ME 450
Fall 2023 Semester
Final Report

Innovating the Driver Controls for the Mirror Eye Camera Monitoring System

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December 12, 2023

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Executive Summary

Stoneridge, a manufacturer of electrical systems for the automotive and commercial vehicle industry, has developed the MirrorEye Camera Monitoring System (CMS). The CMS uses a combination of cameras connected to digital monitors inside of a truck cab to replace traditional side view mirrors and ultimately minimize annual tractor-trailer-related accidents. Gabe Lepage, a systems architect at Stoneridge, has tasked our group with improving the current control module for MirrorEye to improve learnability and controller operations.

Although the scope of this project is fairly narrow, several contextual factors are associated with our design decisions. These include ensuring that our team's ethics align with those of Stoneridge, specifically, adhering to their societal goals of improving driver safety through a low-cost yet durable control module. Our team has established a working list of requirements and specifications for this project. The requirements prioritize making the controller easier to use while maintaining its current zoom, pan, brightness adjustment, day/night mode, and camera folding functionalities. Other requirements include a size constraint on the controller, minimizing manufacturing cost, and durability and cleanability considerations.

After evaluating our requirements and specifications and performing a functional decomposition of the controller, our team has completed an in-depth concept generation and selection process. After multiple rounds of concept exploration on an individual level, we came together to converge on an "iteration one design concept". This process included organizing our designs into a classification tree, then using a series of group judgments, existing control module case studies, and direct stakeholder feedback to filter down to 7 potential designs. To further narrow these down, we used a house of quality to systematically rank each design in relation to our requirements, which yielded our chosen design concept.

We have also performed empirical verification and validation testing of our iteration one and iteration two modules. We conducted an icon survey, rotary knob testing as well as controller usability testing and received feedback from which we generated our final build design. We have outlined a bill of materials and manufacturing plan for this design and purchased the necessary materials to build it. We have assembled our iteration two prototype to be a functioning module that is wired to an Arduino UNO, and we wrote code to provide serial monitor feedback for each of the module functionalities.

Our biggest concern is focused on working around our time constraints to present a validated final design to Mr. Lepage at the Design Expo. Specifically, tasks like user testing and 3D printing require several days due to long queues and the need for scheduling. Additionally, there are concerns regarding programming the Arduino to account for fast reaction speeds.

Our team has established and followed a detailed Gantt chart, which includes all project deliverables, internal deadlines, and individual tasks to ensure we are on pace for the semester. We have presented our project at the Design Expo and after the submission of the final report, we have communicated our future steps if we would continue the project such as IP69K testing, FEA analysis, and further testing that would be beneficial to Stoneridge.

Abstract

To reduce the thousands of annual tractor-trailer-related accidents, Stoneridge has developed MirrorEye, a Camera Monitoring System (CMS) that replaces mirrors with digital cameras and monitors. Commercial truck drivers have found that the MirrorEye CMS is difficult to use while operating their trucks. Stoneridge has asked Team 16 to create a durable, easy-to-use, and highly learnable control module that enables them to operate the CMS both while stationary and driving.

Project Introduction

Background

Stoneridge Inc. is a designer and manufacturer of electronic systems and their components for the automotive, commercial, and off-highway vehicle industries based out of Novi, Michigan (*Stoneridge*). According to the Federal Motor Carrier Safety Administration (FMCSA), 400,000 crashes related to blind spots in trucks occur each year (*Truck Blind Spots*). In response to the thousands of annual commercial vehicle accidents, Stoneridge has made significant strides in improving road safety by developing the MirrorEye Camera Monitoring System (CMS), which is the first FMCSA-exempted driver vision system that replaces side view mirrors on trucks with external cameras and digital monitors inside the vehicle. The MirrorEye CMS contains a total of 5 cameras integrated into retractable wings that are mounted directly above the cab door as seen in Figure 1.

Figure 1: A total of 5 external Mirror Eye cameras including 2 on the driver's side wing (left) mounted above the cab door and 3 on the passenger side wing (right)

In comparison to traditional mirrors, the MirrorEye CMS provides drivers with a wider view of the roads and eliminates blind spots using both side-view and look-down camera displays. Figure 2 displays a comparison between the traditional side view mirror and the MirrorEye CMS range of vision.

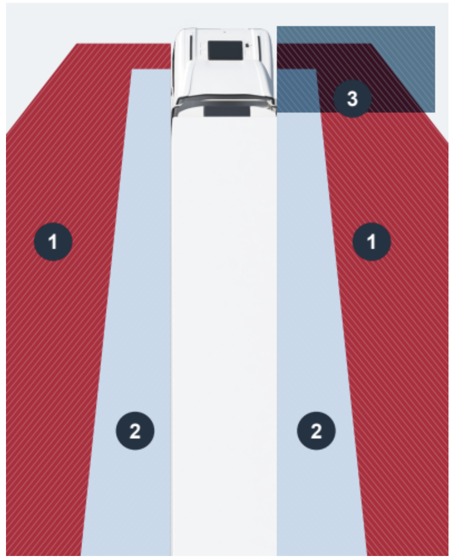


Figure 2: The MirrorEye CMS doubles the field of view (1) compared to traditional side view mirrors (2) and includes a right-side look-down camera (3) to eliminate blind spots

As seen in Figure 2 above, the MirrorEye CMS significantly enhances driver vision compared to traditional mirrors, but drivers need to be comfortable with using the system.

Problem Definition

Over this semester, we will be working closely alongside our sponsor, Gabe Lepage, a systems engineer at Stoneridge, to achieve our primary objective of improving the human-machine interface (HMI) surrounding the MirrorEye CMS. Mr. Lepage has asked us to iterate upon the system's currently existing control module by developing a more durable, easy-to-use, and highly learnable MirrorEye CMS controller. As seen in Figure 3, Stoneridge currently has its generation 1 controller on the market.

Figure 3: The Generation 1 MirrorEye CMS Controller

Based on Figure 3 above, the Generation 1 control module contains a central rotary knob with a selector button and several shortcut buttons to adjust things like display brightness and camera angle. Stoneridge has received feedback from truck drivers with complaints that the controller needed to be more intuitive to use and required extensive training before full comprehension of the controller functionalities. Moreover, Mr. Lepage made us aware that truck drivers are oftentimes driving with gloves on and have reported that the controller is physically difficult to use.

Since driver safety is of utmost importance when it comes to replacing mirrors with cameras, the user complaints surrounding the MirrorEye controller are significant motivation to improve the human factors associated with the design. In this sense, our task this semester puts a heavy emphasis on user experience (UX) design. The UX design process manages the user journey as they interact with a specific product or service ("What Is UX Design?"). Our controller should address the current user complaints without compromising any of the current controller functionalities. To ensure the success of our design, we will be evaluating the user experience through consumer research and in-depth prototype testing. We also plan on using activities such as think-aloud where participants verbalize their thoughts as they use the HMI (Pennington, 2022). Using such a method we can assess things like how intuitive the controller is to use and how distracted drivers get while using it, which will provide us with an accurate gauge of how user-friendly our design concepts are as a whole. Based on this feedback, our goal is to have a selected concept prototyped by the end of the semester.

Benchmarking

Currently, there are no easy-to-use and highly learnable solutions that include the functionality the previous HMI generations had. FalconEye Electronics has made the closest device so far with their EagleEye dash cam system which has an LCD monitor module (*FalconEye Electronics*). FalconEye is a competitor that manufactures dashboards and modules for fleet vehicles. During our benchmarking, we also focused on numerous other modules that emphasized user interaction such as an XBOX controller, an iPod, and various center consoles on vehicles. We summarized the components of each module in Table 1 below.

Table 1: Various Modules Used for Benchmarking

Module Image					
Name	Microsoft Xbox Controller	Kuka smartPad	Preh iDrive Touch-Controller	Apple iPod	FalconEye EagleEye
Dimensions (in)	6.0 x 4.0 x 2.0	11.5 x 10.0 x 2.5	4.0 x 2.0 x 1.0	5.0 x 2.5 x 0.2	7.0 x 4.7 x 0.9
Components	Buttons, Keypad, Joysticks	Buttons, Touchpad, 3D Rotation Knob	Buttons, Keypad, Touchpad	Buttons, Scroll Wheel	Buttons, LED screen

These various models can provide us insight into how to create a product that is well-received by users. Further research into the Xbox controller shows redefined features to enhance comfort during gameplay between versions of models (*Xbox*). Kuka's smartPAD was another example of specifically designed features for "relaxed robot operation" and for inexperienced workers to easily use (*KUKA smartPAD*, n.d.). The Preh Touch-Controller was made for the driver to be able to use the device using one hand (*Preh*.). We can also use various components as inspiration. Components like touchpads seen in the Preh iDrive and Kuka smartPad can be multifunctional for all features needed in our control module. In the Apple iPod as well as the Xbox controller we are reminded of the scroll wheel and joystick and its smooth functionality to compete against dials/rotational knobs. A keypad gives the ability to have several buttons, another component we see in all of the above modules, which is a common standard for control modules in all scenarios. The 3D rotational knob is a possible example to move the camera back and forth. Lastly, the simplistic buttons on the LCD monitor of the FalconEye's EagleEye are the perfect benchmark for a working module in semi-trucks. Together, by understanding various company's designs, we can use them as inspiration for our module's concept generation.

Design Process

Project Model Selection

Our design process follows an activity-based and solution-oriented model. We are using the activity-based model due to the need for "rework-intensive" activities such as prototyping and testing to get to our end solution (Wynn & Clarkson, 2005). Our process involves a solution-oriented model as the end solution will be proposed early in the design process and constantly analyzed and modified based on the requirements and specifications. Considering these details, we decided to choose the University of Michigan's Center for Socially Engaged Design's (CSED) design process over the ME 450 Capstone Design Process Framework.

Figure 4 below displays the CSED design process which is split into Explore, Define, Ideate, Develop, and Realize stages that are wave-shaped signifying the various highs and lows that occur during the design process (*CSED University of Michigan,*2020). The yellow points at the beginning and end of each stage are decision points that require a reflection before the next activity. The blueish gradient running through the process represents the tasks that we engineers will be doing no matter what stage we are at. The CSED places an emphasis on sketching and prototyping to gain valuable insights at each step. It was important for us to pick a model that stresses visualizing and testing our assumptions and ideas early and throughout the process.

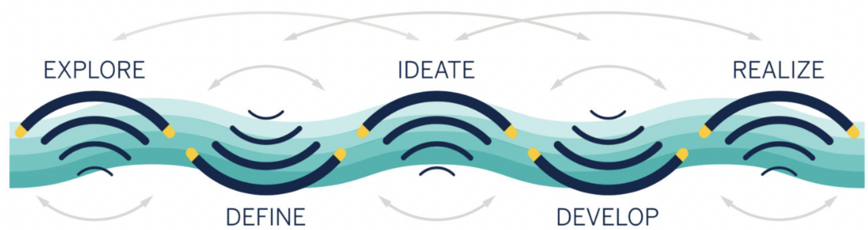


Figure 4: University of Michigan's Center for Socially Engaged Design's design process

Figure 5 below displays the ME 450 design process which is much more of a stage-based and problem-oriented process where the emphasis is on getting through each stage and not on an iterative process flow (Heather L. Cooper, 2020). To create our final prototype, the CSED design process provides a much more iterative process flow signified by the multiple gray arrows.

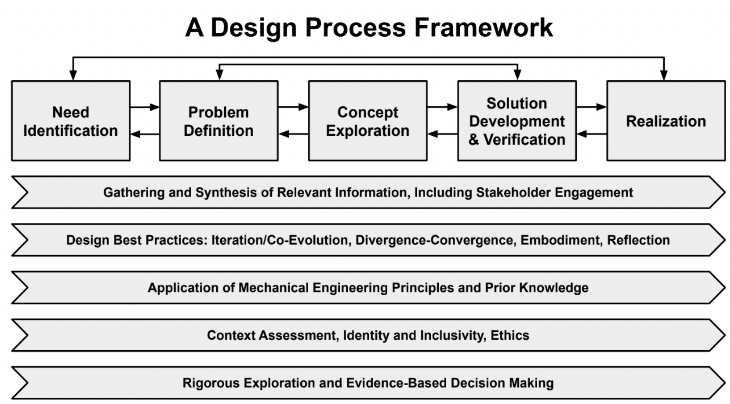


Figure 5: ME 450 Design Process Framework

The CSED design process provides a much more complex process that represents our need to make a prototype, immediately test it, and make changes based on the unintended consequences not taken into account.

Stakeholder Analysis

Our team used stakeholder analysis to further understand what external sources will influence our design decisions, and which stakeholders hold more control over the design than others. These stakeholders were separated into primary, secondary, and tertiary groups, and categorized based on their role within the design process as seen below in Figure 6.

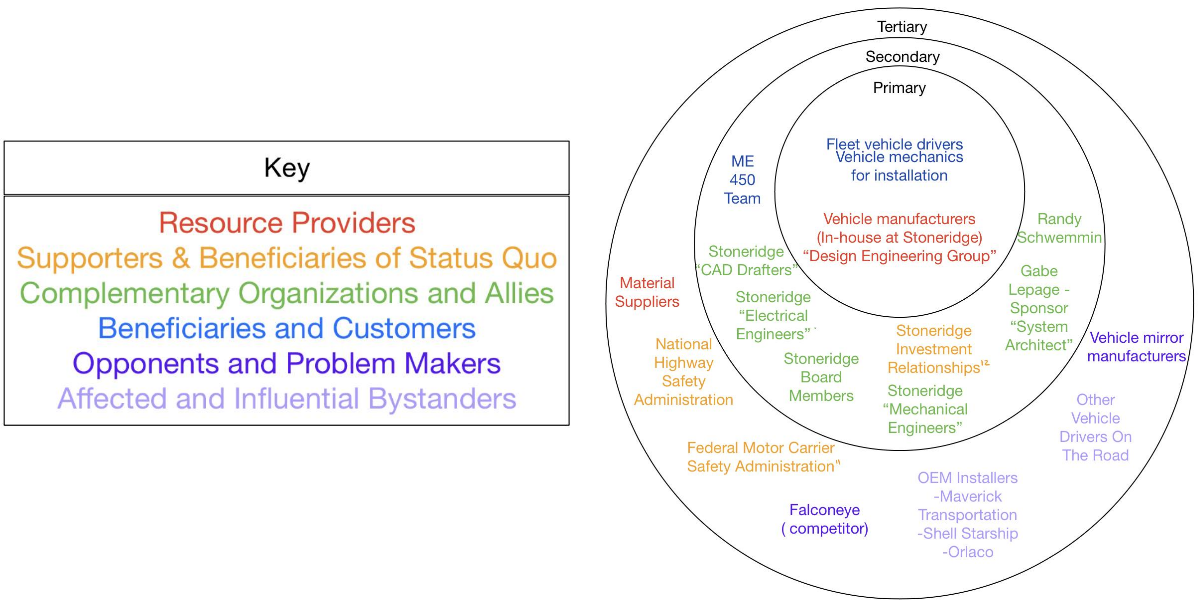


Figure 6: Division of primary, secondary, and tertiary stakeholders with a key that outlines each of their roles as they pertain to our project

The direct beneficiaries and customers who are positively affected by our products include the vehicle drivers who will be using the control modules as well as the mechanics installing the product. As Stoneridge does manufacturing in-house, they are their resource provider for all manufacturing concerns but their materials are externally acquired. Gabe Lepage, Stoneridge board members, and various engineers are examples of complementary organizations and allies as they influence our decision-making process and benefit from the product's success (*Stoneridge, Inc. - Investors*, n.d.). Federal administrations including the National Highway Safety or Federal Motor Carrier Safety are supporters of the status quo as they have allowed exemptions to Stoneridge to implement this product and previous generations within fleet vehicles (Finney, 2019) (*FMCSA*). Opponents include Falconeye Electronics as well as mirror manufacturers for trucks as their services will no longer be needed as OEM installation becomes more standardized for Stoneridge products. Lastly, with our module and the CMS on the market, OEM installers like Maverick Transportation, Shell Starship, and Orlaco will be affected and feel safer as a result of the device (*Stoneridge*, 2021) (*Stoneridge*, 2018) (*Stoneridge-Orlaco*, n.d.).

Relevant Standards

As MirrorEye is replacing mirrors with cameras, several engineering standards are helpful to our project, including SAE J3155 and SAE J3187. SAE J3155 provides test protocols with certain performance requirements for CMS that replace inside and outside rear-view mirrors (*J3155_202112*, n.d.). While we are focused on designing the MirrorEye CMS controller, it is important for us as a team to understand the protocols of the camera technology. SAE J3187 recommends practice in how System-Theoretic Process Analysis (STPA) can be applied to aspects of HMI (*J3187-1_202309*, n.d.). STPA is a hazard identification method that addresses system components and hazards associated with errors or component interaction failures (Karatzas & Chassiakos, 2020). Lastly, one of our critical requirements is adhering to the IP67 rating for protection against water submersion as outlined in the IEC 60529 standard (*IP67 Test Equipment*). The Ingress Protection (IP) rating system is an internationally recognized scale that is related to protection against various liquid and solid environmental factors (*Avery Weigh-Tronix*, n.d.). We will make sure our module continues to adhere to SAE J3155 and SAE J3187 standards and the IP67 rating.

Intellectual Property

Intellectual Property(IP) agreements were signed before our team worked on this project and a Non-Disclosure Agreement (NDA) was signed during a visit to Stoneridge's site. We understand breaking any agreement and infringing on Stoneridge's intellectual property allows Stoneridge to make a decision they deem fit to protect their assets. Stoneridge owns the intellectual property that will be created in our project as well as the MirrorEye's and Generation 1 and 2 Module intellectual property.

Design Context

Social and Environmental Impact

The Stoneridge MirrorEye system aims to provide enhanced vision for truck drivers while driving, parking, and stationary. Stoneridge places a heavy emphasis on the well-being of society with their MirrorEye System by improving the safety of truck drivers, and passengers on the road. Additionally, the road safety provided by the MirrorEye System would indirectly lead to fewer annual deaths caused by vehicular accidents.

Stoneridge emphasizes social and societal concerns as seen through the MirrorEye product, created to enhance safety. Although no specific emphasis has been placed on environmental factors through their manufacturing processes, the company focuses on reducing their vehicle emissions as a positive environmental impact (*Emissions - Stoneridge*, 2018). We as a team hope to also implement several ways to make our design more eco-friendly. These include but are not limited to selecting a manufacturing process with a low waste percentage, choosing materials that produce a low carbon footprint upon manufacturing, and utilizing honeycombing to decrease the quantity of material used.

One way that we can improve our design is by utilizing a highly recyclable plastic such as 2-HDPE to reduce excess waste upon the full lifespan of the module (*Which Plastic Can Be Recycled?* 2021). However, the downside to using 2-HDPE plastic over non-recyclable plastic is that it tends to be more expensive to manufacture, which increases the overall cost of the module (*Why Is Most Plastic Not Recycled?* n.d.). Overall, our design will have positive social impacts from the additional safety it provides truck drivers and others on the road, with the potential to have a positive environmental impact as well.

Ethics and Power Dynamics

Throughout the development process, ethics have to be questioned and considered thoroughly to ensure that the product contributes to the morals that are aligned with the design team and its respective stakeholders. Our team anticipates that we will have to adjust our moral values that may emphasize environmental impact to prioritize social benefit and profit, due to the interests of our Stoneridge and other stakeholders, as our ultimate priority is to create the most durable and cost-effective product. However, we can design the module to utilize a low-waste manufacturing process such as injection molding, which would additionally decrease the cost of manufacturing if produced at a large enough scale, regardless waste and environmental pollution will be minimized.

