of 10 degrees or less to allow for no fish bowling effect in the final image which is not desirable. Requirement 14 is related to the fumigation of the air or other fluids used during testing. The use of a shop vac is ideal due to its little effect on the pressure gradients seen in the image and thus it is necessary to have a way to adapt the shop vac to the extraction method. No visual droplets being seen in the mirrors for this requirement is also desired to minimize image distortion. Requirement 15 was an edited requirement from Requirement 9. The filter, after analyzing adjustability needed for each component, made the Team realize that an X-Y adjustable mount was not sufficient and the Z axis needed to be adjustable as well. Additionally, a better grasp on the precision of adjustability was found and the numerical values of this adjustability were altered to be ¼" in each direction. Another, changed requirement is the system budget from $1500 to $2000. This change was a result of sharing different BOMs to the sponsor. The sponsor favored the more expensive plan and consequently increased the Team's budget. Requirement 20 was added to address the precision of the frame's flatness. This requirement is important because a surface that is not flat would cause the light to hit each surface (i.e.

condenser lens, mirror 1, mirror 2, filter, and camera) at a different angle, deviating the final exit point of the light. Therefore, this specification and requirement was given a very high ranking of 9. The specification was to have no more than 0.002” deviation across the height between the end surfaces.

A number of requirements either compete or complement each other; a brief analysis can be seen in table 3 and table 4.

Table 3: Compiled list of competing requirements, along with analysis of why they are competing

Competing Requirements		
Requirement 1	Requirement 2	Reason for Competing
Must be Rigid	Must be lightweight	More structural reinforcement to add rigidity also adds weight
Must be X-Y adjustable	Must take minimal time to set up/calibrate	Added adjustability may require additional features/functionality that increases calibration time
Must be affordable(excluding camera)	Must be X-Y adjustable	Precise x-y tables are expensive, may add to budget

Table 4: Compiled list of complimenting requirements, along with analysis of why they are complimenting

Complimenting Requirements		
Requirement 1	Requirement 2	Reason for Complimenting
Must be simple for operators to use	Must take minimal time to set up/calibrate	Same features/functionality that lower calibration time may simplify operator usage
Robust to temp changes	Must be Rigid	Added thickness/reinforcement for rigidity will decrease thermal strain

Problem Analysis

The project will need to be analyzed using different engineering fundamentals taught throughout the mechanical engineering curriculum at the University of Michigan. These fundamentals include Fluid Dynamics, Optics, Imaging, Heat Transfer, Mechanical Design and Manufacturing, Solid Mechanics, Controls, as well as cost and budget tradeoffs.

Some key specifications that needed to be implemented included the 3’ by 4’ footprint of the setup. These two specifications will rely heavily on the fundamentals of optics and imaging because each mirror that will be used in the setup has a specified focal length, which will dictate the overall length of the setup. Those mirrors will have to comply with the specifications of the setup area.

Through some research of the various forms of Schlieren imaging, Z-type Schlieren seems to be the most applicable. The advantages and challenges of Z-type include

- Advantages
    - Compact form of Schlieren utilizing two parabolic mirrors and knife edge [2]
    - Widely used for imaging injectors
        - Research conducted in Australia on Z-type Schlieren imaging of gas sprays [3]
- Challenges
    - Large amount of time required for focusing light source and adjusting components minutely
        - Can use expertise of Professor Tropea, main stakeholder, and Aero Dept for help with the challenges of focusing

Other key specifications that will drive the project include the precision and rigidity specifications to ensure that minimal repetitive calibrations will be required. Some key engineering techniques used to address this would include

- Solid mechanics
    - Used to determine loading cases on fixtures and loading of the table during sudden pushes. Aids in determining rigidity.
- Mechanical Manufacturing and Design
    - Used to precision manufacturing of the plate/frame, which may include geometric dimensioning and tolerancing. This will aid in precision of the mounting and overall flatness.
        - May be difficult to precision manufacture large plates. Tuning of custom machines should be considered as well as partnering with school machine shop to develop plan
- Cost Analysis
    - A traditional optical table is too expensive but meets the specifications of flatness and precision of the project , so cost analysis will be necessary to determine what parts should be bought and what parts are worth manufacturing.
- Thermodynamics

    - Used to determine the amount of thermal induced miscalibration due to heat generated from injectors and temperature change from laboratory setting.

The experiments will need to be repeated quite frequently on the setup. One specification calls for injector fire and image capture to be triggered simultaneously. This will aid the technician stakeholders in the operation of the machine with its ease of use. The engineering fundamentals learned in controls, signal processing, and circuitry will help promote the simultaneous trigger. This will require either an Arduino or some sort of DAQ with BNC connectors. The company previously built an arc-flash generator with a similar control scheme that can be used as a model during the control implementation of the Schlieren setup.

Because of the restricted budget for the project of $2000 and the provided equipment, there are limiting factors that the stakeholder has put on the complexity and sophistication of the project. The provided camera will limit the resolution and frame rate at which images and videos can be captured.

Although the main stakeholder is an automotive supplier, it will be important to consider the other stakeholders in this problem. Other automotive manufacturers as well as aerospace companies will be interested in Schlieren imaging for validation purposes. Some stakeholders that fall outside of this industry include the medical and coronavirus researchers that can use this type of machine for experimental particulate testing. It is important that this setup be modular to allow others to use this setup for a wide range of applications in addition to injector testing.

It is important to note that after all stakeholders are considered and the design has been completed to benefit a wide range of customers, the product must be executed completely. The sponsor expects this project to finish as a fully functional product that can be implemented into their test area almost immediately. To address this quick timeline, the team will have to use the engineering fundamentals of scheduling and procuring materials. The concept generation phase will need to move quickly and materials will need to be ordered quickly based on potential lead times to properly schedule the assembly of the product and allow for validation. Because of this tight timeline, scheduling will be a very important concept that will be used.

Project Plan

The sponsor wants a completed and functional test asset by the end of the semester. This means that the project needs to reach a fully realized state. To achieve this, the project timeline must have a faster pace than the timeline set by the design reviews in the course.

The structure of the timeline is similar to the design process which was outlined in the introduction on page 6. The timeline is broken down into the following chronological sections:

Problem Definition, Idea Formation, Idea Selection, Detailed Design, Prototyping, Testing, and Creation of Final Product. By assigning members different tasks in the timeline, multiple tasks will be completed simultaneously. As a consequence, the major timeline sections have some overlap.

A major anticipated challenge for the team is sourcing parts in time to be machined and assembled into the final product. It is possible that lead times for necessary components are several weeks long. To alleviate this issue, the detailed design and prototyping phases of the project will overlap. Some team members will focus on creating CAD models for the final design, while others will be sourcing parts when the team decides we need them, rather than waiting for the CAD to be completed. The design of the system will likely be broken down into subsystems. The subsystems which require parts with potentially long lead times will be finalized first, allowing the parts to be ordered early. A process such as this may lead to a scenario where the team wants to make changes to a part that has already been ordered, but cannot; the team will be forced to adapt instead. Though this situation is undesirable, it is a necessary risk to ensure that the project is completed on time.

Another notable feature of our project plan is the relatively long prototyping and testing phase. Because the goal of the project is to have a fully functional product, the team needs enough time to fix the inevitable complications that will arise in the prototyping and testing phase. Similar to the design phase, the prototyping and testing phases will focus on subsystems of the product. Subsystems will be manufactured and tested as soon as the parts are available and the design is complete. Subsystems that have parts with the longest lead times will likely be tested last.

The team intends to follow this project plan closely; however, the plan is meant to be flexible. It is anticipated that as the team works through the project, new information will allow us to develop a more effective project plan. Tables 8.a-g describe in detail each phase of the project plan and the individual tasks with their corresponding dates.

Aside from the project timeline, another major challenge for the project is budget constraints. The project budget is $2000. High quality Schlieren systems can be upwards of $10,000. There are examples of systems closer to the required price range, but they have limited functionality.

There are a few ways to overcome this challenge. Firstly, the team has access to some of the most expensive parts of the system already. These parts include a camera and parabolic mirrors. If the team is able to utilize these components, then a larger portion of the budget can go towards other areas of the project. The team can further reduce cost by designing and machining their own solutions rather than purchasing off the shelf components. For example, quality Schlieren systems often include an optical table that typically costs over $1000. The team will likely design and manufacture its own solution to an optical table at a significantly reduced price.

Concept Generation

In order to start off concept generation, the team had a brainstorming session where the design was broken down into functional components and possible solutions were brainstormed for each. During the brainstorming session, the team utilized a few different concept generation methods including morphological analysis, design heuristics, and divergent thinking. The team incorporated morphological analysis by breaking the design down into its various subcomponents and generating possible concepts that could be used to satisfy the specific function. Along with this method the team utilized design heuristics to come up with different ideas than they would have originally. Finally, Team 25 employed divergent thinking to come up with ideas that themselves may not have been viable but led to other more useful ideas. Once this process was completed the ideas were narrowed down with “gut checks” and engineering intuition. The results of this brainstorming can be seen in Table 5.

Table 5: The table shows viable ideas in black and eliminated ideas in red.

Frame	Table Attachment	Optical Fixtures	Light Source	Collimating	Optics	Knife edge	Nozzle Fixture	Fume Extraction
Optical Table T-slot Table None Homemade Flat-plate Granite Wood Epoxy-Resi n Welded Steel Tubing Legos Telekinesis	Bolts C-Clamp L-Shape Hold Command Strip Velcro Double Tape Gravity Glue Loctite 2-piece vise Screws Zip-ties Nails	Magnets 3-point set-screw Commerci al posts X-Y Adjustable Tripod 2-axis rotational Goosenec k Machined supports 3D printed fixtures Mag-Lev	Pen Laser Class 12 Laser LED Flashlight Phone Sun Candle Incandescen t Ambient	Pin hole Gypsum Lens Iris	Lenses Parabolic Mirrors Flat Mirrors Glass Crystals Compoun d Lenses Digital Processing Shiny Al SLA Lenses Ice Water Methane	Knife String Razor Pinhole Color scale Iris Disk None Finger Gas Prism Black Hole Rock Size	Nostrum Pred Custom machine 3D printed Cast Chem post T-slot hairclip	Shop vac Regular vac fan-> door Nothing Air purifier HEPA Air condenser Lungs Fume hood Respirator Tree No Fumes

After this brainstorming process was completed and the team had narrowed down the resulting options each team member generated their own overall concept by taking one idea from each functional group. In addition to this comprehensive concept each member chose three specific functions and sketched a more detailed view of possible ideas for each. A few examples of the overall concepts can be seen in Figures 2,3, and 4 and a mix of the individual component designs can be seen in Figure 5.

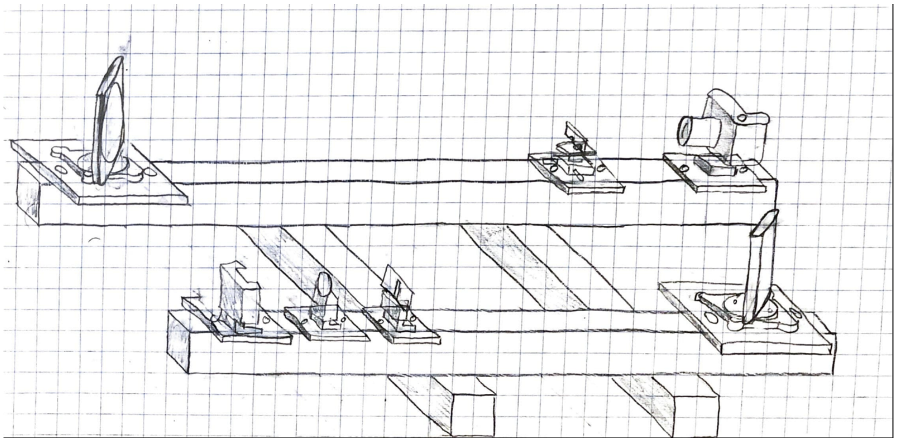


Figure 2: An example of an overall design including parallel extrusions and rotational mirror fixtures. This design also includes an XYZ stage for the razor fixture and custom 3D printed mounts for the light components. The active components are mounted directly to the extrusion frame.

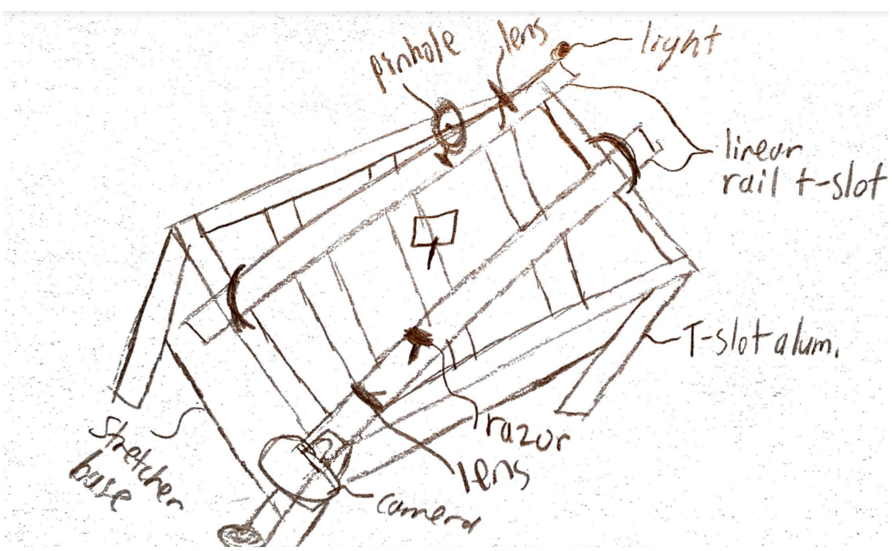


Figure 3: A comprehensive design sketch illustrating angled linear rails paired with T-slot extrusions. The linear rails mount onto a large t-slot table. This design features a lens and pinhole for light conditioning.

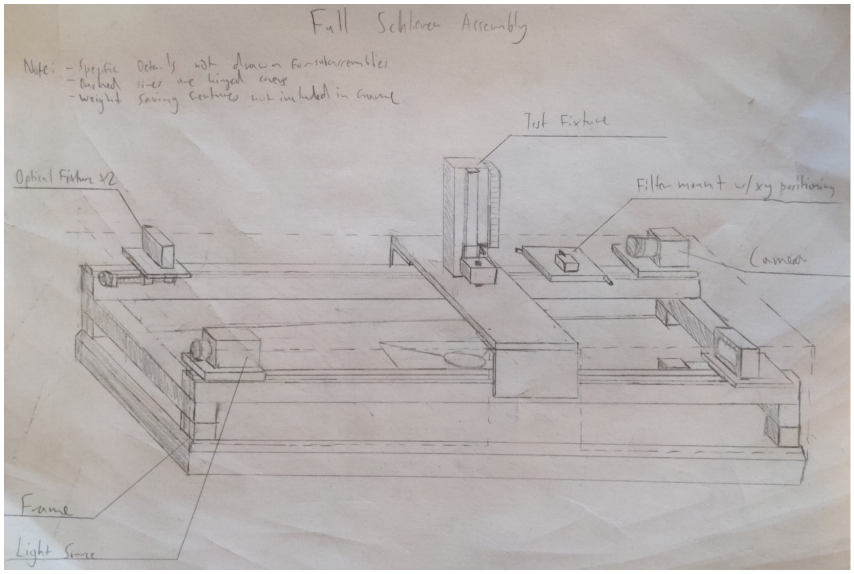
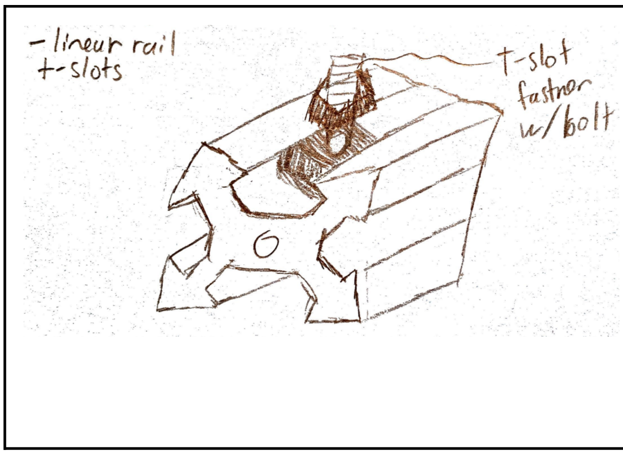
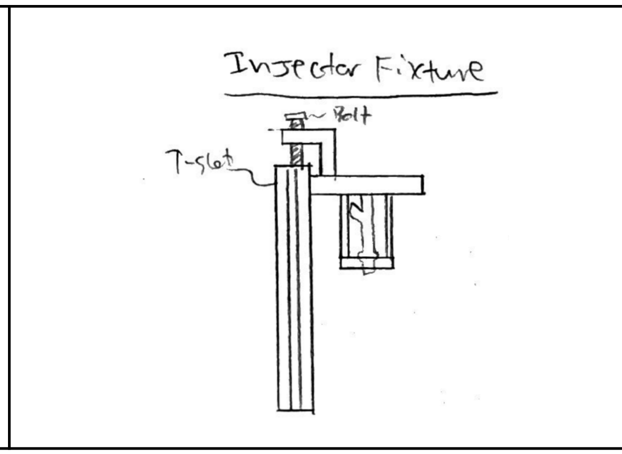


Figure 4: A design sketch with proposed square T-slot extrusions and linear rails. This design has a multilayer extrusion frame. Mounted on the frame are linear rails which provide x-direction translation. Atop the frame is an injector fixture. The active components of the system are placed in the corners.





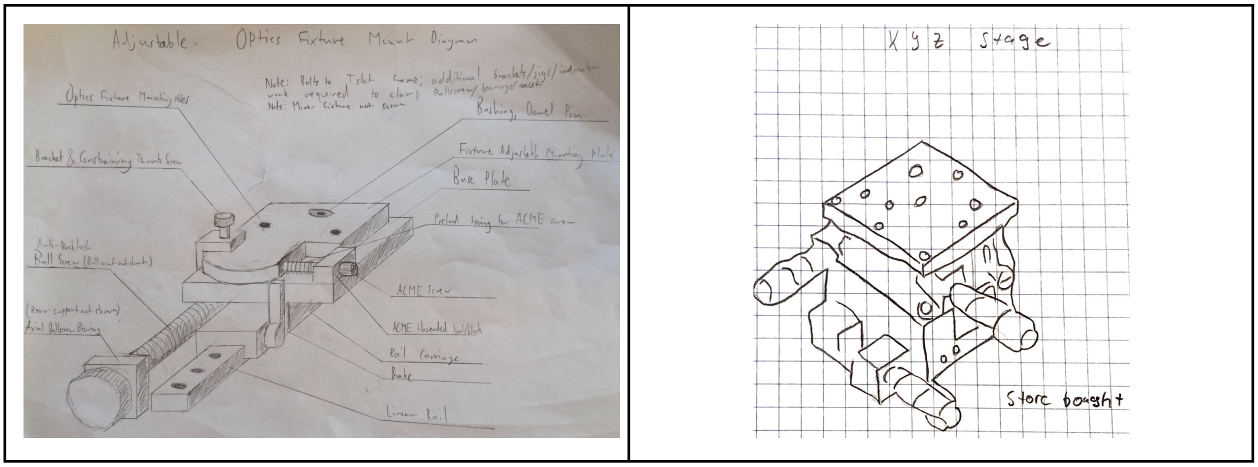


Figure 5: The figure illustrates examples of individual component designs that each team member created.

After each team member presented their concepts, the team started a selection process based on Pugh charts.

<u>Concept Selection Process</u>

After generating as many ideas as possible, the next step is to use convergent thinking to narrow in on the best concept. The first step in concept selection is a "gut check." In a gut check the team members used their intuition and engineering background to remove ideas which are infeasible, or do not meet the requirements of the project. An example of this down selection is shown in Figure 6.

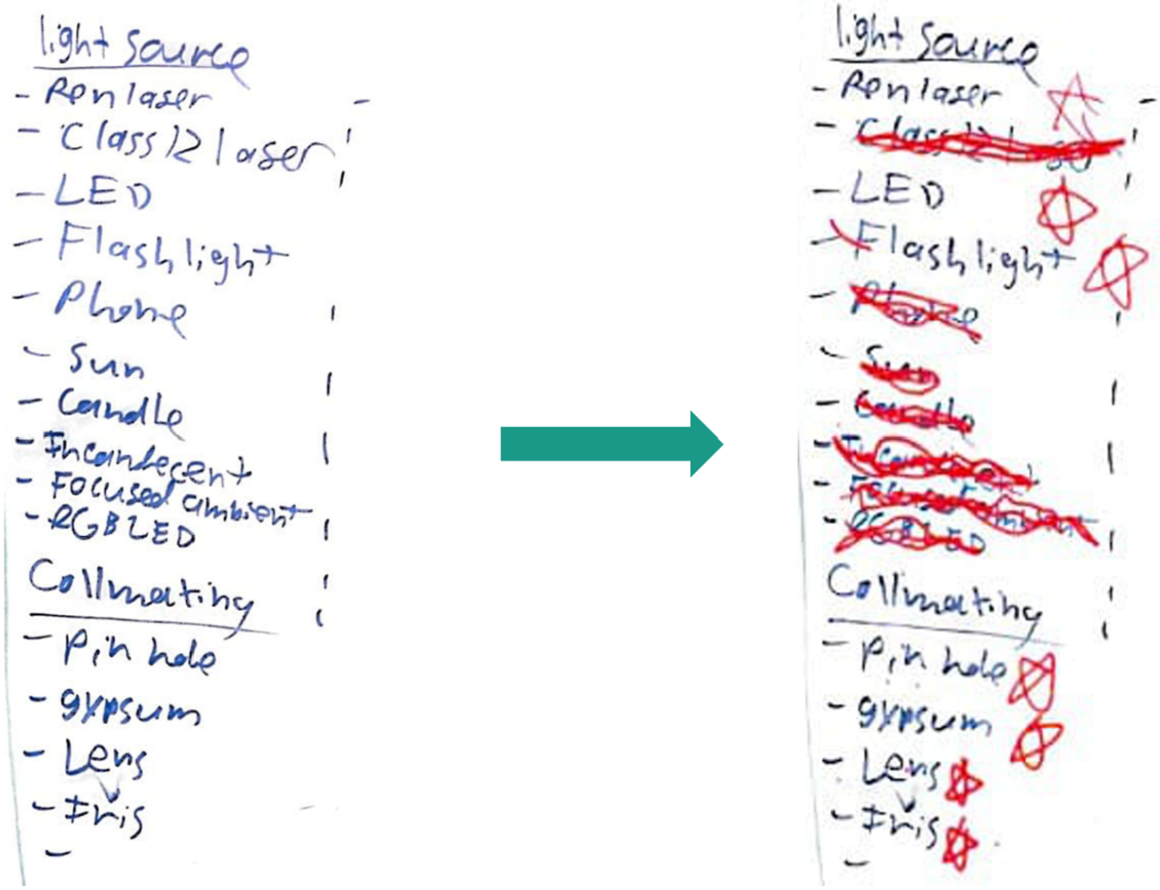


Figure 6: An example of gut check concept selection for the Schlieren system light source. The list on the left is the full brainstorm list. The list on the left shows the selected and removed ideas. The concepts which are crossed out are removed, and the starred concepts are chosen to continue with.

After narrowing down concepts via gut checking, the team generated concept sketches as described in the concept generation section on pages 15-17. Once these drawings were complete the team reviewed the designs and discussed the positive and negative aspects of each. Following the design review, the team used Pugh charts as a more rigorous method of concept selection.

Each Pugh chart focused on one subsystem of the project. The subsystem concepts were judged on their ability to fulfill the requirements which were relevant to that subsystem. Each concept was given a rating for each requirement (10 = best, 1 = worst). Each requirement also has a weight so that the critical requirements are prioritized. The total score of a concept was the sum of the individual requirement ratings multiplied by their respective weights.

When possible, requirement rankings were based upon estimations of true values. This was done for most of the affordability and weight requirements. The process for changing the actual cost and weight values into 1-10 rankings is described in the following list.

1. Estimate the weight/cost of each concept
2. Take the reciprocal of that value (lower cost/weight is better)
3. Make the concept with the lowest cost/weight (highest reciprocal) have a rating of 10
4. Using the same conversion factor as step 3, convert the remaining reciprocals to 1-10

The Pugh charts are shown in Tables 6.a-h. The concepts which scored the highest are highlighted in green.

Table 6.a: The Square T Slot Dampened Frame with Linear Rails was chosen. Though it won by only one point, the team was comfortable choosing it as it is much easier to manufacture than the runner up.

Frame						
	Affordability (1-10)	**Rigidity (1-10)**	**Weight (1-10)**	**Resistance to Temperature Change (1-10)**	**Total**	
Weight of Characteristic:	**4**	**2**	**2**	**3**		**Additional Comments**
Square T slot Frame with granite/concrete bed, parallel linear rails	2	10	2	10	62	- Extremely impractical to manufacture; expensive
Square T slot Dampened Frame with parallel linear rails	8	6	8	5	75	- Rails allow for easier adjustable locating of mirrors
Angled T Slot Frame	10	4	10	2	74	- Lightweight; difficult to calibrate frame and mirror
Square T slot frame with centered cross sectional supports	8	6	8	3	69	- Lightweight; difficult to calibrate frame
Rails; no frame	4	1	7	1	35	- Expensive, easy to machine after purchase

Table 6.b: The Vertical Extrusion with mobile rail mounted injector carriage won. Though it is more complex, the adaptability it provides is invaluable.

Nozzle Locating						
	Affordability (1-10)	**Repeatability (1-10)**	**Injector Versatility (1-10)**	**User Simplicity (1-10)**	**Total**	
Weight of Characteristic:	**4**	**2**	**4**	**3**		**Additional Comments**
Vertical extrusion with mobile rail mounted injector carriage	8	8	10	10	118	Much more versatile pertaining to injector positioning; harder to locate relative to air extraction
Upright extrusion with injector base plate, rail mounted mobile valve plate	10	10	5	9	107	Highly repeatable/simple to use, difficult to adapt to a wide range of injectors

Table 6.c: The Rotational Rail Mounted Plate with ball screw adjustment won as it is the only design that provides precisely adjustable rotation.

Mirror Fixture Locating						
	Affordability (1-10)	**Calibration Time (1-10)**	**Precisely Adjustable on Necessary Axes (1-10)**	**User Simplicity (1-10)**	**Total**	
Weight of Characteristic:	**4**	**2**	**4**	**3**		**Additional Comments**
Rotational Rail Mounted Plate with Ball Screw Adjustment	5	10	10	8	104	Compatible with different types of mirrors
T Slot Fixed Hole Mount	10	2	1	3	57	Difficult to locate precisely due to lack of T channel precision
2 Axis X-Y mount	2	8	7	10	82	Expensive, high cartesian precision, no

						rotational adjustability

Table 6.d the XYZ precision table won over the T-slot mount due to its significantly better calibration time and user simplicity, even though it is much more expensive.

Filter Locating					
	Affordability (1-10)	**Calibration Time (1-10)**	**User Simplicity (1-10)**	**Total**	
Weight of Characteristic:	**4**	**2**	**3**		**Additional Comments**
XYZ Precision Table with dowel pin tool post	2	10	10	58	Compatible with different types of filters
T Slot Mount	10	2	3	53	------

Table 6.e: A LED was chosen as it performed better than the other choices in all categories.

Light Source					
	Imaging Injector Spray (1-10)	**Affordability (1-10)**	**User Simplicity (1-10)**	**Total**	
Weight of Characteristic:	**4**	**3**	**2**		**Additional Comments**
LED	10	10	10	90	Very bright in a small footprint
Incandescent Flashlight	5	5	6	47	Has a large amount of heat generation
Laser Pointer	1	7	5	35	Safety becomes a concern at the necessary power level

Table 6.f: A shop vac was the best because it is much cheaper than the fume hood, even though its extraction capability may be worse.

Fume Extraction					
	Extracts Air/Fluids (1-10)	**Affordability (1-10)**	**User Simplicity (1-10)**	**Total**	
Weight of Characteristic:	**4**	**3**	**2**		**Additional Comments**
Shop Vac	8	10	10	82	Compatible various hoses and reducers
Fume Hood	10	1	9	61	Custom option needing manufacturing

Table 6.g: parabolic Mirrors were chosen because they are the only method that is compatible with Z-type and they are already provided so cost is very low.

Optics						
	Allows Imaging with Supplied Materials (1-10)	**Affordability (1-10)**	**User Simplicity (1-10)**	**Compatibility with Z-Type (1-10)**	**Total**	
Weight of Characteristic:	**4**	**3**	**2**	**4**		**Additional Comments**
Parabolic Mirrors	10	10	3	10	116	Creates real image for camera and already provided
Lenses	1	1	5	1	21	Involves refraction which changes speed of image
Flat Mirrors	1	7	10	1	49	Creates virtual image, tough to image with camera

Table 6.h: Bolts were chosen for a table attachment as they scored highest in all categories.

Table Attachment					
	Rigidity (1-10)	**Ease of Use (1-10)**	**Lightweight (1-10)**	**Total**	
Weight of Characteristic:	**4**	**2**	**1**		**Additional Comments**
Bolts	10	10	10	70	
Clamps	5	8	3	39	
L Shape Hold	7	5	5	43	

ALPHA Design

Following the morphological/Pugh chart selection of ranked concepts, the team selected the ALPHA design for the project.

