UltraLight:
Reducing Disease Spread in Grocery Stores Utilizing Automated UV-C Disinfection
Team A2

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Executive Summary

When Dr. Zhang Jixian first sounded the alarm on a new coronavirus on December 27th, 2019 [1], the delayed global response resulted in the largest pandemic in a century. COVID-19 reached a confirmed 16.1 million in 188 countries, and over 646,000 confirmed deaths in just 7 months [2]. Countries all over the world went into immediate shutdown – however, even during a global shutdown, grocery stores are an essential part of daily life. This creates a possible source for disease spread within communities, and creates the demand for an effective manner of protecting shoppers from contracting diseases when grocery shopping. The goal of this project is to reduce pathogen spread within grocery and large retail stores by focusing on the disinfection of one of the most commonly contacted surfaces: the shopping cart handle. The UltraLight system achieves this design goal by utilizing targeted germicidal ultraviolet light to disinfect each shopping cart handle in an automated process. Not only will this solution reduce the pathogen spread within retail stores under pandemic conditions, but it will also ensure that grocery stores have efficient disinfection procedures for more typical conditions and will be prepared for future pandemics or epidemics.

The primary technical objective is to create a device that kills or disrupts the replication cycle of 99.9% of pathogens on shopping cart handles. Achieving a 99.9% disinfection rate is the key performance specification by which the efficacy of the device is evaluated. Additional objectives include ensuring this device minimizes disinfection time, reduces user interaction, is cost effective, and is able to disinfect a wide variety of cart models within a range of possible store configurations. Resulting technical challenges involve automating the disinfection process, making the process expedient enough to handle high rates of cart throughput, guaranteeing that it can meet a 99.9% disinfection rate, and ensuring the safety for users and the surrounding environment.

The development of the UltraLight system was guided by the use of design tools such as a House of Quality to ensure compliance with a range of customer requirements and engineering specifications. These customer specifications were developed by surveying grocery store managers and shoppers. In order to determine the best solution, morphological charts and evaluation matrices were utilized to generate and evaluate a wide range of solutions. Additionally, tight conformance to technical specifications was facilitated by use of function trees and specification sheets. In order to ensure project success, a Gantt chart was utilized for scheduling purposes and task delineation.

The UltraLight virtual prototype serves as a current proof of concept. While experimental validation of disinfection parameters has not been conducted to verify the efficacy of disinfection, theoretical irradiance values from research have been carefully designed to achieve the intended level of disinfection. This prototype is approximately 13 feet long, and is capable of containing 15 carts at a time. The prototype consists of a delivery device which is applied to shopping cart handles in order to deliver targeted germicidal ultraviolet light, linear actuators which provide automation capabilities by moving the delivery device to each cart handle, and ultrasonic sensors which detect the location of the cart handles. This solution is shown to work for multiple store architectures, even within limited space, due to its compact spatial envelope of 1 by 5 by 13 feet (not including the extended delivery device). Additionally, the system is designed for a wide variety of cart handles and orientations by allowing for a range of handle diameters from 0.75 to 1.5 inches, and is robust to cart misalignment of up to 20°. The system is designed to work inside the cart storage area, allowing for a high level of autonomy and minimal user input. The UltraLight prototype is designed to disinfect each cart handle in 35 seconds, for a throughput of 102 carts per hour, at an energy cost of $0.001 per cart. These values demonstrate the ability of the system to handle high throughput, at a low cost of energy, for an extremely efficient design with distinct advantages over other laborious, wasteful, inefficient, and physically intrusive methods.

Future work involves implementing the electronic and computational architecture necessary for automating the existing prototype, as well as integrating a user interface system. Additional work may include testing of the system to experimentally validate the claim of a 99.9% disinfection rate, as well as to establish safe exposure time for the device for human use. Absence from campus and the manner of online course delivery limited the ability of the team to construct a physical prototype, or conduct these necessary tests. However, they will be crucial moving forward, in order to validate the exceptional promise of the UltraLight system.

Glossary

Active arrangement: As defined here, an active arrangement pertains to the nature of a system which requires a cart to be input for the disinfection process to be initiated, and outputs the cart to the cart return autonomously, on an individual basis.

ASHRAE: American Society of Heating, Refrigeration, and Air Conditioning Engineers.

Autonomous: The ability of a system to be completely in control of oneself with no dependence on outside factors, operating without requiring inputs outside of calibration measures.

Cart Return: The central location where shopping carts are stored and obtained by customers.

Cart Stack/ Stack: A group of carts stored together in the cart return, in a row-like configuration.

CDC: Centers for Disease Control and Prevention, an American public health institute.

Cold Start: The scenario in which a fluorescent lamp is turned on after a significant time of no operation.

Common Contact Surface: A surface or other source which is regularly physically contacted by skin by multiple individuals, which may contain pathogens and create a pathway of transmission.

Coronavirus: A broad group of single-strand RNA viruses.

COVID-19: The disease caused by a strain of coronavirus, leading to the 2020 global pandemic.

Direct Irradiation: Irradiation which travels directly from its source to a surface.

Disinfection: The action or process of eliminating pathogens.

Indirect Irradiation: Irradiation which has been reflected or otherwise redirected through the course of travel from its source to a surface.

IR: Infrared spectrum of electromagnetic radiation, between wavelengths of 800 nanometer and 1 nanometer, emitted by heated objects.

FIFO: First in, first out. A term that applies to a storage method which references the order in which the items stored are input to the stack, and output from the stack.

Finite Element Analysis: The computerized method of solving engineering and mathematical problems through visual modeling and mapping of a product and predicting how it will react to outside elements.

Kill-switch: An automatic shut-down of a system if a certain criterion is violated.

LED: A light emitting diode.

LIFO: Last in, first out. A term that applies to a storage method which references the order in which the items stored are input to the stack, and output from the stack.

Ozone: The only byproduct of a UV lamp, formed when UV wavelengths between 160-240 nanometers collide with oxygen. Can be harmful if inhaled in certain concentrations.

Passive arrangement: As defined here, an passive arrangement pertains to the nature of a system which is placed within the cart return, and which operates based upon the fullness of the cart return itself, rather than individual cart inputs.

Pathogen: Any bacteria, virus, or other microorganism that can cause disease.

Pathway of transmission: Any manner in which one individual, surface, or other source may pass a pathogen to other individuals, surfaces, or other sources, potentially resulting in disease or repeated spread to additional individuals, surfaces, or other sources.

Radiation: The emission of energy in the form of electromagnetic waves.

REL: Recommended exposure limit; when exposure to something is unavoidable but undesirable, the limit that someone can be exposed yet remain relatively safe.

Transmission: An occurrence in which a disease may be transferred from one individual to another, either through the air, biological mass or fluid, or as a result of coming into contact with a surface.

Ultrasonic: A categorization of sound waves above the frequency range humans may hear.

UV/Ultraviolet: A specific category of light that exists outside of the visible spectrum.

UV-C: Ultraviolet light that radiates between wavelengths 200-280 nanometers. Typically used for disinfection as the range of wavelengths listed, as it disrupts pathogen DNA. The optimal disinfection wavelength is 254 nanometers.

Warm Start: The scenario in which a fluorescent lamp is turned on a short time after operation.

Wavelength: The distance between two successive troughs or crests within a wave.

1. Introduction and Background

Across the United States, the COVID-19 pandemic and corresponding response by national supermarket chains exposed a significant issue faced by these stores daily, raising significant national awareness of health issues and concerns. As essential businesses, grocery stores have stayed open during the pandemic. Unlike other businesses, they cannot exclusively transition into drive-through or curb-side pickup models - shoppers must physically enter and come into contact with store items. The central node of the grocery shopping experience, the shopping cart, is utilized by countless individuals each day. Carts travel through stores and change hands as shoppers obtain basic necessities. However, grocery-store customers and employees may transmit pathogens to shopping carts during use, leading to a pathway of transmission to other individuals. In addition to the current pandemic, studies show that cart handles are home to more germs per area than the average toilet seat in public restrooms even during non-pandemic times [3], [4]. While the national response to the COVID-19 crisis has involved store employees disinfecting shopping carts by hand with disinfectant wipes and other means, this labor-intensive method requires significant time, capital, and is subject to human error. Additionally, the heightened apprehension and knowledge around commonly contacted surfaces mean that stores may need to maintain disinfection methods in order to retain their shoppers in the future, even without pandemic conditions [5], [6]. Thus, a need for a more effective solution to neutralize pathogens on the cart handle, thereby reducing disease spread, provides an opportunity for automation using existing technologies such as ultraviolet light disinfection.

A basic storyboard entailing the shopping experience as it relates to the exchange of shopping carts between customers is shown in **Figure 1**, and was used in conjunction with market research conducted in order to inform the design process. The process is characterized by the common pattern of a shopper (shown in blue) entering a store and selecting a shopping cart from the cart storage area, as shown in the first two frames. They then proceed throughout the store and check out, shown in the third frame. The next frames illustrate the steps in which the cart returns to the cart storage area, in which the shopper returns the cart to a secondary storage location, and an employee (shown in green) returns the cart to the cart storage area. This highlights the fact that pathogens may be transferred to the cart handle by multiple individuals before another individual comes into contact, without preventative measures. However, these preventative measures may not always be efficient or cost effective. This implies that not only is there a better solution for disinfecting the primary point of contact, the shopping cart handle, but that it is relevant both within and outside of pandemic conditions.

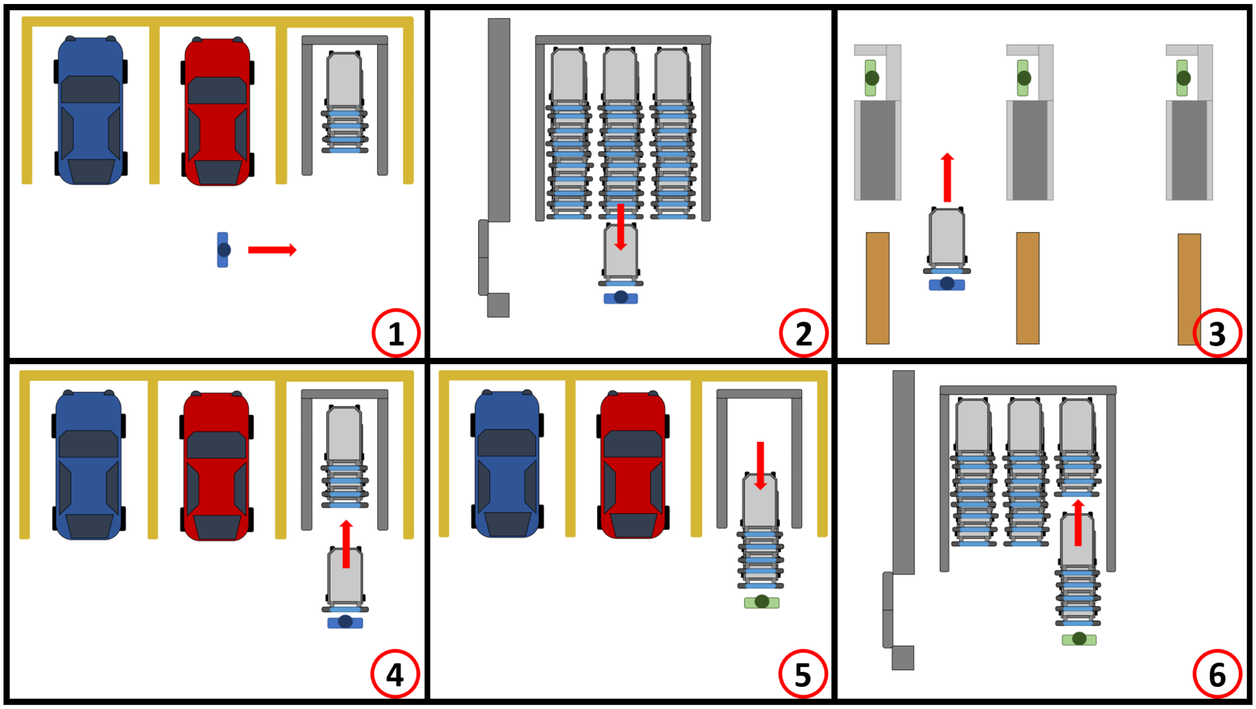

Fig. 1. Storyboard which illustrates the life cycle of a cart using practices.

The intended use of the UltraLight system is to disinfect the most commonly contacted part of the shopping cart, the cart handle, by utilizing an automated UV disinfection system within pre-existing shopping-cart storage areas inside the store. While there are existing solutions such as manual cleaning with disinfectant wipes and automated processes using disinfection solutions, they are often either ignored or subject to incorrect use by customers, lowering the desired percentage of pathogen destruction. Studies have shown that ultraviolet (UV-C) disinfection, or germicidal light, is by far the most effective method of fully disinfecting surfaces [7]. It also removes the need for employee interaction. While it is possible that pathogens may contaminate any part of the cart, rather than clean the entire cart, the UltraLight system focuses on the primary point of contact. Disinfecting the cart handle prevents germ transmission that would otherwise result from unprotected contact with the surface. Users of this device include store customers who rely on shopping carts, as well as store employees tasked with cart collection from outdoor storage points and returning them to a primary shopping cart pickup location. The UltraLight system would also benefit anyone else in the potential pathway of transmission regardless of whether they came in direct contact with the cart or retail store. In addition to the active protection within the community, these stores will also have an increase in revenue in comparison to their competitors without similar systems in place due to greater customer faith in the store's ability to assure their health.

The UltraLight system consists of an delivery device containing UV-C emitting LED bulbs, as well as an automated rail subsystem which allows the UV-C delivery device to be moved to and positioned above the cart handles for disinfection. The UV-C emitting bulbs incapacitate pathogens by destroying their DNA as a result of light beams operating at a wavelength outside the visible spectrum. The UltraLight system is implemented inside the cart return, in order to disinfect carts while they are in storage, enabling the rail system to move the UV-C delivery device to any cart within the row to disinfect in a passive capacity that does not require user input once initiated. Additionally, multiple UltraLight systems may be used in parallel, allowing for multiple rows of carts within any size of shopping cart return environment. The UltraLight system will operate with an array of ultrasonic sensors in order to automate the process by detecting the location, orientation of, and relative distance to each cart handle. Future work involves implementing visual detection systems in order to distinguish stacks of dirty or cleaned carts, as well as provide a visual warning to users to indicate that this cart stack is currently being disinfected. This process may also be tailored to the dimensions of the cart return, as custom size rails may be utilized for the system, as well as implementing multiple UltraLight systems in parallel to accommodate multiple stacks of carts.

The UltraLight system will therefore provide store owners and managers with a cost-effective manner for disinfecting carts which will inspire confidence in the cleanliness of shopping carts and of the store as a whole. Theoretically, this will boost store sales by differentiating these stores from others with more intrusive and ineffective disinfection methods. Additionally, it will allow store employees to enjoy a more streamlined and passive disinfection system that requires less active involvement, and allows store customers the peace of mind that the shopping cart handle surface is safe to touch and to use, regardless of the health of previous cart users. Thus, this system allows for a reduction of stress, and an increase in confidence, of the health aspect of the shopping experience.

In order to ensure accuracy in the operation of the UltraLight system, the accuracy of speed, control, and positioning of the automated rail and subsystem will need to be considered, as well as the confidence in the UltraLight system's disinfection rate. Additionally, other assorted concerns including the structural integrity of the system and the ability to account for wire management and power delivery to the system must be addressed to ensure proper power supply will be delivered. Finally, safety and user interactivity concerns must be considered in order to guarantee the safety of users for the use of the product. These safety concerns include the ability to warn users of operation, detect issues and complete emergency stop functions, and indicate which carts have or have not been cleaned so as to minimize the chance that a customer will obtain a cart which has not been disinfected.

Other considerations involve protecting UltraLight system users from being exposed to excessive amounts of UV-C radiation in accordance with current guidelines by the CDC and other organizations [8], [9]-[11]. Both skin and visual contact with the UV-C will need to be limited in order to avoid issues such as skin burns, welder's flash and other UV-induced injuries, among other risks [12]. Additionally, the wavelength of UV-C light will need to be closely monitored and controlled in order to avoid the production of ozone [13], which will be dependent on the choice of UV-C bulbs and the emitted wavelengths. Finally, it will be necessary to avoid liabilities and follow standards related to protecting users from injury while the system is in operation, including the appropriate labels, warnings, and other preventative measures [8].

Separately, the nature of online instruction impacted the design process in a variety of ways. Primarily, it reduced the ability of the team to meet in person, which meant that any concept ideation work or quick sketch work to convey an idea or to provide detail for a concept became more problematic and arduous. This led to more time being spent elaborating on ideas and communicating concepts than might otherwise be required. Additionally, team members were unable to learn new skills or improve existing skills with the direct assistance of another team member. Another primary consequence was the inability to utilize resources to build physical prototypes, which came at the detriment of having a physical goal to achieve, rather than a theoretical manifestation of the design. The inability to test the effectiveness of disinfection for the final design meant that, while mathematical models were implemented in order to achieve specific goals such as a 99.9% disinfection rate, experimental data could not be collected to verify this claim. Additionally, the inability to physically see issues such as wiring concerns meant that certain elements more critical to the design were not considered at an early stage, as they were not visibly evident as a result of constructing a prototype.

In conclusion, the solution proposed to reduce the threat of disease spread in grocery stores is the UltraLight system, an automated UV-C system capable of disinfecting shopping cart handles. This design was chosen by careful consideration of both active and passive users of the device, as well as the functional requirements to operate with a low space profile and disinfect cart handles more efficiently and cost effectively than current methods, providing a high degree of safety for shoppers without requiring significant overhaul to the shopping environment or change to the daily lives of the users.

2. Existing Products, Prior Art and Applicable Patents

Multiple existing patents were considered throughout the design process, which were evaluated to assess similarities with the initial ideation concepts shown in the morphological chart in **Figure A1** in **Appendix A**. These patents were analyzed for potential parallelities to the concepts, as well as for pitfalls or drawbacks which provided insight into the design process. There are a number of pre-existing patents that have similar goals in mind. One such design can be seen in **Figure 2**. This patent utilizes UV light to disinfect carts, which is an effective mode of disinfection and extremely commercially viable [14]. This concept is a cleaning chamber which disinfects carts in an isolated room, similar to the “Standalone UV Chamber” in the morphological chart. However, analyzing this patent demonstrated disadvantages such as potential danger, wasteful use of power, and large space requirements. Thus, while the design offers the ability to disinfect surfaces, a broad range of improvements is possible. A primary improvement involves optimizing the size of the system, which is currently a major hurdle to the design’s marketability.

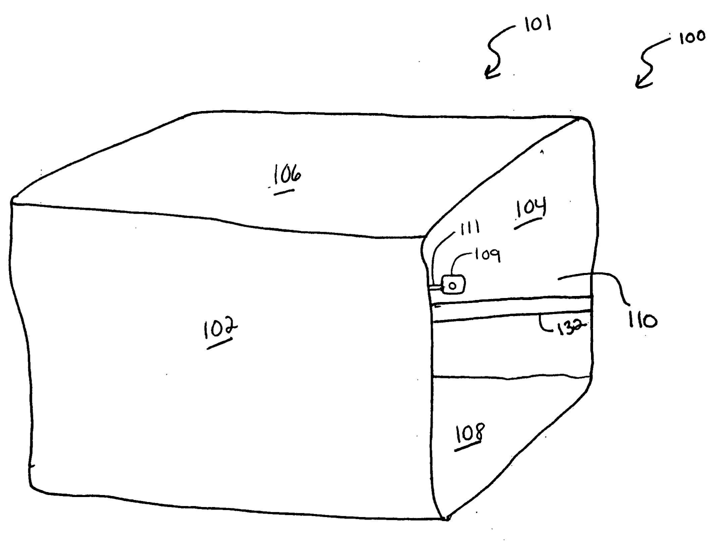

Fig. 2. Patented Concept of an Isolated UV Disinfection Chamber.

An automated cart-cleaning system utilizing conveyor belts to move carts between varying stations was also investigated, as shown in **Figure 3** and **Figure 4**. These patents had a high similarity with the “Conveyor Belt to UV Chamber” concept on the morphological chart. The first patent utilizes a conveyor belt to move carts along, using both water and a cleaning solution to disinfect the carts. The second patent utilizes conveyor belts to move the carts through a wash-cycle, and then through a UV-disinfection chamber. These patents have commercial promise due to their effective cleaning methods and automated operation, but the conveyor-belt-based systems were deemed too obtrusive to have high marketability. Due to the variability in architectural layouts of grocery stores, the space required for operation may be unavailable, severely hampering the implementation of these systems. Evaluating these patents aided in making the design choice to reject a conveyor based system, as these designs visually demonstrate the spatial volume and mechanical complexity necessary for such a system. As a result, more efficient modes of automation were explored.

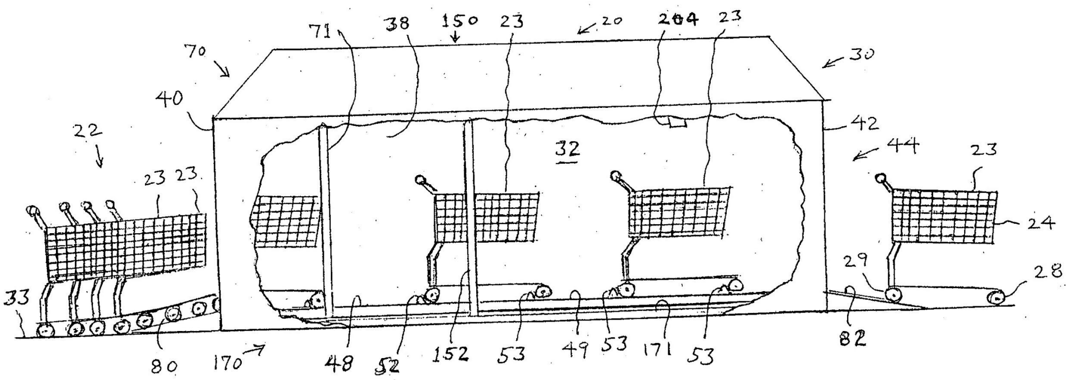

Figure 3: Patented Concept of a Conveyor-Belt Driven Automated Shopping Cart Wash. [15]

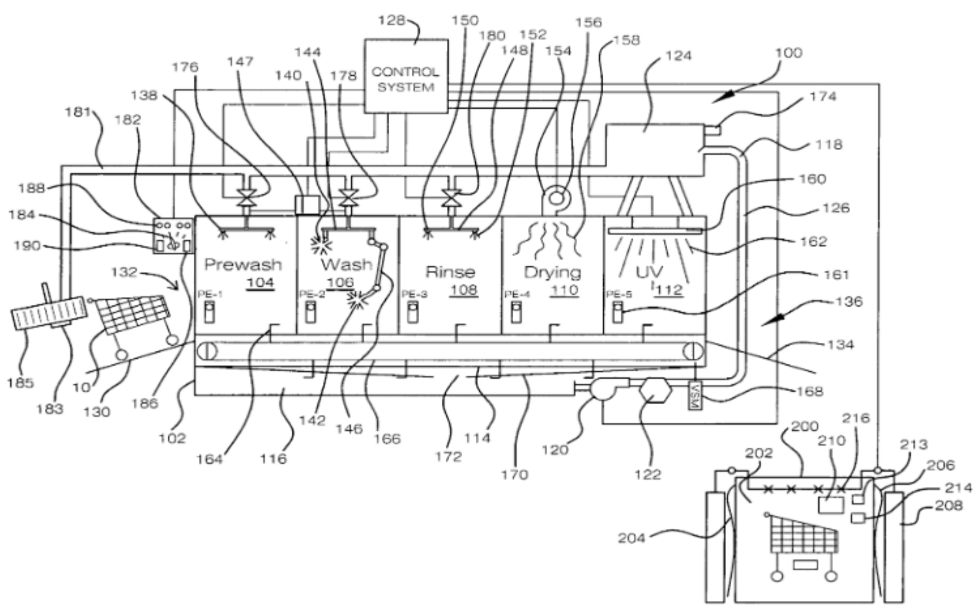

Fig. 4. Patented Concept of a Conveyor-Belt Driven Automated Shopping Cart Wash with UV Cleaning Stage. [16]

Another concept evaluated was the idea of an applicator for disposable cart handle covers, similar to the "Disposable Handle Covers" option in the morphological chart. A patent which utilizes this concept is shown in **Figure 5**. This patent utilizes a series of steps to remove a cover from a dispenser, peel off an adhesive strip, and apply the cover to the cart handle. This concept is commercially viable for a broad range of surfaces, and is not limited to cart handles exclusively, However, while this patent provides a viable method to avoid pathogen spread, it is application with high waste. Additionally, this method does not disinfect the handle itself, and only prevents users from coming into contact with possible existing pathogens. Though improvements may be made to this design in order to patent a more efficient or effective method, it was deemed to be an inefficient method of solving the design problem.

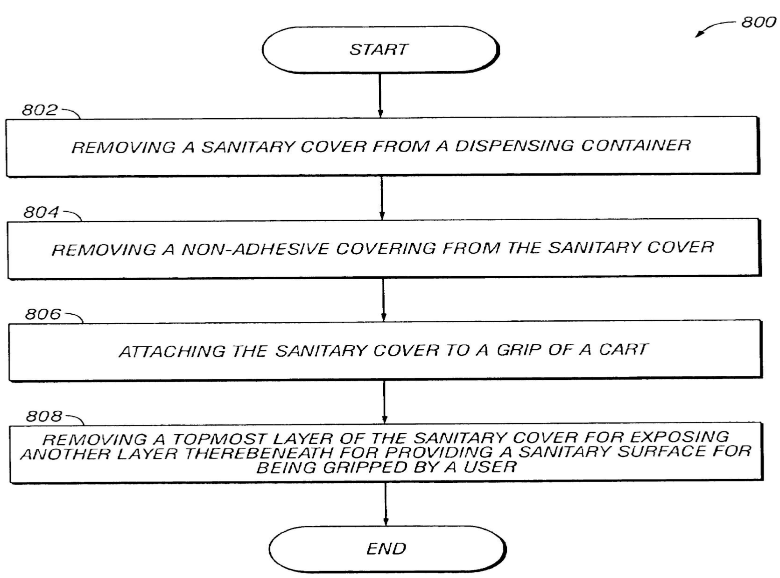

FIG. 8

Fig. 5. Patented Concept for Disposable Cart Handle Cover Dispenser. [17]

Another concept assessed involved a suction device to remove debris from cart handles, shown in **Figure 6**. This concept has unique commercial viability due to the fact that it uses suction for cleaning purposes rather than traditional disinfectant wipes or wash, and was analyzed as a potential candidate in order to solve the design problem by creating a similar device capable of cleaning cart handles. This device operates by leveraging high pressures to blow debris off of a surface before providing suction which collects the debris in an evacuation vent. However ultimately, this concept was dismissed as it does not provide disinfection to the cart handle, and merely removes particulates rather than neutralizing pathogens.

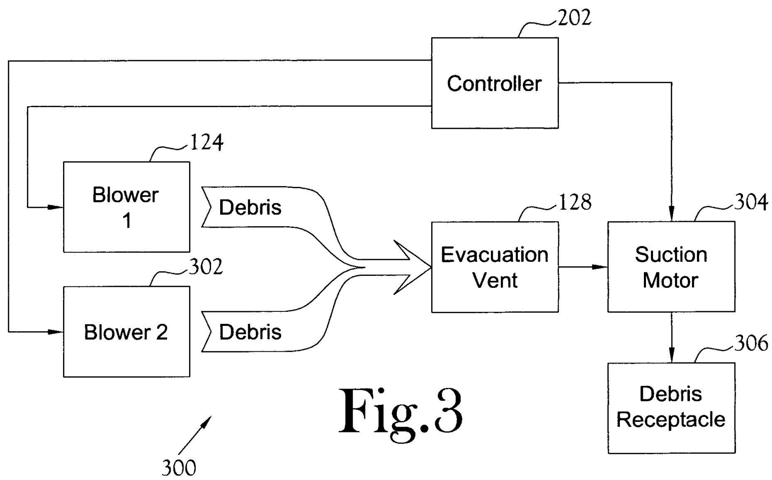

Fig. 6. Patented Concept for Suction Device for Cleaning Cart Handles. [18]

A final patent was assessed in order to implement a method to detect the location of cart handles. A similar patent used for parking vehicles was assessed to consider the feasibility of ultrasonic sensors to achieve this goal, as shown in **Figure 7**. While the patent applies to a different set of design constraints, the use of ultrasonic sensors demonstrates a unique versatility, as they are not reliant on constraints such as transparency or reflectivity, making the concept uniquely suited for marketability. In this patent, the ultrasonic sensors are used to detect the distance and angular orientation of nearby objects, as well as provide feedback regarding changes in these values. This concept was chosen to be implemented in the final design due to these numerous benefits.

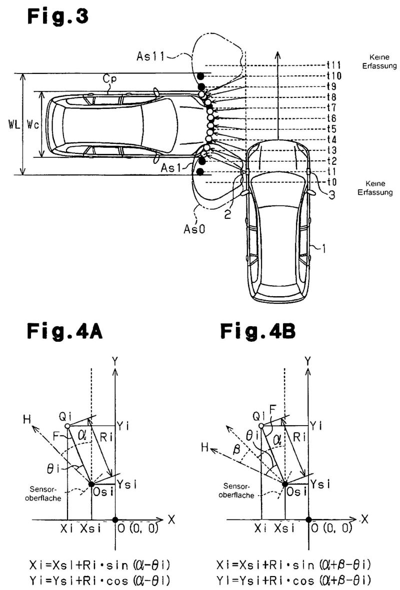

Fig. 7. Patented Concept for Ultrasonic Sensors for use in Parking Vehicles. [19]

3. Code and Standards

The standards used in hospitals and labs concerning UV-C disinfection systems can be applied to the UltraLight system to ensure user safety, as well as for system effectiveness. The primary safety concern with UV-C light is human exposure. Depending on the duration of exposure and the irradiance, UV-C is commonly associated with adverse health effects such as skin burns, skin cancer, corneal injuries, and photokeratitis. Zero exposure is optimal; however, if exposure is unavoidable, whether brief or prolonged, the organization NOISH advises the use of personal protective equipment, such as gloves, protective clothing, and face shields to protect the eyes and skin [9]. If bare skin is exposed to UV-C light, the CDC has a developed REL or recommended exposure limit [10]. The time limit of exposure is dependent on the distance between the surface of exposure and the light, shown as **Table B1** in **Appendix B**.

Additional standards are applicable to malfunction, misuse, and mishandling concerns. In the event of failure or malfunction, a procedure should exist for users to prevent any further exposure [8]. Manual kill switches are recommended and should be placed in a clearly marked and highly accessible area. Sensors may also be implemented into the design of the UltraLight system in order to automatically shut off the UV-C light when irregularities are detected. To prevent or mitigate improper use, warning labels must be placed on the UltraLight system, which indicate the usage of high-intensity UV-C, as well as warning of the danger of operating machinery. Warning labels should be placed where they are visible to the user as well as bystanders [10].

Finally, UV-C systems can have adverse effects on the surrounding environment. At wavelengths less than 280 nm, UV-C radiation can produce ozone. If the system should generate ozone, whether accidentally or as a result of its operation, a maximum acceptable level of 0.5 ppm implemented by the EPA should be upheld. Prolonged exposure to ozone can irritate airways and harm lung tissue [8].