While we desire to be more environmentally focused, our priorities must align with those of our project sponsor since our team does not own the intellectual property for the MirrorEye System. The IP agreement that we signed to work on this project protects Stoneridge's intellectual knowledge from their competitors such as FalconEye and signs overall ownership of our project to Stoneridge (*FalconEye Electronics*). This creates a direct power dynamic such that our team has almost no leverage on certain aspects of this project. Similarly, our team is also obligated to design our module to the liking of the end users. If the end users do not like the module, they will not purchase it, and Stoneridge will be negatively impacted. The only relationship that is truly an equal power dynamic during this project is that between our teammates. All team members possess similar knowledge, but different experiences through internships and backgrounds. We aim to create an inclusive and dynamic environment in which we all have to work together to produce the best possible outcome.

User Requirements and Specifications

Requirements

The engineering requirements for our team were determined through a thorough analysis of the previous MirrorEye controllers, stakeholder analysis, and several conversations with Mr. Lepage. From the previous models, we determined that the baseline functionalities of our module must include the ability to adjust zoom, and brightness, and fold the camera wings. From meetings with Mr.Lepage, we also learned that the design must be able to be power-washed, low-cost, and durable. Mr.Lepage also informed us that user feedback indicated drivers had a hard time operating the older controller generations, so a great emphasis was placed on the new design being easy to operate. In recent weeks, Mr. Lepage discussed that our module should be able to access the current system's software such as settings and the setup menu. He also indicated that the controller should be easy to clean, low cost, and durable because once installed, the controller will not be easy to replace. Our requirements and specifications are displayed in Table 2 found below and ranked by highest priority to least priority.

Table 2: Prioritized list of our requirements (left) and their respective specifications (right)

Requirements	Specifications
1. Easy to Operate	Perform each functionality (see requirements 2-6) ≤ 2 times before being able to operate the controller without looking
2. Brightness Functionality	Brighten screen in 10% increments from 0-100%
3. Day/Night Mode Functionality	Switch between modes within 500ms
4. Pan Functionality	Pan continuously from 0 to ≥ 120 degrees
5. Fold Functionality	Fold the external camera system by ±90 degrees
6. Zoom Functionality	Zoom to 200%, 300% and 400% of standard view
7. Retain Original Module Software	Has accessibility to setup menu
8. Size	Height: 3 in Width: 3.25 in Length: 10 in
9. Low Manufacturing Cost	≤ $40

10. Durability	≥ 15 years
11. Easily Cleaned	Must abide by IP67 (electrical enclosure rating)

Within our requirements, the first is deemed the most important because our goal is to improve upon the existing modules, especially on ease of operability. Requirements 2-6 are all equally important as they are baseline functions in the module as requested by Stoneridge. The Size requirement is placed seventh as we aim for the design to be able to fit within the armrest of the truck so the driver has easy access to the module, which aligns with the operability of the module. Lastly, we have Low Manufacturing Cost, Durability, and Easily Cleaned - these are placed at the bottom of the list because Mr. Lepage indicated a priority for the module to be more function-oriented, and these requirements do not directly affect the functionality of the controller. Mr. Lepage also explicitly asked for the module to be able to withstand pressure washing. Generally speaking, requirements 1-6 must be met, whereas 7-10 are what we would like our design to have.

Specifications

The "Easy to Operate" specification was determined through analysis of our problem statement. Currently, the user will be deemed to have competency in the module when they can operate it without direct eye contact since a driver's vision should be focused on the road. Although research states that humans need 20 hours to learn a new skill, it is not feasible for us to subject multiple users to an extended period of testing. Therefore we have initially set a benchmark for 2 uses as a more feasible specification (Schawbel, n.d.). Upon further testing, this specification will be adjusted based on our user interface testing. The brightness, zoom, and fold specifications were given to us by our sponsor to meet the same quality standards as the previous model. The accessibility to the setup menu specification was given to us by our sponsor to allow the user to access settings and allow Stoneridge to access the back-end software and make changes to it. The size specification was determined to be 3 inches in height, 3.25 inches in width, and 10 inches in length to fit within the armrest of an average-size truck cab. We based this specification on the measurements taken of the armrest in the Stoneridge truck cab. To ensure that the module is easily cleanable it must abide by the limit set by IP67. IP67-rated products go through a test that the device withstands up to 30 minutes of submersion in water up to 40 inches (*IP67 Test Equipment*). From our sponsor, we learned that $30 was the manufacturing cost for previous generations, and since we plan on our module containing enhanced features, we expect a slight increase in manufacturing cost, thus resulting in the $40 specification. Finally, we would like to aim for our module to withstand a truck's average lifespan, so we deemed a 15-year module life expectancy as sufficient considering trucks are oftentimes replaced after this time period (Rechtien International n.d.).

Concept Generation

Concept Exploration

To begin the concept generation cycle, it was important for our team to decompose the functions of the MirrorEye CMS controller. Given that the system consists of both a driver-side and passenger-side camera, the controller must be able to perform the zoom, fold, and pan functions for each of those cameras. Additionally, the controller should include ways to perform adjustments specific to the in-cab monitors, including brightness control, day/night mode, and menu selection capabilities. These necessary capabilities of the controller are depicted using a functional decomposition chart seen in Figure 7 below.

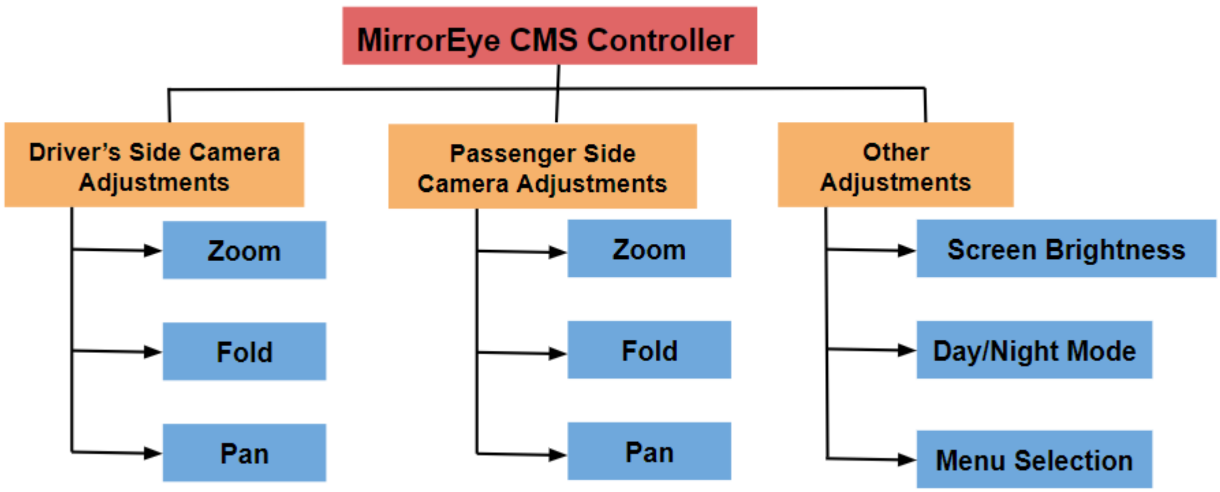


Figure 7: Functional decomposition of the MirrorEye CMS controller

Keeping in mind the functional decomposition of the controller, along with our requirements and specifications, our team was able to begin developing solution concepts.

Solution Development

We began our solution development process on an individual level with each team member generating 40 ideas to be further evaluated as a team. As part of this initial ideation phase, our team members utilized the design heuristics seen in Figure 8 to iterate on previous concepts to achieve the targeted 40 ideas.

1. Add levels
2. Add motion
3. Add natural features
4. Add to existing product
5. Adjust function through movement
6. Adjust functions for specific users
7. Align components around center
8. Allow user to assemble
9. Allow user to customize
10. Allow user to rearrange
11. Allow user to reorient
12. Animate
13. Apply existing mechanism in new way
14. Attach independent functional components
15. Attach product to user
16. Bend
17. Build user community
18. Change direction of access
19. Change flexibility
20. Change geometry
21. Change product lifetime
22. Change surface properties
23. Compartmentalize
24. Contextualize
25. Convert 2D material to 3D object
26. Convert for second function
27. Cover or wrap
28. Create service
29. Create system
30. Divide continuous surface
31. Elevate or lower
32. Expand or collapse
33. Expose interior
34. Extend surface
35. Flatten
36. Fold
37. Hollow out
38. Impose hierarchy on functions
39. Incorporate environment
40. Incorporate user input
41. Layer
42. Make components attachable/ detachable
43. Make multifunctional
44. Make product recyclable
45. Merge surfaces
46. Mimic natural mechanisms
47. Mirror or array
48. Nest
49. Offer optional components
50. Provide sensory feedback
51. Reconfigure
52. Redefine joints
53. Reduce material
54. Repeat
55. Repurpose packaging
56. Roll
57. Rotate
58. Scale up or down
59. Separate functions
60. Simplify
61. Slide
62. Stack
63. Substitute way of achieving function
64. Synthesize functions
65. Telescope
66. Twist
67. Unify
68. Use common base to hold components
69. Use continuous material
70. Use different energy source
71. Use human-generated power
72. Use multiple components for one function
73. Use packaging as functional component
74. Use repurposed or recycled materials
75. Utilize inner space
76. Utilize opposite surface
77. Visually distinguish functions

Figure 8: List of 77 possible design heuristics used by our team members to each generate 40 solution concepts

After completing the initial phase of individual concept generation, our team reconvened with 200 total design concepts. After evaluating each of these designs on a high level, we noticed similarities across many of our designs, so we grouped our designs according to the classification tree seen in Figure 9 below.

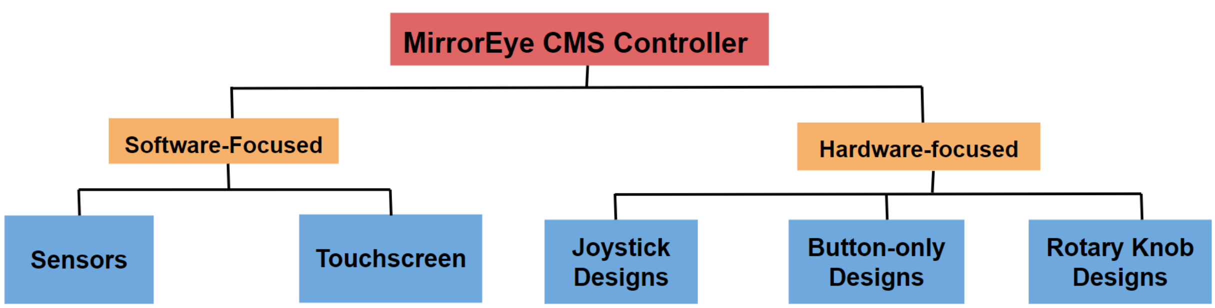


Figure 9: Classification tree used to group the 200 total design concepts generated across our team

To begin filtering out some of the 200 total solutions, our team decided to remove many of the concepts that seemed impractical, such as an AI controller, infrared hand sensor, and neurological controller, which left us with about 100 design concepts. Next, we opted out of designs that were deemed outside the scope of our team's skill sets, especially given the timeline we have for this semester-long project. Our team comprises five mechanical engineers, with one computer science minor and one electrical engineering minor. To avoid roadblocks due to a lack of experience, we discarded computer science and electrical engineering heavy designs such as haptic sensors and voice-controlled designs, leaving our group with about 50 design concepts.

To further converge upon our design concepts, we performed some additional research and found a relevant case study done by ViBilagare, one of the biggest Swedish automobile magazines. In their study, they performed a thorough test of the HMI system in eleven modern cars from various manufacturers. They measured the time needed for drivers to perform various tasks, such as changing the radio station or climate control, and gave an overall score out of 5 (*Physical buttons outperform touchscreens in new cars, test finds | Vi Bilägare*, n.d.). This test did allow for the drivers to get to know the vehicles and the systems before the test which is important to our learnability requirement for our module. As seen in Figure 10 below, the HMI systems included technologically advanced interfaces like the MG Marvel R, a sleek touchscreen system. The magazine also included an "old-school" vehicle, a 2005 Volvo V70 in their test which contains simple but not elegant buttons and knobs.

Figure 10: Examples of HMI systems used in Vi Bilagre's case study. Left: Chinese electric car, MG Marvel R's HMI system. Right: 2005 Volvo V70's HMI system.

Table 3 below shows the results of Vi Bilagre's case study. As can be seen from the table, the car with the lowest time and best score was the 2005 Volvo V70 with a time of 10 seconds and a score of 4.5. Vehicles with more advanced HMI's like touch screens such as the MG Marvel R or the BMW iX performed the worst with times of 44.9 and 30.4 seconds respectively.

Table 3: Vi Bilagre's Case Study Comparing Various HMI's in Cars

Car	Time to perform four tasks, seconds	Score, 1–5
BMW iX	30.4	4.0
Dacia Sandero	13.5	3.75
Hyundai Ioniq 5	26.7	3.5
Mercedes GLB	20.2	3.25
MG Marvel R	44.9	2.5
Nissan Qashqai	25.1	4.25
Seat Leon	29.3	3.25
Subaru Outback	19.4	4.0
Tesla Model 3	23.5	3.75
Volkswagen ID.3	25.7	2.25
Volvo C40	13.7	3.5
Volvo V70 (2005)	10.0	4.5

The results of this case study demonstrated a direct correlation between design complexity and the time it took to perform each task, with more complex designs taking longer to complete. This led us to further eliminate the more complex designs we had left out of our remaining 30, including designs like integrating the controller into the steering wheel and having a mousepad as the main control feature. After this stage, our team was left with 20 remaining design concepts (see Appendix A).

Stakeholder Engagement

Our final step towards converging on our potential design concept included a visit to the Stoneridge headquarters where we met with members of their engineering team as well as talked to one of their fleet drivers regarding his experiences with the MirrorEye controller. The driver gave us a comprehensive demo on how he uses the controller and took us on a ride in his 48-foot truck during which we could see the MirrorEye system and controller in action. Some takeaways that we had from our interactions with the fleet driver were that he preferred buttons as the primary controller elements and that a central knob was indeed a convenient way to navigate the controller functionalities. However, the most major thing we learned was that the location of the controller within the cab was inconvenient for the driver. Currently, the controller is located slightly to the right of and behind the steering wheel next to the trailer break as seen in Figure 11 below.

Figure 11: Location of the MirrorEye CMS controller (circled in red) inside the truck cab

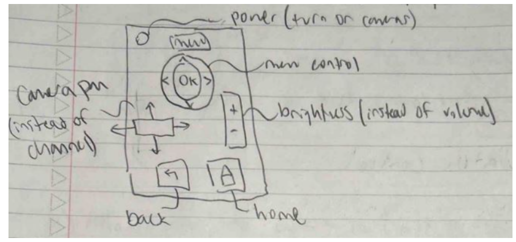
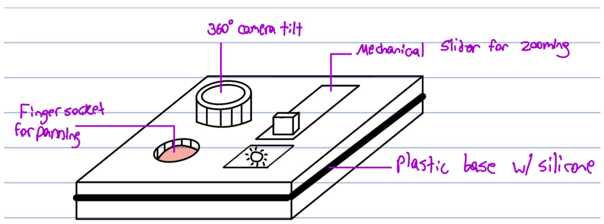
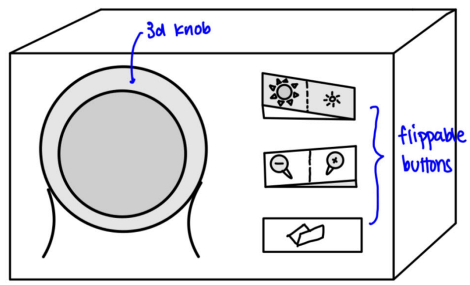
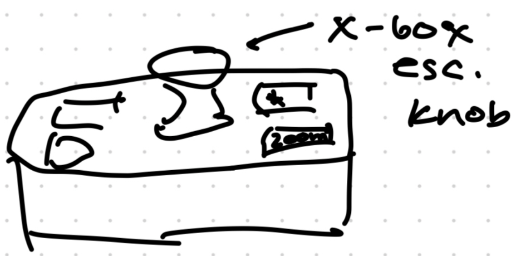
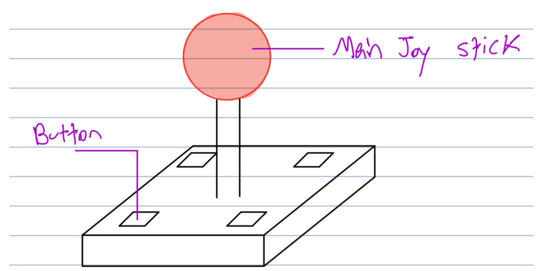
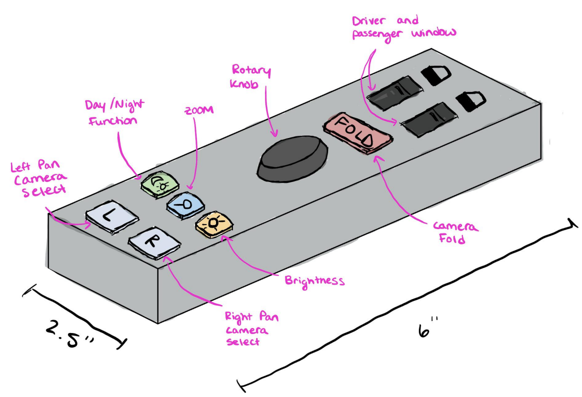
In addition to the fact that it can be potentially dangerous to operate the controller so close to the trailer brake, the fleet driver mentioned that having the module located on the right side requires right-hand-dominant drivers to drive with their non-dominant hand while operating the MirrorEye controller, which is an inconvenience to the majority of truck drivers (Papadatou-Pastou, Marietta, Eleni Ntolka, Judith Schmitz, Maryanne Martin, Marcus R. Munafo, Sebastian Ocklenburg, and Silvia Paracchini., 2020). This new knowledge led us to iterate back and consider which of our design concepts could potentially be relocated within the cab, specifically which ones could be integrated into the driver-side door armrest seen in Figure 12 below.

Figure 12: Driver-side armrest depicting current window and side view mirror controls

It is important to note that design concepts that would integrate the controller into the door's armrest assume that the legislation surrounding the ability to permanently remove mirrors from commercial vehicles in the United States that Stoneridge is working for will be passed. This would mean that the mirror controls currently occupying this area would become outdated and could be removed, making space for the MirrorEye controller. We see this as a fair assumption because the MirrorEye system and hence its controller would not be successful and profitable alongside traditional mirrors.

With the new insight that we gained from our discussions with the Stoneridge fleet driver, we were able to narrow our solution space to a total of 7 unique design concepts, for which we performed a detailed analysis in comparison to the existing controller. These 7 design concepts that our team was left with were different from each other as well as from the existing controller, and they are depicted in Table 4 below.

Table 4: Our final 7 design concepts as they compare to the existing MirrorEye CMS controller

1. Existing controller (baseline)  	2. 
3.  	4. 
5.  	6. 
7.  	8. 

It is important to note that although we removed complex and software-heavy designs earlier on, we kept a touchscreen design to include in our further analysis since it is a common benchmark in modern-day devices. We anticipate that analyzing our other designs about this touchscreen benchmark design will provide valuable insight into re-emphasizing our concept selection decisions.

Concept Selection

Comparison Matrices

With our 7 designs, we decided to create multiple House of Quality (HOQ) matrices to help us systematically analyze our designs about our requirements and specifications. The HOQ is a product planning matrix that is created to show how the requirements relate to the ways we will achieve those requirements. The most integral part of the HOQ is the initial importance given to the requirements which was calculated through an Analytic Hierarchy Process (AHP). An AHP is a process that uses decomposition to deal with complex information and multicriterion decision-making (*Definition of Analytical Hierarchy Process (AHP) - Gartner Information Technology Glossary*, n.d.). The AHP is a matrix in which requirements are measured to each other and given a score based on their relevance to each other (see Appendix B).