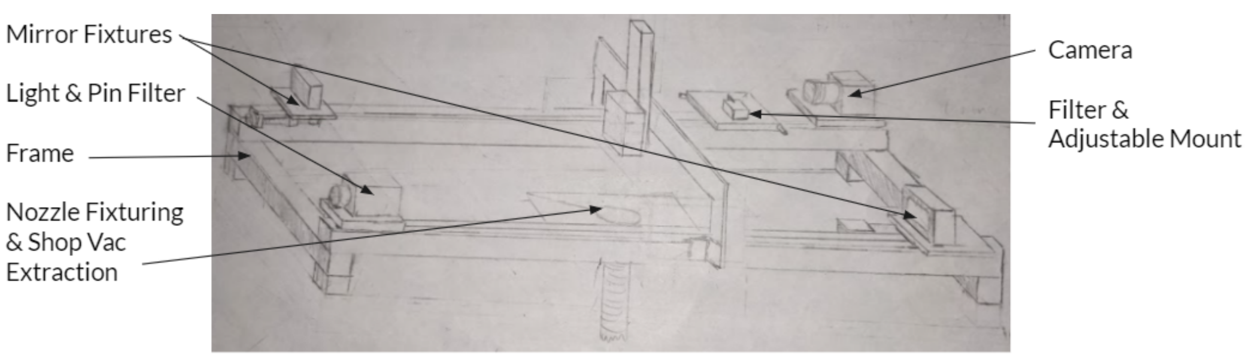


Figure 7: Labeled ALPHA full assembly diagram

The full ALPHA assembly is sketched above, in Figure 7. It uses a rail system to precisely align subassemblies and ensure collinear precision of optical components along each rail. The system is bolted to a work table, and uses an LED as a light source.

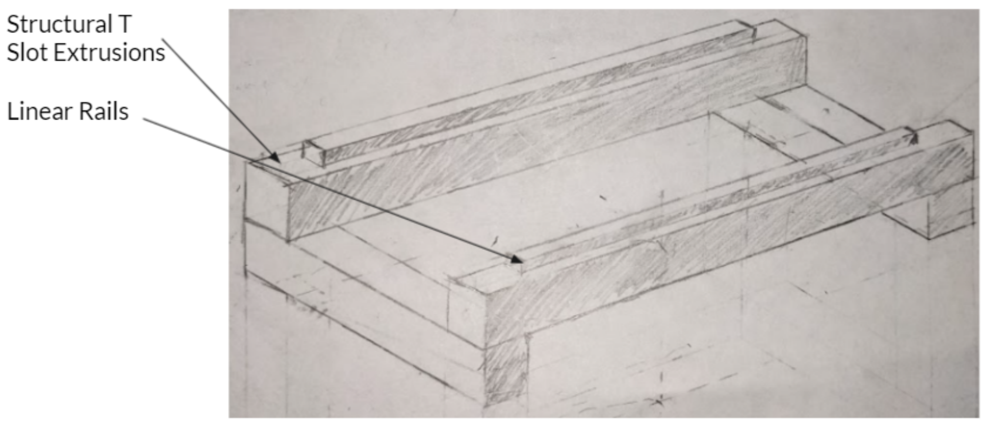


Figure 8: Labeled ALPHA frame subsystem

The ALPHA frame subsystem was selected to be a square t slot structure, and is shown in Figure. 8. Significant details include:

- Cross sectional supports were pushed to the ends of the t slot extrusions along the length of the structure to support precise shimming of the rail supports.
- Parallel linear rails are mounted to the top of the upper t slot extrusions.

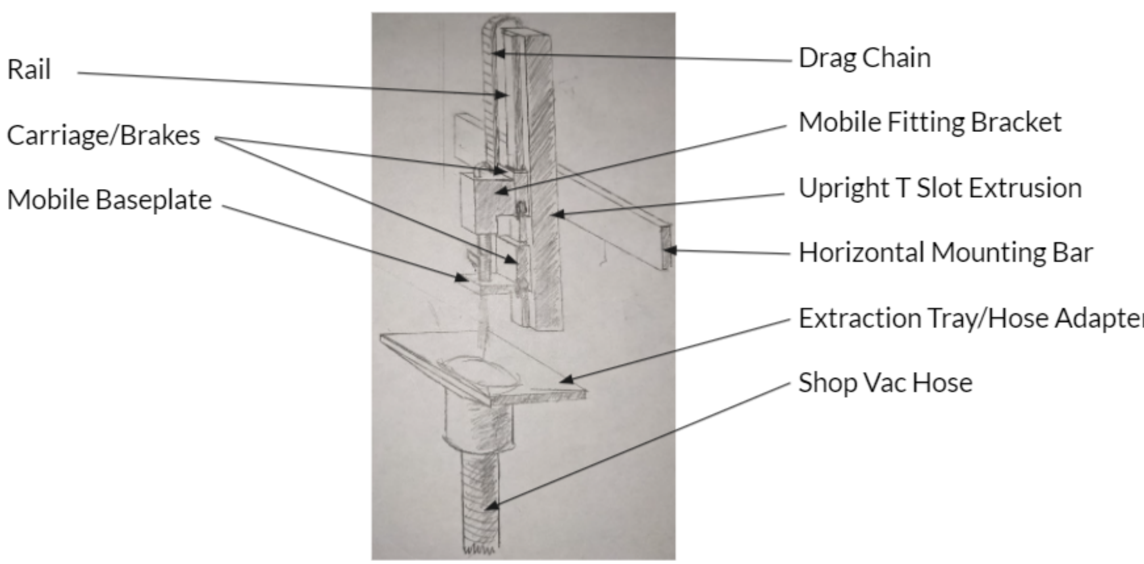


Figure 9: Labeled ALPHA Injector Fixturing System & Fume Extraction

The ALPHA nozzle fixturing subsystem was selected to be a combination of the mobile carriage and fixed plate designs; it is shown in Figure 9. Significant features include:

- Air extraction
    - Shop vac with an adapter to catch the fluid and adapt to the shop vac hose.
- Mobile injector location
    - Carriage and brake system riding along a linear rail
- Structural support with vertical t slot extrusion along horizontal cross bar.
- Wire organization with drag chain

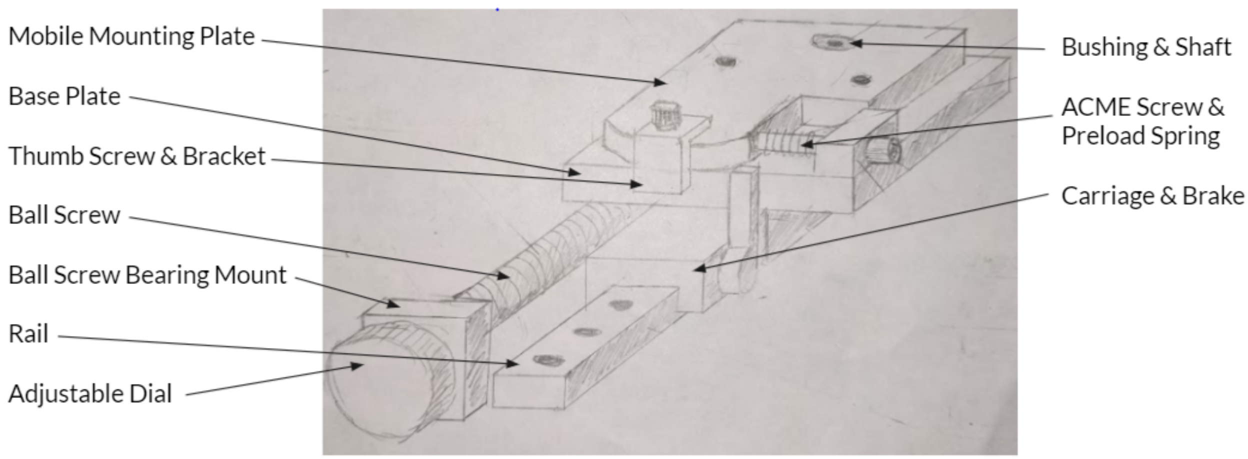


Figure. 10: Labeled ALPHA mirror fixture locating subsystem

The ALPHA mirror fixture locating subsystem is shown in Figure 10. Significant features of this design include:

- Linear and rotational precision adjustment
    - Linear adjustment provided with ball screw/linear rail system
    - Rotational adjustment provided with preloaded ACME screw/rotational nut system, rotating around bushing/shaft
- Linear/Rotational braking
    - Linear brake with carriage
    - Rotational brake with custom thumb screw
- Mounting for mirror fixture provided to us by sponsors
    - Mounting holes

<u>Concept Analysis and Iteration</u>

The ALPHA design was evaluated based off of the Pugh charts used for the Concept Selection section. This determined what component would best serve the requirements and specifications. In order to verify that these components best serve the function of the system and fulfill the specification, the following scientific fields will need to be considered.

- Solid Mechanics
  - Will be used to determine proper architecture of the frame as well as the rigidity of the setup to withstand shock loading discussed in requirements
- Design and Manufacturing
  - Will be used for design and manufacturing of custom parts to replace commercial ones. This will include precision machining and geometric dimensioning and tolerancing
- Fluid Dynamics
  - Will be used for constructing CFD models and analysis of how the injector will fire in the imaging path. Used for verification and planning the fume evacuation route
- Optics
  - Will be used for alignment of mirrors, collimation of light, as well as filtering of gradients. This will be an important fundamental as the entire setup revolves around this concept. An understanding of optics will be used to focus the light appropriately and determine whether the setup fits within the size constraints given in the requirements.
- Controls
  - Will be used to configure the system to fulfill the requirement of capturing and imaging the injector spray simultaneously. This will allow ease of use and will be connected to both the camera and the injector.
- Cost and Budget Tradeoffs
  - Will be used to gauge what parts should be commercially bought or manufactured to stay within the allotted budget and schedule.

Table 7: The table shows a comparison of the cost of commercially available stage and precision equipment to custom manufactured components made by the team. The in-house manufacturing considers the cost of labor, time, and materials. Red prices denote objects that are more expensive in-house while green prices are for components that are cheaper to manufacture in-house.

Monetary budget	Time budget	"Labor Cost"
$1,500	25	$50

		COTS (commercial off the shelf solution)		In house				
Subsystem	Quantity	COTS	COTS cost (total)	In house	In house cost	In house time total (h)	In house combined cost	cost difference
frame	~ 16ft	precision rails	$150	machined rails	$50	5	$250	-$100
mirror fixture	2	rotation stage	$300	limited degree rotation block	$30	6	$330	-$30
razor fixture	1	xyz stage	$130	stacked linear stages	$90	15	$840	-$710
Z-adjustibilty	4	z stage	$480	custom Z	$40	10	$500	$80
X-adjustibility	6	x stage	$780	linear rails	$200	4	$400	$380
Total			$1,840		$410	40	$2,320	

Final Cost	Final Hours
$1,460	14

The table above (Table 7) shows an analysis of the cost of products that can either be sourced or manufactured by the team. Through this analysis, it was determined that it would be cost-effective to only manufacture 2 components, the z-stage and x-stage, as they would be cheaper than the commercially available ones while the other equipment would turn out more expensive if manufactured in-house. This was done to optimize the budget for the scope of the project.

In order to most effectively test the success of the design, the team will undertake both theoretical calculations and empirical testing. Theoretical calculations will include light angle calculations using optical fundamentals to efficiently determine the placement of the rails and mirrors within the footprint of the constraints. This can be validated using a testing plan with a light source and mirrors with different angle placements. The light source and one mirror will remain collinear while a series of angles is swept through (5 through 10 degrees). The other mirror will be swept through these same angles. To verify that the image quality is minimally distorted, this same test can be done with the camera attached to the fixture and a series of images taken at each angle. The results of the images will then be internally compared and compared to an available benchmark to determine the most suitable angle. If this experiment is inconclusive, the aero department lab should be consulted on possible solutions.

To verify that the system is rigid according to the specifications, an empirical test will be performed where the table/frame will have an iNewton placed on it and team members will run through a series of trials to push the table for 0.5 seconds. This will simulate the shock loading requirement and the results requirements and will be analyzed in terms of acceleration and then divided by the mass of the table to determine the force and then compared to the 200 N specification. If the results are very close to the 200 N specification, then FEA will have to be run to more precisely gauge the force being received.

Another test that will have to be run is the spray safety of the system. The goal of the empirical test is to determine the spray radius of the injector and verify if it is large enough to interfere with electrical components and pose a hazard. This test will consist of the injector being fired 10 times from the specified distance from the frame onto a paper sheet. This will determine the radius that is wet and can then be used to determine any safeguards that will need to be altered to the setup. The team is confident in this type of test as paper will absorb any immediate moisture.

The most critical parts of this design are the linear rails, mirrors, collimated light and precision mounting placement of the razor. These components will dictate the success of the design and the imaging quality. The precision of the rail will determine the distortion of the image and the angle of the rest of the components. The mirrors and light source will produce the immediate image and will have to be tuned in order to produce the most accurate picture.

The most difficult aspects of the design include being under budget, while having a very precisely adjustable system. The scope of the project does not allow all precise components to be bought and some parts shown in the ALPHA design will have to be manufactured. There may be tolerance issues when items of varying adjustability are brought together. In order to solve this problem, machine shop experts will have to be consulted during manufacturing for advice on precision of complex parts. Other difficulties will include the alignment of the angle between mirrors. While the carriage system should simplify alignment, there are additional constraints in the setup that other systems don't share. In order to address the problem, our stakeholder as well as Professor Tropea will have to be consulted during alignment. A laser system can also be used to ensure parallelism between the angled mirrors, however this type of calibration may be more than the budget allows.

Due to the scope of this project and the reliance on commercially available solutions and the condensed timeline of the project, procuring the linear rails, carriages, and stages may be difficult. In this case, managing logistics and procurement will be crucial. The team has already begun developing a BOM to expedite the procurement process and stay ahead of schedule in the event of any supply shortages.

Engineering Design Parameter Analysis

Several analytical methods were used to verify different elements of the overall assembly including trigonometry, FEA, and a cost analysis. Initially, some basic trigonometry was performed to determine the distance between the linear rails. Though the calculation was basic, ensuring the distances between the rails is an extremely important part of achieving robust Schlieren imaging since this can determine the angles at which the mirrors are positioned. An angle of less than 10 degrees was used in this calculation to determine this distance because it is an ideal condition to maximize the image quality. The distance between the rails with an

8-degree offset of the mirrors was found to be smaller than originally anticipated by the Team. The value was calculated to be 6.746 inches with a very high confidence in the fidelity of the calculation. Completing this simple trigonometric calculation was a way for the Team to ensure an accurate value with not a large amount of time expended. This calculation ultimately changed the frame design, since there was a distance decrease. This calculation can be seen in Figure 11.

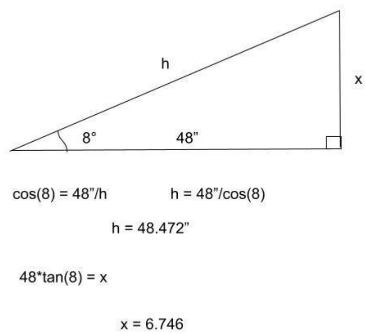


Figure 11: Trigonometric calculations to determine the distance between rails with an 8-degree mirror angle.

FEA on the linear rails was also performed in order to estimate the deflection experienced by the rails. Using FEA was a very helpful tool in determining deflection because it is a metric we wouldn't be able to test in person with the actual rails the Team would be using until the rails had been delivered. Deflection is something that could be a large issue in a Schlieren setup's alignment, so ensuring this was not an issue was important to the Team. An estimate was made for each of the weights on the carriages based off of the CAD model assembly. These weights were inputted at the approximated corresponding locations of the carriages with fixed supports on each end. Deflection values were then outputted from the analysis yielding a maximum value of approximately 32 μm. This deflection is quite small, verifying that deflection of the rails will not be a big issue. Designing for the deflection of the rails is still important, but it is not a large issue that the assembly should ultimately experience and cause a need for resolution by the Team. FEA is not necessarily a very high confidence analysis method, but by using the most accurate information available with regards to the assembly, the confidence level in this analysis is moderate. Performing an FEA analysis was not the quickest analysis method, but it allowed for a relatively accurate value given the number of variables present, support type, and geometry of the rails being used. The image of the FEA with the corresponding scale can be seen in Figure 12.

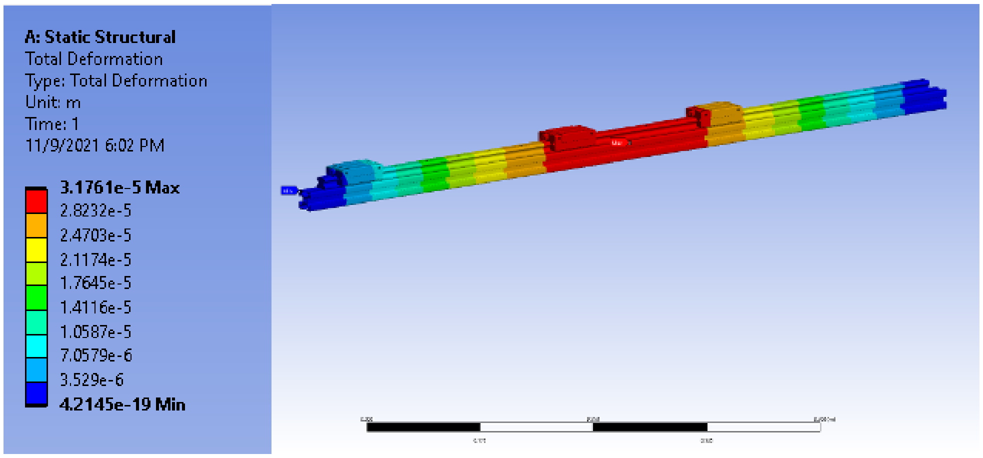


Figure 12: Picture of FEA analysis on a linear rail.

After having some budgetary concerns amongst the Team, a consolidation of several options of Schlieren systems involving varying costs were created in order to locate items eating up large portions of the budget. The Team allowed for iterations of the design to have no theoretical budgetary constraints in order to evaluate the cost of the most preferable system to address the sponsor's problem. Comparisons were then made from the most desirable option to the option closer to the given budget to look at the places increasing the cost. This analysis was not extremely detailed in nature, but it was crucial to perform for the Team to easily understand the cost drivers. Even though these costs were calculated quickly, the confidence in what was identified to be the primary cost drivers is very high. After coming up with three different options and doing some back-of-the-envelope cost evaluations, the costs came out to be $2359, $1574, and $2048 for each option respectively. After reviewing the options, the Team and the sponsor liked Option 1, the most expensive option, but this was about $1000 out of the budget of $1500. The sponsor then decided to increase the budget to $2000 and desired a combination of Options 1 and 2, Option 2 being the more affordable of the three options. Once the team reviewed the two options after the budgetary increase, the brakes for all of the different components were clearly seen to be a large cost driver. To reduce this cost and combine Option 1 and 2, a combination of ball screws on the components needing less precision and the carriages and brakes for the more precise components was decided upon. Images of Option 1(Table 8 on page 32), Option 2(Table 9 on page 32), and Option 3(Table 10 on page 33) can be seen on the corresponding pages below.

Table 8: Option 1 cost breakdown. The motion of each of the

components on the linear rails is placed on a carriage with a corresponding brake to secure it.

part	source	quantity	price total
T-slot	McMaster-Carr	2 x 4-foot, 2 x 1 foot	$53
Rails + 4 carriages	Vevor	1	$134
Brakes	McMaster-Carr	6	$830
1-axis stage	Amazon	5	$408
Carriage	Amazon	2	$50
3-axis stage	Amazon	1	$125
Rotation Stage	Amazon	2	$279
LED		1	$55
Injector assembly			$308
3D printed parts			$50
Bolts			$100
Stock			$200
Total			**$2,593**

Table 9: Option 2 cost breakdown. The motion of each of the components is controlled by ball screws .

part	source	quantity	price total
T-slot	McMaster-Carr	2 x 5-foot, 2 x 1 foot	$57
Rails + 4 carriages	Vevor	1	$134
Carriage	Amazon	2	$50
3-axis stage	Amazon	1	$125
Rotation Stage	Amazon	2	$279
LED		1	$55
Ball Screws		6	$216
Injector assembly			$308
3D printed parts			$50
Bolts			$100

Stock			$200
Total			**$1,574**

Table 10: Option 3 cost breakdown. This option was meant to imitate an optical table without the large coast that would add to the project. The optical table qualities could be mimicked by a series of breadboards secured together.

part	source	quantity	price total
6"x 6" breadboard	Thorlabs	6	306
xyz stage	Amazon	6	750
rotation stage	Amazon	2	$279
LED		1	$55
Injector assembly			$308
3D printed parts			$50
Bolts			$100
Stock			$200
Total			**$2,048**

More engineering analysis may be completed in the future if additional points of interest or concern arise, but the physical construction of the Schlieren imaging will be beginning and will be based on what was learned in the completion of these analyses discussed above. The Team will move forward utilizing engineering principles in the validation and verification of the design.

Final Design Description

Following analysis/testing, the Team drew CAD for the entire assembly, reverse engineering existing components to ensure accurate mounting. Components requiring adjustability were assigned either a brake/stage combination, or a ball screw, depending on the precision of the adjustment required. A figure of the full assembly is shown below.

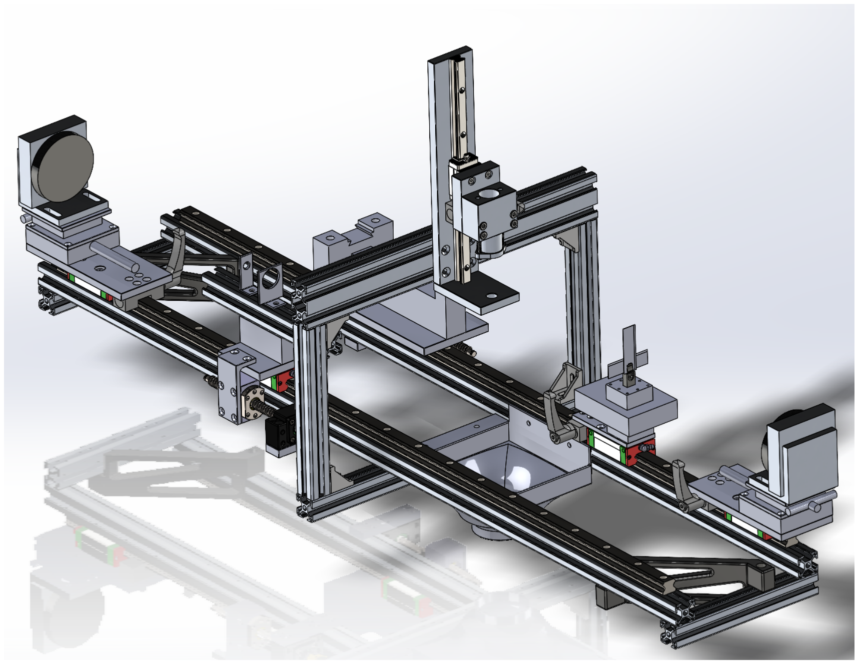


Figure 13: Full Assembly Iso View

The frame's dimensions were calculated from trigonometric analysis of the mirror angles, along with the specifications for the footprint of the machine. Similarly, to the concept drawings, a frame consisting of T-slot extrusions with gussets was chosen, and the frame will be calibrated on the metrology table at Nostrum in order to ensure proper flatness of the frame. A figure of the frame is shown below.

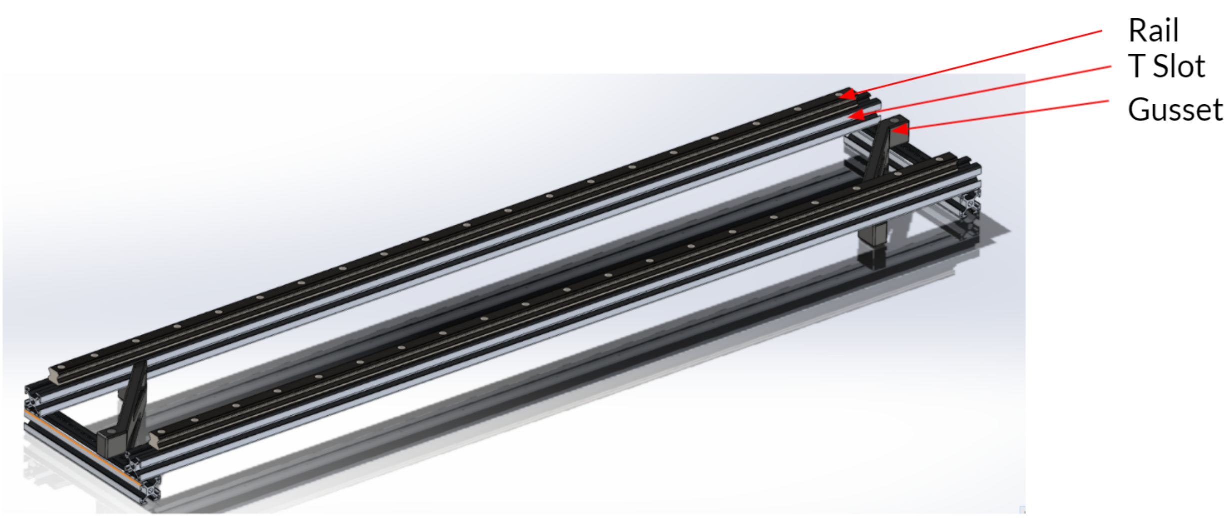


Figure 14: Frame Assembly Iso View - Labeled

Mirror fixtures were designed to allow for both axial and rotational adjustability. Two stages, one single linear axis stage and one rotational stage, are included in the assembly, with mounting plates interfacing one to the other. A brake and carriage system allows for rough adjustability and fixturing prior to fine calibration. A figure of this system is shown below.

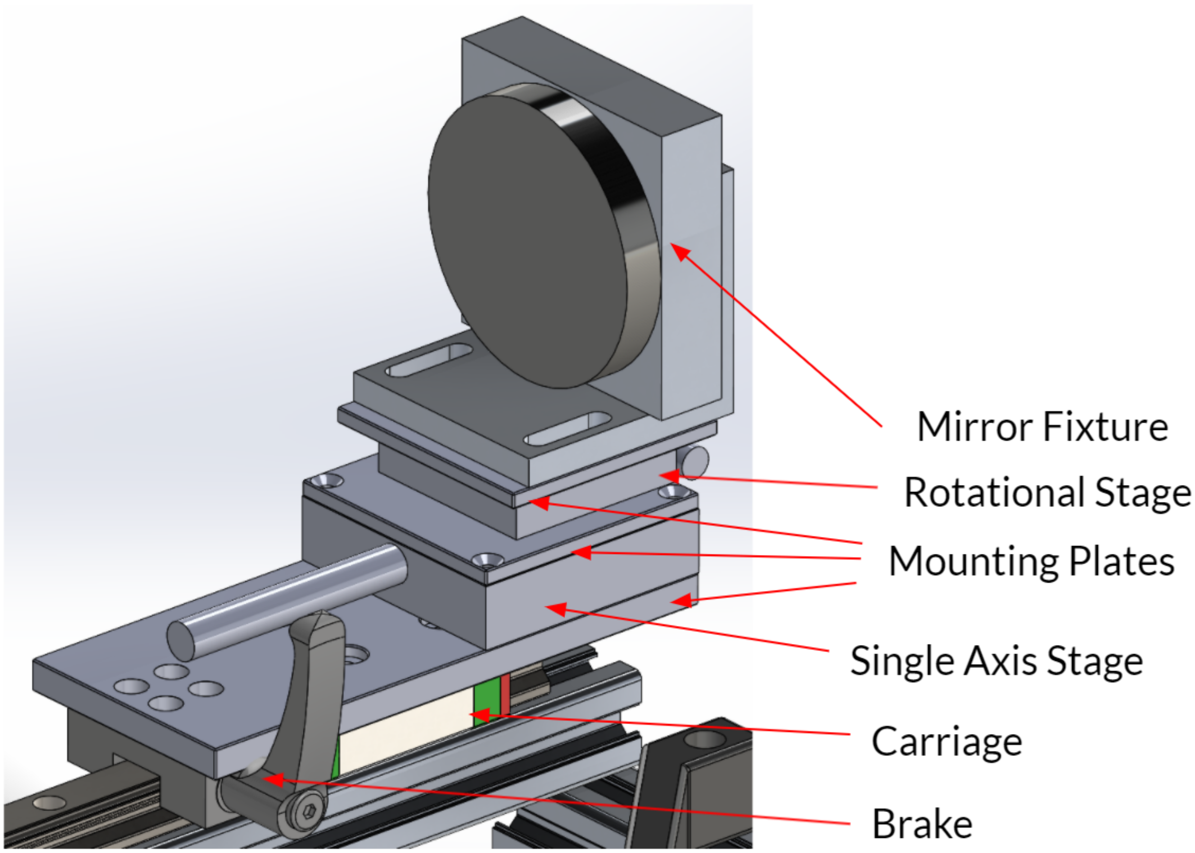


Figure 15: Mirror Fixturing Assembly Iso View - Labeled

Mounting for the camera is conducted using a 3D printed bracket that interfaces with the dovetail mount on the camera we have been provided with. This is mounted on a rail using a carriage with a mounting plate above it, and is adjustable via a ball screw coupled to the baseplate using an angle bracket.

