Developing an Efficient Quality Control Method for Identifying Semiconductor Hot Spots

SCS Solutions

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Executive Summary

This report covers the Final Design Review for the Semiconductor Hotspot Identifier, where we present our successes and learnings from prototype design, iteration, and validation and seek your approval to advance towards production readiness. SCS Solutions remains underbudget with $924.93 out of $1000 spent after incurring $341.11 in additional expenses since CDR.

Hot spots, or locations of high thermal flux, are artificially developed via manufacturing defects and contribute to decreased product reliability and accelerated product failure. There exists no at-scale quality control process to detect these hotspots during manufacturing, and this yearly market gap is sized by SCS Solutions to be $89.6 million. Given a 5-year sales period and product retail price of $3600, SCS Solutions expects $5.76 million in revenue and $1.70 million in profit.

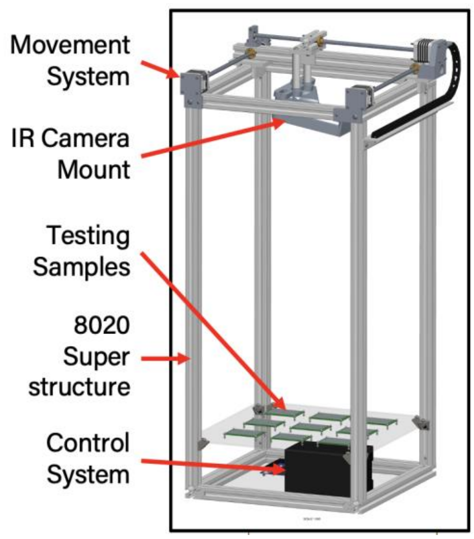


Figure 1: Isometric View of Final Prototype in CAD

The final design (Figure 1) is a compact and rigid 13” x 15” x 30” superstructure with a movement system to maneuver a thermal camera over 9 testing locations. Its acrylic bottom tray houses electrical/control components and its top tray houses sample chipsets. Since CDR, 22 new parts have been added with 19 used for increased structural integrity and 3 used for enhanced movement. To overcome racking issues during testing, the movement system now operates two motors in parallel, one more than before, to move a third motor.

The manufacturing and assembly process, spanning 2 weeks, led to the creation of the final assembled prototype (Figure 2). Within manufacturing, there were 6 3D prints for the movement system and two laser cut acrylic sheets. Drilling, reaming, and deburring operations performed on 80/20 ensured interconnections among the structural segments.

Figure 2: Final Prototype Assembly

To validate this prototype against 6 engineering requirement categories (not including cost), 9 tests were conducted with 7 passing outright, 1 passing with qualifications, and 1 failing. Validations for the primary customer requirements of hot spot identification, quick time to test, and minimal human interaction produced successful results of 88% detection rate compared to an 80% goal, 3:17 average test time for 9 samples compared to a 10-minute goal, and 4 human interactions compared to a 5 human interactions goal. The human interactions test passed with qualifications since the IR camera available for testing prevented integration of camera and motor movement operations into a singular interface. This required operations split between two computers which undermines ease of use. The singular failure involved a 7 cm extension of the camera outside the superstructure, greater than the 5 cm limit, posing a safety hazard.

SCS Solutions identifies three potential improvements – replacement of the current IR camera with a compact industry-grade camera to resolve camera-related validation test failures, opaque encasing around the device's sides to limit image-corrupting incidental light, and finally replacement of current 3D printed parts with metal or carbon fiber alternatives for greater structural rigidity.

In conclusion, SCS Solutions invites you to read the rest of the report which provides detailed evidence of our work, and we formally request your approval to move this prototype forward to production readiness.

Report

Introduction

Throughout this report, SCS Solutions will present the accomplished work and necessary alterations made during manufacturing, assembly, testing, and validation to construct the finalized design presented in the CDR report. The team will review the current product value proposition, learnings from CDR section regarding design, the operations sheets and manufacturing drawings used during the machining stage of production. After a showcase of the assembled high-fidelity prototype, SCS solutions will present the validation tests performed to ensure that the device meets most customer requirements. Next, a series of potential improvements will be proposed to ensure superior functionality of the design. Finally, the team will summarize the unique opportunity presented by this Semiconductor Hot Spot Detector Device and our resulting recommendation to move forward to production readiness.

Background

The semiconductor industry continues to break records as demand for these high-end devices skyrockets. With impacted fields such as consumer electronics, medical devices, and national defense, fabricators of these devices have been left with little choice but to increase production speed. However, the current state of quality control for the industry is unfit to match the growing demand and thus has the need for innovation and profit.

SCS Solutions proposes a solution to one of the semiconductor industry's quality control gaps, hot spot detection, through a non-labor-intensive, automated, and cheap product, the Semiconductor Hot Spot Identifier. Existing solutions on the market include the Optotherm Sentris and the liquid crystal test, which retail for about $10,000+ and $8700 respectively. Further details about each product/method are shown in Appendix E. Both competitors, in contrast to the proposed product, rely heavily on human labor and only process one chip at a time; this is too slow to effectively keep up with production rates. To seize the market gap left by competitors, the team will market the product at $3600 and expects a 5% market penetration given high barriers to entry, selling 1600 units in the first 5 years. This will ultimately yield a profit of $1.7 million in the first five years. The calculations for the product cost and annual profit are shown in Appendix F.1.

As a brief review of the accomplishments from CDR, the down-selected design from PDR was developed into a final design using a preliminary prototype, CAD model, and analysis regimen (preliminary prototyping methods, FMEA, FEA). Key insights from the preliminary prototype fabrication included the need for generous tolerances on 3D printed parts, how to incorporate the IR camera's focal distance into product height, and how to effectively house electronic/control components within the structure. Preliminary FMEA analysis, heavily updated during FDR (see Appendix J), identified structural failures, electrical failures, and short-circuiting as primary concerns and mitigating actions were developed. Finally, Finite Element Analysis, which focused on 3D printed parts, was undertaken given PLA's low material strength. The FOS for the 3D printed parts of Lead Screw Receiver, Motor Mount Plate, and Motor Mount were calculated as 3.205, 1.654, and 9.970 respectively. All analysis methods validated the final design as mechanically sound.

FDR Method

During FDR, SCS Solutions made final design changes, manufactured, and assembled parts, implemented code, and fully tested the hotspot detector.

Assembly started with the superstructure, assembling the entire frame within 48 hours of its arrival. From there, work began on the 2D traversal system. Manufacturing operations requiring operations sheets (Figures 3-4) included machining operations on the 80/20 and creation of the acrylic electric boards. Lead screw holes were machined into the 80/20 sections and all 3D printed parts were started, and iterations made as necessary. Once the 2D traversal system was fully assembled, electrical boards were created out of acrylic to fit into the 80/20 enclosure for the electrical team to take over and begin their assembly and testing, however, as in all projects, not everything went to plan.

Step	Operation	Description	Equipment	Notes
1	Center Drill	#0 Center Drill .05 Deep	Drill Press	S = 150 F = Hand
2	Drill	#30 Drill Thru Piece	Drill Press	S = 150 F = Hand
3	Ream	∅.395 Thru Piece	Drill Press	S = 100 F = Hand
4	Deburr	Deburr all Holes	Deburring Tool	F = Hand

Figure 3: Manufacturing Operations Sheet – 80/20

Step	Operation	Description	Equipment	Notes
1	Trace	Trace outline of acrylic	Laser Cutter	Vector = 40% Power = 100%
2	Cut	Cut Inner Holes	Laser Cutter	Vector = 40% Power = 100%
3	Cut	Cut Outline	Laser Cutter	Vector = 40% Power = 100%

Figure 4: Manufacturing Operations Sheet – Acrylic Electrical Boards

The first problem the team had to overcome was an underestimation of the force of friction in the 2D axis movement system. The initial calculations showed that one motor would be enough to drive the bottom rail. But after assembly, since only one side was being driven, the other lagged behind and become wedged into the 80/20 support, unable to move. To fix this issue, the team used WD40 and added another stepper motor to the undriven side, resolving the issue. Thus, the final movement system leverages two motors to move the third (Figure 5).

Figure 5: Final Prototype Assembly – Movement System

Additionally, there was a near constant issue with the bottom and upper acrylic trays. This first started as the acrylic sheets purchased off of Amazon were advertised to be laser cut-safe, but instead proved to produce chlorine gas when cut/burned. This resulted in new acrylic sheets needing to be purchased, which while safe to laser cut, were more fragile than the original sheets and cracked under the stress of a power drill when new holes were needed. Even with all these challenges in the manufacturing and assembly processes, the project was still able to continue at only a half-week behind schedule allowing the electrical team access to the project after only a week and a half.

All electrical components were wired according to the diagrams in appendix H.2 and soldered down on printed circuit boards (PCB), making the electronics more permanent and less prone to short circuits (Figure 6). The process to bring the circuit from a breadboard setup to its final PCB form, which was crucial in the success of the product, required a large learning curve. The original idea for building the circuits was to have everything on breadboards, however this caused multiple short circuits, popped capacitors and a fried Arduino. Moreover, the breadboard is not meant to sustain 12V for long periods of time, so this idea was discarded since nominal voltage supply needed was 12V. Soldering down all the components on PCBs made everything neater and easier to debug the software and code needed to control the output and behavior of these electronics.

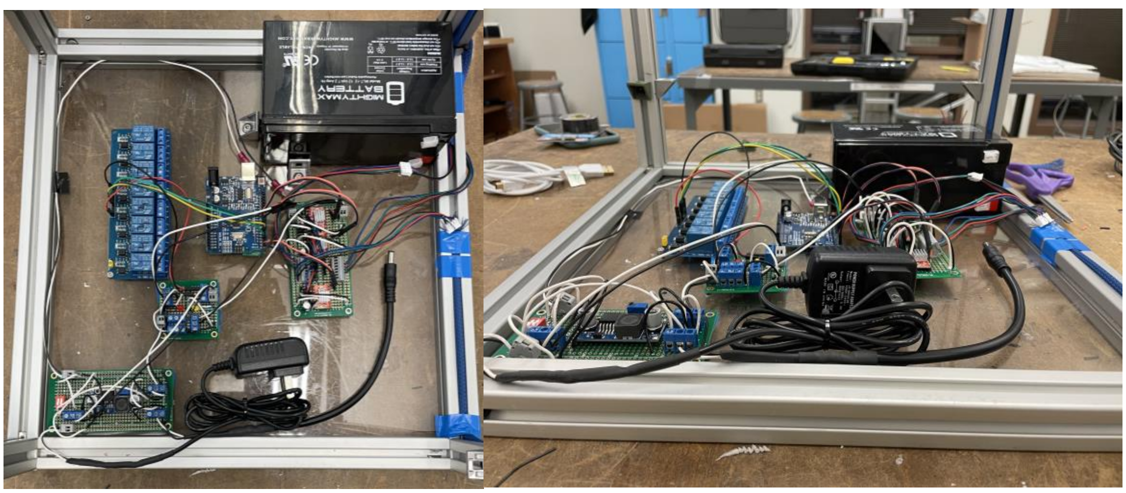


Figure 6: Final Prototype Assembly – Electrical (Top and Side Views)

Python and Arduino scripts were developed and integrated to automate the 2D movement system and image processing. Moreover, a GUI (Figure 7) was coded to be a fully deployable and easilyy operated system that allows the user to input certain parameters (e.g.: number of semiconductors to be tested) and quickly show results (e.g.: heat flux map of the semiconductor). Please see Appendix H.2 for more information on specifics of the code. The team successfully wrote all code needed to operate actions separately, for example, moving the IR camera to a certain position in the imaginary 2D grid or taking a picture remotely and processing the thermal map into a heat flux map; but the team was not able to fully integrate all scripts. All the movement system and relay operations, controlled through the Arduino, were easily merged into the GUI Python-based code thanks to existing coding libraries which enabled compatibility among these systems. Thus, the user can input testing locations to the GUI and then immediately commence operation of the prototype to move the camera to sample locations. Unfortunately, the picture snapping and thermal to heat flux processing codes were not able to be integrated, primarily due to the IR camera not having a direct way to communicate with outside software (Python). Workarounds were found specific to the team's computers, but these would not work in a production environment. Nevertheless, the code performs all actions needed and it is semi-automated.

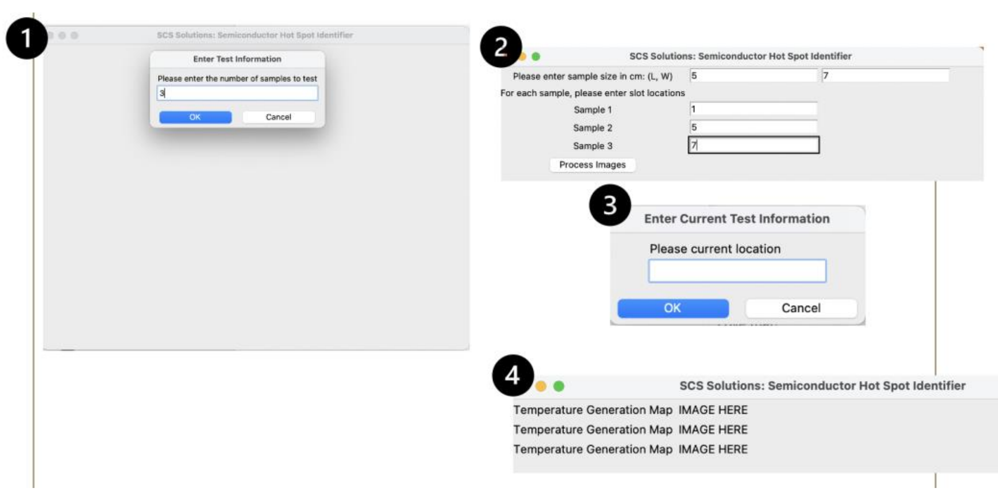


Figure 7: Final GUI

Testing, Results, and Outcomes

Once the team completed the assembly process, 9 validation tests were performed which correspond to 6 customer-defined engineering requirements (with the cost category omitted). As detailed in Appendix L, the tests map to the engineering specifications as follows - one test each for accuracy, resolution, and maintenance requirements, two tests for ease-of-use requirement, three tests for hot spot identification requirement, and four tests for safety requirement.

The final prototype tested well - 7 of the tests passed completely, 1 passed with qualification, and a final resulted in a failure (Figure 8). Of note, color coding for the generated results column in Figure 8 is as follows - green indicates a pass, orange indicates a pass with qualification, and red indicates a failure (Figure 8). Since the team deemed that validation tests focusing on hot spot detection accuracy, test time, and ease of use are of paramount importance to product viability, those specific test results along with the failing result are explained in more depth.

Engineering Requirement	Test Name	Metric	Projected Results	Generated Results
Accuracy	Camera Temperature Accuracy	°C	± 2°C	± 0.9°C
Resolution	Camera Spatial Resolution	Pixel/mm	4 pixel/mm	1.929 pixel/mm
Identification-Detection	Hot Spot Detection	% of hot spots detected	80%	88%
Test Time	Time of operation	minutes	5 minutes	2:57.75 3:17.2 (Origin)
Ease of Operation	Necessary interactions	Human interactions required	5 interactions	4 (Two Computers Needed)
Safety - Mechanical	IR Camera in bounds	Camera extrusion from structure (cm)	5 cm	7 cm

Engineering Requirement	Test Name	Metric	Projected Results	Generated Results
Maintenance	Long Run Feasiblity	Time to print (Hours)	3 hours	3
Identification-Traversal System	Motor Encoding	mm / 360 degrees	< 10 mm	8 mm
Identification-Simulator	Resistor Array Validation	Volts	12 Volts	12.77 Volts

Figure 8: Validation Testing Results

To validate that the assembled design met the customer requirement of “the design must accurately detect the existence of hot spots” the team created a series of resistor arrays on PCB boards which were then thermally analyzed by custom image processing software. Since these boards were developed with known resistance and voltage values, the team was able to calculate the expected thermal flux at each point along the board. So, when image capture and processing occurred, comparisons of generated thermal flux map results were compared to the expected thermal flux maps. The expected and generated thermal flux maps of the tested chip are shown below in Figure 9. The team compared each set of corresponding cells (small rectangle within the grid) between the two maps and determined that if the generated graph’s cell was within 1KW/m^2 (one color on the legend) of the expected graph’s cell, then the prototype accurately detected the hot spot at that location. Ultimately, the prototype was able to detect 88% of the generated hot spots which was far superior to the customer requirement of 70%.

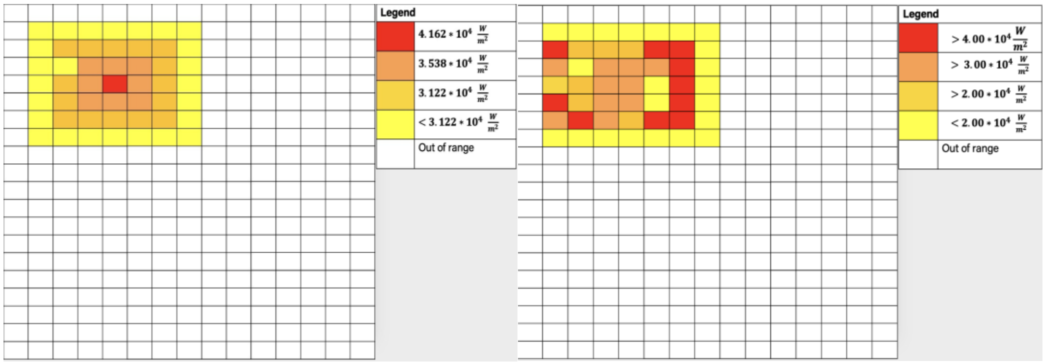


Figure 9: Expected and Generated (Left and Right Respectively) Thermal Flux Maps

After hot spot detection efficacy was validated, the team began work to ensure that the device was fit for a mass manufacturing environment. The test time of the prototype was validated by running 5 trials of 9-sample test runs and the time to test these 5 trials was then averaged. The team determined that the prototype could analyze a set of 9 chips in 3 minutes and 15 seconds which includes time for the camera movement system to return to the origin (test sample location #1). Given that the next closest competitor, the Optotherm Sentris, is capable of single chip analysis in 5 minutes, the Hot Spot Detection Prototype far and away clears the test time customer requirement of performing analysis in under 10 minutes.

This low test-time is further optimized by the devices' ease of use where the user only needs 4 inputs into the system. First, a user must load the device with test samples and input their locations into the user interface. Secondly, a user must operate software to snap the photos. Thirdly, a user must export the temperature maps into the heat flux analysis software. Finally, the user must empty the samples into their respective locations of either back onto the assembly line or to more testing/disposal. While the team did pass the ease-of-use consumer requirement of requiring less than 5 human interactions, the current process requires 2 computers because the camera cannot be directly controlled through the same program that accepts user input and controls the movement system. The team will need to put in further work to reconcile these differences between the software's to ensure interconnectivity among them.

The prototype did fail the mechanical safety customer requirement since the IR camera has a handle which extends outside of the superstructure frame by 7 cm which is greater than the 5 cm maximum extension limit. While this is unfortunate, the team realizes that this camera is predominantly made for field work. If this prototype were to be moved onto the commercialization phase, the team would explore options of exchanging for an IR camera more fitting the team's technological need. Namely, an industry grade camera which is compact.

Next Steps

The team's going forward plan is to implement some changes in the final product to make it fully serviceable for a manufacturing plant. The first and probably most important improvement is to replace the thermal camera with one that is more compact, interoperable with external software, and having higher spatial and thermal resolution. While this camera is perfectly designed for fieldwork and class settings, it would not work in a factory. If the camera changes, its holster must also be updated. Not only will it need to fit the new IR camera, but it should be redesigned for increased rigidity and stability as the current model is prone to shaking when actuated by the motor movement system. Moreover, to not let external radiation affect the effectiveness of the IR camera, opaque encasing around the superstructure and over the electronics will be used. This should help maintain constant emissivity within the testing bay which supports the camera to achieve constant and reproducible results. Finally, to have a more durable product resistant to harsh conditions of a manufacturing plant, the 3D printed parts need to be replaced with stronger components (e.g.: carbon fiber or metal molding). Finally, all programs (e.g.: to move the stepper motors, to extract temperatures from the IR images …) need to be merged together and controllable by a GUI. This GUI needs to be fully deployable and ready for operation, thus increasing ease of operation for the users.

Summary and Conclusions

Throughout this FDR phase the team successfully brought the project’s mechanical, electrical and software designs into a fully operable hot spot detector prototype. The whole process of manufacturing materials, assembling components, and debugging electrical circuits and code revealed several design issues, however, these were considered and fixed to maintain the desired functionality of the product. The team then performed several tests to validate the end-product and make sure the most important engineering requirements were met.

The team understands that the semiconductor industry is in desperate need of an easy to use and accurate quality control device that can match the speed of fabrication. Thus, given the project status as underbudget ($924.93 out of $1000 spent), the development of a capable and validated prototype, and a competitive selling price, SCS Solutions formally requests further funding and support to take this product to the next level: production readiness and commercialization.

Appendices

Appendix 1: Project Management

A. Charter

Please find attached in the current folder SCS Solutions's team charter, labelled "SCS_Solutions_Charter.xlsx". The team charter embodies the team's collective goals of sustainability, efficiency, and technical excellence through its focus on a product which reduces material waste and automates a quality control process. Roles were designated based off each team member's individual skillsets and desire for growth in specific technical and leadership areas. After PDR, the team clarified the project scope to be the design of a product superstructure, movement mechanism, and hot spot analysis technique and removed the capability of "physical marking of hot-spot on semiconductor". No changes have been made since CDR.

B. Schedule

Please find attached in the current folder SCS Solutions' updated project schedule, labelled "SCS_Solutions_Schedule.mpp". The schedule leverages Microsoft Projects software to discretize major project sections, tasks, deadlines, and the dependence relationships among sections and tasks. The schedule is broken down into sections - "Team Setup and Documentation," "PDR," "CDR," "FDR," and "Mallot Competition" each containing subtasks, deliverables, and due dates. Dependence relationships are established among sections and among tasks within a section to define a logical order in which they must be completed; for example, the task of "Concept Generation" on line 15 must be completed before the task of "Feasibility Analysis of Concept Generation Ideas" on line 17 since you must first have generated concept ideas before analyzing them. Of note, the schedule has been designed such that each task represents the smallest definable unit of work; thus, the project schedule defines all potentially achievable tasks in a mutually exclusive and collectively exhaustive manner. Each member has been assigned to lead tasks based off their team roles and the team's collective desire to ensure leadership opportunities for each member.

After analyzing progress during PDR and arriving at a down selected prototype, the team re-defined the CDR and FDR schedules around a set of critical initiatives; these initiatives are the product's financial analysis, risk mitigation, preliminary prototype design and manufacturing, and the final prototype design and manufacturing. The final prototype design and manufacturing is further split into the CAD, code development, analysis, and validation of its three main functions – the superstructure, the movement system, and the hot spot identification system. Finally, the hot spot validation system is a necessary step not for product design but for validation of the design and is concurrently developed with the hot spot identification system.

Component	**Time (Days)**
Assembly	11
Validation	12
Testing/ Iteration	12
Camera Access	28
Report Writing	10
Risk Mitigation	7

Figure B.1: Time Allocation during FDR

To accomplish the above initiatives, 10+ days are devoted to each of assembly, validation, and testing and iteration while additional time is dedicated to identifying and mitigating risks (Figure B.1). In conjunction with the above, the discretization of necessary work into initiatives and the timeboxing of tasks in Figure B.1 assists the team in manageably pacing development.

