Good Clean Fun: Modernizing Toy Sanitation

Good Clean Fun: Modernizing Toy Sanitation

A thesis presented in partial fulfilment of the requirements for the degree of Bachelor of Science

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Abstract

Rapid spread of viral infections via contaminated surfaces is pervasive in crowded indoor places such as schools, day care centers, nursing homes, and hospitals [1]. Children under five suffer twice as many illnesses a year as adults[1, 2], and children in daycare centers have a higher incidence of infection than those cared for at home [3]. Toys have been identified as a significant category of surfaces that spread contamination [4]. This project improves classroom safety through a device that builds on existing technologies that use far ultraviolet (UV) light at 222 nm to sanitize toys. Existing solutions are too time intensive and do not sanitize to the appropriate level. This device is novel due to its focus on complete coverage of surfaces and minimization of required user interaction time.

Acknowledgments

As fun as it is to think so, I could not have completed this project alone, and I have so many thanks to give.

To Steve Cortesa, my advisor: thank you for being there at all times and answering all of my countless questions. Your guidance was irreplaceable, and your patience infinite. I truly could not have done this without your unwavering support and constant assistance. I promise I will chill out now. And to Katia Bertoldi, my reader: thank you for helping me to come up with the idea and being a guiding force and role model throughout the process.

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Chapter 1

Introduction and Motivation

1.1 Problem Statement

Child illnesses acquired in daycares account for 40% of parents' requests for time off from work, costing the national economy hundreds of millions of dollars a year [10]. Children in classrooms without daily surface sanitation were 2.32 times more likely to miss school due to illness than their counterparts in classrooms with sanitation [11]. In daycares, toys were the most contaminated surface, with 39% of toys being contaminated compared to 26% of all other environmental samples [4]. Furthermore, infants and toddlers have the highest attack rates for lower respiratory and enteric diseases due to their preclusion to place contaminated objects and hands in their mouths[3, 12]. Existing solutions to sanitize communal toys in childcare settings are not adequately accessible or easy to use for teachers throughout their daily routines.

1.2 Client and End User

This product is meant for use in preschools and daycares, but could be adapted for use in any communal environment that has shared resources. Shared toys need to be sanitized often. In one study, a DNA marker that was introduced to a daycare room through a toy ball led to contamination of other toys, general classroom surfaces, as well as children and their family members' hands. Although the DNA source was removed after one day, the markers were found on wood, plastic, metal, and fabric samples up to one month later [3]. Teachers spend time every day cleaning and sanitizing toys. Whitni Coleman, a preschool teacher at the Atlanta Speech School in Atlanta, Georgia, said that she has to confiscate toys that children have contaminated at least 6 to 7 times a day. Furthermore, her school has stopped supplying plush toys in the classroom due to their difficulty to clean [13]. This project alleviates some of this time and inconvenience so that teachers can focus on the children. This saved time helps the teachers, and also keeps children safe. The children, in turn, receive greater supervision and are exposed to fewer harmful germs.

Chapter 2

Existing Products

This section describes other sanitizing products that are on the market. Further details on all of the products discussed can be found in Appendix A.

2.1 Category 1: Boxes and Cabinets

UV cabinets are boxes that allow users to put toys in and retrieve them sanitized. There are two types of cabinets on the market. Some are portable and marketed directly to consumers as a personal sanitation box meant for small objects such as sunglasses, phones, masks, and toys. These are small, often less than 1 cubic foot, and can generally hold a maximum of one or two toys [14, 15, 16]. The second version, best exemplified by the ZONO cabinet, is meant to be stored in the back room of a school or daycare where the teachers can sanitize everything that was used in their classroom at the end of each day. These cabinets are only available by special order and are prohibitively expensive [17].

These boxes have several issues that do not make them ideal for teachers. Most are small, and require you to use them one toy at a time, which is inefficient and time consuming. Others are huge, and require a teacher to go to a back room and take a ton of toys at once, therefore requiring them to do it after hours or take all of those toys out of commission. Some require teachers to come back halfway through and flip toys as well.

None of these UV solutions account for the fact that when toys are all dumped into a box together, they touch each other and device components. This touching prevents the light from reaching all sides of the toy. These boxes can still claim 99.9% disinfection because they average across all surfaces. For example 99.999% disinfection on most of the surfaces can even out to 99.9% across all surfaces. However, this leaves portions of surfaces that are covered in microbes. None of the existing UV solutions discovered account for this issue.

2.2 Category 2: Sprayers

Sprayers are another category of toy sanitation devices. This includes any device that sprays some chemical or fluid onto a surface in order to sanitize it [18, 19, 20]. These are not practical around young children. It is time consuming to accurately sanitize all sides of existing objects, and young children frequently place objects in their mouths. Chemical cleaning solutions often leave a residue which is not desirable for consumption. Spray sanitation can be achieved through using a portable device, or through hiring a service [21, 22]. While hiring a service is effective and does not take much time, it can be quite costly, and does not remove chemical concerns related to spray solutions.

Chapter 3

Sanitation Choice

3.1 UV-C Safety and Effectiveness

While UV-A and UV-B rays ranging from 280-400 nm are common in the atmosphere, UV-C rays (200-280 nm) are completely filtered out by the ozone layer [23]. UV-C is known for its germicidal capabilities, and unlike disinfecting sprays, UV-C disinfection has the advantages of not leaving any residues, as well as being relatively easy to apply quickly and easily across many surfaces [24].

Two main wavelengths of UV-C are commonly utilized: 222 nm and 254 nm. In order to create the germicidal effect, both 254 nm and 222 nm UV-C are absorbed by nucleic acid components, damaging the DNA of the cell [25]. When absorbed by DNA, the light causes cytotoxic DNA lesions which interrupt transcription, translation, and DNA replication leading to cell death and viral inactivation. 254 nm UV-C light can also hurt human cells, especially skin and corneal cells, by the same mechanism [26]. All of the cleaning operations in cited 254 nm studies were completed in rooms that were evacuated beforehand [24].

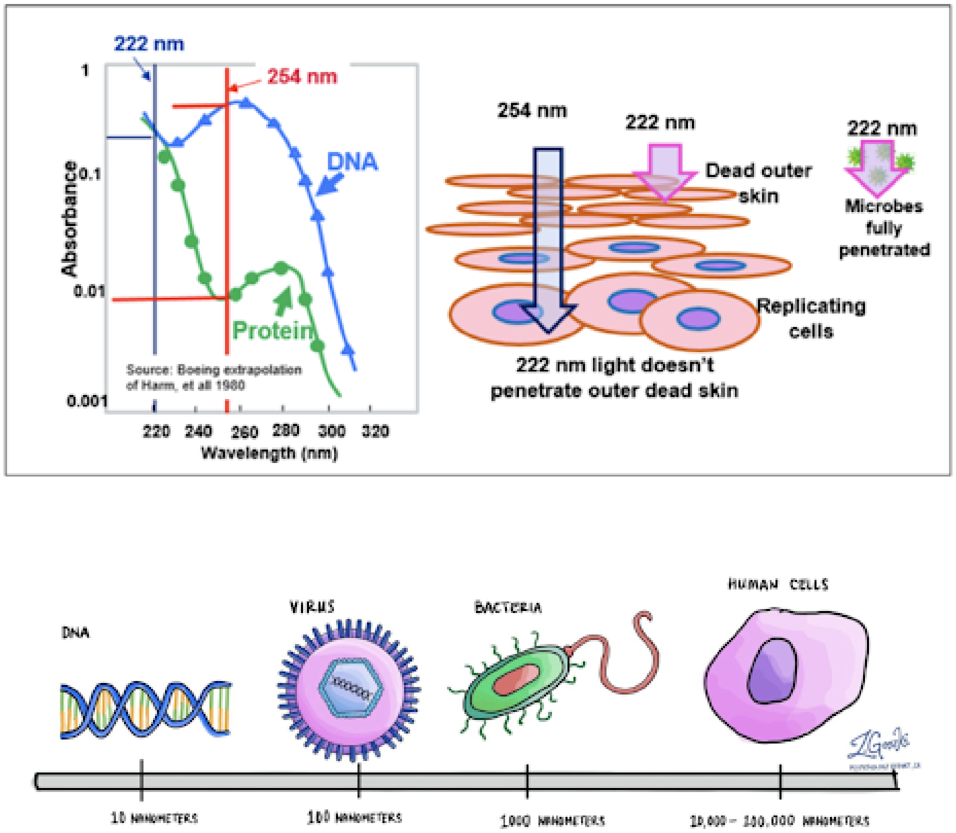


Figure 3.1: Absorbance difference of UV light in proteins and DNA at different wavelengths leads to 222 nm safety [5]. Size differences for DNA, Viruses, Bacteria, and Human Cells allow for UV-C to inactivate microbes while being safe for humans [6].

However, 222 nm UV-C light does not have this problem. As seen in Figure 3.1, 222 nm UV-C has a strong absorbance in proteins, creating a limited penetration distance in mammalian cells that prevents it from causing the same issues. 222 nm is well absorbed by peptide bonds, as well as the amino acids tryptophan and tyrosine due to the wavelengths these molecules bonds vibrate. Thus, it is absorbed by proteins and other biomolecules in mammalian cells before reaching the nucleus and affecting the DNA [25, 27]. Furthermore, there is a protein rich layer of outer dead skin, so the 222 nm rays are absorbed before they reach any replicating cells. There is a similar layer of dead cells on the surface of the eye. However, due to the magnitude of the size difference between mammalian cells and viruses/bacteria shown in Figure 3.1, 222 nm UV-C can still effectively inactivate them [27].

Several studies have confirmed that 222 nm is safer than 254 nm. When UV-C light was focused on open skin wounds from ulcers, the 254 nm light killed both the skin cells and the MRSA, whereas the 222 nm light killed the MRSA but not the skin cells [28]. Similarly, when mice were dosed with equal amounts of UV-B and 222 nm UV-C, 0% of the mice exposed to the far-UV-C irradiation developed skin lesions or cancer, but 100% of the mice dosed with UV-B did [23].

UV-C light at a wavelength of 254 nm has been used to sanitize surfaces in hospitals and labs across the country for years, and has an extensively studied history of effectiveness. A hospital's standard operating cleaning procedure of using a chlorine-based detergent followed by a chlorine-based disinfectant left 63% of surfaces non-compliant with cleanliness standards. In contrast, a 5-10 minute cycle of UV-C exposure left only 18% non-compliant [24]. In high turnover operating theaters, standard operating procedures led to 92% sample compliance while the samples treated with UV-C light were 100% compliant, showing that 254 nm UV-C is not only as effective but more effective than the standard operating procedures for cleaning in these high traffic hospital areas [24].

222 nm UV-C has only recently begun to be studied in depth. Within the last two years, there has been a lot of research into using it in order to inactivate COVID-19 on surfaces as well as aerosolized COVID-19. An exposure of 3 mJ/cm^2 of 222 nm UV-C caused a 2.51 log reduction in COVID-19 on surfaces [29]. It also was effective against the flu virus and several others. 222 nm UV-C has so far been found to be equally as effective as 254 nm [28, 29, 30, 31]. For MS2, a virus surrogate, a 222 Krypton-Chloride lamp was found significantly more effective than LED's and low pressure mercury lamps at a variety of other wavelengths, as shown in Figure 3.2.

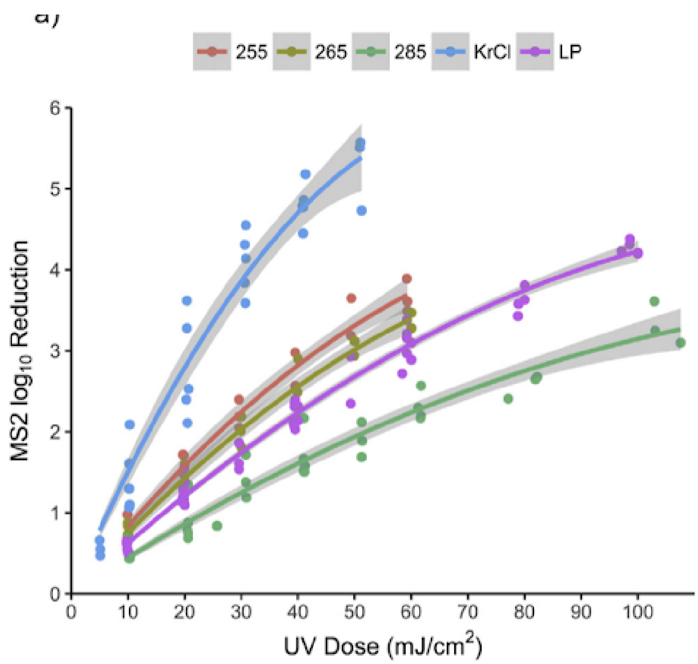


Figure 3.2: Graph showing the relative efficacy of different types of UV-C sources. KrCl lamps create 222 nm light, and Low Pressure (LP) mercury lamps are a common source of 254 nm light.

UV-C light at 222 nm is on its way to becoming the industry standard. Even though the children will not need to be near, see, or be touched by any UV light with this device, when given the option between equally effective wavelengths, choosing the safer option is the obvious choice. Given the information above, the chosen design uses 222 nm light to keep it cutting edge and as safe as possible.