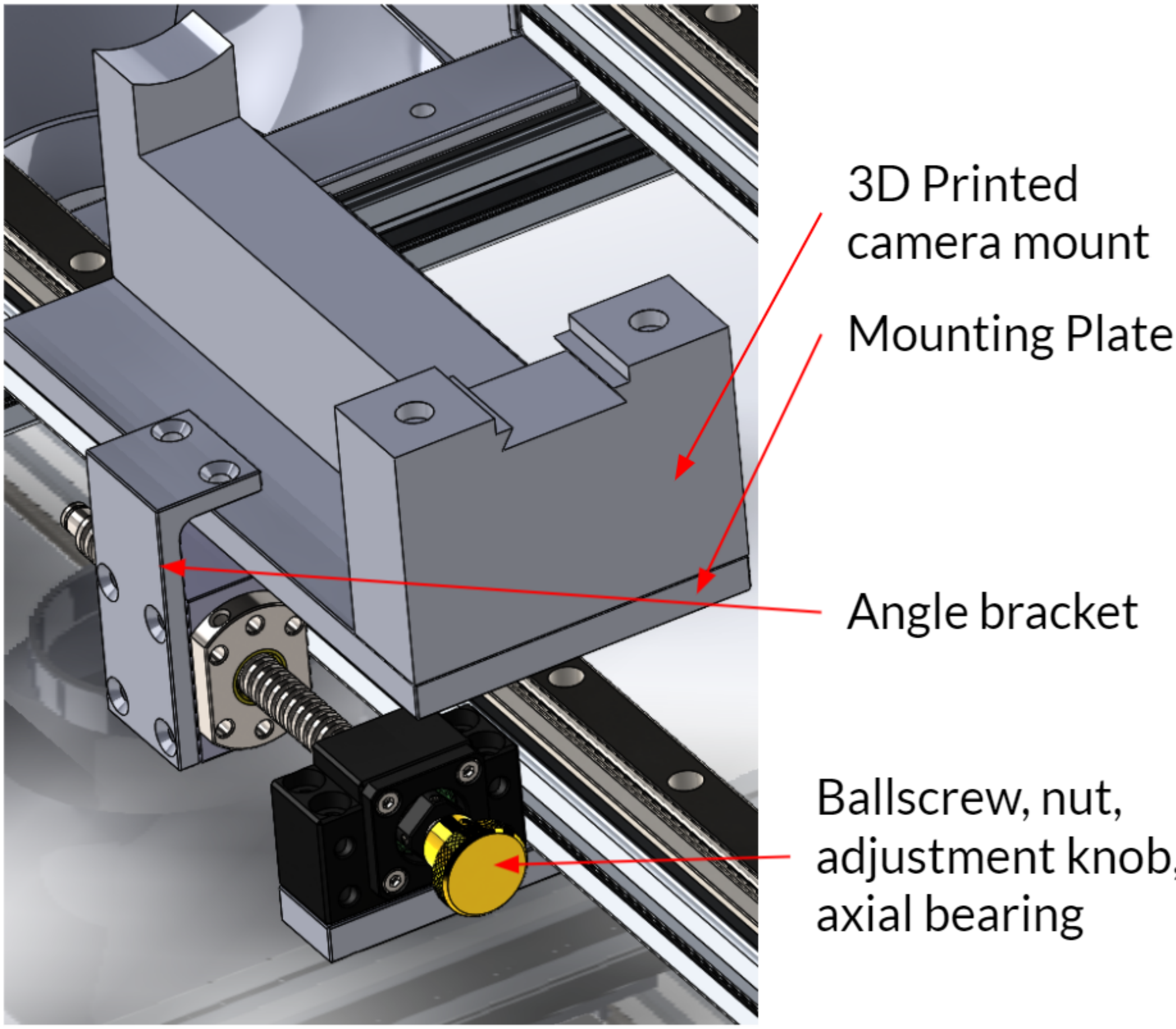


Figure 16: Camera Fixturing Assembly Iso View - Labeled

Injector fixturing was conducted using a vertical fixturing system with a fixed base plate, a carriage mounted injector bracket system with a brake for fixturing, and a t-slot frame for location of the overall system. The injector is placed in the hole marked as the injector mounting plate as shown in figure 16. The injector adapter allows the nozzle to pressure seal against the valves regulating the inflow of water/air as well as clamp down the injector to deter it from moving. The brake allows the fixture to move to different heights necessary.

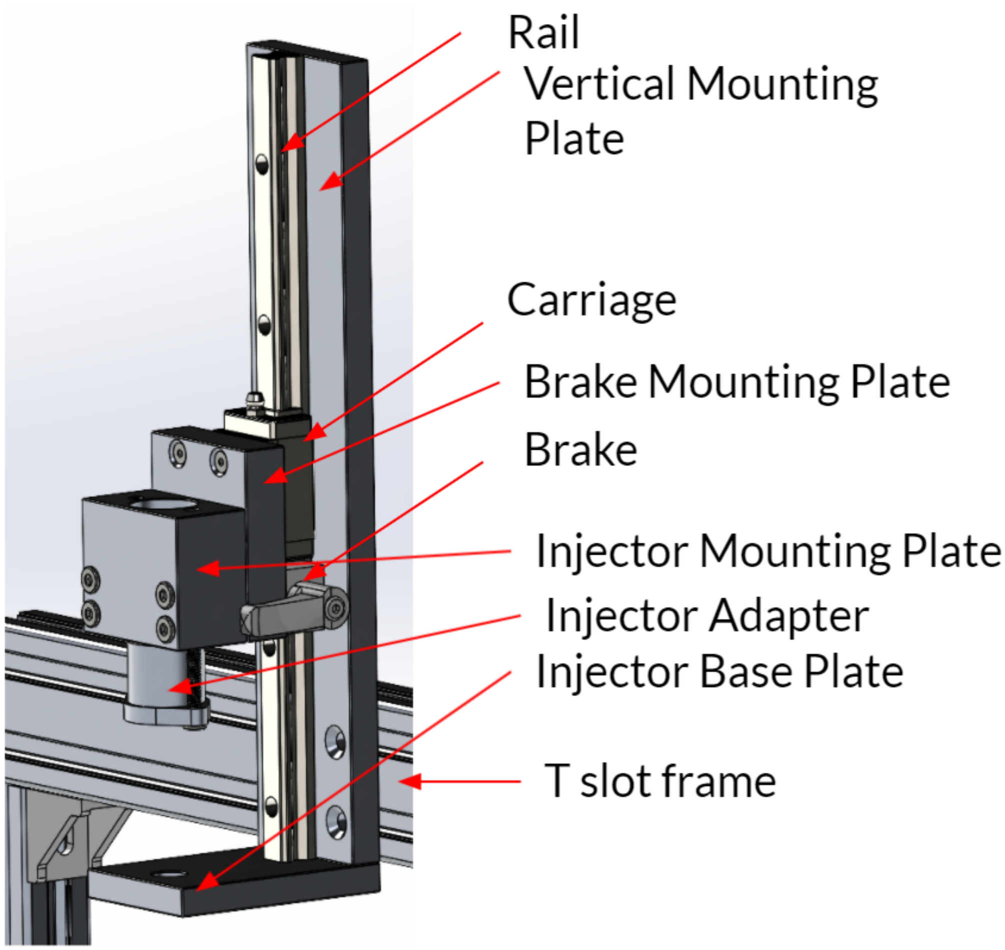


Figure 17: Injector Fixturing Assembly Iso View - Labeled

Fume extraction for the system was designed to consist of a 3D printed drain that couples to a shop vac, mounted directly underneath the injector fixturing system. A figure for that part is shown below.

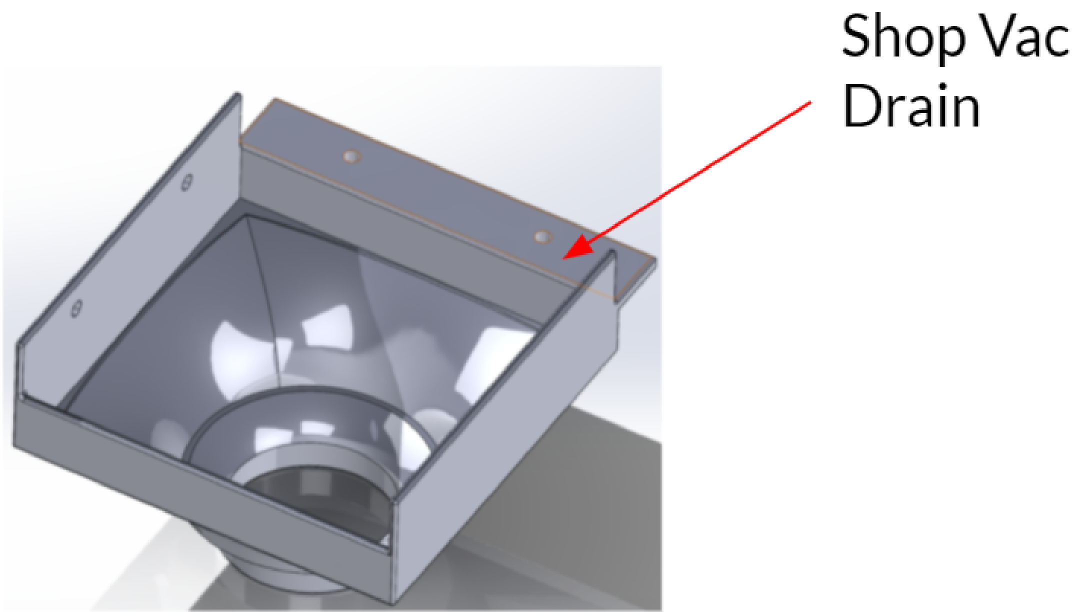


Figure 18: Shop Vac Extraction Iso View - Labeled

Razor fixturing was accomplished using a brake/3 axis stage system, with an off-the-shelf fixturing setup for the razors. A mounting plate interfaces the carriage to the brake and the stage. Note that bolt hole locations need to be changed, as the current setup would make it impossible to fully assemble the structure. A labeled version of the assembly is shown below.

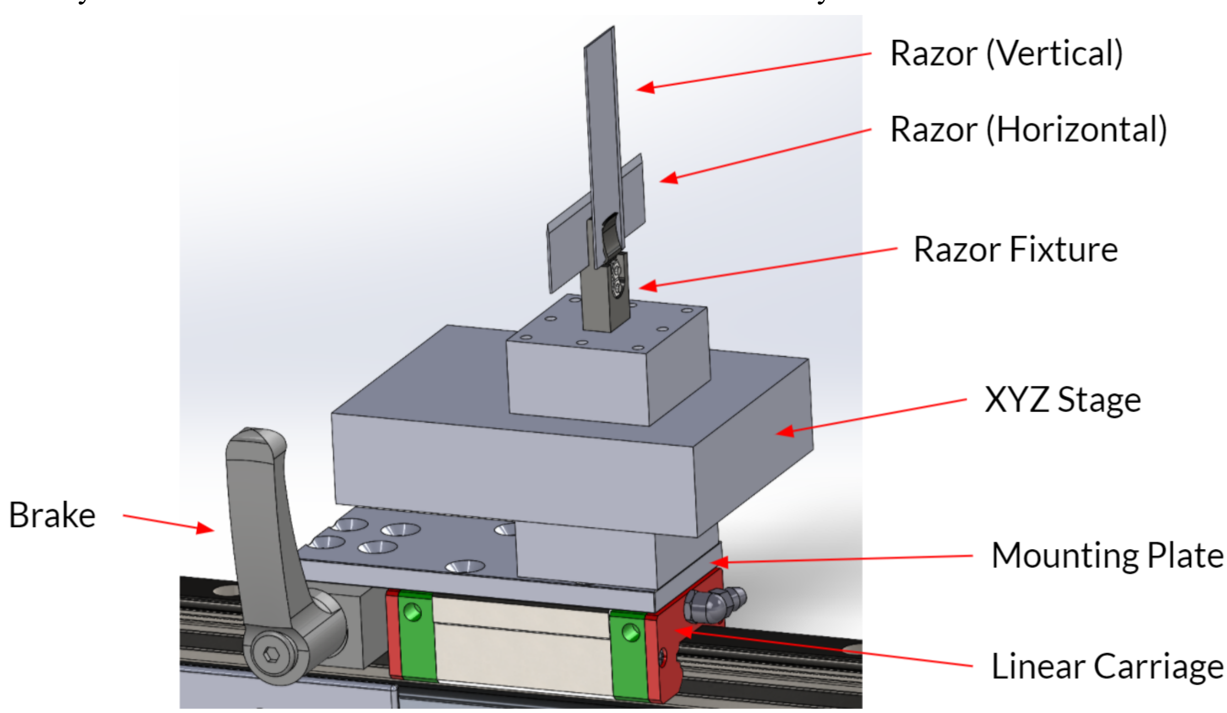


Figure 19: Razor Fixturing Iso View - Labeled

Finally, light fixturing was accomplished using a ball screw driven assembly mounted on a carriage with a spacer between a t slot. Optical features were mounted on 3D printed brackets on top of the t slot, so as to provide rough manual adjustability.

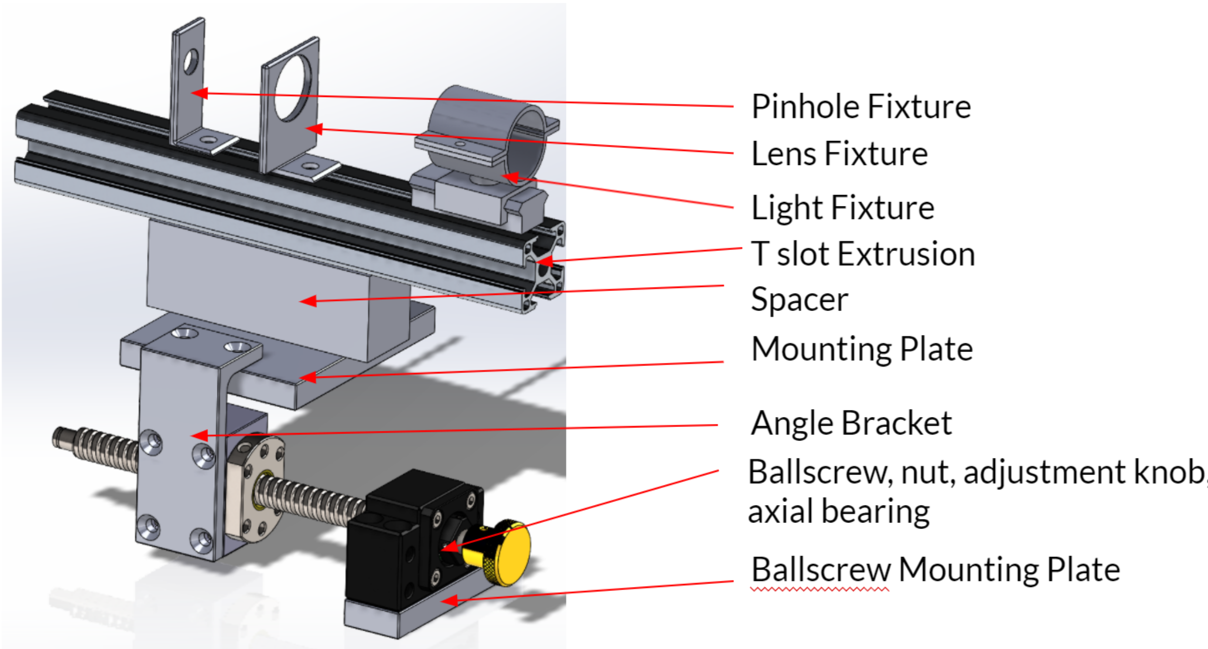


Figure 20: Light Fixturing Iso View - Labeled

Initial Prototype Description

Prototyping was a valuable exercise for the Team in two ways. Firstly, it allowed the team to gain general experience with setting up and using a Schlieren imaging system. This was useful because the Team had no experience with Schlieren before this project. Secondly, the Team was able to test design concepts.

Two prototypes were tested, the first prototype was a one mirror system as shown in Figures 21-22.

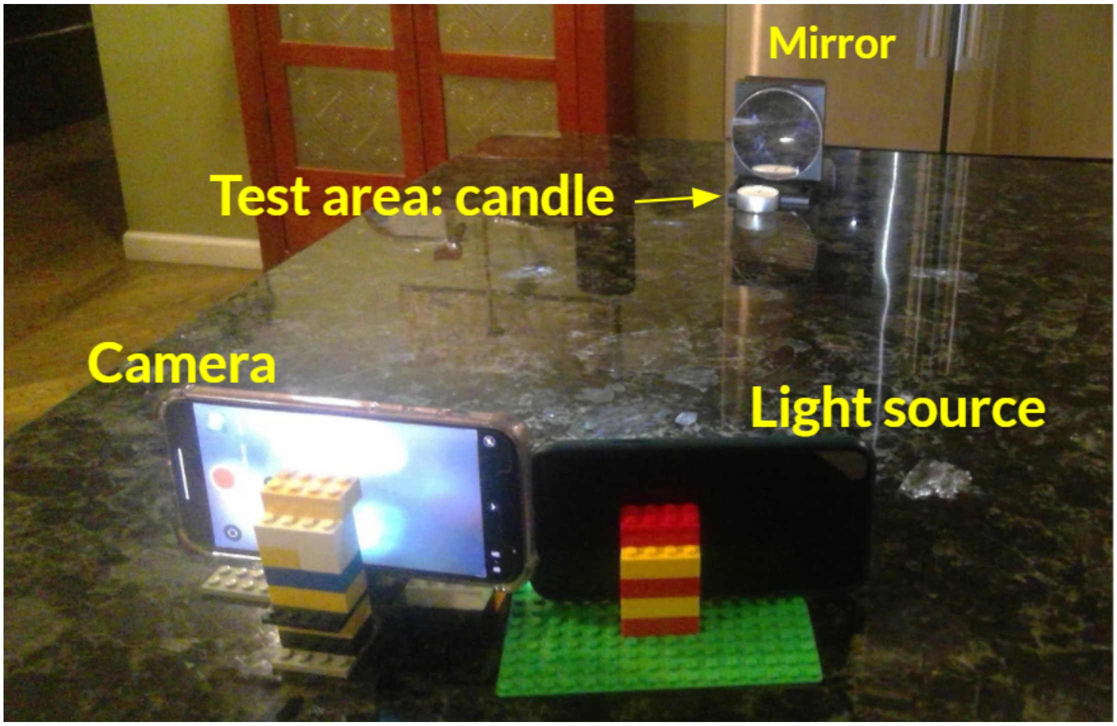


Figure 21: An image of the one mirror prototype. The light source and camera are close together with the mirror across the table at a distance of twice the focal length. The Schlieren components were mounted using Legos and the adjustability was provided by sliding the Lego mounts across the flat table.

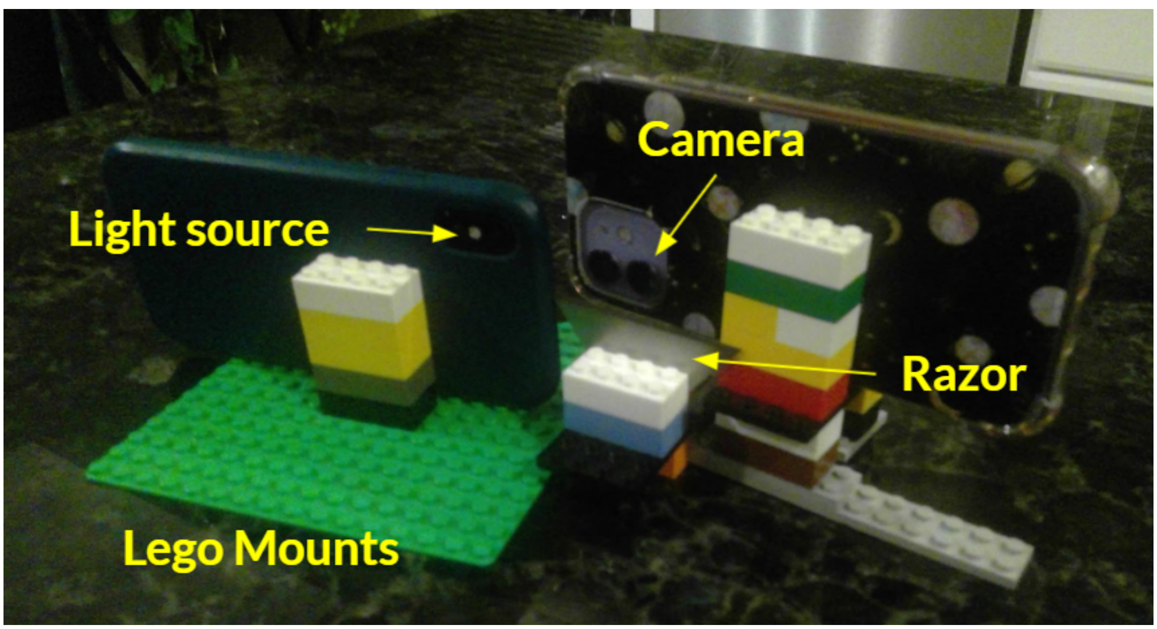


Figure 22: A close up image of the light source, camera, and razor. iPhones were used for the camera and light source.

Tuning the system to produce a Schlieren image took roughly 30 minutes. Figures 23.a-d show the resulting images during different phases of tuning.

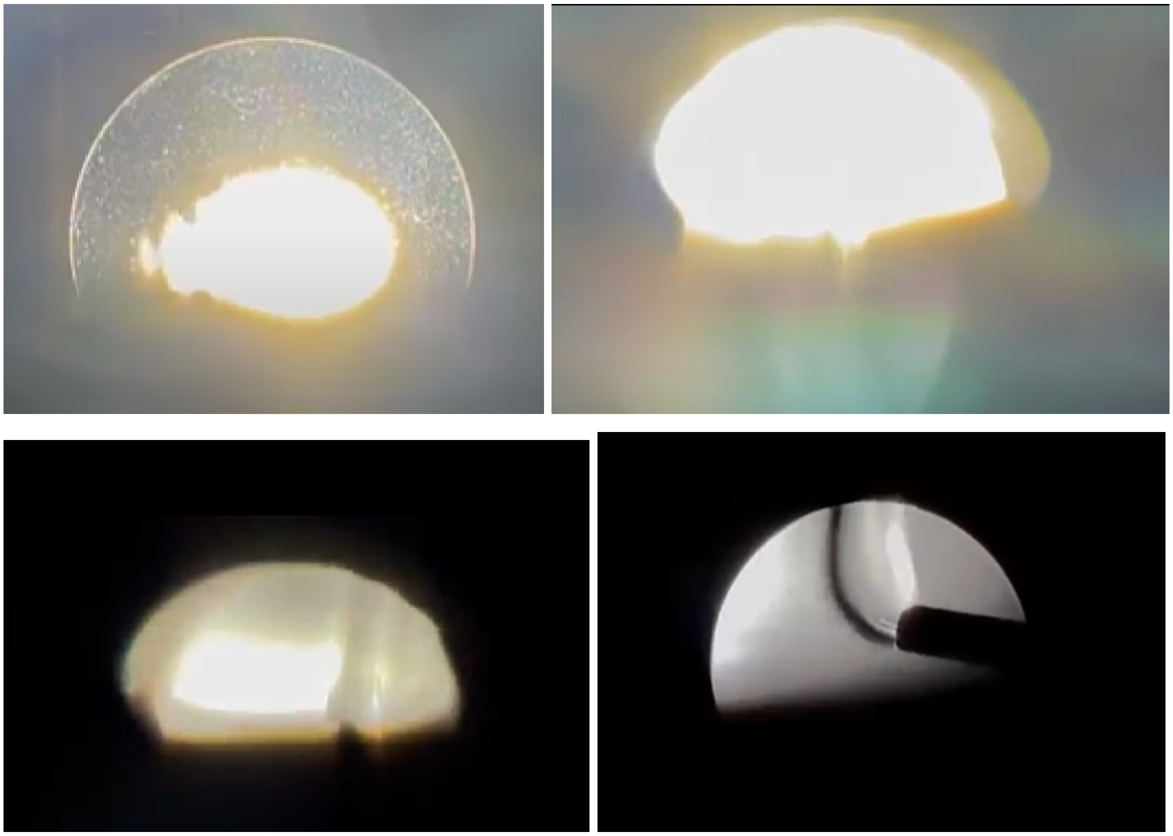


Figure 23.a (top left): shows the initial image viewed after rough tuning. Some Schlieren distortion can be seen on the left side; however, the light does not fill the mirror and the brightness is too high. **Figure 23.b (top right):** The camera was moved closer to the razor in order to fill the mirror with the light source. **Figure 23.c (bottom left):** the brightness of the image was fixed by reducing the exposure on the camera. Schlieren distortions can be seen as vertical streaks on the right side of the image; however, the light is not uniform and the image is not very clear. **Figure 23.d (bottom right):** The light source was tilted away from the mirror in order to create a more uniform illumination. This final adjustment produced a much clearer Schlieren image.

From this prototype the team learned several important considerations listed below.

1. The camera should have a narrow view lens such that the mirror is captured with a high resolution. The larger the mirror appears in the camera image the higher quality the image will be.
2. The camera needs the ability to be placed close to the razor. Moving the camera close resulted in the light source filling the mirror.
3. The light source intensity must be adjustable. A too bright source overexposes the image and too a too dark source will be drowned out by the ambient light in the room.

4. The condenser lens and pinhole must provide a uniform light brightness. Non-uniform light results in a low quality Schlieren image.

The second prototype was a Z-type Schlieren setup which used a DSLR camera. This setup is shown in Figure 24.

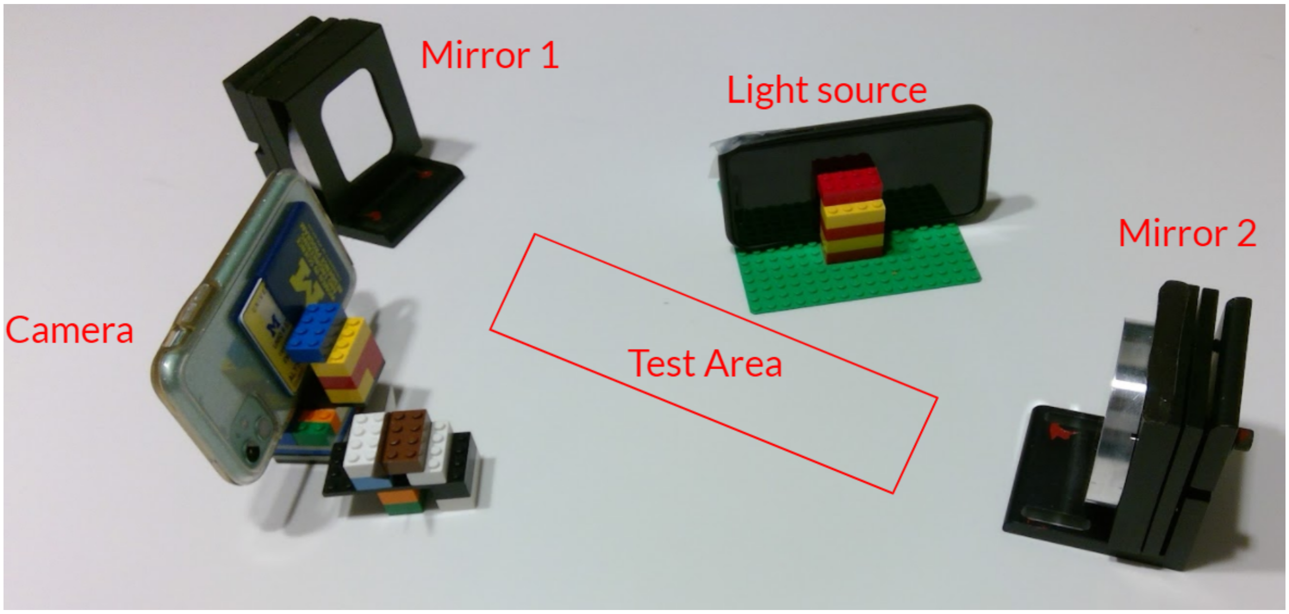


Figure 24: shows the Teams Z-type Schlieren setup which utilizes both mirrors. Not shown is the DSLR camera which replaced the iPhone Camera in some of the tests. The test area is the space between the mirrors where the light is collimated.

The results from this prototype are shown in Figure 25.

Figure 25: An image taken using the Z-type Schlieren prototype. Some Schlieren distortions can be seen however the quality is low.

Tuning the Z-type prototype was significantly more difficult than the single mirror prototype. The Team ran out of time at about 1.5 hours without getting a quality Schlieren image. The lessons learned from the Z-Type prototype are listed below.

1. Using two mirrors makes the system more challenging to calibrate
2. The flatness of our frame will be essential to the effectiveness of our product. The table used for Z-type Schlieren was less flat than the one used for the single mirror prototype. The uneven table caused additional tuning issues.
3. The DSLR camera is more difficult to use than an iPhone. Adjusting the camera settings is needed to generate a quality Schlieren image
4. Tuning the light source to the correct intensity in an important part of calibrating the system

Manufacturing Plan and Bill of Materials

In the initial problem statement, Nostrum Energy asked Team 25 to create a fully functioning test asset by the end of the semester. For this reason, the Team will be creating a very high-fidelity final prototype that will likely evolve directly into a functioning test asset. In order to complete the Schlieren imaging system on time the Team is purchasing a large number of the precision components and machining mounting plates in order to fit them together. In addition to these mounting plates a custom machined injector fixture will also be produced based on an existing Nostrum design.

The Team's decision to purchase a number of components was driven by a few factors. The first being precision. The precision of purchased components is much higher than the team would be able to achieve using the tools and machines that are readily available to them. By purchasing this precision instead of personally engineering it the Team will be able to take advantage of high-quality precision without sacrificing other aspects of the design. The second factor influencing the decision to purchase components is the overall time constraints of the course. The timeline of ME 450 is very quick for any design project but this pace is accelerated further for Team 25 as Nostrum energy asked for a fully functioning test asset to be delivered by the end of the semester. Being able to utilize purchased components allows the Team to reduce the number of hours that they will spend in the machine shop which will allow them to fulfill Nostrum's request of a functioning test asset. The consideration of these two factors is the reason that Team 25 has chosen to purchase a number of components for the manufacturing of their design.

The decision to purchase components that are not from a single manufacturer necessitates that a few custom parts will need to be machined to enable the purchased components to interface with each other. These custom components consist mainly of flat plates with different holes drilled in them in order to allow for two purchased components to interface and work together. An example of one of these mounting plates can be seen in Figure 26.

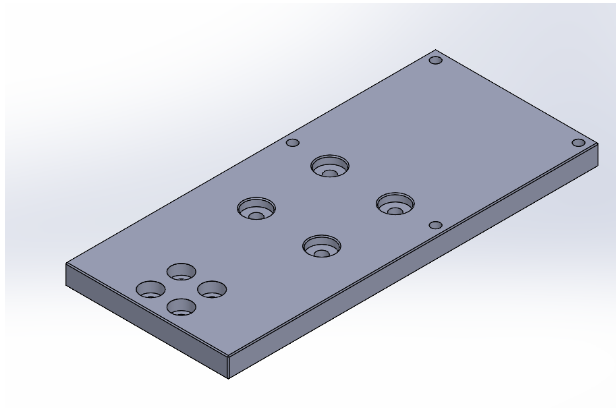


Figure 26: A custom machined plate to allow two purchased components to interface.