While all major tasks listed in the schedule for FDR were completed successfully, there were two primary hindrances which pushed back and led to the compression of downstream tasks – the need for a third motor and the frying of electronics. The late realization of a third motor need delayed assembly and testing for a whole week due to shipping delays; this meant that the safety review and all validation tests were delayed and time for downstream iteration and retesting minimized. The frying of an Arduino board along with a buck booster during the testing stage delayed testing of other prototype subcomponents which needed power. Of note, during each occurrence for motor and electronics hindrances, the team remained agile and pivoted focus to other outstanding tasks – report, presentation, slide creation, and documentation. Further, the team swiftly procured replacements for parts when necessary.

The attached schedule file has been updated to include accurate completion dates and times for pre-existing events and to also include events which were not foreseen but which occurred. Of note, many events listed do not have predecessor/successor relationships because they were accomplished concurrently with other events due to time constrains.

C. Preliminary Budget

Please find attached in the current folder SCS Solutions's preliminary budget, labelled "SCS_Solutions_Budget.xlsx". The excel document identifies items and their quantity which must be purchased by Purdue for project completion, their source, and their associated total cost. Of the $1000 allotted budget, $15.12 was spent on PVC to manufacture the preliminary prototype. CDR projected $568.70 in expenses for final prototype construction and testing with $25 in expected shipping costs. However, during FDR, the addition of 22 components to the BOM - 18 for the superstructure, 3 for the movement system - increased the total spend by $341.11. Thus, SCS Solutions's final budget was $924.93 with $15.58 specific to shipping costs.

D. Risk Register

Please find attached in the current folder SCS Solutions's updated risk register, labelled "SCS_Solutions_Risk_Register.xlsx". The risk register is an effort to define current and potential risks to the project schedule, scope, and budget. Each risk definition contains an outline of its potential cause and effect, a current risk assessment L/M/H of its probability and effect, a mitigation strategy, a residual risk assessment L/M/H after mitigation, and finally a review of the risk.

The register now identifies 19 ongoing risks after the risk evaluation process for CDR added 14 risks associated with manufacturing processes, electrical connections, and IR camera use and after 7 of the 13 pre-existing risks from PDR expired. 5 of the 19 ongoing risks identify residual risk scores of medium to high import; these five risks involve loaning the IR camera from the E shop for testing and demonstration, remotely operating the IR camera, improper electrical connections, and improperly designed 3D-CAD components. Mitigating actions for these risks are outlined in the risk registered and included within the Schedule.

The biggest pre-mitigation risk to project success was the availability of the thermal camera. This situation would prevent testing and validation of the product, leading to failed project goals.

To mitigate this, the team was tasked to continually check out the thermal camera from the E-shop and convey our particular use case for the motor to the E-shop personnel. In retrospect, these actions proved successful, and the team had constant access to the camera for the purpose of making its holster, testing the movement system, validating the device, and capturing and processing thermal images.

The biggest post-mitigation risk to project success was the inability to remotely take photos using the available thermal camera. Mitigating action came in the form of reaching out to fluke, but to no avail. The camera was only operable through Fluke connect software. However, a workaround was found that used software to automate button clicks to operate the Fluke camera software. While this risk did materialize, the team was prepared to expend resources and resolve the predicament.

The risk which levied the greatest impact on project success was the need for a third motor due to racking issues. While this was foreseen as a risk, the group did not judge this event to be highly probable given that mass produced 3D printing systems leverage the intended 2-motor setup. Mitigating actions including using lubrication helped slightly but this risk was only resolvable by ordering and waiting for a third motor to arrive.

Given completion of the FDR phase, section 5 of the risk register has been updated to include risk mitigation results. Out of the 26 total risks present, 19 did not occur, 2 occurred with their impact being highly minimized by mitigating actions, 2 occurred with their impact being moderately minimized by mitigating actions, 1 became out of scope, and finally 2 occurred with their impact not being minimized by mitigating actions. Main successes were found in the mitigating actions of ensuring access to the IR camera, preventing widescale short circuiting, and preventing 3D printed components from breaking. The main failure was associated with ensuring that the movement system was operable with the originally intended 2 motor setup.

Appendix 2: Business / Marketing

E. Market Analysis

To gauge the usefulness of the team's project in industry, the team reached out to 49 industry professionals and professors affiliated with the SCALE program (Scalable Asymmetric Lifecycle Engagement). The team received 18 responses to our emails and communications with key discussions occurring with Dr. Justin Weibel from Purdue University, David Halbrooks from Purdue University, V.S. Devahdhanush from Purdue University, Caleb Keener from SSA INC, and Michael Bourland from Google.

Phase	# Contacted	# Replies
PDR	23	12
CDR	26	15
FDR	49	18

Figure E.1: Customer outreach and response progression across design phases

Breakdowns of consumer survey outreach and results by design phase are summarized in E.1. In every design phase, an increasing number of professionals were reached out to with mixed response rate results among the phases. The team summarized the important results of the consumer research into the Pi charts shown in figures E.2, E.3, and E.4 below.

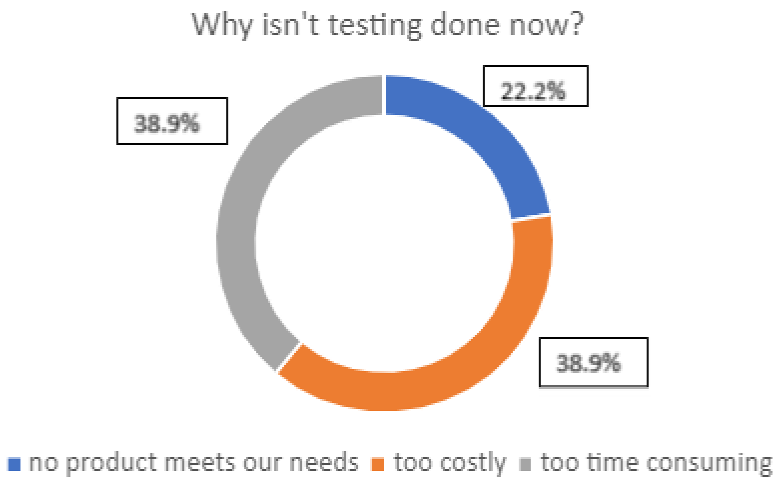


Figure E.2: Customer feedback on why testing is currently being done

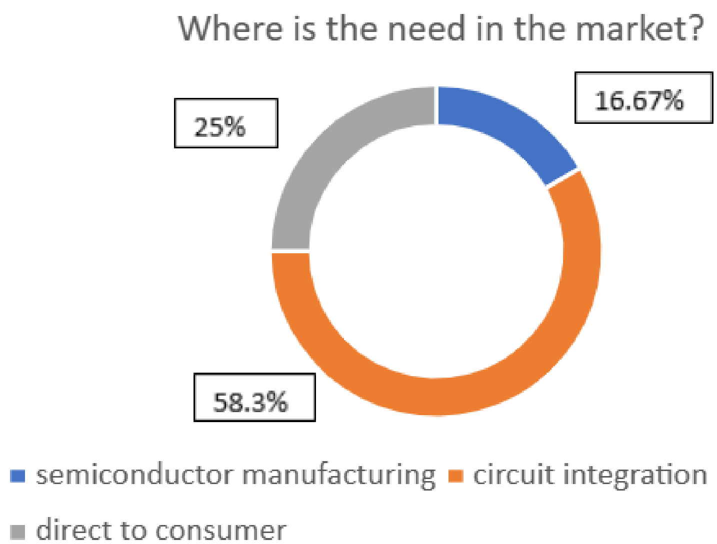


Figure E.3: Customer feedback on where there is need for our product in industry

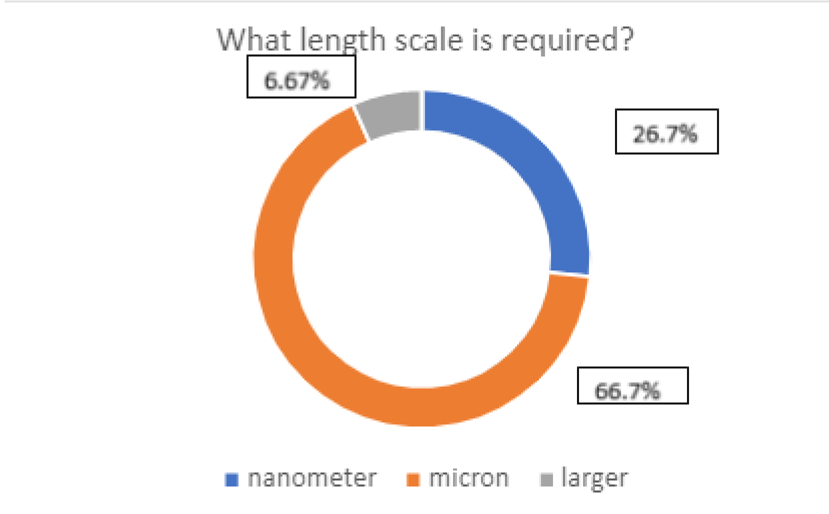


Figure E.4: Customer feedback on the size needed for detection

The importance of figure E.2 was that the team wanted to better understand the flaws in existing quality control techniques for semiconductors. Figure E.2 shows that the previously described methods for hot spot detection are not fast enough to match the rate of semiconductor fabrication. Furthermore, the existing quality control techniques are too expensive. Since companies primarily use the liquid crystal test for hot spot detection right now, this makes sense as it can be assumed that there is a high variable cost associated with testing the performance of each individual semiconductor. The proposed product offers customers a cheaper alternative to similar products but with faster testing time than both the Optotherm Sentris and the liquid crystal test, filling the gap in the market for manufacturing level semiconductor testing. Figures E.3 and E.4 are important results because they reinforce the notions that the team's project should serve the needs of semiconductor fabricators. The project should be primarily designed for these manufacturers and the solution must be able to detect the hot spots at the micron level.

Also attached is a table of potential competing products (Table E.5) that the team investigated during the market research portion of this project. From the table, there are several products that fit some of the desires that customers have, but none of them fit all the wants of the customer. From this table, the team decided that to beat the competition, a lower-cost alternative that can analyze multiple semiconductors at the same time was necessary.

Comps.	Use	Mechanism	Cost	Customer
Optotherm Sentris	Single Chip	Lock-in IR (71"x35"x43")	~$10,000 (Lifetime)	Designers Researchers
Liquid Crystal	Single Chip	Liquid Crystal Solution, Microscope (10"x10"x15")	~$8700 (1000 uses)	Fabs Researchers
Intended Product	Multi Chip	IR, 2D traversal system (13"x15"x30")	$3600 (Lifetime)	Fabs

Figure E.5: Table of potential competitors and their product specifications

Focusing specifically on the physical devices, the Optotherm, shown below in figure E.6, is an effective device that can find the exact position and depth of a manufacturing defect in the semiconductor. However, the Optotherm can only be used on a single semiconductor at a time and is not capable of acting as a quality control device at a mass manufacturing level. Since Optotherm did not respond to a request for a price quote, a white paper analysis was used to assess the Optotherm's primary components, identify their alternatives on the market, and estimate costs accordingly; the total product cost is conservatively estimated at $10,000+ given its sophisticated IR technology (similar to the "FLIR A65sc Benchtop Test Thermal Camera" at $9200), the 71"x35"x43" aluminum and plexiglass enclosure (estimated to be triple the cost of our expenditures since it is nearly triple the size at $1300), and costs for various additional electronics. Given lack of precise cost estimates, an estimate of $10,000+ is employed.

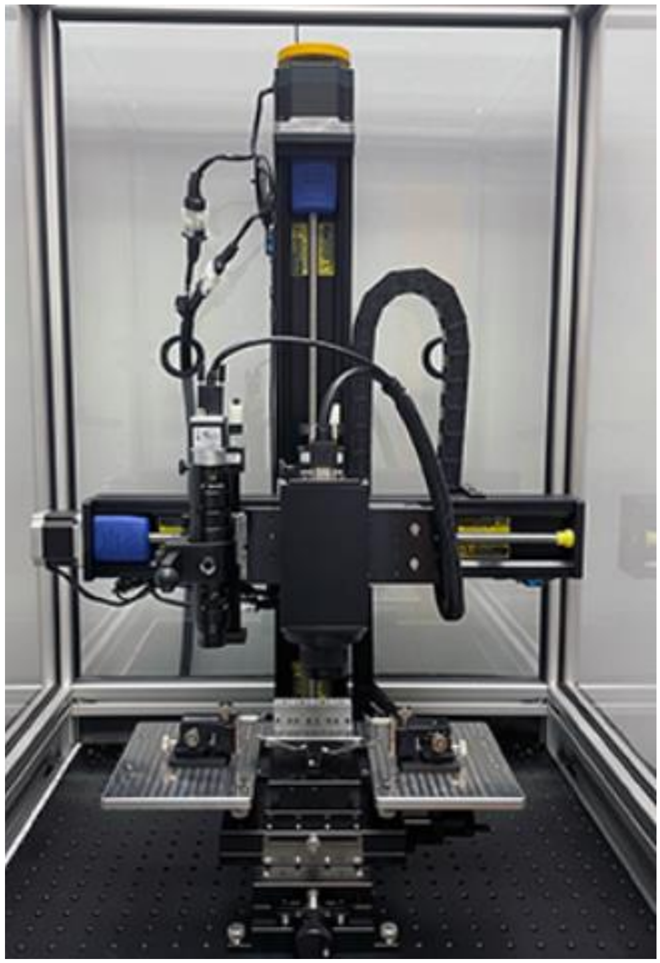


Figure E.6: The Optotherm Failure Analysis System

The most common quality control technique that exists in the semiconductor manufacturing industry is the liquid crystal test (Figure E.7). The primary benefit of this method is that most of the materials needed for the experimental setup are easily available. However, the major flaw of this method is the slow response rate as a chemist must individually douse each semiconductor with the liquid crystal solution and watch it for a long time to observe if a chemical reaction occurs. The testing setup for the liquid crystal solution is shown below in figure 2.1.6. A cost estimate for 1000 uses of liquid crystal (Figure E.5) was performed by identifying a liquid crystal solution on the market, estimating the amount of volume used in a pipette drop (standard industry practice of one drop per one chip), and subsequently scaling that to 1000 drop placements. The liquid crystal product chosen was $125 for 1 mL of solution (Accelerated Analysis), and a drop of liquid is 0.0648524 mL leading to 15 uses per 1 mL. Thus, in conjunction with $300 allotted for a microscope and considering 1000 uses, a conservative estimate of $8700 was achieved for 1000 uses of liquid crystal.

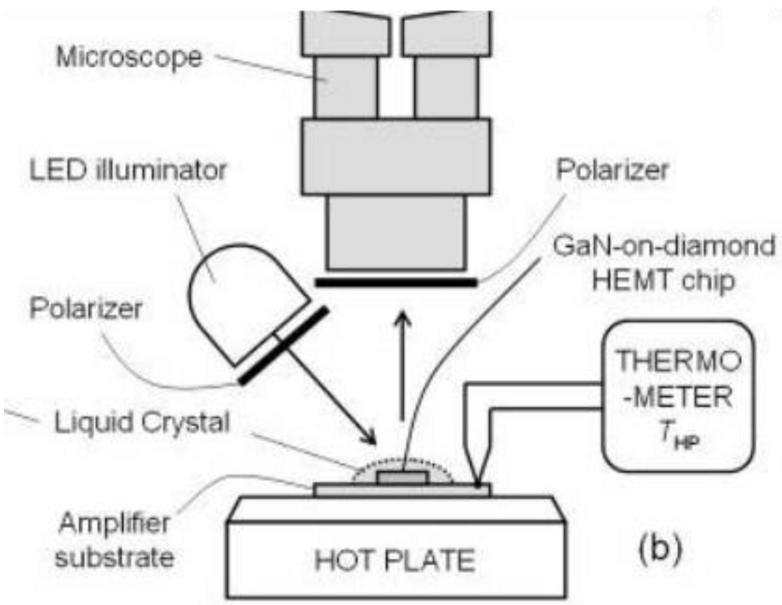


Figure E.7: Liquid crystal experimental setup

F. Value Proposition

Attached below are the cost tables that SCS Solutions used to create the product cost (Figure F.1). The team used the cost tables templates provided to calculate a cost of $2,557.15 Then using the typical price markup in the semiconductor industry of forty percent we found that the sales price for the team's product should be $3,600, which allows the team to make a total of $1042.85 in profit per unit. This price will be acceptable to potential customers as the semiconductor industry spends $2.6 trillion on research and development annually with a great portion of that funneled into various domains of testing equipment. Further, the alternative and less efficient solutions of Optotherm Sentris and liquid crystal tests cost $10,000+ and $8700 (for 1000 uses) respectively (Figure E.1). The Semiconductor Hot Spot Identifier's pricing undercuts these competitors by more than 50% while addressing the customer need for an automated hot spot identification system with quick time to test and minimal human interaction capabilities.

Through a bottom-up market analysis, the team has determined an expected sale volume of 1600 units over the first five years, generating $5.76 million in revenue and $1.7 million in profit. According to a report from IBISworld, there are currently 32,000 semiconductor chip fabrication facilities in use in 2022 and the team conservatively estimates that each fab employs one assembly line. Due to the high market consolidation rate and barriers to entry, a 5% market penetration is estimated, yielding 1600 units being sold to 1600 different fabrication facilities in the first year.

Another effect of the high barriers to entry into the market is that the product is expected to permeate slowly throughout the potential customer base in the first 5 years and stabilize after year 5; thus, revenue and profit after the 5th year are expected to level out at approximately the annualized average of the first five years – $1.152 million in revenue and $0.34 million in profit per year.

Component 1		
Description	IR Camera	
Vendor	Fluke	
Retail Cost		2040
Units / yr		1600
Volumized % of Retail		90%
Part Cost	$	1,836.00
Overhead		8.5%
Component Cost	$	1,992.06

Component 2		
Description	Aluminum Extrusion (3in)	
Vendor	80/20	
Retail Cost		3.9
Units / yr		1,600
Volumized % of Retail		90%
Part Cost	$	3.51
Overhead		8.5%
Component Cost	$	3.81

Component 3		
Description	Stepper Motor	
Vendor	Amazon	
Retail Cost		35.99
Units / yr		4800
Volumized % of Retail		90%
Part Cost	$	32.39
Overhead		8.5%
Component Cost	$	35.14

Component 4		
Description	Arduino Mega	
Vendor	Amazon	
Retail Cost		48.27
Units / yr		1600
Volumized % of Retail		90%
Part Cost	$	43.44
Overhead		8.5%
Component Cost	$	47.14

Component 5		
Description	Cable Raceway	
Vendor	Amazon	
Retail Cost		11.99
Units / yr		1600
Volumized % of Retail		90%
Part Cost	$	10.79
Overhead		8.5%
Component Cost	$	11.71

Component 6		
Description	Chip Resistors	
Vendor	Amazon	
Retail Cost		9.99
Units / yr		1,600
Volumized % of Retail		90%
Part Cost	$	8.99
Overhead		8.5%
Component Cost	$	9.76

Component 7		
Description	12V Battery	
Vendor	Amazon	
Retail Cost		19.99
Units / yr		1600
Volumized % of Retail		90%
Part Cost	$	17.99
Overhead		8.5%
Component Cost	$	19.52

Injection Molded Parts		
Shape of Part	Camera Mount (Box)	
Part Complexity	Simple	
Finish Quality	Opaque	
Material	Polypropylene	
Tolerance	Intermediate	
Unit	Inches	
Dimensions	18x5x5	
Quantity		1600
Part Cost	$	39.54
Overhead		35%
Component Cost	$	53.38

Injection Molded Parts		
Shape of Part	Lead Screw Reciever (Box)	
Part Complexity	Simple	
Finish Quality	Opaque	
Material	Polypropylene	
Tolerance	Fit	
Unit	Inches	
Dimensions	1.5x1x1	
Quantity		3200
Part Cost	$	6.40
Overhead		35%
Component Cost	$	8.64

Injection Molded Parts		
Shape of Part	Corner Motor Mount (Box)	
Part Complexity	Simple	
Finish Quality	Opaque	
Material	Polypropylene	
Tolerance	Intermediate	
Unit	Inches	
Dimensions	2.7x2.27x1.5	
Quantity		1600
Part Cost	$	14.60
Overhead		35%
Component Cost	$	19.71

Injection Molded Parts		
Shape of Part	Motor Mount Plate (Box)	
Part Complexity	Simple	
Finish Quality	Opaque	
Material	Polypropylene	
Tolerance	Intermediate	
Unit	Inches	
Dimensions	1.66x2.67x.125	
Quantity		3200
Part Cost	$	13.35
Overhead		35%
Component Cost	$	18.02

Component 8		
Description	10 Series 3 Slot Mount	
Vendor	80/20	
Retail Cost		54.41
Units / yr		6400
Volumized % of Retail		80%
Part Cost	$	43.53
Overhead		8.5%
Component Cost	$	47.23

0		
Description	80/20 Hidden Connectors	

	Component Cost	$	18.02
Component 9	Description	Ball Bearings	
	Vendor	Mcmaster Carr	
	Retail Cost		19.07
	Units / yr		4800
	Volumized % of Retail		90%
	Part Cost	$	17.16
	Overhead		8.5%
	Component Cost	$	18.62
Component 11	Description	M6 Slide in T-nut	
	Vendor	80/20	
	Retail Cost		1.44
	Units / yr		9600
	Volumized % of Retail		70%
	Part Cost	$	1.01
	Overhead		8.5%
	Component Cost	$	1.09
Component 13	Description	PCB Board	
	Vendor	Amazon	
	Retail Cost		8.99
	Units / yr		14400
	Volumized % of Retail		70%
	Part Cost	$	6.29
	Overhead		8.5%
	Component Cost	$	6.83
Component 15	Description	Acryllic Sheets	
	Vendor	Amazon	
	Retail Cost		48.99
	Units / yr		3200
	Volumized % of Retail		90%
	Part Cost	$	44.09
	Overhead		8.5%
	Component Cost	$	47.84

Component 10	Description	80/20 Hidden Connectors	
	Vendor	80/20	
	Retail Cost		6.38
	Units / yr		12800
	Volumized % of Retail		70%
	Part Cost	$	4.47
	Overhead		8.5%
	Component Cost	$	4.85
Component 12	Description	Economy T-nut	
	Vendor	80/20	
	Retail Cost		0.42
	Units / yr		9600
	Volumized % of Retail		70%
	Part Cost	$	0.29
	Overhead		8.5%
	Component Cost	$	0.32
Component 14	Description	Stepper Driver	
	Vendor	Amazon	
	Retail Cost		5.89
	Units / yr		4800
	Volumized % of Retail		90%
	Part Cost	$	5.89
	Overhead		8.5%
	Component Cost	$	6.39
Component 16	Description	Ring Tongue Terminal	
	Vendor	McMaster Carr	
	Retail Cost		9.22
	Units / yr		3200
	Volumized % of Retail		90%
	Part Cost	$	8.30
	Overhead		8.5%
	Component Cost	$	9.00