3.1.1 UV-C Effects on Plastics

UV light is known to discolor and change plastics, and most toys are made of plastic. UV-C is not present outdoors, as the ozone layer filters it out, so the UV degradation that plastics would experience from UV-C is different from that seen in objects that spend most of their time outdoors [32]. While they are similar, there are several effects that are different or special to UV-C light specifically. However, any and all degradation of plastic materials due to UV-C exposure occurs on the surface, only up to a depth of 0.01 mm [33]. The damage applied by UV has been proven not to affect the structural integrity of the plastics [34]. Boeing simulated the amount of UV cleaning that would occur over the lifetime of an aircraft cabin: multiple cleanings per day for ten years. They concluded that the 222 nm UV light was an effective sterilizer, and that there were no mechanical effects to the materials studied [34]. They did find some color changes and photodegradation in plastics, and even then mainly in plastics that were white as opposed to darker colors. The rubbers, fibers, and variety of other materials present in an airplane all experienced little to no change over the course of the study [34].

Sample	Overall Damage	Microscopy	Roughness	L*A*B* Color	Whiteness	Contact Angle	Hardness
Polypropylene	Minor	Minor	Minor	Minor	Minor	Minor	Moderate
Ultra-high molecular weight polyethylene	Minor	Minor	High	Minor	Minor	Minor	Minor
Polytetrafluoroethylene	Moderate	Moderate	Moderate	Minor	Minor	Moderate	Moderate
Clear polymethyl methacrylate	Moderate	Moderate	Minor	Minor	Minor	High	Moderate
Polyoxymethylene (Delrin)	Moderate	High	Moderate	Moderate	Moderate	Minor	Moderate
Polyester	Moderate	Minor	Moderate	Moderate	Moderate	High	High
Polycarbonate	High	High	Moderate	High	High	High	Moderate
Nylon	High	Minor	High	High	High	High	Minor
Acrylonitrile butadiene styrene	High	Moderate	High	High	High	High	High
White polyethyl methacrylate	High	Minor	High	High	High	Moderate	Moderate

Figure 3.3: Plastic Degradation after 28.8 J/cm^2 of UV Exposure [7]

Simulating seven years of UV-C exposure on a variety of plastics found a wide variety in the severity of the cosmetic changes depending on what plastic was used, with the results shown in Figure 3.3 [7]. This time was simulated by exposing the plastics to 28.8 J/cm^2. At the fluence rate decided upon in Figure 6.1, this is 417 cycles of this device. Polypropylene and polyethylene had very minor to no changes [7], and these two plastics make up 39% of all toys [8]. However, ABS (Acrylonitrile butadiene styrene) was widely affected [7], and this plastic makes up 10% of toys [8], as seen in Figure 3.4. Given that it does not affect mechanical properties, it comes down to the life cycle of toys in a daycare. Whitni Coleman, a preschool teacher from Atlanta, said that toys in her classroom have an average lifespan of 5 years, but that cosmetic changes over a long period of time don't matter given that she receives a new batch of students every year [13].

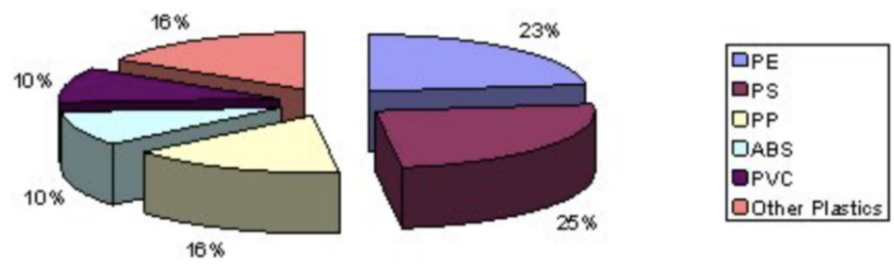


Figure 3.4: Breakdown of Plastics used in Toy Manufacturing [8]

Overall, the previous work in this field proves 222 nm UV-C light to be a safe and effective germicidal solution. Given that a great deal of the research into Far UV-C light is so recent, it is a perfect time to be innovating in this space.

Chapter 4

Technical Specifications

Table 4.1: Technical Specifications

Specification	Metric	How to Measure/Verify	Explanation
1. Solution must create 3-log reduction against *B. subtilis* and *E. coli*.	99.9%, achieved using 69 mJ/cm^2	Inactivation experiment with *B. subtilis* and *E.coli* samples to measure log reduction in samples.	Industry Standard [14, 15, 16, 17].
2. All external surfaces must exhibit 3-log reduction in contamination.	99.9%, achieved using 69 mJ/cm^2	Follow biological testing strategy developed with M. Hancock.	Industry Standard [14, 15, 16, 17].
3. Solution uses Kr-Cl Excimer lamp.	222 nm	Use a spectrometer to verify wavelengths.	Safest effective wavelength of germicidal UV-light [23, 28, 29, 30, 31].
4. Solution must fit in a classroom.	<6 cu. ft.	With measuring tools available in the Active Learning Labs.	This is the approximate size a basket of toys and bucket of bleach would take up on the floor of a classroom. Furthermore, it is a desired client specification [13, 35].

Specification	Metric	How to Measure/Verify	Explanation
5. Solution must be quick.	<1 hr.	Stopwatch.	Comparable to products already on the market [14, 15, 16, 17]. Client specification [13, 35].
6. Device must be safe to exist in preschool classrooms.	No reachable sharp parts, or pinching hazards.	Inspection by Environmental Health&Safety or Active Learning Lab Safety Officer.	Students are likely to interact with device when supervision lapses. Client specification [13, 35].
7. Device must not disrupt classroom environment.	<52 db	Use a sound meter, or phone app that acts as a sound meter.	This is the sound level of an average dishwasher as it runs [36].
8. Solution able to be loaded and unloaded quickly.	<10 seconds	Time multiple users with a stopwatch.	This is what differentiates this product from others on the market. Desired Client Specification [13, 35].
9. Sanitation Machine must accommodate toys of a range of sizes.	Minimum: 2.5 cm^2 Maximum: 3500 cm^2	No gaps in mesh that would allow a 2.5cm^2 piece to fall through. Tray must be at least 3500 cm^2.	2.5 cm^2 is the approximate surface area of the smallest side of Lego part 3003. (4 dot Lego). 3500 cm^2 is the approximate size of 15 plush toys.
10. Solution powered through a typical wall-outlet.	120 V	Plug the final prototype into the wall outlet and verify functionality.	Makes solution adaptable and usable in a variety of locations. Desired client specification [13, 35].
11. Solution requires no human interaction between start and finish.	-	-	This is what differentiates this product from existing solutions.

Chapter 5

Initial Mechanism Ideation

5.1 Design Considerations

In order to manipulate toys so that the light can hit all sides for the designated fluence time, 12 designs were ideated, sketched, and ranked using a pugh matrix. Each criterion in the pugh chart was given an importance from 1-5 to weight the scores, with five being the most important. Then, each design was ranked on each criterion, also from 1-5 with five being the best a design could score. Final scores were calculated as

$$\sum (Criteria\ Weight) * (Design's\ Score\ for\ said\ Criteria). \tag{5.1}$$

The criteria used were decided based on the technical specifications above and given weights as to how important each was. There are many minor variables, such as temperature control, that will possibly be essential considerations in the design as time goes on. However, the criteria here focus on known issues that can help differentiate between designs.

- *Timeliness (7-# of estimated cycles it would take)*
  - While the time needed for one fluence cycle (full disinfection of exposed surfaces) depends on the intensity of the light, some designs require more fluence cycles in

order to sanitize all sides. This is a crucial facet of what makes a design a good one and was given an importance of 5.

- *Noise Level*
  - As mentioned above, the device must not be disruptive in the classroom. This was given an importance of 4.
- *Size*
  - The client discussed how limited space was in her classroom. However, she did list an extensive range of possible sizes she would still be interested in, so this specification was given an importance of 3.
- *Simplicity*
  - Given the number of criteria already being considered, if a simpler mechanism has the same efficacy it should be chosen. This was given an importance of 4.
- *Ease of Loading and Unloading*
  - This corresponds with the technical specification above. It is a client desire and is what differentiates this product from others on the market. Certain designs make this very simple while others require the designing and building of an extra mechanism to meet the specification. Therefore, it was given an importance of 5.
- *Capacity*
  - One of the important differentiating factors between this solution and the others on the market is that this device can accept many toys at once, whereas many are limited by size. Therefore, capacity was given an importance of 4.
- *Durability/reliability*

  - Some of the designs include more parts that are liable to break or get caught on things. The complexity of the design ties in here as well in terms of likelihood to be durable. This was given an importance of 3.

- *Creativity*
  - Creativity was given an importance of 1. It is a great thing to have in a design, but ultimately is not as important as many of the other considerations.

- *Consistency*
  - Some of the designs depend on random motion, whereas others are a lot more controlled and can give more definite results which makes verification easier and gives the user confidence. This was given a weight of 3.

- *Safety*
  - Safety was given an importance of 4. Any machine that exists in a daycare or preschool classroom should be safe enough that children may not accidentally injure themselves.

- *Ability to be adjusted once design is chosen*
  - This criterion was essential, and was given the maximum weight of 5, because there is no guarantee that any of these designs will work perfectly on the first try. Some allow changes to be made once the systems are designed, i.e. you could change the speed or force settings and affect the efficacy of the machine. However, some of the mechanisms, once fully designed and built, are not as easy to change. Having a design be modifiable once built allows more flexibility and room for success in the final product.

- *Cost*

- In order for the client to want to purchase the product it must be affordable. This was given an importance of 4.

5.2 Selected Designs

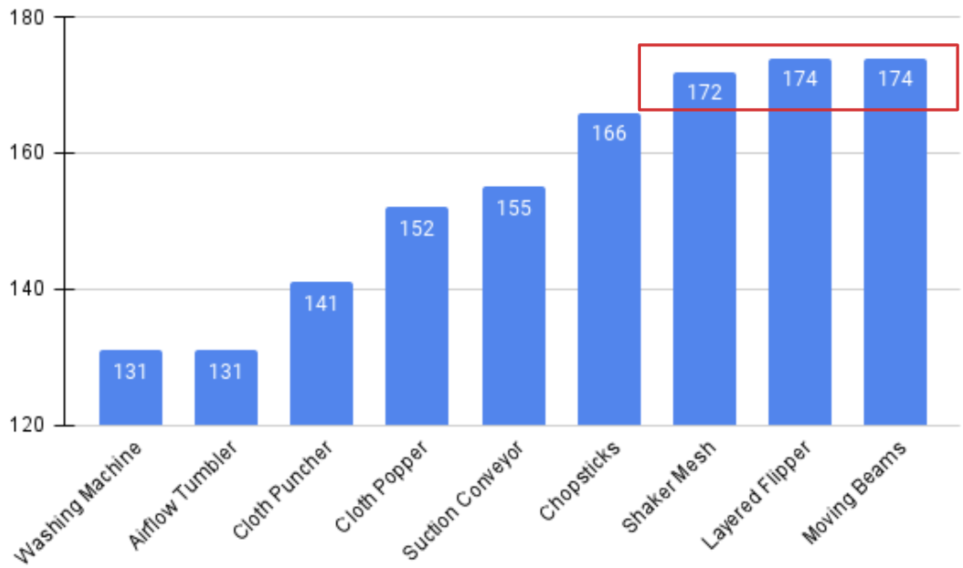


Figure 5.1: Pugh Matrix Scores for Top Nine Ideated Designs

Based on the results of the pugh matrix seen above in Figure 5.1, three designs were chosen to be rapidly prototyped in order to establish proof of concept. The scores ranged from 131-174, with an average of 155. Given that the top three were all so close together in ranking, the final decision is based on the efficacy of the prototypes. The scores they received are outlined in Table 5.1.

Table 5.1: Pugh Chart Results for Top Three Designs

Criteria	Shaker Mesh	Layered Flipper	Moving Beams
Timeliness (7-# of estimated cycles it would take to clean them all)	3	3	5
Noise Level	2	2	5
Size Requirment	5	4	5
Simplicity	5	4	3
Ease of Loading and Unloading	3	5	3
Capacity	4	5	3
Durability/Reliability	5	4	3
Creativity	3	4	4
Consistency	3	3	5
Safety	5	4	5
Ability to be Adjusted Once Design is Chosen	4	5	3
Cost	4	3	3
Totals	**172**	**174**	**174**

5.2.1 Shaker Mesh

Design

This design consists of a box with lights coming from all six sides, and the toys sitting in one layer on a wire mesh. The toys (up to a given capacity limit) can all be dumped into the machine at once. The machine will then shake the toys down into one layer, where they will then settle and stay still for one fluence time cycle. During this cycle, the five sides of the toy not sitting on the mesh will be fully sanitized, and the sixth will be sanitized in the open-air area. At that point, it will shake again to move the toys to a different point and repeat this cycle. At the end of the cycles, a mechanism would be included to raise the toys to the top so they could be easily swept off into a bucket again, without a teacher needing to spend time reaching in and picking up and out each toy or Lego.