The overall machining operations necessary to make these mounting plates are relatively simple and involve mainly milling and drilling. Being able to utilize simple machine operations should help limit the number of hours the Team has to dedicate to machining custom parts. A bill of materials of all the purchased and custom components that will be utilized in the overall design is summarized in Appendix A along with the detailed bill of materials for the fasteners and stock used for assembly of the final prototype. Appendix B Also shows the assembly plan for components, detailed manufacturing plan, and some engineering drawings.

The total price of the bill of materials at $1871 is less than the overall designated budget of $2,000. This leaves room to purchase different components should the Team run into problems or need to source different optical parts than originally planned.

In order for the design to function properly there are a few assembly procedures that require high precision. The first of these procedures is the assembly of the frame itself. It is imperative to the overall design that the two linear rails mounted to the aluminum frame are parallel to each other. This precision should be on the order of $\pm.001$ of an inch across the four-foot length of the linear rail. This precision will be achieved by using Nostrum's flat ground granite metrology table and a dial indicator mounted to the table. A piece of flat ground steel bar stock will be attached to a single carriage on a linear rail and then the dial indicator will be run along the length of the bar stock. With the tolerance of the bar stock being $\pm.001$ of an inch a reading that falls within this value will be considered within the required parallelism tolerance. If the tolerance is not met, the frame will be shimmed with .001-inch-thick shims purchased on McMaster-Carr in order to obtain the required tolerance. Beyond this, the precision of the machined plates will need to be quite high with an overall designed tolerance of $\pm.0025$ for the mounting hole locations in both the X and Y directions. This tolerance should allow for the components to be mounted together without sacrificing the precision that is built into the linear rail system.

The biggest challenges of this assembly plan are going to be the timeline and the necessary precision. With the semester coming to an end and final projects and exams just around the corner the Team will need to source, machine, and assemble components very quickly. This speed is in direct opposition to the time-consuming precision required to manufacture items such as the frame. However, without this precision the Team will be unable to deliver a quality functioning test asset to Nostrum Energy. A balance will need to be found between the necessary precision and time involved in creating and maintaining that precision if the Team is to be successful.

Design vs. Prototype Build

The final prototype/build was made to capture the most important elements of the final design seen in the CAD above. The linear rails, t-slot extruded frame, as well as the carriages and stages seen in the final CAD were implemented here to demonstrate the wide degree of adjustability that are provided in the Team's design. All of these adjustability factors once assembled together can be seen in Figure 26. The goal was to mimic the performance and adjustability of an optical table while minimizing the cost, which was accomplished due to various stages and rails. The tolerance stackup of the vertical surfaces would also aid in providing for a flat surface for light alignment. The resulting manufactured prototype provided a proof of concept for future development work on the Schlieren system. This prototype will help allow for a smooth verification and validation of the design not only by allowing fine adjustments of each subsystem, but also the locking of the subsystem to make calibration more subsystem/fixture specific rather than having each component co-dependent.

It is important to note that this prototype does not yet have an injector fixture nor a camera mount. This is primarily due to time constraints. The timeline for the project was too short and didn't allow for the full manufacturing and assembly of the injector fixture. However, for validation purposes, the Team was able to capture a general Schlieren image, i.e. of a candle or lighter, rather than an injector firing. The camera mount failed to print correctly within the final portion of the timeline of the project and the carriage necessary for the linear adjustment had a long lead time and didn't arrive in time. However, the proper alignment of all of the other features in the assembly allowed the Team to image the Schlieren using a different camera through a paper projection for validation purposes.

This build demonstrates the engineering value that the Team has provided for Nostrum Energy by providing a Schlieren Imaging solution that is far cheaper than competitors, while also being modular and adjustable through the linear rails, carriages, brakes, and stages. The system is also incredibly compact, fitting on the table top provided by Nostrum seen in the figure below. This solution shows that it is possible to make a "low-budget" Schlieren Imaging system, that once validated, could be comparable to other systems.

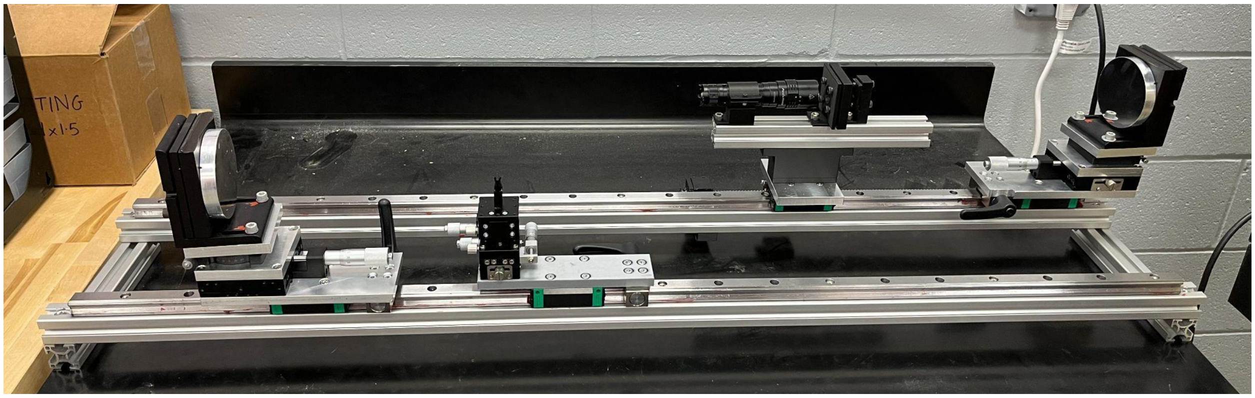


Figure 27: Partial final design prototype showing frame and linear adjustability fixtures excluding the camera mount and injector mounting

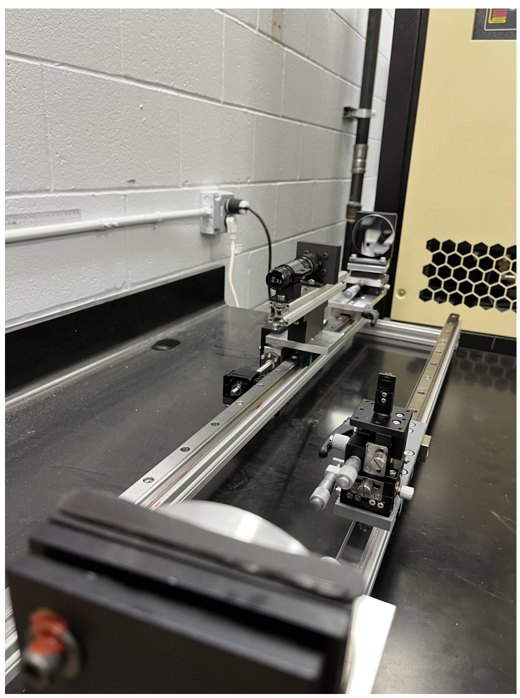


Figure 28: Final prototype setup from the point of view of the top of one of the mirrors.

<u>Validation Plan</u>

Throughout the assembly process, different components and subsystem requirements were validated. During the short period allotted for validation, the main requirements that were validated included adjustability, overall flatness of the frame, and a brief Schlieren visualization to prove functionality of the system. Topics that need to be validated in the future include visualization of Schlieren from injector firing, Mach Diamond formation, and rigidity of the frame. Additional requirements and specifications that will or have been tested, including their method of testing and their current validation status, can be seen in Table 12 below.

Table 12: Requirements and Specifications with their appropriate validation plans (plan listed may lead to further detail in the remainder of the section. Items denoted in black font are validated, blue means future validation, and green denotes the requirement will not be validated.

Req #	Requirements	Specifications	Test?	Validation Plan	Validation Status
1	Must be compact	Table-top size, 3' by 4'	Yes	Validated by measuring length and width with mirror. Can also be placed on the test bench and verified.	Validated
4	Must be simple for operators to use	One button click to operate equipment for data capture	Yes	Please see Calibration Validation and Final Schlieren Validations in below section.	Future Validation
		locating features for repeatable nozzle fixturing with cycle time under 1 minute	Yes		
5	Must be rigid	Must not deform when horizontally shock loaded < 220 N to the table	Yes	Please see Rigidness Validation Plan in below section.	Future Validation
6	Must be lightweight	< 100 lb (not including work table the machine is mounted to)	Yes	Validated by weighing the final frame with mounted components	Validated
7	Must be affordable(excluding camera)	Budget of $2000	Yes	Validated in final BOM and cost analysis.	Validated
8	Must video and image capture flow pattern of supersonic spray from injectors	Capture images at minimum 60fps or max frame rate of provided camera	Yes	See the Final Schlieren Validation in the section below.	Schlieren validated. Supersonic in future validation.
10	Must take minimal time to set up/calibrate	< 5 min to calibrate prior to each usage	Yes	See Calibration Validation in Section below.	Future Validation
11	Robust to temp changes	No calibration required 70 +- 10 degrees Fahrenheit	No	Not viable to isolate the thermal conditions given the testing equipment and environment available. This variable can be lumped together for potential validation in Final Schlieren testing.	Future Validation
12	Must allow imaging using currently supplied mirrors	Image size 2"x2"	Yes	Already validated, since the plan, BOM, and design only utilizes these mirrors. Functionality can be	Validated

				validated in Final Schlieren Validation.	
13	Lens positions must not reduce image quality	Lens angle < 10 degrees	Yes	Validate using a protractor or electronic angle finder to determine the angle of the rear or the mirror relative to the linear rail. Image can be validated in Final Schlieren Validation.	Validated
14	Extracts air/fluids	Fits shop vac hose	Yes	Hose size validated by being able to fit on the elbow. To test for droplets, pieces of paper will be placed over each mirror in the position they would be during an imaging test. The shop vac will then be turned on and the injector will be fired. After the injector is fired, the paper sheet from each mirror will be inspected for droplets. This will be repeated with new sheets for 10 trials to validate the functionality of the fluid extraction.	Future Validation
		No droplets visually seen on mirrors	Yes		
15	Filter must be X-Y-Z adjustable	X travel ¼"	Yes	Validated by taking stages and adjusting them to the full range of motion, checking if each direction has the travel specified.	Validated
		Y travel ¼"	Yes		
		Z travel ¼"	Yes		
16	Camera lens has narrow view	Lens focal length > 100mm	Yes	Validated by testing the focal length of the lens using a piece of paper, ruler, and a light source. Similar to the focal length testing of the mirrors, the light source is shined onto the lens and the piece of paper is moved away from the fixed lens position until the light that passed through the lens is a fine point. This distance should be measured and the validation should be repeated at least twice more.	Future Validation
17	Camera can be placed close to filter	Minimum distance between camera and filter is < 1inch	Yes	Validated by measuring the distance between camera lens and the knife edge with a ruler/ tape measure.	Future Validation
18	Light source must have adjustable intensity	> 5 intensity levels	Yes	Can be validated by pointing a lumen indicator at the light source for 10 trials at each intensity, measuring consistency in light levels.	Validated
19	Light on mirror must be uniform	Max brightness < 1.2 * Min brightness	Yes	Capture images of light shining through Schlieren setup. Take captured images and process with MATLAB Image tools, check for any bright spots, given the specification to the left.	Validated
20	Maintain relative flatness	Maintain 2 thou inch	Yes	See Flatness Validation Section	Validated

	across the frame	difference in height between ends of frame		Below	

Requirements Currently Validated

The following requirements and specifications have been validated using the given test processes. The results are described afterwards as well as any evidence of their functionality.

Maintain Relative Flatness Across the Frame

The purpose of this test was to determine whether each piece of extruded aluminum as well as the overall frame can be considered flat relative to itself with minimal height deviation between ends. Flatness was desired for the system and if the frame itself could not be considered flat, then 0.001” shims would be added until it was deemed flat. The following test procedure was used.

- Place each piece of extruded aluminum that had been cut to length and deburred onto the precision ground granite table.
- For each piece, take a dial indicator and place at one end of the piece of extruded aluminum and gently trace the surface from the starting point to the other end of the tube.
    - Pay attention to any deviations shown in the dial indicator as there is no data acquisition here and will need to be hand read. All values on dial indicator given in microns
- Now assemble the pieces of extruded aluminum as well as the linear rails using the hammer nuts and screws described in the assembly plan.
- Repeat the process of using the dial indicator. Place the frame upside down on the granite bench to make sure the dial indicator can reach the ends of the frame. Again, trace the top surface of the shorter pieces of extruded aluminum and note the deviation indicated. Then, quickly note the output of the dial indicator at the ends of the shorter pieces of aluminum on the same rail/tube. Do this at each rail and end.
    - Note: This method is done given the fact that the granite bench is not large enough for the dial indicator to be used more traditionally.

Results:

After completing the procedure for validating the flatness of the frame, it was found that each rail/tube side that included the smaller pieces of extruded aluminum only varied by 0.0015” and 0.0004” respectively, after logging the reading of the dial indicator at both sides. This meant that the extruded aluminum, linear rails, and the full frame assembly could be considered relatively flat and met the specification of 0.002” height difference. This meant that the Team did not have to adjust the flatness of the frame with any shim stock, further saving time. Some of the procedure can be seen in figure 29 below.

Figure 29: Carson uses a dial indicator to check for deviation in height across the rail. Note: This is an additional step that was taken and not what was described in the procedure above. In the procedure, the entire frame was upside down compared to this view.

Final Schlieren

The purpose of this test was to validate that the final prototype is of a functional form for the client. This validated most of the requirements and specifications since they each contributed to the functionality of this particular system. The one click operation, visualization of supersonic spray flows, imaging using appropriate mirrors and angles, as well as camera functionality are tested here using the following steps; however, due to the time constraints of the project, some of these were not tested and will need to be tested in the future. This future validation includes the one click operation, visualization of supersonic flows, and camera functionality. The one click operation and supersonic flow visualization couldn't be validated at the time because appropriate parts didn't arrive for the injector fixture assembly and the intended camera was not in the office due to off-site use at the time of validation. This coupled with the manufacturing errors of the camera mount and missing parts meant that this camera could not be validated. However, the overall system could still be validated for the functionality of capturing a Schlieren image. All steps are still valid for this test and once the injector assembly and camera are available, they should be integrated into the test.

- With the frame fixed to the granite table, validate that the angle is 8° of each mirror
    - Use a protractor/angle finder for the angle validation as described earlier in Table 12
- Position the carriages with the knife edge and pinhole exactly at the focal length away from the centers of the mirrors
    - Validate with the use of a ruler or tape measure
- Validate that the light is collimated between the mirrors and crosses the path of the injector
    - Using a sheet of paper and the light source turned on, follow the light path and ensure that diameter does not change between the mirrors. Lower the injector into the light path and check with the piece of paper on either side to validate if it is in the light path
- Capture a Schlieren image
    - Place a candle/lighter in the path of the collimated light, open the pinhole, and operate the camera to capture an image. Verify that it is of Schlieren quality, using the benchmark of the images of the candle/lighter from the prototype
    - Now with the injector assembly in place and electronically linked to the camera, fire the injector and capture the image simultaneously, validating the single-touch capture system and the quality of the image.
    - For troubleshooting
        - Adjust pinhole/iris for image contrast
        - Adjust knife edge for image shadow

Results:

This test validated the functionality of each subsystem as well as how they function together. The desired outcome was for the image to be clear, but if necessary, to determine which part of the system needs further attention or tuning. This should mimic how the customer will operate the system.

The Team was able to capture a Schlieren image/video using a lighter to prove the functionality of the system and the result is seen in figure 30. It is important to note that there were some difficulties in this validation process, firstly without the camera mount it was difficult to position an iPhone camera to capture the image. Instead, a piece of paper was held roughly where the camera lens would be and the projection of the Schlieren image was cast onto the paper after the razor blade filter. This image was then captured from an iPhone camera and Schlieren was visualized, although at a lower quality because of the angle that the camera was at the paper being used for the projection. Nonetheless, this proves that the system is capable of capturing a Schlieren image even with the method that was used for its capture. The team is confident that when the original intended equipment is installed, a higher quality image will be captured.

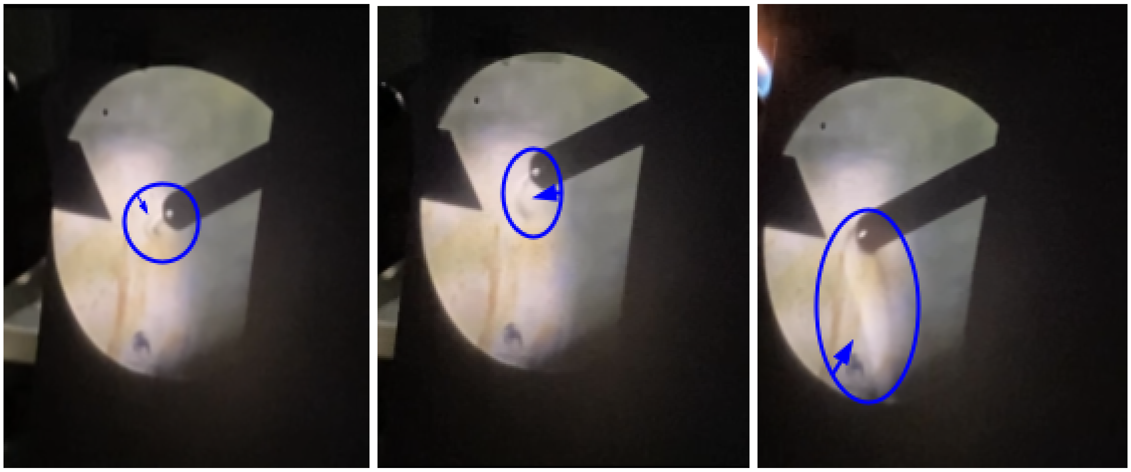


Figure 30: From right to left, a Schlieren image of gas exiting the lighter is seen (annotated with the blue ovals), ignition occurs, and the final image displays the convection waves from the flame.

Requirements That Need Future Validation

The following main requirements were not validated due to the time constraints surrounding the project. Each should be validated using the detailed validation procedure provided.

Rigidness of Frame Validation

The rigidness of the frame will be validated by testing the final frame setup after it has been fully assembled and placed on the granite test bench, which is where it will reside for use by the company. For this validation the frame will be fixed to the granite either through bolts or epoxy and will be tested using the following steps.

- Ensure that Schlieren setup is calibrated and can image test objects (i.e. candle flame, lighter)
- After the frame has been fastened to granite, place iNewton or other accelerometer to the Schlieren Imaging Frame. Ensure that it is secured.
- Apply rough pushes of approximately 0.2 gs to the granite table,
    - The value 0.2 g was deemed appropriate due to prior testing of pushing a table with an accelerometer attached, and can be concluded as the average push force for a person
- Measure the acceleration experienced by the frame.
- With the Schlieren setup powered on and previously calibrated, image a candle flame or lighter to validate the functionality of the system after a shock force.
- Repeat for 5 total trials

- If the Schlieren imaging is not clear after the shock load, recalibrate the setup for the next test

The desired goal is to validate that the Schlieren setup can properly function after being subject to a shock load. This should be successful at least 80% of the time to optimize performance for the technicians operating this system in the future. Note, the actual functionality of the system is more important the acceleration experienced by the frame.

Calibration Time

The calibration time will be validated through trial runs in which calibration is mimicked on an intentionally mis calibrated system in an effort to tune the system as the technicians would. These steps would follow the following test plan.

- With the system built and validated as previously, the mirrors will intentionally be misaligned by 2-3 degrees as random by one member of the Team. The carriages will also be moved at some random distance.
- A different member of the Team, will adjust the angles and carriages to the correct positions. A timer will be started.
- System will then be validated for functionality (the goal) with an image of a candle/lighter and compared to the benchmark images from the prototype.
- This will be repeated for a total of 10 trials.

The desired calibration time is less than 5 minutes excluding the image capture. This will validate the ease of use for the technicians. Schlieren setups are easy to set up once, but are difficult to constantly readjust accurately. This requirement would set this system apart from others.

To validate the injector placement, a similar test will be performed.

- In a timed test, a member of the Team will remove the injector from the fixture and place a new injector in the fixture and secure it.

The goal is to validate that the injector fixture is easy to manipulate and will not impede on the efficient operation of the machine. The goal is for this operation to take less than a minute.

Mach Diamond Testing

The purpose of the Schlieren imaging project was the ability to visualize the spray pattern of supersonic injector sprays, one of the Team's requirements. In supersonic sprays, a phenomenon called Mach (Shock) Diamonds occurs. This is due to the difference in pressure between the ambient conditions and the pressure at the exit of the injector. They can be seen in Figure 31. The following steps will be used to validate the capability of Mach diamond visualization.

- With the previous Schlieren setup that was already calibrated, insert a compressed air nozzle into the injector fixture.
- Check the collimation of light using the previously mentioned paper method.
- Take image and video of air nozzle firing synchronously with the camera capture

The Mach diamonds can be validated by performing a binary check with the Mach diamond images provided by NASA below. These images should also closely align with the CFD performed by the client.

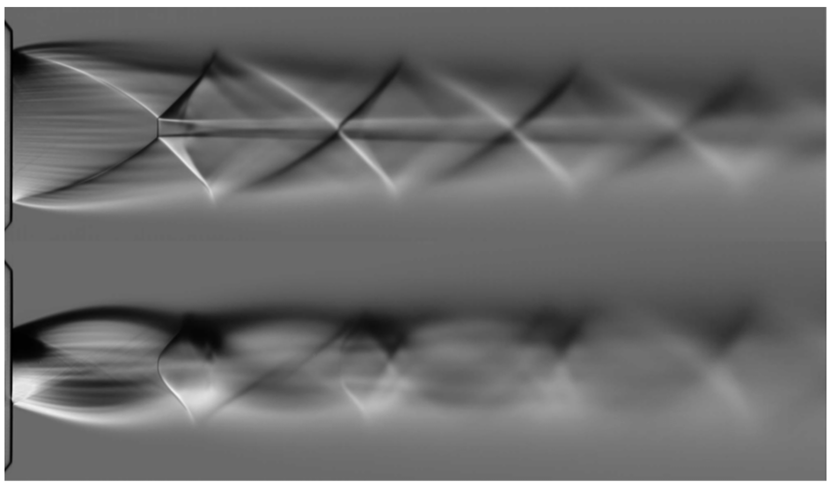


Figure 31: Image showing the Mach Diamond formation upon exit from a supersonic medium.

Discussion

This section will serve as a critique of our final design and the process we used to achieve it.

The first phase of the design process is problem definition. Given more time and resources the team would have modified aspects of this phase. Creating a novel, easy to use, and low budget Schlieren imaging system over the course of three months is challenging. This challenge was intensified by the fact that The Team had no previous experience with Schlieren imaging. The Team was able to utilize stakeholders and library research to understand the fundamentals of Schlieren; however, practical experience working with Schlieren was missing. One of the major requirements was that the system must be easy to tune. It is difficult to understand how to best fulfill this requirement without ever having tuned a Schlieren system. Another challenge in the design was determining how much precision was required in the adjustment of each individual component. The Team managed by asking experts, doing research, and using intuition; however, hands on experience working with Schlieren would have been even more effective. If the Team had more time and resources they would have gained access to an existing Schlieren imaging system in the early phases of Problem definition. With this system, the team would spend time working with the system, tuning it, and running tests in order to gain a practical understanding of what it takes to use a Schlieren system to generate quality images.

The best way to critique the design is to look at which specifications were met. Some of these specifications were explicitly checked via validation testing. For the remaining specifications, though they were not officially tested, The Team's experience working with the system provides insight into how well the system is expected to perform. The following section describes the strengths of the system.

The final system is sufficiently compact. Choosing a Z-type Schlieren set which utilizes mirrors with short focal lengths allowed the team to create a system which fit within the 3' by 4' foot requirement. Furthermore, the compact size combined with the choice of a lightweight aluminum frame led to a relatively lightweight overall system which is easy to transport. Another strength of the system is the adjustability and calibration. The Team has created a design which has adjustability in required areas, while also eliminating unnecessary adjustability in order to improve ease of calibration. A major design choice that allowed the Team to find this balance was the use of linear rails. By mounting the major functional components of the system on two sets of linear rails, the design is able to ensure the required collinearity without the need for adjustment. A final strength of the system is its cost. The Team's Schlieren imaging system cost just under $2000; a commercial system with similar capabilities costs upwards of $5000. The Team was able to reduce cost by replacing expensive optical components with custom solutions. Optical breadboard tables were replaced with aluminum extrusion, and store-bought optical fixtures were replaced with custom machined and 3D printed hardware. Cutting costs does have drawbacks however. The next section will discuss the design weaknesses.

There are several weaknesses in the current design, two of which are due to budget tradeoffs. The first weakness is less relevant to the sponsors specific needs but is still worth discussing. This Schlieren imaging system is poorly suited for large or moderate production volumes. The team was able to cut costs by using many custom parts; however, the custom parts take a significant amount of time and effort to manufacture. If ten Schlieren systems were needed rather than one, it may be beneficial to use more store-bought components and significantly reduce the manufacturing and assembly time required. The second drawback as a result of low cost is adaptability. Store bought fixtures can be used with many different active components, while The Team's custom fixtures only mate with the exact components they were intended for. If Nostrum wishes to replace a component, such as the light source, new hardware must be designed.

There are also a few system weaknesses which are not directly related to budget tradeoffs. The system produces very dim images relative to the ambient light in the room. This makes it difficult to capture images and difficult to tune the system. There are two solutions to this problem, either increase the brightness of the light traveling through the system, or decrease the ambient light reaching the system. The light within the system can be increased by using a larger pinhole, and the ambient light could be decreased with an opaque enclosure. Another system weakness is the method used to direct the light into the camera. Currently the system places the camera directly after the razor and light shines straight from the mirror into the camera. Using this method, the Team was unable to generate a Schlieren image. However, the team was able to generate an image by projecting the light from the mirror onto a flat surface, like a wall or sheet of paper. This projected image could then be captured with the camera.

Recommendations

Though the system is currently not producing high quality Schlieren images, the Team believes that with one or two more weeks of experimentation and updates the system will be functioning as intended. This section describes the recommended next steps of the project that the sponsor should follow. Fortunately, some members of the ME 450 Team also work for the sponsor, Nostrum Energy. This will make the project transition significantly smoother.

The first recommendation is to test the system with a larger pinhole. Rather than purchasing a new pin hole, a prototype can be made from tinfoil. The tinfoil prototypes have been effective in past testing and will still work with the current pinhole fixture. Increasing the pinhole size to see if it is possible to have a bright visible image, even when in a well-lit room without an enclosure would be a desirable test to perform. To simplify testing, projecting the image onto a wall or sheet rather than capturing it with the camera would allow for a quicker validation of whether the larger pinhole is effective or not. Once an effective pinhole has been found, and a quality projection is generated, then the Nostrum techs/employees can move forward with testing the camera. If increasing the pinhole size can create a bright and high-quality image then there is no need to create an enclosure for the assembly.

The next recommendation is to modify the image capture method. Rather than shine the light directly into the camera, experiment with projecting the light onto a semitransparent sheet, then image the back of the sheet with the camera. The sheet should be placed in-line with the second mirror, razor, and camera, and should be located between the camera and razor. The sheet should be as close to the camera lens as possible, while still far enough for the camera to focus on it. The sheet should also be positioned at a distance away from the razor such that the projection nearly fills the view angle of the camera. If this method proves to be an effective way to capture images, then a permanent projection sheet fixture should be designed. The distance between the projection sheet and camera can then be fixed. Therefore, it is recommended to include the projection sheet fixture on the carriage that holds the camera.

Conclusions

ME 450 Team 25 has been tasked by our sponsor, Nostrum Energy, to create a Schlieren imaging system for various injectors tip leak and spray testing. Nostrum Energy currently has CFD simulations of various injectors and an air assisted injection nozzle but currently do not have a way to test if the simulations are representative of how the injectors actually function in the real world. The system should be able to test potential fluids of Viscor, n-heptane, water, and other non-flammable gases and take both images and video of the injector firing. Some of the most important requirements and specifications are a compact system footprint of 3' by 4', maintaining affordability of the $2000 budget, minimal distortion, use of supplied equipment, and simplicity of use with one button click to operate equipment for data capture and repeatable nozzle fixturing of less than one minute. Some key engineering fundamentals that will be analyzed throughout this design solution include Fluid Dynamics, Optics, Imaging, Heat Transfer, Mechanical Design and Manufacturing, Solid Mechanics, Controls, as well as cost and budget tradeoffs. The team used brainstorming and functional analysis during the concept generation phase to form a wide variety of ideas. Then, concept selection was performed using gut-checks and Pugh charts. These inputs were used to form a detailed ALPHA design. This initial design was iterated upon and analyzed using a variety of theoretical analyses and empirical testing. Engineering analysis and prototyping were used to set the parameters for the final design. This final design utilized a T-slot extrusion frame with linear rails, various linear and rotational stages, a DSLR camera, two parabolic mirrors, a flashlight light source, and a knife edge to form a Z-Type Schlieren system. This drove the final BOM for the project. Through various design compromises, the Team was able to come reasonably close within the budget of $2000. This design as well as the requirements and specifications provided a detailed list for validation and future verification testing. The Schlieren imaging system was built using a combination of manufactured, provided, purchased, and custom machined parts in Nostrum Energy's operations room in Ann Arbor where the test asset will be utilized. The Team was able to perform some validation testing of the assembly which included ensuring flatness of the rails with a metrology table and the mirror angles being measured to be less than 10 degrees with a protractor to minimize distortion. An initial video of the system operating and providing a Schlieren image of a lighter used during testing was captured which exhibited the high quality of the assembly and ability for the Team's design to solve the sponsor's problem. Some verification testing and additional time operating and calibrating the system will need to be completed in the future to confirm that the assembly will function well repeatedly and with the qualities outlined in the requirements and specifications.

Acknowledgements

The team would like to thank those who contributed to the success of this project including Sam Barros and Lee Markle from Nostrum Energy for helping guide the team and support us with industry knowledge. We would also like to thank the whole of Nostrum Energy for funding this project and allowing us to be a part of creating this test asset. Additionally, we would like to thank our section instructor, Randy Schwemmin, for helping to guide the team and address any questions that we had regarding our project's progress or potential issues. The stakeholders we interviewed were also crucial to our project's success including Bachir Abeid, Professor Jon Estrada, Professor Mirko Gamba and his lab staff, Steve Dootz from Nostrum Energy, and Professor Cam Tropea from the Technical University of Darmstadt. Lastly, we would like to thank our fellow students in Section 007 of this course for their suggestions and feedback during our update presentations and design reviews.