Component 17	Description	M6 L16 Round Head Hex Screw		Component 18	Description	M5 Economy Tnut
	Vendor	McMaster Carr			Vendor	80/20
	Retail Cost	7.37			Retail Cost	0.42
	Units / yr	576			Units / yr	8000
	Volumized % of Retail	90%			Volumized % of Retail	80%
	Part Cost	$ 6.63			Part Cost	$ 0.34
	Overhead	8.5%			Overhead	8.5%
	Component Cost	$ 7.20			Component Cost	$ 0.36
Component 19	Description	M5 Nut		Component 20	Description	Ring Tongue Terminal
	Vendor	McMaster Carr			Vendor	McMaster Carr
	Retail Cost	4.05			Retail Cost	9.22
	Units / yr	208			Units / yr	3200
	Volumized % of Retail	90%			Volumized % of Retail	90%
	Part Cost	$ 3.65			Part Cost	$ 8.30
	Overhead	8.5%			Overhead	8.5%
	Component Cost	$ 3.95			Component Cost	$ 9.00
Component 21	Description	M5 L14 Socket Cap Screw		Component 22	Description	M5 L10 Round Head Hex Screw
	Vendor	McMaster Carr			Vendor	McMaster Carr
	Retail Cost	10.01			Retail Cost	16.33
	Units / yr	832			Units / yr	64
	Volumized % of Retail	90%			Volumized % of Retail	90%
	Part Cost	$ 9.01			Part Cost	$ 14.70
	Overhead	8.5%			Overhead	8.5%
	Component Cost	$ 9.77			Component Cost	$ 15.95
Component 23	Description	M3 Nut		Component 24	Description	M3 L60 Socket Cap Screw
	Vendor	McMaster Carr			Vendor	McMaster Carr
	Retail Cost	2.62			Retail Cost	15.29
	Units / yr	720			Units / yr	384
	Volumized % of Retail	90%			Volumized % of Retail	90%
	Part Cost	$ 2.36			Part Cost	$ 13.76
	Overhead	8.5%			Overhead	8.5%
	Component Cost	$ 2.56			Component Cost	$ 14.93

Component 25	Description	M3 L 30 Round Head Hex Screw	
	Vendor	McMaster Carr	
	Retail Cost		7.85
	Units / yr		384
	Volumized % of Retail		90%
	Part Cost	$	7.07
	Overhead		8.5%
	Component Cost	$	7.67

Component 26	Description	M3 L16 Round Head Screw	
	Vendor	McMaster Carr	
	Retail Cost		9.28
	Units / yr		32
	Volumized % of Retail		90%
	Part Cost	$	8.35
	Overhead		8.5%
	Component Cost	$	9.06

Component 27	Description	M3 L10 Socket Cap Screw	
	Vendor	McMaster Carr	
	Retail Cost		6
	Units / yr		64
	Volumized % of Retail		90%
	Part Cost	$	5.40
	Overhead		8.5%
	Component Cost	$	5.86

Component 28	Description	M2 Nut	
	Vendor	McMaster Carr	
	Retail Cost		4
	Units / yr		192
	Volumized % of Retail		90%
	Part Cost	$	3.60
	Overhead		8.5%
	Component Cost	$	3.91

Component 29	Description	M2 L10 Socet Cap Screw	
	Vendor	McMaster Carr	
	Retail Cost		7.91
	Units / yr		128
	Volumized % of Retail		90%
	Part Cost	$	7.12
	Overhead		8.5%
	Component Cost	$	7.72

Component 30	Description	Angle Iron Raceway	
	Vendor	80/20	
	Retail Cost		11.79
	Units / yr		1600
	Volumized % of Retail		90%
	Part Cost	$	10.61
	Overhead		8.5%
	Component Cost	$	11.51

Component 31		
Description	5V 8 Channel Relay	
Vendor	Amazon	
Retail Cost		9.89
Units / yr		1600
Volumized % of Retail		90%
Part Cost	$	8.90
Overhead		8.5%
Component Cost	$	9.66

Component 32		
Description	18mm 10 Series Corner Bracket	
Vendor	80/20	
Retail Cost		1.09
Units / yr		12800
Volumized % of Retail		70%
Part Cost	$	0.76
Overhead		8.5%
Component Cost	$	0.83

Component 33		
Description	1010 Anchor	
Vendor	80/20	
Retail Cost		4.15
Units / yr		11200
Volumized % of Retail		70%
Part Cost	$	2.91
Overhead		8.5%
Component Cost	$	3.15

Component 34		
Description	1010 Series Bolt Assembly	
Vendor	80/20	
Retail Cost		1.45
Units / yr		12800
Volumized % of Retail		70%
Part Cost	$	1.02
Overhead		8.5%
Component Cost	$	1.10

Component 35		
Description	1/4-20 Nut	
Vendor	McMaster Carr	
Retail Cost		8.95
Units / yr		48
Volumized % of Retail		90%
Part Cost	$	8.06
Overhead		8.5%
Component Cost	$	8.74

Component 36		
Description	1/4-20 L3/4 Round Head Hex Screw	
Vendor	McMaster Carr	
Retail Cost		10.4
Units / yr		64
Volumized % of Retail		90%
Part Cost	$	9.36
Overhead		8.5%
Component Cost	$	10.16

Component 37		
Description	1/4-20 L2 Pan Head Bolt	
Vendor	McMaster Carr	
Retail Cost		11.84
Units / yr		64
Volumized % of Retail		90%
Part Cost	$	10.66
Overhead		8.5%
Component Cost	$	11.56

Component 38		
Description	M5 Slide in Tnut	
Vendor	80/20	
Retail Cost		1.44
Units / yr		14400
Volumized % of Retail		70%
Part Cost	$	1.01
Overhead		8.5%
Component Cost	$	1.09

Component 39		
Description	Aluminum Extrusion (30in)	
Vendor	80/20	
Retail Cost		13.89
Units / yr		6400
Volumized % of Retail		80%
Part Cost	$	11.11
Overhead		8.5%
Component Cost	$	12.06

Component 40		
Description	Aluminum Extrusions (13in)	
Vendor	80/20	
Retail Cost		14.04
Units / yr		6400
Volumized % of Retail		80%
Part Cost	$	11.23
Overhead		8.5%
Component Cost	$	12.19

Component 41		
Description	Aluminum Extrusions (15in)	
Vendor	80/20	
Retail Cost		8.34
Units / yr		6400
Volumized % of Retail		80%
Part Cost	$	6.67
Overhead		8.5%
Component Cost	$	7.24

Component 42		
Description	Aluminum Extrusion (17in)	
Vendor	McMaster Carr	
Retail Cost		9.08
Units / yr		1600
Volumized % of Retail		90%
Part Cost	$	8.17
Overhead		8.5%
Component Cost	$	8.87

Component 43		
Description	Wires	
Vendor	Amazon	
Retail Cost		14.99
Units / yr		1600
Volumized % of Retail		90%
Part Cost	$	13.49
Overhead		8.5%
Component Cost	$	14.64

Component 44		
Description	Buckbooster	
Vendor	Amazon	
Retail Cost		16.49
Units / yr		1600
Volumized % of Retail		90%
Part Cost	$	14.84
Overhead		8.5%
Component Cost	$	16.10

Assembly	Sub-Assembly 1	1	hrs.
	Sub-Assembly 2	1	hrs.
	Sub Assembly 3	1	hrs.
	Final Assembly	0.5	hrs.
	Total Assembly Time	3.5	hrs.
	Labor Rate	$ 60.00	$ / hr
	Labor Cost	$ 210.00	
	Overhead	35%	
	Component cost	$ 283.50	
	Per Unit Cost	$ 2,557.15	
	Per Unit Sales Price	$ 3,600.00	
	Total Cost / 1600 units	$ 4,091,439.29	
	Total Profit Per 1600 units	$ 1,668,560.71	
	Per Unit Profit	$ 1,042.85	
	Total Revenue	$ 5,760,000.00	

Figure F.1: Cost Tables for Calculating Product Cost and Profit

Appendix 3: Design Process

G. Engineering Requirements and Concepts

G.I Engineering Requirements and Constraints

Attached below is the excel document created to define the engineering requirements. The matrix of information was compiled from personal research and surveys of industry professionals; in it a basis of information for the down selection criteria was compiled. Specified inside of the matrix are the accuracy and cost estimates for our product to be feasible and improve the market accordingly, among several others. These weights were agreed upon as a group after the design requirements were discussed; please refer to Figure G.1.1 below for more information on the particulars of why each weight is assigned.

Category	#	Specification	Criteria	Source	Weights
Accuracy	1	Detector must accurately identify temperature	Must have accuracy under 2.5°C	Customer Requirement	0.5
Resolution	2	Detector must have high temperature resolution	Must detect temperature differences below 1°C	Customer Requirement	0.5
	3	Detector must have high spatial resolution	Must be able to identify hot spots larger than 4000 microns	Customer Requirement	0.5
Hot Spot Identification	4.a	Device must actuate detector to appropriate location over sample such that sample exists within top left half of resulting image	Detector must be actuated to within 10 mm of appropriate spot	Customer Requirement	0.5
	4.b	Detector identifies prominent hot spot occurences	Must be able to detect 70% of hot spots (by area)	Customer Requirement	0.7
Costs	5	Device must be able to be built and tested by us over the course of this semester.	All materials and components minus labor must be sourced for less than $1000	Course Requirement	0.35
	6	Initial cost for industry is not most important requirement, a sizeable sum is available for improvements to the assembly line	Sales Price must be under $5,000 for initial investment to pay off rapidly in saved labor	Customer Requirement	0.2
Ease of Operation / Test Time	7	Prototype Hot Spot Creator must be quick to save on testing time	Test must take less than 10 min from start to end to ensure rapid iterations are possible	Team Requirement	0.3
	8	End product must require minimum human interaction to ensure savings over existing options	Running Device must be automated, requiring no more than 10 human-machine interactions during single operation. Setup and dissasembly will require no more than a 3-5 min of setup and teardown time each.	Customer Requirement	0.4
Safety	9	Prototype Safety is the ME departments number one priority	Device must pose minimal risk to our lives throughout protyping process	Course Requirement	0.2
	10	Final Design should be safe for widespread use	Device must not have extending appendages outside frame and failsafes for any potentially hazardous components	Customer Requirement	0.3
Maintenance	11	Prototype must be easy to maintain so that time can be spent iterating instead of maintaining	Device must require no more than occasional lubrication every 5 uses	Team Requirement	0.25
	12	Final Product must be robust and minimize maintenance to ensure assembly line is not held up	Device must be able to handle 100,000 cycles without serious downtime for maintenance	Customer Requirement	0.3

Figure G.1.1: Engineering Requirements

After CDR and before the validation phase, various changes to the engineering requirements were made, chief among them, the differentiation between accuracy and resolution.

Both deal with camera specifications. The weights on these new sections were ordered based on their importance to the overall design, 0.7 was given to the hotspot identification requirement, as this is the single most important aspect of the product and must be weighted highest as a result. The other new sections of resolution and actuation accuracy were weighted at 0.5 as they are still extremely important to the overall functioning, but not as necessary to demonstrate the purpose of the product. The accuracy requirement of 2.5°C is the standard for the range of cameras similar to the Fluke TIS20+ camera being used. Additionally, after further research into hotspots with Professor Devahdhanush, an accuracy range of less than 1°C in the semiconductor industry would be appropriate for and was chosen to reflect that. The resolution requirement of 4000 microns resulted from the maximum size hotspots that the team can generate. Moreover, the product will be considered successful if it can detect 70% of hot spots by area and accurately move the camera to within 10 mm of the intended target, this was arrived at from talks with Professor Devahdhanush and was chosen as there is inherent error in the reverse ODE analysis but this is the expected accuracy of the results and would be sufficient to show manufacturers if there were aberrant errors in their chips. As for the costs, $1000 is the budget from the course and $5000 was an initial estimate for competitors in the market, although the final price of the product isn’t critical as this new system for quality control would be saving the company tens of thousands of dollars a year in manufacturing time and labor on faulty semiconductors. Ease of operation and test time for personal use is subjective and was arrived at based on further estimation of the expected run time of a reasonable process. The much more important component is the automation and setup/breakdown time for industry on new semiconductors. This automation requirement of a maximum of 10 human-machine interactions and a 3-5 minute setup/teardown were refined after additional market research and identification of the key components of automation. More so than the original time requirements from CDR, a limit on the human-machine interactions is key to the final consumer, so the interaction count of 10 was chosen as the minimum interactions required with 1 being to load, power, enable, etc. As this provides a quantifiable way to measure labor. As for safety, these are just slightly tailored safety objectives for typical manufacturing processes and although safety is important, this object is not expected to pose much risk to the team in testing or end users, so it has been weighted lower. Finally, maintenance requirements for personal use are estimated based on best practice to focus the team's time and are therefore weighted lowly, however the industry maintenance must be low in order to maximize up time of the quality control process and ensure the assembly line of the semiconductor factory has the minimal amount of downtime possible as a result of implementing our process.

G.2 Concept Sketches

The team generated various concepts for each function and summarized them in the following morphological chart.

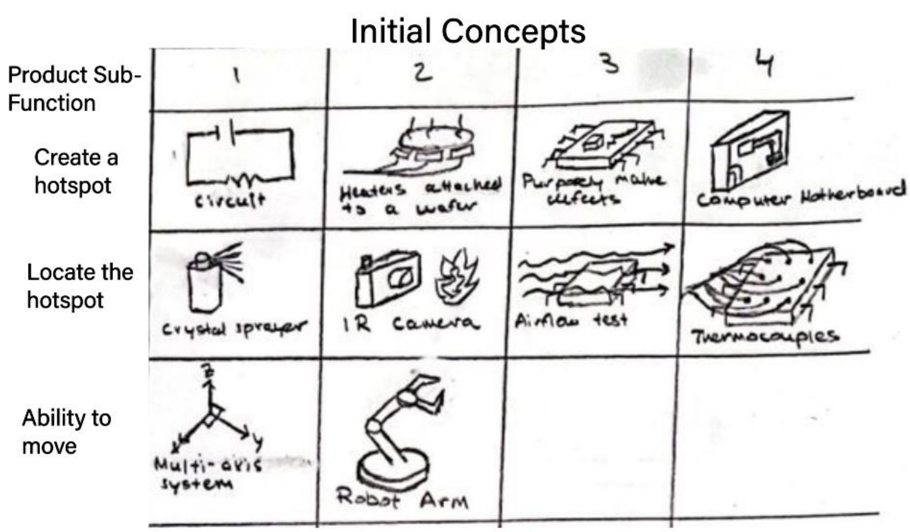


Figure G.2.1: Front view of SCS Solutions proposed design

For the “creating hotspot” feature, the team came up with several concepts: apply a current through real semiconductors in a circuit, heating up semiconductor-like materials (e.g.: wafers), purposely making defects on real semiconductors and applying a current, and finally running a heavy computational program on an old/used computer motherboard.

For the “locating hotspot” feature, the team generated the following concepts: automating a liquid crystal sprayer, using an IR camera or IR laser, applying airflow and implementing a network of thermocouples or thermocouple probes.

Finally, for the “movement options” feature, the team proposed three main ideas: using a 2-axis mount, a robot arm or having a completely stationary system.

The figures below show the preliminary sketches of the team’s product (Figures G.2.2 – G.2.4). A front view and isometric view are provided to better explain each concept. The sketch shows the three main structural components: a rectangular prism structure, a 2-axis motor movement system located at the top of the structure, and two width-spanning plates located at the bottom of the structure. The movement system is at a specific height above the top plate to satisfy the thermal cameras focal distance requirements and the top plate is at a specific height above the bottom plate to satisfy height clearances for the computing and power components. The movement system will carry the thermal camera and move it to any spatial location on a theoretical 2D grid. The top plate houses an insulating material which has cut-outs for 3 PCBs; the PCBs will have arrays of soldered-on resistors (see Figure G.2.4) which are electrically controlled through relays to produce various heat fluxes thus simulating a semiconductor chip. The lower tray will house computational components (e.g.: an Arduino, and batteries).

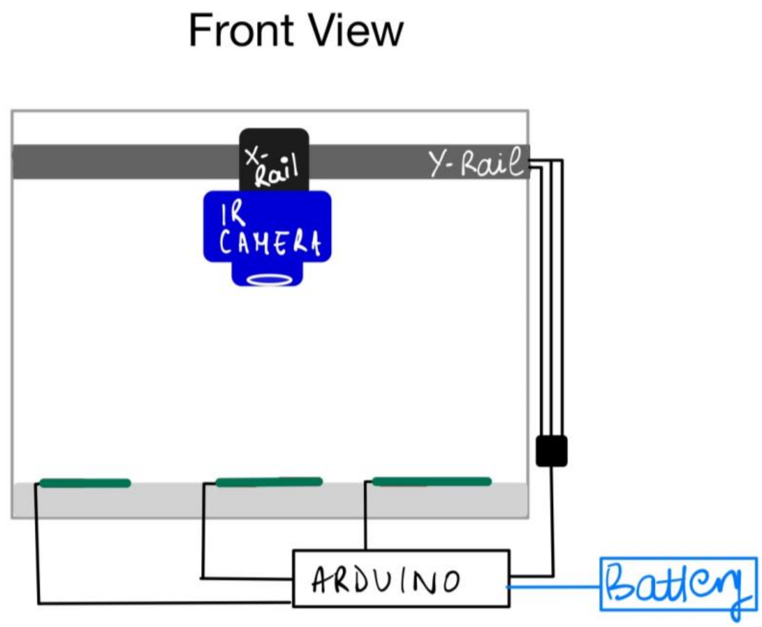


Figure G.2.2: Front view of SCS Solutions proposed design

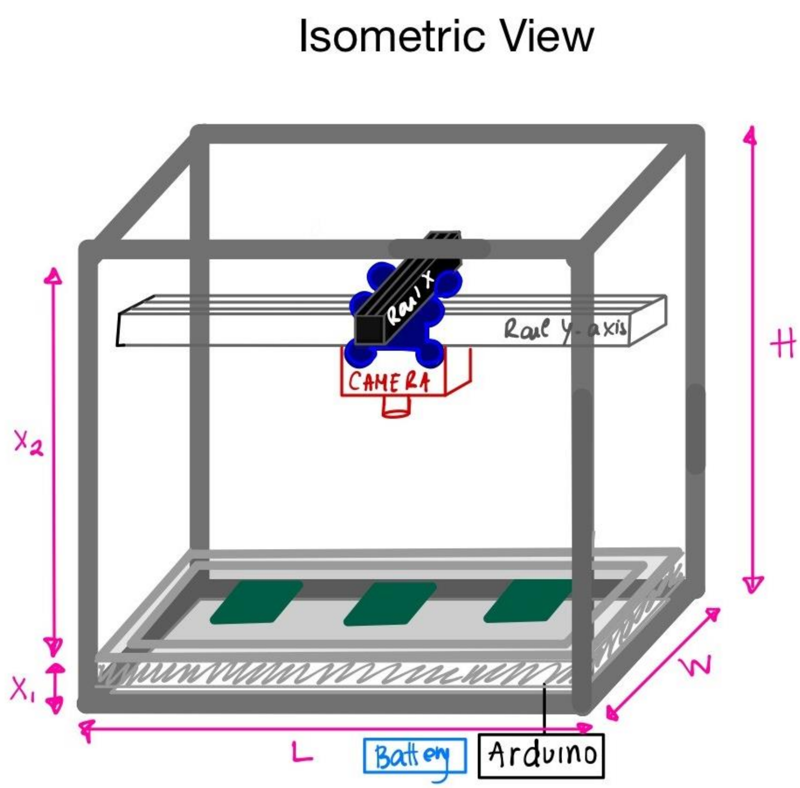


Figure G.2.3: Isometric view of SCS Solutions proposed design

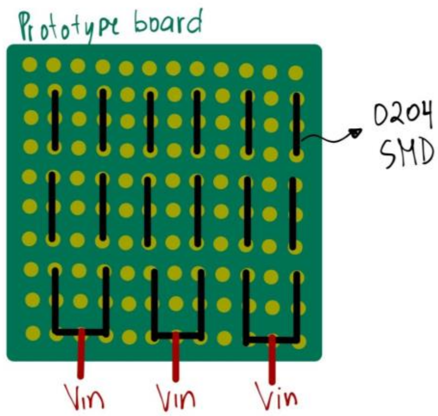


Figure G.2.4: Single PBC Board Drawing

G.3 Down Selection

The following matrices document the down selection process for each one of the product's functions: creating a hotspot, locating it and movement options. The weights are based on the engineering requirements made up by the market analysis, customer requirements and constraints (see Appendix H.1.) The scoring of each concept is recorded on the matrix, along with supportive facts and objective explanations (e.g.: concept's cost, uncertainty measurement). The 1-5 grading scale was considered as a group after researching for concrete and supporting data on each concept. The empirical rationale can be seen to the right of each number, but ultimately it was the group consensus that assigned the final grade to the subject. Overall totals at the bottom of each section can be found by summing the multiplications of the weight by the scores given by the group.

Metrics/Features	Weight		Semiconductor Circuit		Heaters with wafer		Defect on SC + Circuit		Computer Motherboard	
Personal Cost	**0.4**	Budget should be placed in final product, not testing	5	ECE kit+375 Instruments+Extra: $20	3	315 Heaters + Wafer: $60	5	Machine Shop. ECE kit+375 Instruments+Extra: $20	4	New: >$100, Old: $25
Accuracy	**0.5**	Very important to mimic hotspot	5	Exact Analog	4	Can create a close analog with proper research	2	Accuracy would prove difficult	4	Exact Analog with many potential takeaways
Setup and Manufacturing Difficulty	**0.4**	Ease of Setup and manufacturing is key to successful iterations	4	Learn+Setup:1h	3	Learn+Setup:2h	4	Learn+Set up: 1.5h	3	Learn+Set Up: 1h
Ease of Operation / Run Time	**0.3**	Our time is valuable	3	Difficult to create proper circuit tuned to semiconductor	5	Fast to heat up	3	Faster to test	3	Heat sinks will fight semiconductor heating up
Maintenance	**0.3**	Minimal maintenence is ideal so time can be spent iterating and not maintaining prototypes	4	Occasional circuit maintenance is manageable	5	Heaters can be easily replaced in circuit	2	Difficult and time consuming to re-manufacture semiconductors	4	Minimal maintenance will be required on the motherboard
Safety	**0.2**	Safety is the ME department's number one priority	1	short circuit	4	melt wafer, overpower burner	4	cuts, scrapes, machine misuse	1	Overheat board, static electricity
	Totals:		8		8		6		7	

Figure G.3.1 Creating Hotspot Decision Matrix

Metrics/Features	Weight		(Sprayer)		IR Camera		Thermocouples		Airflow		IR Laser		Thermocouple probe	
Accuracy	**0.5**	The most critical compenent to the successful design	3	Visual Change, Approx 1*C	4	Uncertainty: 0.5°C	3	Uncertainty: 1.7-2.5°C	1	Cost dependent, imprecise	2	Uncertainty: 1°C	5	Uncertainty: 0.1°C
Cost	**0.2**	and the differences will mean nothing next to the cost of labor	1	microscope: <$1000+ crystals: $135*#+ curve tracer: $10K	4	camera: $2K	3	Thermocouples: 10*#+ DAQ $200	3	Windtunnel: $100 + sensors: 200*#	4	Laser: $500*# on ebay (need quote)	2	probe: $200*# + dock
Ease of Operation	**0.4**	Critical, the issue we are trying to solve with our design	3	Time Consuming to watch	4	Minimal input required	4	Minimal input required	2	Advanced Controller or time consuming	4	Minimal input required	4	Minimal input required
Safety	**0.3**	Final design should be safe for widespread implementation	4	Minimally hazardous liquid solution	5	Safe	5	Safe	5	Safe	1	Radioactive	5	Safe
Durability	**0.35**	Solution must be robust	3	Liquid and Electronics	4	Fragile lens + dust (need to clean every so often)	2	Extremely flims thermocouples	2	Extreme precision required	3	Precision required and emitter	3	Durable Thermocouples
Maintenance	**0.3**	Customer's time is important	1	Liquid and Electronics	4	Minimal	3	Thermocouple maintenace	3		4	Minimal	4	Minimal
Operational Time	**0.4**	improvement hoping to made over competetors, important	2	Liquid must dry	4	Extremely fast, then just post-processing	3	Slowed slightly for accuracy but relatively fast	1	Slow	2	Slowed significantly for accuracy	1	Extremely Slow
	Totals:		6		10		8		5		7		9	

Figure G.3.2 Identifying Hotspots Decision Matrix

Metrics/Features	Weight		2 Axis		Robot Arm		*Stationary*	
Cost	0.2	Variance in cost is slight and not significant to industry	3	Cheap Rail System ($300)	2	Price depends on complexity (~$500)	4	Just need mounts (cheaper)
Accuracy	0.4	Accuracy of device is derived from accuracy of movement	5	Geared Rails are accurate	5	Hinges are accurate	4	Immobility
Manufacturing Time	0.3	Ideally quick to create for prototyping	3	Design and control scheme is complicated	4	Purchasing	5	Easy
Ease of Operation	0.4	Minimal End User input is required	4	Automated Programs	4	Automated Programs	2	User Input Required
Maintenance	0.3	Resilient designs work for customer longer	4	Rails are easy to maintain	3	Complicated hinges	5	Easy
Safety	0.2	Not critical to these devices	4	Relatively Safe	4	Relatively Safe	5	Safe
Durability	0.35	Tied in with maintenance for customer reqs	4	Resilient System	3	Many points of failure	5	Resilient
	Totals:		9		8		9	

Figure G.3.3 Movement Options Decision Matrix

For the “creating hotspot” feature, this down-selection came down to the semiconductor circuit and heating up wafer idea. The semiconductor in circuit concept, the highest rated, was quickly discarded after understanding how complicated “opening” a semiconductor would be. Conversations with Bert Gramelspacher, from the E-Shop, helped us come up with a solution: building a network of surface mount resistors (SMD) and powering SMD’s individually to generate the wanted heat. The idea is for the network to create a heat map like one of a hotspot. In terms of accuracy, this method would be the best, achievable at a low cost and be very durable.