Figure 5.2: Example Product Similar to the Tray of Shaker Mesh Design [9]

This design scored well on durability, size, simplicity, and safety. The simplicity of the design means that there isn't much of a chance for things to go wrong, or hurt anyone. It is confined within a box, which means that a mechanism could be included to turn off the light if the lid is open, ensuring complete safety in terms of UV's effect on skin and eyes. Similarly, since it is only one tray, this design maximizes its capacity for its size. This design scored poorly on noise and consistency. Shaking hard plastic and wood objects is quite noisy. Similarly, shaking is by definition a very random process, so many cycles may need to be run in order to guarantee all sides are reached.

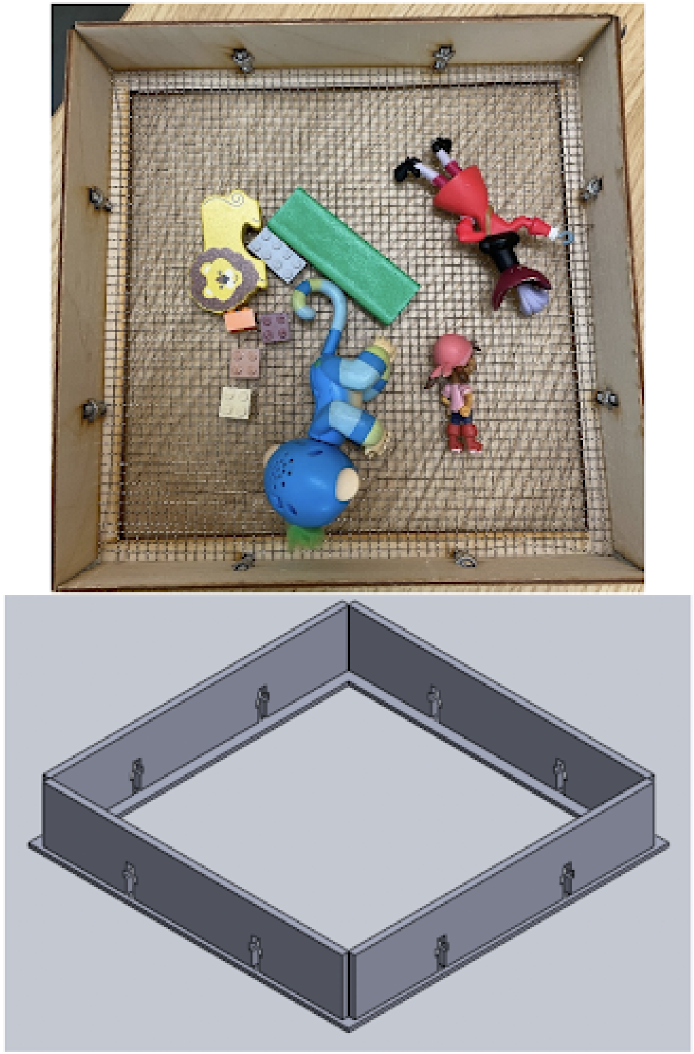


Figure 5.3: Rapid Prototype and Solidworks Model of Shaker Mesh Design

Model and Build

The prototype for this design and corresponding Solidworks model are pictured in Figure 5.3. The box frame was laser-cut out of $\frac{1}{8}$ inch wood found in the Active Learning Labs, and the wire mesh used was ordered and cut down to size. The wire mesh used was marketed as having 25% coverage, so 75% of the bottom was open air. At this rate, it would take five cycles to guarantee a 99.9% likelihood that the bottom face of each toy is completely sanitized.

Measure and Verify

Repeated testing with the prototype showed basic proof of concept. Toys of all shapes and sizes dumped in the middle consistently spread out into a single layer with around 30 seconds worth of shaking. While difficult to measure exactly where toys ended up relative to the first cycle after shaking, no toys were getting caught, crushed, or not moving during shaking cycles. This allows the assumption of random positioning for each cycle, which using the mesh's 75% open air statistic validates the above math.

5.2.2 Layered Flipper

Design

This design consists of several layers of conveyor belts, as sketched in Figure 5.4. The toys are taken along the conveyor belts, while a light shines on them from above. After traveling along the conveyor for the full fluence time, they slide onto a platform. At a predetermined time interval the platform would rotate a full 360 degrees, dumping the toys onto a second conveyor belt stationed below, flipping them over in the process.

This design scored well on capacity, adjustability, and loading ease. The conveyor belts allow a surplus of toys to be placed in the machine and allow the machine to clean all of them without further human intervention. It also has many adjustable qualities, like the speed of the flipper, and distances between the conveyor belts. It scored poorly on noise level and consistency, because flipping rigid objects like Legos creates a lot of noise and there is an element of randomness to the flipping. It is difficult if not impossible to guarantee that every object will flip over at any given flipper speed and height given the variation in object sizes and masses.

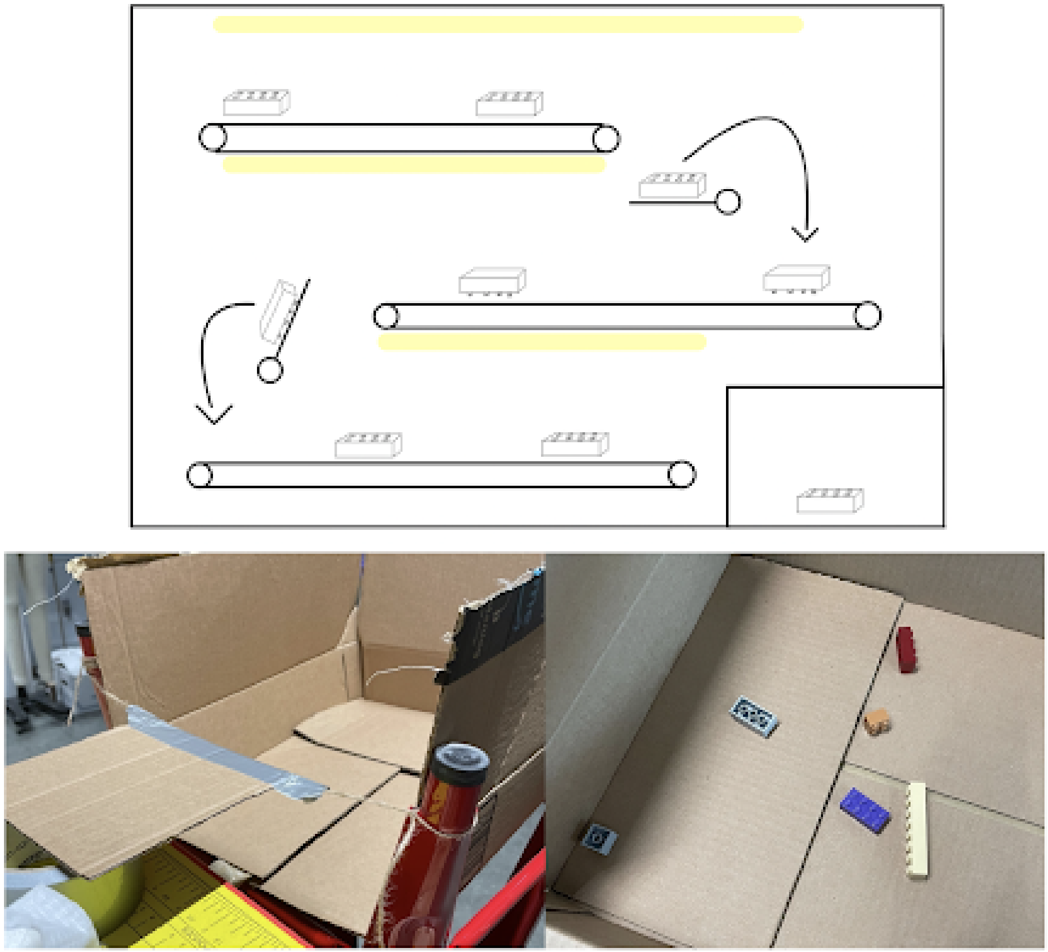


Figure 5.4: Sketch, rapid prototype, and results of a flip attempt with Legos. All started upright, one ended that way.

Model and Build

The prototype for this design is also pictured in Figure 5.4. It was made of cardboard, tape, and string sourced from the Active Learning Labs. The flap is attached to the string along one end to ensure that it rotates around an axis, as it would in the initial design sketch. Two sets of tests were run, flipping objects at a variety of speeds. One set used Legos, and the other used larger plastic dolls. Being "flipped" was defined as landing sitting on one of the 5 sides that had been open to air before. The Lego tests consisted of two 4-dot Legos, three 8-dot Legos, and a 16-dot Lego, pictured in Figure 5.4. After repeated testing in both scenarios, at a variety of orientations and speeds, there were no successful trials. In every trial, at least one toy landed in the same position it had been in before.

To counteract this effect, the machine would need to include many layers, and run for the full fluence time at each layer. Even then, it would be challenging to ensure that each toy had had all sides shined on by the UV light, as it is possible that the same toy could not flip every time. If one assumes only half the toys flip every time, it would take ten layers in order to ensure a 99.9% likelihood that each toy had had all sides exposed. This dramatically extends the machine size, complexity, and run time. For these reasons, this was not the chosen design.

5.2.3 Moving Beams

Design

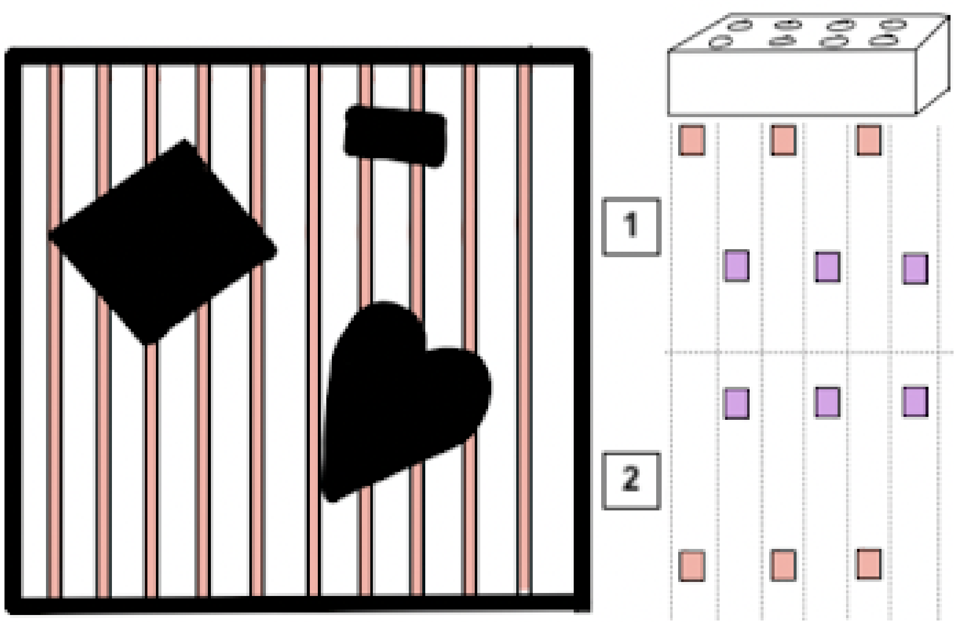


Figure 5.5: Top View and Side View of the Mechanism for Switching Object Holding Positions

This design consists of layered slats that function as shown in the sketches in Figure 5.5. In the top view, the objects are sitting on bars that stretch the width of the machine. Lights are shining from all six directions, and throughout any given fluence cycle, every part of each object is being sanitized besides the parts sitting directly on the bars. They undergo one entire fluence cycle, and then the internal mechanism picks the objects up so that they are being held in places that were already sanitized during the first run. This guarantees that in two fluence cycles, the entire surface of every object will be sanitized.

A mechanism for switching the way the object is held is sketched in Figure 5.5. It shows a side view of the different sets of bars. The bottom layer of bars is placed below, and would not cast a shadow based on the investigations discussed in Section 6.6.1, meaning that in between the fluence cycles the bottom layer would exclusively need to lift, picking up the objects in opposite positions for the second fluence cycle.

This design scored well on timeliness, noise level, size, and consistency. It is guaranteed to expose all sides within two cycles, which none of the other designs can promise. It also does not agitate the objects enough to create significant noise as the other designs do. The standout property with this design, however, is the consistency. The other two designs depend on some level of randomness. Extra cycles can be run to mitigate risk but there is always some chance that parts of an object do not get sanitized. This design functions in a way as to guarantee complete sanitation. This design scored poorly on simplicity and adjustability. It is a more complicated mechanism than some of the others, and the subsystems are interconnected, complicating redesigns.