The HOQ 1 uses the ranked requirements from the AHP compared to our specifications (see Appendix B). The relationship strength between the requirements and specifications is given a score of 0, 1, 3, and 9 with 9 being the greatest strength. Table 5 displays the requirements as green highlights with the final scores in the gray and yellow highlighted boxes. We concluded that the far right specification of performing each functionality was the most important and then the rest followed as the way our requirements were ordered in Table 2 on page 12.

Table 5: House of Quality 1 Results for the Specifications

	Brighten Screen in 100 Lumen Increments	Switch between modes in 200ms	Pan continuously through ≥ ±25 degrees	Fold external cameras by ≥ ±90 degrees	Zoom to 35% of standard view	Dimensions(10"x3.25"x3")	≤ $40	≤ 15 years	Meet IP67 Electrical Enclosure rating	Perform each functionality less than 2 times
Importance	344.64	312.50	312.50	296.43	280.36	221.43	153.57	175.00	132.14	746.43
Relative Importance %	11.58	10.50	10.50	9.96	9.42	7.44	5.16	5.88	4.44	25.09

The HOQ 2 uses the results from Table 5 above to rank the importance of the specifications to features that may be common to use in a module (see Appendix C). These features were from the many preliminary designs that we came up with through our concept generation. Table 6 below displays the importance of gray and yellow highlighted boxes to the features in green highlight. We concluded that the buttons and rotational knob are the features that can achieve the majority of the specifications we set. The button feature can help select specific specifications or switch between modes but may run into issues lasting 15 years after multiple uses. The rotational knob would be an effective feature to move through increments and change values very easily. The joystick and touch screen were the least effective as they are not as intuitive to use to brighten a screen or zoom.

Table 6: House of Quality 2 Results for Features

	Button	Joystick	Rotational Knob	Touchscreen	Touchpad	Mechanical Slider
Importance	607.32	143.90	592.68	148.78	314.63	431.71
Relative Importance %	27.12	6.43	26.47	6.64	14.05	19.28

The HOQ 3 shown in Table 7 below takes our results from Table 6 to rank the importance of the features with our design concepts shown in Table 4. Concept 2 includes easy-to-use buttons and a touchpad as the main controller. The buttons are used to control the brightness with each click of the button increasing or decreasing the brightness while also being used to pan the camera and zoom. The lack of a rotational knob removes the ability to switch between modes and complete functionalities continuously. The design did fit within the dimensions and the price but with so many features, performing them within 2 times would be difficult. Concept 3 used the mechanical slider very effectively to be able to change the zoom and possibly the brightness. The unique joystick made it very complicated to pan the camera and would affect the ease of operation. Lastly, with only one button, it is difficult to switch between modes. Concept 4 includes easy-to-operate flippable buttons but lacks the button to pan the camera. It is a very simple concept that was considered as a potential design.

Table 7: House of Quality 3 Results for Design Concepts

	Existing Controller	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7	Concept 8
Importance	500.00	283.33	333.33	333.33	300.00	300.00	100.00	500.00
Relative Importance %	18.87	10.69	12.58	12.58	11.32	11.32	3.77	18.87

Concept 5 included buttons to change between functionalities but the joystick makes it very difficult to complete each functionality. With joysticks having the least importance, this concept is very ineffective for truck drivers. Concept 6 was a very similar design to 5 with a different joystick so the scores ended up being identical with similar functionality issues. Option 7 was the touchscreen version which was the least effective as it is very hard to learn and cannot guarantee the ability to complete all the specifications from the design. Table 7 above shows the results of our final HOQ matrix in which option 8 was to be the best. Option 8 included easy-to-use buttons with a rotational knob which is the best combination to switch between functionalities and mediate through the various values for brightness, pan, and zoom. Option 8 was selected over the existing concept due to the size and convenience it provided to the driver with its location on the armrest. All these concepts were built to fit the size constraint, assumed to be less than $40, and meet the enclosure rating. This is due to our ability to manufacture it through cheap 3D printing and covering the device with approved IP67 materials.

Preliminary Engineering Analysis and Prototyping

Preliminary Engineering Analysis

For our preliminary tests, we wanted to conduct an empirical test consisting of a four-button and joystick system, using an Arduino. From this test, we aimed to determine the feasibility of creating a functional prototype considering the lack of electrical and software background within our group.

Before wiring and testing our prototype, we designed a simple circuit and calculated the maximum current conducted across the circuit to determine if the circuit would overheat and or ignite. Seen below in Figure 13 is a simple wiring schematic illustrating the planned circuit.

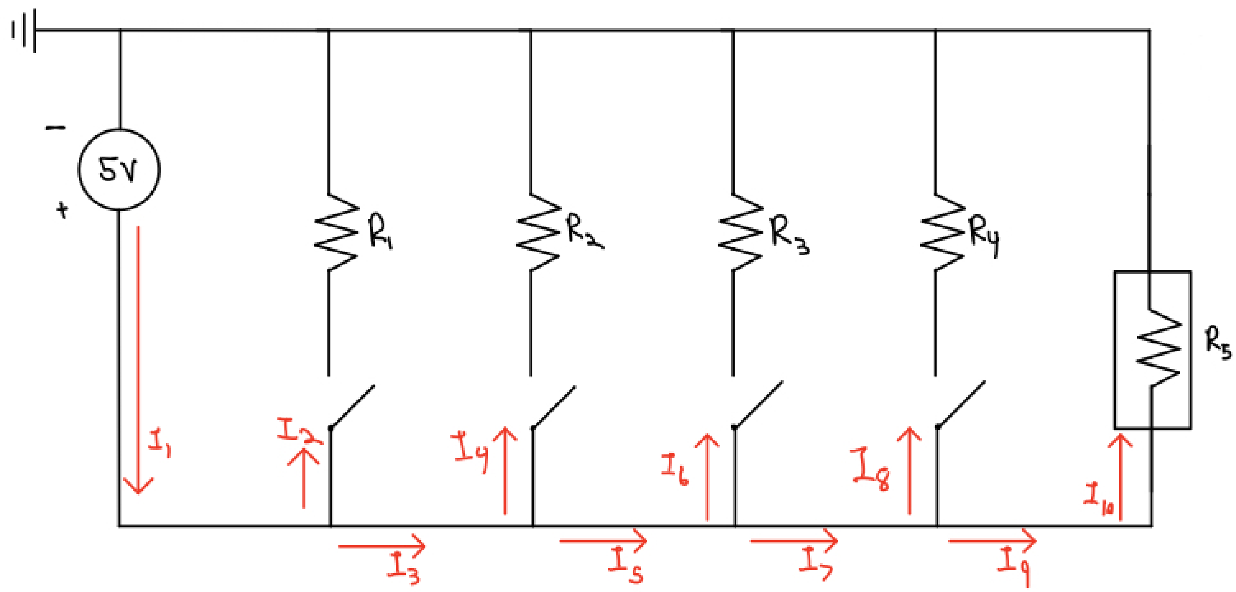


Figure 13: Wiring diagram for the planned electrical component for preliminary tests and future designs. $R_1 = R_2 = R_3 = R_4 = R_5 = 10\ k\Omega$. All wires in the circuit are to be 22 gauge.

The equivalent resistance of the circuit is largest when the switches containing resistance R_1 through R_4 are open. When the switches are open, current flows only through R_5, thus making the equivalent resistance equal to R_5. We can obtain the maximum current, I_{max}, through equation 1.

$$I_{max} = \frac{V^2}{R_{eq}} \tag{1}$$

In equation 1, I_{max} represents the maximum current flowing through the circuit, V represents the voltage supplied by the Arduino, which is 5 volts, and R_{eq} is equivalent to R_5, which is 10 kΩ. From the equation above, we calculated $I_{max} = (5\ V)^2/(10\ k\Omega) = 0.0025$ A. Since the maximum amperage for a 22 gauge wire is said to be 0.92 A (*American Wire Gauge Chart*, n.d.) and $I_{max} = 0.0025\ A < 0.92\ A$, we can conclude that the circuit will not ignite and is safe to operate.

Prototype One

After we deemed the circuit model safe to utilize, we assembled a test device consisting of an Arduino UNO, a breadboard, four 4-pronged buttons, four 10 kΩ resistors, and 1 joystick was constructed. The schematic for this model is shown below in Figure 14.

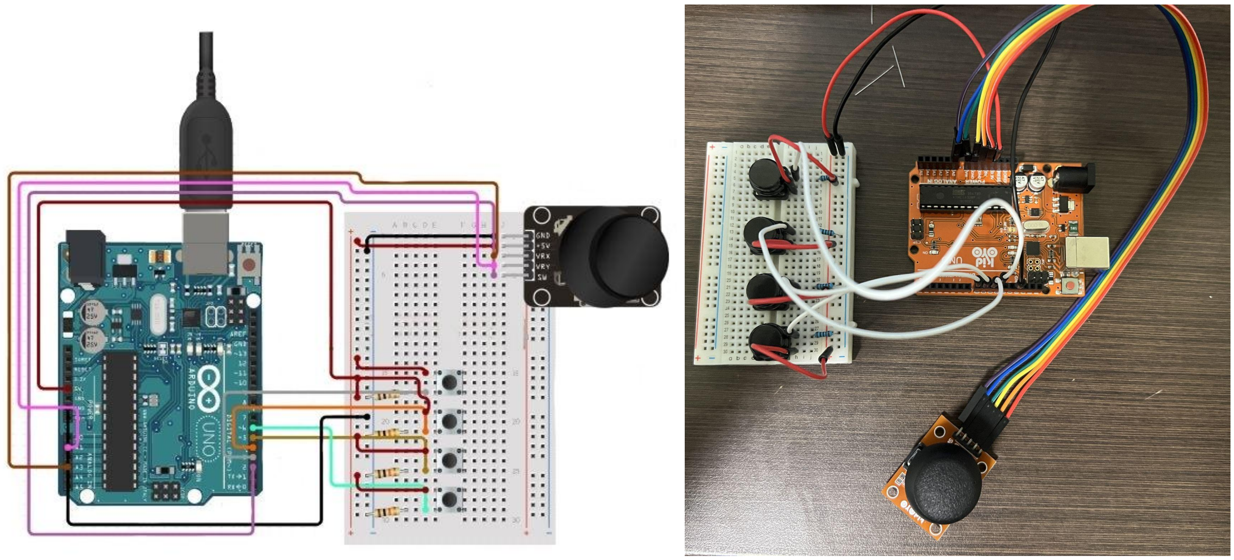


Figure 14: Wiring schematic for the control module simulation (left) ((*Circuit Design App for Makers- Circuito.Io*, n.d.)) and actual depiction of the test device (right).

The four buttons held the functionality of zooming, folding, brightness, and switching between controlling the left and or right side camera. The joystick allowed for the panning of the selected camera. The buttons and joystick were powered by a 5-volt source. When the user pressed a button and the joystick was moved, update messages were displayed on a laptop screen through the 9600 baud Arduino serial monitor. We utilized the serial monitor to act as a substitution for the live feedback or indicators that users would traditionally receive through the in-cab display monitors when operating the CMS. Upon receiving a button press, we coded the serial monitor to display feedback relating to the button's functionality. For example, if we pressed the zoom button, depending on the previous state, the serial monitor displayed a message that said “zoomed in” or “zoomed out”. When testing this module, we used the joystick as a temporary replacement for the rotary knob since it had a potentiometer built into it and behaves similarly to a rotary knob. When we tilted the joystick to the left, the degrees of panning would be increased, and the updated value would be displayed on the serial monitor. We did not include a left and right button within this module since the functions are almost identical, and we were more concerned about the feasibility of using a rotary knob to control the camera panning. After completing the module and conducting basic functions, we were able to determine that the button and joystick/rotary knob setup was feasible for our project.

Iteration One Build Design

Physical Features and Module Operation

Based on the results of our concept selection process, our team has established a leading iteration of one design concept to move forward with for testing. This design, pictured in Figure 15 below, consists of six buttons, a rotary knob, as well as two “window switches” to open and close the driver and passenger side windows. This design combines the necessary functions for the MirrorEye controller with the power-operated window switches as required by code number 118 of the Federal Motor Vehicle Safety Standard (FMVSS) (*Federal Motor Vehicle Safety Standards*, 2008). In this manner, this controller would be robust enough to place on the side of the cab door assuming the necessary legislation is passed, as we found out from our trip to Stoneridge discussed in the “Stakeholder Engagement” section.

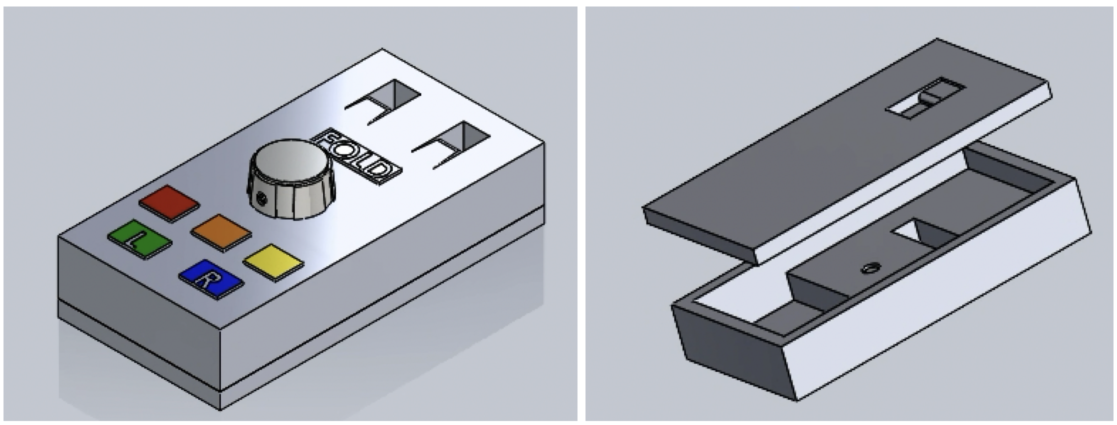


Figure 15: Initial CAD model for our iteration one design concept. The controller consists of selector buttons for the left (green) and right (blue) cameras, buttons for zoom (red), pan (orange), and brightness (yellow), and a button to fold both cameras. There is also a central rotary knob with a push-down button built in to select and confirm menu selections respectively. The rotary knob will also be used to adjust and specify camera angle and screen brightness and navigate a display menu as necessary. The dedicated space for electrical housing and an easy-to-remove lid is also displayed (right).

The buttons and rotary knob act as an interface for completing the zoom, pan, fold, brightness, and day/night mode functionalities listed in our requirements. The specifications for these functions will be programmed using an Arduino, which will be properly wired and soldered to all components to avoid electrical failures. Our team decided to have the housing unit be 3D printed since it is a quick fabrication process that does not involve manufacturing plans and other time-consuming steps. This will allow us to iterate upon several design prototypes throughout the remainder of the semester. We 3D printed out of PLA instead of ABS due to PLA’s increased stiffness and strength (*3D Printing with PLA vs. ABS*, n.d.). While ABS is slightly cheaper, due to the small size of the module, the cost difference will be negligible.

As seen in Figure 16 below, the design is currently 10 in x 3 in x 1 in length, width, and height, respectively, which falls within our size specification dimensions of 10 in x 3.25 in x 1 in.

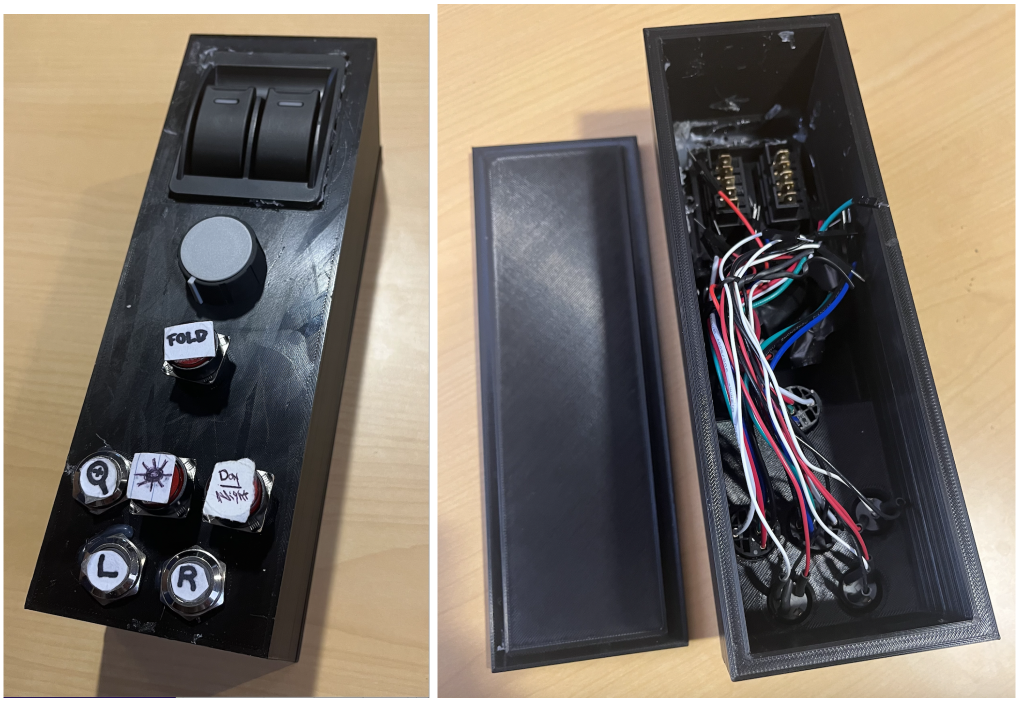


Figure 16: 3D printed iteration one build module front(left) and inside housing unit with lid(right)

There is an initial bill of materials (BOM) for this design concept (see Appendix C), which we plan to use to perform a cost analysis of the controller in the future. The BOM specifies that we obtained the colored buttons from Amazon, and since they did not come labeled, we attached our labels, using epoxy, to each button based on the functionality it will be used for.

Wiring

Below in Figure 17 is an illustration of the planned wiring schematic for the iteration one design. This wiring schematic features one Arduino, one breadboard, 6 momentary buttons, and a rotary potentiometer. All electrical components are powered from the 5V power supply located on the Arduino.

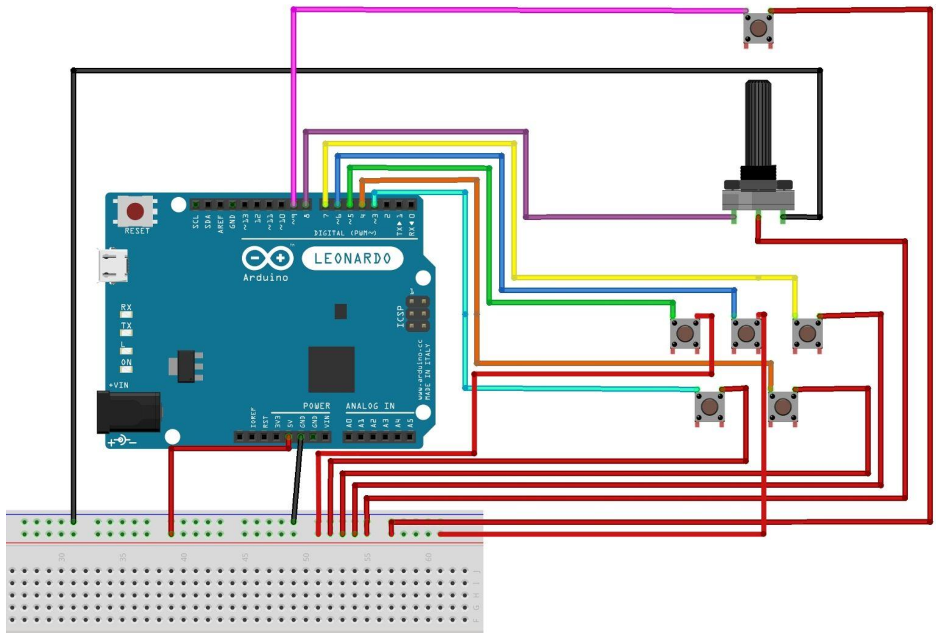


Figure 17: Wiring schematic for iteration one design.