The only downside is the amount of preparation time needed as these SMD are very small resistors that need to be placed on PBC board one by one.

For the “locating hotspot” feature, the parameter with the highest weight is *accuracy*, followed by *ease of operation* and *operational time.* Accurately identifying the hotspot is an essential aspect of the product’s functionality, for that reason it has the highest weight. In that aspect, the IR camera and thermocouple probe are the most accurate with an uncertainty of 0.02°C and 0.5°C respectively. Moreover, in order to compete with existing products and enter the fast-moving manufacturing world, the product needs to be easy to use, efficient and quick. Except for the airflow and crystal sprayer, all other concepts had high scores as they require minimal operator input, although the IR Camera was ranked highest as it had the best accuracy and consistently ranked highly when it came to safety, maintenance, and ease of operation.

Finally, for the “movement options” feature, the stationary concept was dropped because the team identified the necessity of testing multiple semiconductors simultaneously and a stationary camera could not fit the required number of semiconductors in frame. The other two ideas were compared using real products and the scores ended up being very similar. In the end, the 2-axis movement was chosen as edged out the robot arm with its simplicity and durability.

H.1 CAD

To create a final prototype for the team’s design, the project was created inside of Creo Parametric. The overall structure of the assembly can be seen in Figure H.1.1 below.

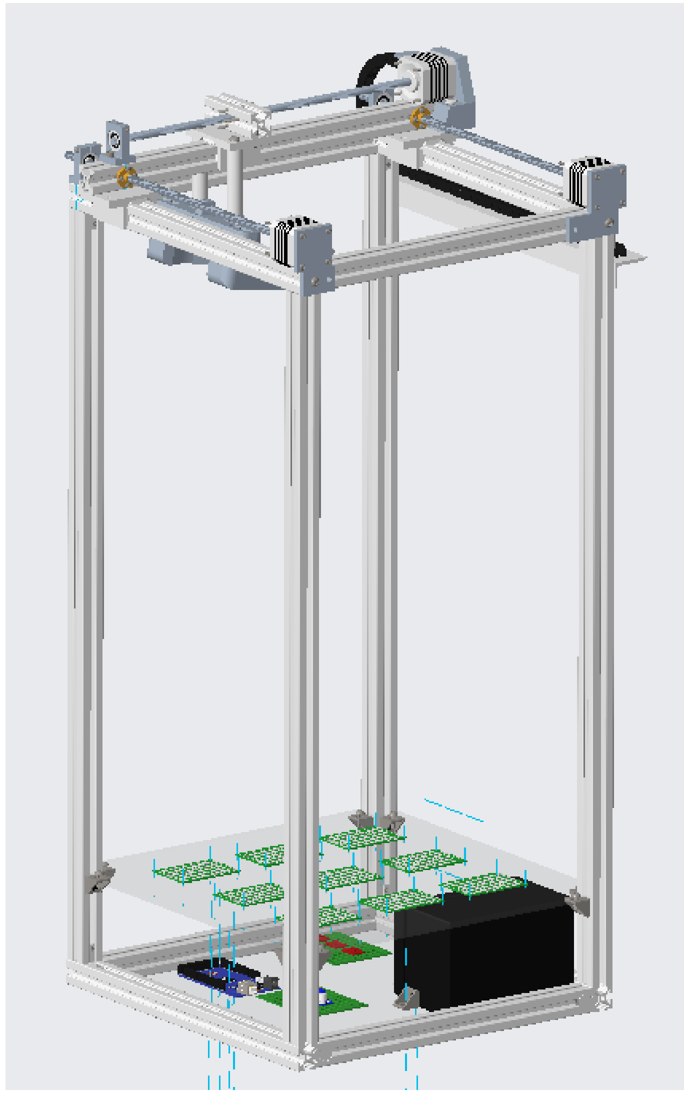


Figure H.1.1 Assembly View

The main update between CDR and FDR was the addition of the third motor to the movement assembly seen above. This new motor mirrors its counterpart and was added after the first motor was unable to move the assembly on its own, as the opposing side would lag and bind up. After this addition, the entire design worked as intended. The assembly hierarchy is pictured below the assembly in Figure H.1.2 with each subassembly expanded for ease of understanding.

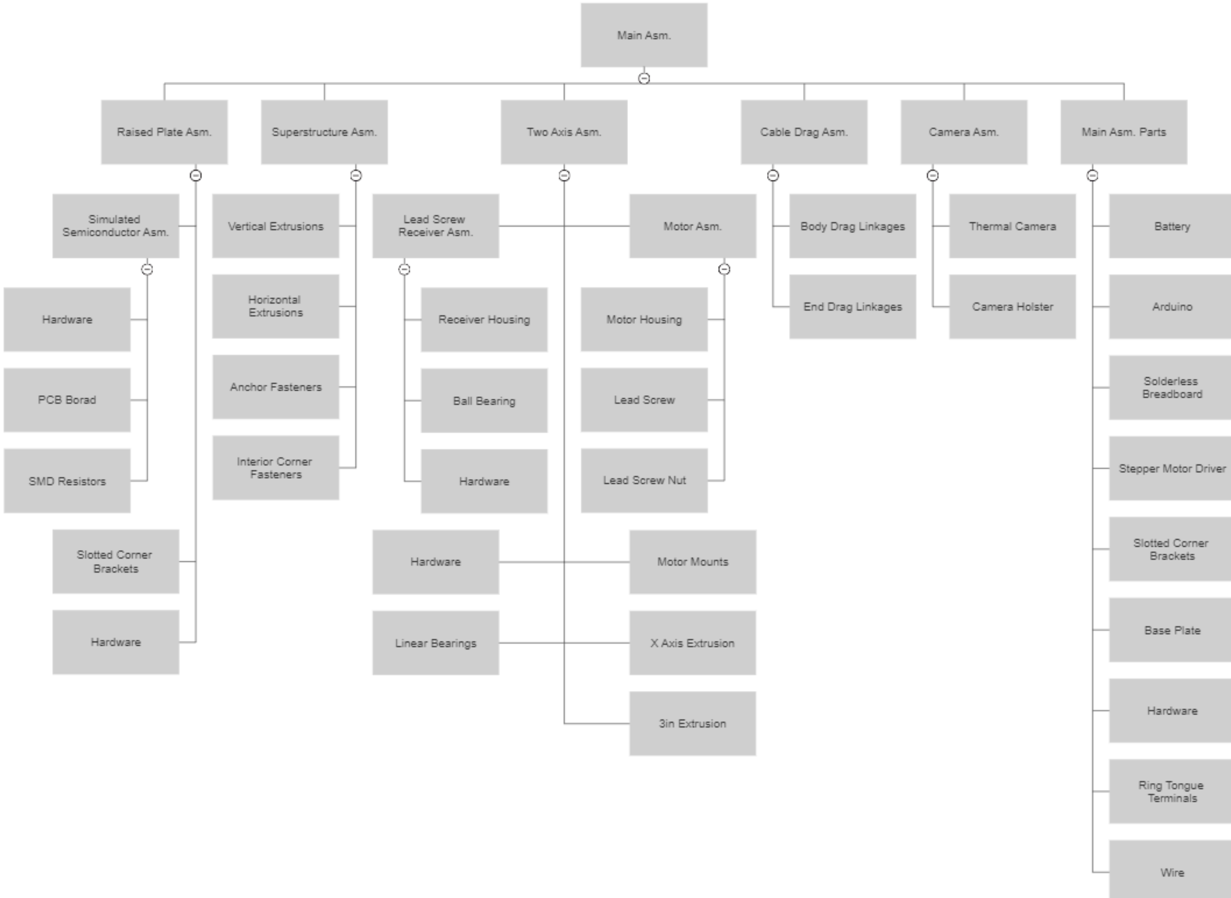


Figure H.1.2 Model Hierarchy Tree

The Make or Buy Table was created to ensure there is a source for every component in the assembly. This can be seen below in Figure H.1.3 followed by the Table of Materials in Figure H.1.4 which lists each component, at times broken down into sections, and details the material and volumetric dimensions. Note that the units vary by part. This is because some of the products, like a ¼-20” bolt or the 1” x 1” extrusions, were designed using the imperial system, so it would not be prudent to convert these to a non-whole number of millimeters.

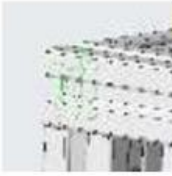
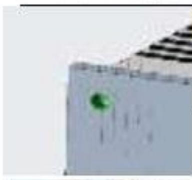
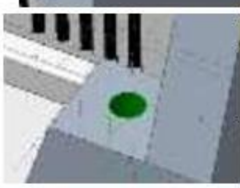
Num	Part	Make or Buy	Vendor
1	Camera Holster	Make	Make
2	Motor Mount Wide Plate	Make	Make
3	Motor Mount Plate	Make	Make
4	Lead Screw Reciever	Make	Make
5	Corner Motor Mount	Make	Make
6	Stepper Motor	Buy	Amazon
7	Stepper Driver	Buy	Amazon
8	Ring tongue terminal	Buy	McMaster Carr
9	PCB Boards	Buy	Amazon
10	M6 Slide in Tnut	Buy	80/20
11	M6 L16 round head hex screw	Buy	McMaster Carr
12	M5 Slide in Economy Tnut	Buy	80/20
13	M5 nut	Buy	80/20
14	M5 L14 socket cap screw	Buy	McMaster Carr
15	M5 L10 round head hex screw	Buy	McMaster Carr
16	M3 nut	Buy	McMaster Carr
17	M3 L60 socket cap screw	Buy	McMaster Carr
18	M3 L30 round head hex screw	Buy	McMaster Carr
19	M3 L16 round head screw	Buy	McMaster Carr
20	M3 L10 socket cap screw	Buy	McMaster Carr
21	M2 nut	Buy	McMaster Carr
22	M2 L10 socket cap screw	Buy	McMaster Carr
23	Chip Resistors	Buy	Amazon
24	Cable Raceway	Buy	Amazon
25	Angle Iron raceway	Buy	80/20
26	Acryllic Sheets	Buy	Amazon
27	608-2RS Ball Bearings	Buy	McMaster Carr
28	5V 8 Channel Relay	Buy	Amazon
29	18mm 10 Series Corner Bracket	Buy	80/20
30	12V Battery	Buy	Amazon
31	1010 Series Hidden Connectors	Buy	Amazon
32	1010 Anchor	Buy	80/20
33	10 Series Bolt Assembly	Buy	80/20
34	10 Series 3 Slot Mount	Buy	80/20
35	1/4-20 nut	Buy	McMaster Carr
36	1/4-20 L3/4 round head hex screw	Buy	McMaster Carr
37	1/4-20 L2 pan head bolt	Buy	McMaster Carr
38	Buckbooster	Buy	Amazon
39	Wires	Buy	Amazon
40	M5 Slide in Tnut	Buy	80/20
41	3in Aluminunum Extrusion	Buy	80/20
42	30in Aluminum Extrusion	Buy	80/20
43	17in Aluminum Extrusion	Buy	80/20
44	15in Aluminum Extrusion	Buy	80/20
45	13in Aluminum Extrusion	Buy	80/20

Figure H.1.3 Make or Buy Table

Num	Parts		Materials	Finished Size	Units
1	1010 extrusions		6105-T5 aluminum	252 x 1 x 1	in
2	stepper motors				
3		motor case	aluminum	39.5 x 31 x 31	mm
4		lead scew	carbon steel	400 x 8 x 8	mm
5		lead screw nut	brass	10.5 x 22 x 22	mm
6	linear bearings			2.936 x 1.218 x 1.875	in
7		mount	6105-T5 aluminum		
8		bearing bads	self-lubricating UHMW		
9	ball bearings			4.7 x 22ID, 8ID	mm
10		ring/cage/balls	steel		
11		seal	Buna-N rubber		
12	angle iron		6105-T5 aluminum	15 x 2 x 1	in
13	raised plate		acrylic	15 x 15 x 1/8	in
14	base plate		acrylic	13.5 x 13.5 x 1/8	in
15	lead screw receiver		PLA	1.5 x 1 x 1	in
16	cable drag		plastic	10 x 15 x 100	mm
17	thermal camera		-	5.7 x 10.5 x 4	in
18	camera holster		PLA	5.7 x 10.5 x 4	in
19	motor mount		PLA	68.3 x 38.1 x 57.7	mm
20	motor mount plate		PLA	42.3 x 67.7 x 46.3	mm
21	battery		sealed lead-acid	3.98 x 3.86 x 5.94	in
22	arduino		-	108 x 53.3 x 12.5	mm
23	stepper driver		-	16 x 20.3 x 15.2	mm
24	solderless breadboard		plastic	81.7 x 54.75 x 8.5	mm
25	M6 slide-in t nut		6105-T5 aluminum	12.4 x 11 x 4.3	mm
26	M5 slide-in t nut		6105-T5 aluminum	12.4 x 11 x 4.3	mm
27	M3 slide-in t nut		aluminum	12.4 x 11 x 4.3	mm
28	resistor			3.6 x 1.5 x 1.5	mm
29		end caps	steel		
30		lead	tin-plated copper on nickel barrier		
31	pcb board			50 x 70 x 1.5	mm
32		contacts	tin-plated copper		
33		board	FR-4 (woven glass and epoxy)		
34	M3 L10 socket cap screw		18-8 stainless steel	13 x 5.5 x 5.5	mm
35	M2 L10 socket cap screw		18-8 stainless steel	12 x 3.8 x 3.8	mm
36	M5 L14 bolt		18-8 stainless steel	16.75 x 9.5 x 9.5	mm
37	M3 L60 socket cap screw		18-8 stainless steel	63 x 5.5 x 5.5	mm
38	M3 L30 bolt		18-8 stainless steel	31.65 x 5.7 x 5.7	mm
39	M5 L10 bolt		18-8 stainless steel	12.75 x 9.5 x 9.5	mm
40	1/4-20 L3/4 bolt		18-8 stainless steel	.9063 x 7/16 x 7/16	in
41	1/4-20 L2 pan head bolt		18-8 stainless steel	2.144 x .492 x .492	in
42	1/4-20 nut		18-8 stainless steel	7/16 x 7/16 x 7/32	in
43	18mm slotted corner bracket		aluminum	18 x 18 x 18	mm
44	1010 internal corner bracket		18-8 stainless steel	.7 x .48 x 1	in
45	1010 anchor		18-8 stainless steel	.93 x .62 x .562	in
46	M5 nut		18-8 stainless steel	8 x 8 x 4	mm
47	M3 nut		18-8 stainless steel	5.5 x 5.5 x 2.4	mm
48	M6 L80 bolt		18-8 stainless steel	83.3 x 10.5 x 10.5	mm
49	ring tongue terminal		18-8 stainless steel	3.6 x 14 x 5.5	mm
50	wire		copper	.0508 x .0508 x 48	in

Figure H.1.4 Table of Materials

Although most of the components below in Figure H.1.5 are unaltered from the supplier, the custom-made parts and aluminum extrusions will require drilling for assembly. In the Table of Fits and Tolerances, these clearance holes are detailed in millimeters or inches according to whether they are interfacing with the metric or imperial components. The tolerances for the bolts and lead screws were gathered from ISO industry standard whereas the first listing in the table is unique. As the extrusions are being ordered precut to the lengths required, the team reached out to the supplier, 80/20, for their tolerances when making the length cut and facing the end. Their cut tolerance is ±.015 inches and they guarantee a ±.002 from square. These tight tolerances will ensure a reliable assembly is possible.

	in	Extrusion Cut	Size/Tolerance	Extrusion Squareness	Size/Tolerance
	MMC	nominal - .015	nominal±.015		±.002
	LMC	nominal + .015			
	mm	Mount Plate Hole	Size/Tolerance	Bolt	Size/Tolerance
	MMC	3	3.025±.025	2.874	2.927±.053
	LMC	3.05		2.98	
	mm	Mount Plate Hole	Size/Tolerance	Bolt	Size/Tolerance
	MMC	3	3.025±.025	2.874	2.927±.053
	LMC	3.05		2.98	
	in	Mount Plate Hole	Size/Tolerance	Bolt	Size/Tolerance
	MMC	0.25	.2515±.015	0.2408	.2448±.004
	LMC	0.253		0.2489	
	mm	Mount Hole	Size/Tolerance	Bolt	Size/Tolerance
	MMC	3	3.025±.025	2.874	2.927±.053
	LMC	3.05		2.98	
	in	Mount Hole	Size/Tolerance	Bolt	Size/Tolerance
	MMC	0.25	.2515±.015	0.2408	.2448±.004
	LMC	0.253		0.2489	
	in	Mount Hole	Size/Tolerance	Bolt	Size/Tolerance
	MMC	0.25	.2515±.015	0.2408	.2448±.004
	LMC	0.253		0.2489	
	mm	Lead Nut Hole	Size/Tolerance	Bolt	Size/Tolerance
	MMC	3	3.025±.025	2.874	2.927±.053
	LMC	3.05		2.98	
	in	Plate Hole	Size/Tolerance	Anchor	Size/Tolerance
	MMC	0.6	.615±.015	14.2148	14.2178±.03
	LMC	0.603		14.2748	

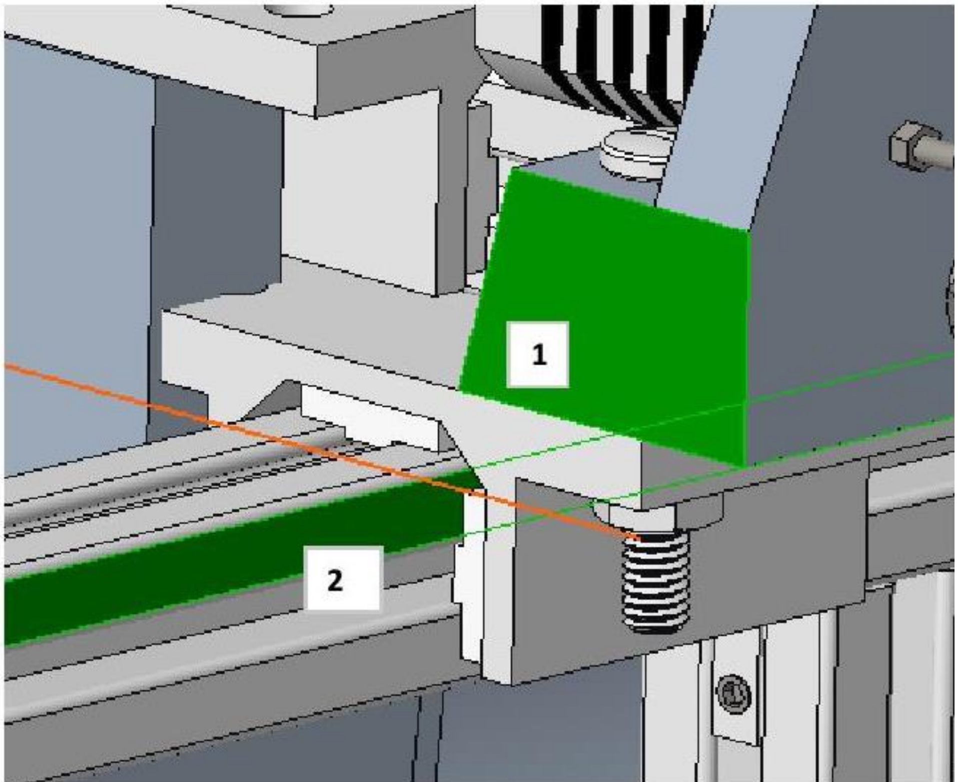
mm	Angle Iron Hole	Size/Tolerance	Bolt	Size/Tolerance
MMC	5	5.025±.025	4.874	4.927±.053
LMC	5.05		4.98	

mm	Plate Hole	Size/Tolerance	Bolt	Size/Tolerance
MMC	5	5.025±.025	4.874	4.927±.053
LMC	5.05		4.98	

mm	Lead Screw Hole	Size/Tolerance	Lead Screw	Size/Tolerance
MMC	10	10.025±.025	7.874	7.927±.053
LMC	10.05		7.98	

Figure H.1.5 Table of Fits and Tolerances

The components that fit together, more specifically that make up the superstructure, motor mount, and camera holster assemblies, are the only parts that would require precise knowledge of the surface finish, as their roughness would impact how they mesh with one another. These components are all made of either PLA or aluminum as can be seen detailed below in Figure H.1.6. The latter components are all sourced from 80/20, and therefore undergo similar surface treatment. The supplied aluminum is anodized, which increases surface roughness, but the specification from the supplier remains well below the standard roughness of 125 µin. The PLA components, the motor mounts and camera holster, will have much more exaggerated roughness, approximately 390 µin, depending on layer height during the 3D printing process. If the roughness interferes during assembly, the parts could be treated, either sanded or dipped in Acetone, to improve the finish quality.



Part #	Material	Finish	Surface Roughness	Units
1	PLA	None	390	µin
2	Aluminum	Anodized	18.5	µin

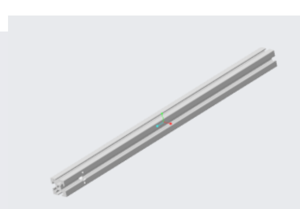
Figure H.1.6 Table of Surface Finishes

To further aid with understanding our product, several additional views can be found below. To start Figure H.1.7 depicts an exploded view of the superstructure to accentuate the connection points and brackets that can be seen in the figure.

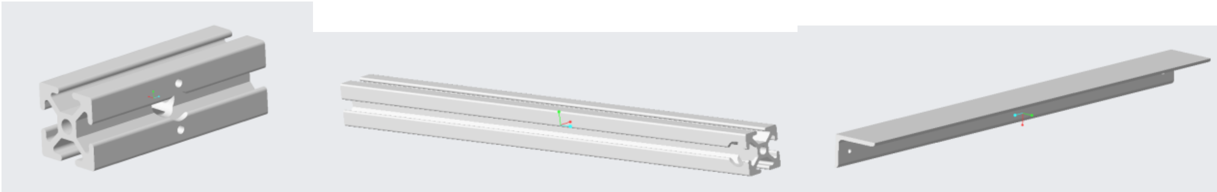
Figure H.1.7 Exploded View of the Superstructure Assembly

Individual screenshots of every part in the product can be found below in Figures H.1.8 - H.1.11. These should assist the reviewer in identifying any particular components of the product that cannot be easily identified in the assembly view above.