4. Customer Requirements and Engineering Design Specifications

This UltraLight system comes with a variety of stakeholders [20]. Customers, managers and employees represent the stakeholders who would likely have a positive view of the design, as well as the most influence on the design. This is because store managers have the most feasibility knowledge that could potentially necessitate changes to the implementation of the design, and the employees and customers would interact with the device and be able to provide direct feedback to the managers and designers. The device benefits the managers and employees with its minimal required maintenance during the disinfection process, and it benefits the customers due to the assurance of cleanliness of the shopping carts without requiring any extra work on their behalf.

Those who would likely have a positive view on the device but less of an influence on the design would be store owners, investors, and the CDC. None of these stakeholders interact directly with the system and its effects to be able to provide significant design feedback, however all benefit directly from the increase in disinfection. The CDC would be in favor of the implementation of this device due to the system's ability to help control disease spread, should all relevant regulatory statutes and safety standards be sufficiently met. The owners and investors would likely benefit as well because customers are more likely to shop at stores with official disinfection procedures as opposed to those without, especially during a pandemic [20]. Stakeholders who would likely have a negative view with the potential for a significant impact on the design would be store owners who are resistant to change, as implementation of this design would be an additional initial cost and add an entirely new system for cart disinfection. Those who would likely have a negative view but less of an influence on the design would be stores primarily based online. This is due to the fact that it would negatively impact their sales when people are more comfortable shopping in physical stores. However, as they are not the intended user of this device, they would not be able to have a significant influence on the design.

For this product, the shoppers are not the target customers. The UltraLight system's immediate customers are grocery stores, while shoppers and grocery store employees are the primary end-users. This distinction is especially relevant when considering customer requirements, as both parties must be satisfied with the UltraLight system to ensure marketability. In assessing the customer requirements, specific to the grocery stores themselves, a few primary needs are evident. These assessments are illustrated in a House of Quality, seen in **Figure A2** in **Appendix A**. The device primarily needs to be compatible with current store infrastructure, disinfect to the same or higher level as current cleaning methods, be cost-effective compared to current disinfection methods, and be safe for grocery store customers and employees. Additionally, other considerations include being aesthetically pleasing, reliable, energy efficient, quiet, autonomous, easy to use, environmentally friendly, low-upkeep, and time effective compared to existing disinfection methods.

Some requirements are more critical than others. Compatibility with store design, cost-effectiveness, disinfection performance, and safety are essential for the product. First, stores are not in favor of implementing a system that requires significant modifications to the existing cart storage area. This was proven by surveying retail store managers, shown as **Table B2** in **Appendix B**. Next, the design cost should not be more expensive in the long run than the methods currently in place; if so, there will be no incentive to implement the design. The model should ideally be designed for the indoors, to avoid the extra waterproofing and durability requirements for creating an outdoor device. The design also needs to disinfect the cart handle to meet the same, if not outperform, current method using disinfectant wipes. This ability can be confirmed by taking a swab test of randomly selected cart handles before and after disinfection by the device as a verification measure. Most importantly, the design must be safe and not pose any risk for the people around it. The system should attempt to restrict the leakage of UV-C light to the surroundings; if not, the design must meet the CDC guidelines regarding the permissible UV-C exposure. The system should also implement sensors and utilize prevention safeguards to prevent physical injuries and mitigate liabilities from the stores.

Minimum user input, reliability, durability, meeting cart throughput necessities, and ease of use are of next importance after the essential requirements. The device should operate at high levels of autonomy, where an employee's job is not solely to disinfect carts like current grocery store policies. This will overall save costs and allow the employees to tackle different duties needed throughout the store, and will reduce the chances that anyone will come into contact with unsanitized surfaces. As the system operates every day, from opening to closing time, it must be reliable and perform without errors. Additionally, the system must be durable enough to withstand various forces over time - this includes anything from shopping cart collisions to the weight of someone leaning on the system. The throughput of shopping carts from the system is vital for customer satisfaction. Carts need to be readily available for shoppers to ensure no added inconvenience to the normal shopping experience. Finally, the system should be easy to operate, where employees of any background can be easily trained to operate it.

Power efficiency, low maintenance, serviceability, aesthetics, sound level of operation, and environmental friendliness are of lesser importance than the other requirements. Having a high-power efficiency and low-maintenance system will save the store money and time. Ease of serviceability will allow anyone, with proper training, to easily maintain the system when needed. Aesthetics of the system are admirable but are of little importance to store managers as long as the device cleans effectively, established in **Figure B2** in **Appendix B**. The average background noise is around 50 dB [21]. The device should operate at or below this noise level to create as little disturbance as possible. Lastly, the system should be environmentally friendly. As long as the system does not disturb the air or surrounding area, the managers mostly care about the system's disinfectant qualities.

Engineering functions are established for the preliminary design. This includes functions that encompass the overall system as well as functions specific to the UV-C subsystem. Functions that concern the entire system are weight, cost, resolution, noise level, autonomy, stability, safety factor, and size. First, the weight of the system should be light enough to where individual parts can be carried by hand instead of implementing heavy machinery. This will allow for an easier setup. As mentioned previously, within the customer requirements, the system's cost should be minimized so that it will be cheaper compared to the current methods of disinfecting with wipes. Next, the system's resolution regarding how accurate the system can translate should be less than 3 mm/m to fit the allowable clearance between stacked shopping carts. Resolution is of primary importance as it is a main factor of both reliability, disinfection effectiveness and safety which are important customer requirements. The noise generated from the system should be below 50dB to not disturb the surroundings. Also, the system should be highly autonomous, where an individual will not have to oversee its operations. To ensure the stability of the system, the floor bearings should not displace more than 5 mm. Additionally, the design of any structures such as bolts or support structures should be designed with a safety factor that meets the category's standards. Lastly, the overall system must be small enough to fit inside the existing infrastructure of the shopping cart storage areas within grocery stores.

Functions specific to the UV-C subsystem include minimizing UV-C exposure, minimizing the plastic cart handle's degradation, achieving a delivery of UV-C encompassing the cart handle, meeting the disinfection rate, and minimizing the time of disinfection. First, the system should be designed to block any external UV-C exposure, and if leakages do occur, it should meet the CDC guidelines of permissible daily exposure. The system should be safe for cart handles where it will not degrade the life of the handle any more than 15% of its life. To achieve the full disinfection of the cart handle, the UV-C light should hit the entire cart handle's circumference. The cart handle must be irradiated with 95 mJ/cm^2 of UV-C to meet the desired 99.9% disinfection rate. To meet cart throughput, the sanitization time of the system should be minimized to be, at most a 1 minute disinfection time per cart.

5. Market Research

Information obtained about the marketability of the product, as well as the feasibility of implementing the UltraLight system, was collected from surveys conducted online and through the phone (in keeping with current social distancing measures). The first online survey consisted of ten questions aimed toward shoppers to determine shopping habits and opinions on current safety and disinfection measures. The second survey was aimed at retail store managers, with seven questions asked to determine feasibility and marketability. These surveys were used as an initial guide in the design process, to determine customer requirements as well as technical elements such spatial requirements.

Several significant results arose from the customer-oriented survey, which had 145 respondents [20]. The demographics of the individuals who participated were mostly white, above 45 years old, and female. The results of this survey are shown in **Table B3** in **Appendix B**. First, the results indicated that 93% of shoppers use a cart instead of a basket. Next, it was shown that on a 1-100 scale, with 1 being the dirtiest and 100 being the cleanest, individuals perceived carts and baskets to have an average cleanliness ranking of 40. Finally, 83% of individuals said they would rather shop at a store that implemented a system to disinfect carts than one that does not. Thus, the design of a system focusing on cart disinfection was seen to be applicable, with high market potential.

For the second survey, eleven store managers from stores such as Publix, Target, Walmart, Whole Foods, and Kroger gave feedback about important issues regarding the marketability and feasibility of possible designs, as seen in **Figure B2** in **Appendix B**. Various takeaways include the fact that managers did not desire the implementation of a conveyor belt system system, valued designs with low spatial requirements, and did not show interest in aesthetics, or whether implementing a system would result in less carts in the cart return at once. Additionally, employee supervision for potential designs was perceived as acceptable if the device did not require a substantial operation time. Logistically, information provided by store managers revealed that the average amount of carts an employee would be returning into the system at a time would be around fifteen carts, which the UltraLight system is capable of disinfecting in 8 minutes and 45 seconds. Analyzing disinfection methods utilized by the stores, an average of roughly 2.5 containers of disinfectant wipes per day to clean shopping cart handles was calculated. Even with economical disinfectant wipe options to minimize cost, this results in a daily expenditure of nearly $6.00, which presents a significant cost over time.

Based on these results, stores would be willing to implement a novel, automated disinfection system that was comparable to current methods in price and disinfection rate. Additionally, the general public seemed to have a strong demand for such a disinfection system, meaning stores that implement the UltraLight system or other automated disinfection systems may see higher traffic and sales. Stores are also spending an estimated $3,628.10 a year on wipes which could be avoided by implementing the proposed system, in addition to the labor wages resulting from manual use of these wipes. This material cost, combined with labor costs, may exceed $40,675.60 per year, based upon estimates of fourteen hours a day of store operation, every day of the year for a single employee paid a minimum wage of $7.25 per hour. Thus, a system which can challenge the cost of current methods, at approximately $40,000 per year, has a high potential for implementation.

6. Design Concept Ideation

A function tree, shown in **Figure 8**, illustrates and connects the hierarchy of various functions the UltraLight system must achieve. The overall purpose of the system is to disinfect cart handles, which is done by dividing it into two key categories: operating autonomously and interacting with the user. Sub-functions listed in the function tree are the foundation of the Morphological Chart, shown as **Figure A3** in **Appendix A**, displaying different steps to carry out each sub-function.

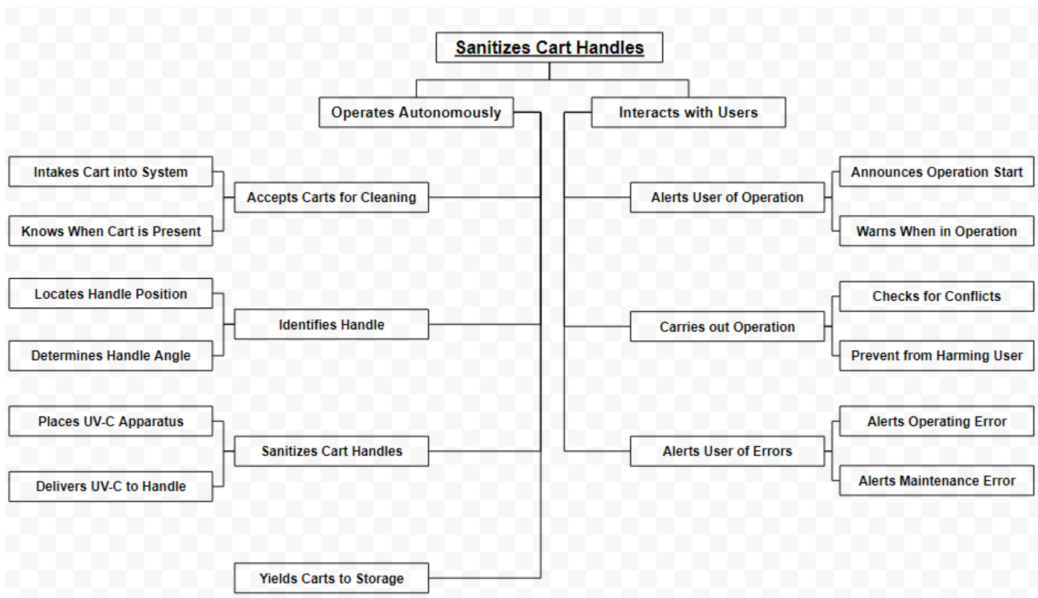

Fig. 8. Function Tree for preliminary design concept.

The UltraLight system's primary purpose is to disinfect the shopping cart handle to a 99.9% disinfection rate, comparable with claims by disinfectant wipe companies. The system should operate to a high degree of autonomy when disinfecting cart handles to prevent any potential harm to the user and any possibility of contamination from the user. First, the system will accept carts for disinfection by detecting carts in the system. Motion, IR, or ultrasonic sensors may be used to locate the carts and ensure no human interference. Once the cart is detected, a conveyor belt, rail system, or automated ramp can guide the cart into the system if not done by manual user input. The system is expected to identify the orientation of the cart handle in space utilizing sensors such as RFID or IR, or force transducers. With the position of the handle determined, the system can disinfect the cart handle by translating the UV-C apparatus to position, controlled by either a servo motor, pulley, rail system, or four-bar linkage, and delivering UV-C light to the handle using a clamping action, rotary action, reflectors, or multi-directional delivery. The different delivery systems are depicted more clearly on the morph chart. Lastly, the system should send the carts to the storage, if not already in storage, utilizing concepts similar to intaking carts.

The UltraLight system also must interact with users. Alerts indicating when the operation starts, when the system is in operation, when there is an operating error, and when the system needs maintenance are all required to appropriately meet this goal. Alerts can include auditory cues such as beeps and voice dialogues or visual cues such as lights turning on or a monitor. The UltraLight system should be able to check for potential conflicts with carts, if not done by the user, and send an operating error out if any obstructions are detected. Sensors aid with detection. The system should prevent harm to the user. Flexible curtain flaps or light enclosures can be used to control the amount of UV-C light exposure to the environment. A kill switch can also be implemented in case of system failure or malfunctions, as discussed.

Various concept ideas are made, shown in **Table B4** in **Appendix B**, utilizing the options provided by the Morphological Chart shown in **Figure A3** in **Appendix A**. The main variation behind each design concept is whether it is an active system placed outside the cart return, which is automated to intake a cart, disinfect the handles, and yield the cart to storage, or a passive system which is placed inside the cart return and operates autonomously to disinfect cart handles on the carts in storage. These concepts and their features will be explored below.

The first concept is an active automated ramp system that utilizes a ramp system to deliver a cart into the system. When a shopping cart is put in a designated position by the user, a pressure plate will sense the change in weight and elevate one side of a floor panel while the opposite side is stationary. This will create a ramp and utilize potential energy to move the cart down into position under the UV-C apparatus. An ultrasonic sensor will help determine the location and angle of the cart handle, and the UV-C apparatus will translate it down using a motor. UV-C light will be delivered with a multi-directional system, with flexible curtain flaps in place to prevent any unwanted UV-C exposure. After disinfection, the cart will be brought into storage using a rail system. Potential concerns for this concept include misalignment and jams caused by faulty shopping cart wheels while moving on a ramp, significant space requirements, and slow input/output rates as the system can only process one cart at a time.

The second concept is an active conveyor belt system that carries a cart into the system when detected by a motion sensor. Curved side rails on either side are utilized with the conveyor belt to funnel the carts into a narrow strait and orient the cart correctly. The conveyor belt will move the cart directly under the UV-C apparatus. As the cart is correctly oriented, there is no need for a handle detection system for this concept. The UV-C apparatus only needs to translate up and down using a servo motor to a calibrated location and use a clamp action to deliver the UV-C light to the handle. After cleaning, the conveyor belt will move the cart into storage. A kill switch will be implemented near the cart intake if the user has to stop the system due to emergencies. Potential concerns for this concept are similar to the first concept, where there is a large space requirement, and a slow input/output rate as the system can only process one cart at a time.

The third concept is an active floor track system that utilizes grooves to ensure the cart is oriented correctly when the user inputs the cart. Once inputted, the ultrasonic sensor will sense the cart and move it to the position under the UV-C apparatus. Like the second concept, a handle detection system is not needed as the cart is already correctly aligned and positioned. The UV-C apparatus will only have to translate up and down using a four-bar linkage and deliver UV-C light to the handle using a rotating action method. Light delivery will be done in a light enclosure to prevent UV-C exposure. After disinfection, the cart will continue to travel on the rails into storage. Potential areas of concern for all the systems listed above include a slow input/output rate as the system can only process one cart at a time.

The fourth and fifth concepts are similar passive rail systems (wall-mounted rail and side rail) that perform disinfection operations on a pre-stack cart in storage. These systems will consist of a UV-C apparatus attached to a rail to move to the different cart handle positions. The UV-C apparatus will have high degrees of freedom, using ultrasonic sensors to orient itself will the cart handles. The main difference between the fourth and fifth concept is that one is a wall-mounted rail system, while the other is a side rail system. Also, the delivery of UV-C light differs as the wall-mounted rail system utilizes a clamping action while the side rails use reflectors. These concepts do not have the slow input/output rate apparent in the previous designs, but they require high levels of sighting to find the carts. A primary consideration for these designs included the issues of being able to directly apply UV-C to the entirety of the cart handle while the cart is in storage, where less area is available for a device to operate within while carts are stacked together.

An initial, preliminary concept for the rail-based design is given in **Figure 9** and **Figure 10**. This concept was chosen moving forward for its ability to achieve the desired functions in a passive arrangement, which integrates more easily with store architecture, as low spatial profile and the ability to move the UV-C device to the carts enables a more automated design. This preliminary concept includes components such a primary and secondary rail in order to achieve translation of the UV-C scanning device so as to place the system in the cart return itself, as well as motorized joints to account for cart alignment or orientation issues. Additionally, IR sensors may be seen, which enable the system to detect the location and orientation of the cart handle. This preliminary concept demonstrated the chosen manner of moving the UV-C device to achieve disinfection while carts are within the cart storage area, rather than requiring cart translation through a device; however, this preliminary concept does not include specifics in terms of the disinfection process itself. Rather, it was used to understand the automation of the process and considerations of the process moving forward.

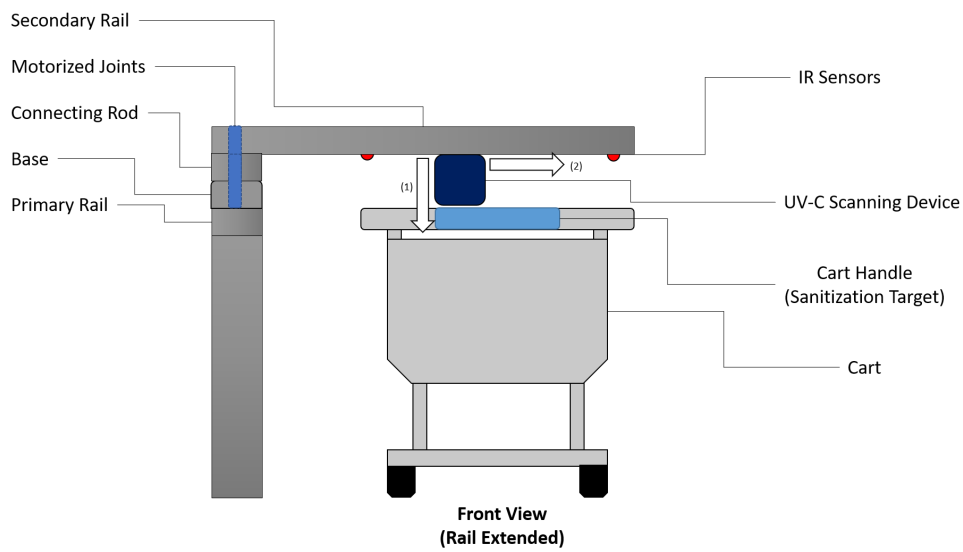

Fig. 9. Front View for Preliminary Design with Labeled Components.

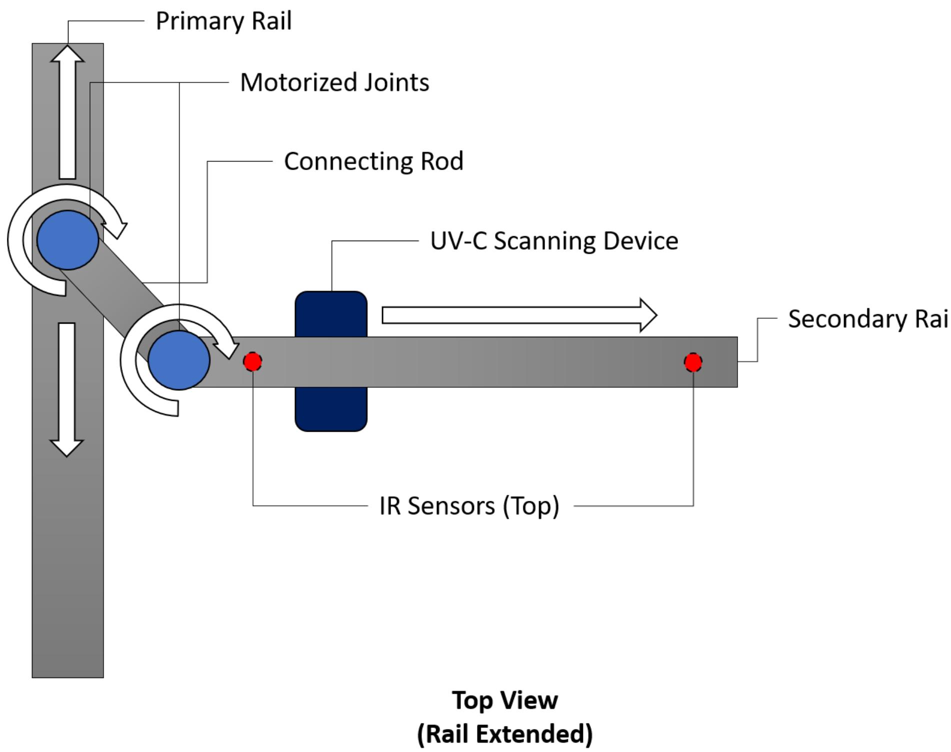

Fig. 10. Top View for Preliminary Design with Labeled Components.

After making a preliminary CAD model of the preliminary concept, shown in **Figure 11**, it was then easier to account for how various components would work in tandem, and generate various considerations for future prototyping. These considerations specifically included the incorporation of rails and motors to achieve the desired translational effects, wherein the system could manage translating the UV-C device anywhere within its spatial profile. This initial prototype of the UltraLight system was based on an ability to store and service fifteen carts, a goal based upon market research previously described, at an estimated distance between carts handle centers of approximately 8.5 inches, as described in **Section 9.1: UV-C Delivery Device Optimization**.

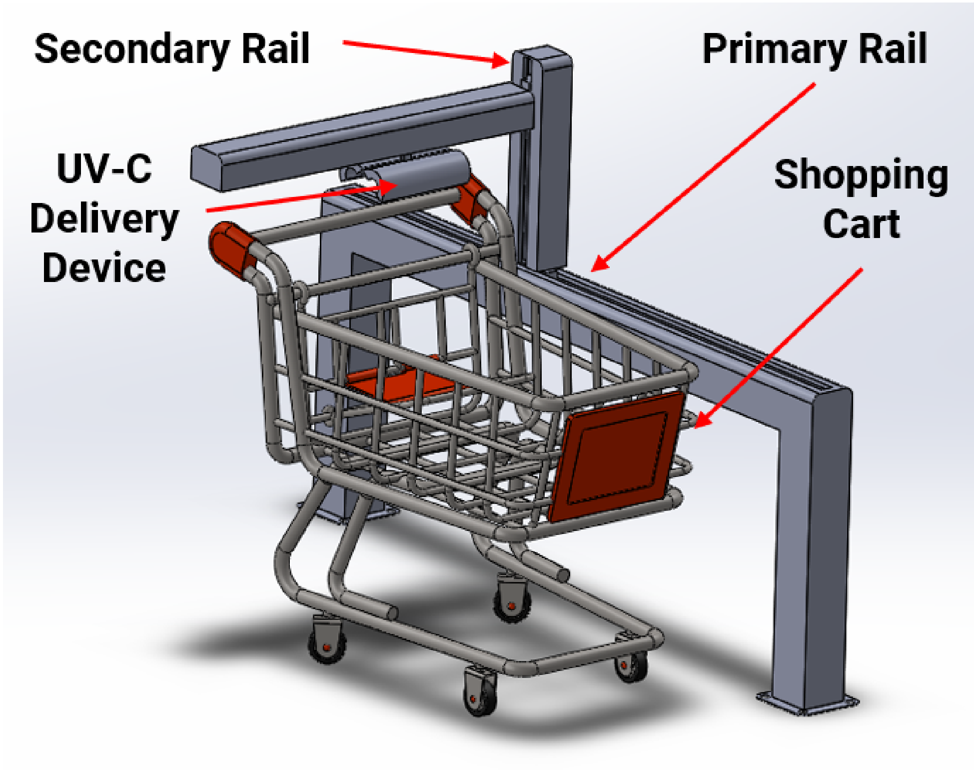

Fig. 11. CAD Model of the Preliminary Concept, with Cart.

For this prototype, the rail is 85 inches long and 36 inches tall, and its legs have a base of 5.5 inches by 5.5 inches. At the base of the legs there is a location for four bolts in order to secure the rail to the floor which is 1.5 inches larger than the leg base. The arm that is being extended in order to carry the UV device across the handle is 42 inches long, with a width of 5.5 inches and a height of 4 inches. Additionally, there is a vertical track that is used to raise and lower the UV device that has a base of 5.5 inches by 4 inches with a height of 24 inches. This track was anticipated to be modified to include a motor at its base in order to turn the track and allow for the UV device to be able to clean any misaligned carts within its area of influence. This prototype's material, and fasteners, were not specified, as information for load bearing components were not included at the stage at which it was developed. However, the virtual prototype proved a helpful visual aid in considering components were required for achieving the listed functions, and what may be altered in the concept moving forward in order to simplify and streamline the design for more efficiency. For the preliminary concept, three rails, or tracks, would be required to provide translation for the UV-C device as well as to provide it with the ability to scan across the cart handle. However, this virtual prototype demonstrated that a stationary, rather than scanning, UV device may provide more efficacy to the design, as an additional degree of freedom would require additional power and increase complexity. Two motors were seen to be required, including one to turn the vertical track and another to close the UV device. Two IR sensors would be placed at opposite ends of the arm in order to identify when the handle is below the arm and if it is aligned properly.

An essential component to this preliminary concept included a key decision for disinfecting the handle. The two primary methods for delivering UV-C include fluorescent bulbs, or more expensive LED bulbs. During the ideation process, multiple variables including the cost, effective irradiance, and size of bulbs were analyzed in order to reach the optimal solution. Although LEDs were proven to be more expensive per unit of delivered irradiance, fluorescent bulbs have many drawbacks as well. The primary concern is the degradation seen in fluorescent bulbs through cyclical usage. While LEDs are not prone to a comparable effect, cyclical usage can drastically diminish the life of fluorescent bulbs. A general representation of how quickly a fluorescent bulb can degrade is shown in **Figure 12**. Given a bulb with a 1-year lifetime, and a cyclical usage of 30 times within 3 hours (a substantial underestimate for the operation of the UltraLight system) the life of the bulb will be reduced to less than two months. Also, while LEDs offer instantaneous maximum power output, fluorescent bulbs have an associated warm-up time in order to reach peak power. A cold start can have a warm-up time ranging from 4-7 minutes, while a warm start can range from 2-7 minutes [22]. This can drastically slow down the sanitization process and make it impractical to meet the system's necessary throughput.

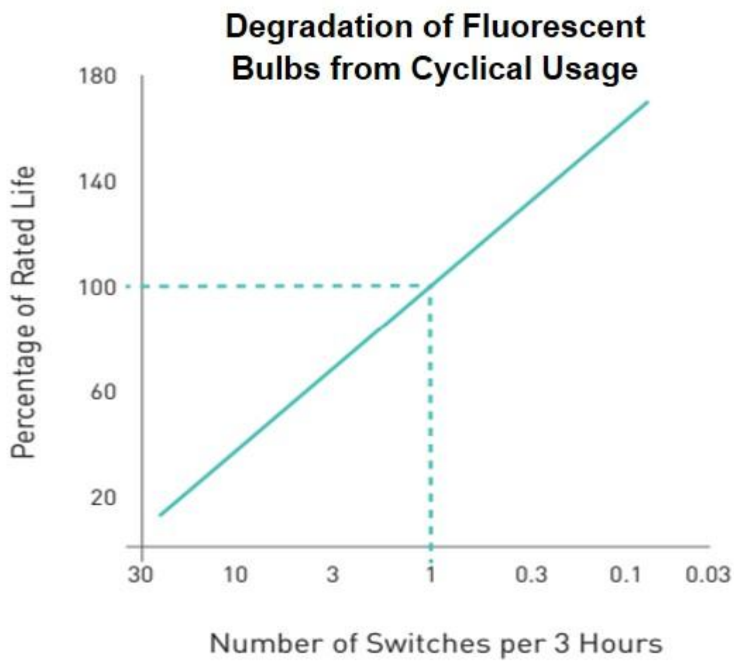

Fig. 12. Degradation of Fluorescent Bulbs from Cyclica Usagel. [23]

Additionally, due to analysis of the virtual prototype, it is evident that spatial requirements limit the feasibility of fluorescent bulbs in disinfecting the entire surface. As the UltraLight system is intended to work in a passive arrangement, carts are tightly stacked. Thus, the only space available to place the UV-C device is either above the handle or between the handles themselves, which is prevented by the radii of fluorescent bulbs capable of outputting the necessary amount of power. Thus, in order to achieve the required irradiation for disinfection for the entirety of the cart handle surfaces with fluorescent bulbs, indirect irradiation, or reflection, would be required. At this stage, multiple concepts to implement reflection were considered, and a broad range of information was considered detailing effective materials and modes of reflection for reflective surfaces [24]-[26]. Multiple considerations and configurations for such an orientation are shown in **Figure 13**. By comparison, the compact size of LEDs mean they may be positioned in the limited space surrounding the handle and provide uniform direct delivery of UV-C without encountering the same spatial issues, and without requiring additional distance losses due to indirect irradiation. These ideation results would later be used in justifications regarding the selection of LEDs rather than fluorescent bulbs.

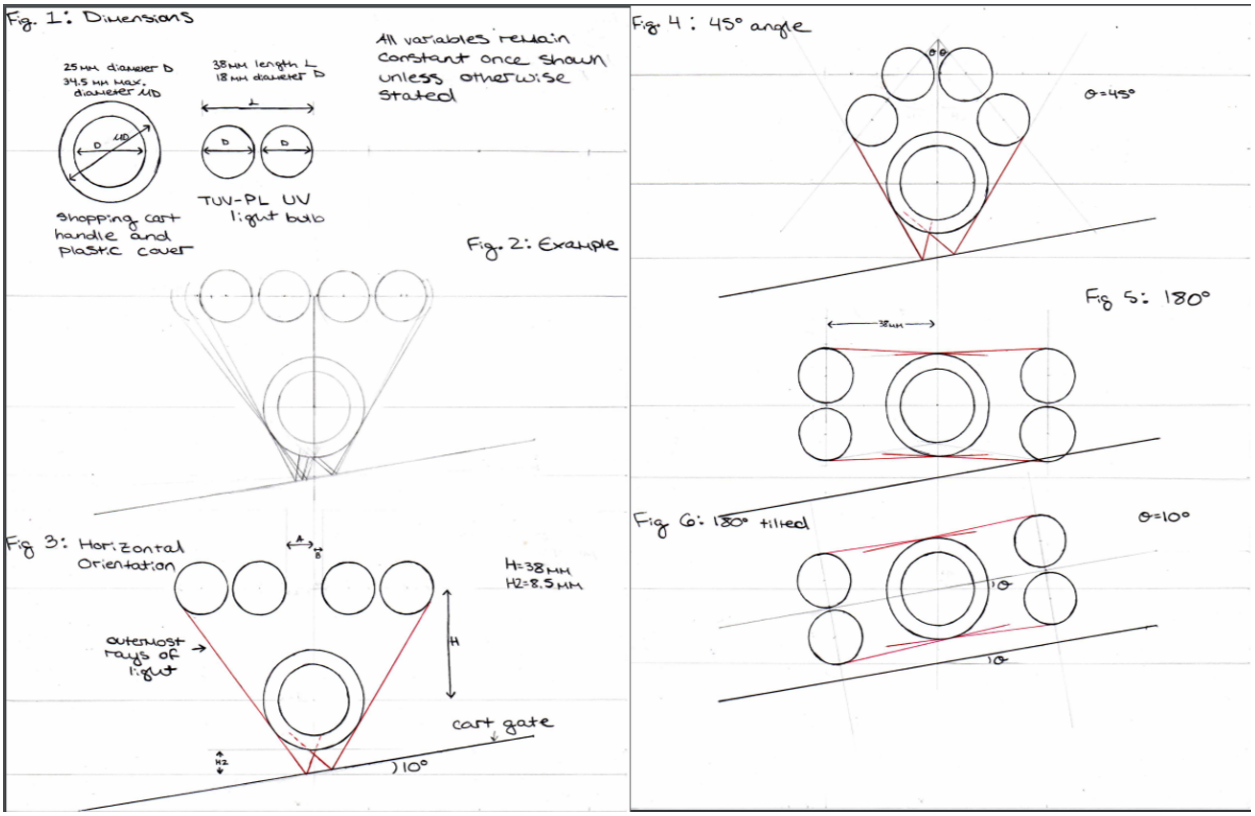

Fig. 13. Possible Orientations for Fluorescent Bulbs and Reflective Surfaces to Achieve Reflection to Disinfect Cart Handle.