Bios

A short bio of each engineering team member including where they are from, why they became an engineer, and their interests is included below. There may even be a fun fact.

David Johns

David is from the south side of Chicago, Illinois. He first became interested in mechanical engineering during his sophomore year in high school, both through experience modeling game environments and through initial exposure to 3D printing. Through a series of internships, David developed a passion for machine design and manufacturing, and has pursued it both in his professional and personal time, building 3D printers and CNC routers as a hobby along with owning and operating a small foundry. This interest is what led him to major in Mechanical Engineering. Continuing this trend, David hopes to pursue a career in additive manufacturing or automation design in the near future, developing the next generation of production machines. Outside of engineering, David enjoys fishing, playing cello, and kayaking.

Alyssa Orlans

Alyssa is from Clinton Township, MI which is about an hour away from Ann Arbor. She has always been interested in how things work for as long as she can remember. This interest coupled with her enjoyment in math and science made it clear to her in high school that engineering was a good choice for her. She decided specifically to major in mechanical engineering because of its many applications in many different fields. It is very versatile and allows for variation in possible areas of impact. Through past job experience and internships, she has become interested in moving forward in her career in the area of automotive with interest specifically in design. She is open to entering different fields of engineering in the future, possibly in other industries. A fun fact about Alyssa is that she loves to travel and has had the pleasure to do some amazing things like fly within a mile close to the largest peak in North America.

Robert Nawara

Robert Nawara is from the southwest side of Chicago, Illinois. Robert first became interested in mechanical engineering when working with his dad installing HVAC systems across northern Illinois. From that moment, Robert knew that he wanted to make tangible things in the world that helped other people; but most importantly, he wanted to create things that he would be able to look back on in 20 years and be able to proudly say that he had an impact. Robert has had experience in the virtual construction industry and diesel-electric engine design, as well as many side projects that include working on an FSAE car as the cooling lead and developing drones. He hopes to work on product development at the intersection of mechanical and electrical engineering with more of an emphasis on mechatronics. He also hopes to be able to give back to the mechanical engineering community in the future and provide more opportunities for first-gen students in STEM, like himself.

Carson Koegel

Carson Koegel was born and raised in Flint, Michigan. The diverse thought and backgrounds in Flint provided a place for Carson to expand his knowledge and view the world from different perspectives. Carson's drive to become a mechanical engineer stems from his love of all things automotive. However, since attending the University of Michigan, Carson has gained an interest in the alternative energy sector and is currently exploring the possibilities of combining his love of cars with this newfound interest. In high school Carson participated in pole vaulting and was a captain on the swim team. He has since started his own business with a friend and is working on creating a foothold in the vintage BMW scene.

Anthony Mazzola

Anthony Mazzola is from the southeast of Michigan. Anthony has always enjoyed making things that he can show to other people, whether it be a trebuchet that throws tennis balls, or a short film about toothpaste. His decision to pursue a career in engineering was solidified during his four years on a high school robotics team. Anthony is currently studying mechanical engineering at the University of Michigan. At the university he spends time with the student rocketry team

MASA, where he designs hardware and procedures for the testing of rocket components. Anthony has also gained internship experience with the industrial automation company Inovision where he has designed protective electronics cases, developed pressure loss calculators, and performed failure mode and effects analyses. Outside of academics, Anthony enjoys athletics, movies, and board games. Anthony hopes to have a career in the field of robotics, aerospace, or anywhere he can make his ideas come true and share them with others.

References:

[1] Veith I, Sonja, et al. "Making Sound Visible - a simple Schlieren imaging setup for schools." *IOP Publishing LTD.* vol. *56* no. *2,* 2021

[2] Tropea, Dr. Cameron, "Visualisierungstechniken in der Strömungsmechanik." Messtechniken in der Strömungsmechanik, TU Darmstadt, Lecture

[3] Kook, Sanghoon, et al. "Z-Type Schlieren Setup and Its Application to High Speed Imaging of Gasoline Sprays." *SAE Technical Papers,* August, 2011

Appendices

Appendix A: Bill of Materials

In figure 32 below, it describes the components purchased as well as the quantity, the subassembly that they belong to, and the link to the supplier. A further breakdown of the cost of overall stock, fasteners, and odd components is provided in figure 33, below as well.

BOM					
Optical tables					
Subcomponent	**part**	**source**	**quantity**	**price total**	**link**
Filter	filter xyz stage	Amazon	1	$125.00	https://www.amazon.com/Pricision-40
	filter mount	ThorLabs	1	$16.23	https://www.thorlabs.com/thorproduct
	filter thread adaptor	ThorLabs	1	$2.10	https://www.thorlabs.com/thorproduct
Frame	Rails + 4 carages	Vevor	1	$133.99	https://www.vevor.com/products/hgh2
Mirror Fixtures	1-axis stage	Amazon	2	$163.38	https://www.amazon.com/Micrometer
	Brakes	McMaster-Carr	3	$415.08	https://www.mcmaster.com/1685N8/
	Rotation Stage	Amazon	2	$279	https://www.amazon.com/MPositionin
Light/Camera	Additional Carriage	Amazon	1	$25.00	https://www.amazon.com/YINGJUN-I
	Ballscrew	Amazon	2	$74.00	**https://www.amazon.com/250mm-S**
	Pinhole	Edmunds	1	$51.75	https://www.edmundoptics.com/p/400
	Condensor lens	ThorLabs	1	$30.84	https://www.thorlabs.com/thorproduct
Injector Fixturing	Linear Rail	Amazon	1	$47.00	https://www.amazon.com/Linear-HGF
	Brake	McMaster-Carr	1	$145.00	https://www.mcmaster.com/1685N6/
	Horizontal T Slot	McMaster-Carr	1	$19.09	https://www.mcmaster.com/5537T52
	Vertical T slot	McMaster-Carr	1	$22.15	https://www.mcmaster.com/5537T97-
Overall	Bar/shim Stock, Fasteners, odds n ends	Various	------------	322.2	------------------
			Total	$1,871.31	

NOTE: Total excludes 3D printed part cost and shipping

Figure 32 This is the final general BOM for the final prototype that was constructed. The total cost was $1871.31 including the fasteners and stock. Items were sourced from Amazon, Thorlabs, Vevor, McMaster-Carr, Edmunds, and various other supplies. All of these items did not need additional manufacturing and were ready for assembly. The stock was used to manufacture mounting surfaces between the bought parts from various vendors.

Fastener	Subsystem	source	quantity	Purchase Quant	price total	link	Comments
3030 Series M5 Hammer Nuts	N/A	Amazon	50	1	8.99	https://www.amazon.com/Fastener-Sliding-Aluminum-Extrusion-Pr	
M5 Bolts	Fume Extraction		4	1			
M5x0.8x12	Rotation Mount Plate to Carriage	McMaster	50	1	9.15	https://www.mcmaster.com/90327A126/	
M5x0.8x12	Rotation Mount Plate to Carriage	McMaster	4	0	Above	Above	
M5x0.8x10	Rotation Mount Plate to Brake	McMaster	50	1	7.56	https://www.mcmaster.com/90327A125/	
M5x0.8x10	Rotation Mount Plate to Brake	McMaster	4	0	Above	Above	
M6x1x20	Mirror to Mirror Adjustment Mount (goes on rotation stage)	McMaster	50	1	6.66	https://www.mcmaster.com/91274A141/	
M6x1x20	Mirror to Mirror Adjustment Mount (goes on rotation stage)	McMaster		0	Above	Above	
3030 Series M6 Hammer Nuts	Gusset to T-slot	Amazon	50	1	8.99	https://www.amazon.com/Fastener-Sliding-Aluminum-Extrusion-Pr	
M6x1x25	Gusset to T-Slot	N/A	4	0	0	N/A	Reused from Past Projects
M5x0.8 15 mm Socket Head Bolt	Frame	McMaster	50	1	11.73	https://www.mcmaster.com/91290A231/	
M6x1mm 40 mm Socket Head Bolt	Frame	N/A	4	0	0	N/A	Reused from Past Projects
M5x0.8 20mm Countersunk Bolt	Injector Mounting	N/A	4	0	0	N/A	Reused from Past Projects
M6x1 mm 40 mm Socket Head Bolt	Injector Mounting	N/A	4	0	0	N/A	Reused from Past Projects
Aluminum Angle Bracket	Injector Mounting	Amazon	20	1	16.5	https://www.amazon.com/Bracket-Aluminum-Brackets-Extrusion-Pr	
M4x0.7 14 mm Countersunk Bolt	Injector Mounting	McMaster	50	1	7.71	https://www.mcmaster.com/93395A259/	
M6x1.0 10 mm Socket Head Bolt	Injector Mounting	McMaster	25	1	13.09	https://www.mcmaster.com/92290A316/	
M5x0.8 12 Bolt	Camera Ballscrew Bracket to Nut/plate	Above	6	0	0		
M4x0.7 Bolt	Camera Ballscrew Nut	N/A	6	0	0	N/A	Reused from Past Projects
M5x0.8 20 Bolt	Camera to Camera Plate	N/A	3	0	0	N/A	Reused from Past Projects
M5x0.8x12	Camera Plate to Carriage	McMaster	4	0	Above	Above	
M4x0.7 40mm Bolt	Mirror x stage plate to mirror x stage	McMaster	25	1	8.95	https://www.mcmaster.com/93395A277/	
M3x0.5 10mm	XYZ stage to filter plate	McMaster	50	1	5.56	https://www.mcmaster.com/91274A105/	
Thin Hex nut M4x0.7mm	filter mount nut	McMaster	100	1	2.73	https://www.mcmaster.com/90695A035/	
M5x0.8 12 Bolt	Light Ballscrew Bracket to Nut/plate	Above	6	0	0		
M4x0.7 Bolt	Light Ballscrew Nut	N/A	6	0	0	N/A	Reused from Past Projects
M5x0.8x12	Light Plate to Carriage	McMaster	4	0	Above	Above	
M5x0.8 20 Bolt	Light T Slot Spacer to Light Plate	N/A	3	0	0	N/A	Reused from Past Projects
M5x0.8 20 Bolt	Light T Slot Spacer to Light T Slot	N/A	3	0	0	N/A	Reused from Past Projects
M5x0.8 10mm bolt	Light mounts to T Slot	N/A	4	0	0	N/A	Reused from Past Projects
M3x0.5 10mm	flashlight mount bolts	McMaster	2	0	0	see "XYZ stage to filter plate"	same as "XYZ stage to filter plate"
M3x0.5 locknut	flashlight mount nuts	McMaster	100	1	4.65	https://www.mcmaster.com/90576A102/	
30x30mm T-slot 3ft	bracket T-slot	McMaster	3ft	1	17.39	https://www.mcmaster.com/5537T511-5537T3/	
30x30mm T-slot 5ft	Frame	McMaster	2x4 ft, 2x1 ft	1	48.96	https://www.mcmaster.com/5537T97/	
0.001" 316 Shim Stock	Frame Calibration	McMaster	8"x12"	1	9.67	https://www.mcmaster.com/2317K51/	
0.5" x 4" x 72" Alluminum Bar Stock	metal stock	McMaster	6'	1	133.91	https://www.mcmaster.com/8975K215-8975K75/	
181.5mm x 80mm x 10mm	Mirror baseplate				Above	Above	2
80mm x 80mm x 11mm	Mirror linear to rotation stage plate				Above	Above	2
76.8mm x 76.8mm x 11mm	Mirror to rotation stage plate				Above	Above	2
45mm x 180mm x 10mm	Filter Baseplate				Above	Above	1
100mm x 210mm x 11mm	camera Baseplate				Above	Above	1
100mm x 80mm x 11mm	light Baseplate				Above	Above	1

Figure 33 BOM for various fasteners, stock, and miscellaneous components. All used to assemble the purchased fixtures as well as the stock seen here that was manufactured into plates to mount the various bought components together.

Appendix B: Manufacturing Plan

As the Schlieren build contained over 15 independently designed machined parts, a traditionally designed manufacturing plan would have been cumbersome and unhelpful to the reader. Instead, as many of the parts were produced using similar machining methods, spreadsheets were made for RPM values per tool, as well as the general dimensions used for each operation. As seen in figures 34, 35, 36.

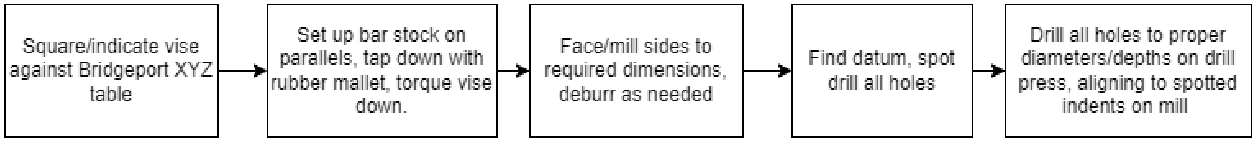


Figure 34 This flowchart shows the general manufacturing workflow on how to manufacture each part using a mill.

Tool	Speed (RPM)
1” OD 2 Flute HSS End Mill	1000
3” OD 5 Flute Indexable Carbide Face Mill	900-1200
½” OD 2 Flute Carbide End Mill	2000
Spot Drill	300
Assorted HSS Cobalt Coated Drill Bits (⅛”-¾” OD)	300-1400

Figure 35 The tools used in the mill as well as the associated RPMs are shown above. There was no power feed and no precise feed.

Part Features/Dimensions (note: all stock Al-6061 T6)

Subsystem	Part Name	Stock Type	Finished Dimensions (mm)	Number of Holes
Mirror Fixturing	Mirror Fixture Mounting Plate	Bar	80x80x10	6
	Rotation Stage Mounting Plate	Bar	76x76x10	8
	Linear Stage Mounting Plate	Bar	80x80x11	12
Frame	T Slot Rail Mounting Lengths	3030 T Slot Extrusion	30x30x1219	2

	T Slot Widths	3030 T Slot Extrusion	30x30x254	2
Injector Mounting Subsystem	Rail Mounting Plate	Bar	50x300x11	10
	Transitional Mounting Bracket	Bar	50x80x11	12
	Injector Mounting Bracket	Bar	50x50x38	7
	Injector End Stop	Bar	50x100x11	3
	Horizontal Mounting T Slot	3060 T Slot Extrusion	30x60x405	0
	Vertical Support T Slot	3030 T Slot Extrusion	30x30x300	0
	Horizontal Lower Support T Slot	3060 T Slot Extrusion	30x60x405	0
Filter	Filter Mounting Plate	Bar	100x150x11	12
Camera	Camera Mounting Plate	Bar	100x150x11	9
	Camera Ball Screw Bracket	Angle	80x80x5	6
	Ball Screw Bearing Mounting Plate	Bar	20x80x11	6
Light	Light Mounting Plate	Bar	100x100x11	9
	Light Ball Screw Bracket	Angle	80x80x5	6
	Ball Screw	Bar	20x80x11	6

	Bearing Mounting Plate			

Figure 36 The table displays each part made, what stock was used, the finished dimensions, and the number of holes. All stock was Al-6061 T6.

Appendix C: Assembly Diagrams

The following appendix section shows the assembly sequence for each subsystem used in the final design. All components were actually assembled excluding the camera mount and related injector fixturing.

Assembly Diagram - Frame

According to figure 37, the small aluminum t-slot is first assembled with the larger t-slot tubes using M5 fasteners and hammer nuts. Once these are locked in place, the 14 3030 Series M5 hammer nuts are placed in the large t-slot extrusions (divided evenly). The M5 screws are dropped into the appropriate counterbored holes in the linear rails and placed on the t-slot. Adjust to line up each hammer nut and screw. Tighten with the appropriate allen wrench and the hammer nut should self-lock in place.

Figure 37 The diagram shows the exploded view for the frame assembly using various screws, linear rails, and t-slot aluminum extrusions.

Assembly Diagram - Mirror Fixturing System:

To put together the mirror fixturing system, please follow figure 38 below. The carriage and brake are first mounted to the base plate using the base plate bolts. Four other bolts/screws are then used to fix the X-stage to the base plate from the underside of the base plate. The rotation stage transfer plate is mounted on the X-stage using 4 M4 bolts. Then the rotation stage is mounted to the rotation stage transfer plate using 4 rotation stage bolts. The mirror fixturing plate is then put on the rotation stage and mounted using 4 M4 screws. Finally, the mirror is fixed to the mirror fixture mounting plate using 2 M8 bolts. All bolts/screws can be fastened with allen keys. This subassembly is then slid onto the linear rail built previously. Note: This assembly sequence will have to be done twice due to there being 2 mirrors in the system.

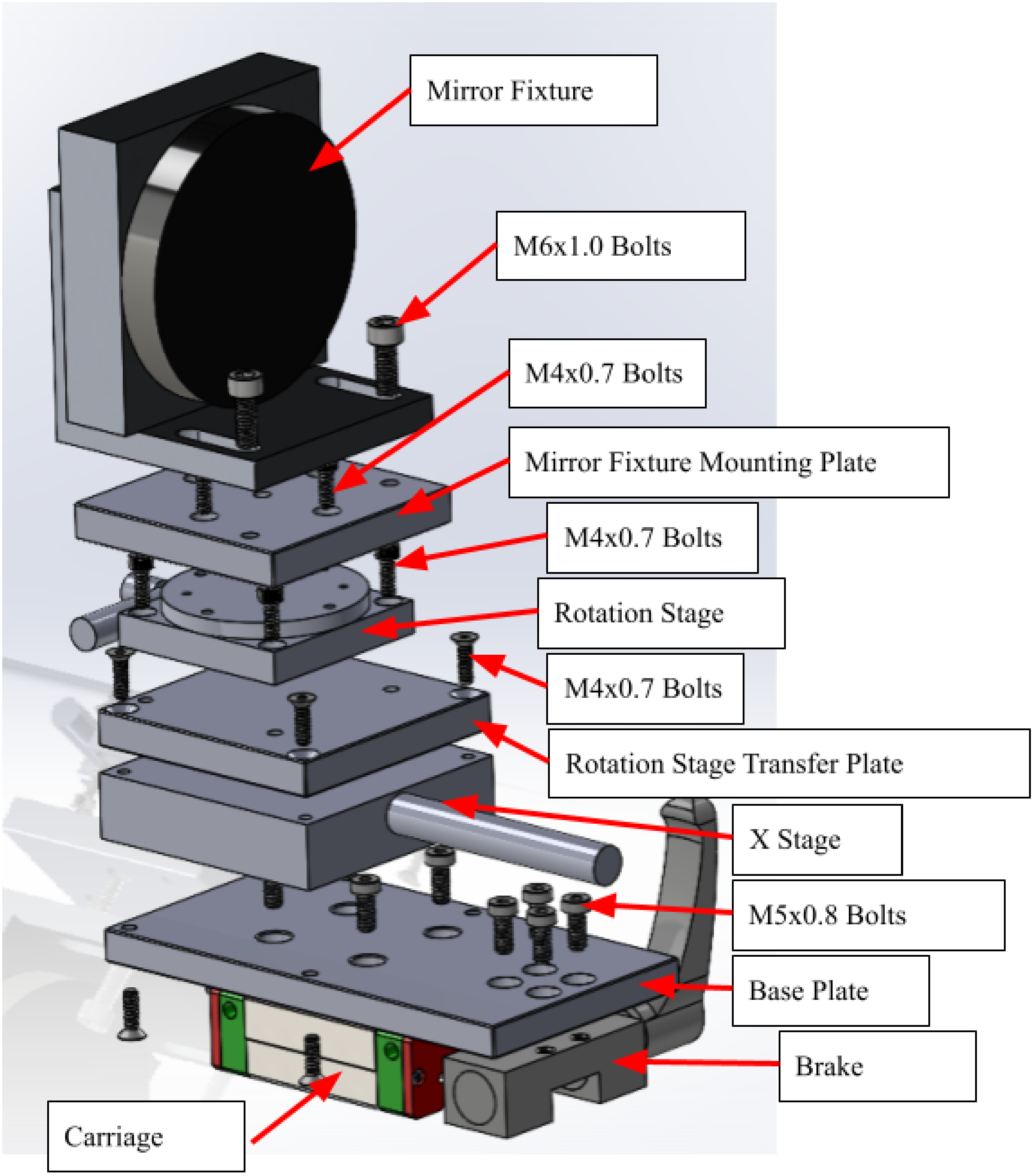


Figure 38 The exploded assembly diagram for the mirror fixture involving the mirrors and specified plates and fasteners. This will be mounted to the linear rail on the frame.

Assembly Diagram - Injector Frame

The assembly in figure 39 below shows the assembly plan for the injector mounting frame. The rail mounted subassembly is bolted to a horizontal t slot gantry, which is supported vertically by two matching t slot columns, fastened using gussets to a horizontal piece of t slot under the assembly. Fasteners vary from M4-M6, depending on application, and are held to t slot using hammer nuts.

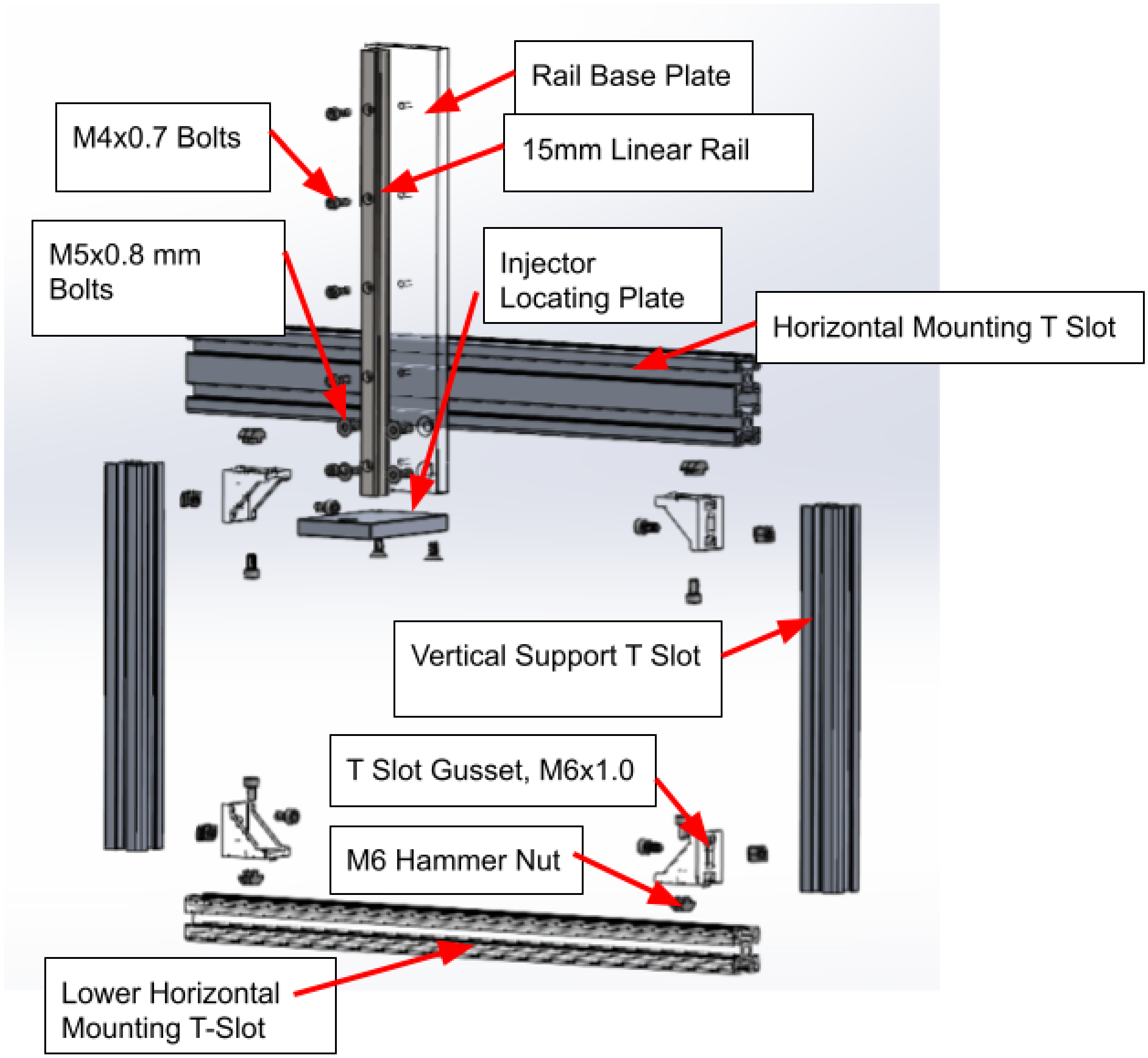


Figure 39 The exploded assembly view shows the fasteners, angle brackets, rail, and t slots needed for the injector frame. The injector fixture is mounted to this. This entire assembly is placed so that the lower t-slot is placed below the frame t slot.

Assembly Diagram - Injector Fixture

Figure 40 below describes the assembly of one portion of the injector mounting. The holder mounting plate was mounted to the brake and carriage using the 4 M4 screws shown below. The injector holder plate is then mounted to the holder mounting plate using 4 M6 screws. The injector holder is placed within the locating hole on the injector holder plate and fastened using 2 M5 screws. This entire assembly is secured onto the linear rail from the injector mounting t-slots by sliding the carriage onto another linear rail that was fastened to the t-slot.

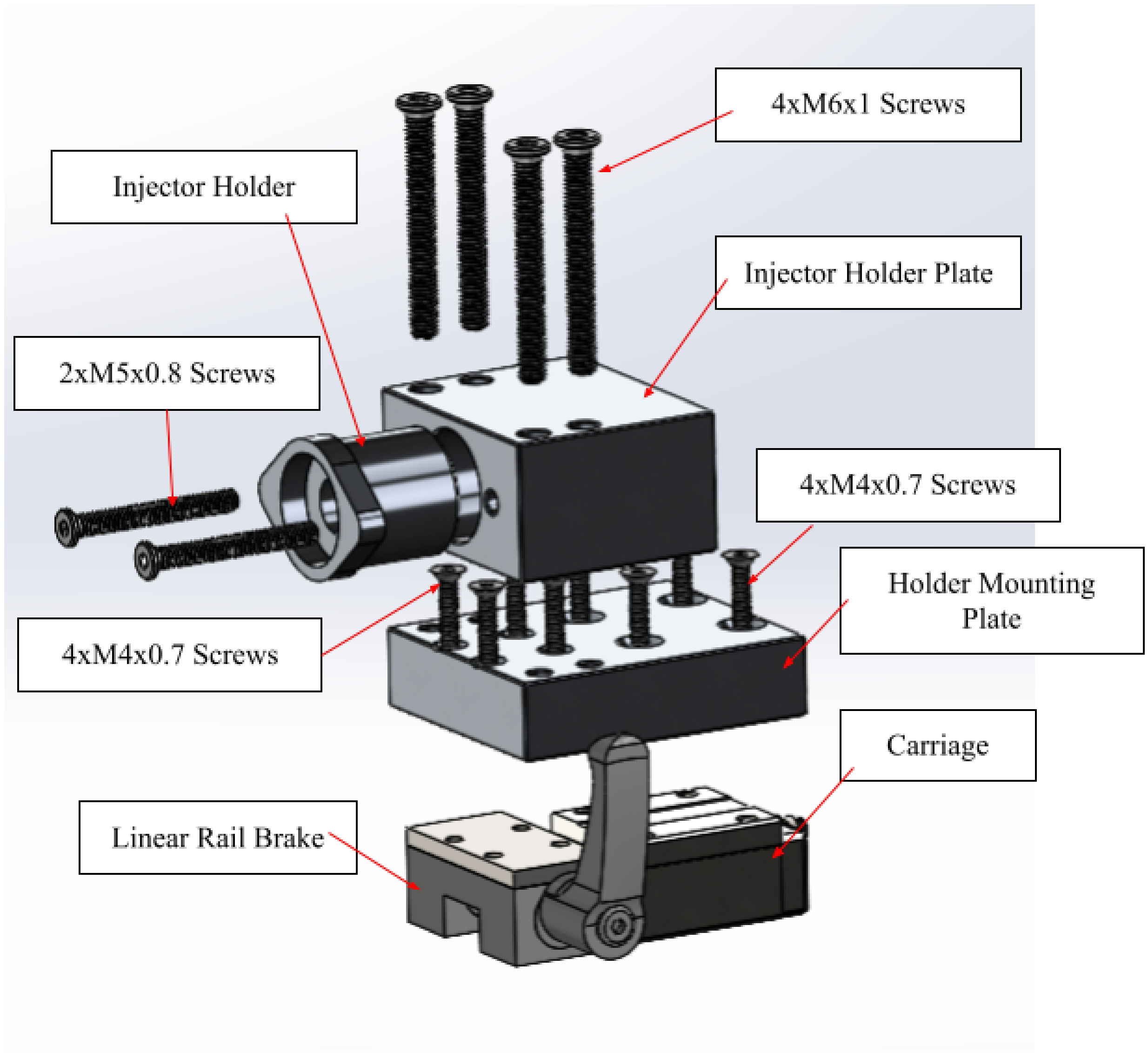


Figure 40 The exploded assembly view of the injector fixture shows the components being mounted together to provide a place for the injector to sit and have its height adjusted.

Assembly Diagram - Razor Fixturing

In figure 41 below, the filter plate is mounted to the carriage and rail break using M5 screws with lengths of 12 and 10 mm respectively. The xyz stage is then mounted to the filter plate from the underside of the current view using 4 M3 bolts. Then to place the filter fixture with razor blade on the stage and M4 to M3 adaptor is fastened into the stage and a low-profile M4 nut is attached. Note: be very careful; the razor is sharp. This entire subassembly is then placed onto the linear rail from the frame by sliding the carriage and brake onto the rail.