Iteration Two Build Design

Physical Features and Module Operation

After processing the data from our user testing, we were able to conclude numerous issues with the buttons and dials that were used, the ergonomics of the controller, as well as the planned functionality of the buttons. From these results, we adjusted the iteration one CAD model and began planning for the assembly of our iteration two design seen below as compared to the previous iteration.

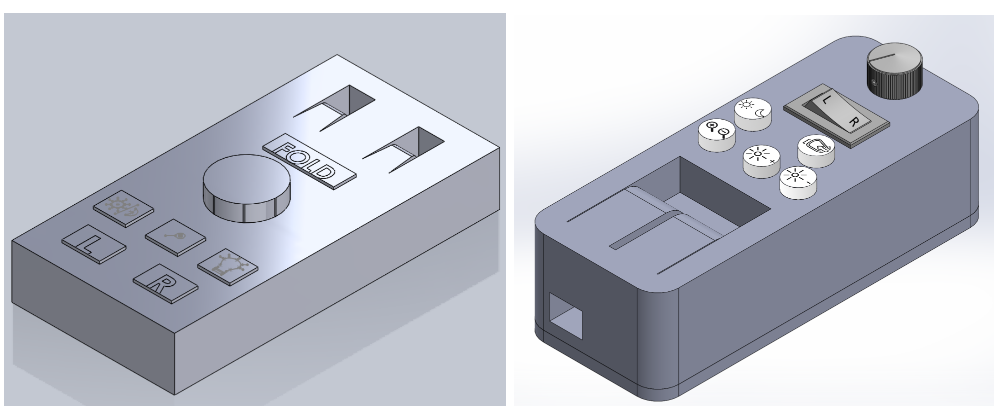


Figure 18: Side by side of the final CAD iteration one (left) and iteration 2 (right) isometric views.

Figure 18 highlights the physical changes that occurred during the development of iteration two. Most notably, the window switches we removed to the bottom of the module and the rotary knob and left and right toggle switches were moved to the top. During the assembly of the iteration one design, we noticed that the user might hit one of the buttons when attempting to operate the rotary knob, so by moving the rotary knob to the top of the module, with ample space surrounding it, we would decrease the likelihood of accidental inputs on the buttons. Also, by including the window switches below the buttons, the user will be able to rest their arms on top of the window switches when operating the buttons if desired.

Additionally, we updated the L/R selector buttons to a rocker switch, which eliminates the need to deselect after every use. With pan now being the only function to use the rotary knob, we relocated the rotary knob to be close to the left and right rocker switch since both features work in conjunction with one another. By doing so we adhere to the UX design law of proximity which increases our module's clarity by helping to "establish a relationship with nearby objects… and understand and organize information faster and more efficiently"(Yablonski, n.d.).

From our user testing, we were able to conclude that day/night mode and fold should be binary functions, zoom should consist of multiple button presses with different percentages of zoom (eventually resetting to the un-zoom state), and brightness should consist of an increase and decrease button that can be held to incrementally adjust the brightness. The changes in module operation from iteration one to iteration two can be seen in Table 8.

Table 8: Table displaying change iteration one operation when compared to iteration two

Function	Iteration One Operation	Iteration Two Design Operation
Brightness	1) Select the button 2) Adjust with the rotary knob 3) Deselect the button	1) Press and or hold the + or - brightness button
Zoom	1) Select button 2) Adjust with the rotary knob 3) Deselect the button	1) Press button once for 200%, twice for 300%, three times for 400%
Pan	1) Select the L/R button 2) Rotary knob rotation 3) Deselect the L/R button	1) Select the L/R on the toggle switch 2) Pan with the rotary knob (no need to deselect anything)
Day/Night & Fold	1) Press the button to toggle on and off	1) Press the button to toggle on and off

The operational changes for the behavior of each of the module functionalities reflect the feedback we received from our controller usability testing. Moreover, it is apparent that for zoom, pan, and brightness, the changes in the design will result in fewer actions needed to complete the same functionalities.

There is an initial bill of materials (BOM) for this design concept, which we plan to use to perform a cost analysis of the controller in the future. The iteration two consists of the following parts as shown in the Bill of Materials(BOM) below: the module base and lid, an indicating knob and set screw, an optical encoder, a rocker switch, five momentary push buttons, some epoxy resin, and an Arduino R3. The total cost of our build design is $39.54, and a cost breakdown per part can be found in Appendix G.

As seen in Figure 19 below, the design is currently 8 in x 3.25 in x 2 in length, width, and height, respectively, which falls within our size specification dimensions of 10 in x 3.25 in x 1 in.

Figure 19: 3D printed iteration one build module front(left) and inside housing unit with lid(right)

There is an initial bill of materials (BOM) for this design concept (see Appendix C), which we plan to use to perform a cost analysis of the controller in the future. The BOM specifies that we obtained the colored buttons from Amazon, and since they did not come labeled, we attached our labels, using epoxy, to each button based on the functionality it will be used for.

Wiring

The wiring schematic for iteration two is built upon the preliminary circuit previously mentioned in the "Preliminary Engineering Analysis" section of this document. We plan to continue using an Arduino as the main control module, but the iteration two wiring differs from the preliminary wiring schematic through the inclusion of a rocker switch and the substitution of a rotary potentiometer for an optical encoder. Figure 20 depicts the wiring schematic for iteration two, which illustrates which ports are used for each button, switch, and encoder, as well as the 5V power line wired to every component.

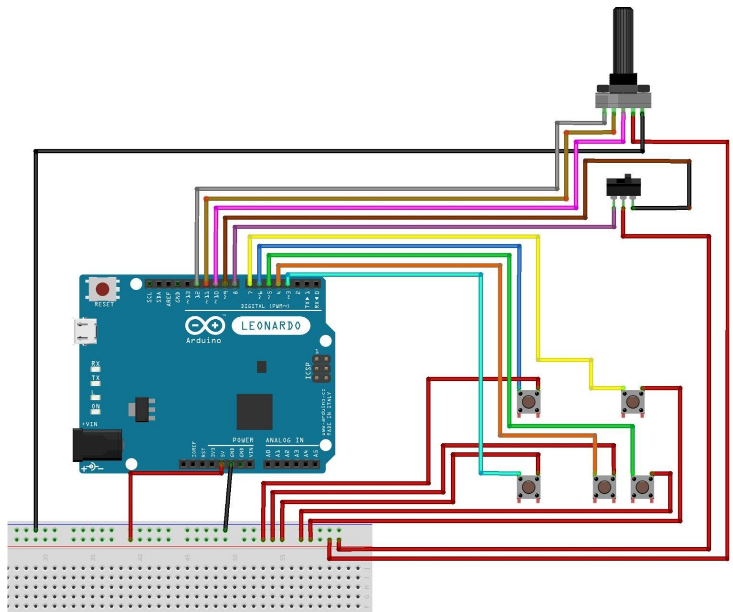


Figure 20: Illustration of the final module design's wiring schematic. All buttons correspond to the position of the buttons on the 3D CAD model of iteration two as seen in the "Physical Features and Module Operation" subsection.

The selected buttons for iteration one contained LEDs that created signaling issues for the Arduino due to an underlying capacitor used for the LEDs. For this reason, we elected to use two-prong buttons, without an included LED, for the iteration two design. The two-pronged buttons solely act as a means to complete the circuit. During iteration one development, we also considered including both latching and momentary buttons due to the functionalities in iteration one having to be toggled on and off. Now that all of the iteration two design's functionalities are either binary functions or several presses to adjust a setting, latching switches were deemed improper, and we determined momentary switches to be the appropriate button type for our iteration two.

During assembly of the iteration one module, we noticed issues that might arise with the rotary potentiometer and the left and right buttons. The rotary potentiometer had a range of motion of 280° and lacked detents, which might be insufficient for comfortable control, and the left and right buttons lacked indicators as to which side is selected. To combat these issues, we opted to utilize an on-off-on switch for the left and right selection and an optical encoder with detents. We are incorporating an on-on switch for the left and right pan to allow the user to see which state is currently active, which is indicated by the side that is pressed down. Using an optical encoder over a rotary potentiometer allows for limitless rotation, which allows for the starting position of the encoder to be arbitrary. This is important in the scenario when the user sets the left side camera to its lowest setting and then plans to adjust the right side camera to the left. After adjusting the left side camera, a rotary potentiometer would be at the left limit, so when the user adjusts the right side camera, they wouldn't be able to rotate left any further. Now with an optical encoder, the user can continue to adjust the other side freely regardless of the other camera's position.

Empirical Testing of Specifications

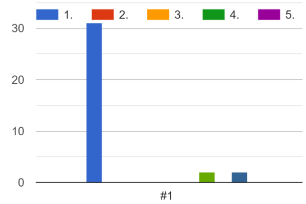
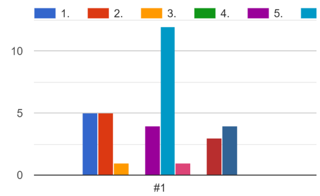
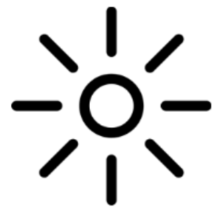
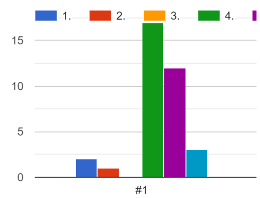
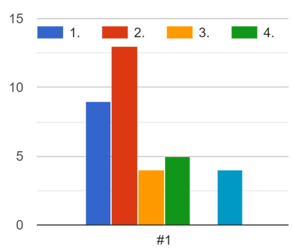
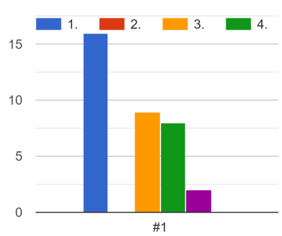
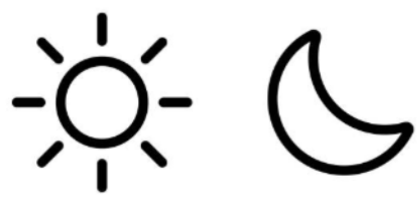
Controller Icon Survey

A key area of usability is the icons chosen to represent each functionality. We want the icons to be intuitive for each user, so they understand the functionality of each button easily. To ensure that we were using the optimal icons, we conducted a controller icon survey (Appendix F). The purpose of this test was to give us a clear confirmation of what icons were intuitive to users.

The survey made through Google Forms showed ten images for zoom, and brightness, and six images for pan, day/night, and fold. The number of images was based on the number of common images available, and zoom and brightness had significantly more options than pan, day/night, and zoom. In the survey, participants were asked to rank their top three image preferences and comment on why they chose their top option (Appendix F). The survey was distributed via QR code to our ME 450 classmates and other university students via email and Slack.

Overall, 35 people participated in the survey. Each icon had a clear winner based on survey results seen in Table 9 below:

Table 9: Controller Icon Results

Functionality	Survey Results (for #1 icon)	Top Image
Zoom		
Brightness		
Pan		
Fold		
Day/Night		

From our icon survey, we were able to select the top 5 icons, which we used on our iteration one module for usability testing.

An important consideration that came out of this testing was the similarities between the day/night icon and the brightness icon. They both involve a very similar-looking sun logo, which may confuse some users when both are included as labels within the same module. Further testing will be needed on a holistic level to see if the brightness logo is confusing when grouped with all other icons. During our final design testing, we will add additional testing to understand the implications of the day/night mode and brightness similarities.

Knob Testing

Another form of testing we conducted was knob testing to determine which type of rotary knob is preferred. Four knobs, seen in Figure 21 below, were placed on a cardboard sheet and participants were asked which type of knob was preferred. 11 users tested four different knobs and gave feedback on which knob was most easy to handle. We took notes on each user's preference and compiled information on knob preferences.

Figure 21: Four knobs used for testing ergonomics for users for the rotary knob. Dial One starts from the left to Dial Four on the far right

Of the 11 users tested, five users preferred Dial Two due to its "larger ridges" while four users preferred Dial 3 due to the feel and simplicity of the smaller size. Additionally, two users preferred Dial Four due to the convenient size and "sleek look". Overall, Dial One was too big for many users. From this data, we concluded that small or medium size dials with ridges were preferred for ease of use.

Our testing did not include people wearing gloves, which truck drivers frequently wear when driving. For our next round of testing, we will have users wear gloves to more closely simulate the experiences of truck drivers.

Controller Usability Testing

The majority of the testing our team conducted was controller usability testing using our iteration one module. We conducted usability testing on ten different users to determine if our module functionalities (Table 2, page 12) are met intuitively.

For each user, we set the module on their left-hand side to simulate the intended general location of the driver's side armrest as seen in Figure 22 below, and conducted a step-by-step test procedure which incorporated specific tasks that encompassed all of the module functionalities (see Appendix D).

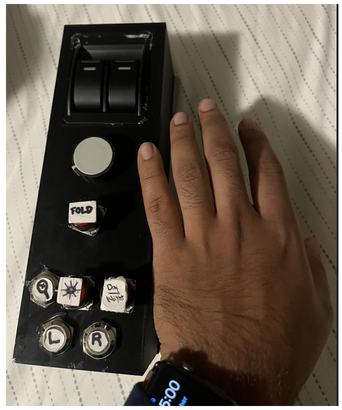


Figure 22: Physical module setup for controller usability testing

For each user, we performed the controller test procedure two times - once without any instruction or module introduction and again after providing them with a brief overview of the module and its functionalities. In both tests, a user had to physically complete the same ten tasks while verbally communicating their decision or reasoning and as proctors, we timed each task and documented their thought process and think-aloud notes to help draw appropriate conclusions. Some of the tasks included brightening the screen by 70%, panning an individual camera 70 degrees to the left or right, zooming in and out, and activating the day and night mode. We took detailed notes on their thought process and compiled the results into Table 10 seen below.

Table 10: High-Level User Think-Aloud Feedback From Controller Usability Testing

Functionality	Positive Feedback	Negative feedback
Fold	*Iteration 1 Testing* 10/10 users completed without issues	*Iteration 2 Testing* 4/10 users thought the fold image was not intuitive.
Day/Night	*Iteration 1 Testing* 10/10 users completed without issues	None
Zoom	*Iteration 1 Testing* 10/10 users were quick to locate and select the zoom button	*Iteration 1 Testing* 8/10 users pressed the zoom button multiple times to set different views *Iteration 2 Testing* 10/10 users pressed the zoom button and moved the knob
Brightness	*Iteration 1 Testing* 10/10 users were quick to locate and select the brightness button	*Iteration 1 Testing* 9/10 users initially tried to press and hold the brightness button for a while
Pan	*Iteration 1 Testing* 8/10 users went to the rotary knob after the L/R selection	*Iteration 1 Testing* 10/10 users criticized having to select and deselect the L/R buttons after every use

From this testing with our iteration one module, we learned that the binary functions, fold and day/night mode, were intuitive to use and users had no issues completing the task. However, for the incremental functions of zoom, brightness, and pan it became clear fairly quickly that users were initially very confused by the multifunctional rotary knob in our iteration one for these functions and it took them a while to figure out. More specifically, for the brightness tasks, users attempted a press-and-hold approach of the brightness button. For zoom, the majority of users pressed the zoom button multiple times to simulate different zoom settings and didn't think to use the knob. Finally for pan, although the left/right selection was straightforward and many users did figure out relatively quickly that the rotation knob could be used to pan the cameras, there was a lot of criticism on having to select and deselect the right or left camera after every use.

Once changes were made to our iteration two, there were only two complaints users had while using the module. 4/10 users thought that the fold image we had was not intuitive and it took them some time to figure out what it did. We specifically made changes to the zoom and brightness due to the way users used it before yet issues still occurred with the zoom functionality. With the lack of consistency between the brightness and zoom, users went to use the knob since there was no increase and decrease zoom button. The controller usability testing provided us with very valuable feedback on how intuitive each function is to perform and allowed us to iterate upon our design.

Final Design

Physical Features and Module Operation

After the second round of user testing was complete and a meeting with our sponsor, we concluded that minor changes needed to be implemented with the buttons and rocker switch that was used to increase intuitiveness and improve the functionality performance. From these results, we adjusted the iteration two CAD model and created our final design seen below as compared to the previous iteration.

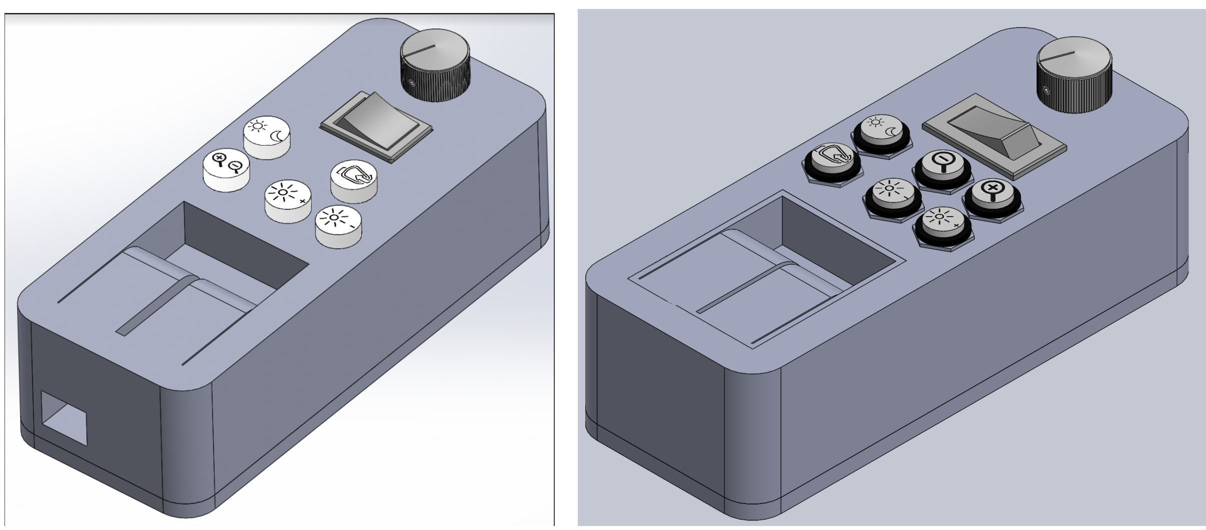


Figure 23: Side-by-side isometric views of the final CAD iteration two (left) and the final design (right)

Figure 23 displays the physical changes that occurred during the development of the final design. Specifically, the zoom functionality changed from using one button controlling increasing and decreasing the zoom to two buttons doing those tasks respectively. During testing, users described issues in consistency with the buttons of the non-binary functionalities. It was confusing that the brightness had two buttons for increasing and decreasing but the zoom functionality only had one. As the Interaction Design Foundation mentions, consistency will limit the different actions a user will need to perform which ensures that the "user do(es) not have to learn new representations" (Wong, 2021). In addition, by moving the zoom buttons to the same side of the brightness, we then isolate the binary and non-binary buttons to their respective sides. Cornell University defines consistency in ergonomic design as the "principle of least astonishment" and our change to the location will not surprise users when using the module by keeping the consistency which improves intuitiveness (*CUergo: Ergonomic Guidelines for Interface Design*, n.d.).

Additionally, we updated the rocker switch from an on-on to an on-off-on switch to allow for a neutral mode to access menu settings and to avoid any safety issues that may occur while a camera is selected. Our sponsor notified us while we were creating the final design that there is another requirement for the module to have a feature in which the settings can be accessed. With an on-off-on switch, when the selection is in the "off" mode, Stoneridge has the capabilities with our module to add a settings menu and keep the original software on the back end.