7. Concept Selection and Justification

The final system, shown in **Figure 14**, was ultimately designed for its ability to achieve the functional requirements of disinfecting shopping cart handles to a 99.9% disinfection rate, while also being fully automated and compatible with cart returns and robust to issues such as cart misalignment. This is accomplished by incorporating specific components, shown in **Figure 15**, from various vendors in order to achieve various functions of the device, as well as essential supporting components.

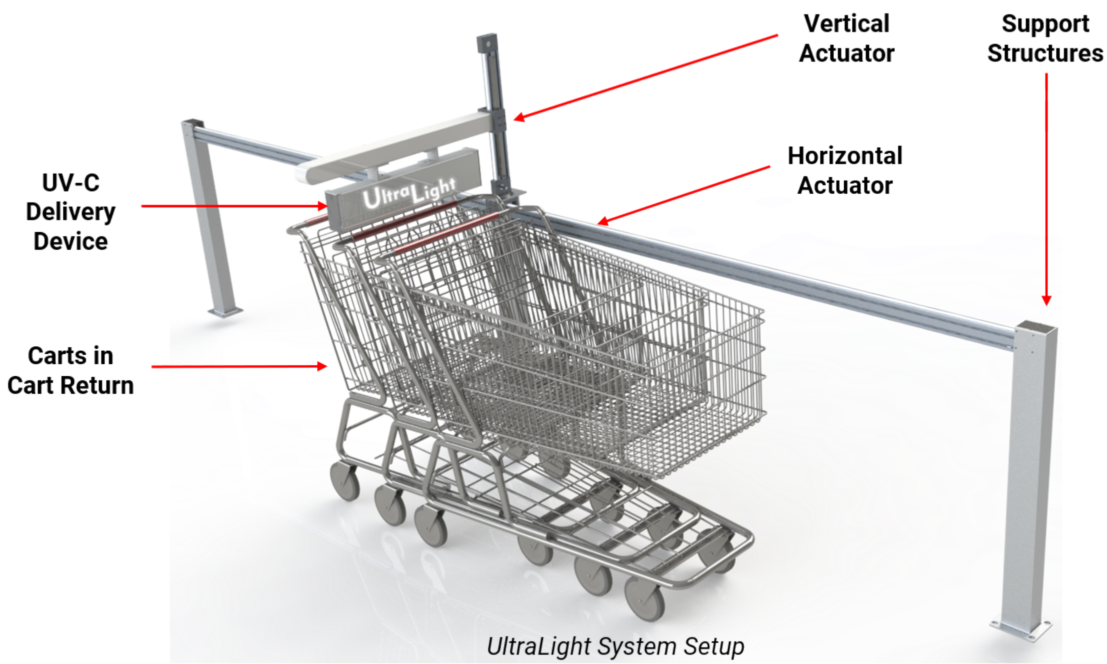

Fig. 14. UltraLight System Final Design Render.

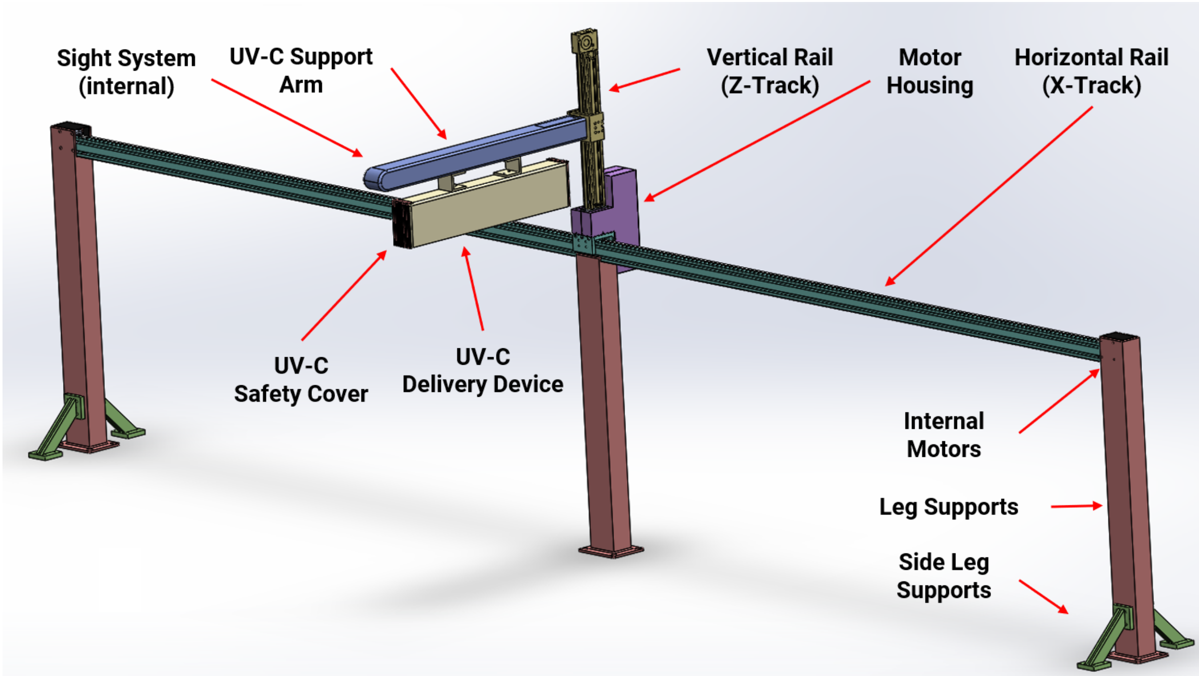

Fig. 15. UltraLight System Final Design with Highlighted Components.

The House of Quality, shown in **Figure A2** in **Appendix A**, was used to inform the design process so that the final design could achieve the chosen parameters identified for success. The most important objectives of the design are compatibility with store layout, minimal user input, cost effectiveness, and safety. Store layouts differ immensely, so the design should ideally be low-profile with a small cross-section. Additionally, this process must be expedient enough to handle high throughput for stores with high traffic. Minimal user input is also a desirable feature which can be achieved by focusing on autonomy as opposed to a user dependency. The system should be as cost effective as possible, which can be achieved by optimizing energy usage and disinfection rates. Disinfection of cart handles is the core objective of the system, meaning that the autonomy and accuracy of the disinfection process are essential. Lastly, the device must be safe and not pose a risk to anyone that may interact with it.

The selection process leading to the finalized UltraLight system was made by carefully iterating through multiple conceptual spaces, utilizing evaluation matrices. This consisted of two levels of evaluation, utilizing three evaluation matrices. First, a third-level evaluation matrix, shown as **Figure A1a** and **Figure A1b** in **Appendix A**, was utilized to determine the concept type to explore and design in order to approach the design problem. After developing multiple ideations of this concept, two additional second-level evaluation matrices, shown as **Figure A4** in **Appendix A**, were utilized to determine the efficacy and issues for five different designs in achieving the functional requirements. This allowed for the exploration of the entire design space before landing on the final choice, providing numerical justification along with qualitative reasoning.

Significant conclusions were derived from the ideation process, such as the efficacy of the passive arrangement. The ability to clean shopping carts while already in the cart storage eliminates the complexity of automation methods for disinfection, such as utilizing a conveyor belt or track system to move carts through a disinfection system to the cart return itself. This means an exponentially reduced level of complexity, at a much higher rate of throughput for carts. This passive arrangement achieves this efficiency by eliminating chokepoints which would otherwise exist for a system which relies on users individually inputting carts. As shoppers do not have to actively engage with this system and employees do not have to significantly alter their process to adjust to the system, the level of effort or attention required from the user is minimal. Thus, the impact to user experience by implementing the UltraLight system is negligible.

Additionally, stores may utilize FIFO cart storage methods as opposed to LIFO methods, such as when employees input carts into a cart stack on one end of the stack and customers obtain their cart from the other end rather than a customer putting a cart in the cart stack for the next customer. This also provides a layer of complication for the system to overcome in terms of the variability of store infrastructure. This means that should a sensor system be used to initiate the disinfection process, a level of complexity will be introduced into the machine logic in order to ensure the ability of the system to work with either a FIFO or LIFO cart return setup. As such, it was determined that designing controls to allow employees to start the process would remove a level of complexity for the design, rather than utilizing motion sensors or other complex means to determine when the UltraLight system is at capacity in order to initiate the disinfection process.

Finally, a principal concern stems from the shopper's ability to distinguish clean carts from dirty carts within the UltraLight system to avoid misuse or mishandling. Visual indicators may provide a remedy for this issue, wherein a color coded system may show whether carts are disinfected, dirty, or that the UltraLight system is completing the disinfection process. The storyboard given in **Figure 16** illustrates the potential for multiple UltraLight systems working in parallel to solve this problem, where the process of disinfection operates cyclically. In the first frame, two stacks of clean carts are pictured. In the second and third frame, the first of the two clean cart stacks are emptied, and dirty carts are put into the input stack, until the output stack is emptied and the input stack is filled. The fourth frame depicts the transition as the former output stack becomes the new dirty cart input stack, the second standby stack becomes the new output stack for clean carts, and the former input stack begins the disinfection process until finalization, at which point it becomes a stack of clean carts for output. This solution, while it requires further analysis, illustrates a potential solution for high cart demand using multiple UltraLight systems in tandem.

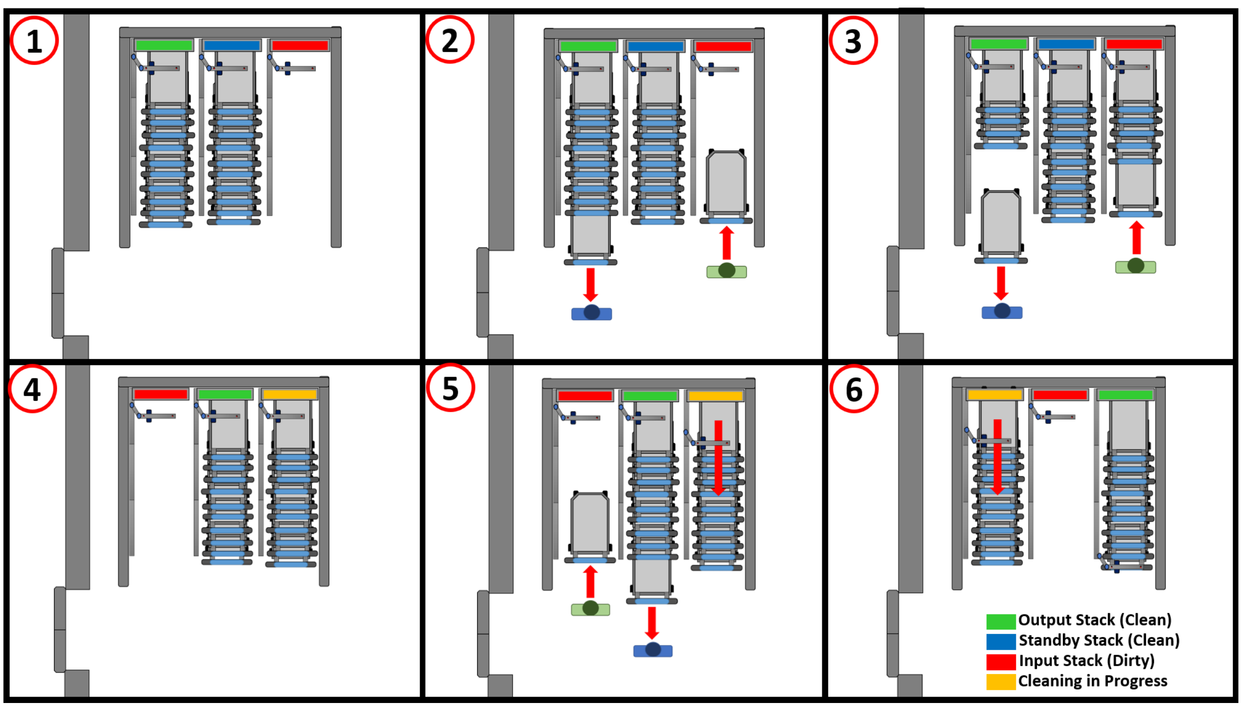

Fig. 16. Storyboard Illustrating Potential of Multiple UltraLight Systems Working in Parallel.

In order to design the motion subsystem for the virtual prototype of the UltraLight system, shown in **Figure 17**, components were selected for their resolution, price point, and load bearing capabilities in order to design a system specific to functional goals. The motion subsystem was designed to translate the UV-C delivery device throughout the cart return and apply it to the cart handles, including horizontal and vertical actuators and motors from Macron Dynamics and Oriental Motors, respectively. Specifically, for the virtual prototype, a Macron Dynamics MSA-R15 Actuator was chosen for both the vertical and horizontal rails with travel lengths of 300mm and 3850mm, respectively [27]. This actuator model is optimal for both the horizontal and vertical system, due to its maximum load of approximately 111 N and maximum moment force of 35 Nm. For the vertical load, this rail choice proves capable of actuating the 45.6 N load and resulting 16.86 Nm moment with an approximate safety factor of two. For the horizontal load, the rail operates with a safety factor of approximately 1.5, with a load of 72.08 N. Additionally, the high positional accuracy of ±0.4 millimeters per meter traveled allows the system to place the UV-C delivery device with a high degree of accuracy. This is necessary due to the both the high dependence on distance of the power required for disinfection, as well as the ability to fit within small clearance volumes in order to place the UV-C delivery device on the cart handle without interference from environmental obstructions. Load bearing capabilities were also considered, such as a maximum load of 35 Nm, which is sufficient for bearing the load required. For further development of the UltraLight system, past an initial prototype, longer rails may be custom ordered from Macron Dynamics, to account for the longer rail lengths necessary for various cart return lengths.

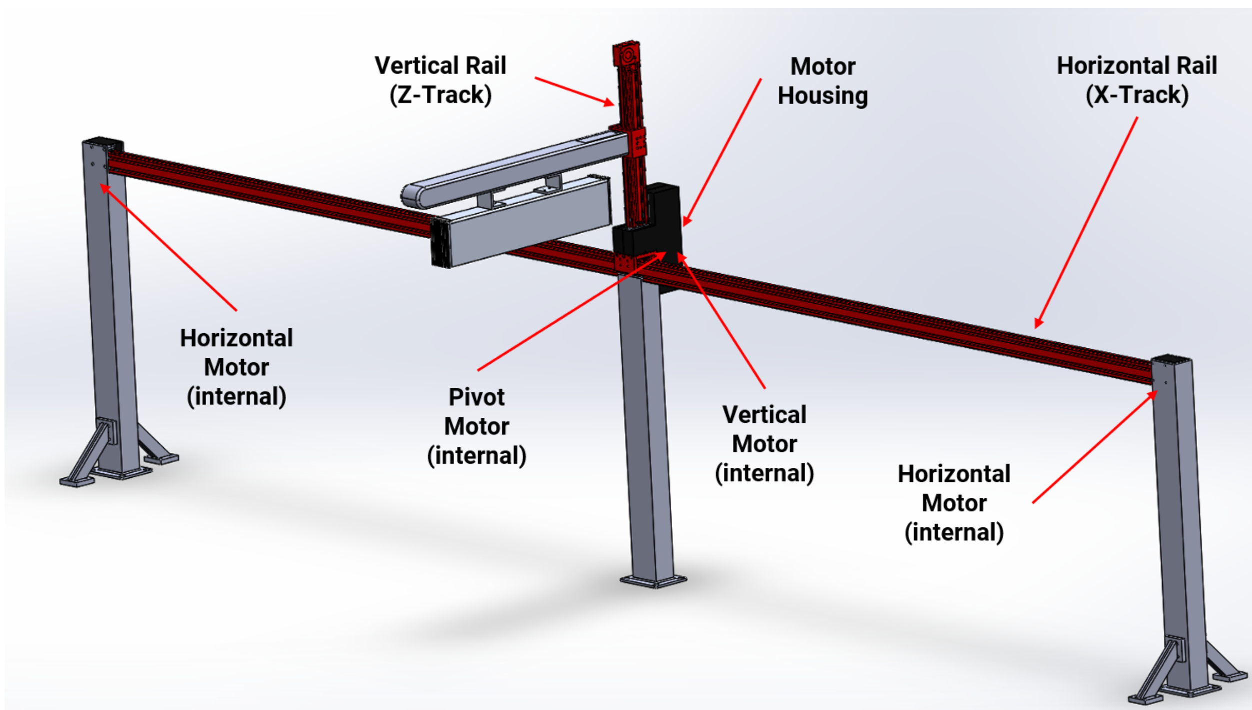

Fig. 17. Motion Subsystem of the UltraLight System, Highlighted in Red.

In addition to linear actuators, motors were required which were capable of achieving the appropriate values for torque and resolution, compatible with the rail system. Two horizontal motors were needed, at each end of the horizontal track, as shown in **Figure 17**. An

ARM46AC-PS25, 1.65 in. Closed Loop Stepper Motor from Oriental Motor was selected for this purpose [28]. This motor was chosen through a sizing process, in order to provide proper actuation for the rail and load with a required torque of 1.5 Nm, resolution of 0.0144°/pulse, and stop position accuracy of ±0.067°. In order to reduce the spatial profile required for the system and provide an efficient, compact design, the horizontal motors were placed in hollow support legs as shown in **Figure 18**.

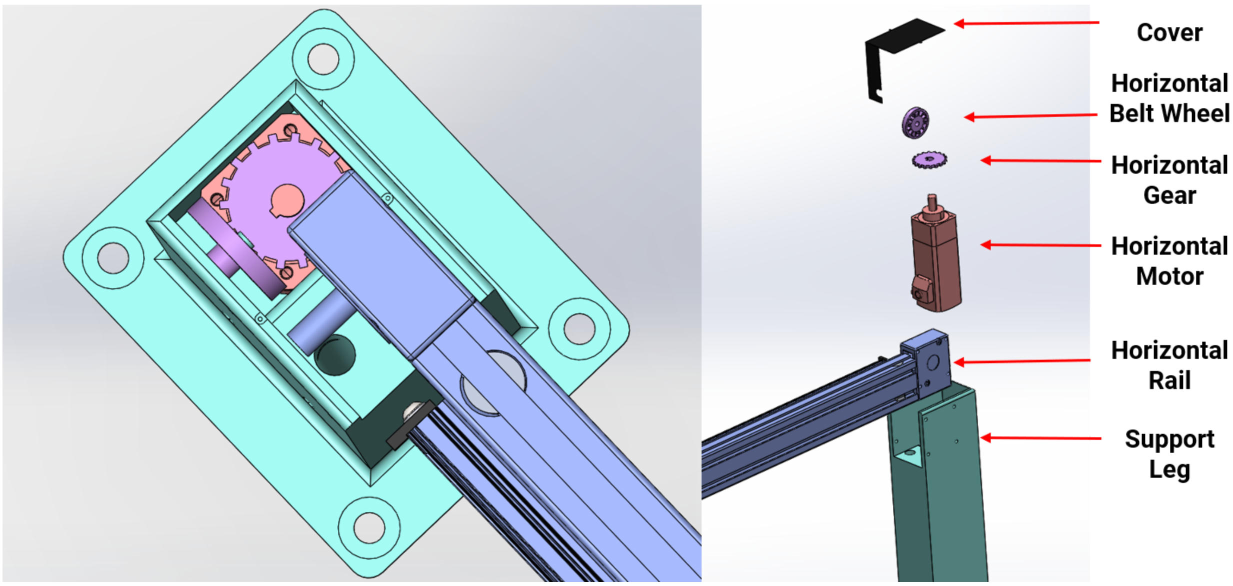

Fig. 18. Support Leg with Internal Horizontal Motor (Left) with Exploded View (Right).

In order to provide the system with the ability to account for misoriented or misaligned carts within the cart return, a pivot motor was also introduced, located in the motor housing shown in **Figure 17**. The same model, the ARM46AC-PS25, 1.65 in. Closed Loop Stepper Motor, was utilized for the pivot motor as well as the horizontal motor. This pivot motor provides rotation to the vertical rail, and therefore the UV-C delivery device, resulting in an ability for carts to be misaligned by approximately ±20°. However, the vertical motor required was chosen for its ability to actuate the vertical rail and load while acting against gravity, requiring a higher value for torque. This model was chosen to be the ARM66AC-N25, 2.36 in. Closed Loop Stepper Motor from Oriental Motor, capable of outputting a required torque of 6.57 Nm, resolution of 0.0144 °/pulse, and stop position accuracy of ±0.067° [29]. This motor was also placed in the motor housing along with the pivot motor, utilizing a compact arrangement intended to minimize the volumetric requirements of the system, as shown in **Figure 19**.

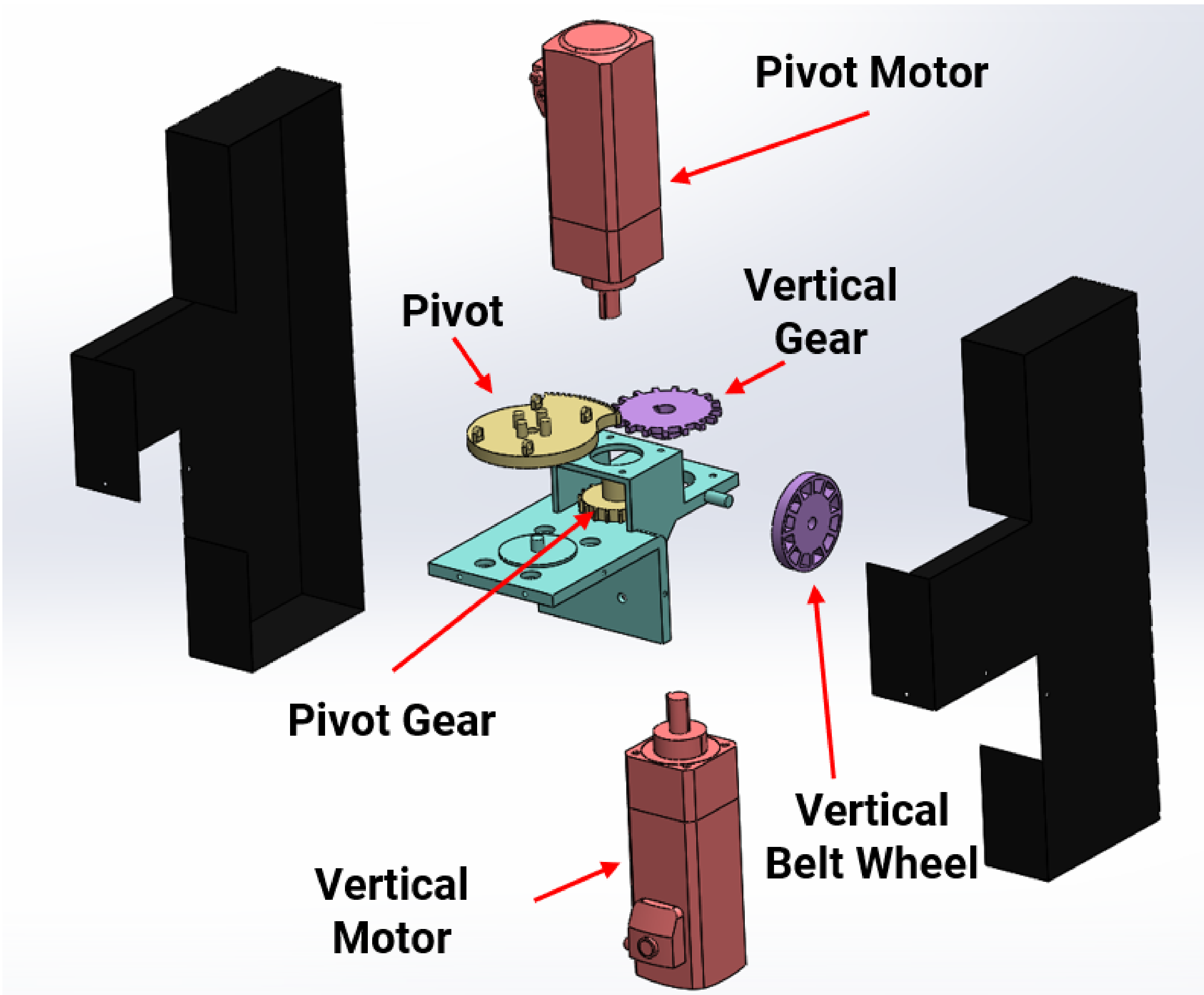

Fig. 19. Exploded View of Motor Housing, with Internal Components.

Additionally, support structures were designed by the team in order to fit the specific requirements for load bearing, and prevent against such concerns as tipping or yielding, as well as minimizing the spatial requirements for implementing the system in the support subsystem, as shown in **Figure 20**. These structures included the leg supports, UV-C support arm and arm brackets, and side leg supports in order to provide stability for the system. It was chosen to design these components rather than to select standard components from vendors in order to create parts specific to supporting the rail components, and maintain the ability to hollow out the supports in order to house the horizontal motor as previously discussed. These components were iteratively designed and evaluated with finite element analysis in order to account for failure modes and appropriate structural stability concerns.

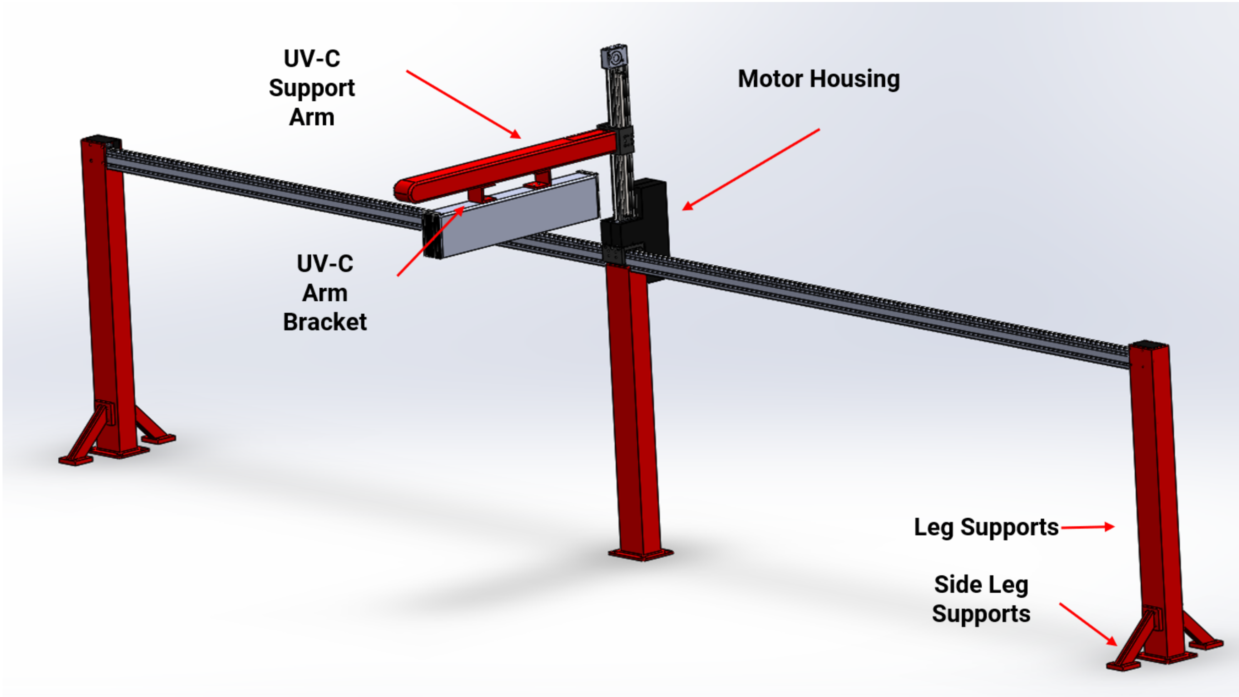

Fig. 20. Support Subsystem of the UltraLight System, Highlighted in Red.

Material considerations included primarily considering cost, weight, and strength. For the UV-C support arm, UV-C arm bracket, and motor housing, ABS plastic is chosen for its low cost to strength ratio and low weight. Additionally, utilizing ABS allows for multiple color and surface texture options, allowing for aesthetic versatility. For the leg supports and side leg supports, carbon steel was initially chosen to maximize strength. While stainless steel is also an applicable material, implementing carbon steel may minimize cost, though future analysis will be required to assess the marginal benefits of either material. Further details regarding material specifications may be found in **Figure A5** in **Appendix A**.

Fasteners required for the support system were also implemented. These components were each selected as a result of considerations for failure modes of the system, as well as for their ability to provide the required forces [30]. To secure the leg supports to the ground, stainless steel 316, ¼" diameter bolts were chosen with a shear strength of 1590 lbs at a safety factor of 3.11. To secure the leg supports to the rails themselves, grade-8 steel 1¼" diameter plated bolts with coarse threads were used, with a withstandable torque of 1101.02 ft-lbs at a safety factor of 1.86. Finally, to secure the UV-C support arm and UV-C arm brackets, grade-8 steel, ⅞" diameter, 9 thread per inch bulbs were utilized, with a withstandable torque of 388.404

ft-lbs at a safety factor of 1.55. These safety factors, all within the range of 1.5 to 3, satisfy the requirements for safety factors of this nature, exceeding the recommended value of 1.3-1.5 [31].

The UV-C subsystem is shown in **Figure 21**. This subsystem includes the UV-C delivery device, which houses the LEDs and is made of Aluminium 1060. This material choice was made to optimize density and strength, as well as ensure a high melting point. Thus, while the weight of the load on the horizontal and vertical rails is minimized, the material of the device is durable and resistant to the heat generated by the UV-C emitted LEDs, though this claim requires future testing not conducted at this stage. Further details regarding material specifications may be found in **Figure A5** in **Appendix A**. The objective of the system is to impart a minimum of 95 mJ/cm^2 on the entirety of the handle in order to achieve a minimum 99.9% disinfection rate [32].