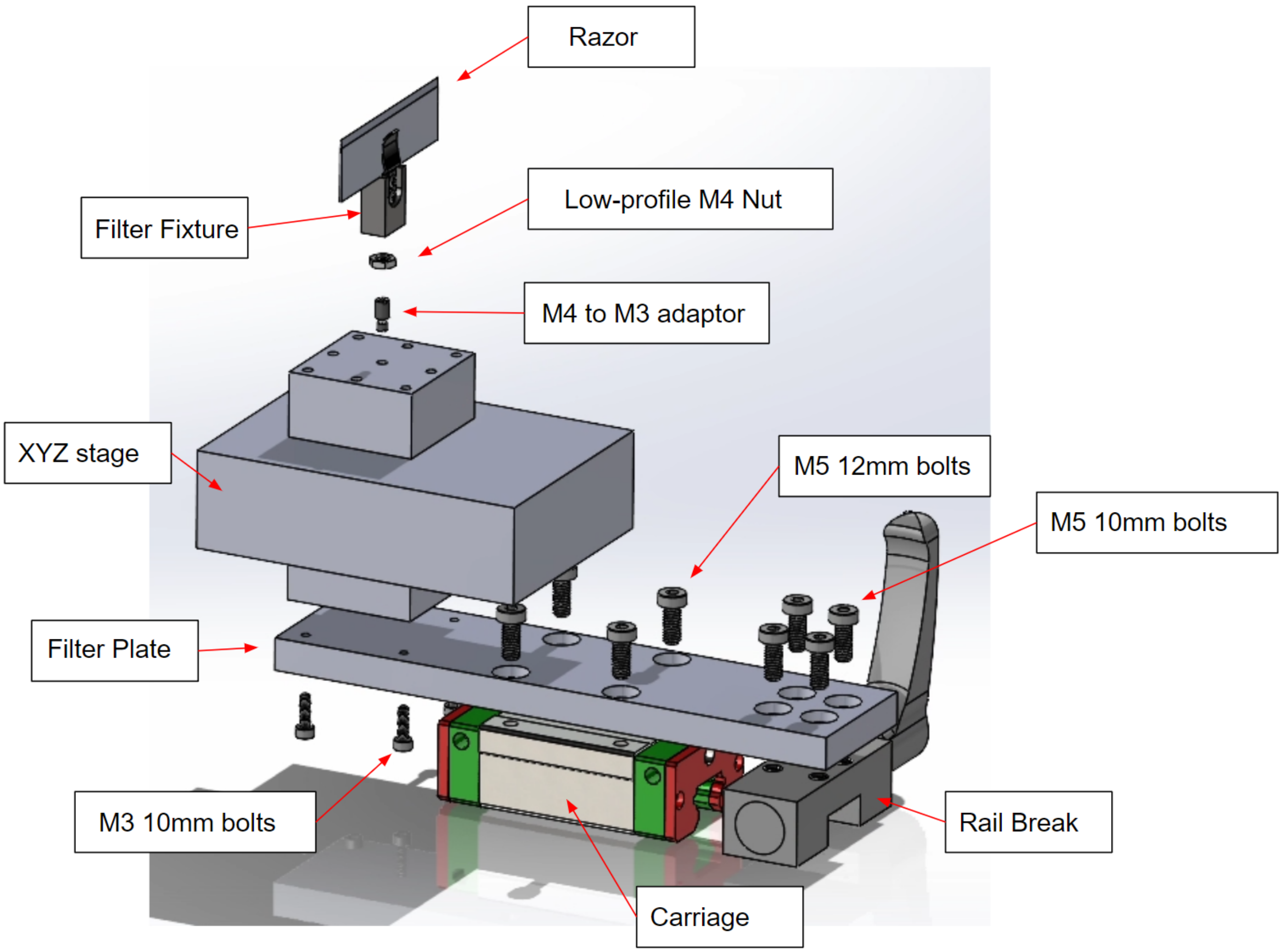


Figure 41 The exploded assembly sequence shows the assembled components of the razor fixture mount that is placed on the linear rail from the frame.

Assembly Diagram - Light Fixtures

In figure 42 shown below, optical components are mounted to a horizontal section of 3030 T slot using M6x1.0 socket head bolts. Components are held down to threaded holes in the brackets using M4x0.7 bolts. The T slot is spaced from its mounting plate (which is itself held to a ball screw drive fastened to a piece of angle stock by a series of M5x0.8 mm bolts) using a 3D printed spacer with M6x1.0 socket head bolts.

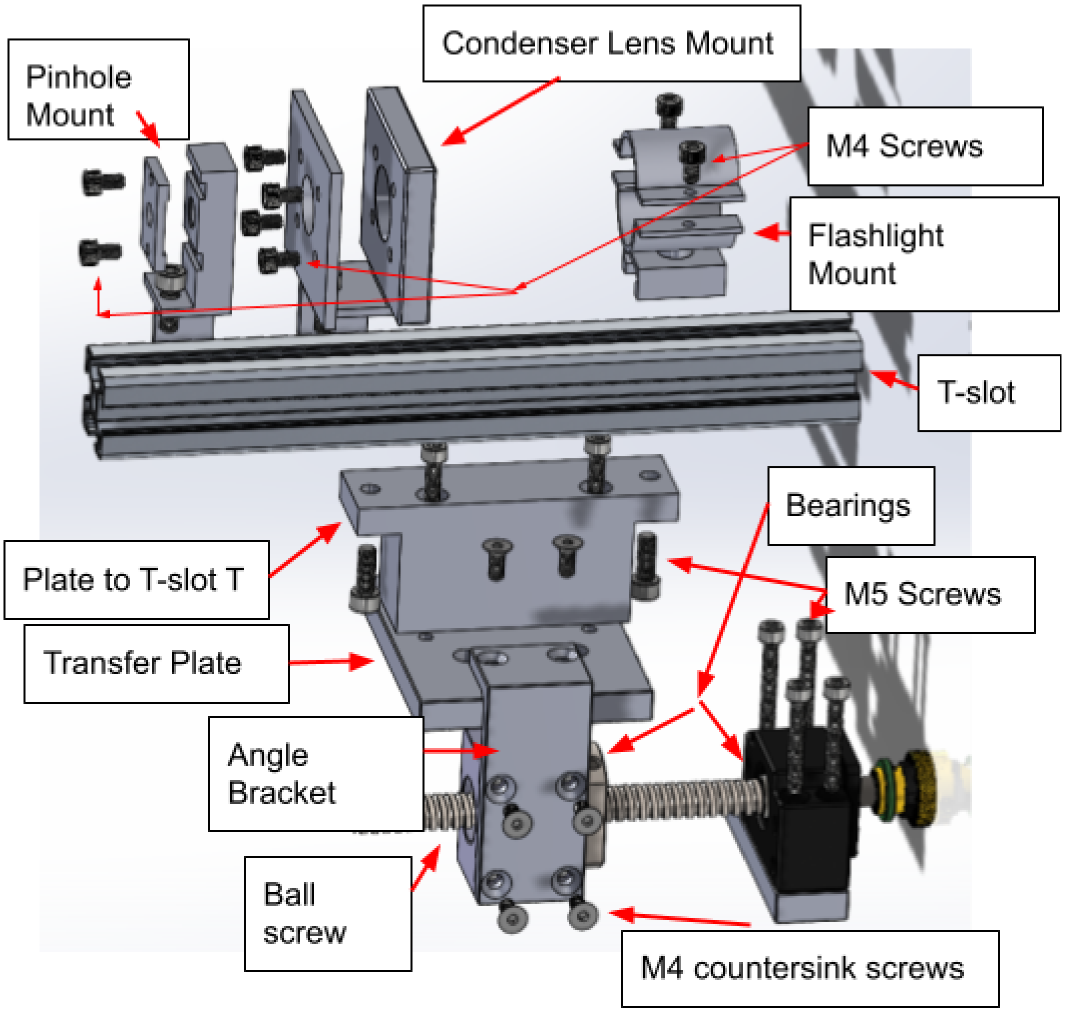


Figure 42 This assembly diagram shows the light fixturing components and how they are mounted to the t slot, which is then mounted to a plate that is adjusted by a ball screw. Although not seen in the diagram, a carriage resides beneath the transfer plate to allow easy maneuvering on the rail.

Assembly Diagram - Camera Mounting Fixture

The camera is mounted to a 3D printed dovetail mount fixed to a machined base plate using M5 socket head bolts as shown in figure 43. It is connected to a ball screw drive using an angle bracket fastened using M5 bolts, and bolted to a carriage.

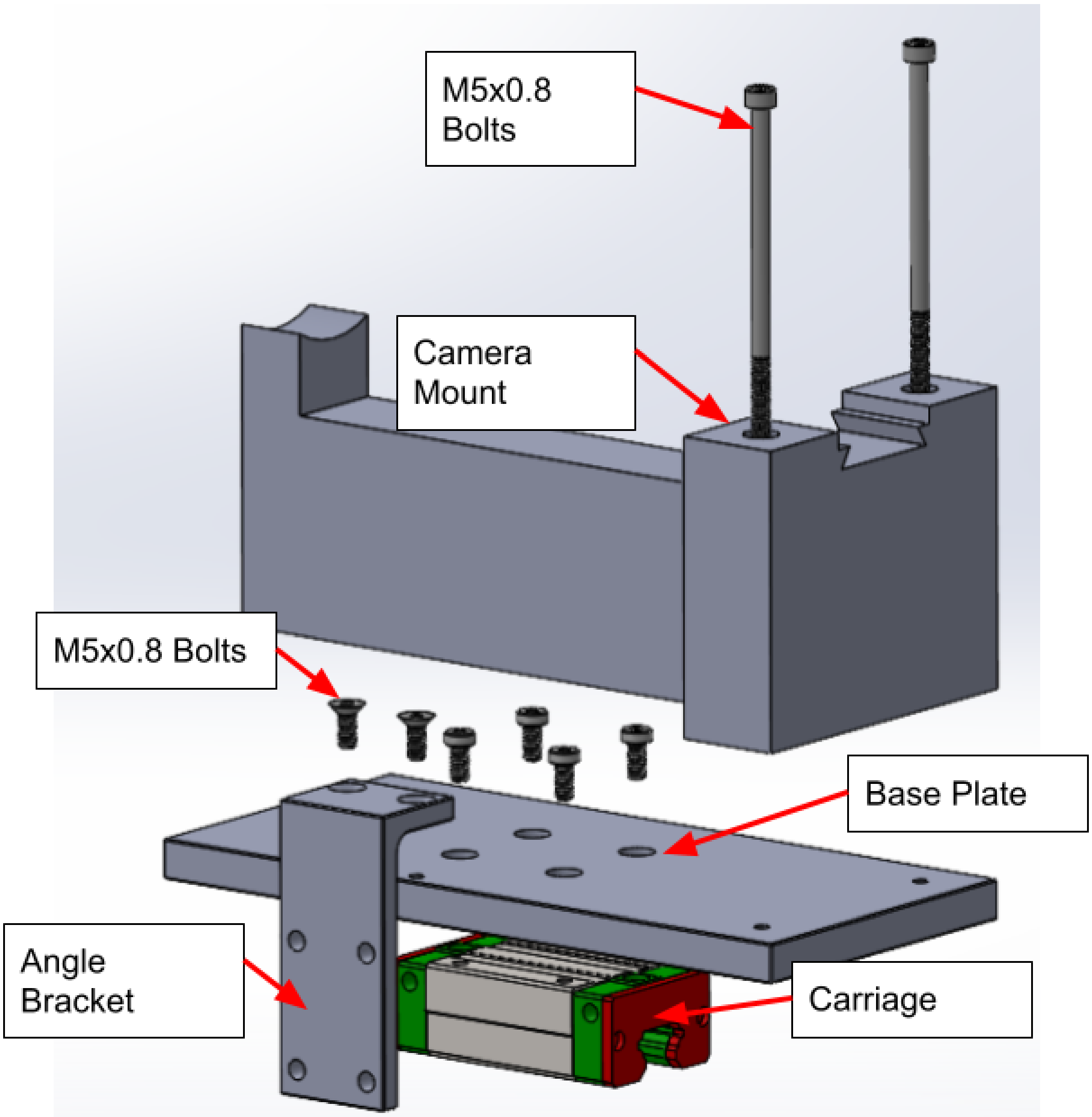
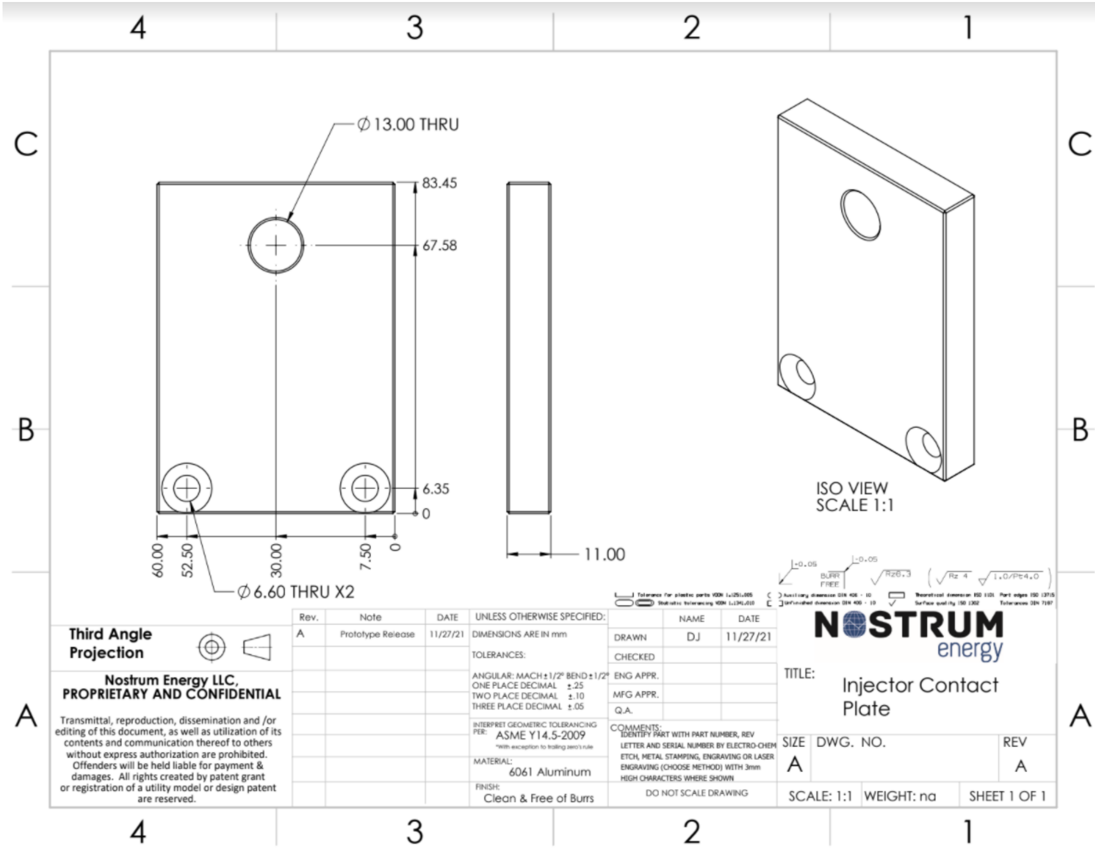
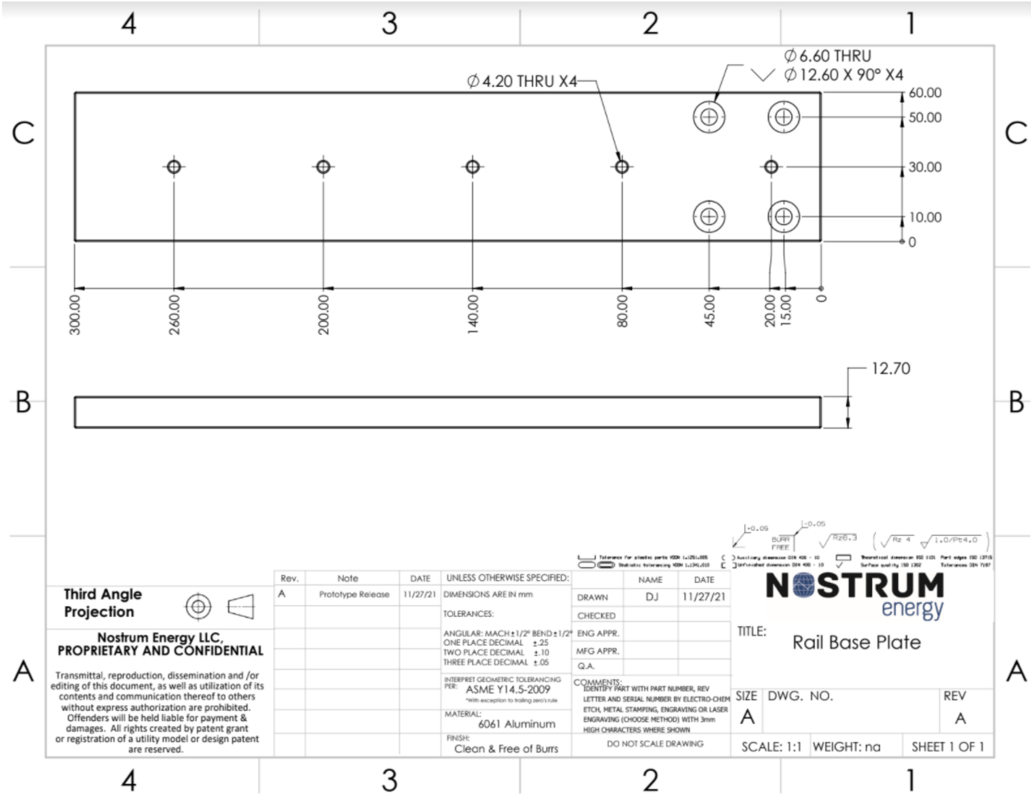


Figure 43 The diagram shows the assembly of the 3D printed camera mount and how it is fastened to the base plate which is fastened to the carriage. This assembly is maneuvered using the ball screw assembly (please refer back to the light fixture for more specific instructions on assembling the ball screw interface with the bracket assembly.

Appendix D: Engineering Drawings

The following are some of the engineering drawings that were made for milling various pieces of stock to interface with the pre-purchased parts. All parts follow the manufacturing plan discussed earlier Appendix B. All parts that were made via 3D printing on the company's Markforged printer did not have drawings made and are not included in this section.

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∅4.20 THRU X4
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50.00
30.00
10.00
0
300.00
260.00
200.00
140.00
80.00
45.00
20.00
15.00
0
12.70
Third Angle Projection
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Rev. | Note | DATE
A | Prototype Release | 11/27/21
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN mm
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TWO PLACE DECIMAL ±.10
THREE PLACE DECIMAL ±.05
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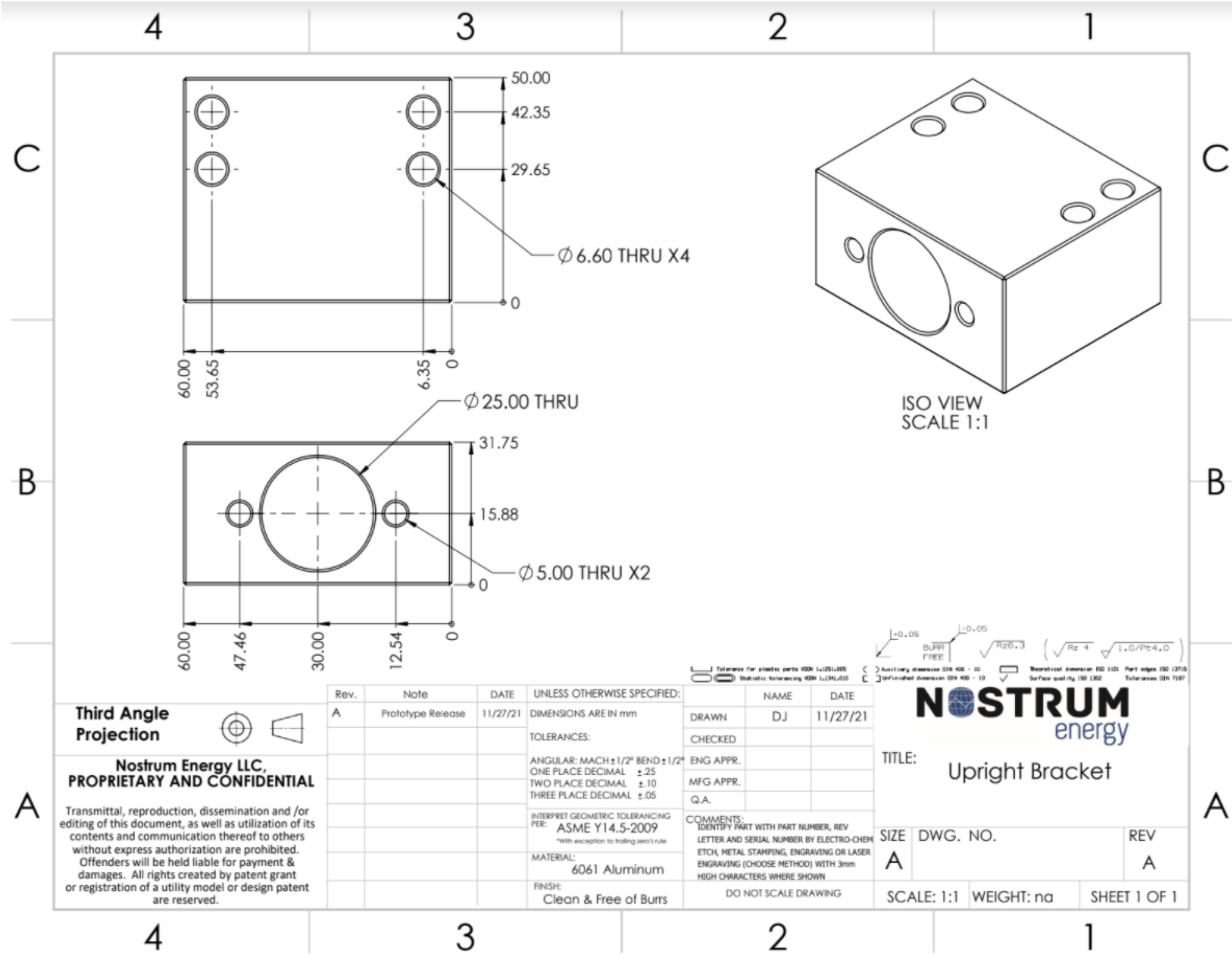
MATERIAL: 6061 Aluminum
FINISH: Clean & Free of Burrs
NAME | DATE
DRAWN | DJ | 11/27/21
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS: IDENTIFY PART WITH PART NUMBER, REV LETTER AND SERIAL NUMBER BY ELECTRO-CHEM ETCH, METAL STAMPING, ENGRAVING OR LASER ENGRAVING (CHOOSE METHOD) WITH 3mm HIGH CHARACTERS WHERE SHOWN
DO NOT SCALE DRAWING
NOSTRUM energy
TITLE: Rail Base Plate
SIZE A
DWG. NO.
REV A
SCALE: 1:1
WEIGHT: na
SHEET 1 OF 1



50.00
42.35
29.65
0
60.00
53.65
6.35
0
Ø 6.60 THRU X4
Ø 25.00 THRU
31.75
15.88
0
Ø 5.00 THRU X2
60.00
47.46
30.00
12.54
0
ISO VIEW
SCALE 1:1
Third Angle Projection
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DIMENSIONS ARE IN mm
TOLERANCES:
ANGULAR: MACH ±1/2° BEND ±1/2°
ONE PLACE DECIMAL ±.25
TWO PLACE DECIMAL ±.10
THREE PLACE DECIMAL ±.05
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MATERIAL: 6061 Aluminum
FINISH: Clean & Free of Burrs
NAME DATE
DRAWN DJ 11/27/21
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ENG APPR.
MFG APPR.
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NOSTRUM energy
TITLE: Upright Bracket
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DWG. NO.
REV A
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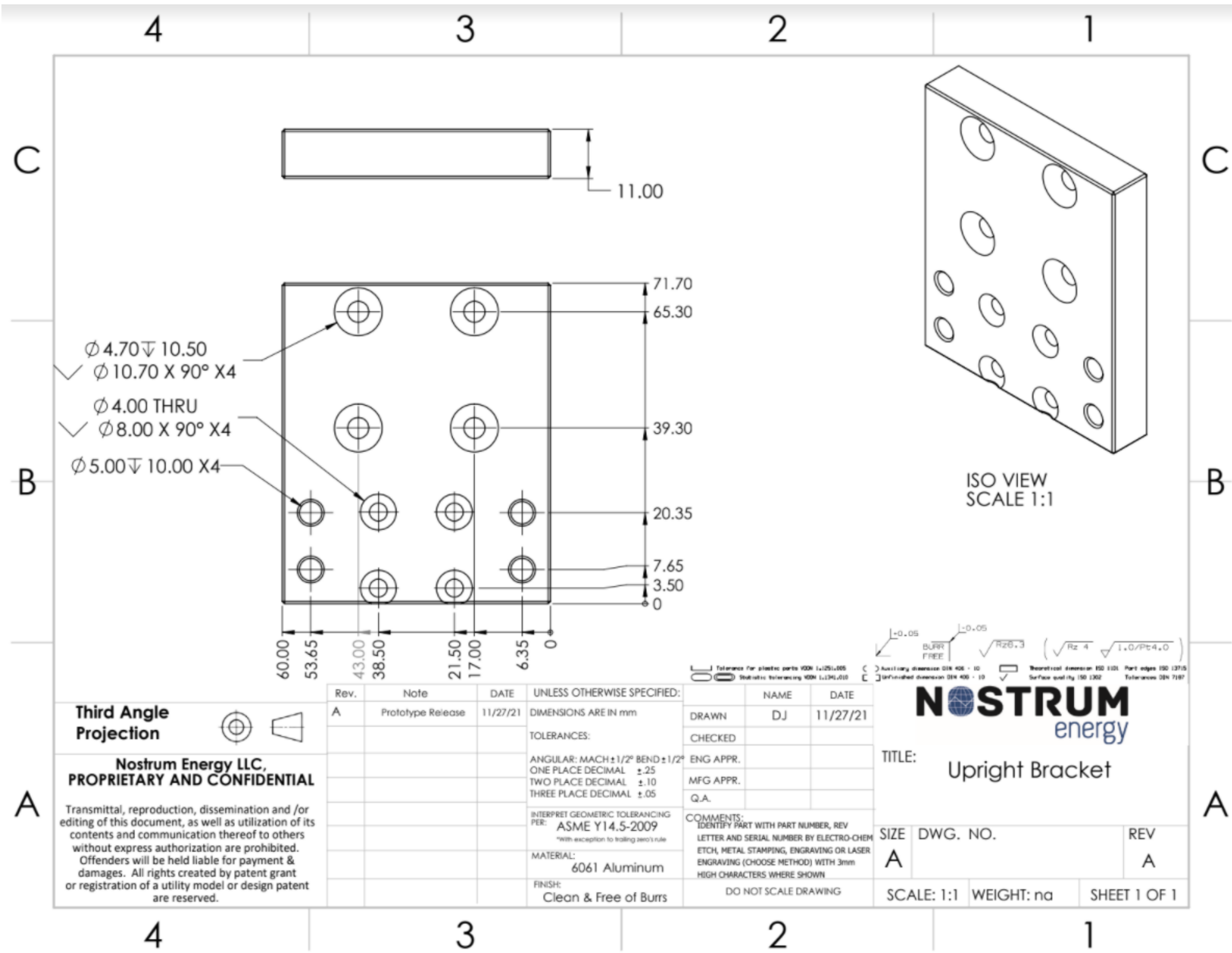
WEIGHT: na
SHEET 1 OF 1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39.30
20.35
7.65
3.50
0
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Ø4.00 THRU
⌵ Ø8.00 X 90° X4
Ø5.00 ↧ 10.00 X4
60.00
53.65
43.00
38.50
21.50
17.00
6.35
0
ISO VIEW
SCALE 1:1
Third Angle Projection
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DIMENSIONS ARE IN mm
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TWO PLACE DECIMAL ±.10
THREE PLACE DECIMAL ±.05
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5-2009
MATERIAL: 6061 Aluminum
FINISH: Clean & Free of Burrs
NAME | DATE
DRAWN | DJ | 11/27/21
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS: IDENTIFY PART WITH PART NUMBER, REV LETTER AND SERIAL NUMBER BY ELECTRO-CHEM ETCH, METAL STAMPING, ENGRAVING OR LASER ENGRAVING (CHOOSE METHOD) WITH 3mm HIGH CHARACTERS WHERE SHOWN
DO NOT SCALE DRAWING
NOSTRUM energy
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SIZE A
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REV A
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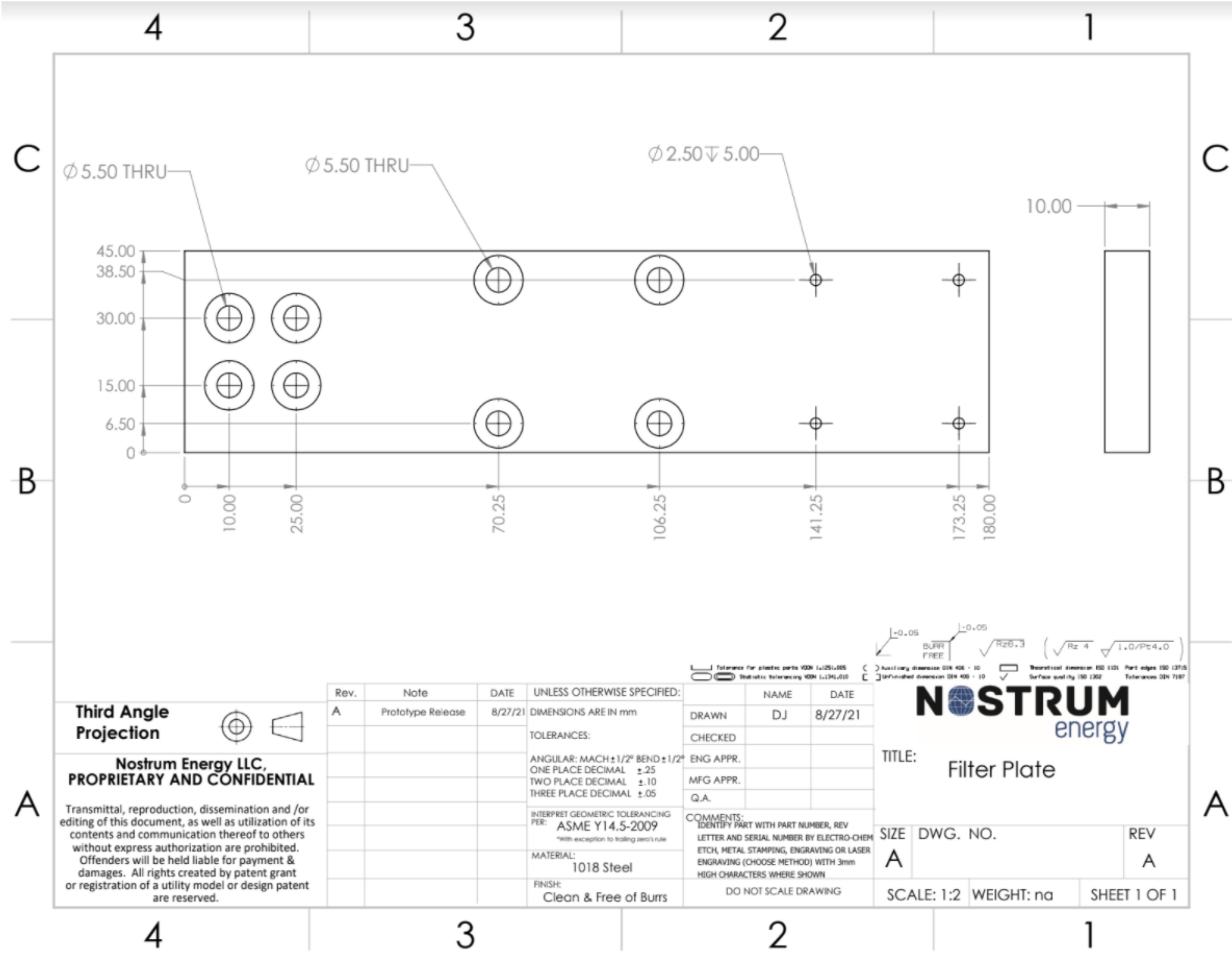
WEIGHT: na
SHEET 1 OF 1