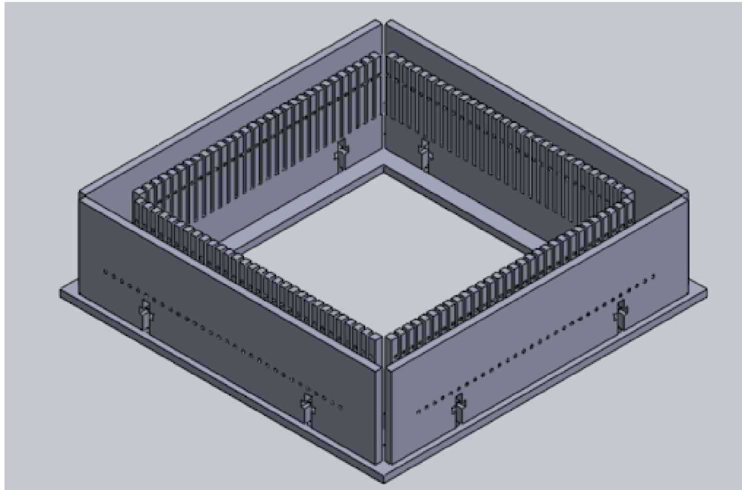


Figure 5.6: Solidworks Model of Moving Beams Prototype

Model and Build

The small-scale prototype for this design is pictured in Figure 5.7, with the corresponding Solidworks model in Figure 5.6. The two frames were fabricated using laser-cut pieces of $\frac{1}{8}$ inch wood, and strung using wire from the Active Learning Labs. Preliminary testing showed that it was possible to switch how an object was being held without that object sliding or moving in any way. This provided proof of concept that it would be possible to sanitize all sides of an object simply by changing how it is held. However, the wires used in this prototype could not be pulled taut, which meant they hit each other on the way up and down, jostling the toys slightly in the process.

Figure 5.7: Small Scale Prototype for Moving Beams Design

Another prototype was built in order to resolve the issues with the wires jostling. Making sure that the toys would not move when the platforms switch places is integral to the efficacy of this design. If they move at all the claim that all sides can be sanitized in two cycles is incorrect. The second prototype used acrylic to form both platforms to avoid the problem of the wire interactions. It also used springs and locating rods to ensure that the movement was consistent and controlled. The Solidworks model and prototype are pictured in Figure 5.8. With this prototype, it was evident that this mechanism would work as ideated.

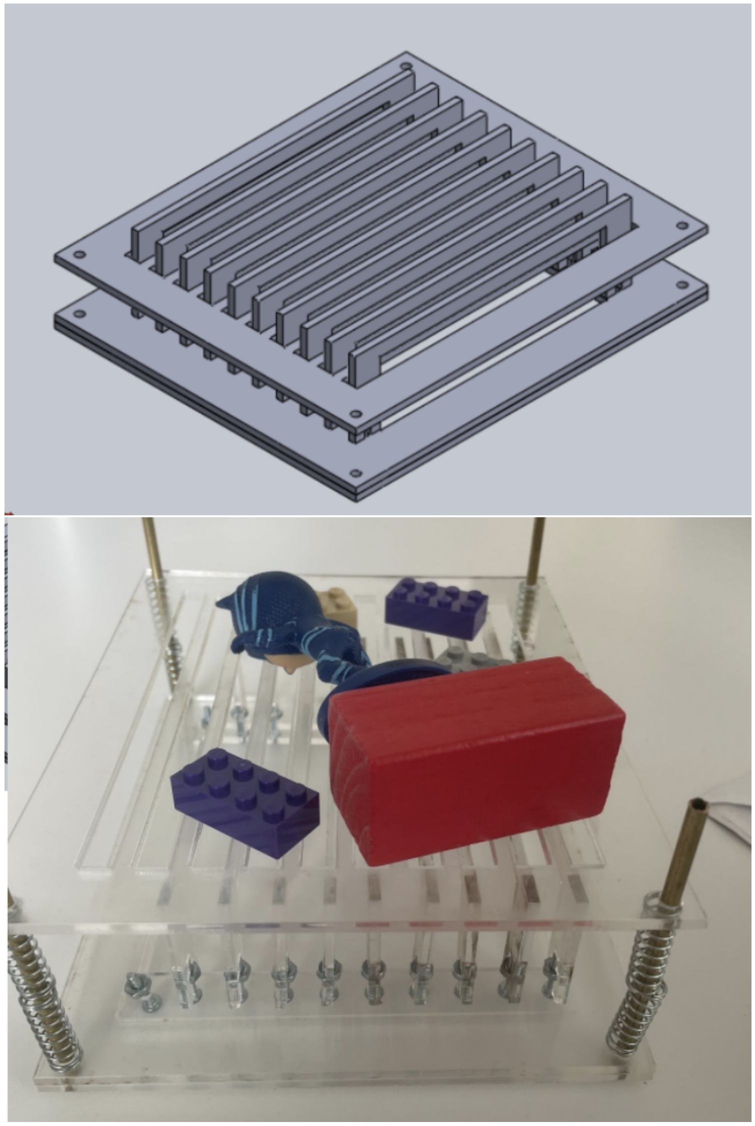


Figure 5.8: Moving Beams Second Prototype Model and Build

5.3 Mechanism Decision

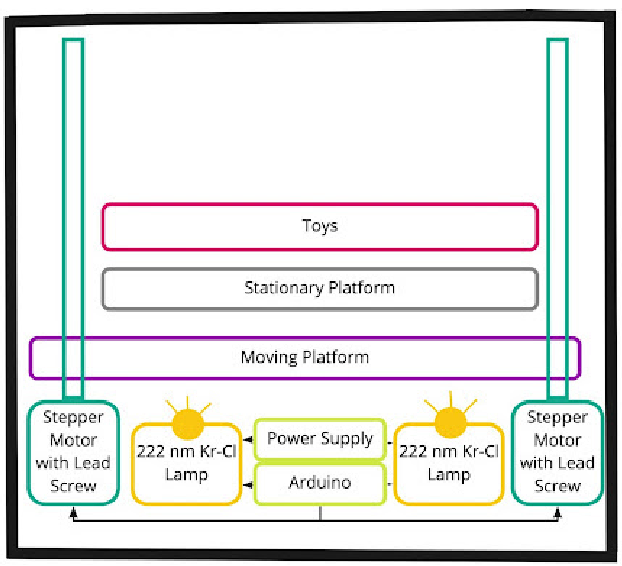
Once the three top scoring designs had been prototyped and tested, it was clear the Moving Beams design was the best choice. The Layered Flipper testing showed that it would not work, or would take at least 5-8 cycles to do so. The Shaker Mesh design would have worked but again would have required many more cycles. The Moving Beams design works in two cycles, and doesn't involve the random motion that the other two depend upon. The certainty of this design requiring only two cycles along with its efficacy ensured that it was chosen as the final mechanism to manipulate the toys.

Chapter 6

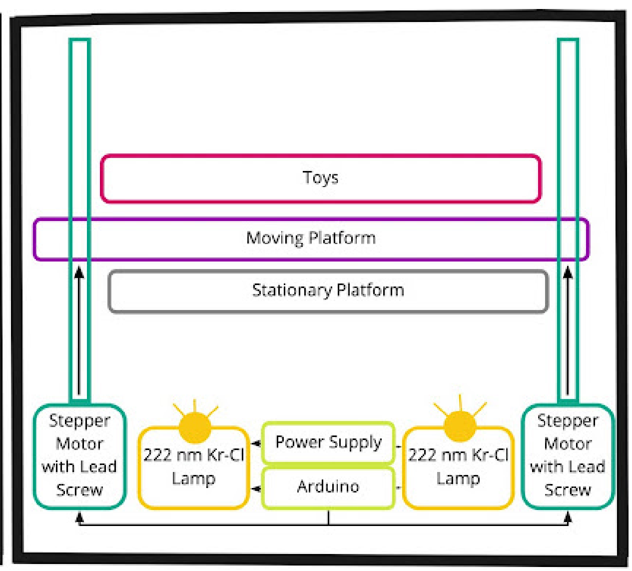
Subsystem Design

Once the mechanism decision had been made, the next step was figuring out how to move the various platforms to their positions, and design those platforms themselves.

6.1 Systems Diagram



(a) Fluence Cycle One



(b) Fluence Cycle Two

Figure 6.1: Systems Diagram

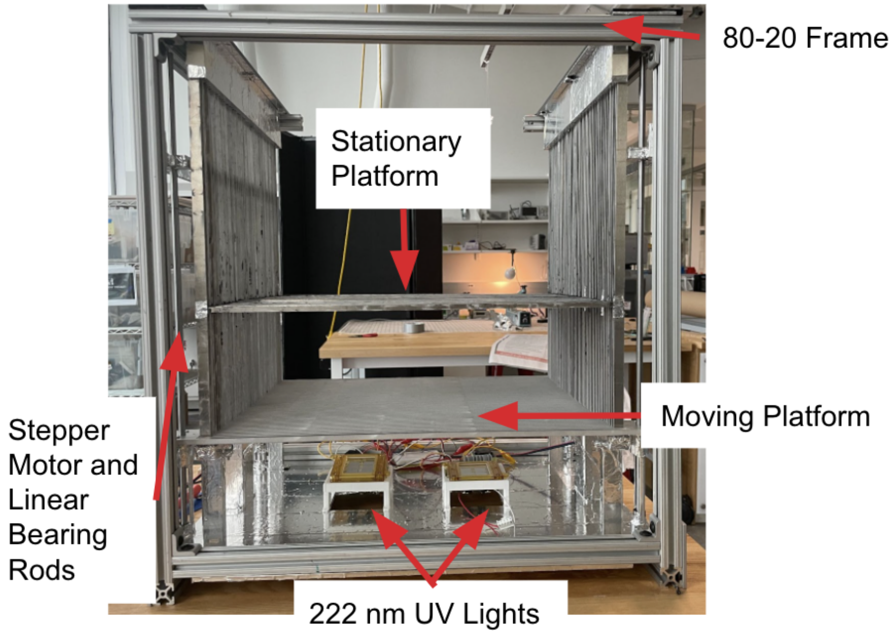


Figure 6.2: Photo Of Built Machine Showing Off Major System Diagram Components

The systems diagrams in Figure 6.1 represent the major building blocks of the system. The teacher dumps the toys in, where they sit on the stationary platform, as seen in Figure 6.1a. The teacher would then spend a few seconds spreading the toys out into one smooth layer, and then start the machine. The machine then runs one full fluence cycle in the configuration shown in Figure 6.1a. The light shines up from the bottom, and reflects off of the different components and walls to sanitize all sides of every object except for the parts that are actively touching the slats of the stationary platform. Every component within the interior of the machine is made of aluminum or covered in aluminum tape, as aluminum is the most reflective material at the 222 nm wavelength [37]. After one full fluence cycle, the stepper motors lift the moving platform from below the stationary platform to above it, as seen in Figure 6.1b. The moving platform is then holding the toys, and given the design, the toys will be supported in exactly opposite spots than they were before. At this point, a second full fluence cycle runs, sanitizing the newly exposed parts of the toys. The motors are powered by and run by an Arduino MKRZero. A photo of the build specifying the location of each system from the system diagram can be seen in Figure 6.2.

6.2 Solidworks Model

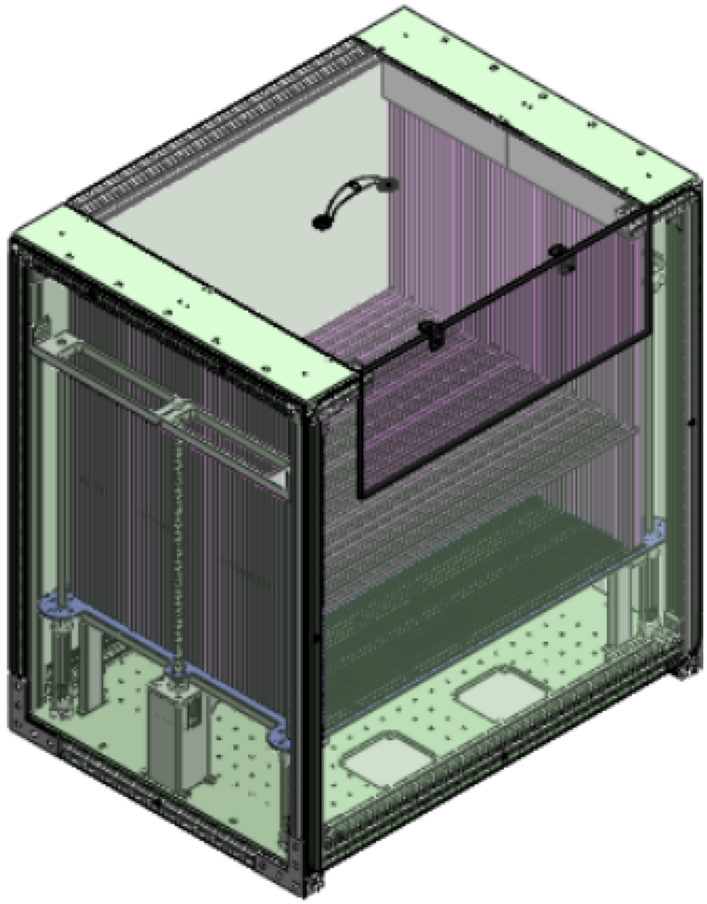


Figure 6.3: Full CAD Model of the Device in which All Subsystems can be Seen

The full Solidworks model for the machine can be seen in Figure 6.3. The model consists of 258 individual components. The assembly is made in a way to mimic how the device is built, using only concentric mates to represent screws and coincident mates to replicate things touching.

6.3 222 nm Kr-Cl Lamp

The vast majority of the research done on 222 nm Krypton-Chloride lamps has been completed using one lamp, created by Ushio America. They have the patent on a filter that keeps only the safe Far-UV-C wavelengths and eradicates all the dangerous ones that are higher in the UV-C spectrum. Given that the research on 222 nm UV-C is all fairly recent, costs on these lamps are still coming down. After talks with Ushio America, they agreed to donate two lamps to this project for use, at a commercial value of approximately $3000.