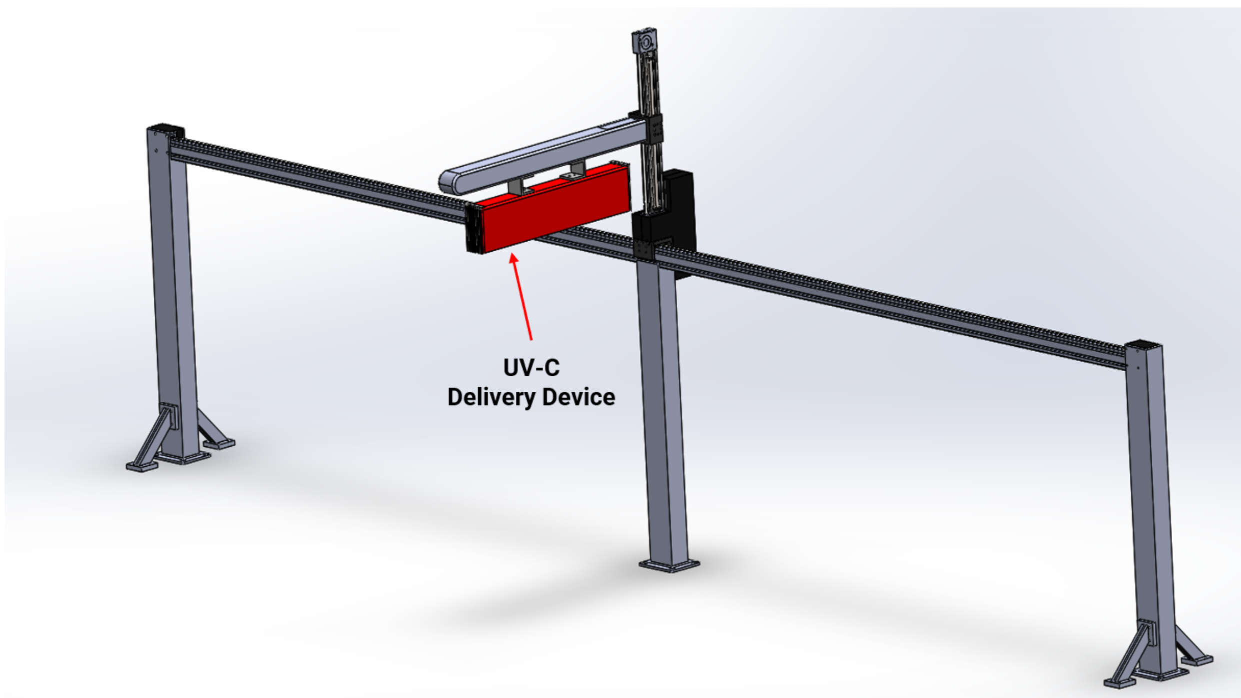

Fig. 21. UV-C Subsystem of the UltraLight System, Highlighted in Red.

A primary justification process for the final concept involved quantitative analysis to determine whether fluorescent or LED bulbs would be a more effective method in delivering UV-C to the cart handle. As previously discussed, a major limitation for fluorescent bulbs to achieve the goal of disinfecting the cart handle is their inability to be placed within the volumetric clearance of the cart, limiting their ability to provide direct irradiation to the bottom of the cart handle. Therefore, reflective surfaces are necessary for any fluorescent-based design. However, due to a lack of fidelity in modeling techniques for reflection and the inability to conduct experimental testing for the efficacy of reflectors or other methods, a fluorescent bulb system was deemed ineffective for disinfection. Thus, the design choice to use LEDs was made in order to avoid relying on reflection methods, circumvent other issues with fluorescent bulbs such as cyclical degradation, and benefit from the small size of LED bulbs. These small sized bulbs allow a configuration of LEDs to be placed within the clearance volume, minimizing the distance from the cart handle surface, and thereby optimizing the efficiency of the UltraLight system in terms of irradiation of the cart handle.

The analysis between fluorescent and LED methods was also completed to determine cost estimates for each option, and analyze the maximum efficiency of each option in order to inform design decisions for the UV-C delivery device design. The process of this analysis was to calculate the irradiance projected by fluorescent bulbs onto a cart handle of a set length from a set distance, and assess the number of LEDs which would be required to match the power of the fluorescent bulbs. This analysis shows the efficacy of both types of bulbs at providing the same power at the same distance, demonstrating the decision to minimize the distance between bulbs and the surface of the cart handle.

Several assumptions were made in modeling these scenarios. The key assumptions included modeling LEDs as a point sources, as LEDs are much smaller than the area of consideration, while fluorescent bulbs were modeled as linear sources, as they possess a long filament which can be modeled as a distributed source. The point sources are assumed to emit light in all directions from a single point, where the projection of light increases the further the distance from the source, but the intensity decreases proportionally to the inverse square of the distance. A distributed or linear source is assumed to function as a collection of point sources [33]. Two primary equations were employed for these models. The point source equation and inverse square law, shown in **Equation 1** and **Equation 2** in **Appendix C**, are assumed to be applicable for LEDs, which are treated as point sources. The Corrected Kietz Equation, shown in **Equation 3** in **Appendix C**, is applicable for linear sources such as fluorescent bulbs, with the assumptions that the linear source has a constant power per unit length, and the distance from the source to the surface is at least twice the length of the linear source. The cart handle is modeled as a two dimensional surface with a length of 0.61 meters (24 inches), while a distance of 0.0985 meters between the light source and the cart handle is used to satisfy the Kietz equation [34].

The fluorescent bulb used in this analysis was an 11 watt UV TUV PL-L UV bulb [35]. This specific bulb was chosen as it provided the highest amount of UV-C power for the size constraint of the system, optimizing power for given size. The theoretical setup with the selection of fluorescent bulbs, where three bulbs are placed end-to-end to fulfil the minimum requirement to irradiate the entire cart handle, is shown in **Figure 22**. Applying the Kietz equation, the irradiance of the handle's surface can be calculated to be 33.9 W/m^2. As fluorescent bulbs are priced at $12.98 each [36], the total cost for bulbs in this theoretical system setup would be $38.94, at a cost of $1.15 per W/$m^2$ delivered.

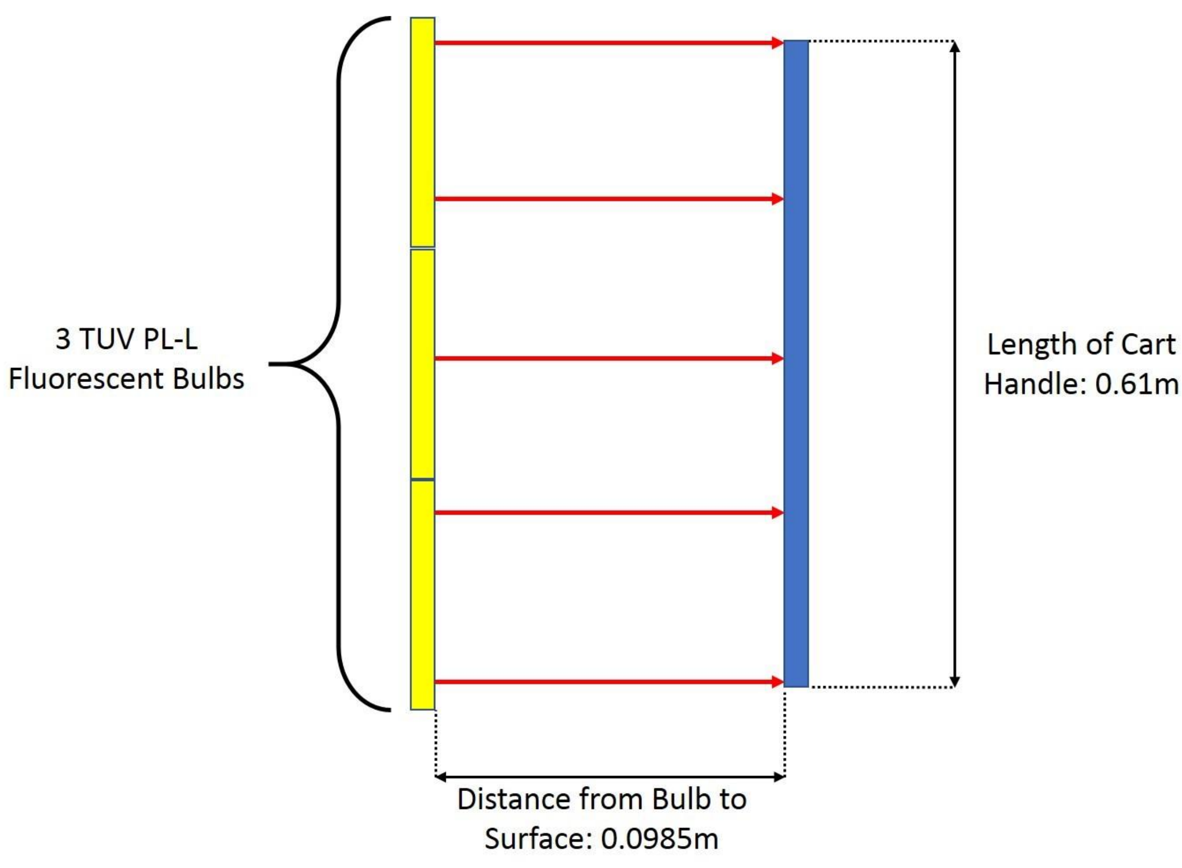

Fig. 22. Potential Disinfection Scenario with TUV PL-L 35W/4P HO Bulbs.

Providing the cheapest cost per unit of UV power at $0.10 per milliwatt for LEDs, the Luminus XBT 3535 LED was chosen to evaluate the LED-based equivalent scenario [37]. These LEDs have 0.0575 watts of UV-C power and a view angle of 130° [38]. To determine how many LEDs are needed to match the fluorescent bulbs' irradiance output of 33.9 W/m^2, the projected area and irradiance of one LED is calculated, as illustrated in **Figure 23**. Using the point source equation, the irradiance per bulb is calculated to be 0.4 W/m^2 projecting a circle with a diameter of 0.4225 meters. To facilitate the model, LED clusters are used and assumed to be a point source. Even though the LEDs are small, this assumption may not provide the most accurate results, as it does not account for the size of the LEDs. However, this assumption was primarily implemented to provide a low-level cost analysis. Using the calculations of one LED, in the case shown in **Figure 23**, it can be determined that a minimum of two clusters of 85 LEDs each will be needed to envelop the cart handle length and match the fluorescent bulbs' irradiance, as shown in **Figure 24**. The total cost of LEDs for the system to match the irradiance of the florescent is significantly higher, totaling $2,234 or $13.14 per LED, at $65.90 per W/$m^2$ delivered [39].

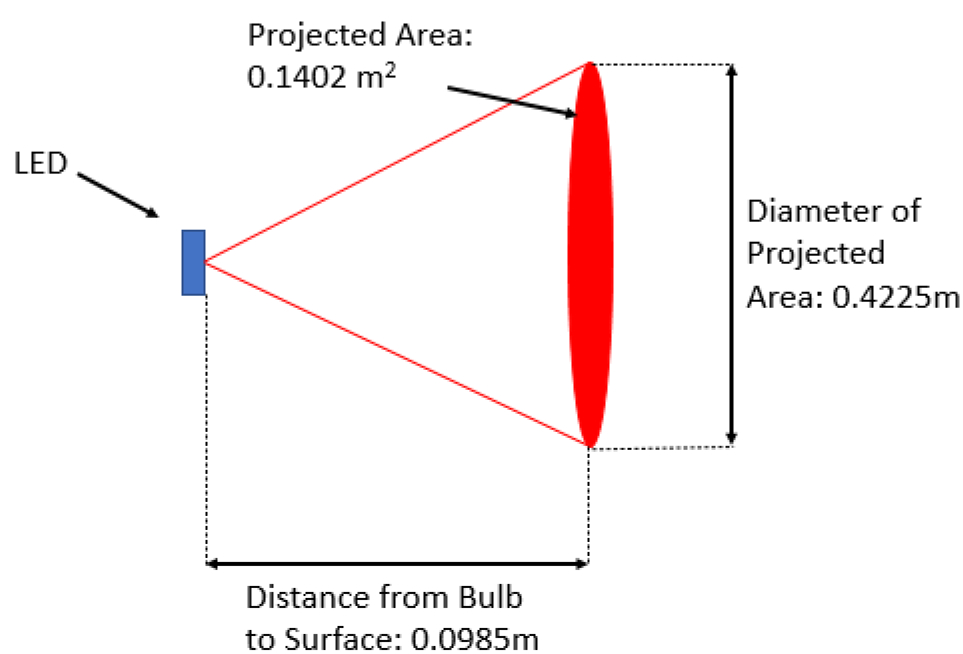

Fig. 23. Potential Disinfection Scenario with a Single Luminus XBT 3535 LED.

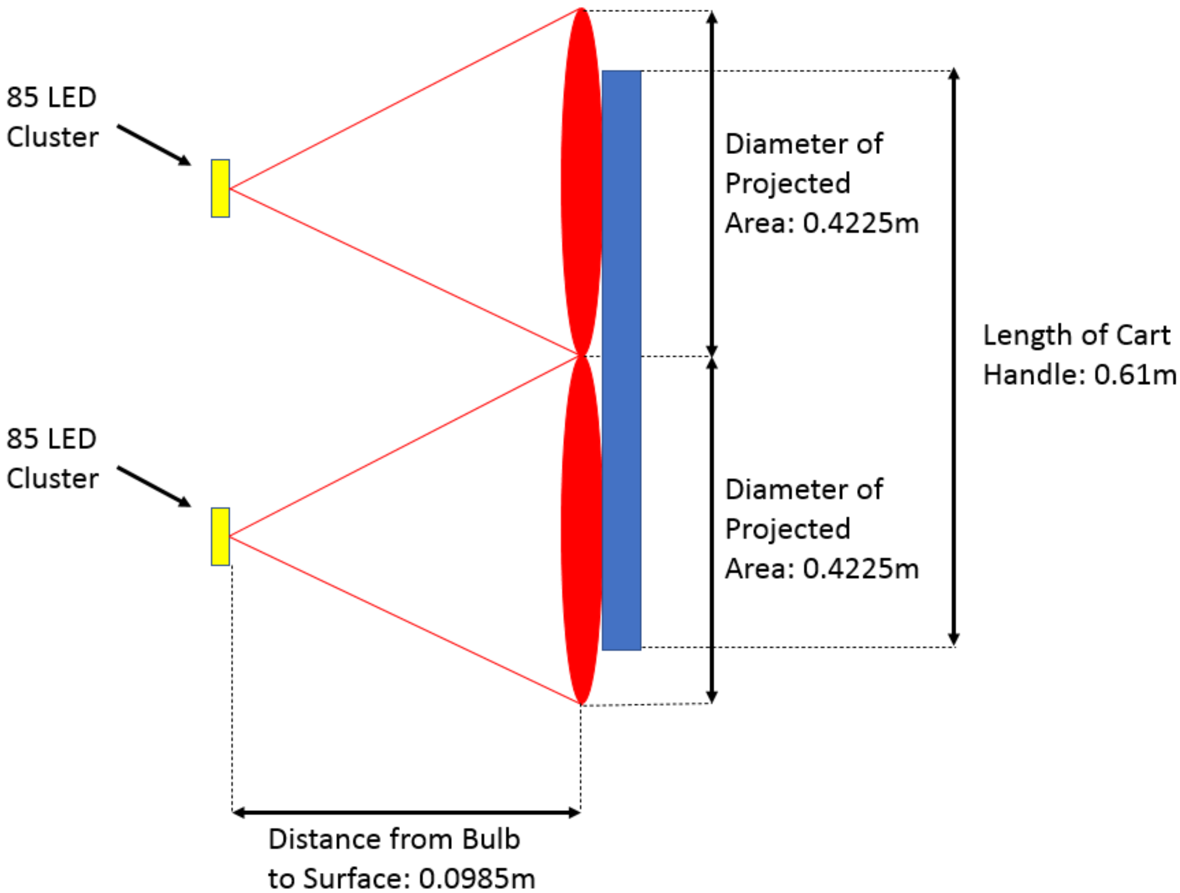

Fig. 24. Potential Disinfection Scenario with Clusters of Luminus XBT 3535 LEDs.

Through this analysis, LEDs are proven significantly more expensive per unit of power than fluorescents at the same distance. However, their small size means they may be placed much closer to the surface, which increases irradiance on the surface but decreases the diameter of the projected area from the source. Thus, a greater number of LED clusters are required in order to provide a sufficient projected area, while the amount of LEDs in each cluster may be decreased. Therefore, in order to minimize cost per unit power, it becomes necessary to minimize the distance between the LEDs and the cart handle while maximizing the number of clusters. In summary, this means that a linear series of "rows" of LEDs at a minimum distance, as implemented in the final design, is calculated to be the most cost effective method of delivering irradiance to the cart handle for LEDs. Utilizing LEDs in the UV-C delivery device is more expensive than the fluorescent alternative, however it is the preferable option as it removes the dependency on reflection methods and can directly irradiate the cart handle. The

Luminus XBT 3535 was specifically selected for its ability to provide the most amount of power for the least amount of cost, further ensuring the efficiency of the system. This LED is 3.5mm by 3.5mm by 1.2mm in size, has a 130-degree view factor, and provides an average UV-C power of 0.0575 watts. Further analysis of the UV-C delivery device may be found in **Section 9: Detailed Technical Analyses, Experimentation, and Design Performance Prediction**, where specific methods and calculations ensuring maximum cost effectiveness and power use are discussed.

Finally, in order to construct a system capable of sensing the location of cart handles relative to the UV-C device, an ultrasonic sensor was chosen as they are not prone to detection issues stemming from the color, reflectivity, transparency, moisture on, or cleanliness of a surface in comparison to other sensors. These benefits make ultrasonic sensors an optimal choice for detecting shopping cart handles, which may involve variation in color, material, surface finish quality, wear and cleanliness. Specifically, an opposed mode ultrasonic sensor was determined to be favorable for the UltraLight implementation, as they have a faster response time and higher level of precision than most ultrasonic sensors. The specific model selected, the Baumer U500.PAO.2-GP1J.72F Sensor, was chosen due to its resolution of ±0.5mm, compatibility with the resolution of the rail components selected, and favorable cost among comparable models [40].

8. Industrial Design

The industrial design component of the UltraLight system lies mostly within the branding, including a logo, slogan, and their combination in the wordmark. The product name “UltraLight” was chosen for multiple reasons. First, it highlights the use of germicidal ultraviolet light for use in disinfection through hyphenation. However, it also blends the quality of disinfection, “ultra,” with the manner of disinfection, “light.” Additionally, the term “light” also has a connotation relating to weight or size, which emphasizes the lean application of the system, evoking the concept of an extremely “light”, or elegant, solution to the problem it solves.

The logo emphasizes the product name at two different levels to create a contrast that draws the eye, highlighting the two-word combination and painting a modern look to represent a modern solution. Written in white to symbolize purity and cleanliness, the glowing appearance of the logo is also intended to capture the eye and further symbolize the use of light in the system. On the product, the logo is placed on the UV-C delivery device because of its high visibility and labeling of the actual UV-C device to further indicate the process to onlookers.

The wordmark introduces a blue background, as the color blue represents trust, while the slogan is written white to match the logo, as shown in **Figure 25**. The wordmark was created to display the slogan and logo in an extremely simple yet comprehensive manner, mirroring the simplicity of the stated claim. The font “Mr Eaves Mod OT bold italic” was chosen because of its readability, while the bold italics provide additional visual emphasis on the words, without being overwhelming. The slogan “99.9% Disinfection Rate in 35 Seconds” is simple, direct, and avoids unnecessarily complicated language to avoid any potential confusion. It is also designed to inspire confidence and provide comforting symbolism to all of those who interact with the product. For store managers, the wordmark symbolizes the claim that they can provide extra protection to their customers and employees. For employees, it represents the simplicity and efficiency of the solution, and a streamlined workload aided by the implementation of the system. Finally, for customers, it serves as a visual indicator of trust, inspiring an elevated sense of cleanliness and safety that other stores without the UltraLight system cannot provide.

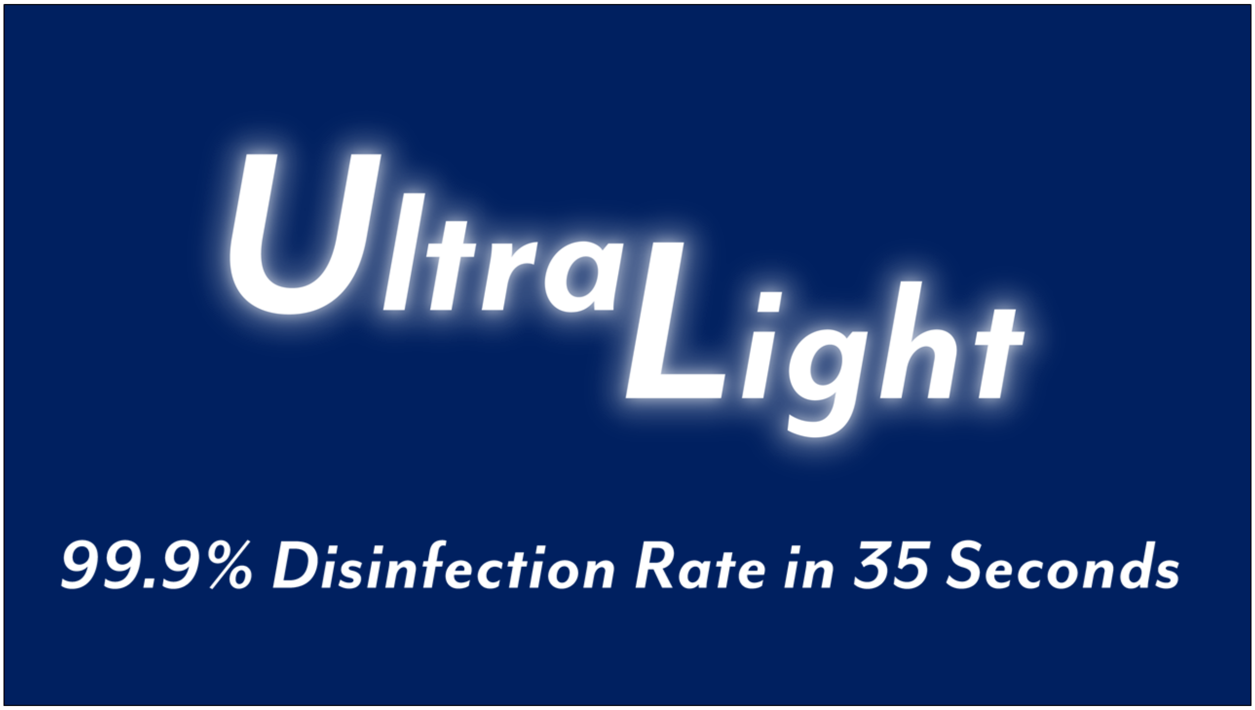

Fig. 25. UltraLight Product Wordmark.

9. Detailed Technical Analyses, Experimentation, and Design Performance Prediction

9.1 UV-C Delivery Device Optimization

The primary analysis conducted on the UltraLight system involved the design of the UV-C delivery device, as well as optimizing for a particular set of carts to ensure that the UltraLight system would be compatible with a wide range of shopping carts and a variety of dimensions. In order to deliver a minimum of 95 mJ/cm^2, a geometric optimization of UV-C LEDs within the delivery device was performed. This process was initiated by establishing the configuration of LEDs within the profile, or cross-section of the device. In the end, a layout was created using Solidworks to ensure full handle UV-C coverage from the LEDs. A row configuration of LEDs was determined to be the most optimal orientation for the system due to its ability to disperse light to the cart handle while conserving space within the UV-C delivery device. A triangular configuration was chosen as it employs the least number of rows of LEDs to fully encompass the handle circumference in UV-C light. To gain an accurate representation of the amount of space surrounding the cart handle, a series of measurements were taken at various grocery stores, including Walmart, Publix, and Kroger, as shown in **Figure 26**.

A) Diameter of the Handle
B) Max Diameter of Plastic Cover
C) Length of Cleanable Handle
D) Max Length of Handle
E) Diameter of Connection Piece of the Cart to the Handle
F) Tolerance Below Cart Handle
G) Tolerance Inside Cart Handle
H) Tolerance Outside Cart Handle
I) Angle of Gate
J) Handle to Handle

Fig. 26. Clearance Measurements for UV-C Delivery Device Optimization.

With these measurements, the minimum clearance volume available for the UV-C device was established, as shown in **Figure 27**. This minimum clearance volume is constructed by assessing the minimum clearance values given obstructions from other carts in the cart stack, as well as accounting for the largest cart handle diameter, measured at 1.5 inches. The primary consideration for LED placement involves allowing for clearances of ±0.06 inches both vertically and horizontally, to account for the maximum possible deviation in placement as a result of the linear actuator resolution. A secondary consideration regards the orientation of the LEDS. As the LEDs were limited to a view factor of 130°, each row was oriented utilizing Solidworks geometric constraints to ensure that irradiation would encompass the entirety of the handle, regardless of deviations in position due to linear actuator resolution. Finally, an overlap in the UV-C irradiation emitted by light sources was imposed to account for these deviations in position, in order to minimize power use.

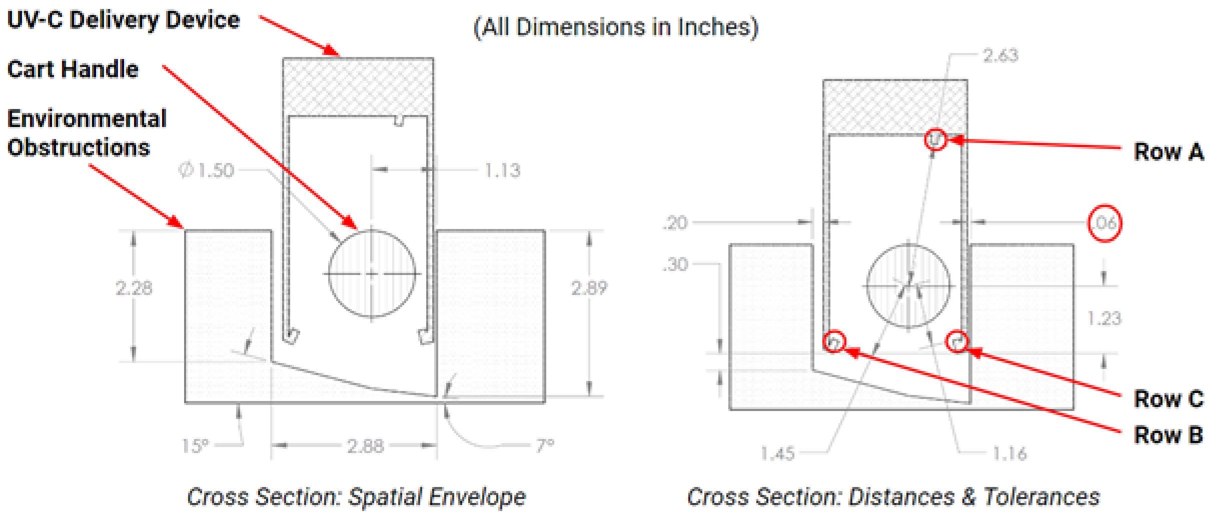

Fig. 27. Cross-Section of Clearance Dimensions (Left) and LED Row Distances (Right) for UV-C Delivery Device Optimization.

An algorithm was then created to optimize the number of evenly spaced LEDs in each row of the UV-C delivery device. The intention of this optimization was to tune the number of LEDs in each row in order to provide the same amount of UV-C power to the handle within a set amount of time, to minimize energy expenditure and achieve a constant irradiation across the circumference of the handle. In these calculations, several assumptions are utilized, including that the handle diameter is assumed to be largest measured diameter at 1.5 inches, that the LEDs used for analysis have 0.0575 watts of UV-C power, a 130° view factor, and a 3.5mm by 3.5mm by 1.2mm volumetric profile, and that LEDs are point sources where inverse square law applies, as shown as **Equation 2** in **Appendix C**. Additionally, the distances between the cart handle and Rows A, B, and C as shown in **Figure 27** are utilized for the calculation. Finally, the irradiation values were measured at the furthest point of influence for each LED bulb, in order to ensure the minimum irradiance value on the handle exceeded the target value of 95 mJ/cm^2.

To achieve a minimum sanitization time, the row furthest from the cart handle (Row A) was maximally packed with LEDs. This choice was made as a result of the inverse square law, which states that as distance is increased, the irradiance of the LEDs will decrease proportionally by the square of the distance. Therefore, to minimize the disinfection time, the irradiation from Row A must be maximized. After calculating the resulting disinfection time from this configuration, the algorithm could then calculate the number of LEDs needed in Rows B and C to achieve an equivalent sanitization time, given different distances from the cart handle to each row.

It is important to note that increasing the amount of evenly spaced LEDs in each row may not necessarily decrease the disinfection time. This is due to the view factors of the LEDs, which limit the area of influence, and consequently, the amount of irradiance received at the edge of the handle. Therefore, the algorithm considers a range of LEDs to create a graph of cost at various disinfection times, as shown in **Figure 28**. It can be concluded that, under these assumptions, a constant disinfection time of 24 seconds per handle can be achieved with 164 LEDs in row A, 90 LEDs in row B, and 60 LEDs in row C at the cost of approximately $3837. This process is further detailed in **Sequence 3** of **Appendix D: LED Optimization Algorithm**.

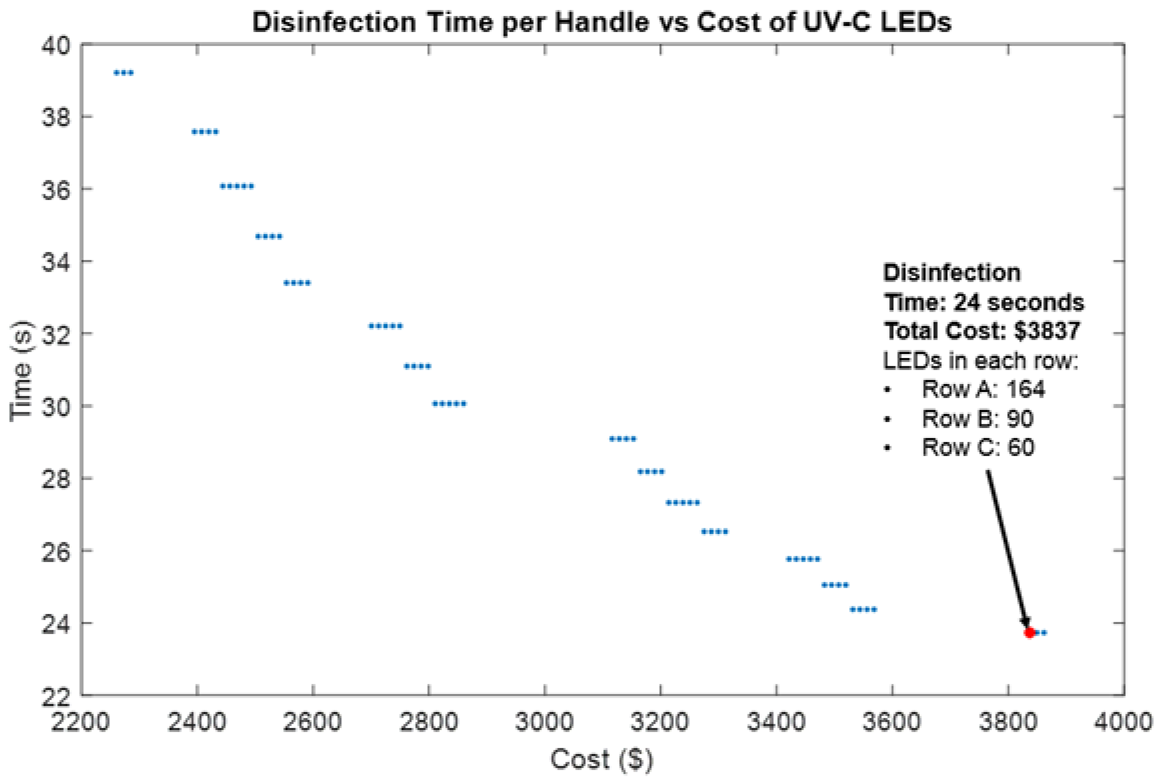

Fig. 28. Disinfection Time as a Function of Initial Cost of LEDs for the UltraLight System, Initial Estimate Case.