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Ø 2.50 ↧ 5.00
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0
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10.00
25.00
70.25
106.25
141.25
173.25
180.00
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TOLERANCES:
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TWO PLACE DECIMAL ±.10
THREE PLACE DECIMAL ±.05
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REV A
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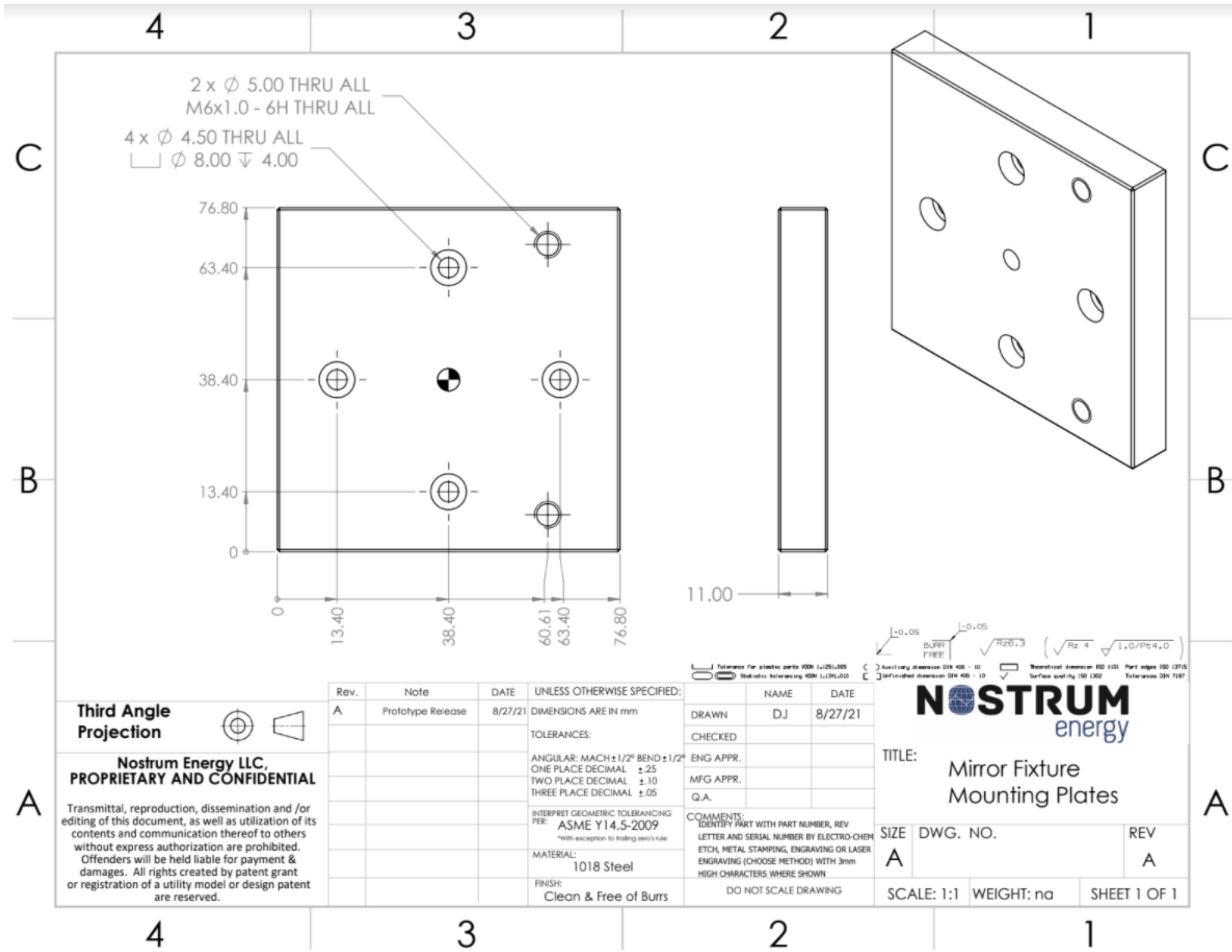
WEIGHT: na
SHEET 1 OF 1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M6x1.0 - 6H THRU ALL
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∅ 8.00 ↧ 4.00
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38.40
13.40
0
0
13.40
38.40
60.61
63.40
76.80
11.00
Third Angle Projection
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DIMENSIONS ARE IN mm
TOLERANCES:
ANGULAR: MACH ±1/2° BEND ±1/2°
ONE PLACE DECIMAL ±.25
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THREE PLACE DECIMAL ±.05
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FINISH: Clean & Free of Burrs
NAME DATE
DRAWN DJ 8/27/21
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS: IDENTIFY PART WITH PART NUMBER, REV LETTER AND SERIAL NUMBER BY ELECTRO-CHEM ETCH, METAL STAMPING, ENGRAVING OR LASER ENGRAVING (CHOOSE METHOD) WITH 3mm HIGH CHARACTERS WHERE SHOWN
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REV A
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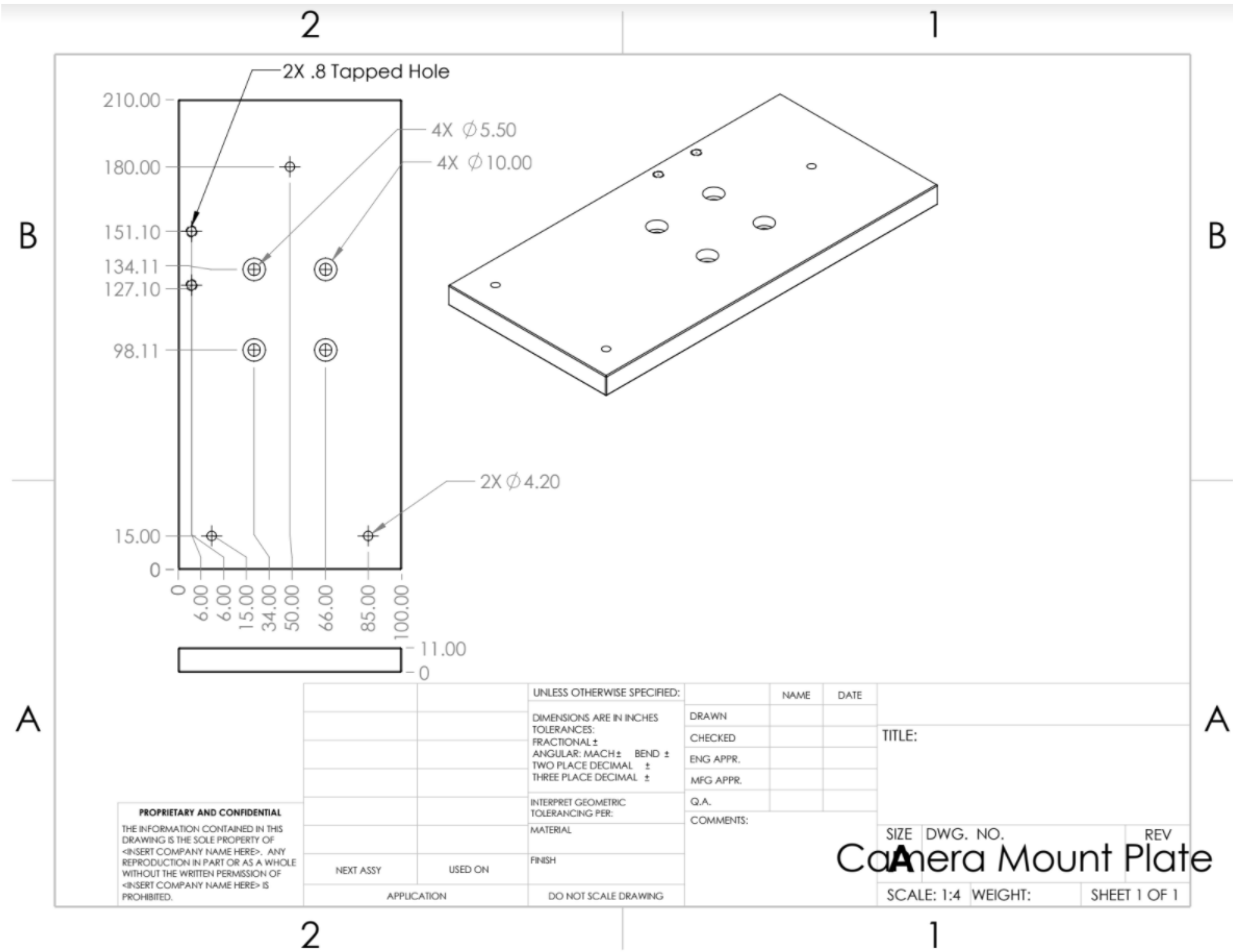
SHEET 1 OF 1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15.00
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6.00
6.00
15.00
34.00
50.00
66.00
85.00
100.00
11.00
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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
DWG. NO.
REV
A
Camera Mount Plate
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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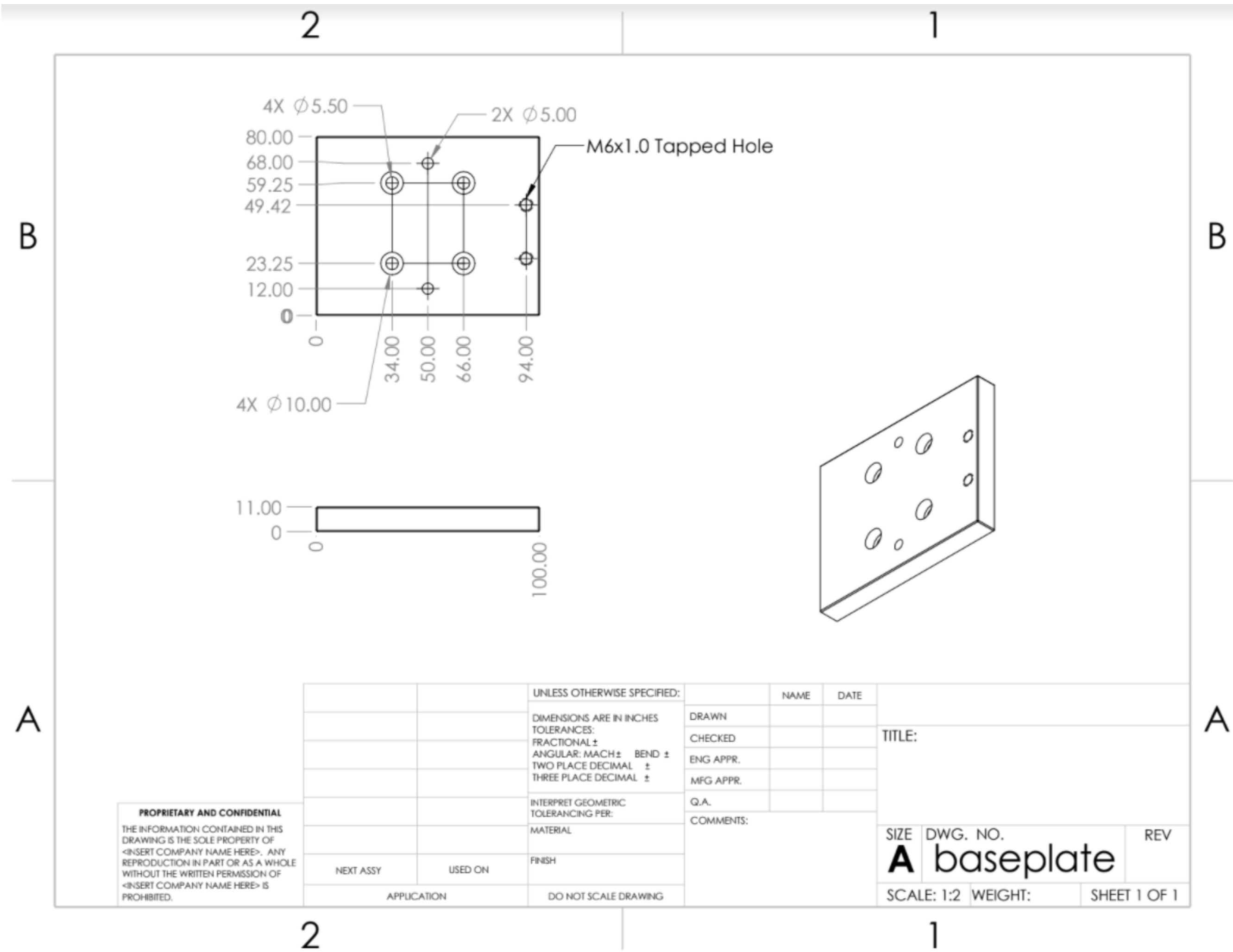
2
1
B
A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66.00
94.00
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11.00
100.00
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FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
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DO NOT SCALE DRAWING
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USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
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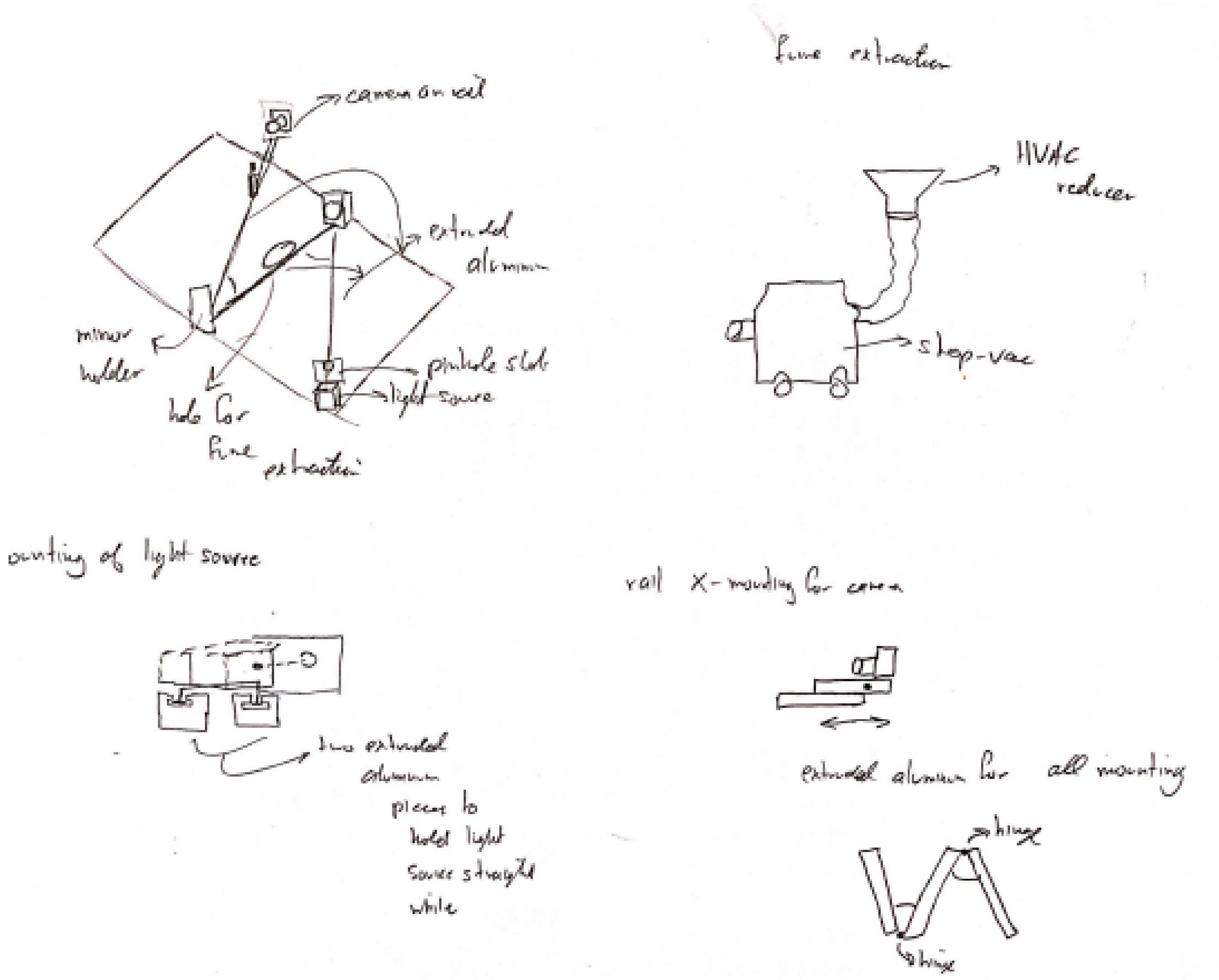
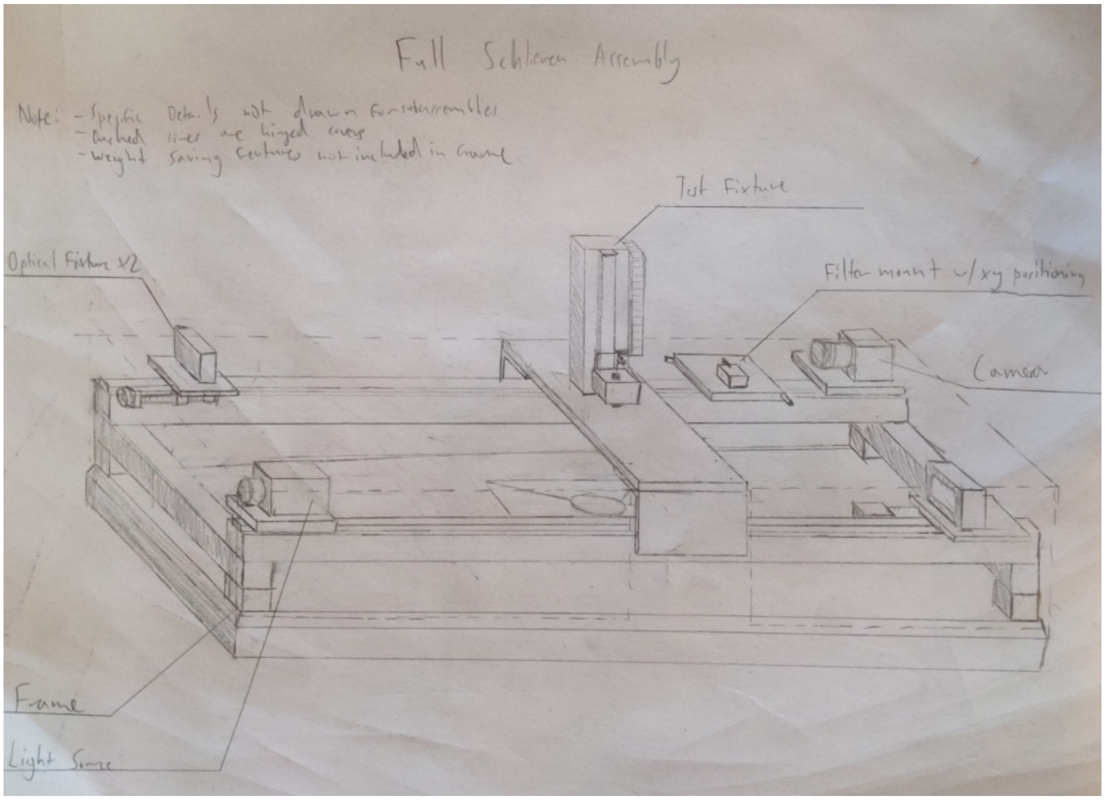
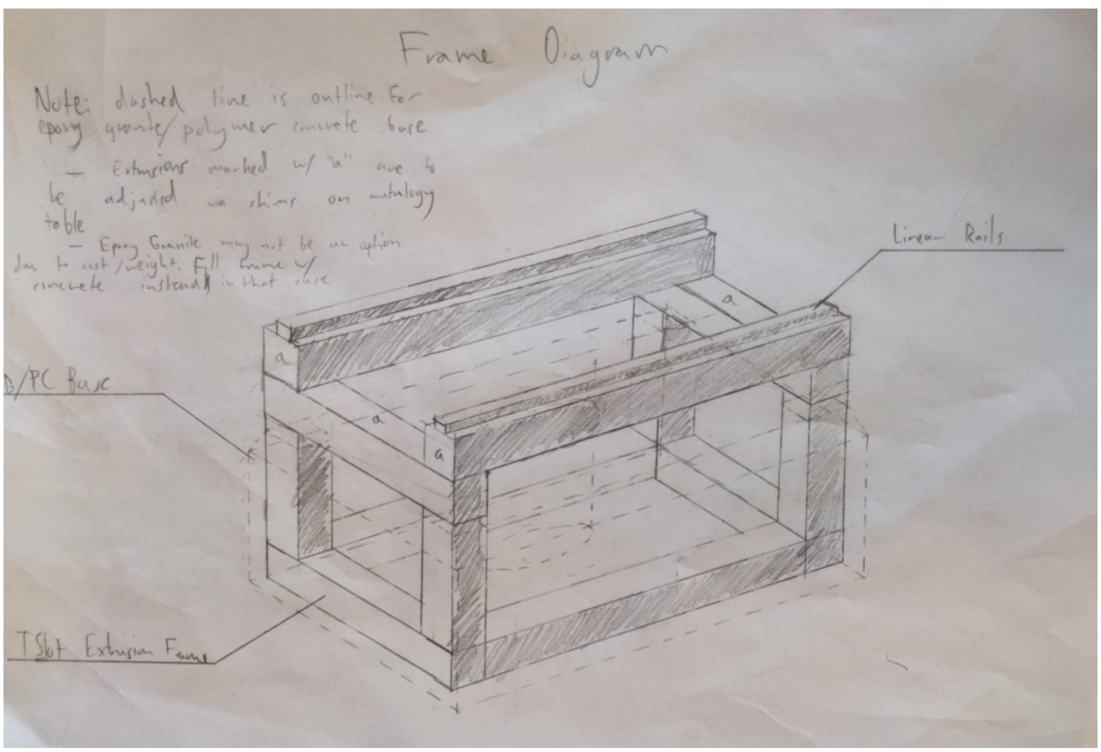
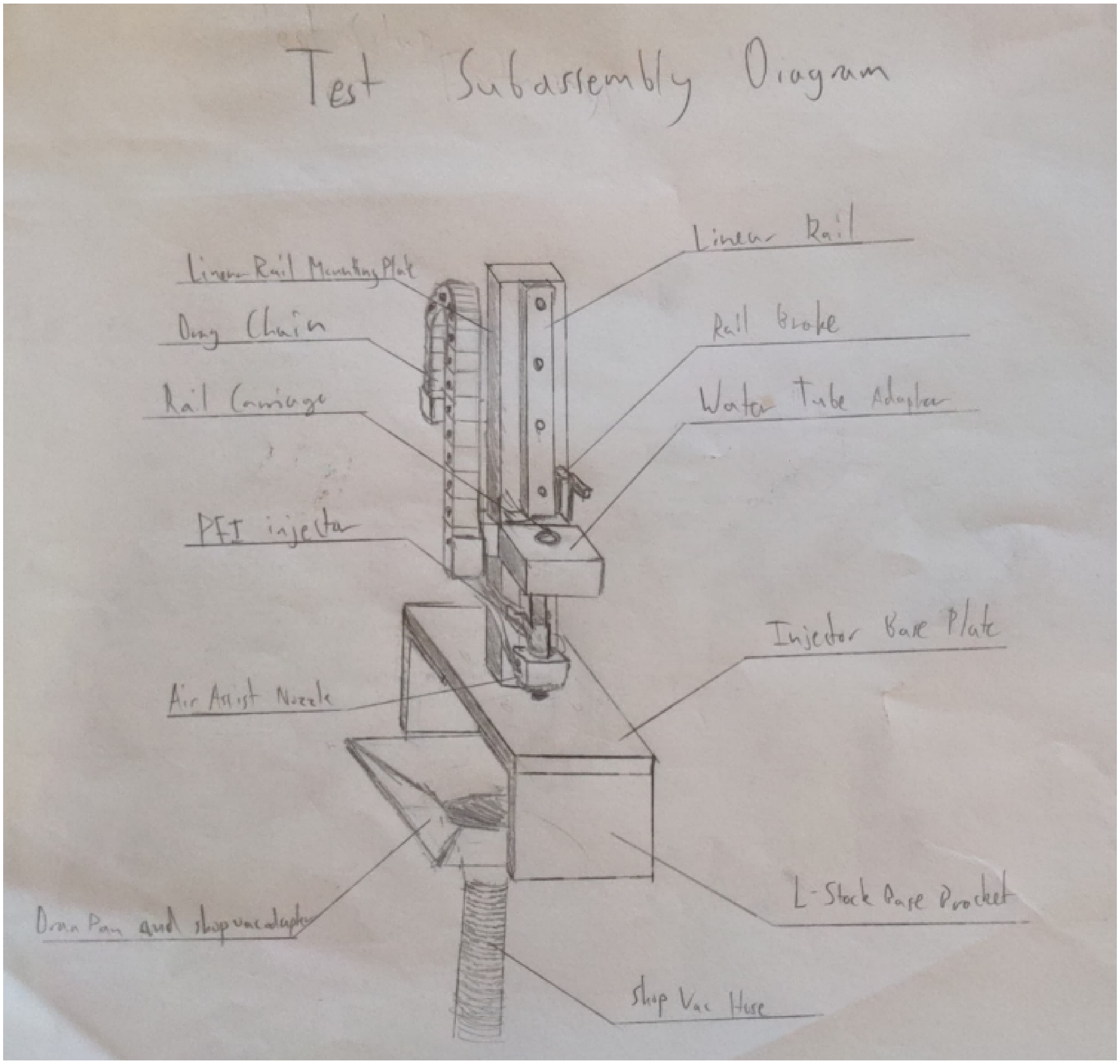
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