Furthermore, we realized with the iteration two rocker switch, one camera was always selected to pan and there was a chance that the user would bump into the rotary knob which could affect the view of the driver. If no selection is desired and the user wants to avoid accidentally changing the pan settings, the user can put the switch into the off state. User testing concluded that the two binary functionalities, day/night mode and fold continue to be easy to use and no other changes have been made. The changes in module operation from iteration two to the final design can be seen in Table 11 below.

Table 11: Table displaying operation changes made between iteration two and the final design

Function	Iteration Two Operation	Iteration Two Design Operation
Brightness	1) Press and or hold the + or - brightness button	1) Stays the same
Zoom	1) Press button once for 200%, twice for 300%, three times for 400%	1) Press and or hold the + or - magnifying glass to change to/between 100%, 200%, 300%, 400%
Pan	1) Select the L/R on the rocker switch 2) Pan with the rotary knob (no need to deselect anything)	1) Stays the same 2) Stays the same
Day/Night & Fold	1) Press the button to toggle on and off	1) Stays the same
Retain Original	1) Unable to complete	1) Select the middle option of the

Module Software	functionality	rocker switch

As can be seen in Table 11, the zoom feature and functionality in addition to our new requirement of retaining original module software was the only change. From our user testing results, we kept the same buttons to operate brightness, day/night, and fold while keeping a rocker switch and rotary knob to pan the camera. The changes in the operation of the functionalities are based on the evidence from our controller usability testing feedback as well as sponsor feedback. The changes to the final design reflect core ergonomic goals from features that adhere to proximity and consistency.

As seen in Figure 24 below, the design remained with the same general style and size specifications at 8 in x 3.25 in x 2 in length, width, and height, respectively. We left it at these dimensions as they continue to fall within our size specification dimensions of 10 in x 3.25 in x 1 in.

Figure 24: Final Module 3D printed with a rotary knob, rocker switch, six buttons, and window switches

Wiring

When creating our final design, slight adjustments were made to the wiring of our module, which can be seen in Figure 25 below. Most notably, we included an additional button and excluded a breadboard. Our team decided to exclude the breadboard not only because of the limited space in the module but also due to final designs utilizing soldered wires together or housing crimps. In the wiring diagram below, soldered wires and or soldered locations are indicated by a black dot with a white outline. The two soldered areas are for all of the positive and negative ends. The pin selections have also been adjusted since the optical encoder needed to utilize the Arduino's input pull-up function, which is only available for components using ports 2 and 3.

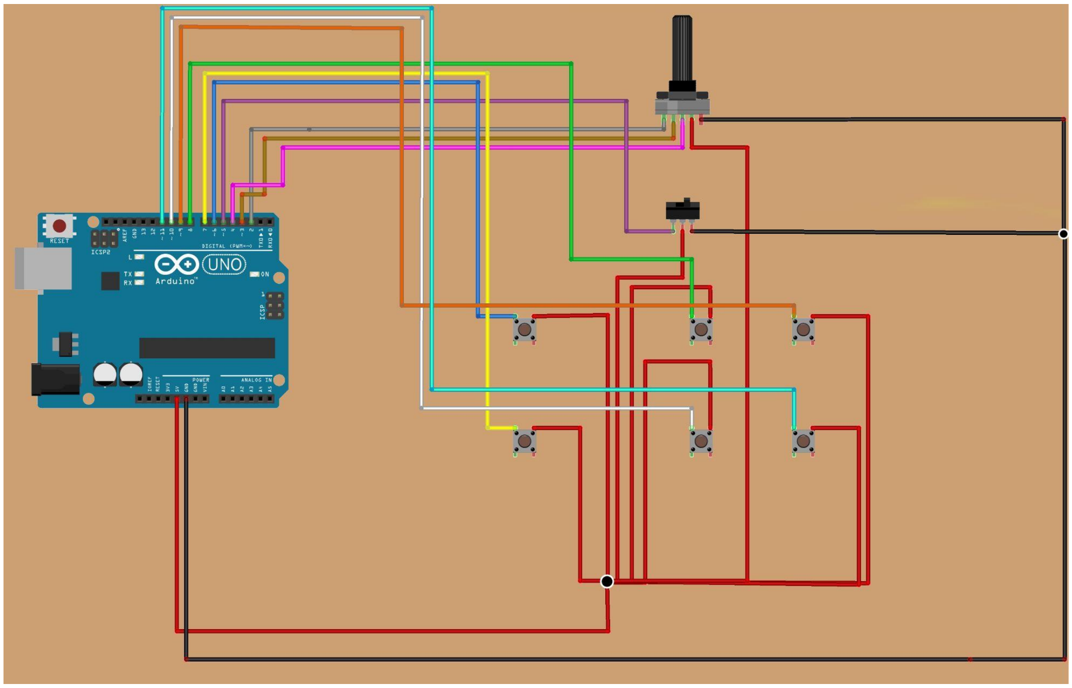


Figure 25: Wiring diagram for the final design. Soldered wires are indicated by the black dots with a circle outline.

BOM and Manufacturing Plan

With the final design, also known as the building design, completely developed, we were able to gain an understanding of what parts were required, and how we intend to manufacture and assemble iteration two The final build consists of the following parts as shown in the Bill of Materials(BOM) below: the module base and lid, an indicating knob and set screw, an optical encoder, a rocker switch, six momentary push buttons, some epoxy resin, and an Arduino R3. The total cost of our build design is $61.64, and a cost breakdown per part can be found below in Table 12.

Table 12: Build Design BOM, Cost of Supplies, Price per Assembled Build Design

Part No.	Part Title	Material	Dimension(s)	Supplier	Quantity	Price Per Unit	Price	Notes
1	Module Body	ABS Plastic	8" x 3.25" x 2"	3D Printing	1	$3.43		3D Printed
2	Module Lid	ABS Plastic	8" x 3.25" x 0.35"	3D Printing	1	$2.72	$23.99	3D Printed
3	Encoder Mounting L Bracket	ABS Plastic	1.2” x 0.76” x 0.26”	3D Printing	1	$0.59		3D Printed
4	Indicating Knob & Set Screw	Anodized Aluminum	15/16" x 5/8" & #6-32	McMaster-Carr	1	$3.60	$3.60	6332K44
5	Optical Encoder & Mounting screws	N/A	3.5" x 2.6" x 1.3"	Tegg	1	$8.99	$8.99	Amazon
6	Rocker Switch	Plastic	1.614" x 0.945" x 1.653"	McMaster-Carr	1	$26.02	$26.02	6797T13
7	Push Button Switch Momentary Circular Cap	Plastic	1.02" x 0.75" x 0.75"	APIELE	6	$1.92	$11.49	Amazon
8	Gorilla Epoxy	Epoxy Resin	N/A	Outdoor Gear & Hardware	1	$1.26	$12.57	Amazon
9	Arduino R3	N/A	3.15" x 2.36" x 0.39"	ELEGOO	1	$12.99	$12.99	Microcenter
					Total Cost	**$61.64**	**$101.67**	

Parts 4-8 were flat rates upon purchasing the line item, but the cost of the module base and lid and the potentiometer mounting bracket had to be calculated. From our CAD models, we were able to obtain the volumes of the module body, lid, and mounting brackets, which were 10.55 in^3, 8.36 in^3, and 1.82 in^3 respectively. We plan to print these parts with a 50% infill, which will result in a total volume of filament used to be roughly 10.365 in^3. The standard cost of ABS filament is $0.65 per in^3, which led us to the costs of the 3D printed parts as seen in the iteration two bill of materials.

The total cost of manufacturing the build design is mainly dependent on the rocker switch, optical encoder, and Arduino. According to our specifications, we aim to have the total cost of manufacturing to be ≤ $40. After further investigation, $5.79 from Robotistan was the most inexpensive Arduino we could find, but we have found a cheaper rocker switch for $4.94 from Morris which would bring the total cost of manufacturing to $33.96 (*Robotistan*, n.d.) (*Morris*, n.d.) For iteration two, if we implement these more inexpensive alternatives, we expect to obtain a final build design cost that meets our ≤ $40 specification.

Manufacturing Plan

Upon completion of our 3D prints, the module for iteration two will be assembled under the following procedure presented in Table 13 below. The epoxy sealant application zones and the mounting bracket orientation can be found in Appendix I and J respectively.

Table 13: Assembly Procedure for Final Build Design

Step Number	Description
1	All electrical components will be soldered, heat-shrunk, and crimped as necessary.
2	All 5 buttons, the rocker switch, and the window switches will be brushed underneath with epoxy and adhered to the module body.
3	The encoder will be fastened to the L bracket using 2 #4-40 mounting screws
4	The mounting L bracket will be brushed with epoxy and adhered to the inside portion of the module body.
5	The rotating knob will be fastened to the optical encoder D-shaft using a #6-32 set screw.
6	All electrical components will be wired to the Arduino according to our wiring schematic.
7	The bottom portion of the module body and the top portion of the module lid will be brushed heavily with epoxy and clamped together until the epoxy sets, thus keeping all electrical components inside the body.
8	An additional coating of epoxy will be applied along the seams of the module to ensure an IP67K rating is reached.

We have confirmed that Stoneridge possesses injection molding technology, so we have planned for our final design to be injection molded. Our final design is made out of ABS plastic, one of many thermoplastics suitable for injection molding, has a uniform thickness, filets on all corners, and does not require a tighter tolerance than ±0.005”, which is the tolerance of injection molding (Technologies, 2020). At first, we held concerns about the tolerances of holes and slots for the electric components, so to combat this issue, the holes were adjusted such that the holes and slots would never be too small for the electrical components. The scenario in which the holes are slightly too large due to tolerances is insignificant due to the buttons, switches, and encoder being epoxied or screwed to the module body. Figure 26 below is the exploded view of all the parts that will be assembled. This figure does not include the wiring that will be completed in step six but does peak into the placement of the L-bracket with two #4-40 mounting screws.

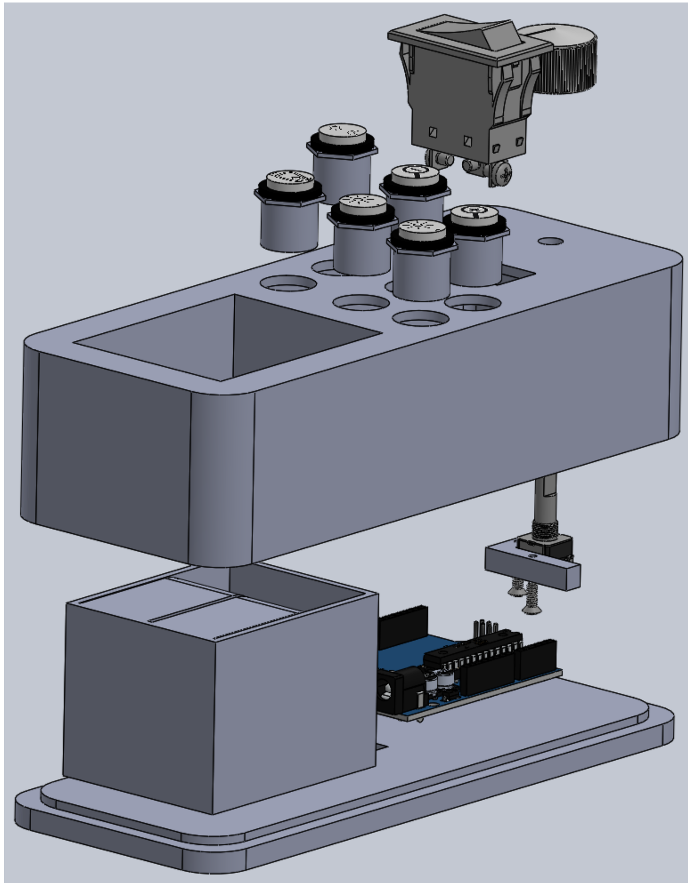


Figure 26: Exploded view of the final module with the placement of parts such as module body, lid, rocker switch, rotary knob/optical encoder, L-bracket, Arduino R3, window switches, and six buttons.

Another concern that exists with injection molding is the initial cost since a new die must be designed for our specific design. The die for this part must also include cores for the holes and slots which will inherently increase the cost of development. Considering how Stoneridge has utilized injection molding for their previous module, we are not concerned about the feasibility of creating a new die, since it is apparent that Stoneridge has completed cost analyses on various manufacturing systems and determined die development and injection molding as the most cost-effective choice. Upon confirming our plan to utilize injection molding, we created a list of the steps needed to manufacture the final design as seen in Table 14.

Table 14: Manufacturing Plan for the Final Design

Step	Process Description	Machine	Notes
1	Injection Mold Parts	Plastic Injection Molding Machine	Diecast will require cores to form the holes for the buttons and switches
2	Buttons, switches, and rotary knob adhered to module body	Assembly Line	
3	Electrical components wired with pre-crimped ribbons	Assembly Line	
4	The back cover adhered to the main module body	Assembly Line	
5	Module dipped in a pool of epoxy resin to create an outer shell of sealant	Silicone Coating Station	Protective cover
6	Rubber cover with icons imprinted on the design placed over the buttons	Assembly Line	Externally Manufactured/Outsourced

Further Verification and Validation Approach

Although we have already begun verification and validation of our design with usability testing of our iteration one module, we did so without a fully functional controller. The iteration one testing was performed without having the controller wired to an Arduino with serial monitor feedback, which limited us to testing mostly the ergonomics and intuitiveness of our module. However, our iteration two final build design will be properly wired and fully functional with serial monitor feedback, which we will use to appropriately verify and validate our specifications. Table 15 below depicts our verification and validation(V&V) plans for each of our requirements.

Table 15: V&V Plan of Every Design Specification Organized by Priority

Requirement	Specification	V&V Plan	P/F ?
1. Easy to Operate	Perform each functionality (see reqs 2-6) ≤ 2 times before being able to operate controller without looking	- Ask multiple users to perform a predetermined list of tasks 2x while looking, 1x without - Time users for each task and note # of times it takes to memorize - Necessary equipment: controller, laptop, stopwatch	**P**
2. Brightness Functionality	Brighten screen in 10% Increments	- Connect prototype controller to laptop - Confirm Arduino serial monitor feedback is capable of meeting each specification. - Necessary equipment: controller, laptop	**P**
3. Day/Night Mode Functionality	Switch between modes within 200ms		**P**
4. Pan Functionality	Pan continuously from 0 to ≥ 120 degrees		**P**
5. Fold Functionality	Fold external cameras by ≥ ±90 degrees		**P**
6. Zoom Functionality	Zoom to 200%, 300%, 400% of the standard view		**P**
7. Retain Original Module Software	Has accessibility to setup menu		
8. Size	Length: ≤10 in Width: ≤3.25 in Depth: ≤3 in	- Use Solidworks "measure" tool, ensure the controller dimensions are within the appropriate dimensions.	**P**
9. Low Cost	≤ $40	- Perform a cost analysis using GRANTA based on BOM (Extrapolate current Stoneridge material and manufacturing costs as needed). - Necessary equipment: GRANTA software	**P**
10. Durability	≥ 15 years	- Perform an FEA analysis to simulate the 15-year usage cycle of the controller. - Necessary equipment: ANSYS software	
11. Easily Cleaned	Must abide by IP67 (Electrical Enclosure Rating)	- Perform IP69K Degree 9 Testing - Perform IP67 Degree 7 Testing - Shared Dust Rating (place module in blowing chamber and expose to dust)	

Validation Testing

Our main focus will be completing validation testing on our high-priority requirements indicated in green in Table 15 above. We have already completed the first round of usability validation testing, from which we came up with our iteration 1 final build design. We re-ran our usability test procedure (see Appendix D) using the iteration 2 build design to create our final build design. To validate that our module meets the highest priority "Easy to Use" specification, we used the same testing procedure 2x while the user was looking at the module and 1x without looking. While looking at the module, all the users were able to complete the functionalities successfully. Table 16 below displays the results of our validation testing when users were not looking at the module to confirm our module is "Easy to Use."

Table 16: Validation results for Easy to Operate Functionality

Functionality	Results
Fold	9/10 users used the button without looking on the first attempt Average time to complete: <1 sec
Day/Night	10/10 users used the button without looking on the first attempt Average time to complete: <1 sec
Zoom	8/10 users were able to increase and decrease without looking on the first attempt 10/10 users were able to complete tasks without looking on the second attempt Average time to complete: 5 sec
Brightness	7/10 users were able to increase and decrease without looking on the first attempt 10/10 users were able to complete tasks without looking on the second attempt Average time to complete: 6 sec
Pan	10/10 users used the button without looking Average time to complete: 3 sec

As can be seen from the table, a high majority of users were able to use all the functionalities without looking once they were taught how to use the module multiple times. The reason certain users had trouble with zoom and brightness is due to accidentally hitting the decrease zoom or brightness when increasing the functionality was the goal. They were quick to correct themselves as the module provided feedback to indicate they were pressing the wrong button.

Our validation continued with our build module in which we used the Arduino to provide serial monitor feedback. We verified that our module can meet the specifications for each of the functionalities listed in requirements 2-5.

Our second build design and final module included serial monitor feedback testing and allowed us to test our easy-to-use requirement in addition to functionality requirement. Additionally, we have already passed our size specification after using the Solidworks “measure” tool feature. We confirmed that our size is within the specification specifically being 8 in. x 3.25 in. x 3 in. We were unable to validate the retaining original module software requirement with the time we had once we learned of its need. We do know that the “off” feature on the rocker switch, would enable Stoneridge to insert their back-end software here for users to access the menu settings.

Verification Testing

With our final BOM, we generated a cost analysis using GRANTA. We extrapolated the current Stoneridge material and manufacturing costs as needed. Below are the results of our cost analysis to prove that the cost to manufacture this product is below the $40 threshold.

Table 17: Verification results for cost analysis using GRANTA

Phase	Energy (kcal)	Energy (%)	CO2 footprint (lb)	CO2 footprint (%)	Cost (USD)	Cost (%)
Material	1.46e+04	84.2	7.1	79.6	2.63	89.1
Manufacture	340	2.0	0.239	2.7	0.000698	0.0237
Transport	331	1.9	0.204	2.3	0.126	4.28
Use	2.04e+03	11.8	1.36	15.2	0.192	6.49
Disposal	23.8	0.1	0.0154	0.2	0.0032	0.109
Total (for first life)	**1.73e+04**	**100**	**8.91**	**100**	**2.95**	**100**
End of life potential	0		0			

For our lower priority requirements 10 and 11, we have V&V test plans in place, but it is possible performing the plans for these specifications is outside the scope of this semester-long project.

Our team has a high level of confidence that we will be able to meet our lower-priority specifications. For durability testing, we do not anticipate having the time to learn the necessary FEA techniques in time to perform an accurate analysis, but we plan to account for this with necessary material research, which we will use in our recommendations to Stoneridge. Finally, for our last requirement of being easily cleaned, although we likely will not have the time to perform physical ingress and enclosure testing of our module, we have included these considerations in our manufacturing plans and have outlined a detailed test procedure for verifying this specification, which can be seen in Appendix H.

Anticipated Challenges and Solutions

Throughout this project, there were several challenges that we had and problems solved as a team. Our biggest concern focused on the time constraints that we dealt with from our planning and perseverance. Our primary challenge occurred from putting together our module in a timely fashion to have enough time for user testing and validation/verification testing. While adjusting the CAD model and reordering buttons is not time intensive, 3D printing at the UM machine shop took several days due to the queue for the printers as well as the time it took to print the module. Additionally, when we would change the buttons or switches, we also had to re-solder and re-crimp the buttons as well. To reduce the overall time to manufacture and assemble the module, our solution was to use one of our team member's 3D printers and at times complete tasks like wiring ahead of time.