However, the previous calculations are only accurate for one specific case where the rows of LEDs are at their ideal distance from the cart handle, with the cart handle set at a 1.5-inch diameter. This time value was further refined to calculate a time value for achieving 99.9% disinfection accounting for a variation in cart handle sizes, as well as a positional accuracy of ±0.06 inches. The minimum cart handle was taken to be 0.75 inches, at a standard size which accounts for the smallest cart handle diameter evaluated in empirical measurements described above. The algorithm was then able to recalculate the maximum distances between the handle and the row of LEDs and obtain a new disinfection time which reflected this minimum cart handle diameter and positional variations. The previous distances between the cart handle and the rows of LEDs will include an additional 0.375 inches, to account for the decrease in handle size from 1.5 inches to 0.75 inches, and 0.085 inches to account for the maximum allowable clearance of 0.06 inches horizontally and vertically. This scales the time considerably in a process further detailed in **Sequence 2** of **Appendix D: LED Optimization Algorithm**.

Additionally, the degradation of LED UV-C power had to be accounted for. Depending on the current input to the LEDs and the temperature conditions in which they operate, the degradation of emitted power can vary drastically. A general representation of how current can influence an LED's output UV power is shown in **Figure 29**. Further experimental testing, simulating grocery store environments and the fluctuation in current, will be required to gain insight on the rate of degradation of the LEDs. For calculation purposes, the LEDs are assumed to operate at ±10% of their rated UV-C power. This rate can be adjusted accordingly after experimental data is gathered. To acquire a conservative disinfection rate, the LEDs are then assumed to operate at 90% of their rated power, at a 10% degradation. Using the same calculation process for adjusting the cart handle lengths, a new disinfection time was calculated to be approximately 35 seconds. This process is further detailed in **Sequence 3** of **Appendix D**.

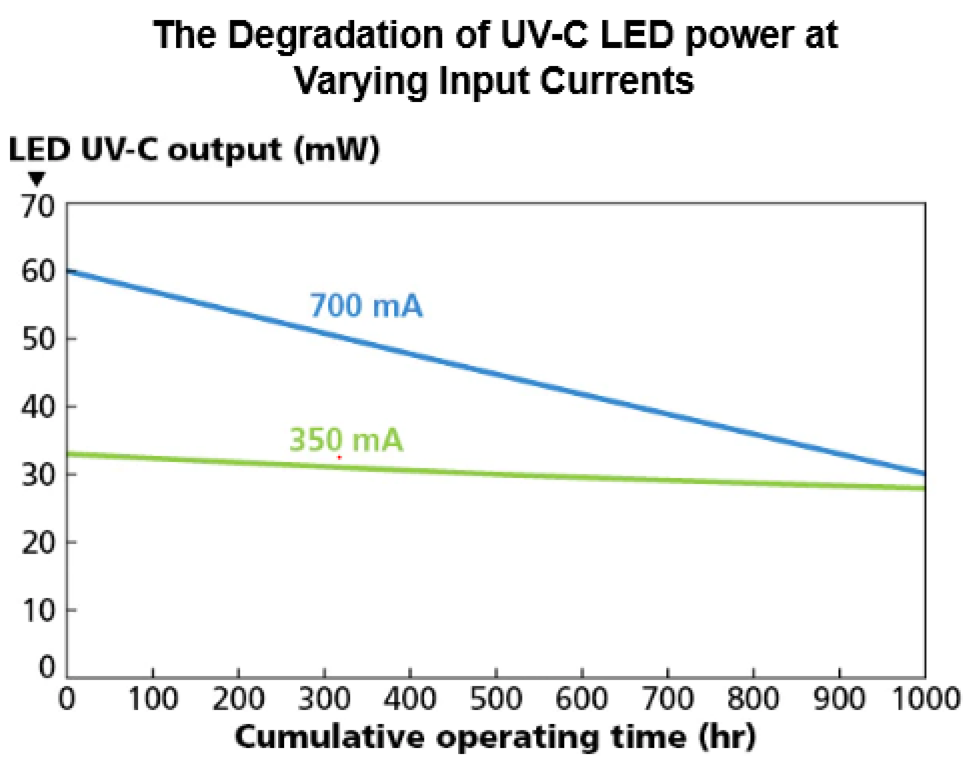

Fig. 29. The Degradation of UV-C LED Power at Varying Input Currents.

In conclusion, a time of 35 seconds was calculated in order to achieve 95mJ/cm^2 of irradiance on the handle. This value accounts for a range of shopping cart handles in the range of 0.75 to 1.5 inches, and a 10% rate of degradation in UV-C output from the LED bulbs. This calculation utilizes a total of 314 LEDs, with 164 placed in Row A, 90 placed in Row B, and 60 placed in Row C, at the distances shown in **Figure 27**, with a tolerance of ±0.06 inches horizontally and vertically. This calculation also assumes a 23-inch-long handle, allowing for nearly two feet of disinfected surface. The initial cost of the LEDs required is $3,837.08, shown as a function of disinfection time in **Figure 30**. A more in-depth analysis of the algorithm utilized to perform this analysis is shown in **Appendix D**.

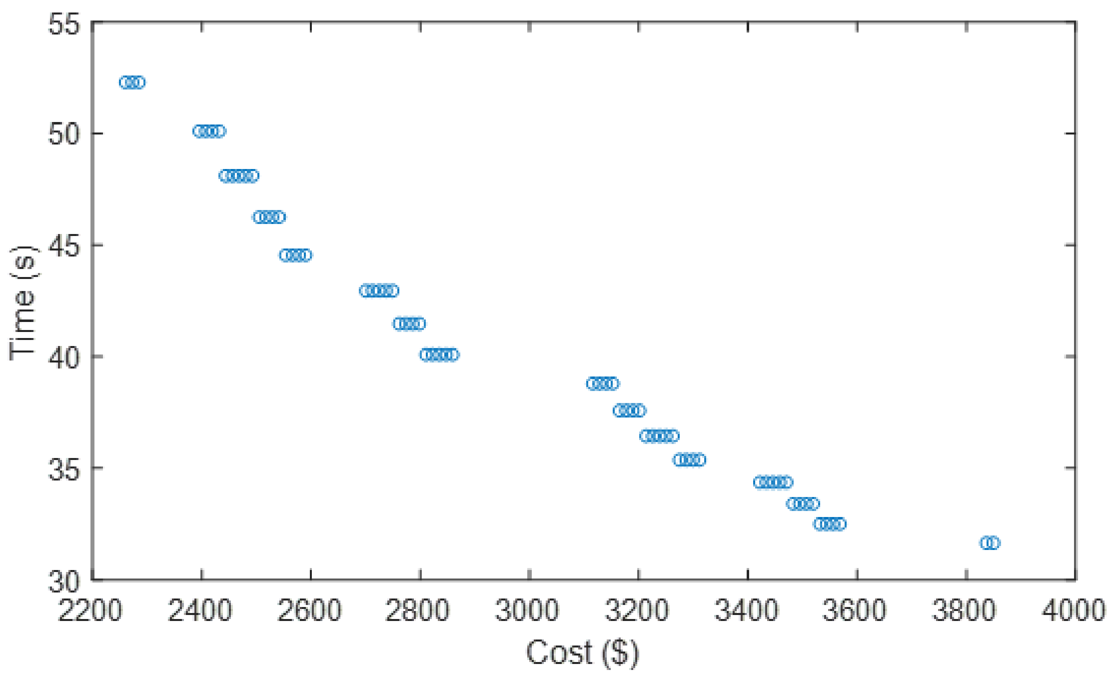

Fig. 30. Disinfection Time as a Function of Initial Cost of LEDs for the UltraLight System.

9.2 Finite Element Analysis

As the support structures for the UltraLight system were designed by the team in order to achieve specific functions for structural stability, detailed analyses were required to ensure functional requirements were met. Primary analysis entailed analyzing von Mises stresses in order to understand yielding criteria for the design. This enabled the team to ensure cooperation with the stresses and possible scenarios which may be experienced by the system and iterate the design of the components accordingly. Additionally, displacement factors were considered for resolution considerations to ensure that the deflection of components would not result in operational failure of the system.

These analyses were conducted on all the custom components designed by the team. These components include the UV-C support arm, UV-C support brackets, and leg supports. Each component was confirmed to comply with the specification sheet, shown in **Figure A5** in **Appendix A**. A summary of the FEA analysis and associated results may be found below, while screen captures of the Solidworks window for each analysis may be found in **Appendix E.**

Analysis on the UV-C support arm revealed a von Mises stress of 1.109 MPa and that yielding failure does not occur until a stress of 29.6 MPa. This demonstrates that the choice of ABS plastic is more than sufficient for the UV-C support arm, and that a cheaper material may be selected if desired. Additionally, the maximum possible displacement of 1.838 mm at the unsupported end of the UV-C support arm was halved to find the displacement at where the UV device is placed on it. This was then accounted for in the vertical clearance of the UV-C delivery device. In terms of power delivery and irradiance on the surface, this deflection results in a difference of 2%, or 1.9mJ/cm^2, and can therefore be considered negligible. Illustrations of this analysis may be found in **Figure E1** and **Figure E2** in **Appendix E**.

The analysis on the aluminum 1060 UV-C arm bracket demonstrates that it is optimally designed for the system. The maximum stress was found to be 1.7 MPa, considered small when compared to the 17 MPa yield strength of the UV-C delivery device. Additionally, the FEA analysis demonstrated that a maximum displacement was on the order of hundredths of millimeters, a negligible displacement compared to the allowances integrated into the system. These analyses prove to the team that further material optimization can be done to reduce cost and improve ergonomics. Though further analysis to consider heat transfer is necessary, structurally, the UV-C arm bracket was determined to be optimal. Illustrations of this analysis may be found in **Figure E3** and **Figure E4** in **Appendix E**.

Analysis on the support legs resulted in the primary conclusion that yielding would occur prior to buckling. The safety factor from yielding is 6.4, while the safety factor for buckling is 450. Illustrations of this analysis may be found in **Figure E5 - Figure E7** in **Appendix E**. Additionally, tipping concerns were considered by simulating a force on the side of the leg where the rail connected into it of a magnitude of 2135 N. This force is equivalent to the weight of the whole design, plus an additional 250 lb, meant to simulate the weight of a learning person. This analysis demonstrated a flaw in the design, showing that the leg would not be able to overcome tipping failure without additional reinforcement, as shown in **Figure E8**. Side leg supports, shown in **Figure 20,** were implemented and analyzed with the same force as before (2135 N) to ensure structural integrity and showed a factor of safety of 4.3 as shown in **Figure E9**. Finally, integrating these side leg supports into the design, the stress was shown to be greatest at the upper corners of the legs, at $6.750e^{8}$ MPa, while the yielding strength of carbon steel is $2.827e^{8}$ MPa.

9.3 Cost Analysis

An analysis to evaluate a break-even cost for the UltraLight system, compared with current methods, was conducted in order to gain insight into the financial feasibility of the system, as well as the long-term benefits of implementation. This analysis was conducted by comparing an average labor and material cost for the grocery stores surveyed, as detailed in **Section 5: Market Research**. These surveys are given in **Table B2** and **Table B3** in **Appendix B**. By conducting this analysis, an initial break-even value was established for a single UltraLight system, as well as for three UltraLight systems in parallel. Though this value is highly dependent on a variety of factors specific to individual grocery stores, this baseline break-even value provides a helpful initial estimate.

The assumptions of this analysis are that a store is open for fourteen hours a day, and that one employee is paid a minimum wage of $7.25 an hour to disinfect cart handles to establish a minimum cost estimate. Additionally, based on market research, it is assumed that stores are utilizing approximately 2.5 boxes of disinfectant wipes per day. At a cost of $4.00 per box, this results in an hourly cost of $0.71 for disinfectant wipes. This culminates in an annual material cost of $3,628.10, and labor cost of $37,047.50, resulting in a grand total cost for current disinfection methods of $40,675.60 per year, or $111.44 per day.

To compare the UltraLight system to current methods, a value of 188 carts per day was estimated. This was based upon an estimate of one disinfectant wipe used per cart, with the average disinfectant wipe container carrying 75 wipes, in addition to the market research value of 2.5 boxes of wipes used per day. Power consumption for the system was then approximated at 1.25 kW-hr for LEDs and 0.83 kW-hr for the motors, leading to an overall consumption of 2.08 kW-hr for a single UltraLight system. This power consumption value is derived from time estimates of 35 seconds to disinfect each cart handle, as well as an assumed 1 second to move the system to the next cart handle, 2 seconds to translate vertically to move the UV-C delivery device to the cart handle, and 5 seconds for the system to move back to its original position after disinfecting carts. Based on an estimated local price of $0.09/kWh for Georgia Power rates, the cost of energy for one UltraLight system was then estimated to be $68.96 per year, or $0.19 per day. For three UltraLight systems, this comes to $206.88 per year, or $0.57 per day. Overall, this results in a cost of $0.001 per disinfected cart.

An initial material cost estimate was taken to be $9,428 for a single system, or $28,284 for three systems working in parallel. These values were based on an overall LED cost of $3837.08, linear actuator cost of $3742.00, and motor cost of $1849.00 [27]-[29], [38]. These values do not reflect the cost of material, cost of manufacturing for custom components designed by the team, or the cost of assembly. They also do not reflect the final cost of the system included in the Bill of Materials, shown in **Figure A6** in **Appendix A**. However, this analysis was conducted for a baseline measurement of the cost of the system for different cases.

Based upon these values, a single UltraLight system breaks even with current disinfection methods in 85 days, or about 3 months, at a cost of $9,444. This is illustrated in **Figure 31**. This cost is based on an assumption the system is sold at cost, and an estimate of 188 carts per day, meaning higher cart throughputs may result in a marginally longer break-even time. However, the cost of energy is extremely low ($0.19 per day) compared to the initial cost of the system, meaning that breakeven time is not highly dependent on the amount of carts utilized, and the cost of the system remains relatively stagnant over time. However, past the breakeven point, this system has a cost of $69.35 per year, at a savings of $40,606 per year compared to current disinfection methods.

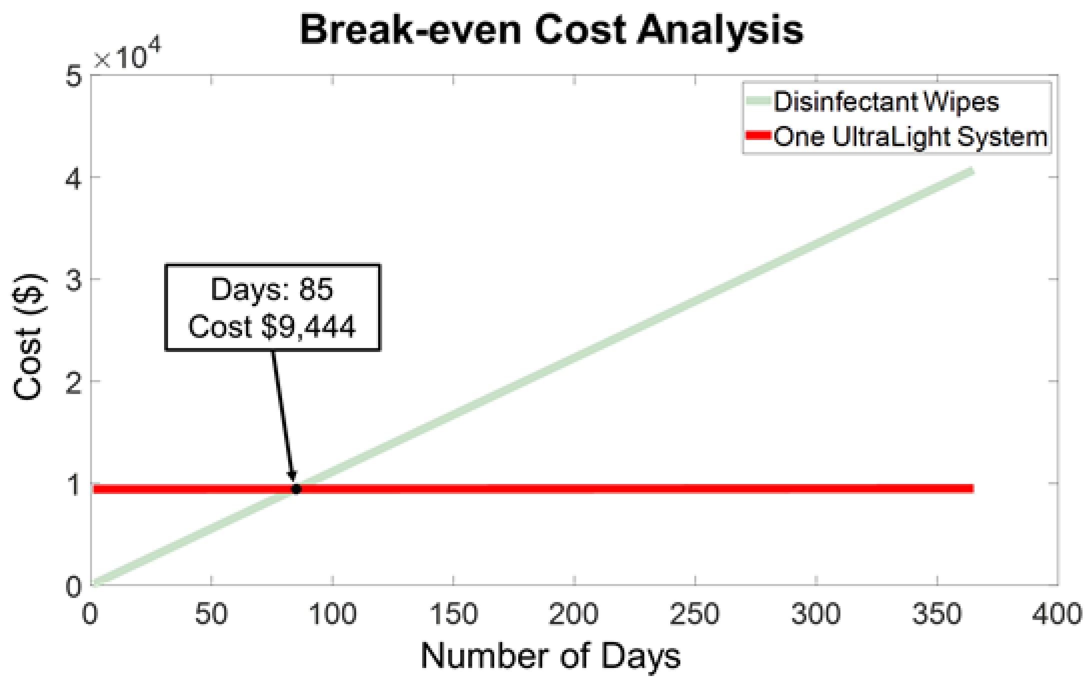

Fig. 31. Break-even Cost Analysis for One UltraLight System, Compared to Current Methods.

For three UltraLight systems, the break-even cost occurs at 255 days, or approximately nine months. This is illustrated in **Figure 32**. This value is based upon an assumption for throughput of 563 carts per day, as well as the assumption that the system is sold at cost. The same case can be seen for three UltraLight systems, where the break-even point is not largely dependent on increases in cart throughput. Past the breakeven point, these systems have a cost of $208.05 per year, at a savings of $40,467 per year compared to current disinfection methods. Thus, a relevant conclusion is that tripling the number of UltraLight systems, and therefore tripling the cart throughput, results in a reduction in savings of only 0.34%. Therefore, the UltraLight system can be seen to be extremely cost effective in the long run due to its low energy consumption compared to both the initial cost of the system and to the cost of current methods.

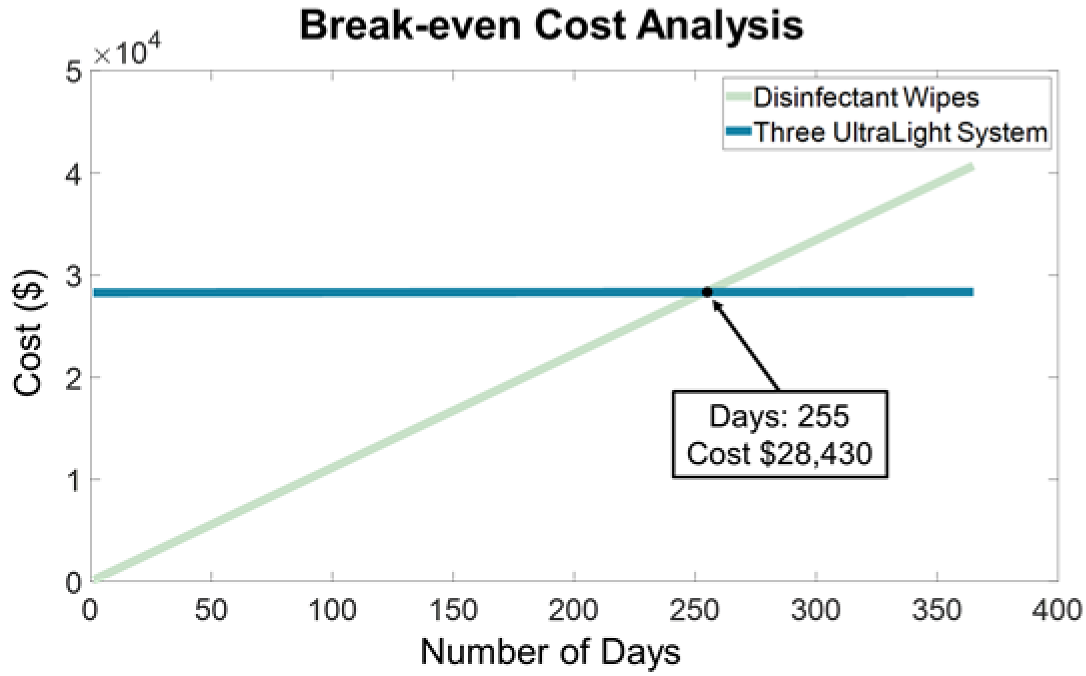

Fig. 32. Break-even Cost Analysis for Three UltraLight Systems, Compared to Current Methods.

10. Final Design, Mockup and Prototype

The UltraLight virtual prototype is shown in **Figure 33**. This prototype includes all of the subsystems necessary for an operating design excluding the electric, computational, and controller components. This prototype includes 316 UV-C LEDs to provide a 99.9% disinfection rate to the entire surface of the cart handle in 35 seconds per cart, for a range of cart handles between 0.75 and 1.5 inches in diameter. The throughput of the UltraLight system is 1.7 carts per minute, or 102 carts per hour, at an estimated energy cost of $0.001 per cart. It is designed to operate with a maximum of 15 carts, stacked with approximately 8.5 inches between each cart handle, and is compatible with current models of shopping carts from Walmart, Publix, Kroger, and Sprouts. The UV-C has a travel length of approximately 12 feet, provided by linear actuators and motors, which also ensure that the system is robust to cart misalignment of up to 20°. This system also utilizes ultrasonic sensors in order to detect carts, eliminating any problems the UltraLight system could face stemming from cart handle color, reflectivity, transparency, or surface finish.

Fig. 33. UltraLight System Completed Prototype.

Each factor of the UltraLight prototype is calibrated to achieve the established customer requirements and engineering specifications, as shown in the House of Quality in **Figure A2** in **Appendix A**. These specifications are also given in the Specification Sheet in **Figure A5** in **Appendix A**. Key parameters include the ability to disinfect cart handles, compatibility with store layouts, being cost effective, and safety, all of which the UltraLight system achieve through use of targeted germicidal ultraviolet light applied at a minimum distance from the cart handle, with an enclosed delivery device which minimizes light leakage. The UV-C deliver device is carefully designed to provide 95 mJ/cm^2 to the handle, using 316 LEDs all placed within 3 inches of the cart handle, fulfilling primary engineering specifications and targets such as meeting the 99.9% disinfection rate, ensuring that the entire surface of the cart handle, and achieving this disinfection in less than a minute. As a result, the speed of disinfection exceeds target values established by the House of Quality. Autonomy and size considerations are fulfilled by the implementation of linear actuators, with a maximum cross section of 1.1 by 2.8 inches, which may move the UV-C delivery device to each cart handle. These low-profile actuators enable the system to operate without human aid. Additionally, the motors required to power these actuators are placed either within the frame of the system or in a motor housing for an efficient, compact design, as shown in **Figure 34**. Autonomy is also aided by ultrasonic sensors, which when integrated with a logical control system or other computational element, may be used to detect the location of and relative distance to the cart handles. Finally, this system is able to be placed within the cart return without requiring excessive amounts of space. This is made possible by a compact 1 by 5 by 13 foot spatial envelope, not including the UV-C support arm and UV-C delivery device.

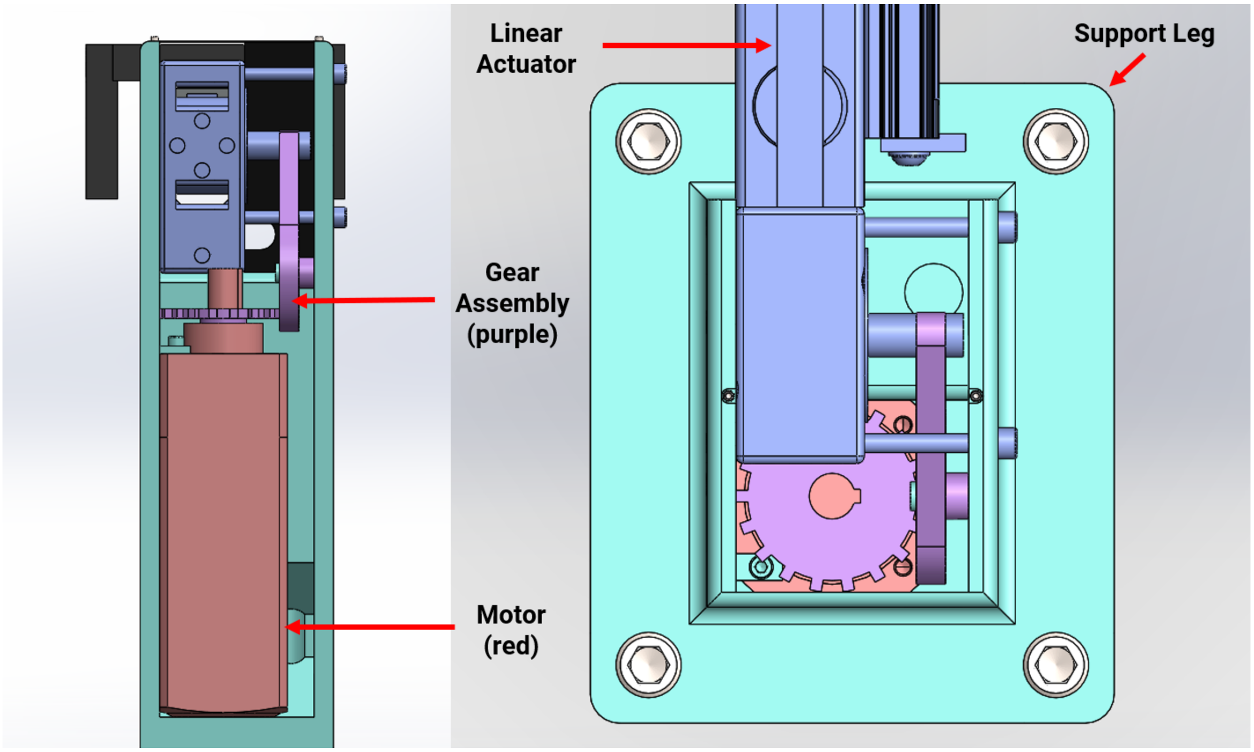

Fig. 34. Support Leg Section View (left), and Top View (right), Detailing Internal Motor.

The purpose of the virtual prototype includes testing feasibility, performing stress analyses, aiding in visualization, and establishing volumetric parameters. While lacking components such as visual indicators, force transducers, or controllers such as user interfaces or kill-switches, the construction of the prototype helped to visualize the design in virtual space. Thus, future components may be implemented more easily with the visual perspective the virtual prototype affords. Another primary benefit of the virtual prototype was the ability to create an animation which helps convey the function of the design to the public and aid the team in visualizing areas of improvement. One such benefit was the ability to measure the maximum possible tolerance for misaligned carts. Overall, this prototype provided a visual representation of the automated disinfection process which was useful in identifying issues, potential errors, and future work required for the operation of a physical prototype. A detailed Bill of Materials for the prototype and its components in **Figure A6** in **Appendix A**.

11. Societal, Environmental, and Sustainability Considerations

The COVID-19 pandemic initiated a rapid global change that grocery stores had little to no time to prepare for. If the UltraLight system had been placed in a grocery store before or even during a pandemic, the system could have eliminated a major pathway of pathogen transmission. Consequently, in preparing for a future pandemic, the UltraLight system could play a key role in reducing disease spread and ensuring safer shopping environments.

The UltraLight system impacts the community by serving as a physical reminder that stores understand their responsibility towards safeguarding their customers. The system will also ease the workload for employees and ensure their safety by automating a potentially risky cleaning process. It provides the community with a system that inspires confidence in the shopping experience, and encourages prioritizing the safety of the shopping environment. This may lead to an increase in in-store shopping in pandemic and non-pandemic conditions alike, and therefore lead to increased profitability for brick-and-mortar stores. The concerns raised in pandemic conditions regarding cleanliness will continue to linger even when environments revert to typical conditions. Thus, market demand for a cart handle disinfection method will only increase moving forward, and stores which possess such a system will be at a unique advantage. These considerations are validated by market research which showed that 83% of shoppers would rather shop at a store with an implemented disinfection system [20].

The main environmental impacts of the UltraLight device include ultraviolet radiation, as well as the energy consumption. The energy consumption is low, at a rate of 2.08 kW-hr per day, meaning that high electricity will not be required during use. UV radiation is also linked to ozone, however, ozone can only be produced if the UV wavelength is between 160 and 240nm [AG4]. As the UltraLight system uses LEDs which emit a wavelength between 275 and 285nm, ozone will never be produced, and therefore environmental concerns will be limited to human interaction, as displayed in **Figure A1** in **Appendix 1**. The UltraLight system is also more sustainable than commonly used alternatives. Unlike sanitizing fluids and wipes, the system doesn't require fluids, disposable materials, ventilation changes, and produces no waste or residue. Therefore, the UltraLight system is an environmentally safe and sustainable option for implementation.

12. Risk Assessment, Safety and Liability

Risks for system error and failure, as well as the surrounding risks, must be considered. Warning labels should be placed on or around the system to mitigate liabilities and warn users of potential risks associated [10]. This decreases the liability of the grocery stores in the event of human related error, as the signage will describe the risks, appraise the users of possible dangers, and provide clear warnings to avoid improper interaction with the UltraLight system. Thus, users will bear the burden of liability should they misuse or mishandle the system. In case of the failure or malfunction of the UltraLight system, manual kill switches may provide a level of safety to prevent potential liabilities [8].

Other misuse and mishandling concerns were considered in order to mitigate liability. Visual indicators may be integrated into the UltraLight system to aid shoppers and employees in distinguishing clean carts from dirty carts if multiple UltraLight systems are used. This discourages misuse or mishandling cases such as individuals accidentally or willfully obtaining dirty carts, or placing dirty carts within the clean cart stack. A concern is that the UltraLight system will rely on the shopping community to make the correct choices when obtaining carts, though the majority of dirty carts will be placed into the UltraLight system by trained employees, decreasing potential error.

A primary risk involves UV-C exposure to humans [8]. For the final UltraLight design, a safety cover utilizing flaps has been designed to minimize the amount of direct UV-C exposure outside of the device, shown as **Figure F1** in **Appendix F**. However, without physical prototyping or the ability to collect data regarding the efficacy of such a device, it is impossible to guarantee that this device is capable of fully eliminating the direct exposure to users who may be nearby. In order to ensure compliance with REL codes, further experimentation will be necessary. However, for the final design, maximum exposure limits were established in order to comply with CDC standards, utilizing research by ASHRAE [41]. To assess the maximum exposure limits associated with maximum UV-C exposure from the side of the device, a scenario assuming no safety cover is illustrated in **Figure F2** in **Appendix F**. These exposure limits at various radial distances for this scenario are given in **Figure F3** in **Appendix F.**

Finally, a possible liability includes the UltraLight system not disinfecting cart handles sufficiently due to system error, which may be grounds for lawsuit should it lead to infection of shoppers. Specifically, disinfection capabilities of the UltraLight system can diminish over time, as the power of UV-C LEDs can degrade due to high currents and operating temperatures. While the manufacturer should provide the rated life for LEDs operating at various temperatures and currents, experimental testing remains crucial to verify the operating lifetime of the LEDs to ensure disinfection. After the rated lifetime, the LEDs must be replaced to not compromise the effectiveness of the system. Additionally, extra precautionary steps can be implemented to guarantee the performance of the LEDs. UV indicator strips are a low-cost method to monitor the UV intensity of the system. When exposed to UV, the indicator strip will undergo a gradual color change, directly related to the energy of UV received [42]. These strips can be utilized once a month, and more frequently near the end life of the LEDs, at various locations on the desired surface of disinfection. This will account for any decline in the UltraLight system's UV-C performance. It is important to use the correct UV indicator strips rated for the intensity range of the specific system.

13. Team Member Contributions

Design tasks were delineated into different categories which each team member covered. For scheduling purposes, a Gantt chart was closely followed in order to ensure the team had a clear visualization of the design process as a whole, as well as of their specific responsibilities, as shown in **Figure A7** in **Appendix A**. Bi-weekly virtual meetings were held for the entire team each week, in which time team members could communicate progress, delegate new goals and tasks, and complete deliverables while moving forward. Additionally, smaller sub-team groups met as needed to complete various tasks.