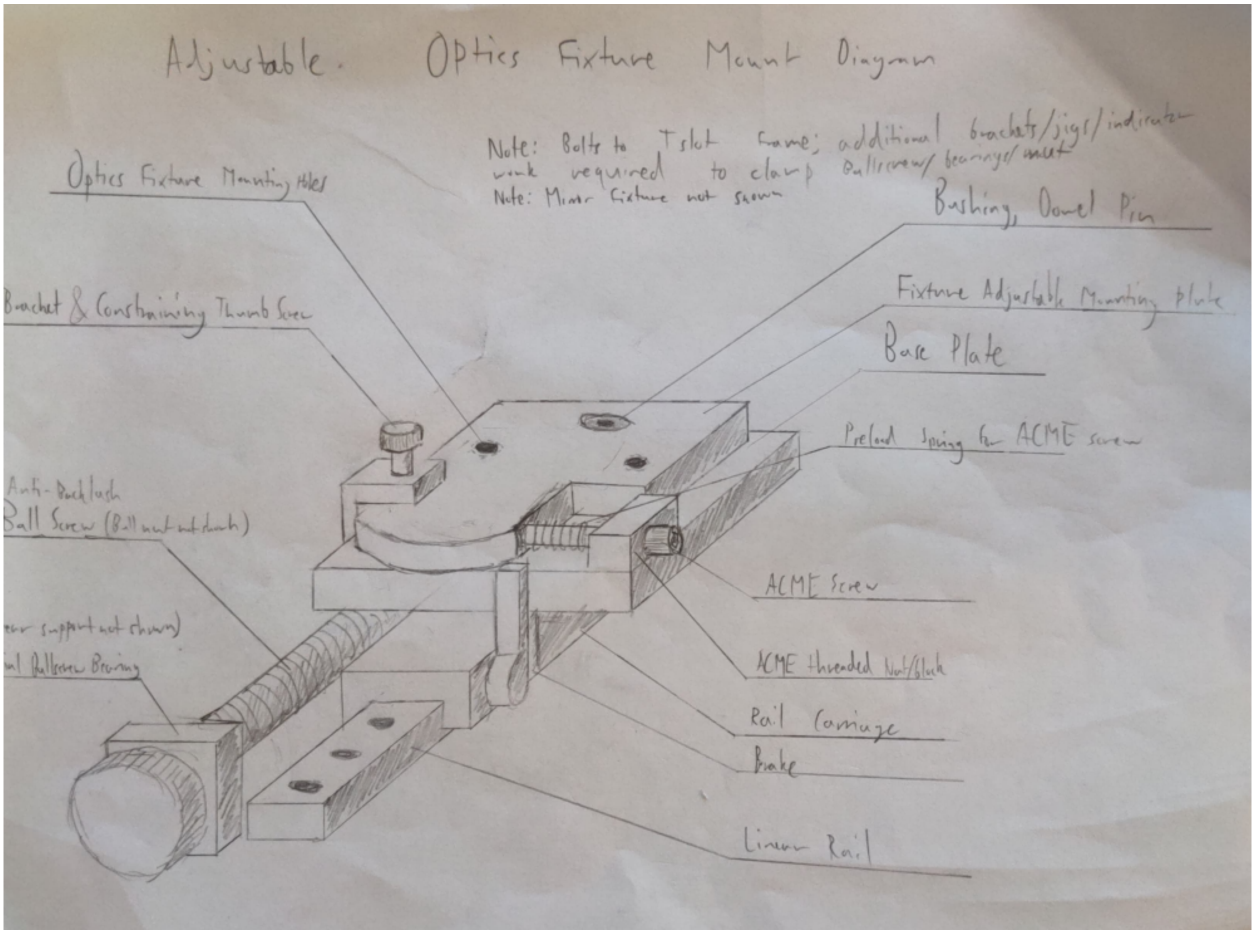
Appendix E: Concept Drawings

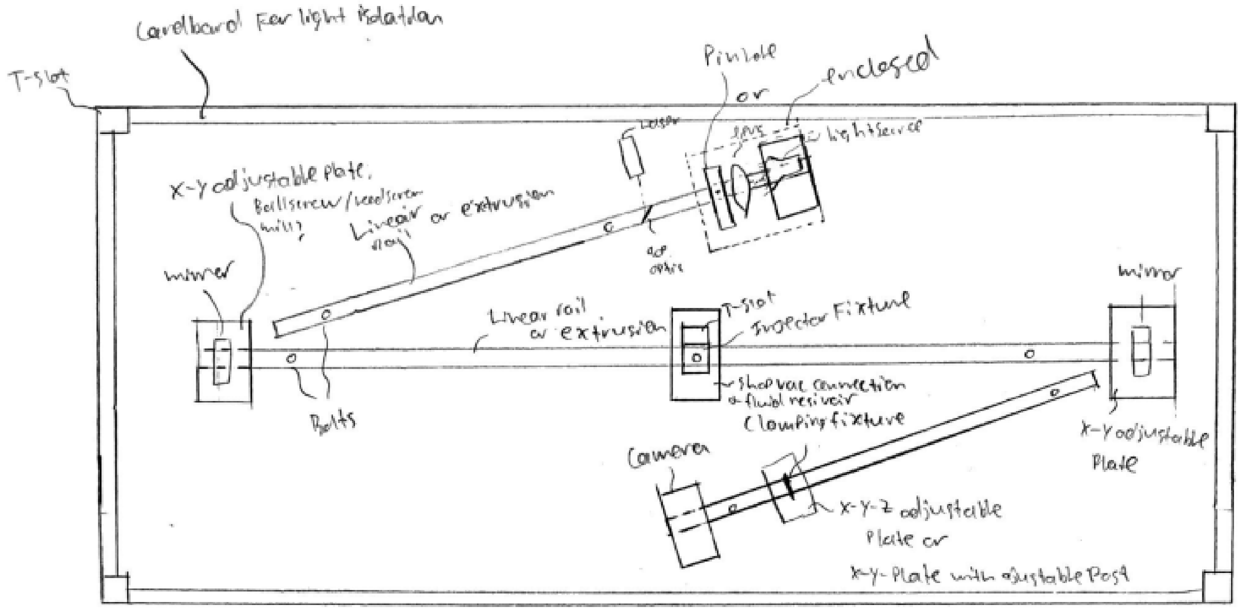



Full Schlieren Assembly
Test Fixture
Optical Fixture x2
Camera
Frame

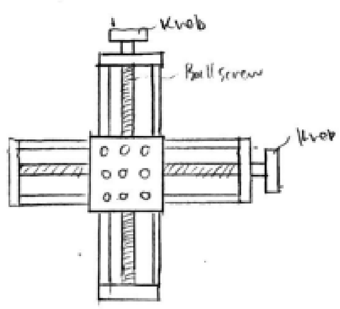

Frame Diagram
Note: dashed line is outline for
Linear Rails
T Slot Extrusion Frame


Test Subassembly Diagram
Linear Rail Mounting Plate
Drag Chain
Rail Carriage
PFI injector
Air Assist Nozzle
Drain Pan and shop vac adapter
Linear Rail
Rail Brake
Water Tube Adapter
Injector Base Plate
L-Stock Base Bracket
Shop Vac Hose

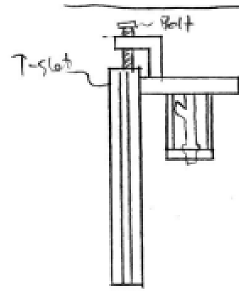

Adjustable. Optics Fixture Mount Diagram
Note: Bolts to Tslot frame; additional brackets/jigs/indicator work required to clamp ballscrew/bearings/mount
Note: Mirror fixture not shown
Optics Fixture Mounting Holes
Bushing, Dowel Pin
Bracket & Constraining Thumb Screw
Fixture Adjustable Mounting Plate
Base Plate
Preload Spring for ACME screw
Anti-Backlash
Ball Screw (Ball nut not shown)
ACME Screw
support not shown)
Ballscrew Bearing
ACME threaded Nut/block
Rail Carriage
Brake
Linear Rail



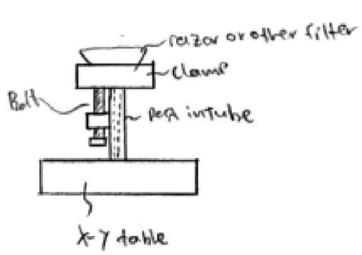
X-Y adjustable Plate

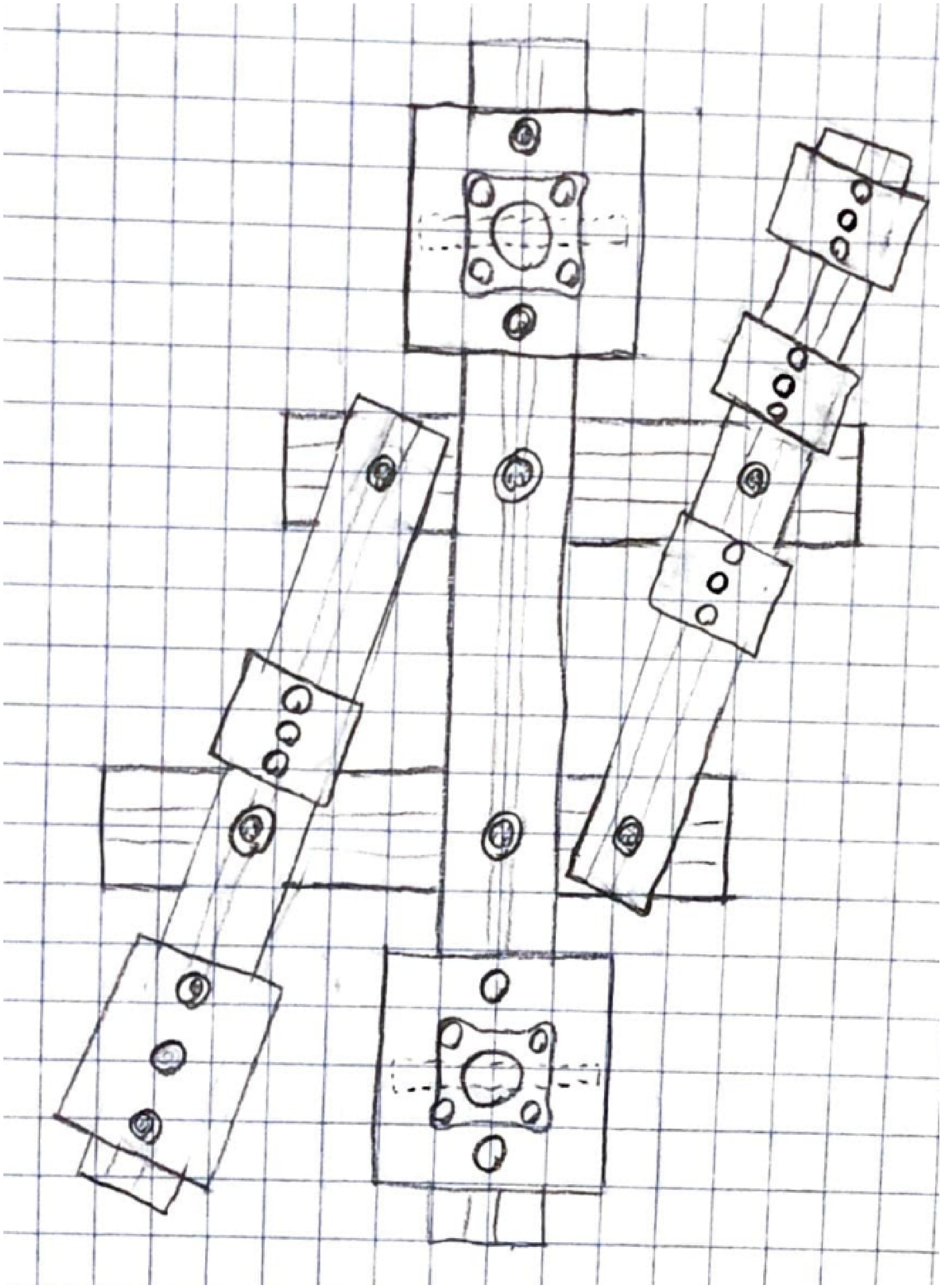


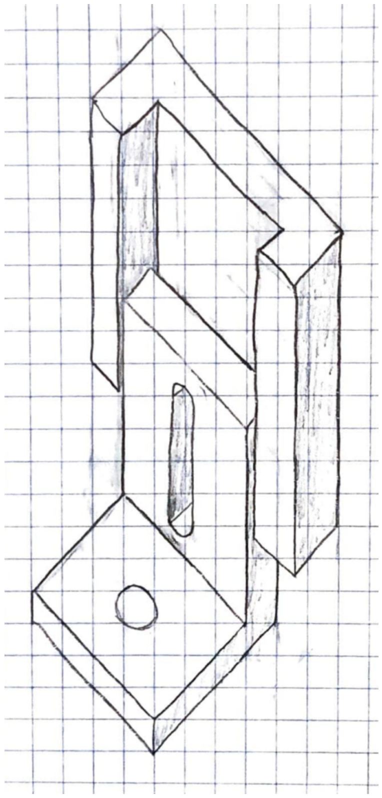
Injector Fixture

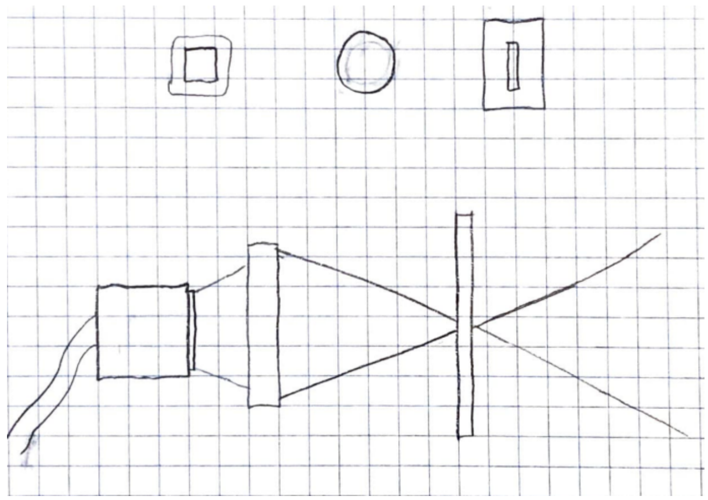


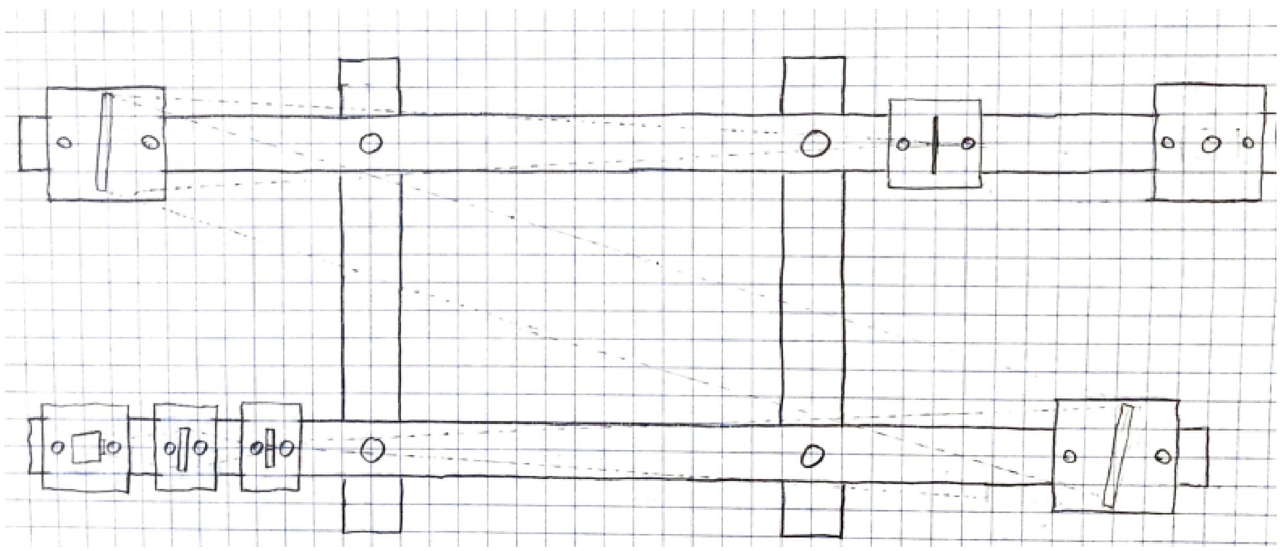
Filter Fixture

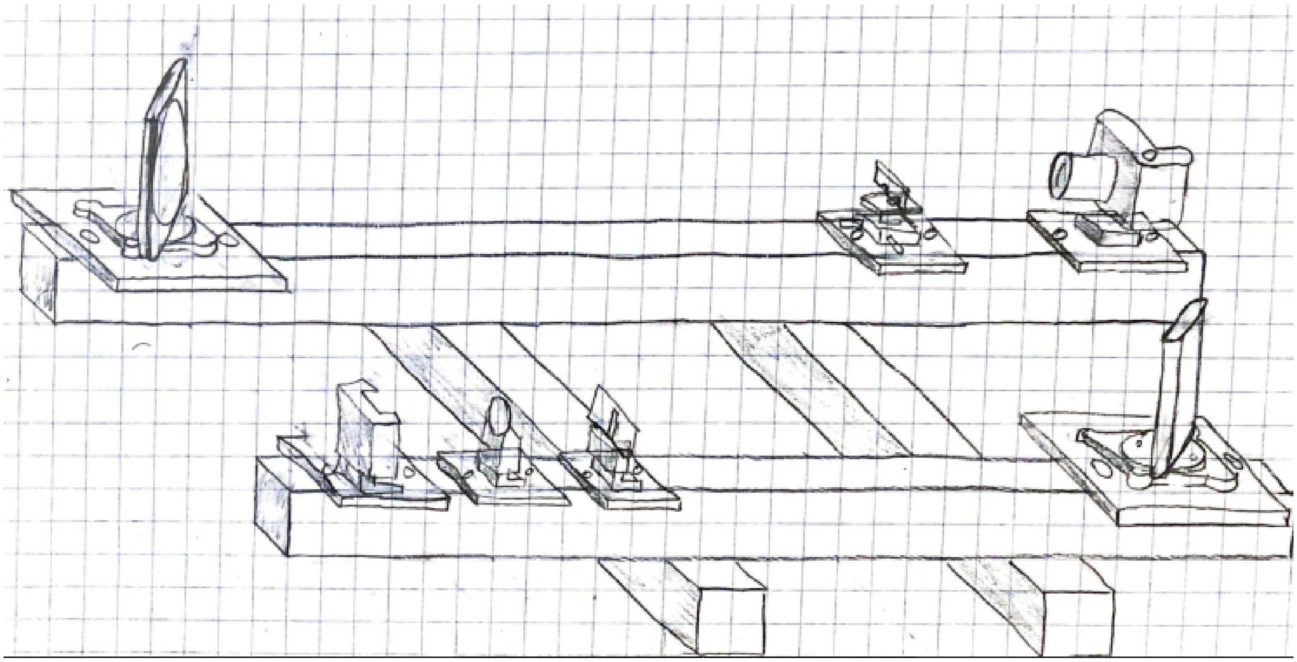


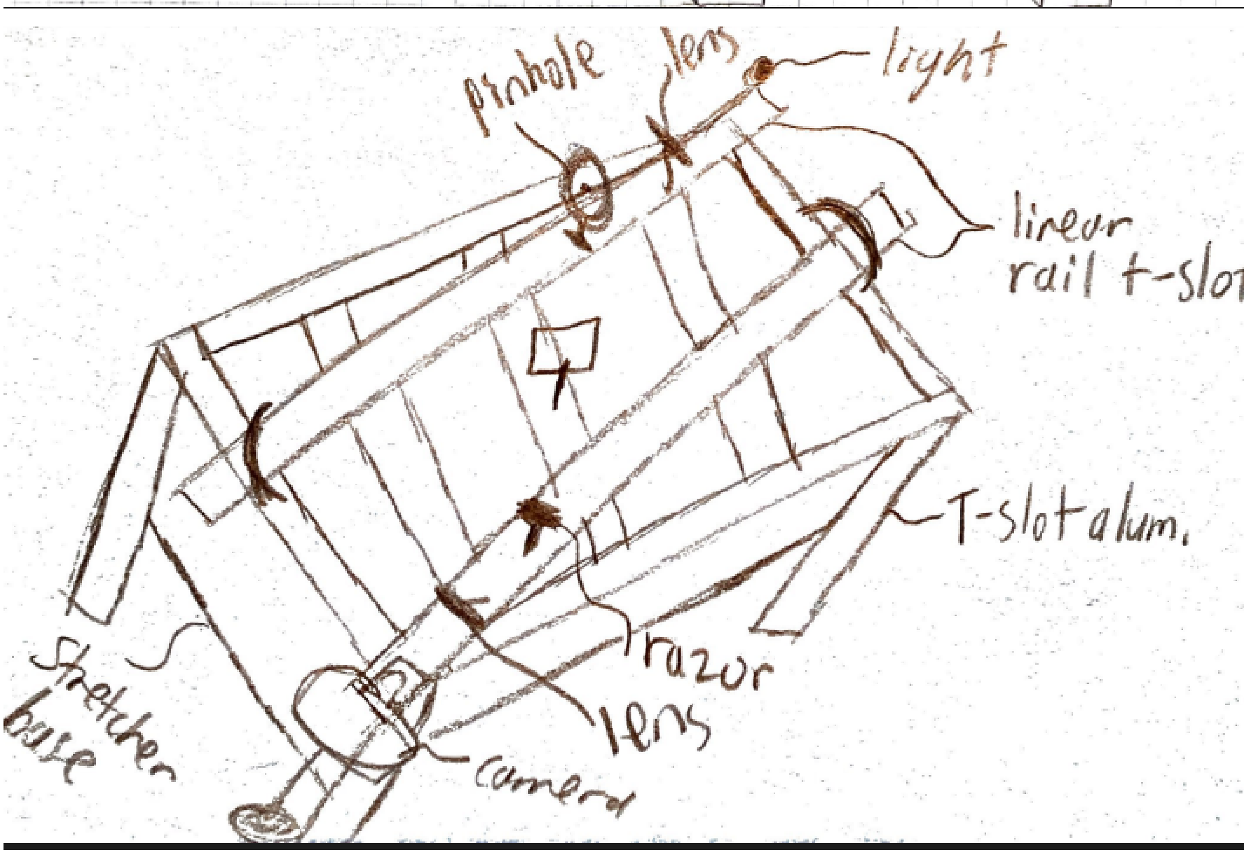


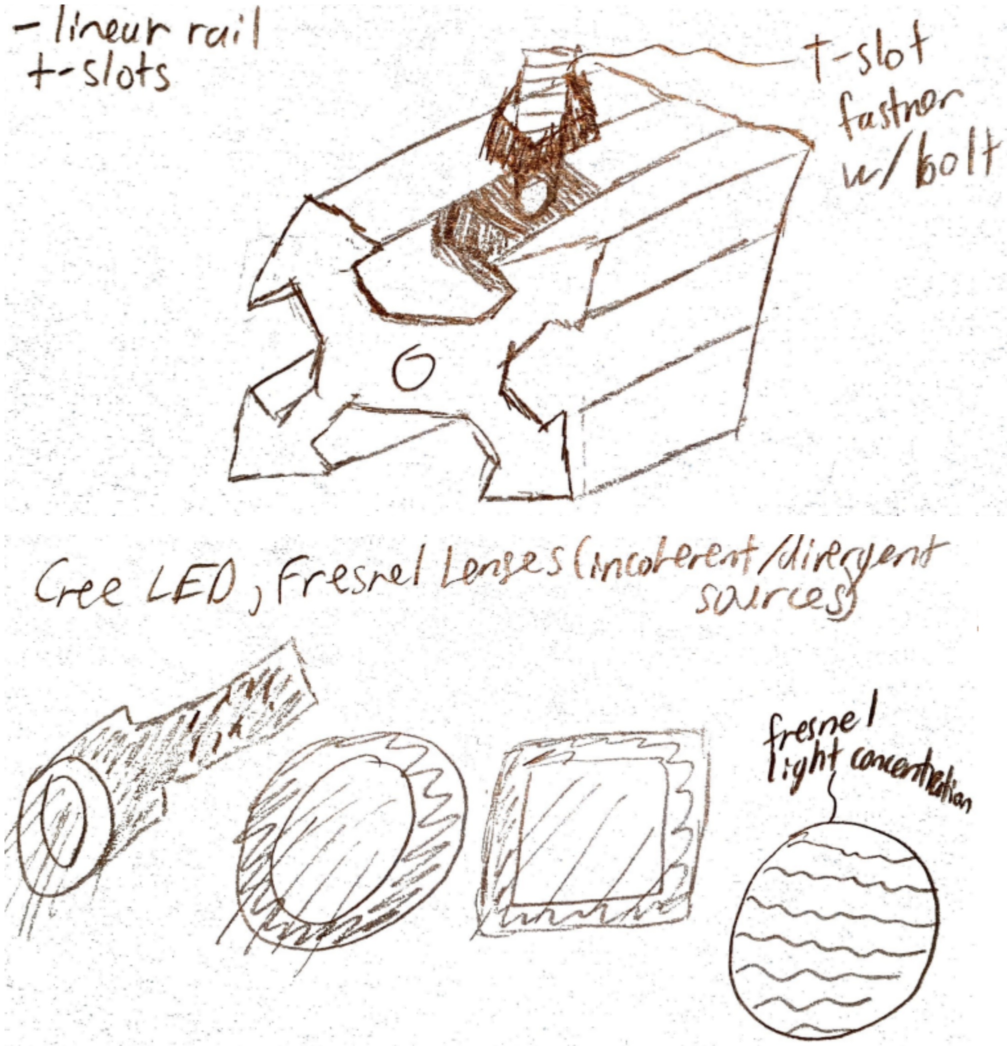


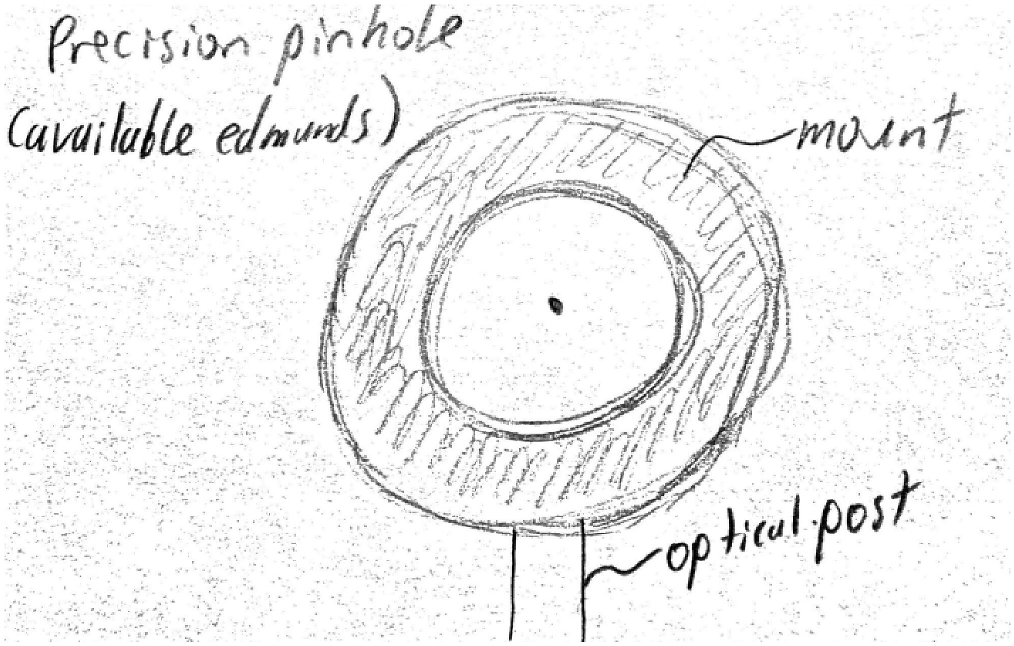







pinhole
lens
light
linear rail t-slot
T-slot alum.
razor
lens
camera
Stretcher base


-linear rail
t-slots
t-slot fastner w/bolt
Cree LED, Fresnel Lenses (incoherent/divergent sources)
fresnel light concentration



Appendix F: Project Timeline

Table 12.a: The Problem Definition phase encompasses most of the work that has been completed before design report 1. The red bar on Tuesday week 6 indicates the date of Design Review 1.

TASK TITLE	START DATE	DUE DATE	WEEK 4						WEEK 5					WEEK 6					WEEK 7				
			F	M	T	W	R	F	M	T	W	R	F	M	T	W	R	F	M	T	W	R	F
Problem Definition																							
Initial Stakeholder Meetings	9/17/21	9/30/21																					
Initial Requirements formation	9/17/21	10/4/21																					
Initial Specification Formation	9/22/21	10/4/21																					
Literature review	9/24/21	10/8/21																					
Engineering Principles	9/29/21	10/11/21																					

Table 12.b: The Idea Formation phase will last roughly two weeks. At the end of the two weeks each team member is expected to have sketches of the design concepts they wish to present to the rest of the team.

TASK TITLE	START DATE	DUE DATE					WEEK 7				
			T	W	R	F	M	T	W	R	F
Idea Formation											
Benchmarking	10/1/21	10/6/21									
Brainstorming	10/7/21	10/13/21									
Rough Sketches	10/21/21	10/15/21									

Table 12.c: The Idea Selection phase is one of the most condensed. The team will have roughly one week to choose a final design concept from those generated in the Idea Formation phase. The short duration of this phase helps ensure that part ordering begins early enough.

TASK TITLE	START DATE	DUE DATE	WEEK 8				
			M	T	W	R	F
Idea Selection							
Design Review	10/18/21	10/19/21					
Performace Evaluation	10/19/21	10/20/21					
Final Selection	10/20/21	10/21/21					

Table 12.d: The Detailed Design phase also has a fast pace. The team will have a little less than two weeks to have a full cad model and completed bill of materials. The red bar on Tuesday week 9 indicates the date of Design Review 2. During this phase the team will likely divide up the tasks to its team members; some will make CAD for the product subsystems, some will source parts, and others will work on the DR2 report. This is the current project phase at the time of writing this report.

TASK TITLE	START DATE	DUE DATE	WEEK 8					WEEK 9					WEEK 10				
			M	T	W	R	F	M	T	W	R	F	M	T	W	R	F
Detailed Design																	
Detailed Sketch	10/22/21	10/22/25															
Hand Calculations	10/22/21	10/22/28															
CAD	10/26/21	11/1/21															
Part Selection	10/26/21	11/1/21															

Table 12.e: The Prototyping phase is one of the longest, roughly four weeks. This is a consequence of needing to order parts early. The extra time will allow the team to overcome any unexpected challenges in manufacturing and assembly. In addition, it will provide a buffer if certain parts of the product take longer to design than anticipated. The red bar on Tuesday week 12 indicates the date of Design Review 3.

TASK TITLE	START DATE	DUE DATE	WEEK 9					WEEK 10					WEEK 11					WEEK 12						
			M	T	W	R	F	M	T	W	R	F	M	T	W	R	F	M	T	W	R	F	M	T
Prototyping																								
Part Ordering	10/26/21	11/3/21																						
Manufacturing	11/2/21	11/17/21																						
Assembly	11/8/21	11/22/21																						

Table 12.f: The Testing phase is a little over two weeks long and has lots of overlap with the Prototyping and Final Product phases. When a subsystem is assembled, some team members will continue to manufacture other systems, while other team members will begin testing the completed subsystem. When issues with the subsystem performance are found, some team members will begin working on solutions to the issues, while others will remain testing subsystems. The red bar on Thursday week 14 indicates the date of the Design Expo.

TASK TITLE	START DATE	DUE DATE					WEEK 13					WEEK 14				
			T	W	R	F	M	T	W	R	F	M	T	W	R	F
Testing																
Low fidelity testing	11/16/21	11/19/21														
Subcomponent testing	11/18/21	11/24/21														
Full System Testing	11/23/21	11/29/21														

Table 12.g: The Creation of the Final Product is the last phase. As stated previously, this phase begins with subsystem testing. After the major updates have been made, a week is given to verify that the design meets its specifications, and any final adjustments can be made. The red bar on Thursday week 14 indicates the date of the Design Expo.

TASK TITLE	START DATE	DUE DATE			WEEK 14					WEEK 15				
			R	F	M	T	W	R	F	M	T	W	R	F
Creation of Final Product														
Updates to Prototype	11/26/21	12/6/21												
Design Varification	12/6/21	12/10/21												