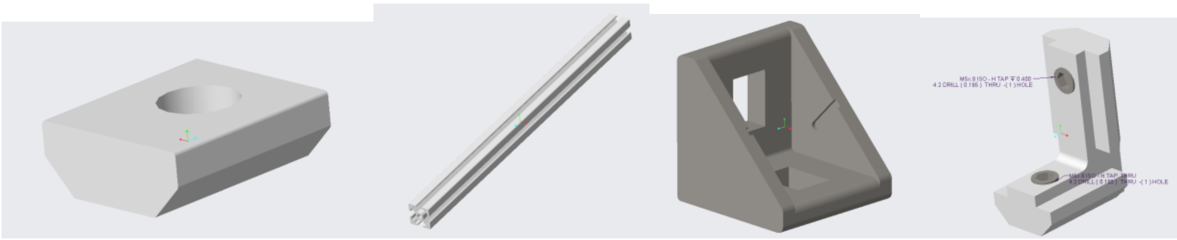



80/20 13” 80/20 Slider 80/20 Upper Crossbar 80/20 Upper 17”

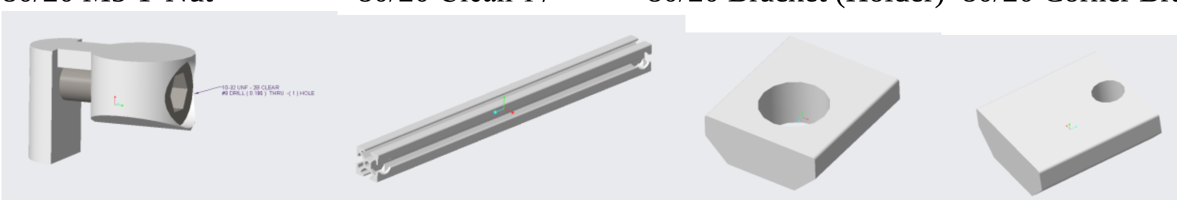


3

in Lead Screw 80/20 80/20 1 cut 17“ Electrical Chain Holder

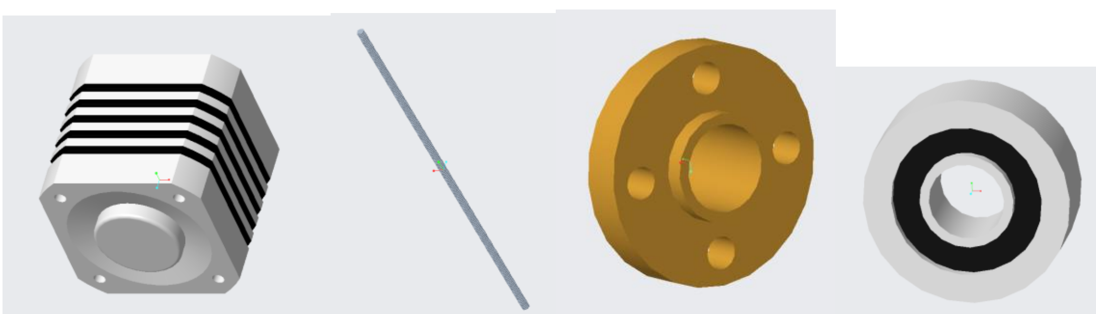


80/20 M5 T-Nut 80/20 Clean 17” 80/20 Bracket (Holder) 80/20 Corner Bracket

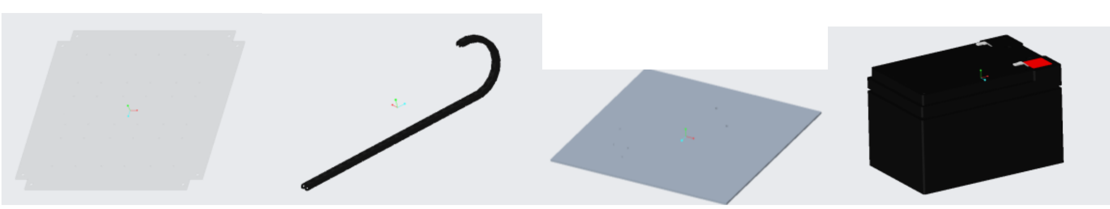


80/20 Corner locknut 80/20 13” w/ holes 80/20 M4 T-Nu 80/20 M3 T-Nut

Figure H.1.8 80/20 Thumbnails

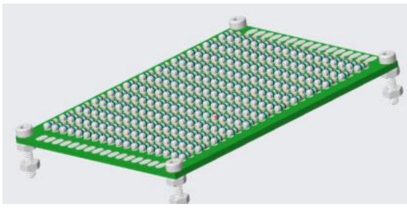


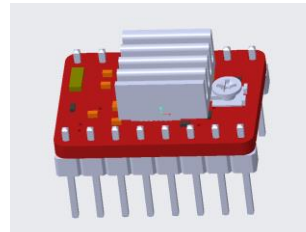
Motor Lead Screw Lead Screw Nut Bearing



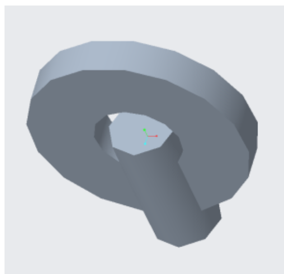
Top

Electrical Plate Electrical Chain Bottom Electrical Plate 12 V Battery



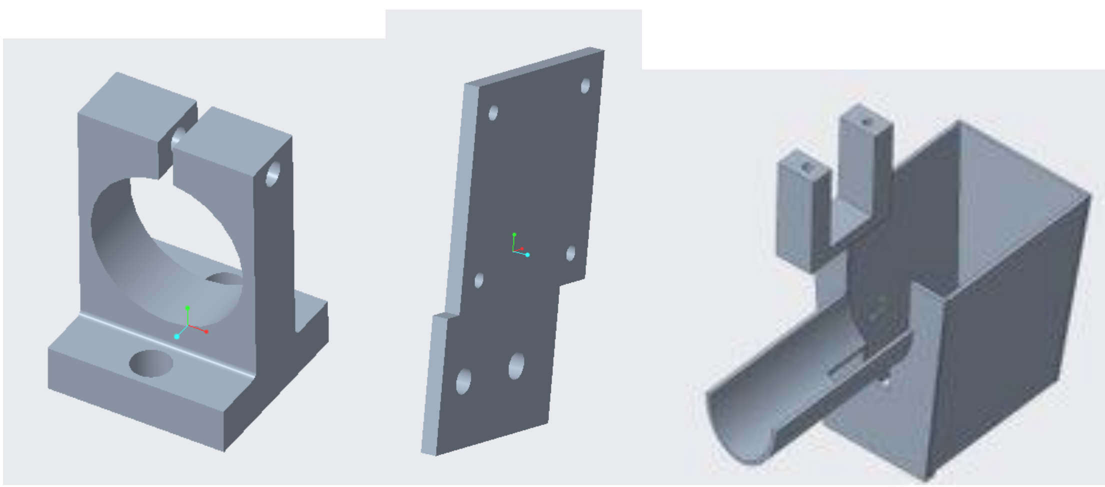


PCB Board with resistors Arduino Controller (1) Stepper Motor Driver (2)

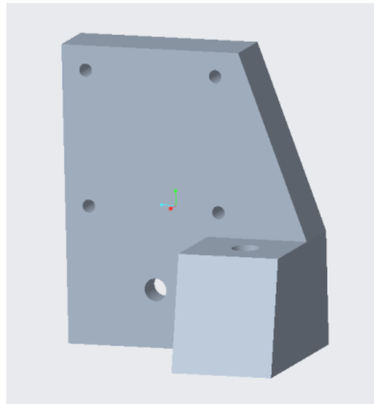



Battery Terminal Initial Wiring for Chain placement

Figure H.1.9 Electrical Thumbnails

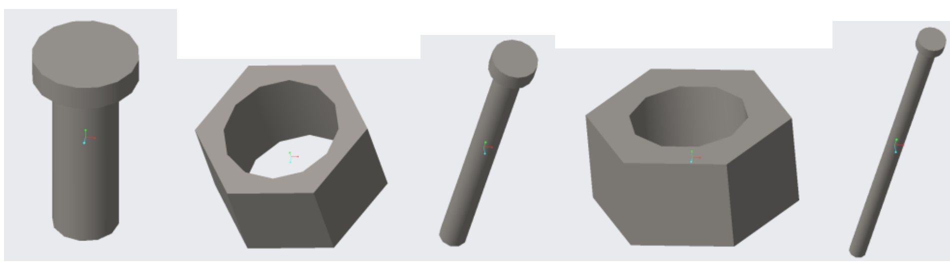


Lead Screw Reciever Stat Motor Backplate Camera Holder Assembly

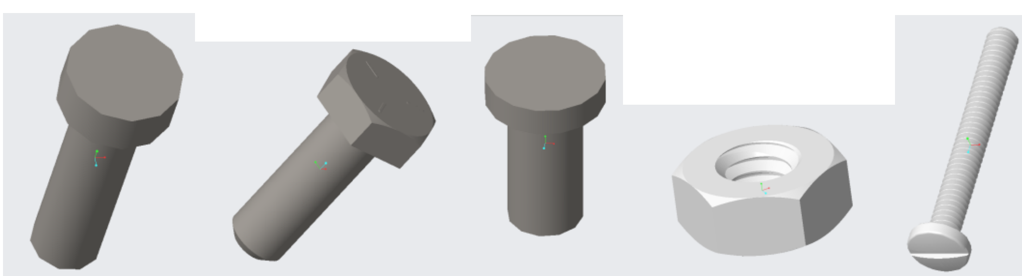


Moving Motor Backplate

Figure H.1.10 3D Printed Parts Thumbnails



M5 bolt M5 nut long M3 bolt M3 nut M2 bolt



M3 Socket screw M3 Bolt M2 Socket Screw M2 Nut M2 Bolt

Figure H.1.11 Misc Screws/Bolts/Nuts Thumbnails

H.2 ELECTRONICS AND SOFTWARE

This section will explain what electrical components will be used along with their purpose, and the software needed to implement them. Circuit diagrams will be provided to explain how all the components will be wired, and flowcharts are shown to explain the sequence of actions the product will take in order to take thermal images of the hotspots and compare them to thermal maps of existing semiconductors.

Several electrical components were selected for the final product. All devices will be controlled by the microcontroller Arduino Uno and powered by a 12V and 5V battery. To move the 2D axis system, 3 bipolar DC brushless stepper motors will be used along with h-bridges. The stepper motors take in electrical signals and translate them into one-step movements, the direction of these movements (rotations) is driven by the h-bridge (see Figure H.2.1). Moreover, prototype (PCB) boards with soldered on surface mount resistors (SMD) will be used for testing purposes, to mimic that hotspot (instead of using a real semiconductor). The PCB board will be connected to relays (see Figure H.2.2), which are programmable electrical switches that are also meant to protect the Arduino from the high currents that will flow through the network of SMDs on the PCB board (see Figure H.2.3). The following images show how all these components will be wired separately:

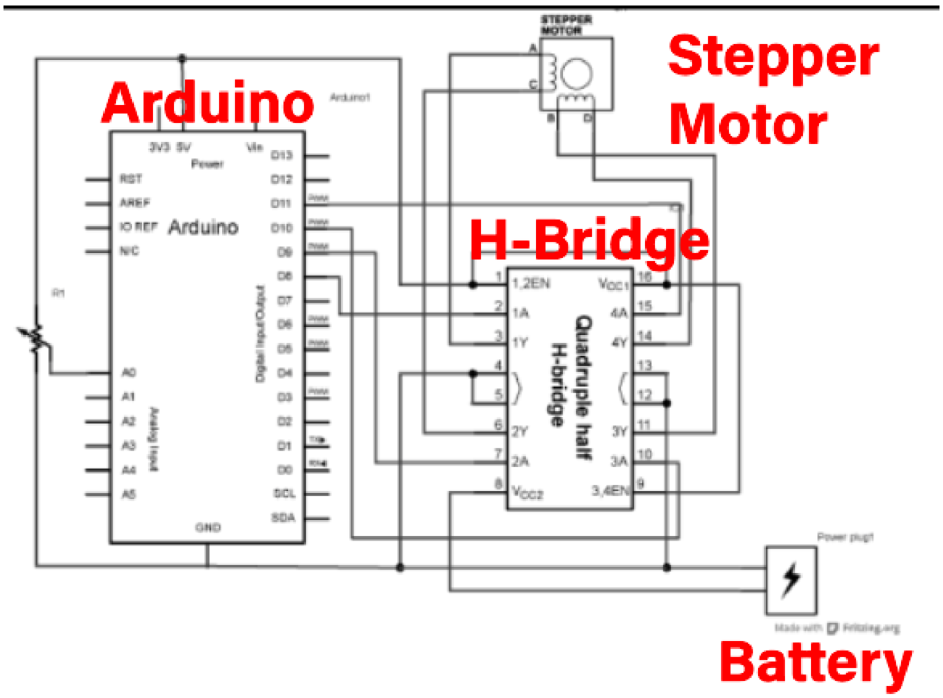


Figure H.2.1 Arduino + H-Bridge + Stepper Motor Circuit Diagram

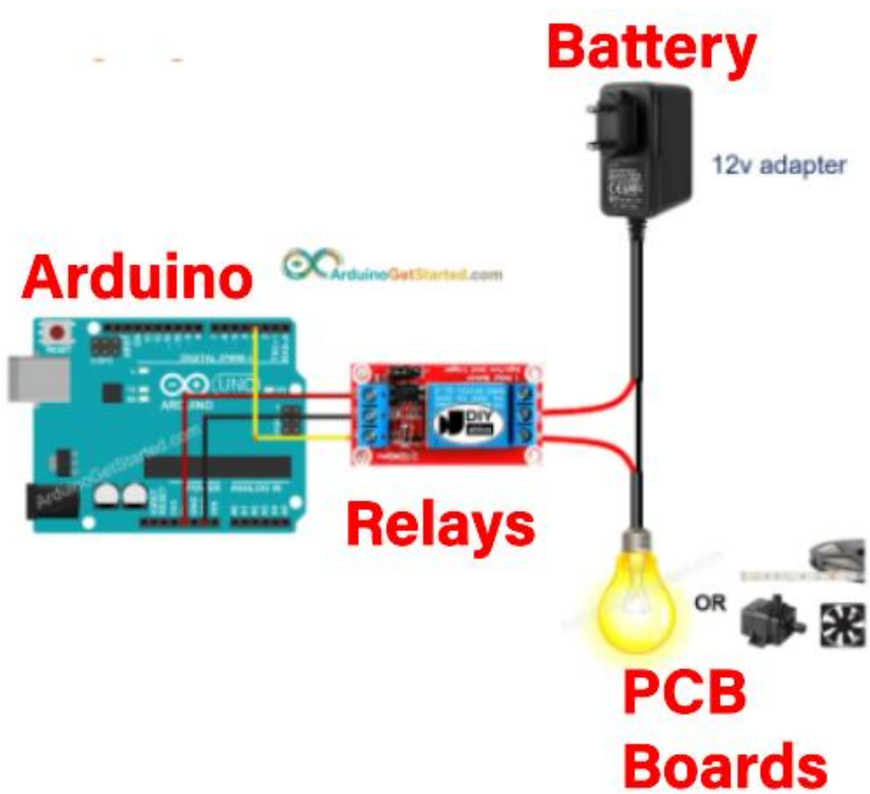


Figure H.2.2 Arduino + Relay + PCB Boards Circuit Diagram

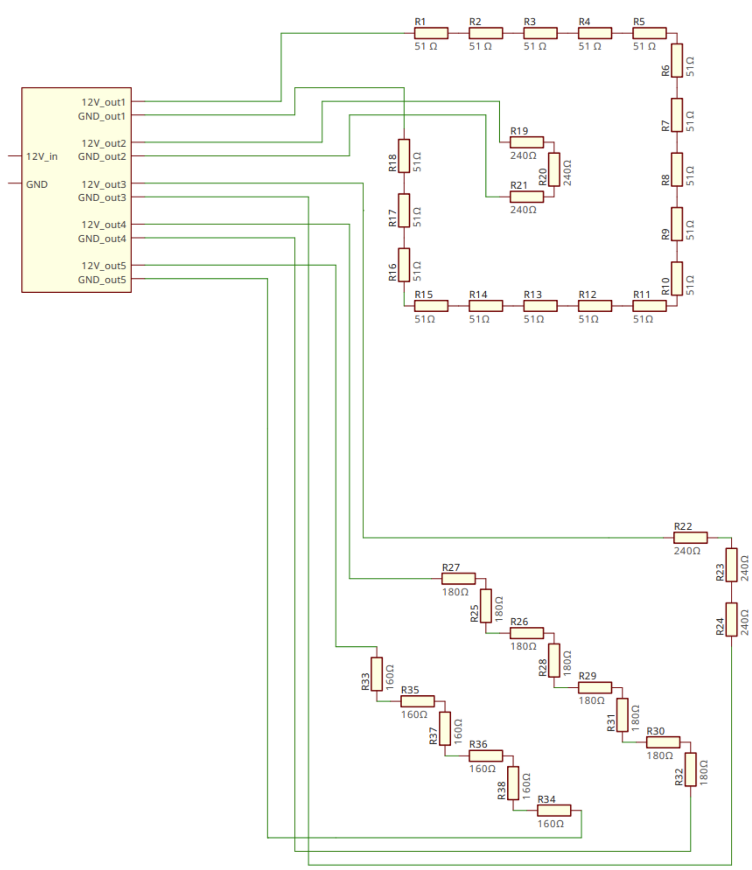


Figure H.2.3 Circuit diagram of SMD network to be placed on PCB boards for testing

All the separate circuits above, can be connected and are shown in the following full wire diagram:

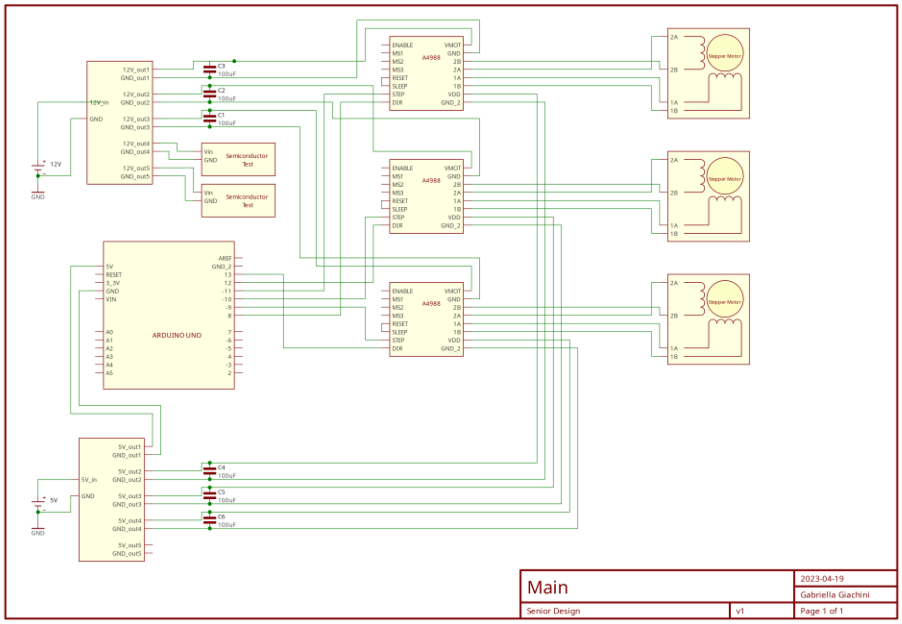


Figure H.2.4 Circuit diagram of SMD network on three PCB boards

The final product relies on several programs: the first controls the movement system, the second connects to the camera to snap and process a picture, and finally, the third performs heat and mass transfer calculations to obtain the heat flux map. For ease of explanation, a flowchart was generated (Figures H.2.5 – H.2.6).

Figure H.2.5 Flowchart Key

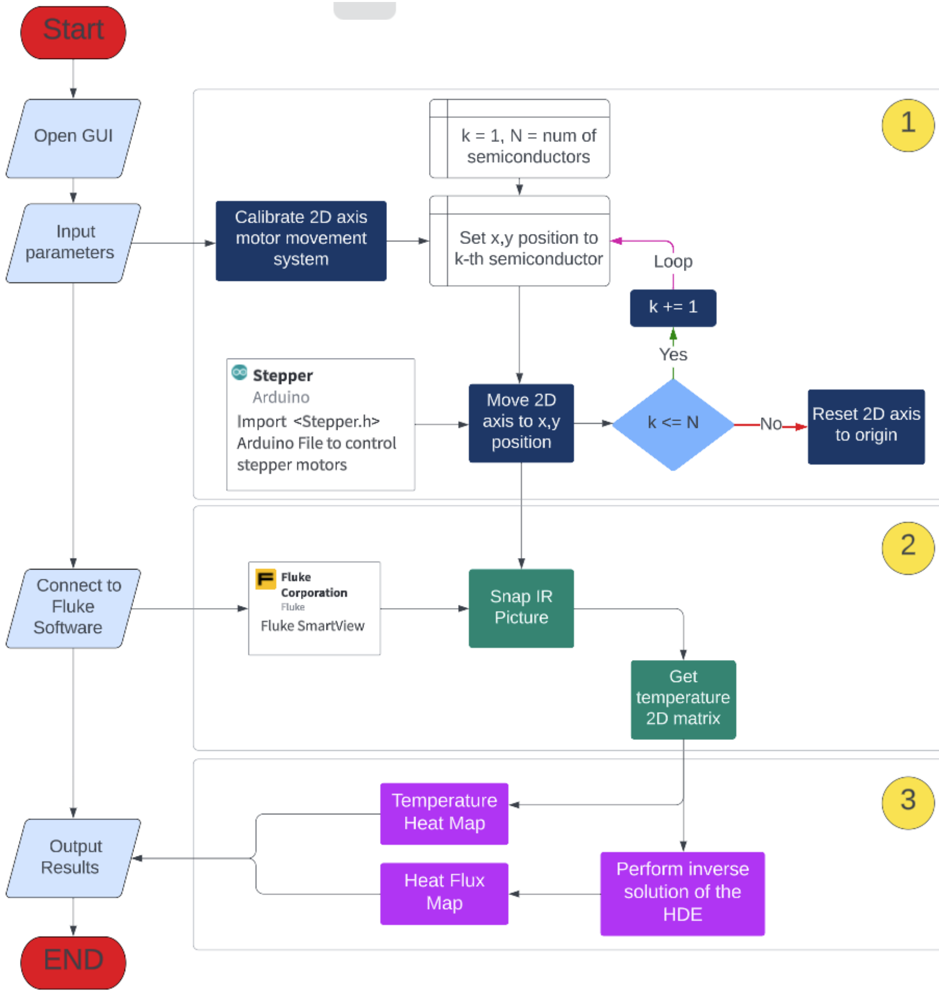


Figure H.2.6 Flowchart

Figure H.2.6 shows the entire code process from opening the GUI to obtaining temperature and heat flux maps as results. Everything is controlled by the GUI: initially, the user inputs the number of samples to be tested, their location in the imaginary grid, and the current location of the camera. This initiates the movement system, and at the end, outputs the temperature and heat flux map for each semiconductor sample tested.

The flowchart has three main parts, led by the steps on the left side of the flowchart. The first is the moving mechanism algorithm. Everything is turned on and the 2D axis movement system is calibrated (the camera must be at the origin of the imaginary grid). A loop will be started, this will update the location of the camera to be on a semiconductor for 12 seconds. This idle time is left for the camera to capture the IR image, which is the second part. In here, initially the camera is connected to Fluke SmartView. Then, 12 seconds are given for the system to send a signal to another code that will snap a picture using Fluke SmartView. This image will be saved in a specific location to be used by an additional Python code that will convert the IR image into a 2D grid of temperatures, each temperature will correspond to each pixel of the image. Finally, the third part will perform the inverse solution of the heat diffusion equation that will convert the 2D temperature grid into a 2D heat flux grid. This will give users two different results to look at, to compare with existing results and see how accurate the device is.