Responsibilities were divided into categories for different design elements, as well as for different tasks completed. Chad Foster was in charge of market research, responsible for researching vendors, selecting components to utilize in the prototype, conducting FEA analysis on custom components, and was jointly responsible for the construction of the virtual prototype. Clark Jacobs assisted in preliminary background research and other tasks, and was responsible for choosing fasteners. Audrey Gillen was in charge of research, responsible for evaluating areas of global, societal, environmental, and sustainability considerations for the design, and jointly responsible for creating major deliverables including reports and presentations. Nolan Gulledge was in charge of facilitating task delineation such as scheduling and evaluating areas of work required, and was jointly responsible for creating design tools, designing the UV-C delivery device, and creating major deliverables including reports and presentations. Keegan Smeenk was in charge of CAD and designing custom components, and was jointly responsible for creating design tools and constructing the virtual prototype. Will Tran was in charge of ensuring compliance with safety standards, responsible for performing detailed calculations and designing algorithms, jointly responsible for creating design tools and designing the UV-C delivery device, and contributed extensively in multiple capacities to ensure timely completion of all objectives.

14. Impact of Online Course Delivery

The unique setup of the senior design course created a distinctive environment that resulted in both unexpected difficulties and opportunities. The team was scattered throughout the American South, with the majority of members remaining in the metro Atlanta area, so time zones were never an issue. While the team was provided with “labs” as a set time on Tuesday and Thursday to dedicate to the project, meetings were held on Monday, Wednesday and Friday. The allowance for this choice to be made on students’ terms not only fit better with members’ individual schedules, but it also unexpectedly resulted in better time efficiency when it came to research, design, communicating final results, and presentation planning. For scheduling purposes, the team closely followed the Gantt chart shown in **Figure A7** in **Appendix A**.

Without the ability to meet in person, communication was facilitated exclusively on the BlueJeans and GroupMe applications. During the ideation process, visual aids and ideas could not be drawn in real-time on paper or dry erase boards, and often required either an exhaustive verbal description, or an awkward drawing on a screen-shared Paint application. However, the distance communication was convenient in unexpected ways as well. Without the need to travel to meet up, any number of group members could request to meet at any odd hour and there would always be someone willing and able to hop onto BlueJeans to collaborate in a moment’s notice. This also eliminated any apprehension or danger of physically leaving a location when work extended well into the night. The distance and time constraints of the summer semester also impacted the team’s ability to share skills, and made it difficult to learn new skills or improve existing skills with the direct assistance of another team member. Even had the class been taken in-person, the team would have relied on GoogleDrive to share and collaborate. However, because of the distance, it became the only option to share large sets of information. The team became quite adept with the setup, and created an organized Drive to store, share, and collaborate on everything from research, design tools, presentations, CAD models and reports.

The most debilitating factor of taking the class in a distance format was the inability to physically prototype and test the design. The Georgia Tech Invention Studio and other on-campus labs and resources were closed, so the team had to rely on SolidWorks for physical prototyping, and Matlab to conduct modeling to determine the theoretical number of LED’s that the system would need to disinfect 99.9% of pathogens on a surface. In order to test and confirm the theoretical data, the team would have likely machined a portion of the UV-C delivery device and purchased some LED UV-C bulbs to create a miniature setup to test the accuracy of the intended LED positioning and ratio. Samples from the surface of a test object before and after disinfection would be taken to a lab and incubated in petri dishes to confirm the actual decrease in pathogens. This would allow the team to confirm the actual disinfection rate as opposed to relying on theoretical results.

15. Conclusions and Future Work

Thus far, the team has designed a virtual prototype of the UltraLight system which is the result of a detailed design process, and included multiple ideation cycles to solve the problem of disease spread through the common contact point of shopping cart handles. This solution was chosen to be a system which disinfects the cart handle using a targeted application of germicidal ultraviolet light in order to reach a goal of a 99.9% disinfection rate, in an automated process which minimizes user input, time and energy costs. The system is compatible with a range of shopping cart models, works with handles of various diameters and materials, and is robust to cart misalignment of up to 20°. This final design met the target for disinfection time at 35 seconds, and fulfills other relevant customer requirements and engineering specifications.

A key conclusion is that the process is an extremely efficient solution to the design problem. A low energy consumption of 0.011 kW-hr and rapid disinfection time of 35 seconds per cart ensure that the UltraLight system is both low cost and low energy. Due to its disinfection time, it can sanitize 1.7 carts per minute, or 102 carts per hour, at an estimated cost of $0.001 per cart, for a high rate of throughput. Additionally, the efficacy of this solution demonstrates the promise for adaptation and implementation to address a variety of global challenges and environments. Not only is this concept an effective solution for shopping cart handles, but the system is also applicable for other common contact surfaces such as door handles, gasoline pumping handles, elevator buttons, handrails, or desks and conference-room tables.

Future work may be performed in several key areas. First, testing may be performed to validate several aspects of the UltraLight system and ensure conformance with the design specifications. One such aspect involves testing the validity of the inverse square law assumptions used to design the UV-C delivery device by collecting data and samples before and after a cart handle is disinfected to assess whether the goal of a 99.9% disinfection rate is met. Testing is also required for safety validations, and can be conducted by collecting irradiance measurements at various distances from the UV-C delivery device. This testing will be relevant for assessing the efficacy of the UV-C safety cover, and potentially informing possible redesigns. Additionally, this testing will provide experimental data in order to recommend safe exposure limits in keeping with current guidelines.

Additional future work involves implementing electrical and computational components, as well as visual indicators and control systems. These systems will be crucial for a functional physical prototype, will provide the ability to automate the components already present in the virtual prototype, and will ensure proper user interaction with a physical model. These future components and subsystems include a manual on/off switch, an emergency kill-switch, force transducers or other components for interference detection, and LEDs which emit color or other visual means to indicate which carts are clean, dirty or in the process of being disinfected. Computational controls will also be required in order to provide the machine logic by which the automation may function. Finally, wiring considerations must be evaluated, as wired components are in motion as the linear actuators move. This may be remedied by a spooling device or other such component.

Manufacturing techniques must also be considered in order to construct a physical prototype. Thus far, while materials have been selected, no specific manufacturing techniques have been chosen as the most optimal to create the custom parts utilized in the UltraLight system. An exploration of effective methods to create each custom component must be performed to judge feasibility moving forward. Additionally, related to the manufacturing of these parts, analyses must be conducted to ensure the efficacy of manufactured components to achieve the performance goals. This process may demonstrate potential issues which may be introduced by various manufacturing processes. This may include physical testing mirroring the previously conducted FEA analysis, and experimental verification that the system will not fail due to various conditions.

Finally, the nature of online instruction impacted the design process by reducing the ability of the team to meet in person, resulting in concept ideation work becoming more problematic and arduous. It also led to more time being spent elaborating on communicating in order to bridge the virtual gap, often to the detriment of time. Additionally, a primary consequence was the inability to build physical prototypes, at the detriment of having a physical goal to achieve, rather than a theoretical manifestation of the design. However, these limitations were offset by the benefit of virtual communications techniques, which enabled team meetings whenever required, without the necessity to physically meet.

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Appendix A: Design Tools

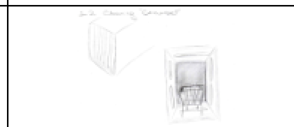
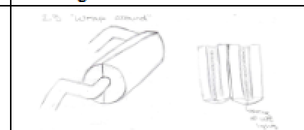
TEAM A2: Evaluation Matrix Alpha		**Conveyor Belt to UV Chamber**		**Standalone UV Chamber**		**Targeted Area UV Device**	
Goal: Reduce Disease Spread in Major Retail Stores by Reducing Risk from Contact with Grocery Cart Handles Score: 5= Exceptional, 4= Good, 3= Satisfactory, 2= Tolerable, 1= Deficient, 0= Unnacceptable							
Criteria:	**Importance**	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
User Safe	**5**	4	*20*	3	*15*	5	*25*
Effectively Sanitizes/ Guards User	**5**	5	*25*	5	*25*	5	*25*
Safe for Cart Handle	**5**	1	*5*	1	*5*	1	*5*
Environmentally Safe	**5**	5	*25*	5	*25*	5	*25*
Accurate (Automation)	**5**	4	*20*	5	*25*	4	*20*
Precise (Automation)	**5**	4	*20*	5	*25*	4	*20*
Accurate (Sanitation)	**5**	5	*25*	5	*25*	5	*25*
Precise (Sanitation)	**5**	5	*25*	5	*25*	5	*25*
Reliable	**5**	5	*25*	5	*25*	5	*25*
Robust to Variation	**5**	4	*20*	5	*25*	4	*20*
Autonomous	**4**	5	*20*	5	*20*	4	*16*
Low User Interaction	**4**	4	*16*	4	*16*	4	*16*
Fits in Provided Space	**4**	2	*8*	4	*16*	5	*20*
Marketable	**4**	4	*16*	4	*16*	4	*16*
Weather Proof	**4**	4	*16*	5	*20*	5	*20*
Durable	**4**	3	*12*	5	*20*	5	*20*
Physically Stable	**4**	5	*20*	5	*20*	4	*16*
Serviceable	**3**	3	*9*	3	*9*	4	*12*
Quick Operation	**3**	4	*12*	3	*9*	4	*12*
Low Cost	**3**	3	*9*	3	*9*	3	*9*
Low Energy	**2**	2	*4*	3	*6*	3	*6*
Low Waste	**2**	4	*8*	4	*8*	5	*10*
Aesthetically Pleasing	**2**	2	*4*	2	*4*	5	*10*
Ease of Setup	**1**	1	*1*	2	*2*	2	*2*
Maximum Possible Score:	**TOTAL SCORE:**	**365**		**395**		**400**	
470	**% OF POSSIBLE TOTAL:**	**77.66%**		**84.04%**		**85.11%**	

Fig. A1a. Third-level Evaluation Matrices for Concept Evaluation (Primary Concepts).

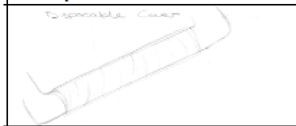
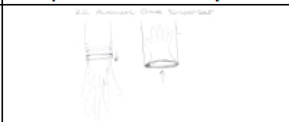
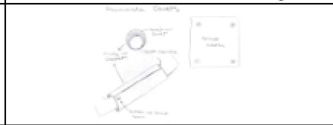
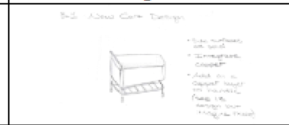
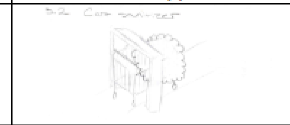
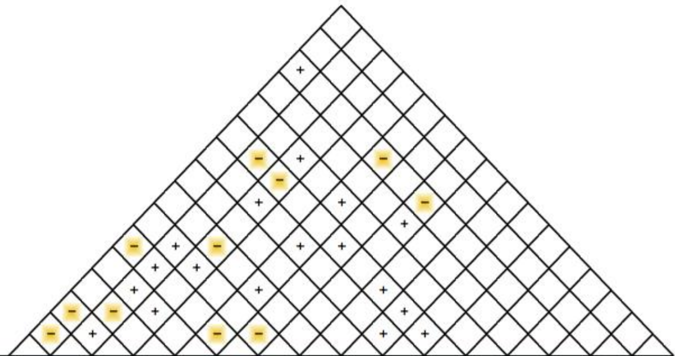
Disposable Handle Covers		Disposable Glove Dispenser		Reusable Cover & Sanitizer System		Redesigned Cart		Sanitizer Applicator	
									
Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
5	*25*	5	*25*	5	*25*	5	*25*	4	*20*
4	*20*	4	*20*	5	*25*	2	*10*	4	*20*
5	*25*	5	*25*	4	*20*	5	*25*	4	*20*
2	*10*	1	*5*	5	*25*	4	*20*	4	*20*
3	*15*	4	*20*	2	*10*	5	*25*	4	*20*
2	*10*	4	*20*	2	*10*	5	*25*	4	*20*
4	*20*	4	*20*	5	*25*	3	*15*	4	*20*
4	*20*	4	*20*	5	*25*	3	*15*	4	*20*
5	*25*	5	*25*	5	*25*	5	*25*	4	*20*
4	*20*	4	*20*	4	*20*	5	*25*	4	*20*
2	*8*	2	*8*	2	*8*	5	*20*	5	*20*
2	*8*	2	*8*	3	*12*	5	*20*	5	*20*
5	*20*	5	*20*	5	*20*	5	*20*	4	*16*
2	*8*	1	*4*	4	*16*	4	*16*	5	*20*
5	*20*	3	*12*	5	*20*	5	*20*	3	*12*
5	*20*	4	*16*	4	*16*	3	*12*	4	*16*
5	*20*	5	*20*	5	*20*	5	*20*	5	*20*
3	*9*	4	*12*	4	*12*	4	*12*	5	*15*
5	*15*	4	*12*	3	*9*	5	*15*	3	*9*
2	*6*	3	*9*	3	*9*	1	*3*	4	*12*
4	*8*	4	*8*	3	*6*	5	*10*	4	*8*
0	*0*	0	*0*	5	*10*	3	*6*	4	*8*
3	*6*	3	*6*	2	*4*	5	*10*	5	*10*
5	*5*	5	*5*	5	*5*	5	*5*	4	*4*
343		340		377		399		390	
72.98%		72.34%		80.21%		84.89%		82.98%	

Fig. A1b. Third-level Evaluation Matrices for Concept Evaluation (Additional Concepts)

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong = 5	●
Moderate = 3	○
Weak =1	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



Weight	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	Direction of Improvement	▼	▼	◇	▼	▲	▲	▲	▼	▼	◇	▼	◇	◇	▼		
Weight	Customer Requirements (Explicit and Implicit) / Engineering Requirements	Weight	System Cost	System Resolution (Accuracy)	Minimum Noise Level	High Level of Autonomy	Ease of Installation	Physically Stable	Minimize External UV-C Exposure	Minimize Degradation of Handle	Uniform Delivery of UV-C to Handle	Minimize Time of Disinfection	Meet Disinfection Rate	Meet Design Safety Factor	Minimize Size of System		
9	Compatibility with Store Layout (Size)	▽	▽				○			●					●		
10	Disinfect Cart Handles		○	●		○			○	○	●	●	●				
4	Aesthetically Pleasing	▽	○		●	▽								▽	○		
8	High Reliability		●	●		●		●	▽		●	○	●	●			
6	Low Noise		▽		●												
8	Minimal User Input		●			●	○				▽						
9	Cost Effective	●	●	●	▽			○		▽	○	○	▽	○	▽		
10	Safe	○				▽			●			▽		●			
7	Meet Cart Throughput Needs	▽	●			▽			▽		○	●	▽				
7	Durable		●					●						●			
6	Energy Efficient	●	○			○			○		○	●					
5	Easily Serviceable	○				○											
6	Low Maintenance													○			
7	Ease of Use		▽			●											
4	Environmentally Friendly	▽			●				●	○							
	Weighted Absolute Importance	144	268	135	79	199	51	102	147	105	164	176	106	174	66		
	Relative Weight (%)	7.52	14	7.05	4.12	10.4	2.66	5.32	7.67	5.48	8.56	9.19	5.53	9.08	3.44		
	Target	Individual parts can be carried without use of machines	Cost less than employee using wipes per year (< $40,606)	Must have a resolution of at most 3 mm/m	Less than 50 dB	At least 95% autonomous	Less than a day	Less than 5mm displacement around floor bearing	Meet CDC guidelines of limited exposure of less than 6000 uW/cm2 per day	Limit Cart Handle Degradation to less than 15%	Cover the circumference of the handle with UV-C	Maximum of 1 minute	99.9% disinfection rate or 95 mJ/cm2 achieved on the handle	Meet standard design safety factors for specific parts	System can exist within existing shopping cart storage areas		

Fig. A2. House of Quality for the Preliminary Design Concept.

Product Sub-Functions	Function Fulfillment Options			
Intakes Cart into System	Manual User Input	Conveyor Belt	Rail System (pulling)	Automated Ramp
Knows When Cart is Present	Pressure Plates	Motion Sensor	IR Sensor	Force Transducer
Locates Handle Position	N/A	RFID	IR Sensor	Force Transducer
Determines Handle Angle	N/A	RFID	IR Sensor	Force Transducer
Place UV-C Apparatus	Servo Motor	Rail System	Pulley	4 Bar Linkage
Delievers UV-C to Handle	Clamp Action	Rotary Action	Reflectors	Multi-Directional Delievery
Yields Cart to Storage	N/A	Rail System	Conveyor Belt	Push Piece
Check for Conflicts	User Input	Motion Sensor	IR Sensor	Force Transducer
Prevent from Harming User	N/A	Flexible Curtain Flaps	Kill Switch	Light Enclosure
Announces Operation Start	Auditory Cue (Beep)	Auditory Cue (Voice)	Visual Cue (Light)	Visual Cue (Monitor)
Warns When in Operation	Auditory Cue (Beep)	Auditory Cue (Voice)	Visual Cue (Light)	Visual Cue (Monitor)
Alerts Operation Error	Auditory Cue (Beep)	Auditory Cue (Voice)	Visual Cue (Light)	Visual Cue (Monitor)
Alerts Maintenace Error	Auditory Cue (Beep)	Auditory Cue (Voice)	Visual Cue (Light)	Visual Cue (Monitor)

Fig. A3. Morphological Chart for Iterated Design Concepts.

TEAM A2: Evaluation Matrix Beta **Goal:** Reduce Disease Spread in Major Retail Stores by Reducing Risk from Contact with Grocery Cart Handles		**Automated Ramp**	**Conveyor System**	**Floor Track System**	**Wall-Mounted Rail System**	**Side-Rail System**
Intakes Cart into System		3	3	4	5	5
Knows When Cart is Present		4	4	4	3	3
Locates Handle Position		3	4	4	4	4
Determines Handle Angle		3	2	4	4	4
Places UV-C Apparatus		4	4	4	4	4
Delivers UV-C to Handle		5	5	5	4	4
Yields Carts to Storage		1	2	3	5	5
Announces Operation Start		4	4	4	5	5
Warns When in Operation		4	4	4	4	4
Checks for Conflicts		4	4	4	4	4
Prevents from Harming User		4	4	4	4	4
Alerts Operating Error		4	4	4	4	4
Alerts Maintenance Error		4	4	4	4	4
Maximum Possible Score:	**TOTAL SCORE:**	**47**	**48**	**52**	**54**	**54**
65	**% OF POSSIBLE TOTAL:**	**72.31%**	**73.85%**	**80.00%**	**83.08%**	**83.08%**
		Score: 5= Exceptional, 4= Good, 3= Satisfactory, 2= Tolerable, 1= Deficient, 0= Unnacceptable				

TEAM A2: Evaluation Matrix Gamma **Goal:** Reduce Disease Spread in Major Retail Stores by Reducing Risk from Contact with Grocery Cart Handles		**Automated Ramp**	**Conveyor System**	**Floor Track System**	**Wall-Mounted Rail System**	**Side-Rail System**
Size of System		2	1	3	5	4
System Sight & Sensors		4	4	4	4	4
Cart Alignment & Orientation		3	2	4	3	4
UV Apparatus Alignment & Orientation		2	2	4	4	5
Cart Throughput (Relocation to Storage)		1	2	4	5	5
Cart Throughput (Speed of Sanitization Process)		2	3	3	4	5
Maximum Possible Score:	**TOTAL SCORE:**	**14**	**14**	**22**	**25**	**27**
30	**% OF POSSIBLE TOTAL:**	**46.67%**	**46.67%**	**73.33%**	**83.33%**	**90.00%**
		Score: 5= Exceptional, 4= Good, 3= Satisfactory, 2= Tolerable, 1= Deficient, 0= Unnacceptable				

Fig. A4. Second-level Evaluation Matrices for Iteration Evaluation, Including Function Fulfilment and Design Issue Evaluation.

				Issued:5/20/20		
			For: Targeted UV Cleaner		Page:	1
			Specification			
No.	Date	D/W	Requirements	Responsib	Source	How Validated
General - Parts						
1	7/25/20	D	1st Joint Cover	Keegan		Used to cover the pivot joint from customers
2	7/25/20	D	2nd Joint Cover	Keegan		The cover was split in half in order to efficiently cover everything with the least parts
3	7/25/20	D	Arm	Chad		Used to maneuver the UV device into position to clean the cart handles
4	7/25/20	D	Arm Cover	Chad		Allows acces inside of the arm for an easier time wiring and securing the arm
5	7/25/20	D	ARM46AC-ps25 (Motor) (2)	Chad		Based off of the torque needed to move the horizontal rail, also used to pivot the vertical rail
6	7/25/20	D	ARM66AC-N25 (Motor)	Chad		Based off the torque needed to move the vertical rail
7	7/25/20	D	Baumer u500 (ultrasonic sensor) (2)	Clark		Sensors used to locate where the cart handles are
8	7/25/20	D	Belt for horizontal rail (Length = 7.5in)	Keegan		Belt used to move the horizontal rail. Distance is from the rail end to the horizontal wheel
9	7/25/20	D	Belt for vertical rail (Length = 14.7in)	Keegan		Belt used to move the vertical rail. Distance is from the rail end to the vertical wheel
10	7/25/20	D	Empty Leg Cover	Keegan		Cover over the leg that does not house the motor
11	7/25/20	D	End Legs (2)	Keegan		The two main legs that support the horizontal rail on either end
12	7/25/20	D	Horizontal Gear	Keegan		Gear attached to the motor that moves the horizontal rail
13	7/25/20	D	Horizontal Wheel	Keegan		Wheel used as an in between for the gear and belt that move the horizontal rail
14	7/25/20	D	Leg Supports (4)	Keegan		Supports placed on either side of the end legs to prevent tipping
15	7/25/20	D	Macron rail (Length = 300mm)	Chad		The vertical rail used to maneuver the UV device into position over the cart handles
16	7/25/20	D	Macron rail (Length = 3850mm)	Chad		The horizontal rail used to move the UV device along a line of carts
17	7/25/20	D	Motor Leg Cover	Keegan		Cover over the leg that houses the motor
18	7/25/20	D	Pivot Gear	Keegan		Gear attached to the motor that pivots the vertical rail
19	7/25/20	D	Pivot Platform	Keegan		Platform that the vertical rail sits on to allow it to pivot
20	7/25/20	D	Rail Joint	Keegan		Piece used to secure the vertical rail to the horizontal rail
21	7/25/20	D	Support Leg	Chad		Extra leg to support the horizontal rail and to protect the rail from any deflection from wieght
22	7/25/20	D	Ultrasonic sensors (2)	Chad		Used to identify where the cart handles are located
23	7/25/20	D	UV Brackets (2)	Nolan		Used to attach the UV device to the arm
24	7/25/20	D	UV Frame	William		Used to house the UV LEDs
25	7/25/20	D	UV LEDs (314)	Nolan		Used to clean the cart handles (cleans one handle in around 30 seconds)
26	7/25/20	D	UV Pin (40)	Nolan		Used to keep the UV light contained
27	7/25/20	D	UV Pin Plate (2)	Keegan		Used to attach the UV pins to the side of the UV frame
28	7/25/20	D	Vertical Gear	Keegan		Gear attached to the motor that moves the vertical rail
29	7/25/20	D	Vertical Wheel	Keegan		Wheel that is used as an in between for the motor and belt that move the vertical rail
30	7/25/20	D	HX-SHCS 0.19-32x0.875x0.875-N (16)	Keegan		Bolts used to secure the leg supports to the end legs
31	7/25/20	D	HX-SHCS 0.125-44x0.5x0.5-N (6)	Keegan		Botls used to secure the pivot motor to the rail joint, and the vertical motor to the end leg
32	7/25/20	D	HX-SHCS 0.164-36x0.625x0.625-N (4)	Keegan		Bolts used to secure the vertical motor to the rail joint
33	7/25/20	D	HX-SHCS 0.164-36x1.375x1-N (2)	Keegan		Botls used to secure the vertical rail to the pivot platform
34	7/25/20	D	HX-SHCS 0.164-36x2.5x1.125-N (8)	Keegan		Botls used to secure either end of the horizontal rail to the end legs
35	7/25/20	D	HX-SHCS 0.06-80x0.125x0.125-N (5)	Keegan		Botls used to secure the leg covers and the arm cover
36	7/25/20	D	HX-SHCS 0.099-56x0.125x0.125-N (2)	Keegan		Bolts used to secure the front end of the pivot joint covers
37	7/25/20	D	HX-SHCS 0.099-56x0.375x0.375-N (4)	Keegan		Botls used to secure the sides of the pivot joint covers
38	7/25/20	D	HX-SHCS 0.375-24x2x1.5-N (12)	Keegan		Bolts used to secure the end legs to the floor
39	7/25/20	D	HX-SHCS 0.19-32x0.5x0.5-N (2)	Keegan		Bolts used to secure the bottom of the rail joint
40	7/25/20	D	HX-SHCS 0.19-32x2x1.125-N (16)	Keegan		Bolts used to secure the leg supports to the floor
41	7/25/20	D	CR-BHMS 0.19-32x0.625x0.625-N (8)	Keegan		Bolts used to secure parts to the two rails
42	7/25/20	D	UV Arm Connector (8)	Chad		Bolts used to secure the UV brackets to the UV frame and the arm

Fig. A5a. Specification Sheet.

Geometry						
1	7/25/20	D	Total Length = 166.2 in	Keegan		Measured from either end of the end legs
2	7/25/20	D	Total Base Width = 14.5 in	Keegan		Measured from either end of the leg supports
3	7/25/20	D	Max Width with Arm+Pivot = 37.5 in	Keegan		Measured from the farthest point of the pivot cover and the max distance the arm will be at
4	7/25/20	D	Total Height = 58.5 in	Keegan		Measured from the bottom of the support leg to the top of the vertical rail
5	7/25/20	D	Horizontal Travel Length = 153.7 in	Keegan		Measured from the center of the vertical rail at both ends of the horizontal rail
6	7/25/20	D	Vertical Travel Length = 14.8 in	Keegan		Measured from the bottom of the UV device at both ends of the vertical rail
Kinematics						
1	7/25/20	D	Motor torque to move horizontal rail = 1.5 Nm	Chad		motor has a max torque of 6 Nm
2	7/25/20	D	Motor torque to move vertical rail = 6.57 Nm	Chad		motor has a max torque of 16 Nm
3	7/25/20	D	Motor torque to pivot vertical rail = 1.5 Nm	Chad		motor has a max torque of 6 Nm
Forces						
1	7/25/20	D	Weight moved by vertical motor	Chad		FEA analysis - 10.26 lbs
2	7/25/20	D	Weight moved by horizontal motor	Chad		FEA analysis - 48.36 lbs
3	7/25/20	D	Weight among legs for buckling	Chad		FEA analysis - 687.26 lbs split between 3 legs = 229.08 lbs per leg
4	7/25/20	D	Moment from arm on end legs	Chad		FEA analysis - 230 lbs
Energy						
1	7/25/20	D	Horizontal motor takes 200-240V at 1.5+A	Chad		The motor should be able to move the vertical rail and all its attachments
2	7/25/20	D	Pivot motor takes 200-240V at 1.5+A	Chad		The motor should be able to turn the vertical rail
3	7/25/20	D	Vertical motor takes 200-240V at 2.3+A	Chad		The motor should be able to move the arm up and down
4	7/25/20	D	Ultrasonic Sensors take 12V at 35mA each	Clark		24V at 35mA Total
5	7/25/20	D	UV LEDs take 0.0575 W per LED	William		18.055 W Total
6	7/26/20	W	Enough UV output to clean a handle in about 30s	William		After 30s of cleaning, check bacteria on handle to ensure 99.9% of germs are dead
7	6/19/20	W	Uses power from an outlet	Keegan		
Material						
1	7/25/20	D	Carbon steel for legs and their supports	Chad		Strong material that won't buckle under the wieght of the other componets
2	7/25/20	D	Aluminum 1060 for all other metals	Chad		Sturdy material that doesn't need to bear any weight
3	7/25/20	D	ABS Plastic for covers and arm	Chad		Cheap plastic whose only purpose is to hide componets
4	7/25/20	D	Rubber for belts	Chad		Flexible material
Signals						
1	6/3/20	W	Light when on	Audrey		
2	6/3/20	W	Light when active	Audrey		
3	6/3/20	D	Start/stop button	Audrey		
4	6/3/20	D	Emergency stop button	Audrey		
Safety						
1	6/3/20	W	Should be monitered	Audrey		
2	6/3/20	D	Ensure no UV escapes	Audrey	NIOSH	Publication Number 73-11005, 1973
Ergonomics						
1	6/3/20	W	Person to start/stop and moniter	Audrey		
2	6/3/20	D	Entirely Automatic once started	Audrey		
3	6/3/20	W	Simple design	Audrey		
Production						
Quality Control						
1	6/3/20	D	Ensure no UV escapes	Nolan	NIOSH	Publication Number 73-11005, 1973
2	6/3/20	D	Automation works	Nolan		
3	6/3/20	D	Can go through motions without problem	Nolan		
Assembly						
1	6/19/20	D	Securing all legs to the floor	Keegan		
Transport						
Operation						
1	7/25/20	W	Quiet (around 80dB)	William		
2	6/3/20	W	Wear resistant	William		
3	6/3/20	W	Occasional outside installation	William		

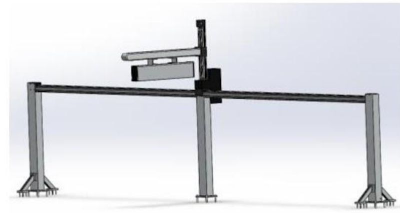
Fig. A5b. Specification Sheet.

Maintenance						
1	6/3/20	W	Easily accessed parts	William		
2	6/3/20	W	Periodically cleaned	William		
Recycling						
Cost						
1	7/25/20	W	Cost = $11,825.14	William		Bill of Materials
Schedule						
1	6/3/20	D	7/21/20 Capstone Expo	Nolan		
2	6/3/20	D	7/26/20 Final Report Due	Nolan		

Fig. A5c. Specification Sheet.

Bill of Materials

Assembly Name :	UltraLight	
Assembly Number :		1
Assembly Revision :		1
Approval Date :		**07/25/2020**
Pieces :		**42**
Total Cost :	**$**	**11,825.14**



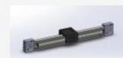
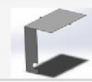
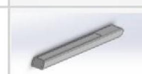
Part ID	Category	Part Name	Qty	Picture	Unit Cost	Cost
1	Rail	Horizontal R15 Acutator (Vendor: Macron Dynamics)	1		$ 3,700.00	$ 3,700.00
2	Rail	Vertical R15 Actuator (Vendor: Macron Dynamics)	1		$ 1,030.00	$ 1,030.00
3	Cover	Motor End Cover	1		$ 1.50	$ 1.50
4	Cover	Empty End Cover	1		$ 1.50	$ 1.50
5	Structural	End Leg	2		$ 70.12	$ 140.24
6	Structural	Leg Support	4		$ 2.87	$ 11.48
7	Structural	Support Leg	1		$ 68.96	$ 68.96
8	Belt	Horizontal Belt	1		$ 5.50	$ 5.50
9	Gear	Horizontal Wheel	1		$ 1.50	$ 1.50
10	Gear	Horizontal Gear	1		$ 1.50	$ 1.50
11	Motor	Arm46AC-PS25 Motor (Vendor: Oriental Motor)	2		$ 389.00	$ 778.00
12	Structural	Arm	1		$ 131.63	$ 131.63
13	Structural	UV Bracket	2		$ 3.00	$ 6.00

Fig. A6a. UltraLight System: Bill of Material.