Once the module was printed, we had challenges associated with accurate testing with a short timeline that we created for ourselves. We were worried about finding those that would test our module promptly and provide us with concrete data to make our design changes. Our solution was to create a concrete test protocol as seen in Appendix D that prepared our team with steps to ask each user. We also created tests that could reach a larger audience such as the Google form for icon testing as seen in Appendix F. In addition, we found a confirmed network of volunteers that we could rely on to get all our testing done. This group consisted of multiple demographics including differences in gender and race.

Another concern that occurred was the proper functionality of our code. Since the module required fast reaction speeds to user inputs, it is critical that we programmed the Arduino to utilize O(1) or O(n) run-time and minimize memory consumption. We had to consider false inputs that might occur from the car vibration or half-pressing a button on accident. To account for these false inputs, we elected to use debouncing sequences within our code. The debouncing sequence operated by checking inputs every 200 milliseconds, as opposed to every 1 millisecond, and only considered the input valid if both inputs were positive or negative.

Project Plan

To track our project progress, we used a Gantt chart that contains all project deliverables, internal deadlines, and additional tasks (see Appendix E). Tasks were scheduled several weeks in advance, with general deadlines established at the beginning of the project. As deadlines approached, more specific tasks were assigned to each member of the team. From our Gantt chart, we saw that the scope of the project is achievable. Team members could mark their progress on the chart, which kept us on track and aware of each other's progress.

After the Design Expo, we completed the remainder of our verification and validation testing for all our requirements. Afterward, we were able to complete a final CMS Controller CAD prototype, which we plan to deliver to Stoneridge by December 12th, along with our final report. Due to our time constraints, we did not complete durability testing using Ansys or ingress testing to an IP69k rating on our module. However, we outlined detailed protocols for each of these tests and have communicated with Stoneridge that they will perform these tests.

Although we completed everything we set out to do within this semester-long project, there remain a few action items that would be beneficial to fully complete this project. This includes connecting our module to Stoneridge's MirrorEye CMS and having their drivers validate the new design. This would involve mounting the module in the new location and ensuring the Arduino is compatible with their software system. However, this would provide the most realistic and accurate feedback on our final design, which Stoneridge can use before making any tooling updates and manufacturing the production control module.

Recommendation

Our recommendation for this final module is based on future legislation of current mirror controls being removed from trucks and buses and our module replacing them. We recommend that any further work completed on Stoneridge's HMI module is completed using the CSED design process described in this report. Further testing will be needed to verify and validate the final design before further improvements are made.

From our final validation and verification testing, the prototype is our recommendation for a MirrorEye CMS controller that is more easy-to-use and highly learnable than current generations. Table 18 below lists the specific improvements our module contains compared to the Generation 1 CMS controller.

Table 18: Differences between Stoneridge's CMS controller and Team 16's Final Module

	Generation 1 CMS Controller	Team 16's Final Module
Location	- Placed next to tractor break - Hard to reach while driving	- Placed on the driver's side armrest for easy use while driving
Functionality	- Multiple steps to complete brightness, zoom, and pan	- Only panning requires two steps to complete
Intuitiveness	- Requires drivers to be taught multiple times and need to look at module while using	- Can be used without looking after two times of teaching
Durability	- All durability tests have been passed and used for commercial purposes	- Requires durability testing before commercial use

If legislation for removing current mirror controls does not get passed, we do have further recommendations on features that are integral and continue to meet the goals of driver safety and the intuitiveness of a module. However, the passing of this legislation is quite integral to the success of the MirrorEye system as a whole. Nonetheless, Figure 27 below is a design that we believe will still adhere to our problem statement.

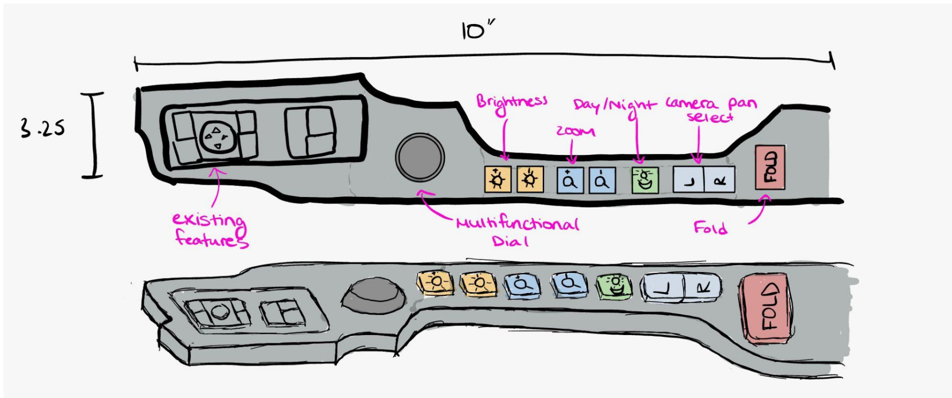


Figure 27: Drawing of alternative final design solution if legislation to remove current mirror controls does not get passed

This design still contains all the features we tested and approved to be easy to use and have high learnability. With more time, we would go on to test a module like this and see if it is feasible to use while driving. A weakness of this design is that it does not include a place for the driver to rest their arm. With further user testing, we would try to create multiple iterations that would allow us to provide a final recommendation for Stoneridge.

Discussion

Our problem definition and iteration process would be expanded upon if we had more time with the project. Specifically, we were focusing on the ergonomics and location of the features like a button or rocker switch and not on the chip that Stoneridge should utilize or the housing unit the module contains for efficient wiring connections. In the interest of providing the most data for our ergonomic and human factors testing, we only focused on electronics that would allow us to create a functional prototype for user testing.

Strengths and Weaknesses of Design

We do believe that our final design has a lot of strengths that are useful to Stoneridge. Our biggest strength is that all our decision-making is evaluated based on evidence. We did not make any design decisions without concrete evidence from user testing or ergonomic research on consistency and proximity. Our design does satisfy almost all our requirements except the durability requirement which is a lower requirement for our team and our sponsor. Lastly, our module does solve the problem that we set out which is easy to operate and highly learnable. Our goal was to increase driver safety and we are confident our module solves the problem Stoneridge set us out to complete.

There are a few weaknesses we would address if we had more time on this project. During our concept generation stage, there was a narrow exploration of the design space. While we did create a multitude of designs, the quality of all the designs was not high enough and it helped us narrow down our designs to the top 6-8 easily. With more time, we would conduct more brainstorming and possibly do some testing into center console modules and features that we can add to a module. Next, while our design changes are based on evidence, we do acknowledge our small testing sample size with users of only up to 30 people. Ideally, we would spend more time testing our module on over 100 users and provide our iterations to Stoneridge to have actual drivers test it.

Lessons Learned

Throughout our design project, there were numerous lessons that we learned. As a team, we learned the importance of a project manager handing out tasks to the team and planning out when different tasks need to be completed. We had challenges that were time-oriented and with a better project plan, we could have solved those problems much easier.

For Stoneridge, lessons were learned specifically on design ergonomics and what users preferred when using a device. In ergonomic design, we learned that to get a device that is easiest to operate, features with the same functionality on the device should be close in proximity. At first, we learned problems occurred that users never used the rotary knob due to the distance from the pan buttons that were associated with it. Our design change was to keep a rocker switch and rotary knob close to each other. Next, we learned that consistency is needed between functionalities that have similar tasks.

As mentioned earlier in the report, users had problems understanding how to increase and decrease the singular zoom button. This is due to the brightness functionality having an increase and decrease button and a lack of consistency between functionalities. Consistency is very important as we learned that a device that has similar features to what users use on a day-to-day basis leads to higher learnability and usability.

Reflection

Social, Global, and Economic Factors

Throughout this project, we have learned about important global, social, and economic contexts that impact engineering decisions. We have applied these different factors to our project to examine how our controller module impacted social, economic, and global welfare. Our module is connected to public health, safety, and welfare through its use in the semi-truck. The controller module operates the Camera Mirror Eye System connected to semi-trucks, which makes semi-trucks safer and prevents devastating truck accidents. By preventing truck accidents, our controller module makes the roads safer for all drivers, which improves public safety and welfare. In a global marketplace context, the controller module improved the global economy by improving the safety of semi-trucks. Improved semi-truck safety means that more deliveries are completed faster, which improves the local and thus global economies.

There are different social impacts throughout the lifecycle of our module. The primary manufacturing technique associated with the final module design is injection molding, which can have significant environmental impacts due to the release of pollutants during production. However, injection molding is also associated with improved manufacturing techniques which leads to more jobs and more advanced manufacturing capabilities. During the use phase of the controller's lifecycle, there are positive social impacts. The controller enables drivers to control their truck cameras, which eliminates blind spots and makes semi-trucks significantly safer. Socially, the disposal of our module should not have huge negative impacts. Our module has a fairly long lifespan of 15 years and is small in size, so it will not take up significant space in the landfill. However, the module would end up in a landfill which would have an overall negative impact, especially if there is a module in every semi-truck. From an economic standpoint, the manufacturing of our module is fairly cheap. The module is injection molded, which is a cheap process capable of producing large amounts of consistent parts, making the module cheap and easy to mass produce. Running the module should not have an extensive economic impact on the truck driver, as the module is electrically powered by the truck's battery. The module will provide a positive economic impact, as drivers will be able to complete their deliveries faster and safer. The cost to dispose of the module is relatively low. Per our GRANTA cost analysis, the cost of disposal will be $0.0032 per module.

To characterize the social impacts of our module, we used a stakeholder map (page 10). We completed a thorough stakeholder analysis to consider all stakeholders impacted by and involved with our module. Our stakeholder map allowed us to identify important design considerations and constraints based on who we were designing for. To analyze our module's lifecycle, we used GRANTA to understand the entire lifecycle of our project. GRANTA helped us understand the environmental and economic factors impacting our design. Overall, the largest environmental impact comes from the materials used to make the module, contributing a total of 7.1 lbs of CO_2.

Designer Privilege

As a team of five coming from different backgrounds, our backgrounds influenced our team approach. While we all have a common educational background as seniors at the University of Michigan, we had different approaches to the project based on our previous experiences. Our different perspectives enabled us to consider innovative solutions that considered a broad range of viewpoints. While we occasionally had contrasting approaches to various aspects of our project, we were able to successfully discuss as a team and move forward in a way that benefited the team and project.

Between our sponsor and us, there were some significant privilege, stylistic, and power differences. Our sponsor was responsible for giving us background knowledge on our project and helping guide us through the process. As a full-time employee, Mr. Lepage had more power over our team of five college students, due to the nature of his job and our responsibilities as students. Based on the course format, we had specific course deliverables we had to meet during the project that did not allow us to take detours from our original project plans. Our sponsor had significantly more engineering experience than us, which gave him more power over us as designers. He also had the privilege of working on the project for a much longer duration than us. We had to step into the project quickly with a limited time frame and understand all aspects of the project within our available time frame.

Inclusion and Equity

Between our team and stakeholders, there were different types of power dynamics. There was designer power between us and the truck drivers since we made the design decisions that would impact the truck drivers' use of the module. Between our team and Mr. Lepage, there was a formal authority power dynamic. Mr. Lepage is a full-time employee at the company we were doing the project for, and we were 5 university students working on a project for him, thus making him an authority figure over us. There was a cultural power difference between teammates as we come from different cultural backgrounds, and a gender power difference between Grace and Tank and Ben, Alan, and Govind. To include diverse viewpoints, we made sure to listen to all team members and give ample opportunity for everyone to be involved and work on different aspects of the project. In our testing processes, we attempted to poll a variety of different people to get opinions from people of multiple backgrounds. Despite our best efforts, we acknowledge that our data is skewed toward University of Michigan students and does not accurately represent the stakeholders we were designing for.

Among the team, we balanced ideas by ensuring that our decisions were based on clear evidence. Our design was fully evidence-based on our user tests, so our design decisions were not made by the team but were made from clear user evidence. When we did need to make decisions we had a thorough team discussion of various pros and cons, and came to a team consensus on design decisions.

Our team consisted of a wide variety of different cultural backgrounds. We had many different religious backgrounds, different ethnic backgrounds, and different origins, making us a diverse team with a wide range of life experiences. Our different backgrounds influenced how we approached our project, specifically how we believed users would interact with the device. Based on this, we used an evidence-based approach to ensure that our design incorporated the views of stakeholders other than our personal beliefs. As a team, we had multiple discussions where we set expectations and agreed on the direction our project was going to take, using a team approach to ensure everyone was on the same page.

Ethics

Our project was not ethically complicated. Improving the safety of semi-trucks benefits society on the whole, as it prevents devastating traffic incidents and keeps roads safe. While the semi-truck industry has a negative impact on the environment, our project would not change the semi-truck industry as a whole. Making the trucking industry safer also prevents accidents which may spill hazardous material into the environment, so overall the environmental impact of our project is a net positive. If our project was to enter the marketplace, we believe that it is relatively straightforward ethically. Society on the whole benefits if the roads are safer and if deliveries are made safely.

At the University of Michigan, we follow a strict honor code that outlines the expectations of engineering students and prepares us to be engineers with integrity and strong moral values. As a team, we upheld the values expected of us as students at the University of Michigan and as a Stoneridge-sponsored project team. We considered the project from an ethical basis to ensure that our project upheld all ethical standards as University of Michigan students. Working with Stoneridge gave us exposure to working with the ethical standards in the industry. Going forward, we plan to abide by the ethical standards of the companies we work for and ensure we meet the strong moral values learned during our time at the University of Michigan.

Conclusion

After an in-depth evaluation of the contextual factors, relevant stakeholders, requirements, specifications, and anticipated challenges surrounding our MirrorEye controller project this semester, our team established a clear understanding of the project scope and developed a final prototype to present to Stoneridge. Generally speaking, our project had a strong emphasis on user experience, stressing the importance of design iteration to achieve our desired end goal of a fully functioning 3D printed controller prototype. We created first and second-iteration modules and conducted user testing to determine what buttons and functionalities worked well and where we needed to improve between each iteration to arrive at our final design. We also conducted a survey to determine which icons were most intuitive for users and a knob test to determine which rotating knobs users preferred. We presented our final design at the ME 450 Design Expo and completed verification and validation of our final design. We were unable to perform our last validation and verification tests such as durability, ingress testing, and the requirement to keep the original module's software within the semester-long time frame, but have outlined those test protocols and communicated the next steps to Stoneridge.

Acknowledgments

There were several important contributors to the success of our project this semester. Our team would like to acknowledge Gabe Lepage, Banuprakash Murthy, and the remainder of the Stoneridge MirrorEye engineering team for their guidance. We would also like to thank Randy Schwemmin, the ME Machine Shop Personnel, and the rest of the ME 450 instructional team for their help throughout the semester.

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Bios

Govind Menon is a senior Mechanical Engineering student graduating in December of 2023 from Sunnyvale, CA. He started his ME career at the University of Portland prior to arriving at the University of Michigan. He gained an interest in engineering as a kid from his love of all kinds of vehicles from fire trucks to sportscars. He has lots of experience in the workforce with being an IT intern, a chef as well as a sales associate at Golf Galaxy. At GM he was a manufacturing engineering intern with a project objective to 3D print a car. He needed to replace typical sheet metal prototype parts with 3D-printed parts for cell validation purposes. At Gulfstream he was a design engineer involved with designing various shop aids with Catia V5. In addition, he assisted with flight tests as well as creating a new print request form for the 3D printing team using Alchemer and Microsoft Power BI. Outside of the classroom, he is involved as an Engineering North Campus Tour Guide and an operations member of the UM Solar Car team and loves to cook and watch sports. His favorite memory at UM is the Michigan football team defeating the "team down south" during his first year at Michigan. After his time at Michigan ends, he wants to pursue a career in the aerospace/defense industry as a design and systems engineer. After a few years in the technical side of the industry, he wants to go into the management side and be able to lead teams or eventually a company.

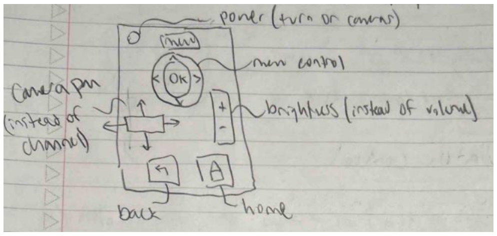
Alan Solovey is a senior from Westfield, NJ majoring in Mechanical Engineering (ME) and graduating in May 2024. His inspiration to pursue ME came from his curiosity of how things worked and love of building things from a young age. As he progressed through school, he found that his math and physics skill set made him well suited for the major. Alan has had several rewarding experiences while being an ME at the University of Michigan. After his sophomore year, he interned as a product development engineer at Ford working on the rear frames for their next generation electric pickup truck. His junior year, he was an instructional aide (IA) for ME 382 during the first semester and for the second semester, he took a break in his studies to pursue a co-op at ZOLL Medical where he was part of the R&D team focussed on the designing ventilators. Here, he designed a test fixture for ventilator cable cycle testing and was involved with several other design and testing projects over the course of 7 months at the company. He really enjoyed his experiences in the medical device industry and hopes to pursue a postgraduate career in the field with a focus on design or controls. Outside of school and work, Alan loves to cook, spend time outdoors, travel the world and is a huge sports fan.

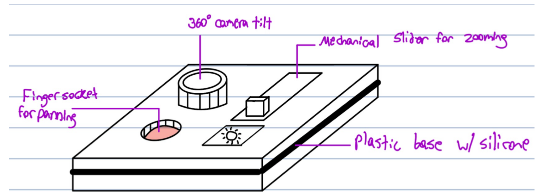
Grace Haller is a Senior in Mechanical Engineering graduating in December 2023, with plans to pursue a masters in Mechanical Engineering immediately after graduation. Her inspiration to become an engineer started in 3rd grade when she discovered she enjoyed math. Her love of math, physics and building things turned into pursuing engineering as a career. Grace grew up in Bellevue, WA, and her love of aerospace came from watching the Blue Angels fly over her house during SeaFair, and close proximity to Boeing. Grace has spent a semester and summer working for Gulfstream Aerospace in Savannah, GA as a structural design intern and an experimental test intern. As an experimental test intern, Grace had the opportunity to conduct high priority, high visibility flammability certification tests for the G700 and special missions planes. Grace is continuing to pursue a career in the aerospace industry, and eventually wants to work as a test engineer in the Space Industry. At the University of Michigan, Grace works as an instructional aide for ME 250 and is a part of the Mars Rover Research and Test team. Grace has also rowed on the Women's Crew team, been a part of the Naval Reserve Officer Training Corps, and held several positions in Phi Sigma Rho Engineering Sorority. Outside of school, Grace enjoys working out, cooking, and hiking, and has a personal goal to visit all 62 national parks.

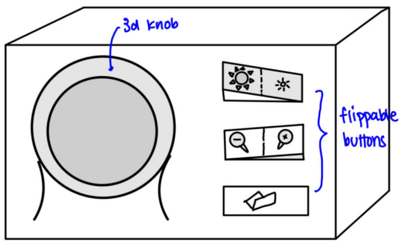
Benjamin Davidson is a Senior in Mechanical Engineering graduating in April of 2023 and also holds a Computer Science minor. Originally from Syosset, New York, 5 minutes away from where the double helix DNA structure was discovered, Benjamin initially found interest within mechanical engineering from the television show How It's Made, and his passion for solving Rubik's Cubes. His best time was 13.74 seconds, but it was an extremely short lived passion. Throughout highschool, Benjamin spent his free time on the robotics team as well as practicing and performing free form improvisational comedy and stand up comedy. He also aided with tutoring sessions varying for all K-10 students. Upon arriving at the University of Michigan, he continued his passion for stand up comedy, but wanted to make studying for his classes his main priority. Freshman and sophomore summers were spent teaching K-12 students how to program as well as increasing his proficiency in SolidWorks. During Junior year, Benjamin realized that he had a passion for Structural Engineering, and decided to switch career paths. He spent 7 months studying for the FE examination, and fortunately passed the exam this august. This past summer was spent working for Modular Steel Systems, which is a modular manufacturer based out of Bloomsburg, PA. He spent his time there working on calculating the gravity and lateral loads on modular homes consisting of solid sawn lumber and flitched beams. He also began to familiarize himself with structural code books such as the IRC, IBC, and ASCE 7. Outside of university, Benjamin aims to work for a structural group for 4 years in order to qualify for the PE examination and hopefully obtain his license. Outside of school work, Benjamin enjoys listening to music, lifting weights, cooking, and watching movies.