H.3 IR CAMERA SELECTION

The Fluke TiS20+ (Figure H.3.1) was chosen given its availability through the Purdue Mechanical Engineering Department. The IR camera boasts commendable metrics considering its lower-end price-point of around $800-1000; specifically, the camera may sense changes in temperature at a level of 60 mK, has an instantaneous field of view of 7.6 mRad, and takes photos with 10,800 pixels (Figure H.3.2).

An important metrological consideration for a thermal camera is identifying the smallest distance that may be measured by a single pixel dimension. An equation from Flir calculates the IFOV in inches or mm using equation H.3.1 as 3.8608 mm per pixel. This means that the length of one pixel on an image corresponds to 3.8608 mm in length.

$$IFOV(inches) = IFOV\frac{(in\ mRad)}{1000} * Focal\ length\ (in\ inches)$$

Figure H.3.1: Fluke Thermal Imaging Camera TiS20+

Specifications

Key features	TiS20+/TiS20+ MAX
Infrared resolution	120 x 90 (10,800 pixels)
IFOV (spatial resolution)	7.6 mRad, D:S 130:1
Field of view	50° H x 38° V
Minimum focus distance	50cm (20 inches)
Focus system	Fixed focus
Data transfer	Mini USB used to transfer image to PC
Wireless connectivity	Yes, (802.11 b/g/n (2.4 GHz))
Fluke Connect instant upload	Yes, connect your camera to your building's WiFi network (802.11 b/g/n (2.4 GHz)), and images taken automatically upload to the Fluke Connect system or your local server for storage and viewing on your PC
Image quality	
Level and span	Smooth auto and manual scaling
IR-Fusion technology	AutoBlend continuous 0 % to 100 %. Adds the context of the visible details to your infrared image
Display	3.5" LCD touchscreen (landscape)
Display resolution	320 x 240 LCD
Thermal sensitivity (NETD)	60 mK
Frame rate	9 Hz
Data storage and image capture	
Memory	Internal 4GB memory (includes slot for optional micro SD card up to 32GB)
Image capture, review, save mechanism	One-handed image capture, review, and save capability
Image file formats	Non-radiometric (jpeg), or fully radiometric (.is2); no analysis software required for non-radiometric (jpeg) files
Software	Fluke Connect desktop software—full analysis and reporting software with access to the Fluke Connect system
Export file formats with software	.bmp, .dib, .jpg, .tif, .tiff
Battery	
Batteries (field-replaceable, rechargable)	Lithium ion smart battery pack with five-segment LED display to show charge level
Battery life	≥ 5 hours continuous (without WiFi)
Battery charging time	2.5 hours to full charge
Battery charging system	In-imager charging. Optional 12 V automotive charging adapter
AC operation	AC operation with included power supply (100 V AC to 240 V AC, 50/60 Hz)
Power saving	Automatic Shutdown: 5, 10, 15 and 20 minutes or never
Temperature measurement	
Temperature measurement range (not calibrated below 0 °C)	TiS20+: -20 °C to 150 °C (-4 °F to 302 °F) TiS20+ MAX: -20 °C to 400°C (-4°F to 752 °F)
Accuracy	Target temp at or over 0 °C: Accuracy: ± 2 °C or ± 2 % at 25 °C, whichever is the greater.
On-screen emissivity correction	Yes, material table
On-screen reflected background temperature compensation	Yes
Center-point temperature	Yes
Spot temperature	Hot and cold spot markers

Specifications *continued*

Key features	TiS20+/TiS20+ MAX
Color palettes	
Standard palettes	6: Ironbow, Blue-Red, High Contrast, Amber, Hot Metal, Grayscale
General specifications	
Infrared spectral band	8 µm to 14 µm (long wave)
Operating temperature	-10 °C to 50 °C (14 °F to 122 °F)
Storage temperature	-40 °C to 70 °C (-40 °F to 158 °F)
Relative humidity	95 % non-condensing
Safety	IEC 61010-1: Pollution Degree 2
Electromagnetic compatibility	EN 61326-1, CISPR 11: Group 1, Class A
US FCC	CFR, Part 15C
Vibration and shock	10 Hz to 150 Hz, 0.15 mm, IEC 60068-2-6; 30 g, 11 ms, IEC 60068-2-27
Drop	Engineered to withstand 2 meter drop
Size (H x W x L)	26.7 cm x 10.1 cm x 14.5 cm (10.5 in x 4.0 in x 5.7 in)
Weight	0.72 kg (1.6 lb)
Enclosure rating	IP54 (protected against dust, limited ingress; protection against water spray from all directions)
Warranty	Two-years (standard)
Supported languages	Czech, Dutch, English, Finnish, French, German, Hungarian, Italian, Japanese, Korean, Polish, Portuguese, Russian, Simplified Chinese, Spanish, Swedish, Traditional Chinese, and Turkish

Figure H.3.2: Fluke Thermal Imager 20+ Datasheet

I. Analysis

The parts that most needed to be analyzed were the 3D printed custom connectors. The main superstructure is composed of 80/20 segments whose strength far exceeds the loads to be put on the superstructure. The weight of the camera is only 1.6 lbs and the maximum force while moving/stopping is estimated at an impulse of 4 times that or 6.4 lbf. The boundary conditions used in the analysis are depicted below in section 2 of Figure 1, with both ends secured with a concentrated force in the exact middle. This was chosen as this is how each of the crossbeams will be secured in the final design, and leaves a safety factor for the superstructure of 2395, meaning the structure is far stronger than is necessary for daily operation. More interesting however, is the safety scenario of someone falling onto the superstructure whether during operation or in storage. In this case, with a weight of 200 lbs applied as a centered load, the factor of safety is only 76.6, proving the superstructure can withstand even the momentary safety risk of someone falling on it without collapsing and damaging the camera or potentially shorting the electrical board.

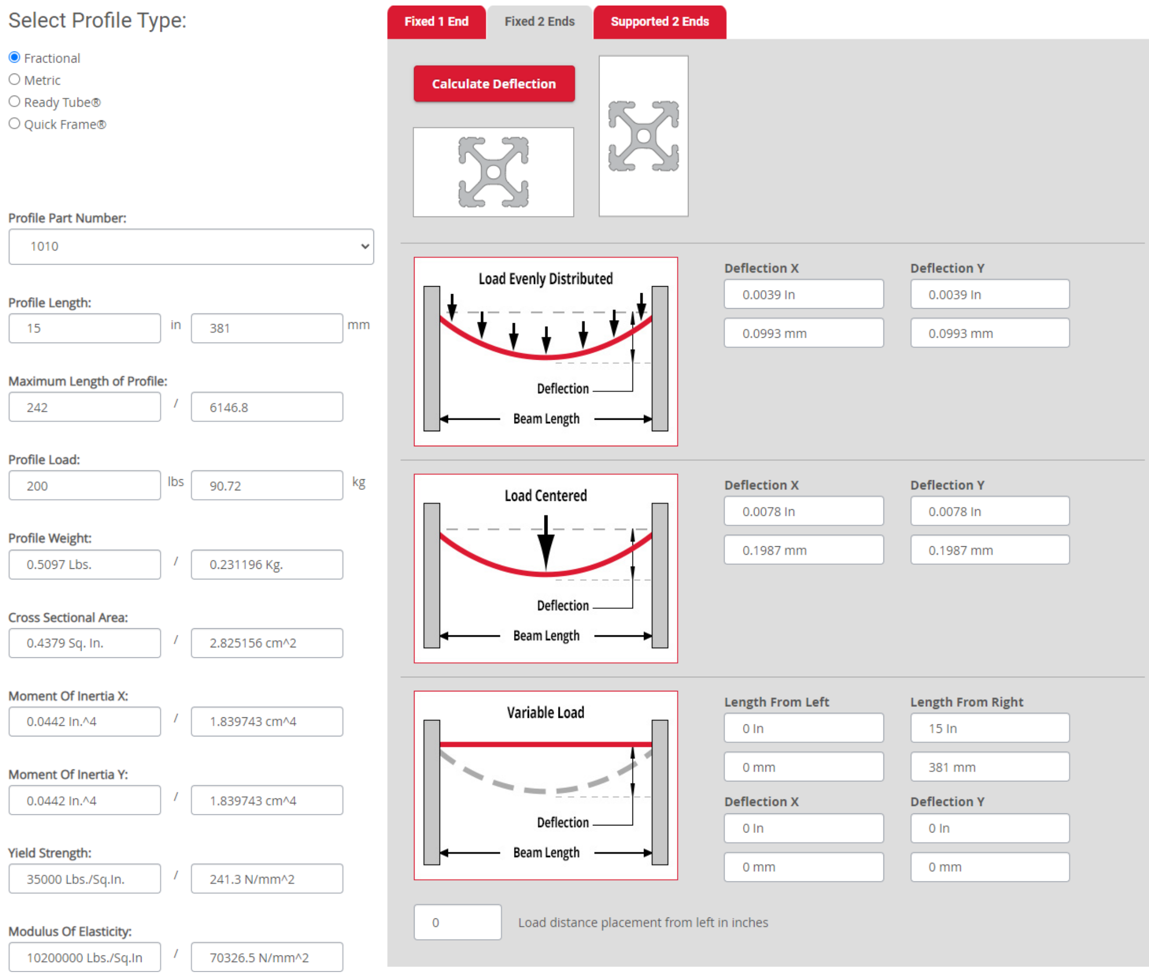


Figure I.2.1: Official 80/20 Deflection Calculator

Instead, the parts that are most at risk are the 3D-printed connectors between the 80/20 and the drive screws. The FEA analysis run on these connectors was done inside Inspire as can be seen in Figures I.2.3-I.2.5. For the setup of the FEA analyses a force of 12.5 kilograms was used because that is the maximum force that the stepper motors the team is using are capable of outputting. This force is centered on the cross section that the motor will occupy as can be seen by the red arrow in the center of the orange section depicted in Figure I.2.2. The mounting plate is further secured with fix constraints centered on the lower holes, as these will be where the screws will be used in the final design to attach the motor to the superstructure. Also pictured below in Figure I.2.2 are the hand calculations run to validate the FEA software, with Figure I.2.3 showing the FEA results. The hand-calculated value of 3.07 is slightly higher than the FEA calculation, but this can be accounted for by the assumptions made for the hand calculations, namely the additional material as the plate was estimated as a rectangle with the given outside dimensions.

Variables:

$I_{yy} = 1.214\ in^4$

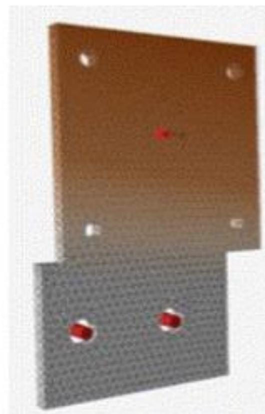
$c = \frac{t}{2} = 0.0625\ in$

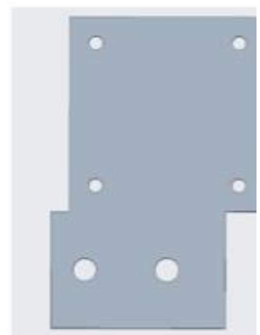
$M_y = 25\ kgf\ - in$

$Form\ Factor\ (FF,\ wear) = 1.33$

$Hole\ Factor\ (HF) = 100$

$Strength\ PLA = 526.3\ in^2$





Calculation:

$$\boldsymbol{F_b} = \frac{(M_y * c)}{I_{yy}} = \frac{25 * 0.0625}{1.215} = \mathbf{1.286}\ \frac{\boldsymbol{kgf}}{\boldsymbol{in^2}}$$

$$\boldsymbol{FOS} = \frac{S_{PLA}}{FF * F_b * HF} = \frac{526.3}{1.33 * 100 * 1.286} = \mathbf{3.07}$$

Figure I.2.2: Hand Calculations for Motor Mount

Figure I.2.3: Inspire FEA Analysis of Motor Mount Plate Using Factor of Safety and Displacement

On the lead screw receiver, four roller constraints were used because the lead screw receiver is attached to the superstructure in a way that allows for it to slide in the direction that the force is applied. On the motor mount analysis two fixed constraints were used on the two holes where the mount attaches to the superstructure. These constraints represent the bolts that will be used to fasten the mount in place. Finally, in the motor mount plate analysis, two more fixed constraints were used where the plate will connect to the superstructure. Like with the motor mount these fixed constraints mimic the fasteners that will be used when attaching the piece to the superstructure.

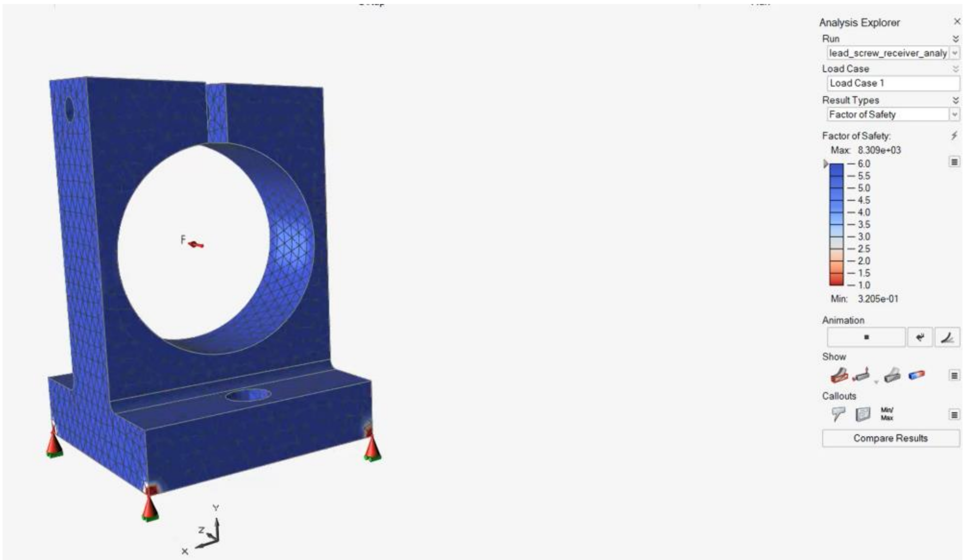
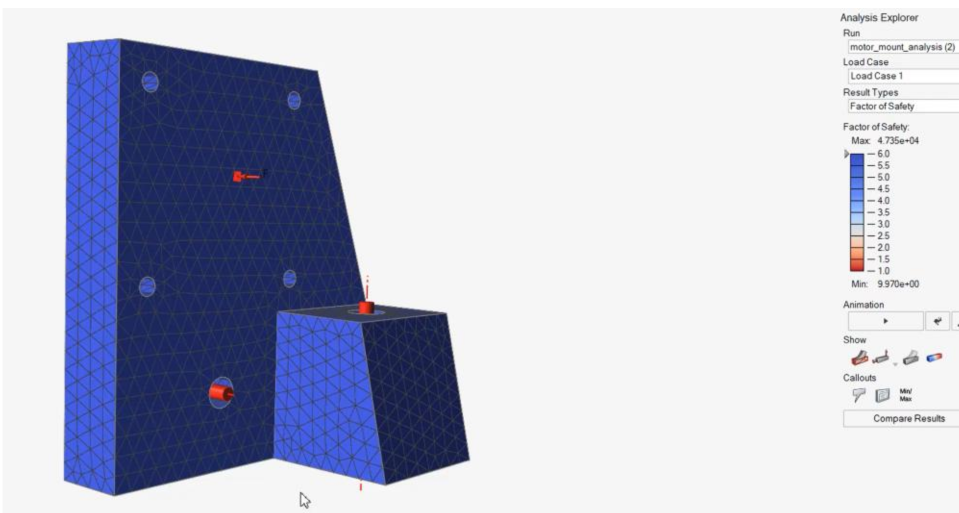


Figure I.2.3: Inspire FEA Analysis of Lead Screw Receiver Using Factor of Safety



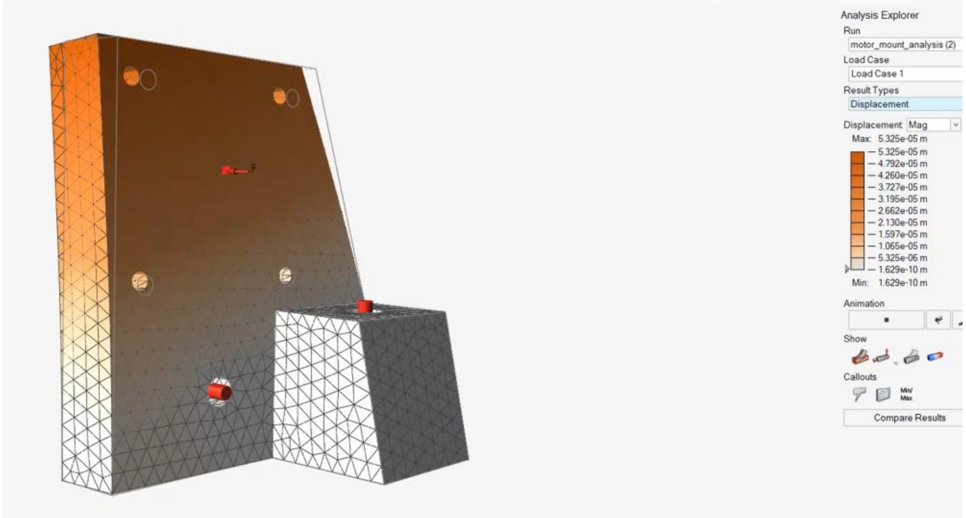


Figure I.2.4: Inspire FEA Analysis of Motor Mount Using Factor of Safety and Displacement

From the analysis of the lead screw receiver, there is a maximum factor of safety of $8.309 \cdot 10^3$ and a minimum factor of safety of 3.205. This factor of safety leads the team to believe that the lead screw receiver will be more than capable of withstanding the force from the motors as well as be able to withstand infinite life. Furthermore, the analysis of the motor mount revealed a maximum factor of safety of $4.735 \cdot 10^4$ and a minimum factor of safety of 9.970 as well as a displacement of only 5µm. This leads the team to be confident that the motor mount will also be able to withstand the forces from the motors and achieve infinite life. Finally, from the analysis of the motor mount plate, a maximum factor of safety of $2.043 \cdot 10^4$ is achieved and a minimum factor of safety of 1.654 is achieved. Next, from the displacement analysis of it, a maximum displacement of only 2 µm was found. The impact of these analyses on the final design is a better understanding that the entire structure is durable enough to routine operation, as can be seen from the high factors of safety and small displacements referenced above. This is ideal as it was the original end goal of the team's design for durability and maintenance.

I.3 Preliminary Prototype

Figure I.3.1 Preliminary Prototype Photo

The main lessons learned were a practical look at how the structural components are being fastened and how the motors are being attached to the structure. Attempting to make everything fit using duct tape and PVC pipe was a reminder of how complex the assembly was and how important it was to use the nuts and bolts exactly where they were planned minimize mistakes. The second half of the assembly tips picked up were the importance of properly securing the motors. These will be the basis of the movement of the design and proper brackets will be essential to ensure there is no slipping or bending resulting in unintended movement. Finally, the importance of camera focal length was fully realized as it became apparent that the combination of camera hanging down from the camera mount with the further elevation of the upper electrical board and components meant the exact height the camera would be taking its images from would be slightly more complicated to calculate than originally thought. Even so, none of these revelations proved to be difficult issues to overcome, but merely drew attention to some of the more obscure but critical components of the design and ensure they were kept in mind throughout assembly.

J. FMEA

The FMEA, housed in “SCS_Solutions_FMEA.xslx,” has been re-completed since CDR to document the past and current issues for the FDR phase. Of note, since these risks were developed after CDR, they pertain mostly to the prototyping, testing, and validation stages of the prototype. There are 11 risks analyzed which touch on primary aspects of the prototype design including the “2D Movement System,” the “Hot Spot Simulation Mechanism,” the “Electrical Operation of the Device,” the “IR Camera,” and finally the “Superstructure”.

The risks are ranked according to “Severity,” “Occurrence,” and “Detection”. “Severity” scales, from 1-10, with emphasis on the potential risk to prototype operability, an increased budget, and an increased time sink where 1 is low likelihood of each and 10 is high likelihood of each. “Occurrence” quantifies, from 1-10, the likelihood of the risk occurring; an increment of 1 represents a 10% higher likelihood of occurrence. “Detection” quantifies the likelihood of the problem being detected where 0 represents 100% detection rate and 10 represents 0% detection rate.

After preliminary analysis, 6 out of the 11 risks exceeded the groups collective standard for of a 50 maximum point value for Risk Priority Number (RPN); the tests exceeding the limit are (#1) “Stepper Motors Burning out due to High Load,” (#3) “3D Printed Components fail due to shear …,” (#4) “circuit boards short circuit,” (#5) “circuit boards receive too much current,” (#6) “wiring, relays, control components short circuit,” and (#7) “improper relay actuation provides power to components when not supposed to.” Associated scores are 56, 162, 56, 126, 192, and 72. Mitigations to these risks came in the form of leveraging outside experts (namely the E-shop and Mike Sherwood) to double check wiring for the electrical and control components specifically for tests 4, 5, 6, 7, having more than one team member present for a test was made mandatory for all tests, and double checking the set up before running any test. These actions together decreased RPN score to become 14, 36, 10, 24, 28, and 8.

As a reflection on these identified risks post-validation phase, the predictions were largely correct. The main impediments experienced during assembly, iteration, and testing came in the form of the stepper motors not operating smoothly which a need for a third motor and the short circuiting of two electrical components – an Arduino Mega and a buck booster. The motor issue arose due to the underestimation of the friction existing on one end of the linear segment since the segment was actuated on its other end. Despite lubrication, this issue persisted until the addition of the third motor. The electrical events occurred despite checking circuits with the E-shop and Michael Sherwood and diligent double checking of electrical connections by team members. Nevertheless, the awareness and thought process for mitigating actions engendered through FMEA proved helpful when the team worked towards quickly remedying these issues as they arose. Namely, double checking wiring across multiple individuals ensured that more than one person was empowered to help diagnose electrical failures. Also, having more than one member present for tests enabled more robust and detailed data collection.

K. BOM and Sourcing Plan

Through the FDR stage, and the completion of the prototype, the team was able to further specify what was necessary for the building of SCS Solutions’ final product. The following figure shows the team’s final bill of materials. The team made a total of 5 parts, all of which were made with a 3D printer and bought a total of 37 parts which is 22 more than was projected to be purchased in the CDR stage 18 of the added purchased parts were for the superstructure while 4 were for the movement system. Once completed the bill of materials consisted of 42 parts to make the completed project.