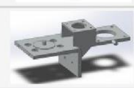
14	Structural	UV Frame	1		$ 6.00	$ 6.00
15	Structural	UV Pin Plate	2		$ 0.98	$ 1.96
16	Structural	UV Pin	40		$ 0.25	$ 10.00
17	Cover	Joint Cover Right Half	1		$ 3.20	$ 3.20
18	Cover	Joint Cover Left Half	1		$ 3.20	$ 3.20
19	Structural	Pivot Gear	1		$ 1.50	$ 1.50
20	Structural	Pivot Platform	1		$ 3.57	$ 3.57
21	Gear	Vertical Gear	1		$ 1.50	$ 1.50
22	Gear	Vertical Wheel	1		$ 1.50	$ 1.50
23	Belt	Vertical Belt	1		$ 5.75	$ 5.75
24	Motor	ARM66AC-N25 (Vendor: Oriental Motor)	1		$ 789.00	$ 789.00
25	Structural	Rail Joint	1		$ 11.62	$ 11.62
26	UV source	LED Lights (Vendor: Luminus)	314		$ 12.22	$ 3,837.08
27	Sensor	Baumer U500.PAO.2-GP1J.72F Ultrasonic Sensor (Vendor: Baumer)	2		$ 250.10	$ 500.20
28	Motor	Motor Driver (Vendor: Oriental Motor)	1		$ 590.00	$ 590.00

Fig. A6b. UltraLight System: Bill of Material.

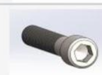
29	Motor	Extension Motor Cable 16' (Vendor: Oriental Motor)	1	N/A	$ 150.00	$ 150.00
30	Bolt	HX-SHCS 0.19-32x0.875x0.875-N (Grainger)	16		$ 0.36	$ 5.76
31	Bolt	HX-SHCS 0.125-44x0.5x0.5-N	6		$ 0.17	$ 1.02
32	Bolt	HX-SHCS 0.164-36x0.625x0.625-N	4		$ 0.17	$ 0.68
33	Bolt	HX-SHCS 0.164-36x1.375x1-N	2		$ 0.30	$ 0.60
34	Bolt	HX-SHCS 0.164-36x2.5x1.125-N	8		$ 0.35	$ 2.80
35	Bolt	HX-SHCS 0.06-80x0.125x0.125-N	5		$ 0.15	$ 0.75
36	Bolt	HX-SHCS 0.099-56x0.125x0.125-N	2		$ 0.15	$ 0.30
37	Bolt	HX-SHCS 0.099-56x0.375x0.375-N	4		$ 0.18	$ 0.72
38	Bolt	HX-SHCS 0.375-24x2x1.5-N	12		$ 0.48	$ 5.76
39	Bolt	HX-SHCS 0.19-32x0.5x0.5-N	2		$ 0.35	$ 0.70
40	Bolt	HX-SHCS 0.19-32x2x1.125-N	16		$ 0.41	$ 6.56
41	Bolt	CR-BHMS 0.19-32x0.625x0.625-N	8		$ 0.37	$ 2.96
42	Bolt	UV Arm Connector	8		$ 0.33	$ 2.64
					Total Cost	**$ 11,825.14**

Fig. A6c. UltraLight System: Bill of Material.

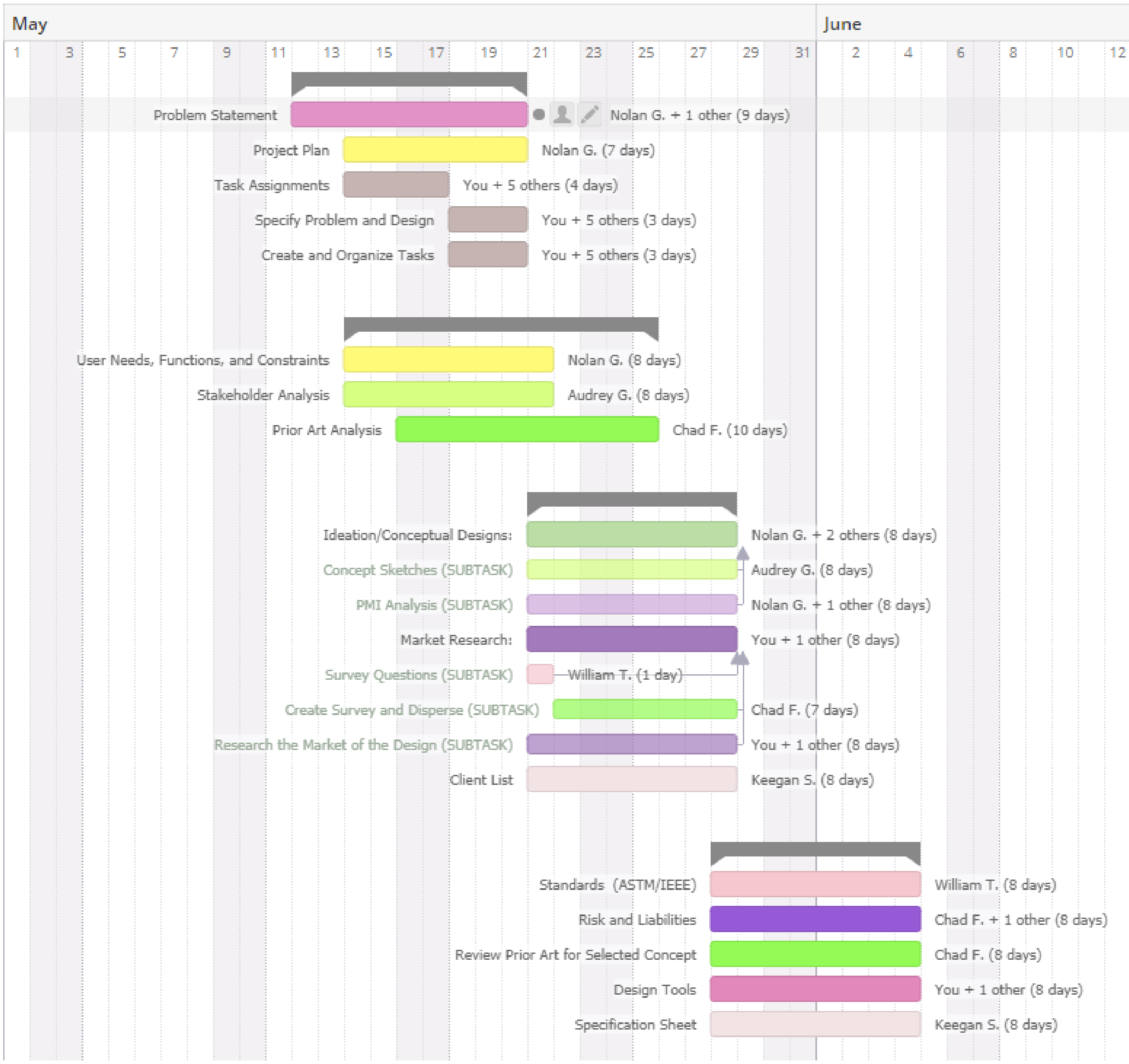


Fig. A7a. Gantt Chart for Design Process: May-Early June.

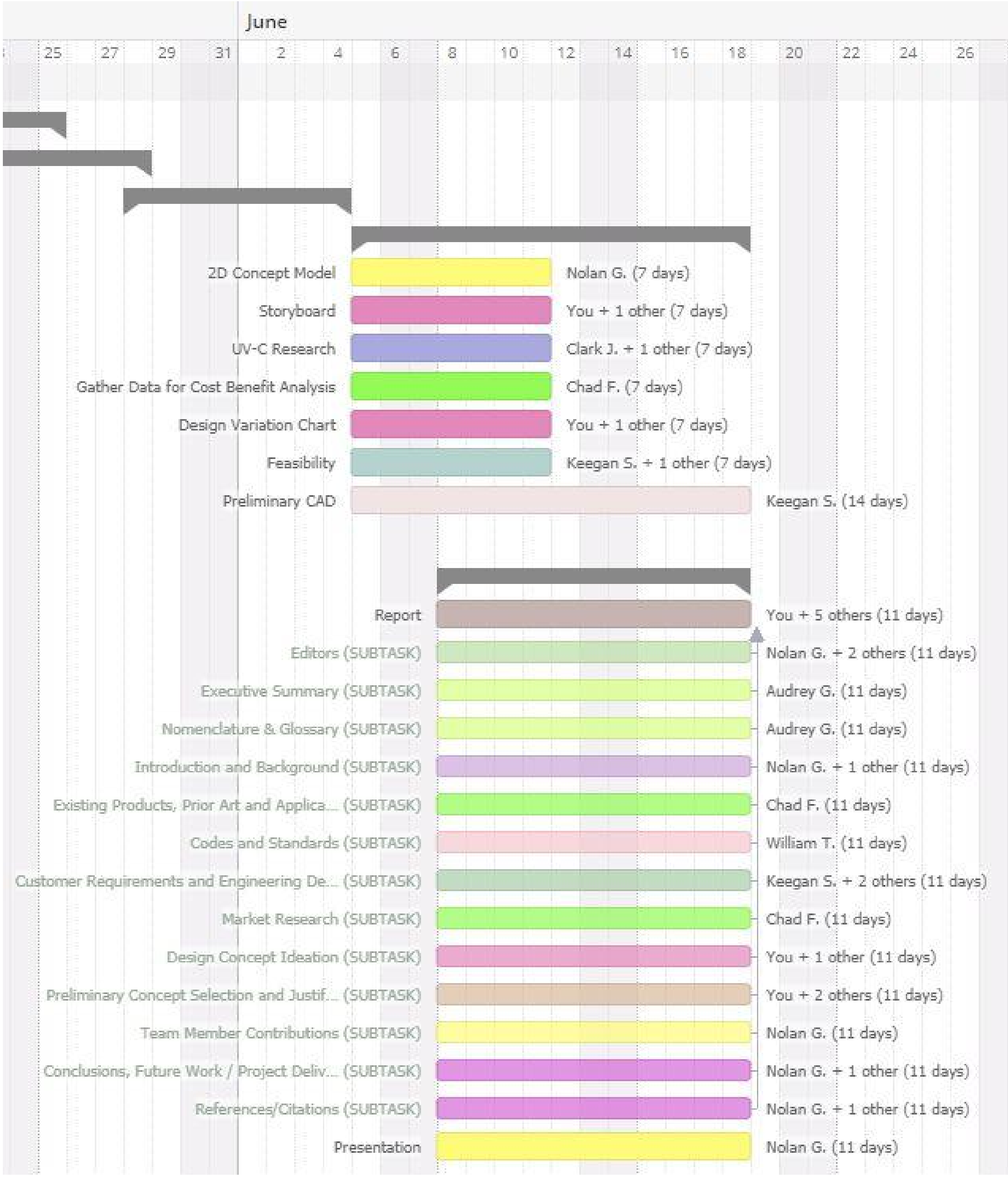


Fig. A7b. Gantt Chart for Design Process: Mid-June.

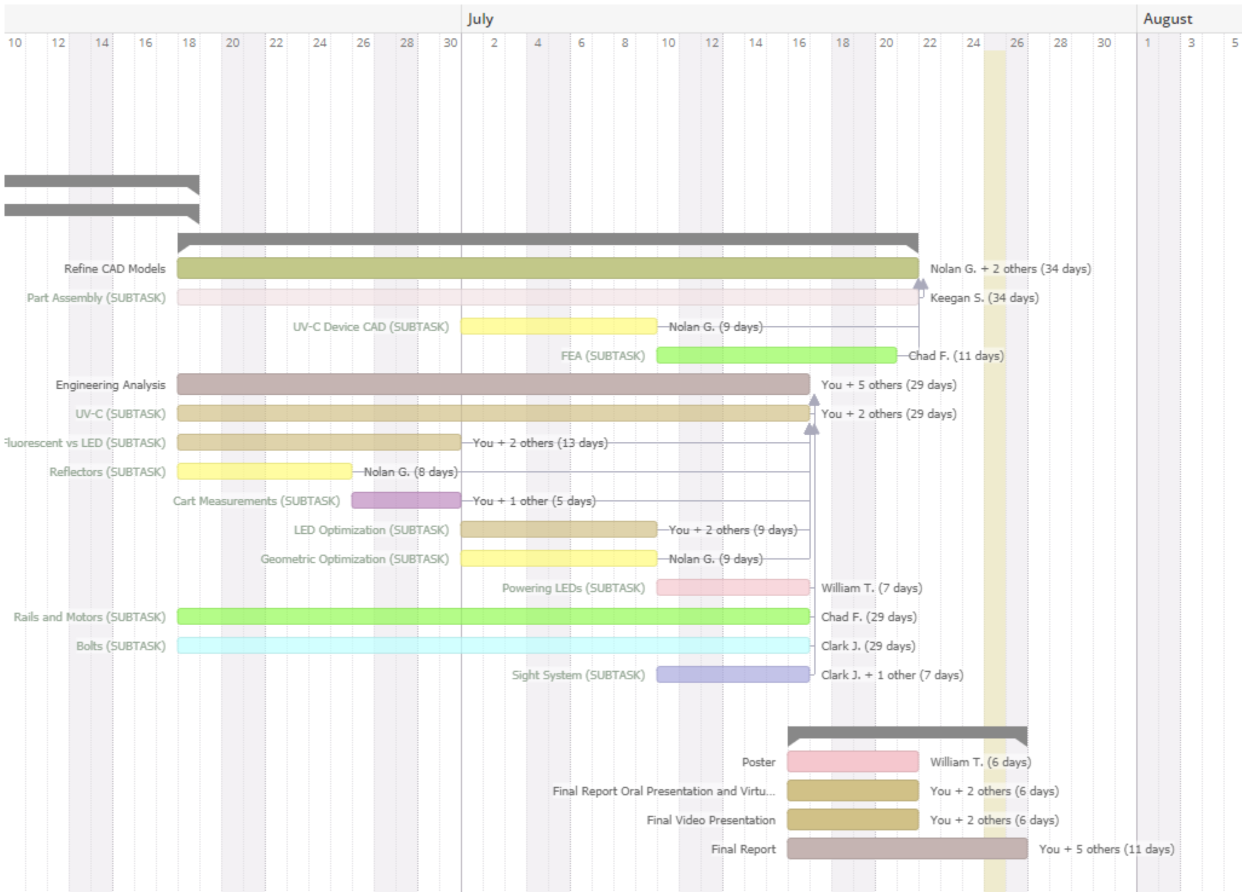


Fig. A7c. Gantt Chart for Design Process: Late June and July.

Appendix B: Tables

Permissible Exposure Time*	Effective Irradiance, μW/cm²
24 h	0.07
18 h	0.09
12 h	0.14
10 h	0.17
8 h	0.2
4 h	0.4
2 h	0.8
1 h	1.7
30 min	3.3
15 min	6.7
10 min	10
5 min	20
1 min	100
30 s	200
15 s	400
5 s	1200
1 s	6000

Table B1. Permissible Exposure Times for UV-C at 254 Nanometers.

	Disinfectant Wipes Used (Containers per Day)	Interested In UV-C?	Estimated Carts to Be Cleaned at Given Time	Is a Conveyor System Acceptable?	Are a Slower Throughput of Carts Acceptable?	Care for Aesthetics of Device?	Care if Device Required Some Supervision
Target (GA9)	2-3	Yes	Unsure	Yes	Yes	No	No,if not too much required
Target (Cobb Pkwy)	Unsure	Yes	20	No	Yes, if not too slow	No	Yes, if too much required
Target (Atl Station)	2	Yes, if energy efficient	10-15	Yes	Yes	A little	No, if not full time
Publix (Spring Street)	2	No	10	No, no space	Yes	No, if out front	No, if not full time
Publix (Midtown)	1-3	No	Unsure	No	Yes	No	Yes
Walmart (Cobb Pkwy)	3-5	Yes	20-25	Yes, if low cost	Yes, if customers don’t have to wait	No	No
Walmart (Windward)	Unsure	Yes	20-30	No	Yes, if customers don’t have to wait	No	No
Kroger (S Cobb)	1-2	Yes	15-20	Yes, if small enough	Yes	No	No
Kroger (Mansell)	Unsure	No	10	No, hard to integrate	Yes	No	No, if not too much required
Kroger (Power Ferry)	2	Unsure	10-15	No	Yes	No	Yes, if a lot required
Whole Foods (Cobb Pkwy)	Unsure	No	15	No	Yes	Depends how bad	No

Table B2. Responses from Market Survey of Store Managers.

Suvey Questions	Results: 147 Participants					
Select the grocery store you usually shop from:	Target	Publix	Kroger	Costco	Walmart	Other
	8.16%	41.50%	24.49%	2.04%	6.80%	17.01%
Do you typically use a cart or a basket in a grocery store?	Cart	Basket	Neither			
	93.20%	6.12%	0.68%			
If you use a cart, do you typically get it from inside or outside in the parking lot?	Outside	Inside				
	8.16%	91.84%				
If provided the option of sanitation wipes to clean shopping carts and basket handles, what are the chances you	Very Likely	Likely	Neutral	Unlikely	Very Unlikely	
	72.79%	12.24%	8.16%	3.40%	3.40%	
On a scale of 1 to 100, with 1 being dirty and 100 being clean, how clean do you think shopping carts and baskets are ?	Average Number					
	40					
If a grocery store can implement a system to sanitize shopping carts, would you shop there more often than stores that don't?	Yes	No				
	82.99%	17.01%				
What ethnicity are you?	American Indian	Asian	Africian American	White	Hispanic	
	0.00%	7.48%	2.04%	85.71%	4.76%	
How old are you?	Under 18	18-24	25-34	35-44	45-54	55+
	0.00%	21.77%	3.40%	5.44%	31.97%	37.41%
What is your gender?	Female	Male				
	84.35%	15.65%				

Table B3. Responses from Market Survey of Store Customers.

	Automated Ramp System	Conveyor Belt System	Floor Track System	Wall-Mounted Rail System	Side-Rail System
Product Sub-Functions	1	2	3	4	5
Intakes Cart Into System	Ramp System	Conveyor Belt	Rail System (pulling)	Manual User Input	Manual User Input
Knows When Cart Is Present	Pressure Plates	Motion Sensor	IR Sensor	IR Sensor/Etc	IR Sensor/Etc
Locates Handle Position	IR Sensor	N/A	N/A	IR Sensor	IR Sensor
Determines Handle Angle	IR Sensor	N/A	N/A	IR Sensor	IR Sensor
Place UV-C Apparatus	Servo Motor	Servo Motor	4 Bar Linkage	Rail System + 4 Bar Linkage	Rail System + Motor
Delievers UV-C to Handle	Multi-Directional Delievery	Clamp Action	Rotating Action	Clamp Action	Reflectors
Yields Cart to Storage	Rail System	Conveyor Belt	Push Piece	N/A (Manual User Input)	N/A (Manual User Input)
Check for Conflicts	User Input	IR Sensor	Force Transducer	Force Transducer & Motion Sensor	Force Transducer & Motion Sensor
Prevent from Harming User	Flexible Curtain Flaps	Kill Switch	Light Enclosure	Kill Switch	Flexible Curtain Flaps & Light Enclosure
Announces Operation Start	Visual Cue (Monitor)	Auditory Cue (Voice)	Auditory Cue (Beep)	Visual Cue (Monitor)	Visual Cue (Monitor)
Warns When In Operation	Visual Cue (Monitor)	Auditory Cue (Voice)	Auditory Cue (Beep)	Auditory Cue (Voice)	Auditory Cue (Voice)
Alerts Operation Error	Visual Cue (Monitor)	Visual Cue (Light)	Visual Cue (Light)	Auditory Cue (Beep)	Auditory Cue (Beep)
Alerts for Maintenace	Visual Cue (Monitor)	Visual Cue (Light)	Visual Cue (Light)	Visual Cue (Light)	Visual Cue (Light)
Areas of Concern	1	2	3	4	5
Size of System	Requires space	Requires space	Requires minimal space	N/A	Requires minimal space
Throughput	Output issues w/ cart stacking	Output issues w/ cart stacking	Output issues w/ cart stacking	Stacking requires separation	Stacking requires separation
Sighting	(From alignment/orientation)	From measured data	(From grooves)	Finding carts in stack/orientation	Finding carts in stack/orientation
Cart Alignment (x-y)	Faulty wheel changes path	Based on track width	(From grooves)	(From sighting)	(From sighting)
UV Alignment (x-y)	(From sighting)	From measured data	(From grooves)	(From sighting)	(From sighting)
Cart Orientation (θ)	Faulty wheel changes path	From input	(From grooves)	(From sighting)	(From sighting)
UV Orientation (θ)	(From sighting)	From measured data	(From grooves)	(From sighting)	(From sighting)

Table B4. Iterative Design Chart for Function Fulfilment Options.

Appendix C: Equations

Irradiation: Point Source Equation

$$E = \frac{P}{A}$$

$$E = Irradiance\ \left(\frac{W}{m^2}\right)$$

$$P = UV - C\ Power\ \ (W)$$

$$A = Area\ of\ Light\ Projection\ (m^2)$$

Equation 1. Point Source Equation for Irradiation.

Irradiation: Inverse Square Law

$$E \propto \frac{1}{d^2}$$

$$E = Irradiance\ at\ Surface\ \left(\frac{W}{m^2}\right)$$

$$d = Distance\ from\ Source\ (m)$$

Equation 2. Inverse Square Law for Irradiation.

$$P = [2\boldsymbol{J}(\mathrm{R})ELD\pi^2]/(2\alpha + \sin 2\alpha)$$

where,

P = total UV power of the linear lamp (watts)

R = $L/2D$ (= l/D) (unitless ratio)

$\alpha = \arctan(L/2D) = \arctan(\mathrm{R})$ (radians)

E = measured irradiance (watts/m^2)

L = lamp total arc length (m)

D = distance from lamp arc center to detector (m)

$\boldsymbol{J}$(R) = lamp correction factor per Table B (Chart B)

Equation 3. Corrected Keitz Equation for Measured UV Irradiation.

Appendix D: LED Optimization Algorithm

The goal of this algorithm is to minimize constant sanitation time across the different rows of LEDs. The overview of the process involves maximizing the number of LEDs in the top row (row A), obtaining a sanitation time for row A, and calculating the number of LEDs needed in the bottom rows (row B and C) to meet that sanitation time. It is important to note that increasing the amount of evenly spaced LEDs in each row may not necessarily increase the sanitation time. This is due to the view factors of the LEDs and how adding a few more evenly spaced LEDs may not influence the amount of irradiance received at the edge of the handle.

Sequence 1:

Assumptions and Measurements:

- LEDs are modeled as a point source where inverse square law applies
- Distance between each row and the handle (from geometric optimization)
  - Row A: 0. 050 m (1.965 in)
  - Row B: 0.025 m (0.985 in)
  - Row C: 0.016 m (0.645 in)
- The diameter of cart handle: 1.5 inches
- Luminus XBT-3535-UV LEDs (average of 0.0575 watts of UV-C power, 130° view factor, 3.5mm by 3.5mm by 1.2 mm) are used
- 99.9% sanitization rate is achieved with 95 mJ/cm2 of radiant exposure
- Cart handle length: 0.5842 m (23 in)

1) A vector of the number of LEDs in row A is chosen, ranging from 100 to a maximum of 166. The maximum is 166 LEDs as any more will exceed the cart handle length; 166 LEDs side by side in a row will have a length of 0.581 meters

2) The distance between each LED, measured from center to center, in row A, must be calculated. This is achieved by:

$$Distance\ Between\ Each\ LED,\ x\ = \frac{Length\ of\ the\ Cart\ Handle}{Number\ of\ LEDs\ in\ Row}$$

Equation D1. Distance Between Each LED.

3) The radius of projection of the LEDs in row A is then needed. With the distance between Row A and the cart handle (0.050 meters) and the view factor of the LEDs (130 degrees), the radius can be calculated, as shown in **Figure D1** and **Equation D2**.

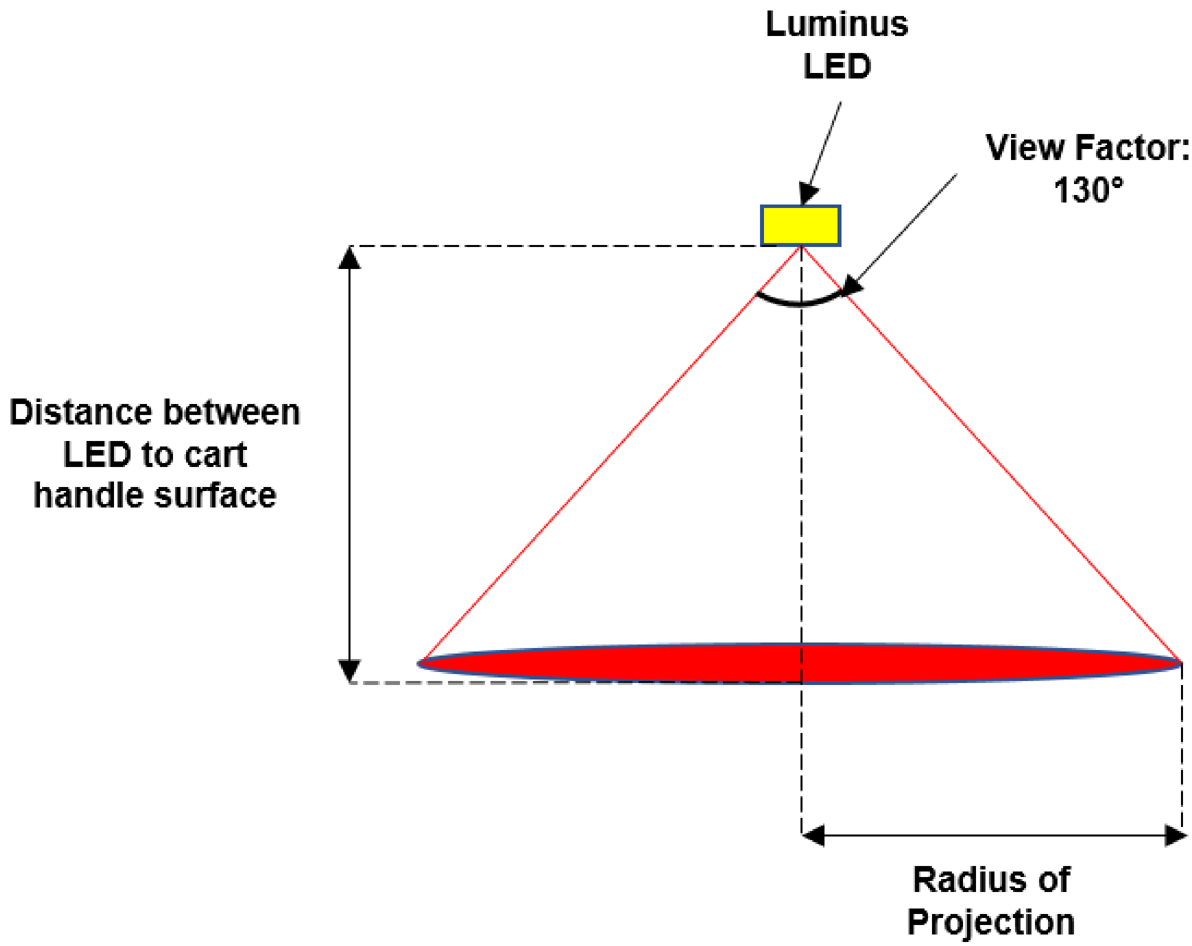


Figure D1. Radius of Projection.

$$Radius\ of\ Projection,\ r\ =\ tan(65°)\ *\ Distance\ between\ LED\ to\ the\ cart\ handle$$

Equation D2. Radius of Projection.

4) To calculate the number of LEDs that will project to the edge of the handle from Row A:

$$Number\ of\ LEDs\ Projecting\ on\ the\ Edge\ of\ the\ Handle,\ y\ =\ \frac{r}{x}$$

Equation D3. Number of LEDs Projecting on the Edge of the Handle.

(This value will always be rounded down)

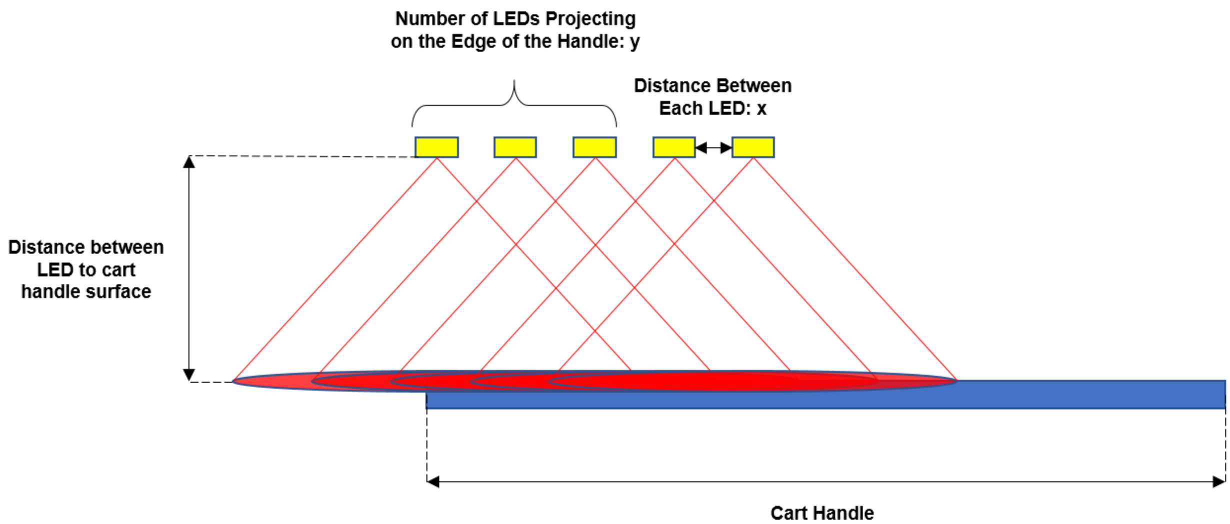


Fig. D2. Numbers of LEDs Projecting on the Edge of the Handle.

5) The irradiance of one LED, in Row A, is calculated using inverse square law:

$$Irradiance\ of\ One\ LED,\ E\ =\ \frac{Power}{Area\ of\ Projection} = \frac{Power\ per\ LED}{\pi * r^2}$$

Equation D4. Irradiance of One LED using the Point Source Equation.

6) Time of sanitization is acquired to reach a sanitization rate of 99.9% or a radiant exposure of e = 950 J/m2 for Row A

$$Time\ of\ Sanitation,\ t\ =\ \frac{e}{E*y}$$

Equation D5. Time of Sanitation.

7) With the time of sanitation for Row A acquired, Row B and Row C are designed to reach the same sanitation time. Row B and Row C will follow the same calculations as each other

8) For the bottom rows, Row B and Row C, find the irradiance of 1 LED provided the set distances between the handle and the row of LEDs. Refer to **Equation D2** and **Equation D4**.

9) Using **Equation D5**, where t is the time of sanitization calculated for Row A, the number of LEDs projecting on the edge of the handle, y, can be calculated for both rows B and C

10) Using the radius of projection, r, and the number of LEDs projecting on the edge of the handle, y, the distance between each LED, x, can be calculated for rows B and C

$$x\ = \frac{r}{y}$$

Equation D6. Radius as a Function of Distance.

11) The bulb in the bottom rows can be calculated:

$$Number\ LEDs\ in\ row,\ n\ =\frac{Length\ of\ the\ Handle}{x}$$

Equation D7. Number of LEDs in Row.