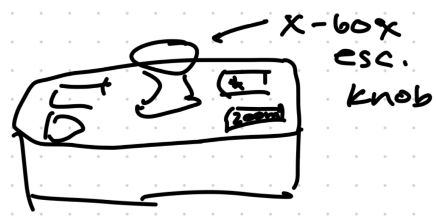
Lamia Tank is a senior in Mechanical Engineering with a concentration in Robotics, graduating December 2023 from Farmington Hills, MI. Growing up in the state that is the home of automotive Tank's interest in mechanical engineering started from going to the Detroit auto show since the age of one, and carried on into highschool being the computer aided design (CAD) lead for her FIRST robotics team. Tank's career has progressed by spending two summers at General Motors Defense (GMD), where she will be returning full time in June 2024 as a subsystems architect engineer, after beginning her masters in systems engineering come January 2024. During her time at GMD, Tank's focuses were on additive manufacturing brackets and prototype parts to fit, as well as harness engineering to set up test benches for military vehicles. Harness engineering included creating pinouts while clearance filtering as well as laying down every wire from each module connector pin, to connecting each physical module in a vehicle skeleton for bench testing. Outside of engineering, Tank works as an Architect and an Intramural sports referee, is pursuing her certification in sign language interpretation, and loves riding her motorcycle.

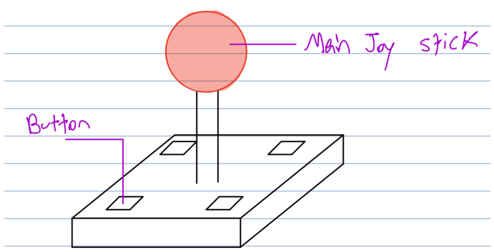
APPENDIX A: Concept Generation

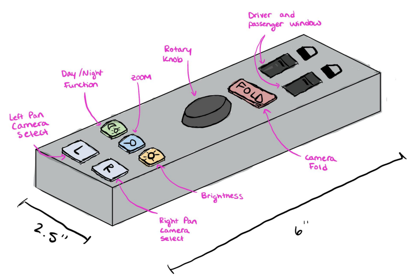


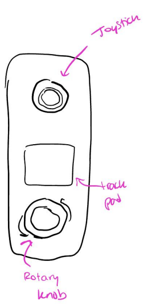


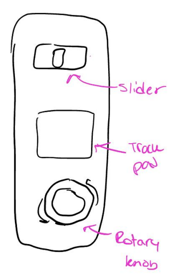


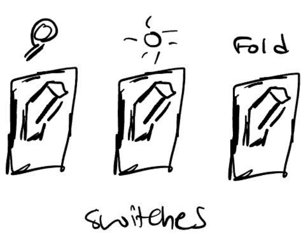


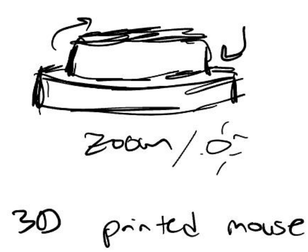


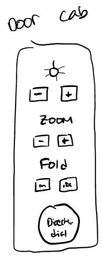


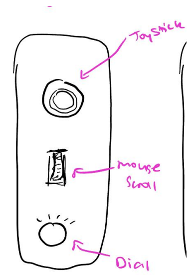


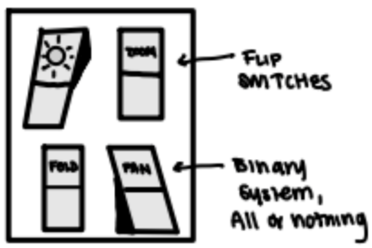


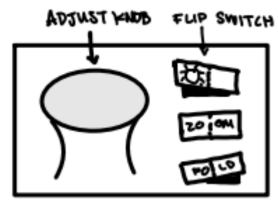


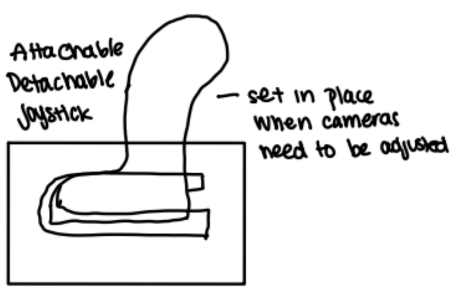


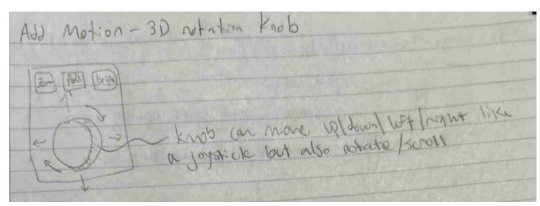

Door cab
Zoom
Fold

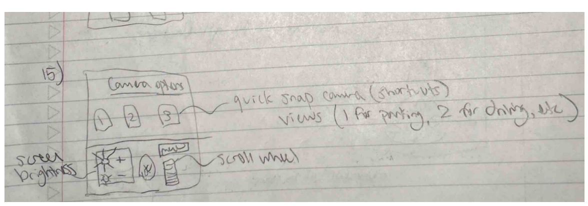

Joystick
Mouse Scroll
Dial

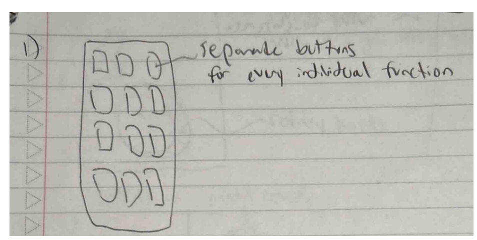

ZOOM
FOLD
PAN
Flip switches
Binary system,
All or nothing

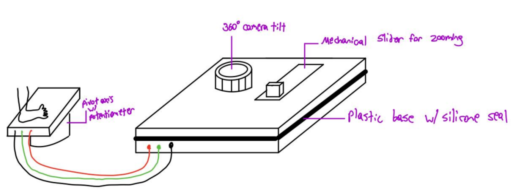

ADJUST KNOB
FLIP SWITCH
ZO OM
FO LD

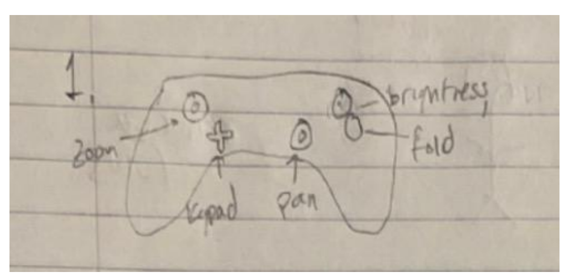

Attachable
Detachable
Joystick
set in place
when cameras
need to be adjusted


Add Motion - 3D rotation knob
knob can move up/down/left/right like
a joystick but also rotate/scroll


15)
Camera options
quick snap camera (shortcuts)
views (1 for parking, 2 for driving, etc)
screen brightness
scroll wheel


1)
separate buttons
for every individual function


360° camera tilt
Mechanical slider for zooming
Plastic base w/ silicone seal


1.
brightness,
fold
Zoom
pan

APPENDIX B: Concept Selection

AHP for Functionalities

Functionalities	Brightness Functionality	Zoom Functionality	Fold Functionality	Pan Functionality	Day/Night Mode Functionality	Easy to Operate	Size	Easily Cleaned	Low Cost	Durability	SUM = Relative Weight
Brightness Functionality	1	3	3	3	3	0.33333	3	3	3	3	**25**
Day/Night Mode Functionality	0.333333	3	3	1	1	0.33333	3	3	3	3	**21**
Pan Functionality	0.33333	3	3	1	1	0.33333	3	3	3	3	**21**
Fold Functionality	0.3333	3	1	0.333	0.333	0.33333	3	3	3	3	**17**
Size	0.333	1	0.333	0.333	0.333	0.33333	1	3	3	3	**13**
Zoom Functionality	0.33333	1	0.33	0.333	0.333	0.33333	1	3	3	3	**13**
Easy to Operate	3	3	3	3	3	1	3	3	3	3	**28**
Low Cost	0.3333	0.33333	0.3333	0.333	0.33333	0.3333	0.3333	3	1	1	**7.3**
Durability	0.33333	0.333	0.3333	0.333	0.3333	0.333	0.333	3	1	1	**7.3**
Easily Cleaned	0.11111	0.1111	0.1111	0.111	0.11111	0.3333	0.11111	1	0.333	0.333	**2.7**

House of Quality 1

Requirements	Importance(out of 10)	Relative Importance %	Brighten Screen in 100 Lumen Increments	Switch between modes in 200ms	Pan continuously through ≥ ±25 degrees	Fold external cameras by ≥ ±90 degrees	Zoom to 35% of standard view	Dimensions(10"x3.25"x3")	≤ $40	≤ 15 years	Meet IP67 Electrical Enclosure rating	Perform each functionality less than 2 times
Brightness Functionality	9	16.07	9	0	0	0	0	1	1	1	1	9
Day/Night Mode Functionality	7	12.50	0	9	0	0	0	1	1	1	1	9
Pan Functionality	7	12.50	0	0	9	0	0	1	1	1	1	9
Fold Functionality	6	10.71	0	0	0	9	0	1	1	1	1	9
Size	5	8.93	3	3	3	3	3	9	1	3	3	3
Zoom Functionality	5	8.93	0	0	0	0	9	1	1	1	1	9
Easy to Operate	10	17.86	9	9	9	9	9	3	1	1	1	9
Low Cost	3	5.36	1	1	1	1	1	3	9	3	1	1
Durability	3	5.36	1	1	1	1	1	1	3	9	1	1
Easily Cleaned	1	1.79	1	1	1	1	1	3	1	3	9	1
		Importance	344.64	312.50	312.50	296.43	280.36	221.43	153.57	175.00	132.14	746.43
		Relative Importance %	11.58	10.50	10.50	9.96	9.42	7.44	5.16	5.88	4.44	25.09

House of Quality 2

Specifications	Importance(out of 10)	Relative Importance %	Button	Joystick	Rotational Knob	Touchscreen	Touchpad	Mechanical Slider
Brighten Screen in 100 Lumen Increments	6	14.63	9	1	9	3	9	9
Switch between modes in 200ms	5	12.20	9	1	3	1	0	1
Pan continuously through ≥ ±25 degrees	5	12.20	3	1	9	3	9	3
Fold external cameras by ≥ ±90 degrees	4	9.76	9	1	3	1	0	1
Zoom to 35% of standard view	3	7.32	3	3	9	3	0	3
Dimensions(10"x3.25"x3")	3	7.32	9	9	9	3	9	9
≤ $40	2	4.88	3	3	3	3	3	3
≤ 15 years	2	4.88	3	3	3	3	3	3
Meet IP67 Electrical Enclosure rating	1	2.44	3	3	3	0	1	3
Perform each functionality less than 2 times	10	24.39	9	3	9	1	3	9
		Importance	607.32	143.90	592.68	148.78	314.63	431.71
		Relative Importance	27.12	6.43	26.47	6.64	14.05	19.28

House of Quality 3

Features	Importance(out of 5)	Relative Importance %	Existing Controller	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7	Concept 8
Button	5	27.78	9	9	3	3	9	9	0	9
Joystick	1	5.56	0	0	3	0	9	9	0	0
Rotational Knob	5	27.78	9	0	3	9	0	0	0	9
Touchscreen	2	11.11	0	0	0	0	0	0	9	0
Touchpad	2	11.11	0	3	0	0	0	0	0	0
Mechanical Slider	3	16.67	0	0	9	0	0	0	0	0
		Importance	500.00	283.33	333.33	333.33	300.00	300.00	100.00	500.00
		Relative Importance	18.87	10.69	12.58	12.58	11.32	11.32	3.77	18.87

APPENDIX C: Bill of Materials for Iteration One

Part No.	Part Title	Material	Dimension(s)	Supplier	Quantity	Price	Notes
1	Module Base	ABS Plastic	6" x 3" x 1"	3D Printing	1	n/a	3D Printed
2	Module Lid	ABS Plastic	6" x 3" x 0.4"	3D Printing	1	n/a	3D Printed
3	Indicating Knob	Polypropylene plastic	1-1/8" x 9/16"	McMaster-Carr	1	$3.60	60955K72
4	Multipurpose 304 Stainless Steel	Stainless Steel	1" x 1/4"	McMaster-Carr	1	$1.93	8953K85
5	Cup-point Set Screw	Zinc Plated Alloy Steel	8-32 1/8"	McMaster-Carr	1	$16.07	91375A188
6	Push Button Switch Momentary Rectangular Cap	Plastic	1.97" x 2.36" x 0.79"	Baomin	10	$9.99	Amazon
7	Gorilla Epoxy	Epoxy Resin	N/A	Outdoor Gear & Hardware	1	$12.57	Amazon

APPENDIX D: Test Procedure

Task	Status	Time to Complete	Notes(Think-A-Loud)
1. Set Module on the left side of the User	Not started		
2. Ask the User to brighten screen by 70%	Not started		
3. Ask the User to reduce the brightness to 0%	Not started		
4. Ask the User to pan the right camera 70 degrees to the left	Not started		
5. Ask the User to pan the left camera 70 degrees to the right	Not started		
6. Ask the User to pan the left camera 40 degrees to the left	Not started		
7. Ask the User to pan the right camera 40 degrees to the right	Not started		
8. Ask the User to zoom into the screen/camera	Not started		
9. Ask the User to zoom out of the screen/camera	Not started		
10. Activate from Day to Night mode	Not started		
11. Ask user to fold the cameras	Not started		

APPENDIX E: Project Tracking

TASK TITLE	TASK OWNER	START DATE	DUE DATE
Project Conception and Initiation			
In-Class Presentation	Everyone	9/11/23	9/13/23
Stakeholder Map	Tank	9/11/23	9/18/23
Problem Statement	Govind	9/12/23	9/18/23
Gantt Chart	Grace	9/16/23	9/18/23
Draft of Requirements and specs.	Govind & Ben	9/12/23	9/18/23
Background Research	Alan	9/12/23	9/18/23
Draft of DR 1 presentation	Everyone	9/14/23	9/19/23
Gantt Chart	Grace	9/16/23	9/18/23
Reach out to truck drivers	Grace	9/11/23	9/23/23
DR 1 Presentation	Everyone	9/14/23	9/21/23
DR1 Report	Everyone	9/16/23	9/28/23
Draft of DR 1 Report	Everyone	9/19/23	9/24/23
Model current Stoneridge designs	Alan	9/28/23	10/4/23
Test current Stoneridge designs	Ben	10/04	10/8/23
Update Specs and Justification	Govind	10/1/23	10/8/23
CAD for 1st prototype	Grace	9/28/23	10/4/23
1st prototype	Govind	10/4/23	10/10/23
Initial Engineering Analysis	Tank	10/4/23	10/10/23
DR 2 Presentation	Everyone	10/1/23	10/10/23
DR 2 Report	Everyone	10/9/23	10/19/23
Cost Analysis	Tank	10/19/23	10/23/23
CAD iterations	Govind	10/15/23	10/30/23
Order Parts	Ben	10/23/23	10/23/23
Establish User Testing Protocol	Grace	10/24/23	10/26/23
User Testing and Reflection	Grace	10/30/23	11/1/23
Review testing results	Ben	10/30/23	11/2/23
3D-Print adjusted iteration	Govind	11/3/23	11/5/23

TASK TITLE	TASK OWNER	START DATE	DUE DATE
DR 3 Presentation	Everyone	11/4/23	11/14/23
CAD Final Design	Govind	11/14/23	11/16/23
DR 3 Report	Everyone	11/11/23	11/21/23
3D Print Final Design	Grace	11/16/23	11/21/23
Assemble Module	Ben/Alan	11/21/23	11/26/23
Code Button Functionalities	Ben/Alan	11/15/23	11/26/23
User Testing of Final Prototype	Tank	11/26/23	11/28/23
Prepare Poster for Expo	Grace/Govind	11/27/23	11/30/23
Make Changes to Final Design	Ben/Alan	11/27/23	11/30/23
Design Expo	Everyone	11/20/23	11/30/23
Verify Easy to Operate (User testing)	Grace, Alan	12/1/23	12/4/23
Connect prototype to laptop and test (Functionality verification testing)	Ben	11/26/23	12/8/23
Perform Cost analysis in GRANTA	Tank	12/4/23	12/8/23
Investigate Environmental/Social ramifications of device	Tank	12/4/23	12/8/23
3D Print Updated Final Design	Govind	12/6/23	12/10/23
Assemble Module	Ben	12/10/23	12/11/23
Provide Final Module to Stoneridge	Everyone	12/12/23	12/12/23
Final Report	Everyone	12/1/23	12/12/23
Project Deliverables			
DR 1 Presentation	Everyone	9/10/23	9/21/23
DR 1 Report	Everyone	9/19/23	9/28/23
DR 2 Presentation	Everyone	10/1/23	10/10/23
DR 2 Report	Everyone	10/9/23	10/19/23
DR 3 Presentation	Everyone	11/4/23	11/14/23
DR 3 Report	Everyone	11/11/23	11/21/23
Design Expo Poster	Everyone	11/11/23	11/21/23
Design Expo	Everyone	11/20/23	11/30/23
Final Report	Everyone	12/1/23	12/12/23

APPENDIX F: Icon Survey

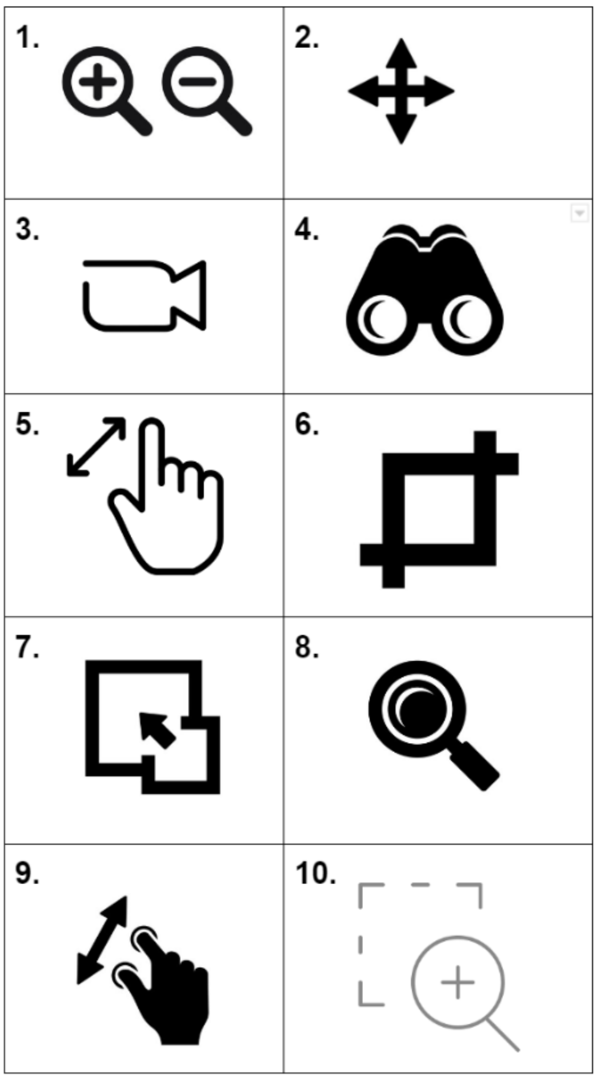
Controller Icons

My ME 450 team is redesigning a Camera Mirror Systems controller module for Semi-Trucks. As a part of our project, we are conducting usability tests on various aspects of the controller. This survey asks you to compare various icons that represent zooming, folding, panning and brighness to determine which icons are the best/worst in each category. This survey will help inform our design decisions to maximize the usability of our controller.
This survey should take about 10 minutes to complete. Thank you for participating!