6.3.1 Fluence Chart for Common Spores, Bacteria, and Viruses

In order to determine the amount of time the machine should run, knowing the fluence to eradicate the target bacteria, spores, and viruses is essential. The chart below details the fluence required to create the specified reductions in active microorganisms. A 1-log reduction corresponds to a 90% reduction in viable microorganisms, 2-log reduction is a 99% reduction, 3-log is a 99.9% reduction, and 4-log is a 99.99% reduction in viable microorganisms. Every entry in Table 6.1 is fluence data collected while using a 222 nm Krypton Chloride Excimer lamp. This table represents the available data about the effectiveness of these lamps.

Many common spores, bacteria, and viruses are represented in Table 6.1. All three categories have numbers in fairly similar ranges. For the few species with available 4-log reduction data, the largest number for a 4-log reduction in pathogen activity is 30 mJ/cm^2. This is from MS2. MS2 is a commonly used surrogate for pathogenic disinfection studies, and is a surrogate for adenoviruses, a common class of virus that can cause a range of illnesses. However, adenoviruses are more susceptible to UV disinfection at low wavelengths than MS2, making MS2 a conservative surrogate under study [40].

The sanitation device being designed will sanitize up to a 3-log reduction in microbial pathogens. There is both more and better data about 3-log reductions, and generating a 3-log reduction is comparable to other products on the market [14, 15, 16, 17]. The highest requirement for a 3-log reduction is 69 mJ/cm^2. The machine's defined fluence cycle will therefore be 69 mJ/cm^2. This covers all of the plausible bacteria, spores, and viruses in the above data, and gives a significant safety factor for the vast majority of them. That means that even if there are somehow other microorganisms with higher fluence requirements, an

Table 6.1: 222 nm Kr-Cl Excimer Lamp Fluence (UV dose) (mJ/cm²) for a given log reduction without photoreactivation

Microorganism	1-log	2-log	3-log	4-log	Source
Spores					
Bacillus Cereus	25	43	69	-	[38]
Bacillus Subtilis	7	12	18	23	[38]
Clostridium pasteurianum	4.3	6.1	7.9	9.6	[38]
Penicillium expansum	22	33	42	-	[38]
Streptomyces griseus	13	17	20	26	[38]
Bacteria					
Arthrobacter nicotinovorans	10	15	18	20	[38]
Bacillus cereus (veg. bacteria)	9	11	14	18	[38]
Escherichia coli	4.9	7.7	9.1	10.3	[38]
Pseudomonas aeruginosa	3.1	4.8	5.9	7.5	[38]
Staphylococcus aureus	9.3	12	14	18	[38]
Yersinia enterocolitica	3.1	6.1	7.6	8.8	[38]
MRSA (from graph)	1	2	5	20	[28]
Viruses					
Human RhinoVirus	2.72	19.36 (2.36 log reduction)		-	[39]
HCov 229e	0.95	-	19.42	-	[39]
Influenza A	0.75	2.0	-	6	[25, 30]
MS2	6	10	18	30	[40]
COVID-19	1	3 (2.51 log reduction)		-	[29]

overall 3-log reduction is still achievable through reducing the other viruses far beyond their fluence requirement.

6.3.2 Light Placement and Cooling

To prevent wayward hands from accessing high voltage points, the 222 nm lights both were placed on the floor of the machine. Ushio America donated two lights, so the lights are placed with their centers along the same center line as the two motors, and one-third of the way along the floor. The two inverters are placed at a distance specified by the manual as far enough from the lights to be safe, but still close enough that the wires could reach the lights without being stretched and stressed. Under each light and each inverter, a hole was cut in the floor to allow the heat given off by these components to escape. The metal frame also has the bottom horizontal bars placed above the floor. This allows for full airflow beneath the floor, ensuring that the heat can dissipate. This system was also tested. The light has a 5 minute on, 5 minute off duty cycle. After running 8 of these cycles, there was no measurable rise in heat near the light or inverter, so this system was deemed adequate.

6.4 Stepper Motors

6.4.1 Calculations and Motor Choice

The most affordable and most readily available stepper motor with incorporated lead screw is the NEMA 17 stepper motor. It is also highly recommended on a variety of websites for similar applications, lifting a platform. Furthermore, these motors are easily programmed to run concurrently, allowing the use of two or more motors to lift one platform.

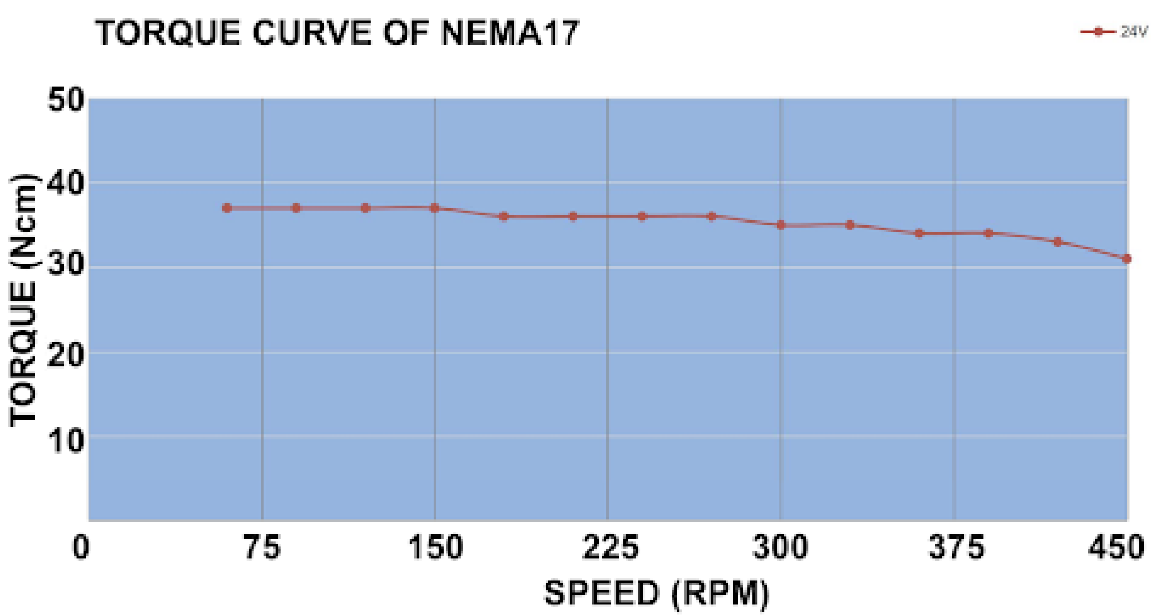


Figure 6.4: NEMA 17 Torque at Various Speeds

The NEMA 17 torque curve is pictured in Figure 6.4, and shows that the torque output is fairly constant across all operating speeds, at approximately 38 Ncm. This number can be plugged into Equation 6.1, which relates output torque to output force for stepper motors with lead screws.

$$T_{raise} = \frac{Fd_m}{2}(\frac{l + \pi\mu d_m}{\pi d_m - \mu l}) \tag{6.1}$$

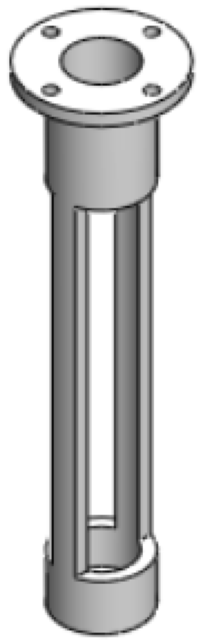
In this application, with a Tr8x8 lead screw, the diameter of the lead screw is $d_m = 8mm$, and the lead is also $l = 8mm$. The lead screw is steel, and comes with a brass nut. The friction range provided was 0.15-0.19, so the upper limit for the coefficient of friction $\mu = 0.19$ was used. Plugging in $T_{raise} = 38Ncm$, the force output is 175.6N, which corresponds to a lifting capacity of over 17 kg per motor. Using Solidworks mass properties, the moving platform as designed weighs around 0.5 kilograms, and two motors are being used to maximize stability. Given that no reasonable bucket of toys will weigh anything close to 34 kg, this motor is overpowered. However, since it is the cheapest and most widely available motor, these calculations show that it has enough power for this application and will perform as desired.

6.4.2 Linear Bearing Design

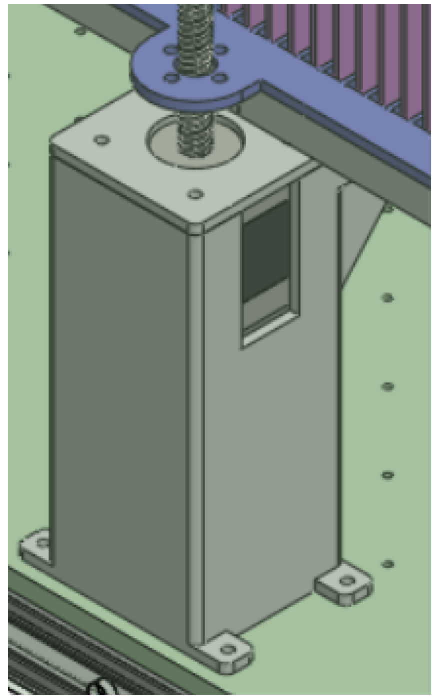
Ideally to lift a platform, there would be a motor in each corner to make sure it is supported evenly and will lift cleanly. However, this is not cost effective. In this design, two motors are used, lifting from the center of their respective sides. In the four corners, shafts with linear bearings are used to keep the platform stable and allow it to lift smoothly, even if there is more weight on one side of the platform than the other. Without these linear bearings, an uneven distribution of weight would cause binding and inhibit smooth movement. In order to prevent binding, the rule of thumb introduced by PBC Linear in the 1990s and widely followed after required a 2:1 ratio [41]. This means that however far the bearings are from the motor, they must be half that length apart from each other. In this design, each linear motion shaft is 8 inches from the closest motor, and so the linear bearings are placed 4 inches apart along those shafts to prevent binding.

6.4.3 Extra Parts for Linear Motion System Support

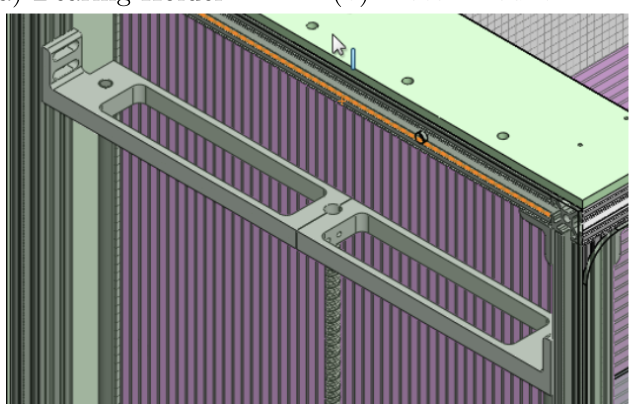
Several extra 3D printed parts are required in order to make the linear motion system move smoothly. The bearing holder, pictured in Figure 6.5a attaches to the bottom of the moving platform, and uses a friction fit to hold two linear bearings in place, 4 inches apart, as discussed in Section 6.4.2. Given that the platform cannot move all the way down to the ground, the motor mount is designed to lift the motor off the ground, as well as stabilize and immobilize it. Long thin objects like lead screws bend more the longer they are, so lifting the motor up minimizes the needed lead screw length, thus removing some risk of lead screw deformation. The third part is the shaft stabilizer. This attaches to the 80-20 frame near the top of the device and holds the lead screw and linear motion shafts in place. This allows these shafts to remain vertical, encouraging smooth movement.



(a) Bearing Holder



(b) Motor Mount



(c) Shaft Stabilizer

Figure 6.5: 3D Printed Add-ons to make Lifting Mechanism Run Smoothly

6.5 Moving Platform

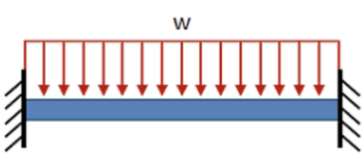
6.5.1 Slat Spacing

For both the moving and stationary platforms, the objective is to hold up all of the toys while exposing them to as much light as possible. In order for the platforms to be able to move through each other, slats were used as opposed to a grid pattern of any kind. The thinnest aluminum rods sold at McMaster-Carr are $\frac{1}{16}$ in in diameter. This was chosen to be the slat width, as the thinnest standard commercial width available.

The technical specifications require that the machine be able to accept toys as small as Lego 3003, a "four dot" Lego. The smallest dimension of this Lego is its height, which is 0.43 in. For stability, the Lego needs to rest stably on two slats on both platforms. Each slat is 0.0625 in wide. In order to maximize open space while keeping the smallest toy stable, the space between each slat was calculated to be 0.23 in.