Bill Of Materials				
Item	Quantity	Used For	Make or Buy	Machine Used (Make parts only)
Camera Holster	1	Hot Spot Detection	Make	3D Printer
Motor Mount Wide Plate	1	Movement System	Make	3D Printer
Motor Mount Plate	1	Movement System	Make	3D Printer
Lead Screw Reciever	3	Movement System	Make	3D Printer
Corner Motor Mount	1	Movement System	Make	3D Printer
Stepper Motor	3	Movement System	Buy	
Stepper Driver	3	Movement System	Buy	
Ring tongue terminal	2	Building Superstructure	Buy	
PCB Boards	9	Hot Spot Simulation	Buy	
M6 Slide in Tnut	6	Building Superstructure	Buy	
M6 L16 round head hex screw	9	Building Superstructure	Buy	
M5 Slide in Economy Tnut	5	Building Superstructure	Buy	
M5 nut	13	Building Superstructure	Buy	
M5 L14 socket cap screw	13	Building Superstructure	Buy	
M5 L10 round head hex screw	4	Building Superstructure	Buy	
M3 nut	45	Building Superstructure	Buy	
M3 L60 socket cap screw	12	Building Superstructure	Buy	
M3 L30 round head hex screw	12	Building Superstructure	Buy	
M3 L16 round head screw	2	Building Superstructure	Buy	
M3 L10 socket cap screw	4	Building Superstructure	Buy	
M2 nut	12	Building Superstructure	Buy	
M2 L10 socket cap screw	8	Building Superstructure	Buy	
Chip Resistors	216	Hot Spot Simulation	Buy	
Cable Raceway	1	Cable Management	Buy	
Angle Iron raceway	1	Cable Management	Buy	
Acryllic Sheets	2	Building Superstructure	Buy	
608-2RS Ball Bearings	3	Movement System	Buy	
5V 8 Channel Relay	1	Hot Spot Simulation	Buy	
18mm 10 Series Corner Bracket	8	Building Superstructure	Buy	
12V Battery	1	Hot Spot Simulation	Buy	
1010 Series Hidden Connectors	8	Building Superstructure	Buy	
1010 Anchor	7	Building Superstructure	Buy	
10 Series Bolt Assembly	8	Building Superstructure	Buy	
10 Series 3 Slot Mount	3	Movement System	Buy	
1/4-20 nut	3	Building Superstructure	Buy	
1/4-20 L3/4 round head hex screw	2	Building Superstructure	Buy	
1/4-20 L2 pan head bolt	1	Building Superstructure	Buy	
Buckbooster	1	Hot Spot Simulation	Buy	
Wires	2ft	Simulating Hotspot	Buy	
M5 Slide in Tnut	9	Building Superstructure	Buy	
3in Aluminunum Extrusion	1	Building Superstructure	Buy	
30in Aluminum Extrusion	4	Building Superstructure	Buy	
17in Aluminum Extrusion	1	Building Superstructure	Buy	
15in Aluminum Extrusion	4	Building Superstructure	Buy	
13in Aluminum Extrusion	4	Building Superstructure	Buy	

Figure K.1: Bill of Materials

Furthermore, the following figure shows the team's sourcing plan showing where the team sourced all the materials they used.

Sourcing Plan	
Item	Vendor
Camera Holster	Made Part
Motor Mount Wide Plate	Made Part
Motor Mount Plate	Made Part
Lead Screw Reciever	Made Part
Corner Motor Mount	Made Part
Stepper Motor	Amazon
Stepper Driver	Amazon
Ring tongue terminal	Amazon
PCB Boards	Amazon
M6 Slide in Tnut	80/20
M6 L16 round head hex screw	McMaster Carr
M5 Slide in Economy Tnut	80/20
M5 nut	McMaster Carr
M5 L14 socket cap screw	McMaster Carr
M5 L10 round head hex screw	McMaster Carr
M3 nut	McMaster Carr
M3 L60 socket cap screw	McMaster Carr
M3 L30 round head hex screw	McMaster Carr
M3 L16 round head screw	McMaster Carr
M3 L10 socket cap screw	McMaster Carr
M2 nut	McMaster Carr
M2 L10 socket cap screw	McMaster Carr
Chip Resistors	Amazon
Cable Raceway	Amazon
Angle Iron raceway	80/20
Acryllic Sheets	Amazon
608-2RS Ball Bearings	McMaster Carr
5V 8 Channel Relay	Amazon
18mm 10 Series Corner Bracket	80/20
12V Battery	Amazon
1010 Series Hidden Connectors	Amazon
1010 Anchor	80/20
10 Series Bolt Assembly	80/20
10 Series 3 Slot Mount	80/20
1/4-20 nut	McMaster Carr
1/4-20 L3/4 round head hex screw	McMaster Carr
1/4-20 L2 pan head bolt	McMaster Carr
Buckbooster	Amazon
Wires	Amazon
M5 Slide in Tnut	80/20
3in Aluminunum Extrusion	80/20
30in Aluminum Extrusion	80/20
17in Aluminum Extrusion	80/20
15in Aluminum Extrusion	80/20
13in Aluminum Extrusion	80/20

Figure K.2: SCS Solutions Sourcing Plan

K.2 Manufacturing Drawings

The manufacturing drawing below in Figure K.3 shows a simple breakdown of the original 2-axis plans. While the core concept remains the same, once the 3rd motor is added and camera system integrated into the design, Figure K.4 depicts the final design as seen in the final prototype.

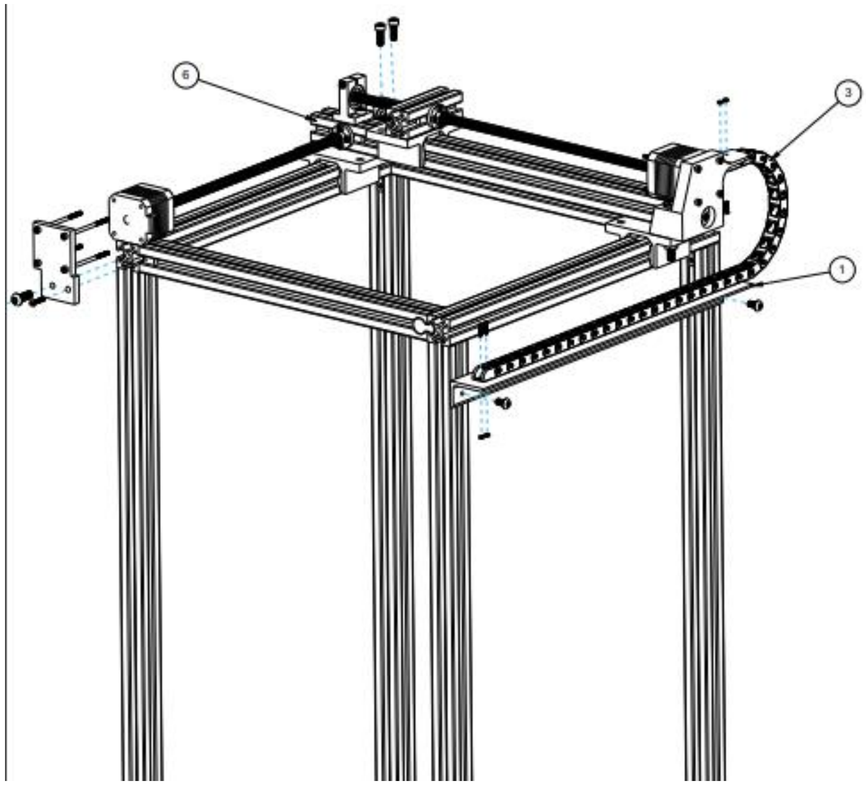


Figure K.3 Original Assembly Drawing

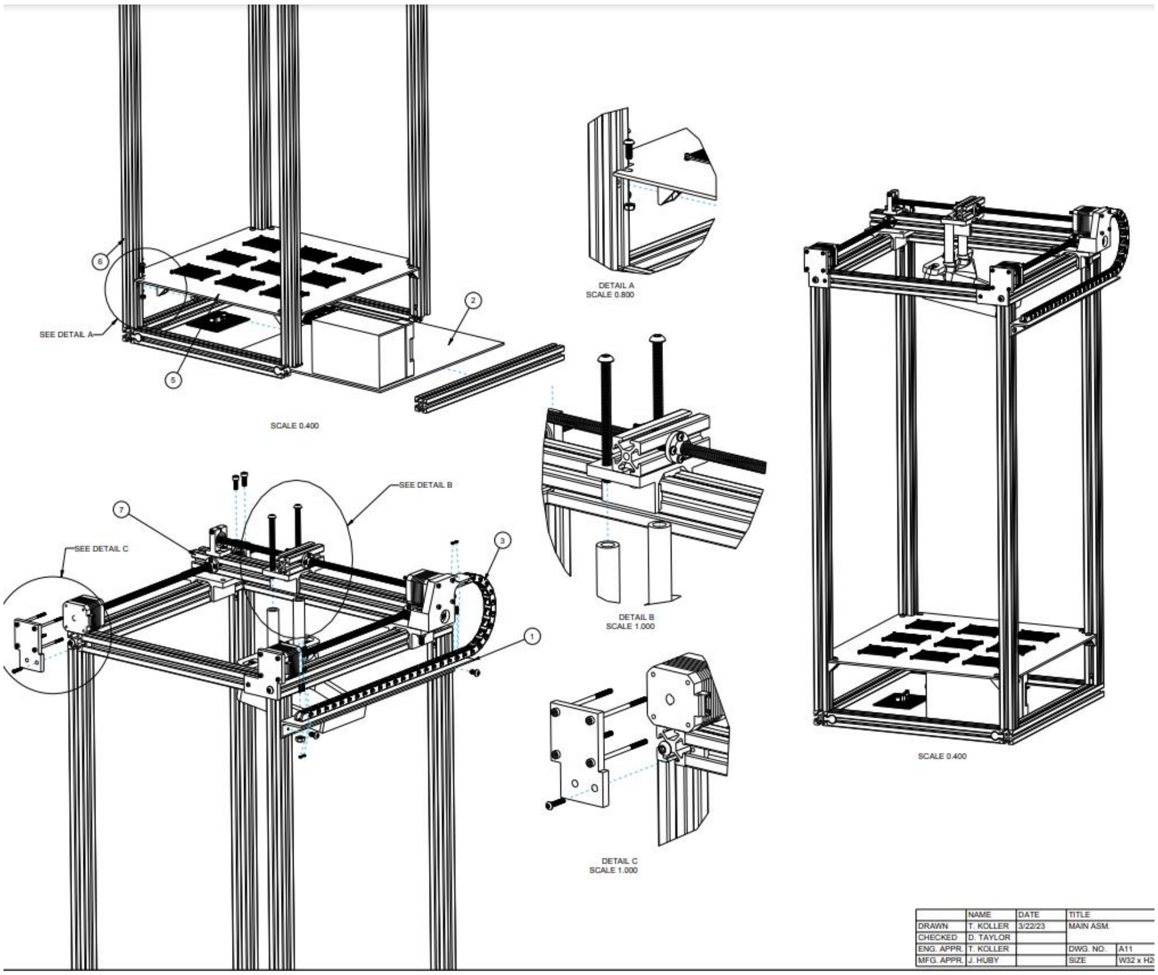
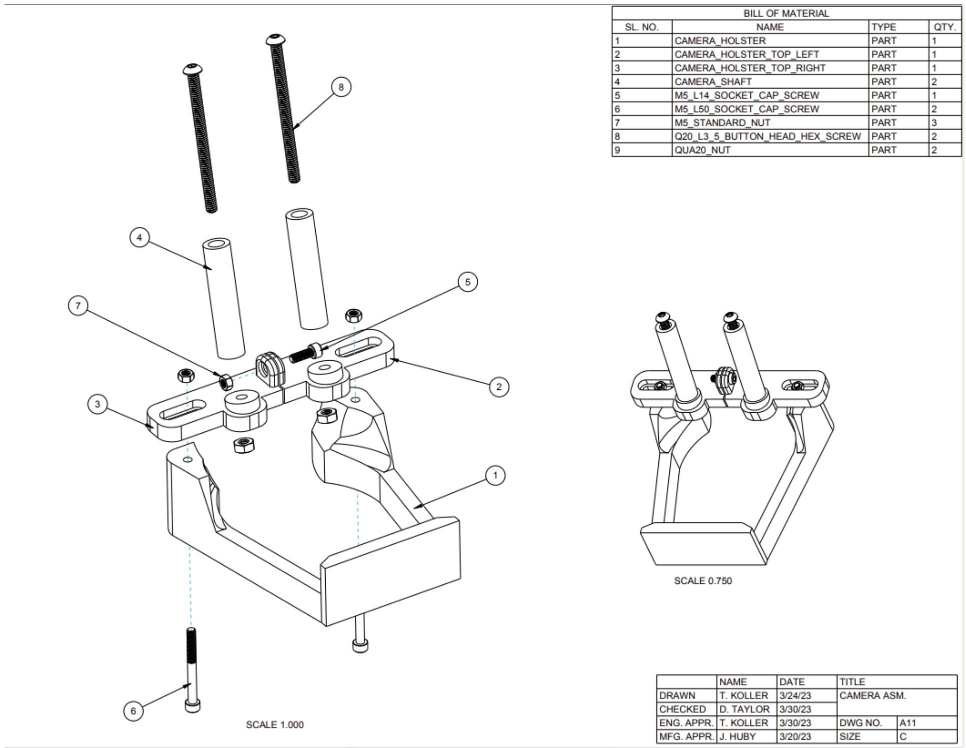


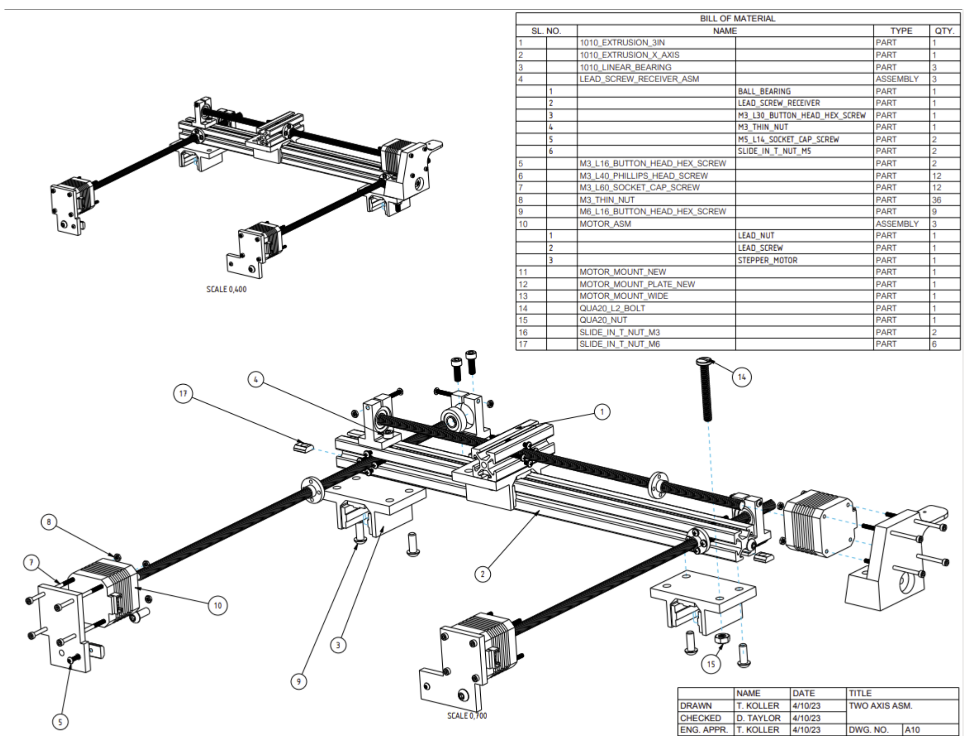
Figure K.4 Updated Assembly Drawing

Delving further into the assembly drawings, the team would specifically like to highlight the IR camera mount, two-axis movement system, the superstructure, and the individual 80/20 components. The camera mount shown below is made from a PLA filament and is constructed using additive manufacturing from a 3D printer. Two screws connect the mount and the two-axis movement system via the linear movement actuator. The motors drive around the mount over the top of the prototype. All this movement is supported by an 80/20 superstructure that is in the shape of a simple rectangular prism. The assembly drawings for each of these are shown below in figure K.5.



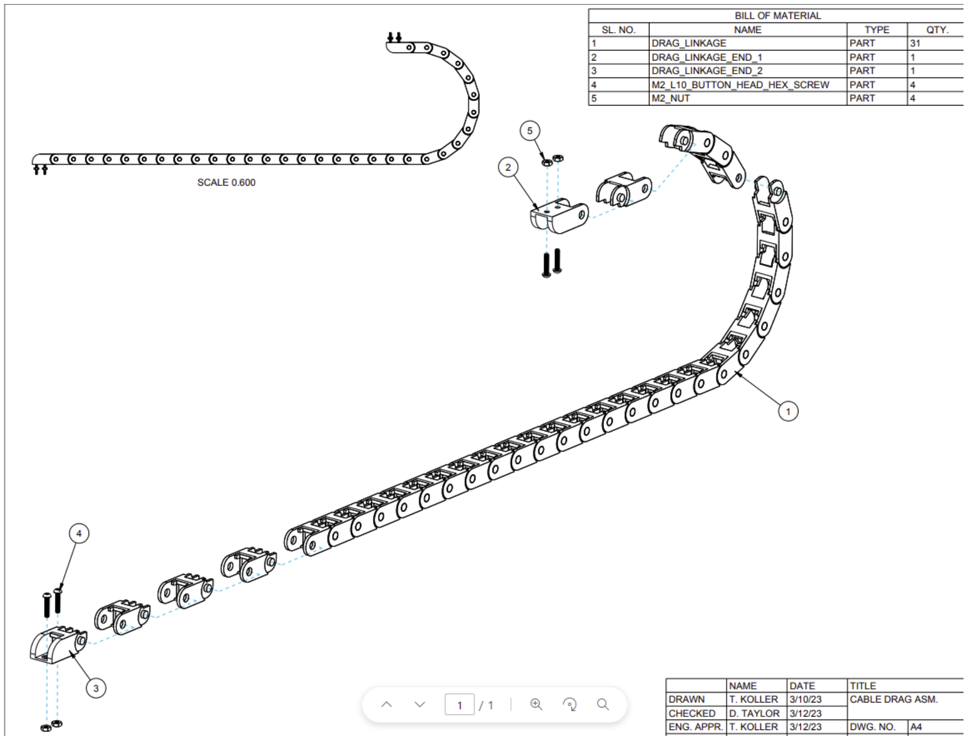
BILL OF MATERIAL			
SL. NO.	NAME	TYPE	QTY.
1	CAMERA_HOLSTER	PART	1
2	CAMERA_HOLSTER_TOP_LEFT	PART	1
3	CAMERA_HOLSTER_TOP_RIGHT	PART	1
4	CAMERA_SHAFT	PART	2
5	M5_L14_SOCKET_CAP_SCREW	PART	1
6	M5_L50_SOCKET_CAP_SCREW	PART	2
7	M5_STANDARD_NUT	PART	3
8	Q20_L3_5_BUTTON_HEAD_HEX_SCREW	PART	2
9	QUA20_NUT	PART	2

	NAME	DATE	TITLE	
DRAWN	T. KOLLER	3/24/23	CAMERA ASM.	
CHECKED	D. TAYLOR	3/30/23		
ENG. APPR.	T. KOLLER	3/30/23	DWG NO.	A11
MFG. APPR.	J. HUBY	3/20/23	SIZE	C



BILL OF MATERIAL					
SL. NO.		NAME		TYPE	QTY.
1		1010_EXTRUSION_3IN		PART	1
2		1010_EXTRUSION_X_AXIS		PART	1
3		1010_LINEAR_BEARING		PART	3
4		LEAD_SCREW_RECEIVER_ASM		ASSEMBLY	3
	1		BALL_BEARING	PART	1
	2		LEAD_SCREW_RECEIVER	PART	1
	3		M3_L30_BUTTON_HEAD_HEX_SCREW	PART	1
	4		M3_THIN_NUT	PART	1
	5		M5_L14_SOCKET_CAP_SCREW	PART	2
	6		SLIDE_IN_T_NUT_M5	PART	2
5		M3_L16_BUTTON_HEAD_HEX_SCREW		PART	2
6		M3_L40_PHILLIPS_HEAD_SCREW		PART	12
7		M3_L60_SOCKET_CAP_SCREW		PART	12
8		M3_THIN_NUT		PART	36
9		M6_L16_BUTTON_HEAD_HEX_SCREW		PART	9
10		MOTOR_ASM		ASSEMBLY	3
	1		LEAD_NUT	PART	1
	2		LEAD_SCREW	PART	1
	3		STEPPER_MOTOR	PART	1
11		MOTOR_MOUNT_NEW		PART	1
12		MOTOR_MOUNT_PLATE_NEW		PART	1
13		MOTOR_MOUNT_WIDE		PART	1
14		QUA20_L2_BOLT		PART	1
15		QUA20_NUT		PART	1
16		SLIDE_IN_T_NUT_M3		PART	2
17		SLIDE_IN_T_NUT_M6		PART	6

	NAME	DATE	TITLE	
DRAWN	T. KOLLER	4/10/23	TWO AXIS ASM.	
CHECKED	D. TAYLOR	4/10/23		
ENG. APPR.	T. KOLLER	4/10/23	DWG. NO.	A10



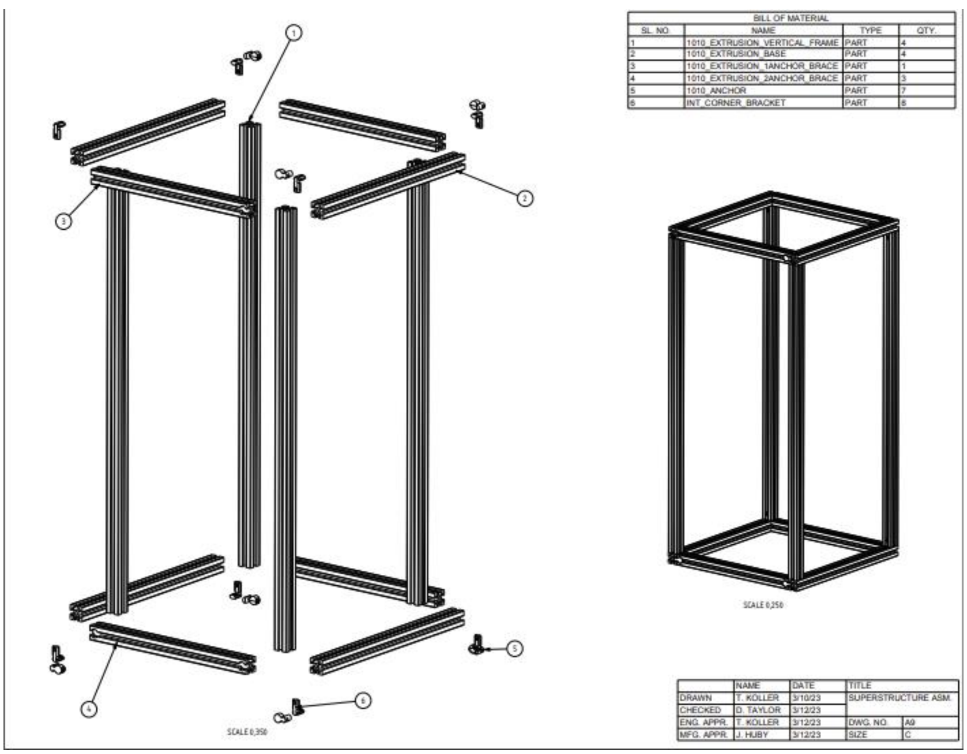
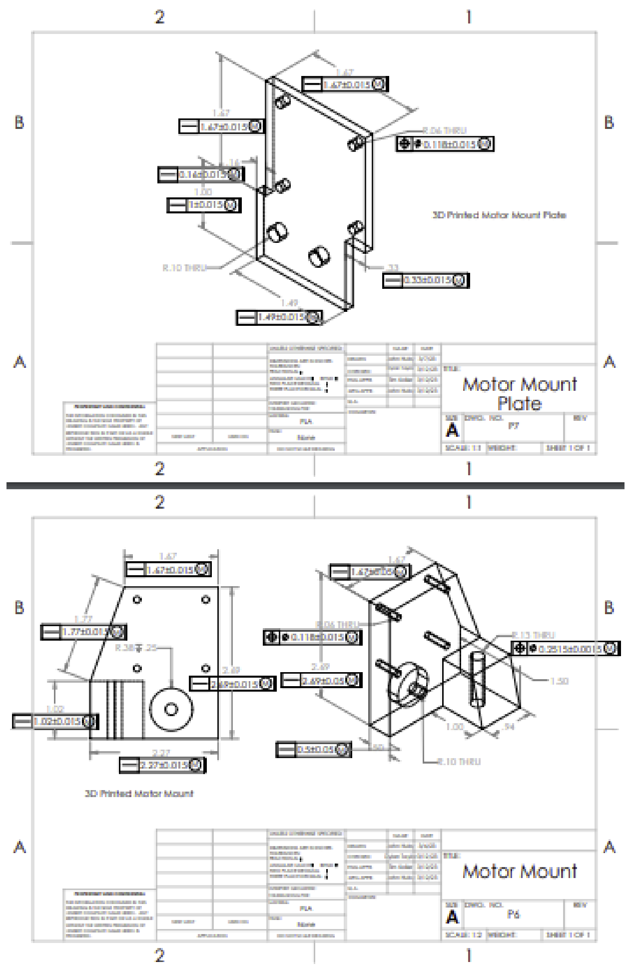