Zoom Icons

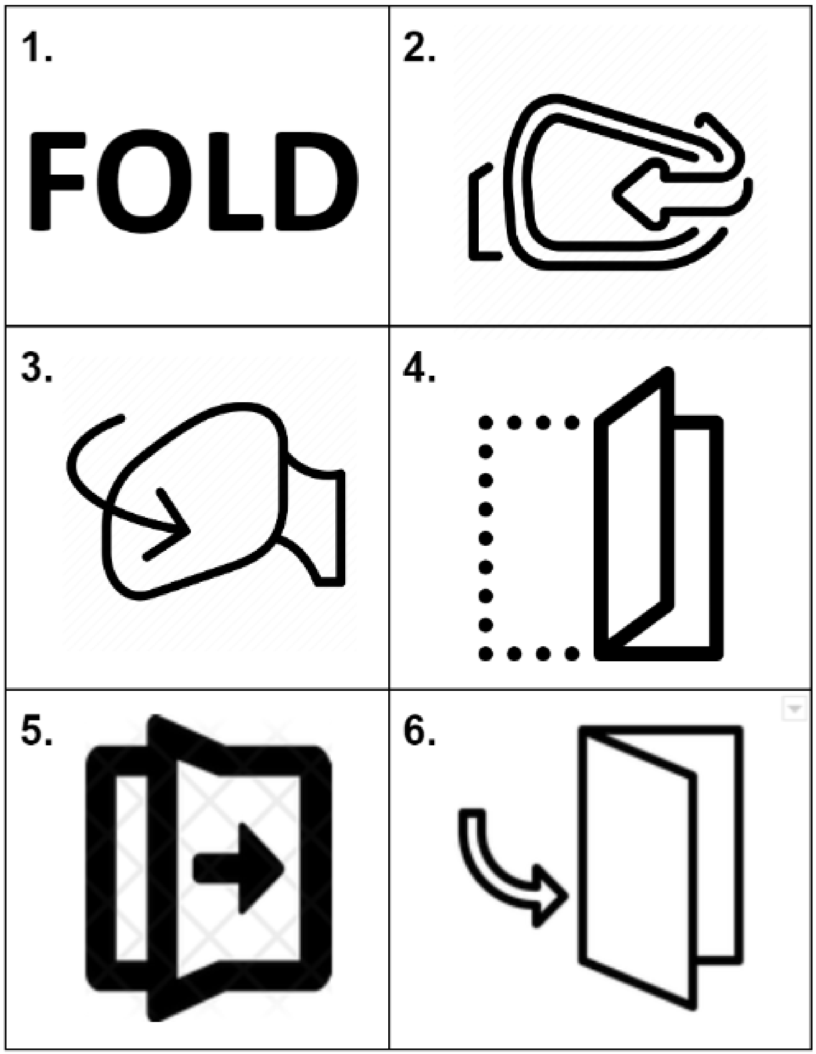
The zooming function zooms the cameras in and out.

Zoom Icons



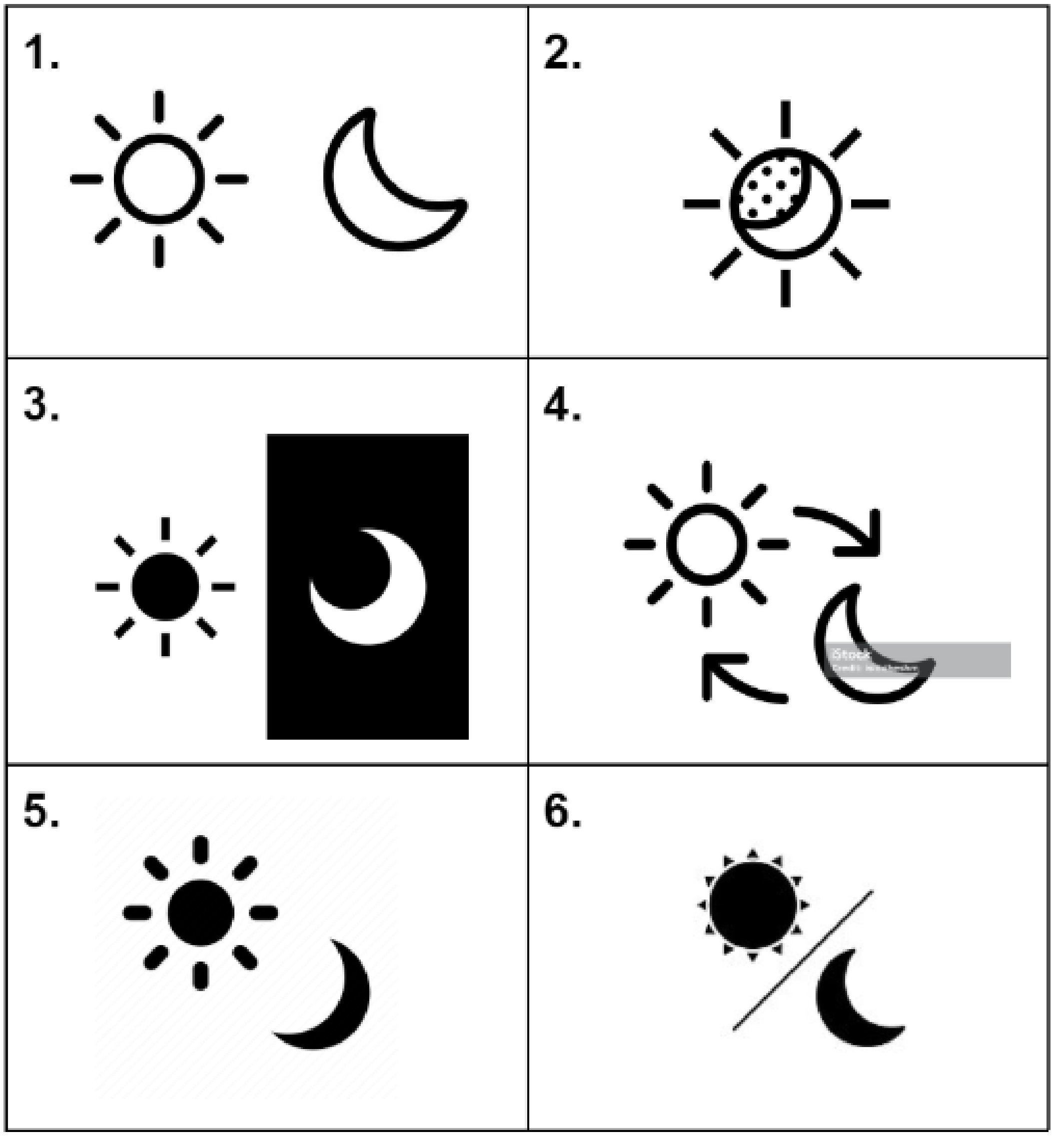
Fold Icons

The fold function folds the cameras in and out, just like folding car mirrors in and out.



Day/Night Mode Icons

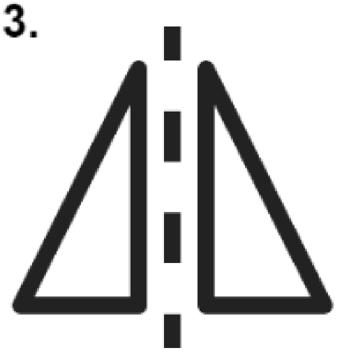
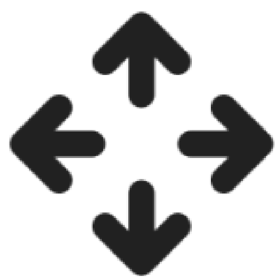
Day/Night Mode Icons



Pan Icons

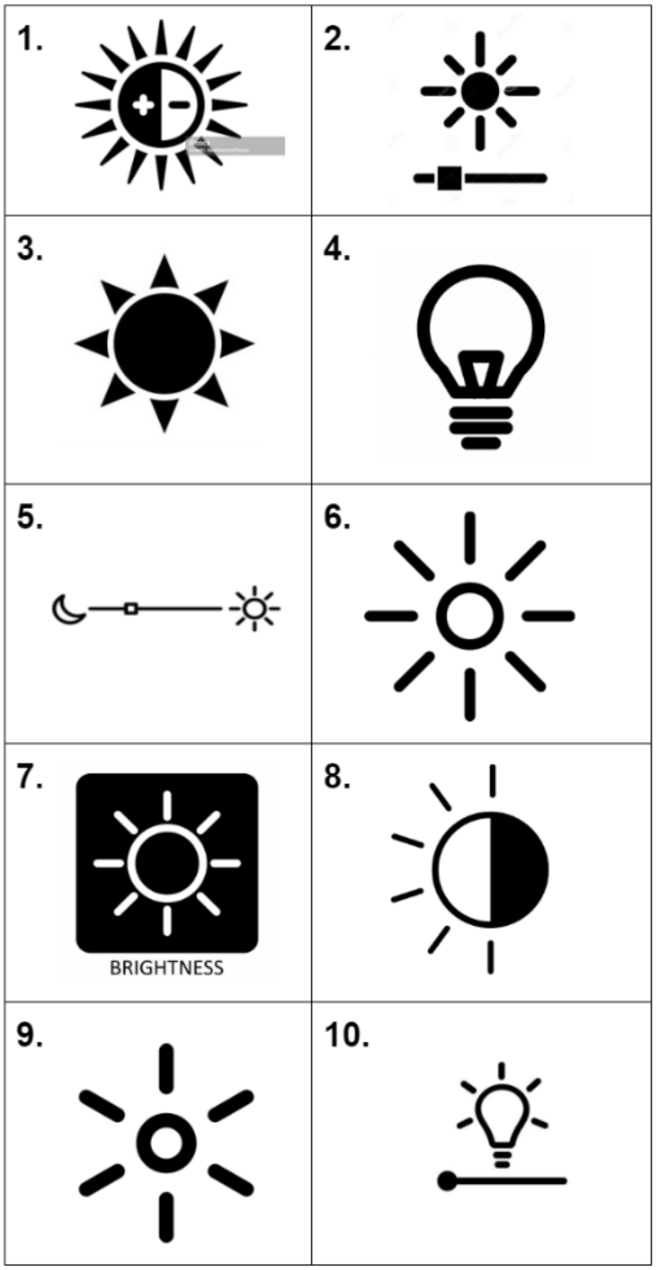
The pan function changes the angle of the camera and pans it across the field of view.

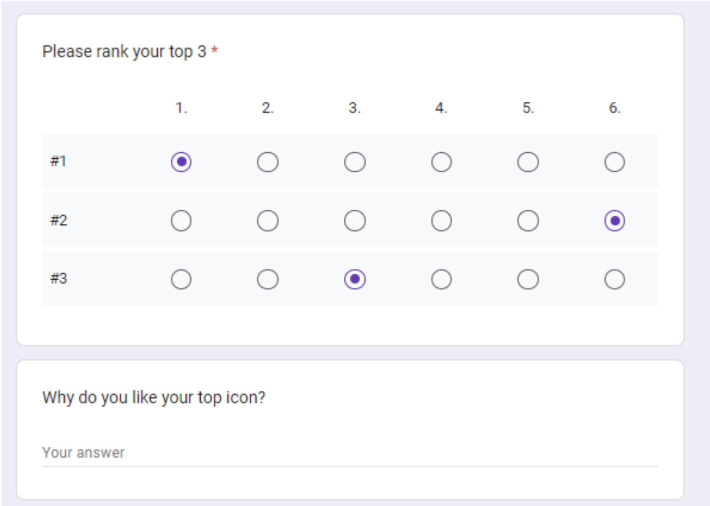
Pan Icons

1. 	2. 
3. 	4. 
5. 	6. PAN

Brightness

The brighness functionality increases/decreases the camera screen brightness.





Participants were asked to rank their top 3 options after each set of images.

APPENDIX G: Bill of Materials for Iteration Two

Part No.	Part Title	Material	Dimension(s)	Supplier	Quantity	Price Per Unit	Price	Notes
1	Module Body	ABS Plastic	8" x 3.25" x 2"	3D Printing	1	$3.43		3D Printed
2	Module Lid	ABS Plastic	8" x 3.25" x 0.35"	3D Printing	1	$2.72	$23.99	3D Printed
3	Encoder Mounting L Bracket	ABS Plastic	1.2” x 0.76” x 0.26”	3D Printing	1	$0.59		3D Printed
4	Indicating Knob & Set Screw	Anodized Aluminum	15/16" x 5/8" & #6-32	McMaster-Carr	1	$3.60	$3.60	6332K44
5	Optical Encoder & Mounting screws	N/A	3.5" x 2.6" x 1.3"	Tegg	1	$8.99	$8.99	Amazon
6	Rocker Switch	Plastic	1.614" x 0.945" x 1.653"	McMaster-Carr	1	$5.37	$5.37	7395K12
7	Push Button Switch Momentary Circular Cap	Plastic	1.02" x 0.75" x 0.75"	APIELE	5	$0.48	$11.49	Amazon
8	Gorilla Epoxy	Epoxy Resin	N/A	Outdoor Gear & Hardware	1	$1.26	$12.57	Amazon
9	Arduino R3	N/A	3.15" x 2.36" x 0.39"	ELEGOO	1	$12.99	$12.99	Microcenter
10	#4-40 Mounting Screws	Stainless Steel	0.65” x 25” x 0.315”	Keystone Electronics	2	$0.12	$2.02	DigiKey
					Total Cost	**$39.54**	**$81.02**	

APPENDIX H: Ingress Testing Procedure

IP69K Degree 9 Liquid Test

Ingress Limit: High-Pressure and High-Temperature water jetting / No ingress of dust permitted
Effective Against: High-Pressure and High-Temperature jet sprays, wash downs, or steam cleaning procedures

Step 1: For the high pressure portion of the IP69K test, 30 seconds per surface at a distance of 10 to 15 cm with a water pressure between 80 and 100 bar

- This can be achieved with a standard pressure washer
- A "light" grade power washer is around 2000 PSI which is equivalent to ~137 Bar
- Timed to a minimum of 30 seconds with a stopwatch
- Measured distance of 10cm between nozzle and object

Step 2: The nozzle must be held stationary at four angles, 0°, 30°, 60°, and 90°

- A protractor can be used to measure the various angles the nozzle is aimed at the module
- Each angle will be held the the testing procedure listed in Step 1

Step 3: The module should be rotated 5 times per minute to ensure ingress protection from all potential angles

- As module is subjected to procedures listed in Step 1 and Step 2 it shall also be rotated, this can be achieved by a turntable type tool the module is set on or by any other means that can be achieved safely

Step 4: For the High temperature portion of the IP69K test, temperature must be tested at 80°C

- Step 4 can be completed in concurrence with the previously listed steps if a temperature of 80° C is able to be achieved by the power washer
- Note this is around 176° F which may not be achieved by every power washer and that safety equipment should be worn by the users

Passing criterion would entail no liquid being found inside the module and no external damage from pressure and/or heat verified by inspection
Failing criterion would entail liquid being found inside the module and external damage from pressure and/or heat verified by inspection

IP67 Degree 7 Liquid Test

Ingress Limit: No ingress of dust permitted/ Protection against immersion in water between 15 cm and 1m deep for 30 minutes.
Effective Against: Water submersion for generally superficial depths

Step 1: for the immersion portion of the IP67 test, 30 minutes at 1m deep

- This can be achieved by placing the module in a water filled tub at 1m deep
- Timed for 30 minutes

Passing criterion would include no liquid being found inside the module verified by inspection

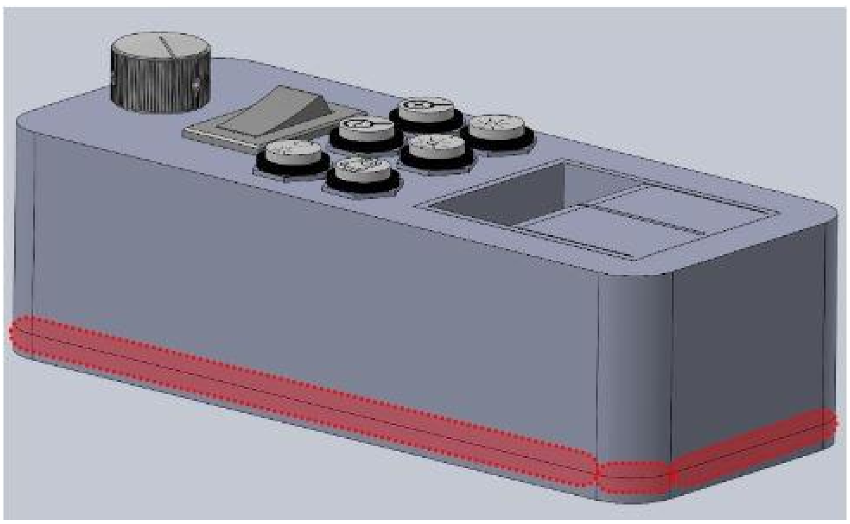
Failing criterion would include liquid being found inside the module verified by inspection

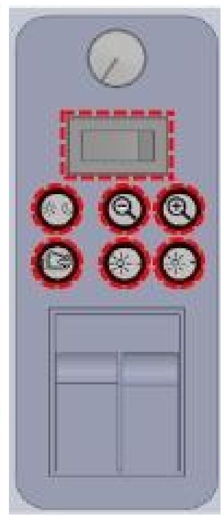
<u>Shared Dust Rating of Degree 6</u>

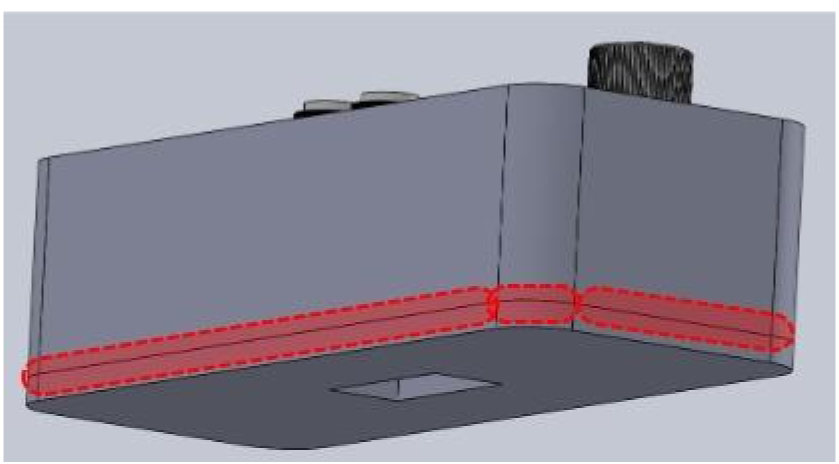
Module is placed in a particle-blowing chamber and exposed to sand or dust particles
Step 1: Often using talcum powder the module is placed into the chamber and the fan is turned on causing the talcum powder to blow everywhere
Step 2: the fan will shut off but the dust will continue moving around for three hours
Step 3: the module is cleaned off and removed from the chamber before it is opened up and checked for particles inside

Passing criterion entails no dust particles being found within the module verified by inspection
Failing criterion entails dust particles being found within the module verified by inspection

APPENDIX I: Silicone Application Zones







APPENDIX J: Mounting Bracket Orientation