6.5.2 Model and Prototype

The initial ideation of this platform involved simply supported aluminum rods, but rapid prototyping revealed these were way too weak to hold up toys. To increase the strength without increasing the width, the second idea has fixed rectangular rods that are $\frac{1}{4}$ in tall. This plate is manufactured by cutting it from a single sheet of $\frac{1}{4}$ in aluminum. In order to verify the strength before making a cut, maximum deformation of this platform is calculated, as seen in Equation 6.2 for the maximum deflection of a fixed beam.



$$\delta_{max} = \frac{wL^4}{384EI} \qquad @ \quad x = \frac{L}{2} \tag{6.2}$$

In order to calculate w, the distributed force, a load of $10lbs = 4.54kg = 44.497N$ of toys distributed across the 52 slats is applied, as seen in equation 6.3.

$$w = \frac{F}{nL} = \frac{44.497N}{(50bars)(.52324m)} = 1.7008\frac{N}{m} \tag{6.3}$$

The width, b = 0.0015875m, and height, h = 0.00635m, of each slat are then used to calculate the moment of inertia.

$$I = \frac{bh^3}{12} = 3.387 * 10^{-11} \tag{6.4}$$

Finally the length, $L = 0.52324$m, and the Young's Modulus, $E = 69 * 10^9$GPa are plugged into Equation 6.2, and the maximum deflection is calculated to be $\delta_{max} = 0.000142\ m = 0.0055\ in$. When the same calculations are applied to the initial prototype, the max deflection is 3.03 in, which is corroborated by its inability to hold anything. The calculated deflection is not noticeable in the functioning of this platform, and at this point a prototype was cut, as seen in Figure 6.6, and as expected it was able to hold the toys with ease.

The imperfections seen in Figure 6.6 are due to this cut being the first ever completed on this WaterJet, and did not occur in the final product.

Figure 6.6: Waterjet Cut Scale Initial Prototype of the Moving Platform

6.6 Stationary Platform

Similar to the moving platform, the key objective for the stationary platform is to hold the toys while leaving as much of their surface area open to the air as possible. The slats need to be positioned by hardware which cannot interfere with the movement of the moving platform, allowing it to move through this stationary one.

A "U" shaped design is able to accomplish this. The slats are hung from the top of the device, so that the supports can function as walls as well, keeping the toys from falling off either platform. The moving platform has extra slots on either end to be able to implement a barrier on the other two sides as well. This allows the toys to be walled in so that they cannot fall off into the depths of the machine.

The slats that make up the stationary platform are cut using the waterjet out of $\frac{1}{16}$ inch aluminum. Each slat is cut in three separate pieces in order to minimize the material waste

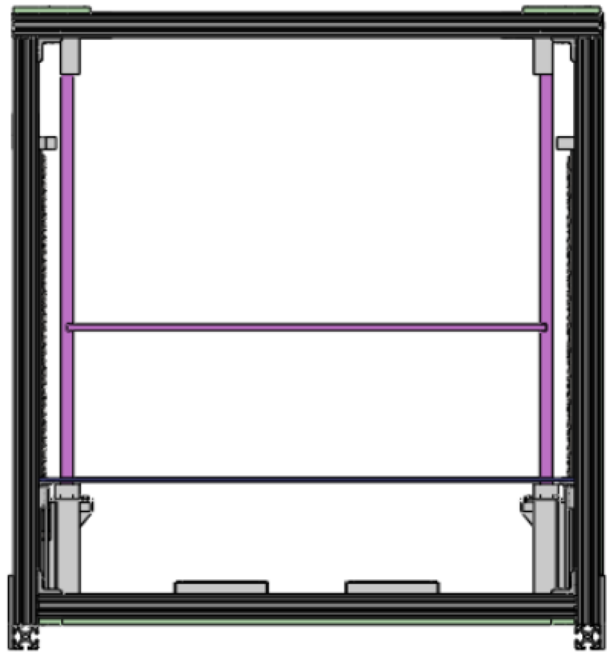


Figure 6.7: Solidworks Model shows Stationary Platform “H” Shape Highlighted in Pink

during fabrication. To form the final slat, the three pieces are then epoxied together.

An initial prototype proved that the slats would not stay the correct distance apart while only supported from above. Spacers were added on the other end to keep the slats supported from below as well. This is essential for the moving platform to be able to move consistently. This also changed the shape to an “H”, as seen in the final design pictured in Figure 6.7. This design accomplishes the goals of maximizing open air space while keeping the toys supported and allowing all of the movement necessary for the machine to run smoothly.

6.6.1 Platform Shadow Eradification

One important aspect of this design is that every part of a toy that is open to the air must be exposed to the germicidal light. Given that during each cycle, there is a platform beneath the platform that the toys are sitting on, it was essential to investigate the shadow casting abilities of the platforms.

While the spectrometer is able to measure wavelengths down to 200 nm, Harvard does not have any available machines that can measure light intensity at 222 nm. Instead, 222

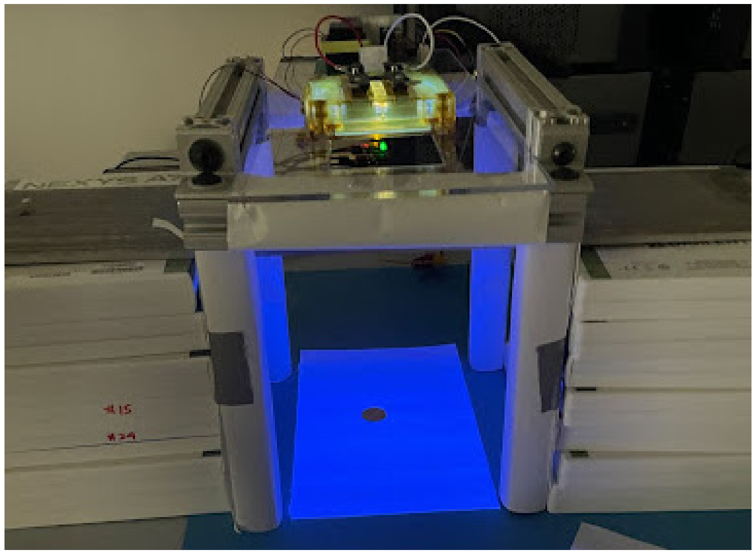


Figure 6.8: Testing Environment used to Investigate Shadows Cast By each Platform

nm sensitive stickers were ordered. A testing environment was built in order to discover at what distance after hitting an obstacle the light would fully diffuse. Essentially, how far apart do the two platforms need to be for there to be no shadows that would affect the premise that open air is equal to sanitized.

The testing environment was set up as seen in Figure 6.8, with the light approximately 9 inches from the ground. For each test, a sticker was placed beneath the lamp, and the lamp was turned on for four minutes. The "No Metal" Column of Figure 6.9 shows the before and after of our control test, in which there was nothing in between the lamp and the sticker. The stickers are an inexact measure of dosage, but based on the final color, $40 - 50\frac{mJ}{cm^2}$ was delivered in the 4 minutes of every test.

The second test run was to ensure that the sticker color did not change uniformly. The moving platform prototype seen in Figure 6.6 was placed 1 inch above the sticker, and the results are seen in the"1 *in*" column of Figure 6.9, with the top row being the raw image, and the bottom being the image with the contrast and brightness edited to show better what was clear in real life. This test proved that the sticker would show shadows cast by the slats of the platform through a color differential.

Once it was clear that the stickers would serve as a reliable metric to calculate how far

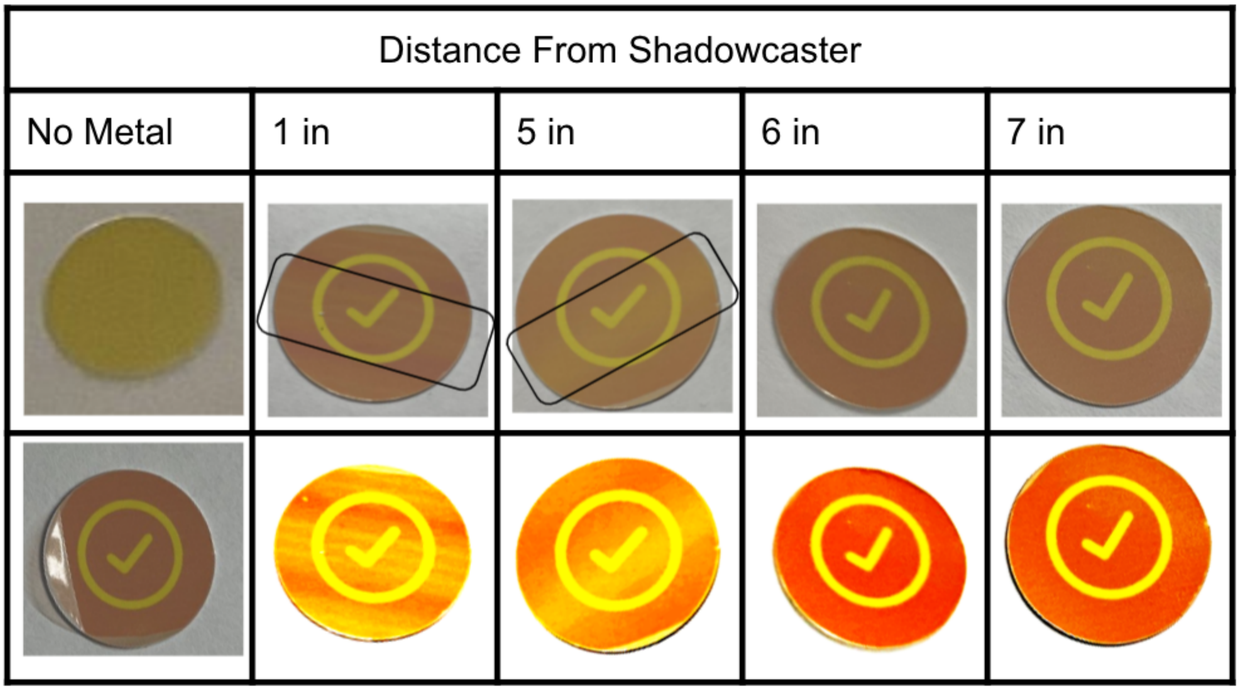


Figure 6.9: Results from shadow testing showing that by 6 *in* the light is dispersed. The top row is the raw photos and the bottom row is the photos edited for contrast to better show on a computer what was obvious in person.

apart the platforms needed to be, tests were run at other heights. As seen in Figure 6.9, there was a clear shadow cast when the platform was 5 inches away from the sticker. However, at 6 and 7 inches, the sticker was a uniform color, showing that the light had diffused enough after hitting the platform that it caused no color differentials on the sticker. Based on these results, the final decision was made to have the platforms be 6 inches apart. At this height between the platforms, there are no longer shadows. This validates the premise that all areas of the toys that are open to air are also being sanitized.

6.7 Electronics

A full schematic of the electronic systems in this machine is pictured in Figure 6.10. The circuit is powered through wall power, and the microcontroller is an Arduino MKRZero. This schematic can be divided into a few key sections with different purposes: power input, running the UV lights, running the motors, the indicator light, control buttons, and the Arduino code itself.

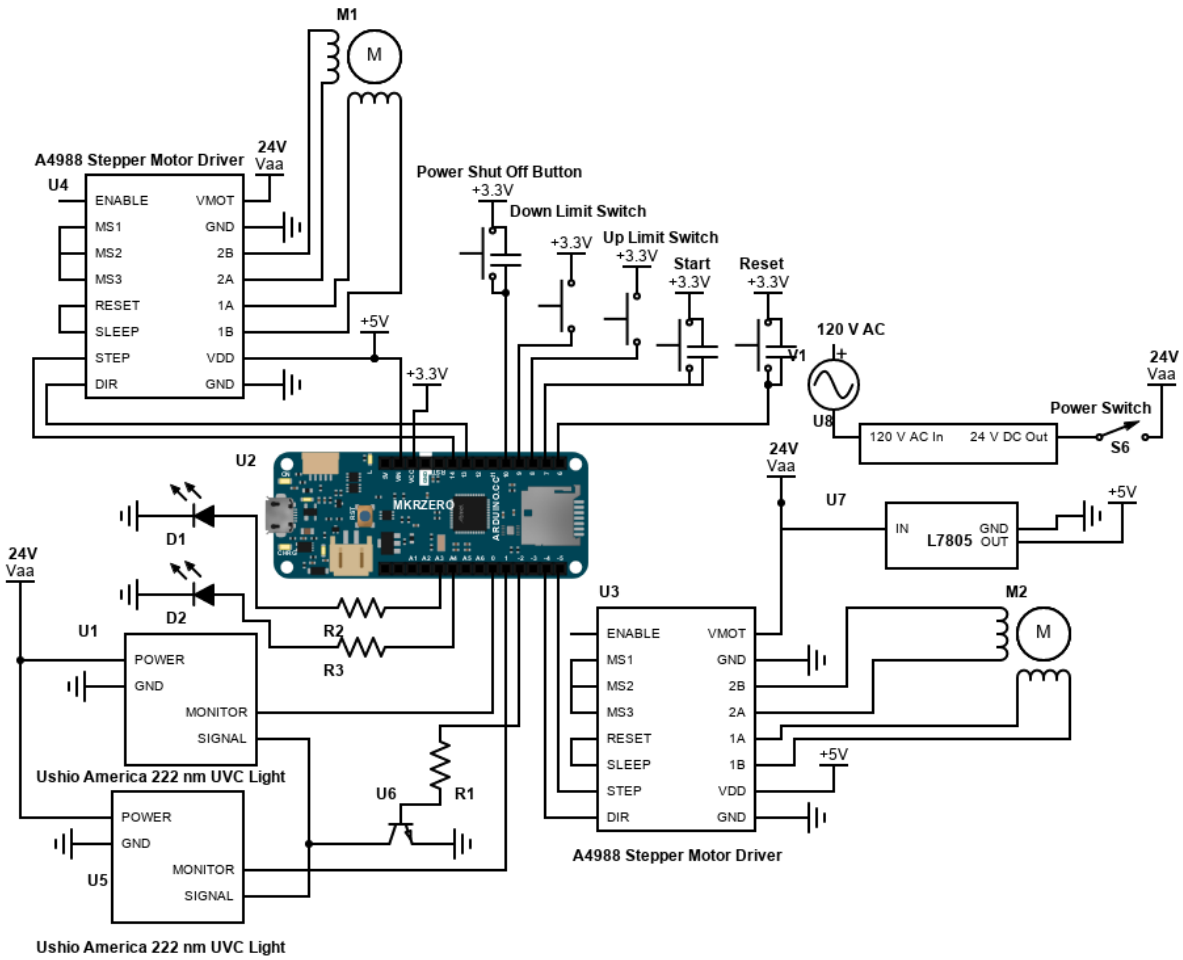


Figure 6.10: Full Schematic of Electronics in Device

6.7.1 Power Input

In order for this machine to be a functional consumer product, it is important for it to run off of wall outlet power. This allows it to be used anywhere and everywhere, and moved easily. The lights and motors require 24V DC input, and at least 2A of current in order to function. A cord was purchased that can convert the 120V AC power from the wall to a 24V DC signal with the required amount of current. This power input is also switched, as seen