Figure K.5 Sub Assembly Drawings

There were no major changes made to the overall design philosophy throughout the FDR process. The key differences lie in the manufacturing drawings presented prior and those shown here is that these have two lead screw receiver holes. During the team's validation of the design, it became apparent that the device required two motors to actuate the camera in the x direction. These updated manufacturing sheets can be performed with the same operation sheet but needs to have a lead screw receiver hole on either end. The updated manufacturing sheets are shown below in figure K.6



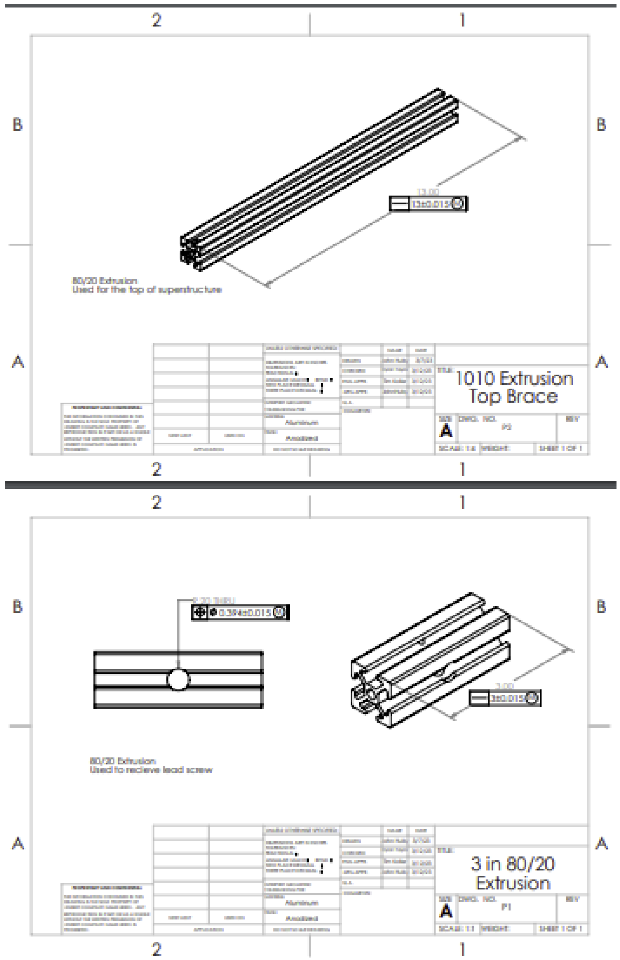


Figure K.6: Updated Manufacturing Drawings

Since the 80/20 components were cut to the correct length by the manufacturer, the team only had to perform two machining operations before assembly. First, the team had to create holes in the 80/20 components that would be used for the two-axis movement system. To facilitate this, the team created the operation sheet which is shown below in figure K.7.

Step	Operation	Description	Equipment	Notes
1	Center Drill	#0 Center Drill .05 Deep	Drill Press	S = 150 F = Hand
2	Drill	#30 Drill Thru Piece	Drill Press	S = 150 F = Hand
3	Ream	∅.395 Thru Piece	Drill Press	S = 100 F = Hand
4	Deburr	Deburr all Holes	Deburring Tool	F = Hand

Figure K.7: Operation Sheet for 80/20 components

In conjunction with the manufacturing drawings found in figure K.5, the team was able to efficiently manufacture each component of the two-axis movement system.

Furthermore, the team needed to laser cut an acrylic plate which would hold the PCB resistor boards so that the IR camera could efficiently photograph each. The operation for this laser cutting is shown below in figure K.8.

Step	Operation	Description	Equipment	Notes
1	Trace	Trace outline of acrylic	Laser Cutter	Vector = 40% Power = 100%
2	Cut	Cut Inner Holes	Laser Cutter	Vector = 40% Power = 100%
3	Cut	Cut Outline	Laser Cutter	Vector = 40% Power = 100%

Figure K.8: Operation Sheet for the acrylic sheet

L. Validation Plan

The initial validation test plan from CDR reflected a highly rudimentary testing regimen for the semiconductor hot spot identifier (Figure L.1).

Engineering Requirements	How to test?	Expected Results	Customer Requirement
Accuracy: Does device identify artificial hot spots	Perform Hot Spot identification te sts	Device identifies Hot Spots	Accuracy
Test Time: 30 seconds per test	Perform Hot Spot tests	Device will perform tests quickly	Low Test Time
Safety: No parts extend beyond frame	Visual inspection	Product is safe for a mass manufacturing environment	Safety
Maintenance: Device runs for 100,000 cycles	Perform a Goodman criteria test	Device will achieve "infinite life"	Durability

Figure L.1: CDR Validation Test Plan

An updated validation plan was designed to evaluate product performance against each engineering requirement excluding the cost requirement (Figure L.2). The plan includes the respective engineering requirement (column #2), the name of the test (column #3), the metric the test is designed to evaluate (column #4), the date of occurrence (column #5), the testing location (column #6), and finally which team members were responsible for completing the tests. Test numbers 1-3 deal specifically with the camera, associated image processing, and hot spot detection while test numbers 4-10 all evaluate the movement and superstructure systems.

Test Number	Engineering Requirement	Test Name	Metric	Test Date	Testing Location	Testing Parties
1	Accuracy – Temperature	Camera Temperature Accuracy	Difference in temperature between camera and thermocouple measurement of same sample (°C)	4/13/23	Pearl Labs 1	JH, ML
2	Resolution – Spatial	Camera Spatial Resolution	Pixel Size in terms of physical length (Pixel/mm)	4/13/23	Pearl Labs 1	JH, ML
3.a	Hot Spot Identification – Traversal System	Motor Encoding Validation	Average degree increment per 1 mm lateral movement	4/13/23	Pearl Labs 1	GG, TK
3.b	Hot Spot Identification - Simulator	Resistance, Voltage, and Current Validation	Ohms, Volts, Amps	4/13/23	Pearl Labs 1	GG, ML
3.c	Hot Spot Identification – Area	Hot Spot Identification by Area	Percentage of hot spot areas detected	4/13/23	Pearl Labs 1	JH, ML
4	Safety – Electrical Subcomponent	Isolated power supply for Arduino and Relays	Amps	4/13/23	Pearl Labs 1	GG, ML
5	Safety – Electrical Assembly	Wiring Implementation	Amps	4/14/23	Pearl Labs 1	GG, ML
6	Safety – Mechanical	IR Camera within bounds	cm (length of extrusion outside the Superstructure)	4/14/23	Pearl Labs 1	JH, POB
7	Safety – Fixed Components	Loose component test	Number of free hanging components	4/14/23	Pearl Labs 1	JH, POB
8	Test Time	Average Time to Test 9 Samples	Average time required to test 9 consecutive grid-arrayed samples	4/14/23	Pearl Labs 1	DT, GG
9	Ease of Operation	Average required human interaction per test run	Average number of individual human inputs needed to complete a test	4/14/23	Pearl Labs 1	DT, TK
10a 10b	Maintenance	Average Time for 3D printed part replacement	Time needed to replace parts	4/14/23	Pearl Labs 1	JH, POB

Figure L.2: Redesigned Validation Plan

Each test from Figure L.2 is explained in further detail as to its purpose, design, and required materials. Sample photos (Figures L.1 – L.11) taken during the validation process are included with each of these descriptions to visualize their respective implementations. Following these introductions to the tests, a summary of the testing results (Figure L.12) including how they compare with target metrics will be reviewed in depth.

Test 1 (Figure L.3), “Camera Temperature Accuracy”, measures in units of Celsius and validates engineering specification #1, the “Detector must accurately identify temperature.” Testing is accomplished using a cup of water poured at the coldest setting from the faucet. The IR camera snaps a thermal photo of the cup from the top and a thermocouple will be placed on the glass surface. The temperature values will be compared among the thermocouple and the IR camera. Required equipment includes a glass to hold water, water, a thermocouple, and the IR camera.

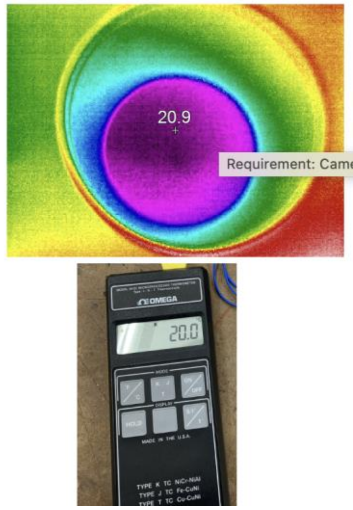


Figure L.3: Image Evidence for Validation Test #1

Test 2 (Figure L.4), “Camera Spatial Resolution”, measures in units of pixels/mm and validates engineering specification #3, the “Detector must have high spatial resolution.” Spatial resolution testing involves recording an image of a ruler aligned 20 inches away from the camera (the rated camera focal distance) to analyze the number of pixels which constitute a mm on the ruler. Required equipment include an IR Camera, a ruler, and a computer.

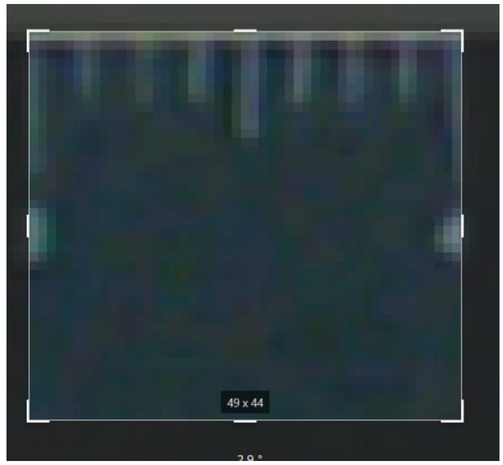


Figure L.4: Image Evidence for Validation Test #2

Test, 3.a (Figure L.5), “Motor Encoding Validation”, measures in degrees / mm and represents an auxiliary test required before validating engineering requirement #4, “Detector identifies prominent hot spot occurrences.” The test validates the 2D axis motor system which will be implemented to actuate the camera above chip samples. The motors are programmed to increment motor degree count until the system moves along intended direction by 1 mm. These findings are used for precise actuation of the movement system. Required equipment includes an assembled Superstructure and 2D axis system, and an IR Camera.

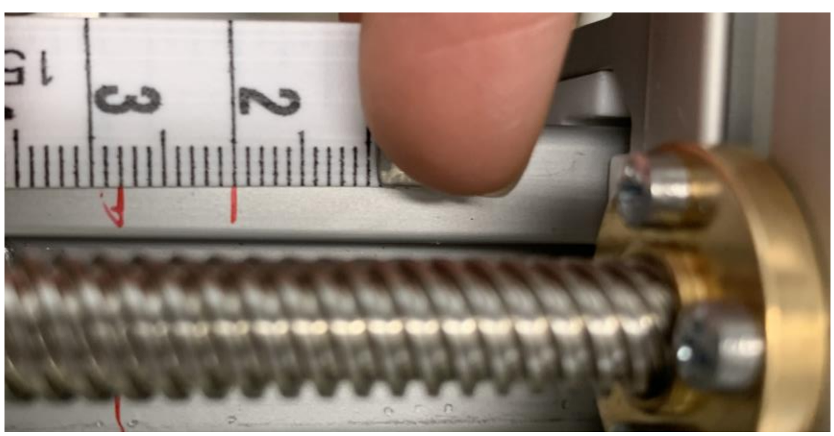


Figure L.5: Image Evidence for Validation Test #3a

Test 3.b (Figure L.6), "Resistance, Voltage, and Current Validation", measures in Ohms, Volts, Amps and represents an auxiliary test required before validating engineering requirement #4, "Detector identifies prominent hot spot occurrences." The test validates that the hot spot simulation samples are constructed and perform as designed. The simulation samples (constructed using PCB boards and 0204 smd resistors) are checked such that all intended resistor components are used, that all wiring connections are sound, and that the system achieves intended current and voltage values during operation. Required equipment includes the hot spot simulation circuit boards, a DMM, and a 12V battery supply.

Figure L.6: Image Evidence for Validation Test #3.b

Test 3.c (Figure L.7), "Hot Spot Identification by Area", measures the percentage of hot spot areas detected and validates engineering requirement #4, the "Detector identifies prominent hot spot occurrences." The simulation samples are powered, the device is operated, and the thermal map results are developed into thermal flux maps; these flux maps are compared to the simulation flix maps map on an area to area basis. Required equipment includes hot spot simulation circuit boards, superstructure, 2D movement system.

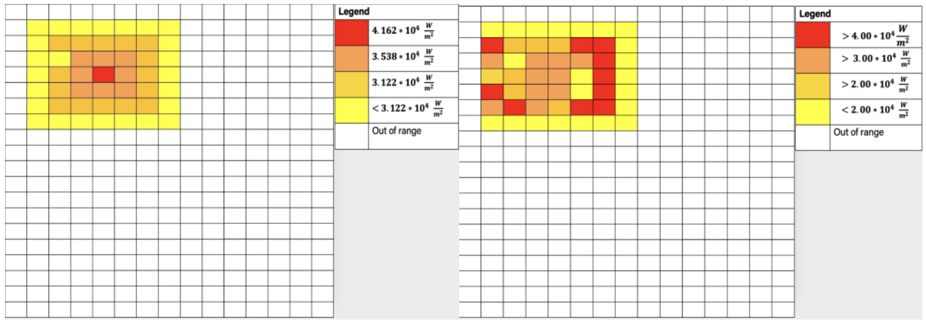


Figure L.7: Image Evidence for Validation Test #3.c

Test 4, “Electrical Subcomponent Safety”, measures in units of Amps, and validates engineering requirement #9, “Device must pose minimal risk to our lives throughout the prototyping process.” The electrical components are connected to the battery to see if the electrical system works prior to installation into the superstructure. All current measurements will be taken and compared against the design. Required equipment includes hot spot simulation circuit boards, battery, relays, and an Arduino Uno.

Test 5, “Electrical Assembly Safety”, measures in units of Amps, and validates engineering requirement #9, “Device must pose minimal risk to our lives throughout the prototyping process.” The resistors are soldered onto the PCB board with appropriate ground and power wirings and the lead screw motors are wired appropriately to the H-bridges (motor drivers). The ME E shop and Mike Sherwood are asked to verify that the wiring is completed safely. Current measurements are taken to validate that correct output is achieved. Required equipment includes an assembled hot spot simulation circuit board, lead screw motors, and a 12V battery.

Test 6 (Figure L.8), "Mechanical Subcomponent Safety", measures in units of cm, and validates engineering requirement #10, "final design should be safe for widespread use." The IR camera is placed into the camera mount with ample precautions to ensure the camera is locked in place before accomplishing camera movement. The IR camera is actuated to all edges of the prototype (with respect to the top view of the prototype). The superstructure is monitored to evaluate if any part of the IR camera exceeds the bounds of the superstructure, and this excess is measured. Required equipment includes the IR camera, the IR camera mount, an assembled superstructure, an assembled movement system, and a ruler.

Sample Position	IR Camera Length Outside (cm)
1	0
2	0
3	0
4	0
5	0
6	0
7	7
8	7
9	7

Figure L.8: Image Evidence for Validation Test #6

Test 7, "Fixed Component Safety", measures in units of number of free-hanging components, validating engineering specification #10, "final design should be safe for widespread use." After final assembly of the prototype, the team measures the number of loose pieces within the structure. Required equipment includes the assembled superstructure, the assembled 2-d axis movement system, and an IR camera.

Test 8 (Figure L.9), “Test Time”, measures in units of minutes, specifically the amount of time needed to complete a 9 testing-sample semiconductor analysis. The test validates engineering specification #7, “Prototype Hot Spot Creator must be quick to save on testing time.” Five 9-sample prototype tests are conducted and averaged for an average expected testing time. Required equipment includes an assembled 2-d axis movement system, assembled superstructure, an IR camera, a running GUI, and a stopwatch.

Test Number	Testing Time	Sample Location
Prelim 1	3:54 mins	1-9
Prelim 2	2:57 mins	1-3, 6-4, 7-9
1	2:54 mins 3:15 mins (Origin)	1-3, 6-4, 7-9
2	2:58 mins 3:17 mins (Origin)	1-3, 6-4, 7-9
3	2:58 mins 3:17 mins (Origin)	1-3, 6-4, 7-9
4	3:00 mins 3:19 mins (Origin)	1-3, 6-4, 7-9
5	2:59 mins 3:18 mins (Origin)	1-3, 6-4, 7-9

Figure L.9: Image Evidence for Validation Test #8

Test 9 (Figure L.10), “Ease of Operation”, measures in units of number of human interactions per test, validating engineering requirement #8, “end product must require minimum human interaction to ensure savings over existing options.” Concurrent with the testing time validation test, the team counts the required number of interactions needed per test and averages results. Required equipment includes an assembled superstructure, assembled 2-d axis movement system, a running GUI, and an IR camera.

Test Number	Human Interactions needed
1	4
2	4
3	4
4	4
5	4

Figure L.10: Image Evidence for Validation Test #9

Test 10a, “Maintenance-Lubrication”, measures in units of number of lubrication events, validating engineering requirement #10, “Prototype must be easy to maintain so that time can be spent iterating instead of maintenance tasks.” During validation tests, the number of times lubricant must be applied is recorded since accelerated testing on the prototype is not possible. Required equipment includes an assembled superstructure, assembled 2-d axis movement system, lubricant, and an IR camera.

Test 10b (Figure L.11), “Maintenance-Assembly Line Usage”, measures in units of hours needed to 3d print replacement components, validating engineering specification #11, “Final product must be robust and minimize maintenance to ensure assembly line is not held up.” The team analyzes the time needed to 3D print replacement components for the 5 custom 3D printed components used in the superstructure. Required equipment includes an assembled superstructure, an assembled 2-d axis movement system, and an IR camera.

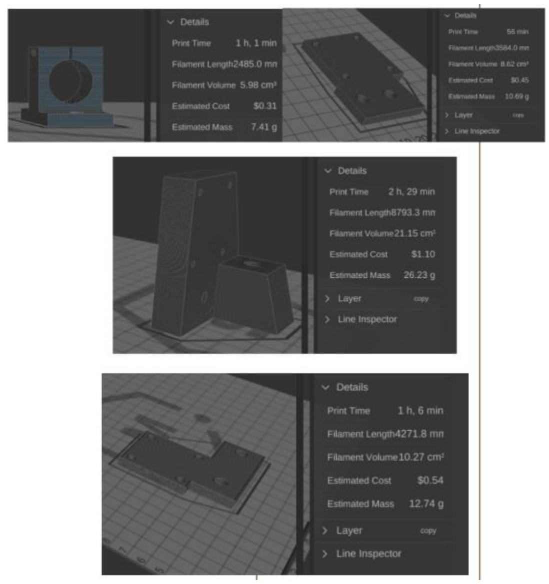


Figure L.11: Image Evidence for Validation Test #10b

Engineering Requirement	**Test Name**	**Metric**	**Projected Results**	**Generated Results**
Accuracy	Camera Temperature Accuracy	°C	± 2°C	± 0.9°C
Resolution	Camera Spatial Resolution	Pixel/mm	4 pixel/mm	1.929 pixel/mm
Identification-Detection	Hot Spot Detection	% of hot spots detected	80%	88%
Test Time	Time of operation	minutes	5 minutes	2:57.75 3:17.2 (Origin)
Ease of Operation	Necessary interactions	Human interactions required	5 interactions	4 (Two Computers Needed)
Safety - Mechanical	IR Camera in bounds	Camera extrusion from structure (cm)	5 cm	7 cm

Engineering Requirement	Test Name	Metric	Projected Results	Generated Results
Maintenance	Long Run Feasibility	Time to print (Hours)	3 hours	3
Identification-Traversal System	Motor Encoding	mm / 360 degrees	< 10 mm	8 mm
Identification-Simulator	Resistor Array Validation	Volts	12 Volts	12.77 Volts

Figure L.12: Validation Testing Results

Validation testing results are visualized in Figure L.12. Of note each engineering requirement corresponds to a test name, a metric to evaluate results, projected results (which are at some points more stringent than the engineering requirements), and the generated results. For the generated results, green indicates a passed test, orange indicates a passed metric with a qualification, and red indicates that the test was not passed. The final prototype passed 7/9 or 77.78% of the validation tests, passed one with qualifications, and didn't meet a final one. Standout performances are "Camera Temperature Accuracy," "Camera Spatial Resolution," "Hot Spot Detection," and "Time of Operation." In conjunction, these validation performances indicate that the product achieves veritable thermal imaging results at a length scale appropriate for the samples tested, that the product accurately identifies hot spots, and that the product achieves an average testing operation well under anticipated values.

For the validation test "Necessary Interactions," while only 4 interactions were required to test 9 samples, these 4 interactions needed the use of more than one computer program and thus represented a hindrance to quick and easy operation in a factory setting. Specifically, the 4 interactions are (1) placing the samples, (2) running the GUI, (3) running python code to operate camera, (4) processing temperature image into heat flux image using excel. The camera in use cannot be operated remotely through computer code and instead must be interfaced through using its custom app, “Fluke Connect.” This quality prevented SCS Solutions from incorporating camera operation into the GUI functionality. Further, because this camera operation was not incorporated into the GUI, the image processing was completed in excel since postprocessing the images was more convenient to the user. Thus, while this test needed 4 interactions which is less than the projected requirement of 5 interactions, its requirement for multiple separate computer programs merits this test as passed but with qualifications. In future iterations, the use of a industrial grade and non-field use IR camera will enable integration of camera functionality into the GUI, resolving this issue.

For the validation test “IR Camera in Bounds,” the IR camera, when operated to access sample locations 7-9 exceeded 7 cm outside the bounds of the superstructure. In a production environment, self-containing all components into the superstructure is essential for operator safety and this extension of the IR camera outside the superstructure is unacceptable. In future iterations, the use of a compact industrial grade camera will eliminate this issue since the camera mount itself never exceeds the bounds of the superstructure, but the holster of the IR camera did. Industrial grade IR cameras are handle-less and often compact rectangular prism like shapes.

The next steps for a prototype would be to spray paint the acrylic sheet which holds the PCB resistor arrays. This would allow any IR camera to read a constant emissivity background and enable further accuracy. Furthermore, opaque surfaces would be added to the exterior of the superstructure to stop any ambient and surrounding radiation to skew the temperature measurements of the device. If this device were to begin commercialization, the IR camera would need to be exchanged for a higher accuracy device with easier access to its data.

M. List of Applicable Standards

The team followed ANSI standards throughout the creation of the operating sheets and manufacturing drawings. Specifically, the team used ANSI tolerancing tables during the creation of the tolerance stack up shown previously in appendix H.1.5.

Sources:

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