(This value is always rounded down)

12) Given a range of LED inputs for Row A, a time of sanitation vs cost analysis can be creating by totaling the number of LEDs of the three rows and using the cost per LED to be $13.14

Sequence 2:

To acquire a more accurate time of disinfection, different cart handle sizes have to be accounted for as well as the ± 0.06 inches allowable clearance from the geometric orientation. A minimum cart handle diameter of 0.75 inches was chosen for this analysis. The goal is to obtain a new sanitization time for the UltraLight System that encompasses a range of different cart handle diameters (0.75 -1.5 inches) and account for the ± 0.06 inches allowable clearance using the optimized number of LEDs calculated in **Sequence 1.**

Assumptions and Measurements:

- LEDs are modeled as a point source where inverse square law applies
- Distance between each row and the handle (from geometric optimization) with the addition of 0.375 inches from the diameter change and 0.085 inches to account for the allowable clearance
    - Row A: 0. 0616 m (2.425 in)
    - Row B: 0.037 m (1.445 in)
    - Row C: 0.028 m (1.105 in)
- Diameter of cart handle: 0.75 inches
    - This will provide the maximum sanitization time for the system; any other handle diameter between 0.75 inches and 1.5 inches will have a shorter sanitization time
- Luminus XBT-3535-UV LEDs (average of 0.0575 watts of UV-C power, 130 view factor, 3.5mm by 3.5mm by 1.2 mm) are used
- 99.9% sanitization rate is achieved with 95 mJ/cm^2 of radiant exposure
- Cart handle length: 0.5842 m (23 in)
- LEDs in each row
    - Row A: 164 LEDs
    - Row B: 90 LEDs
    - Row C: 60 LEDs

1) The calculations are the same for all three rows. The longest sanitization time will be the new sanitization rate of the system. The series of calculations are very similar to steps 2 through 6 of **Sequence 1**

2) Given the amount of LEDs in each row, calculate the distance between each LED center to center), x, using **Equation D1**

3) Obtain the radius of projection, r, for each row using **Equation D2**

4) Calculate the number of LEDs that will be able to project to the edge of the handle, y, for each row using **Equation D3.** *(This value is always rounded down)*

5) Find the irradiance of one LED, E, for each row using **Equation D4**

6) Acquire the time of sanitization for each row using **Equation D5.**

(The largest time will be the new time of sanitization for the system that will encompass handle diameters ranging from 0.75 inches to 1.5 inches and account for the ± 0.06 inches allowable clearance)

Sequence 3:

To account for degradation, repeat steps 1-6 in **Sequence 2** with a degradation factor, DF, will be applied to the power of the LED within **Equation D4**. The adjusted equation, **Equation D8,** will be as followed:

$$Irradiance\ of\ One\ LED,\ E\ =\ \frac{Power}{Area\ of\ Projection} = \frac{Power\ per\ LED*DF}{\pi*r^2}$$

Equation D8. Irradiance of One LED.

The calculated irradiance will be fed into **Equation D5,** where new sanitation times will be obtained, incorporating a degradation factor. The longest sanitation time will be the new sanitation time of the system.

Appendix E: Finite Element Analysis

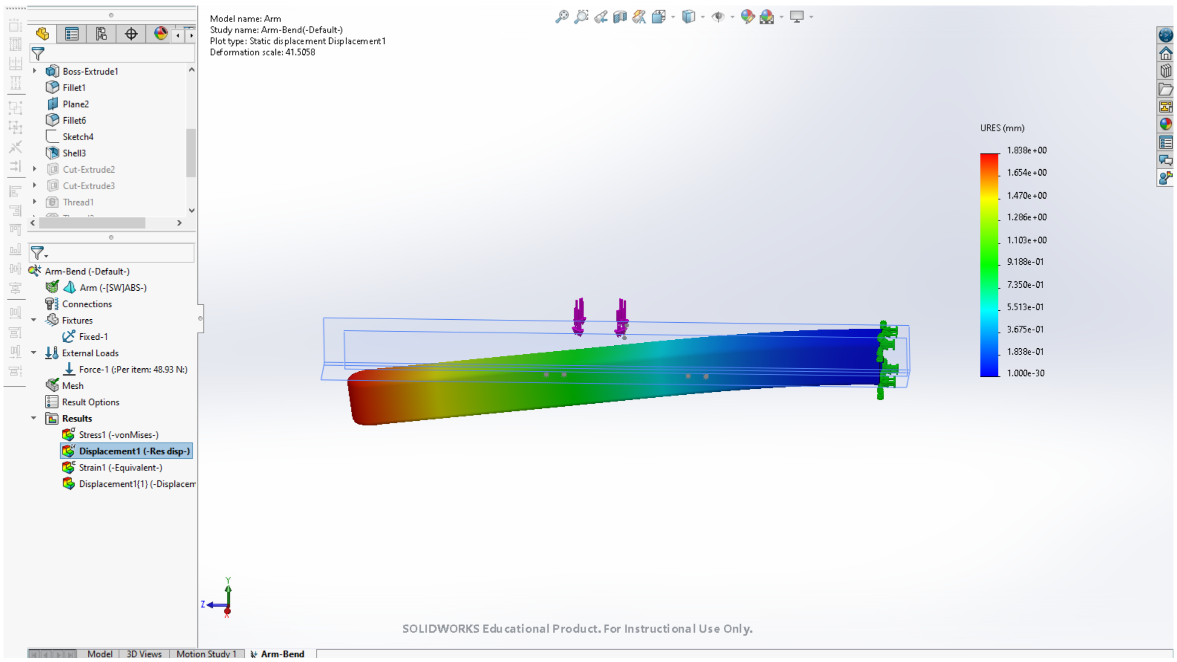


Fig. E1. Amplitude Analysis for UV-C Support Arm.

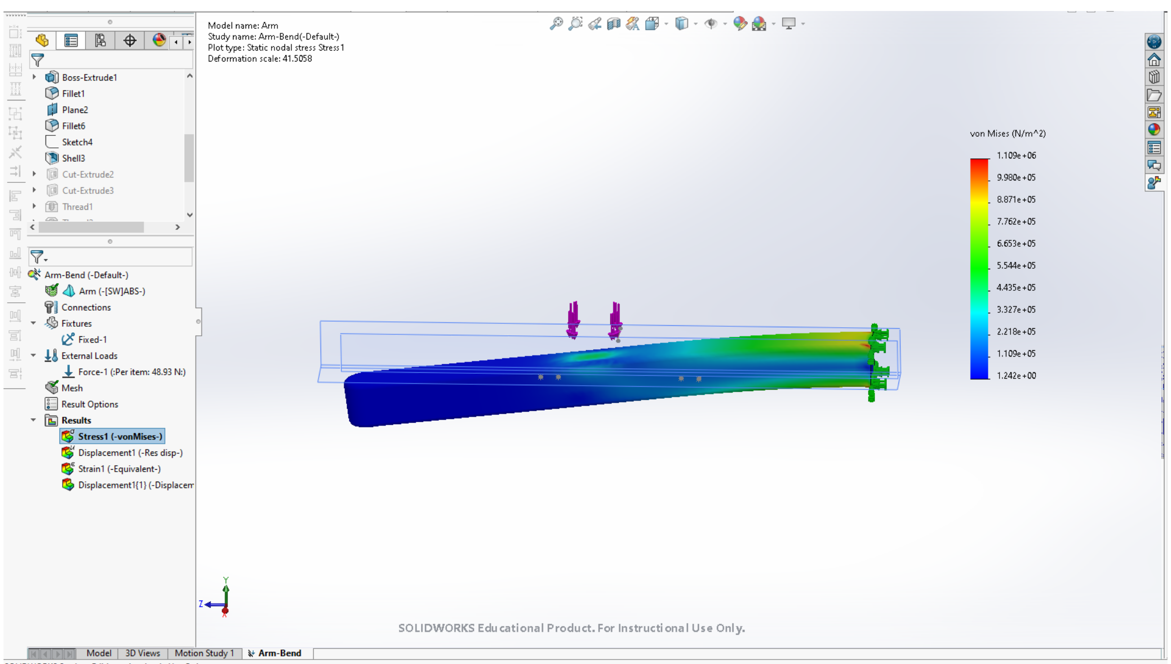


Fig. E2. Stress Analysis for UV-C Support Arm.

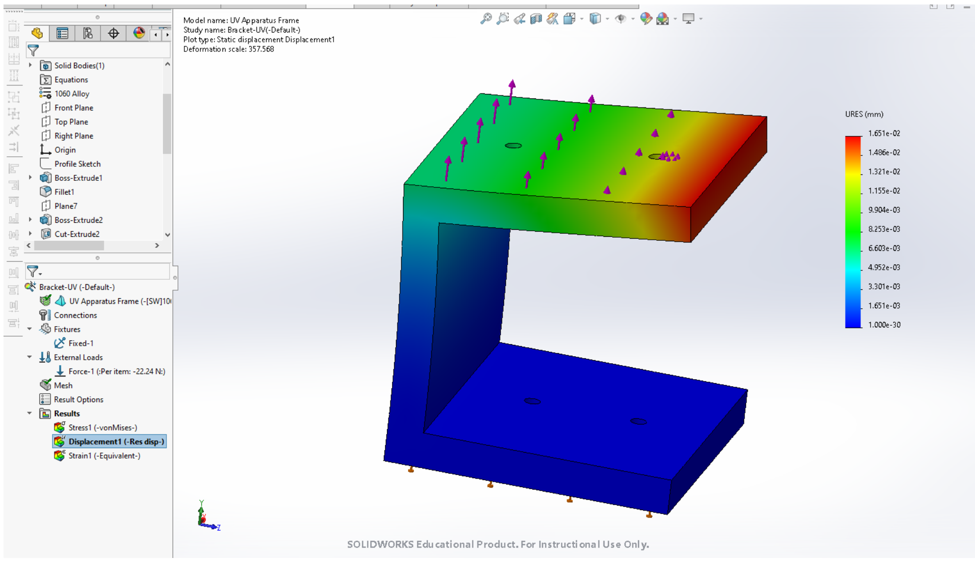


Fig. E3. Amplitude Analysis for UV-C Arm Bracket.

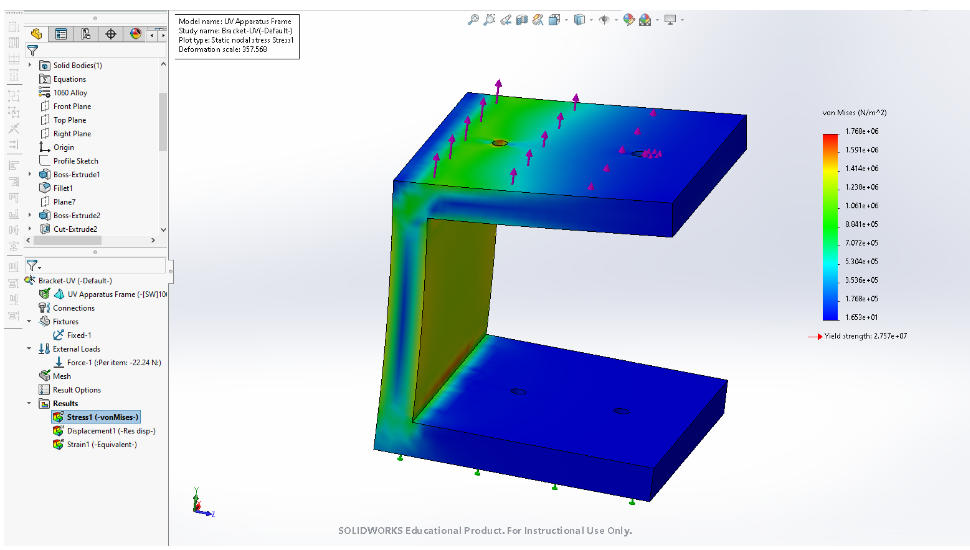


Fig. E4. Stress Analysis for UV-C Arm Bracket.

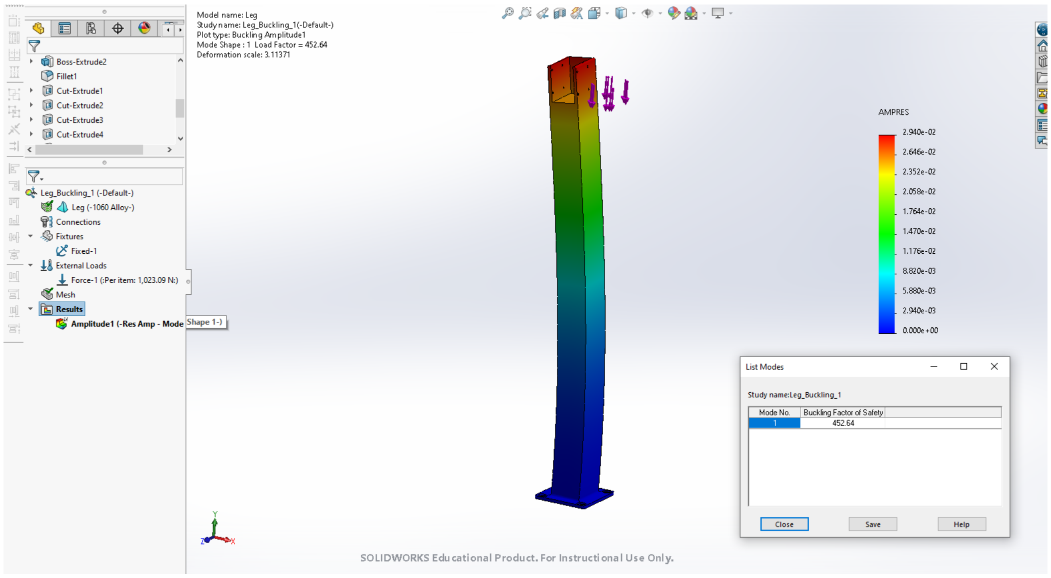


Fig. E5. Amplitude Analysis for Support Leg.

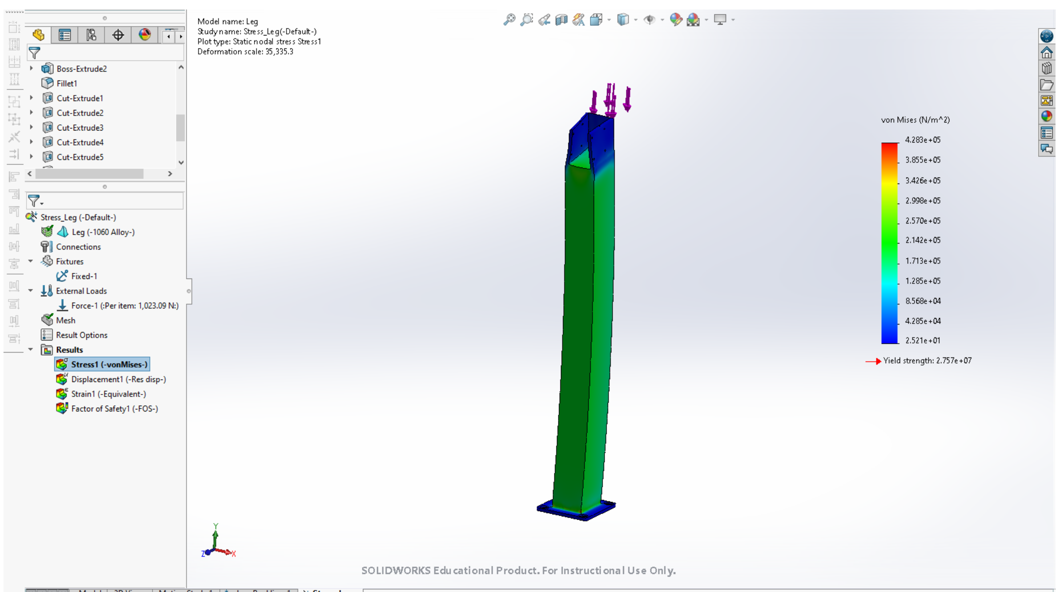


Fig. E6. Stress Analysis for Support Leg.

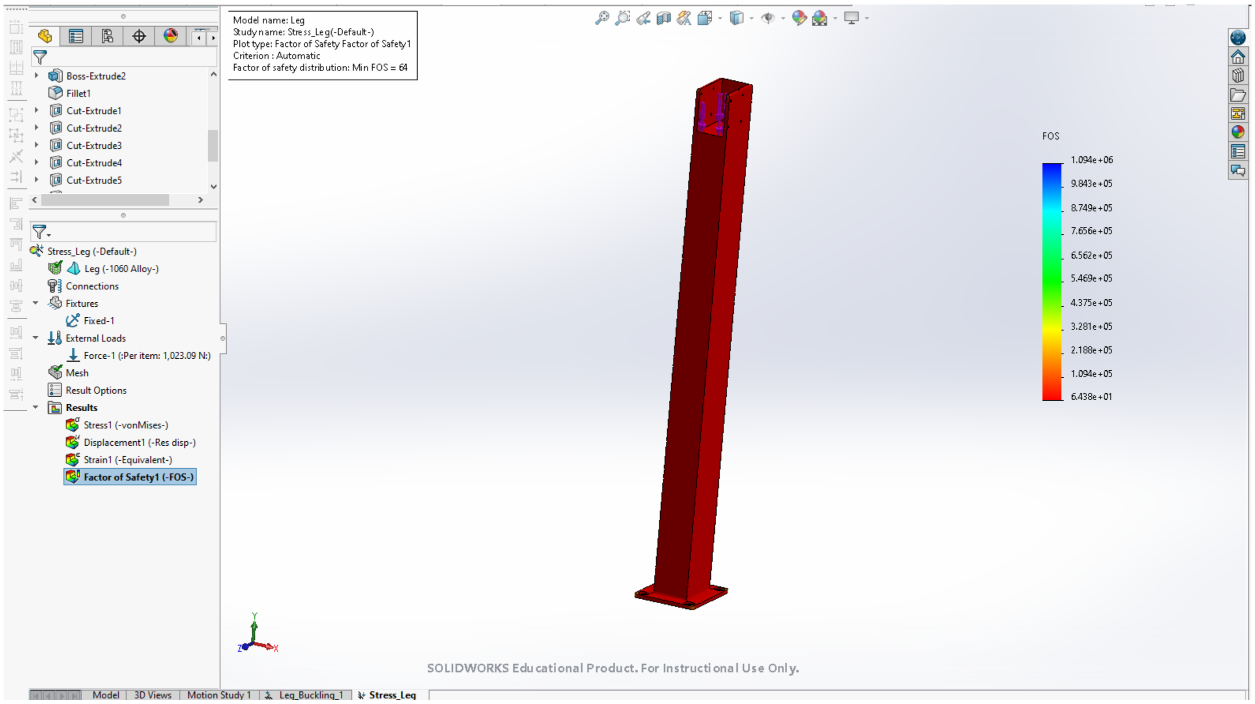


Fig. E7. Buckling Analysis for Support Leg.

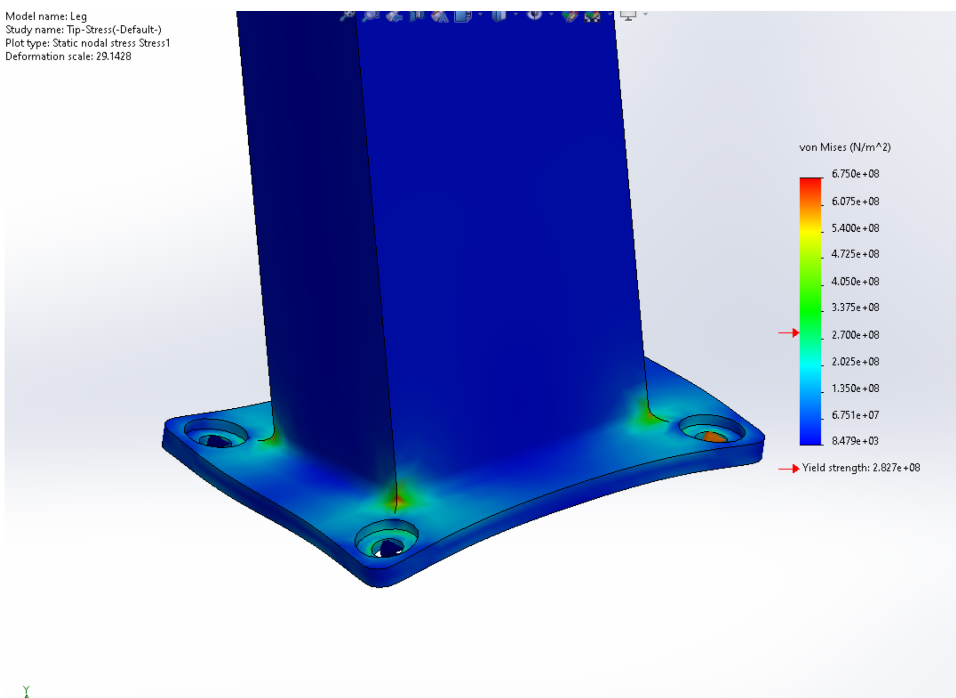


Fig. E8. Tipping Analysis for Support Leg.

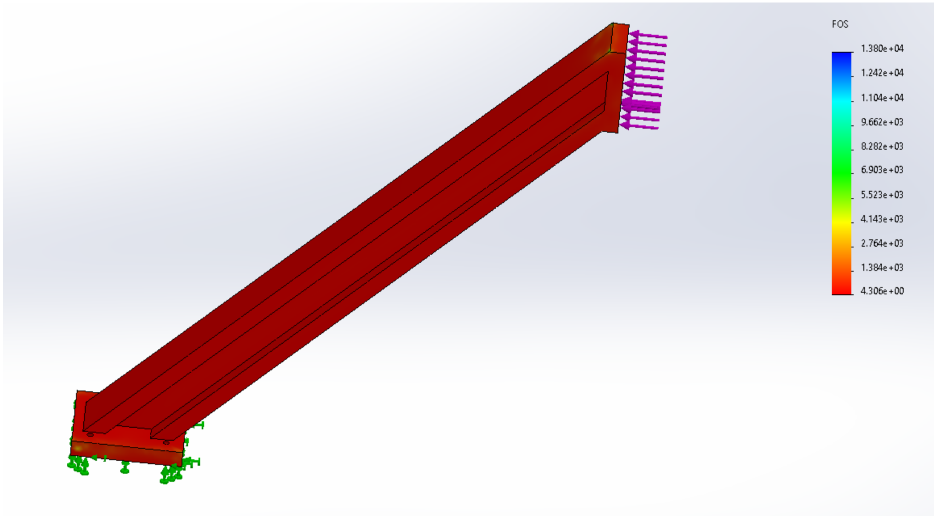


Fig. E9. Side Support Leg Analysis.

Appendix F: UV-C Safety

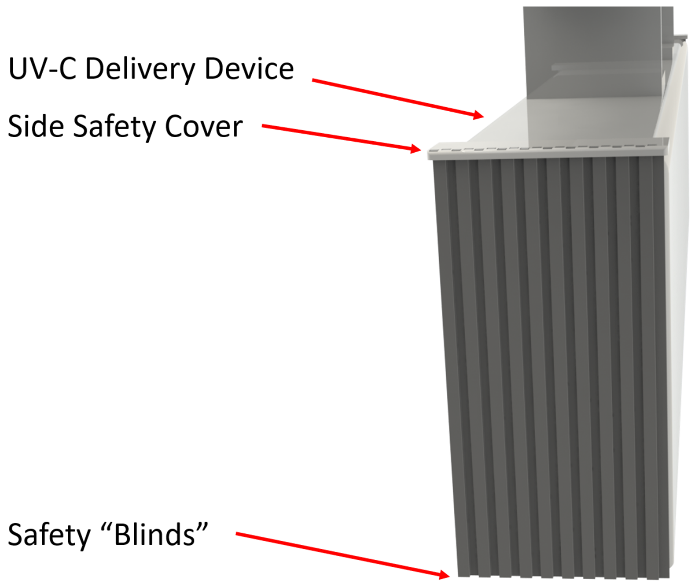


Fig. F1. UV-C Delivery Device with Side Safety Cover.

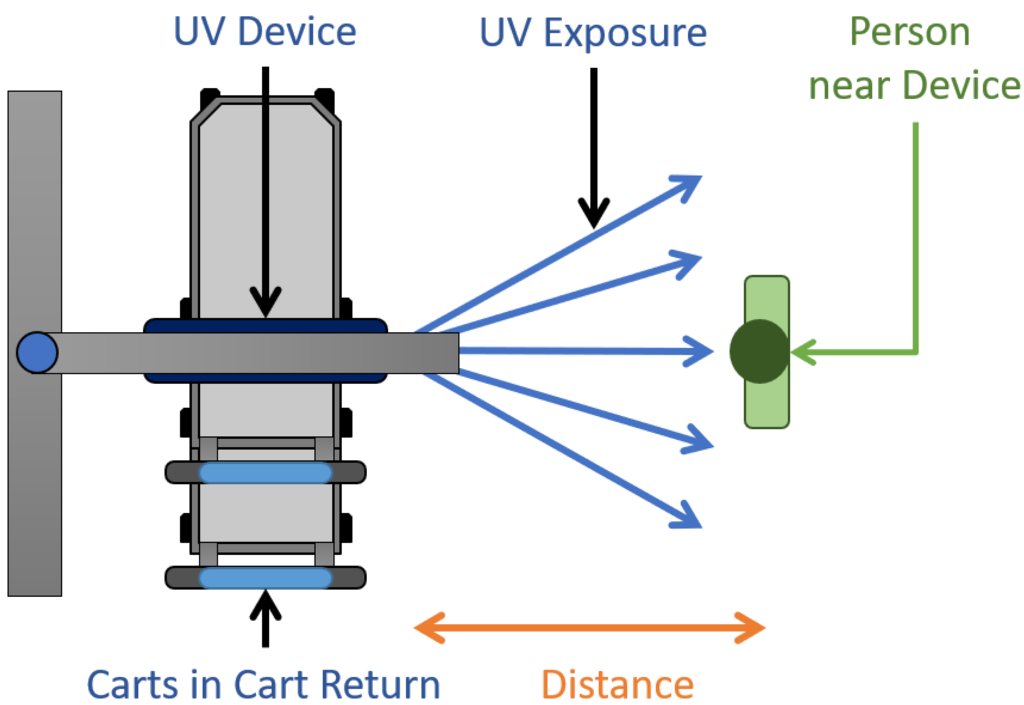


Fig. F2. Scenario for Direct Exposure at a Distance from the Side of the UV-C Delivery Device.

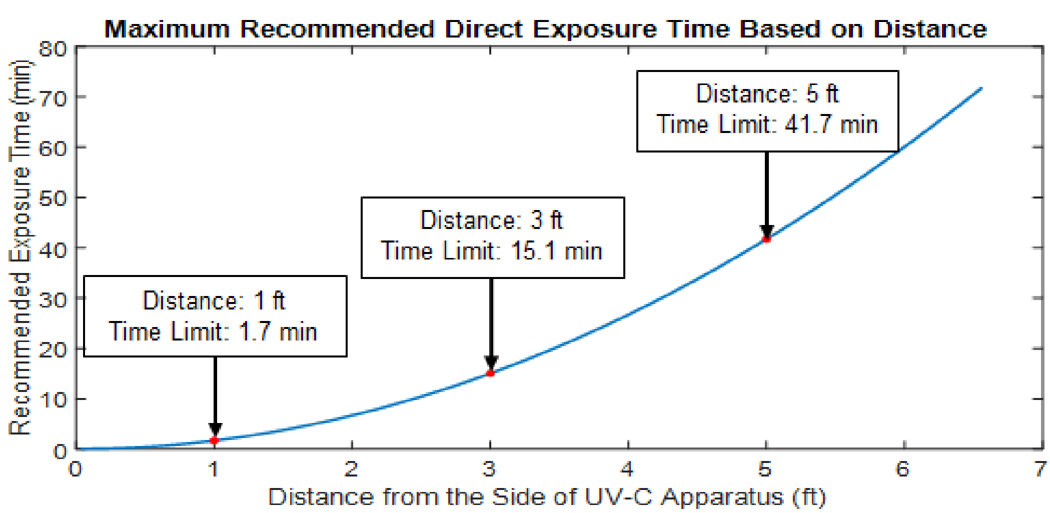


Fig. F3. Maximum Direct Exposure Times for Various Distances from the Side of the UV-C Delivery Device with No Safety Cover.

Appendix G: Global Issues

The United States is the current epicenter of the COVID-19 pandemic, however pathogen spread is a global concern. The continents of Europe and Australia were chosen for an analysis on how the UltraLight system could be implemented in foreign regions. The shopping experiences in Europe and Australia, while similar to each other, differ from that in the United States. First, there are fewer large grocery stores, or “supermarkets,” which are large enough to utilize shopping carts. Many supermarkets are located inside a mall as opposed to a standalone building, often resulting in compact layouts that rely on a cart return with a single first in, first out (FIFO) setup. Additionally, almost all carts use a coin-activated locking system that is attached to the cart handle. If implemented in these continents, the UltraLight system would need to have a logic system capable of accounting for this FIFO setup, and the UV-C subsystem would need to be redesigned to circumvent the locking device. The research behind the targeted UV-C component can also be used to design a device that can disinfect baskets in the stores that do not use carts.

An additional consideration regards the fact that the UltraLight system was designed to integrate seamlessly into an existing store setup without altering the typical shopping experience. However, most areas in Europe, and even some in Australia, are not as high-tech as the United States. It might be jarring to see this type of modern technology implemented locally, as the design may not merge well with a traditional setting. Nevertheless, while pre-pandemic culture might have opposed the addition of the system in more traditional areas, the global experience of COVID-19 has demonstrated its necessity, likely reducing potential opposition.

The economic feasibility of the UltraLight system exists for applications across the globe. Many components of this design may be sourced globally. While parts such as actuators, motors, and LEDs were chosen based upon an American market, similar components may be obtained from European and Australian markets in order to yield the same engineering specifications, though cost for these components in local markets may fluctuate. Additionally, the cost of one UltraLight system is approximately $10,000 USD, making it economically feasible globally, at an energy consumption of only 2.08 kW of energy per hour. Thus, even in localities where energy is more expensive, the UltraLight system is a feasible option. The break-even time may be sooner in European and Australia than in the United States due to higher labor costs in some countries, which drive up the price of manual disinfection methods. Considering the scale of the pandemic, many people are likely to become more concerned about the cleanliness of public spaces even when life returns to normal, so continuous disinfection will likely need to remain a high priority even post-pandemic. Thus, the UltraLight system has a high demand and feasibility across multiple continents.

In the United States, Australia and Europe, the main concerning safety feature is the implementation of UV-C. The United States has no UV-related laws outside of CDC guidelines for maximum exposure time to UV-C, as shown in **Fig. C3** in **Appendix 3**. Individual countries within Europe might have laws regarding UV, for example the Artificial Optical Radiation 2006/25/EC Directive in the United Kingdom that imposes duties on companies whose employees are at risk from UV light [43]. However, the European Union has no laws or regulations outside of cosmetic recommendations and the disinfection of food. Australia on the other hand is no stranger to UV concerns. Safe Work Australia has developed The Guide on Exposure to Solar Ultraviolet Radiation that can also be used as a guide for artificial radiation, with references to Work Health and Safety Acts to protect anyone who comes into contact with the UV source. This guide focuses on the education and training of employees, the need to have UV devices clearly marked and labeled, and the importance of individual responsibility [44]. As the final design was intended to provide thorough warnings with labels, no design changes are needed.

The UltraLight system was designed to integrate into existing setups in the United States, however relatively basic logic and actuator changes can make the system viable globally. In light of the recent pandemic, with a focus on optimized cleanliness and low costs, the UltraLight system is the ideal product to implement in supermarkets throughout the world.