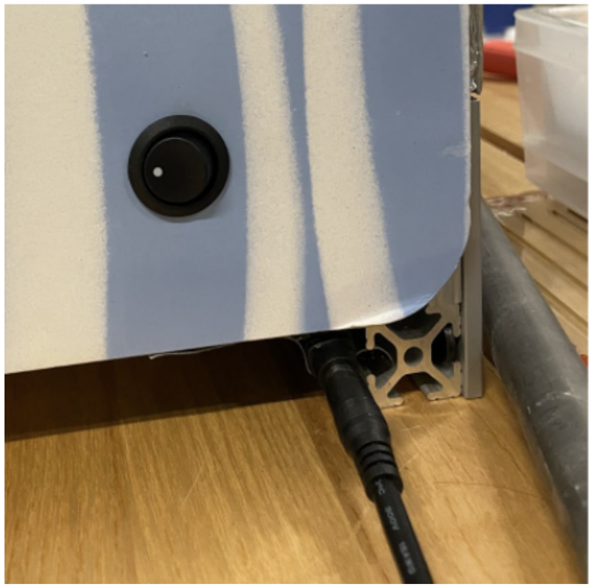


Figure 6.11: Input from Wall Plug and Power Switch on the Front of the Device

in Figure 6.11 in order to create an added level of safety. This switch allows a user to turn off the power to the machine without having to unplug it from the wall. When the machine is turned off, it will not have any latent power consumption.

From the 24V input, two other power rails needed to be created in order for the device to run smoothly. A L7805 chip is used to step the 24V down to the 5V needed to power the Arduino safely, as well as an input on the motor driver. The Arduino VCC output of 3.3V is also used to create a rail to power all of the switches and buttons.

6.7.2 Light Electronics

The Ushio America lights require careful wiring in order to operate safely and effectively. There are four wires that extend from the inverter of each light to be considered. The lights are powered by the 24V DC input to the machine from the wall outlet converter, taking care of the power and ground inputs. The third input is a yellow signal wire. This wire goes to the collector of an NPN BJT, with the base then going through a resistor to pin 2 of the Arduino. This pin is set as an output, and setting it high turns on the BJT, pulling the inverter signal pin low which turns on the light. The final wire is a monitor wire. This wire

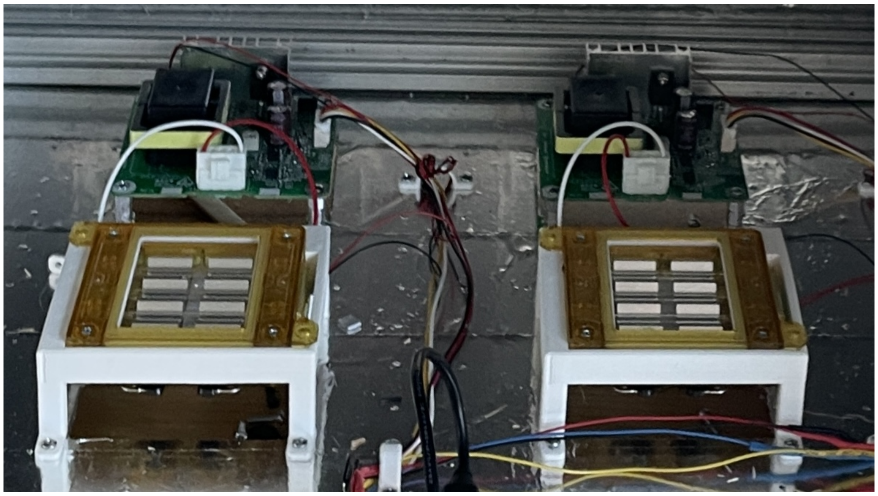


Figure 6.12: The Lights and Inverters Installed onto the Floor of the Device

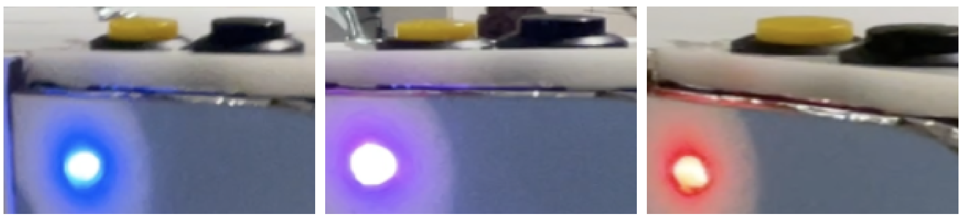
on each light is wired directly into pins 0 and 1 as an input pullup. These pins are then checked ten seconds after the light is turned on to ensure that the monitor signal has gone low, meaning that the lights are truly on. This is a built in fail safe from the manufacturer so that if the light fails to ignite, the program will recognize that and halt. Due to the fact that the lights and the inverters take 24V in and produce 6kV of power, the wiring and controlling of these lights was done extremely carefully, under the supervision of ALL staff member Ben Brown.

One other important safety wiring factor with the lights has to do with the proximity of other current carrying wires. The lights and inverters are not meant to be within 1 cm of any other wires. This means that careful wire management is important. Approximately 250 holes are cut into the floor and tapped, with brackets 3D printed to screw in to the floor. This floor grid allows careful management of wire location, which keeps the machine safe and makes everything look organized as well.

6.7.3 Motor Electronics

The motors are powered and run through the Arduino MKRZero and an A4988 Stepper Motor Driver Chip, as seen in Figure 6.10. Given this projects' needs from the motor, only two control pins are used, the step and direction pins. For both motors these pins are wired directly to Arduino output pins which can be set high and low to control the motor speed and direction. One motor uses pins 4 and 5, and the other uses pins 13 and 14.

6.7.4 Indicator Light



(a) Standby Mode (b) Program Running (c) Reset Running

Figure 6.13: Indicator Light Meanings

Another feature that is integral to making this device usable for consumers is the indicator light. This is an LED that is right below the Start and Reset buttons that indicates whether the machine is currently running. When the machine is on and waiting for input, the light is blue. Once the Start button is pressed it switches to purple and stays purple for the duration of the program. Once the program finishes, the light turns back to blue. This allows a user to know when the program is complete, and not have to time the machine. They can check the light anytime to know. The light also turns red when the reset program is running just so the user knows movement is happening.

6.7.5 Control Buttons

Five different buttons are used as inputs to control the machine. Each button is powered by 3.3V and then wired directly to an Arduino pin set to input pullup mode. The momentary buttons also have 10 microfarad capacitors in parallel in order to debounce them and prevent unintentional triggering.

The most important button is the power shut off safety button, the red button in Figure 6.14. This button is designed to add an extra layer of safety to the machine by making

Figure 6.14: From Left to Right: Power Shut Off Button, Program Start Button, and Reset Button

sure that nothing can move or turn on without the lid being on the machine. This button is placed in a hole drilled in the 80-20 frame, so that when pushed it is flush with the top of the frame. The acrylic lid is heavy enough to push the button. The button is wired in to the Arduino, and if the lid is removed it can turn off the lights and stop the motors from moving almost instantaneously. This is an extra mechanism that keeps this machine as safe as possible. While the lights are safe for human skin and eyes, ensuring that the lights and motors cannot function when the lid is off adds an extra layer of safety, which is very important with a product that is used in a daycare or preschool. The American Conference of Governmental Industrial Hygenists UV threshold limit value is 23 $\frac{mJ}{cm^2}$ per eight hour period [30]. Since the box is completely enclosed, and has this power shut off switch, it ensures that the exposure during the use of the machine is 0 $\frac{mJ}{cm^2}$, which is below this limit.

Turning off the lights the wrong way can damage them, so the power shut off button feature is implemented through software as opposed to hardware. A finite state machine ensures that the status of the power shut off button is checked every few milliseconds, exiting the program if the lid has been removed. A flow chart representing this finite state machine code is pictured in Figure 6.15. This flowchart represents a loop, as every time the chart ends in one state, it starts over using that current state as an input.

The Start button is used to start the machine cycle running. The Reset button can be used to bring the platforms back to their starting positions in the case that the power shut off button is triggered mid program. The up and down limit switches are placed at the positions in which the moving platform is desired to stop. When the platform depresses the switch, it triggers the code to stop movement. The exact use of each button can be seen in the code flowchart pictured in Figure 6.15.

6.7.6 Code Structure

The full Arduino code for the device can be found in Appendix C. The flowchart below describes the finite state machine and the actions that are taken as part of the program. This flowchart exists within the loop portion of the Arduino, meaning that every time that the flowchart is completed and a colored state number circle is reached, it starts back over, rechecking that the lid is on every few milliseconds.

The standby mode state is state 1, and the program stays here as long as the lid is off, and if it is on but program start has not been triggered. If the Start button is pressed, state 2 begins, and the platform moves down until it hits the limit switch at the bottom height. Then, in state 3 the light is turned on and the timer is started. In state 4, what happens depends on the time. After 10 seconds have passed in state 4, enough time has passed for the light monitor signals to be accurate. From that point it will exit back to state 1 if the lights are not on when they are supposed to be. Otherwise, the light will stay on for 5 minutes, and then turn off for 5 minutes (still checking to make sure the lid is on every few milliseconds). This 5 minute on and off cycle will repeat the specified number of times to complete the first fluence cycle. At that point, it checks whether the platform is up or down. If the platform is at the bottom it means that was the first fluence cycle and the program goes to state 5 where the platform rises to the top and then sends it back to state 3 for the

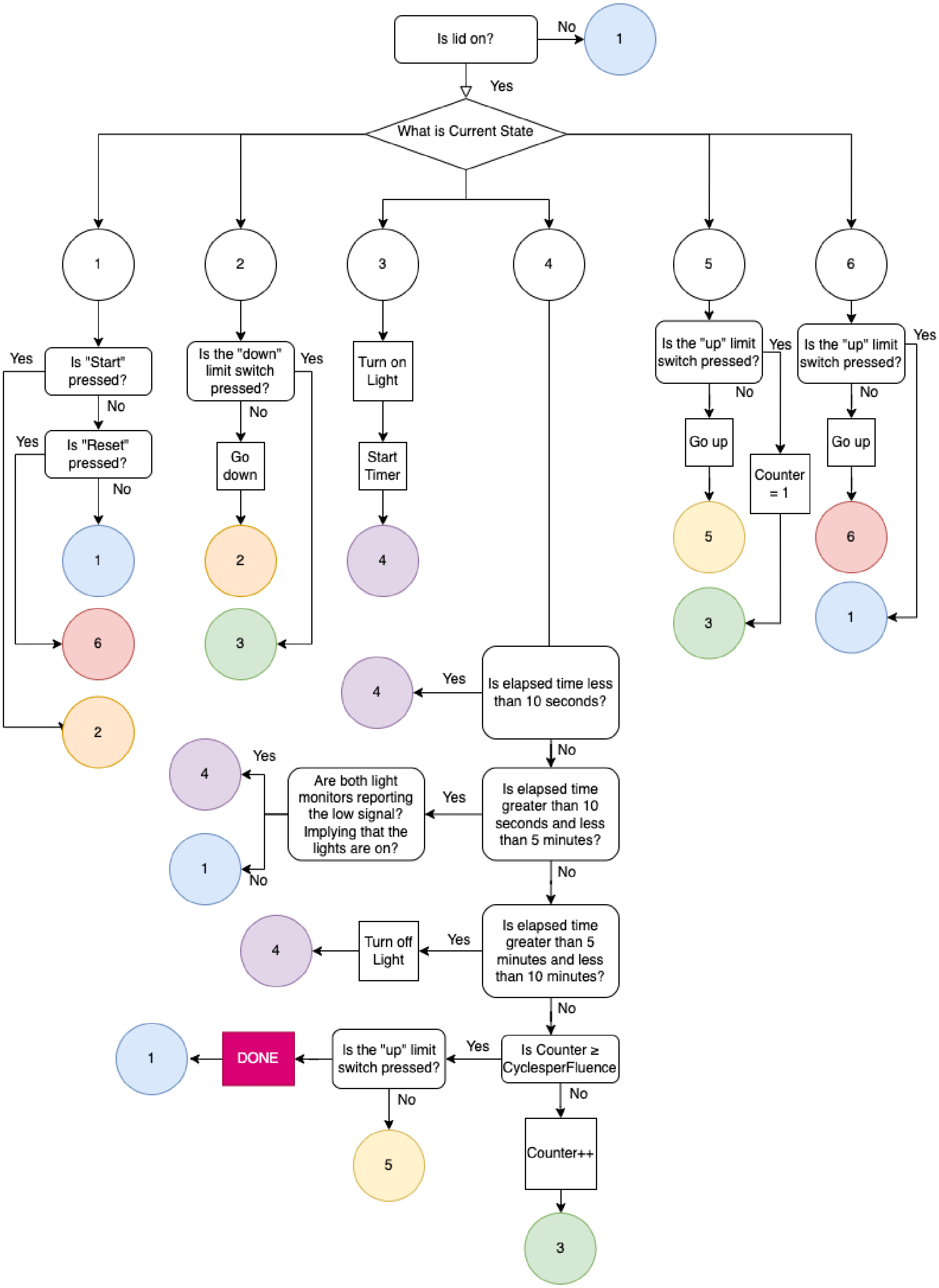


Figure 6.15: Finite State Machine flowchart to represent Arduino Code. Every time that the end of the flowchart is reached and a state is triggered, the chart starts over from the beginning.

second fluence cycle. If at the end of state 4 the platform is at the top it means the full program run is complete, and it sends it back to state 1 to await further command. The other program reachable from state 1 is when the Reset button is pressed, state 6 raises the platform to the top so the program can be ready to start once again.

This flowchart represents the finite state machine that controls the actions of the device, while making sure to maintain safety at every step.

6.8 Reflectivity

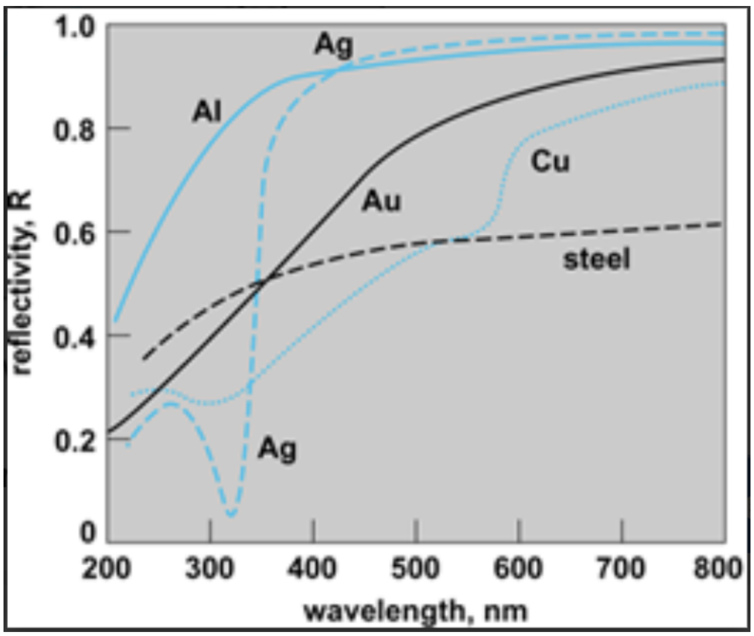


Figure 6.16: Reflectivity of Different Materials to Electromagnetic Radiation at Different Wavelengths

In order to achieve the premise that light is reaching all parts of the toys that aren't touching the platform, the inside of the machine needs to be extremely reflective. This way even though the lights are both at the bottom, the tops and sides of every object are also being sanitized. In order to achieve this goal, everything in the machine that is not already made from aluminum is carefully wrapped in aluminum tape, including the floor, ceiling, and sides. Aluminum is the most reflective material at 222 nm, as seen in Figure 6.16 [37].

6.9 Aesthetics

This machine is meant to be utilized in a daycare or a preschool. Therefore, the aesthetics are very important in order to turn the machine from something that looks more industrial into something that could truly belong and fit in in a classroom with small children. The outsides are painted with a stencil, and a picture of the final decorated device can be seen in Figure 6.17.

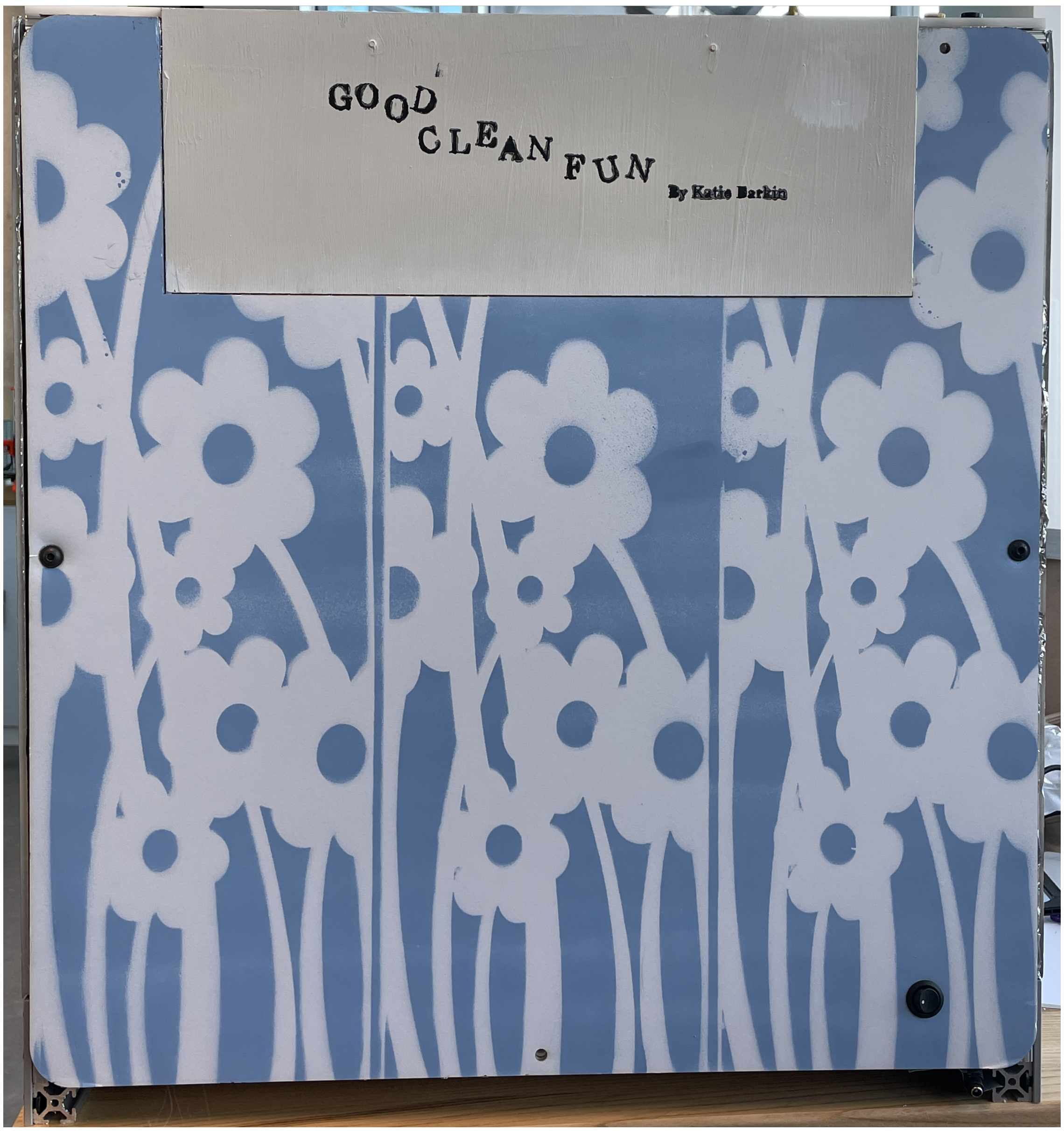


Figure 6.17: Front Image of Final Machine

Chapter 7

Evaluation and Verification

7.1 Prototype 1

7.1.1 Lamp Wavelength Verification

Once the light and the inverter were set up, it was important to verify that the light was emitting only the wavelengths it claimed to emit.

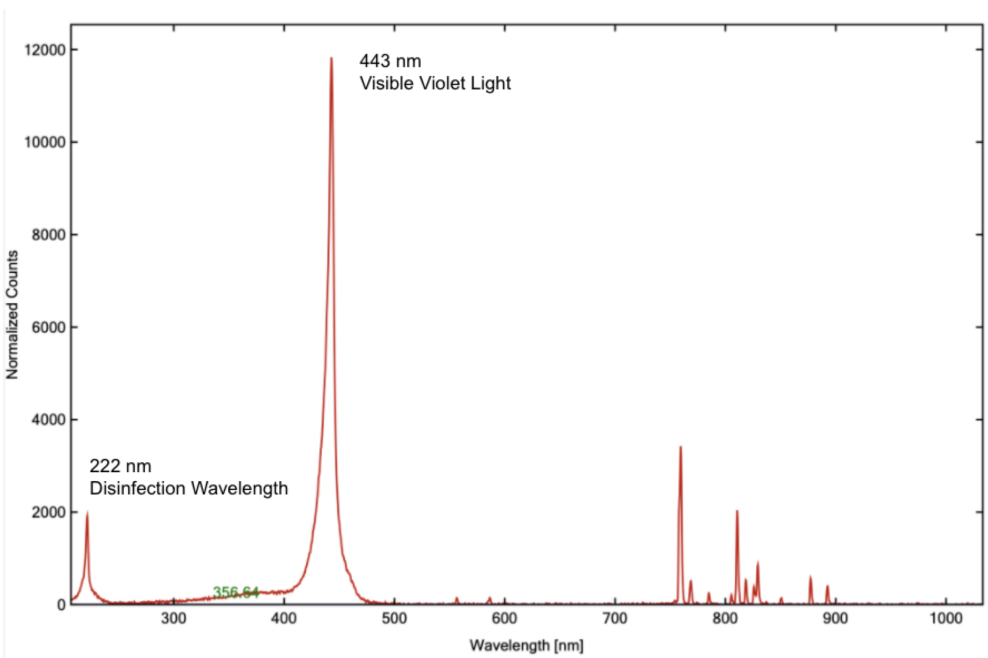


Figure 7.1: Spectrometer Output with Ushio Kr-Cl Lamp

Figure 7.1 displays the spectrometer output of the Kr-Cl lamp that was measured using the equipment in the ALL. There are clear peaks at 222 nm, 443 nm, and in the infrared range. 222 nm is the disinfection wavelength. There is a clear peak there, that quickly dissolves back to zero, showing that all harmful UV wavelengths are being filtered out (230-300 nm). There is a second peak at 443 nm, which corresponds with visible violet light. When the lamp is turned on, since UV is invisible to the human eye, there is a clear visible violet light included to confirm that the lamp is on or off. Finally, the infrared peaks are to be expected with a lamp of this kind, and are not dangerous in any way. This testing verified that the lamp performs as expected, and will have the safe germicidal effects advertised.

7.1.2 Light Placement Verification

Once the first full prototype was formed, it was important to make sure that with the current light placement, all parts of the platform would be hit by the light, verifying the claim that a toy anywhere on the platform would be sanitized. This was analyzed by covering the platforms completely in printer paper, and then putting the sides on to darken the machine as much as possible. This allowed it to be clearly visible that all parts of the white paper were glowing purple, lit up by the UV light, verifying the assumption that all parts of the platform were covered.

7.1.3 Reflectivity Testing

Before detailed testing began, some preliminary testing was done to verify that even with the lights placed on the bottom that UV-C waves would be reflected around and reach the top of the toys as well, so that changes could be made early if proof of concept was not achieved. Two tests were run, one on each platform. The motors were not turned on, and platforms did not switch during this test, so stripes on the bottoms of the stickers are to be expected. The stickers were placed in the same spot on either side of a piece of paper, and the light was run for 10 minutes. The results can be seen in Figure 7.2. The stickers on the bottom received approximately 70 and 100 $\frac{mJ}{cm^2}$ respectively, with the sticker on the stationary platform receiving more fluence as expected as the stationary platform is closer to the light. The stickers on the tops received approximately 20 $\frac{mJ}{cm^2}$ each in the ten minutes of active light exposure. Due to the duty cycle, this would lead to a run time of 70 minutes, which is reasonable with respect to the technical specification of 60 minutes. This also verified the premise of reflectivity, and led to further completion of the design in order to do final testing.

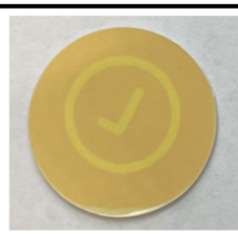
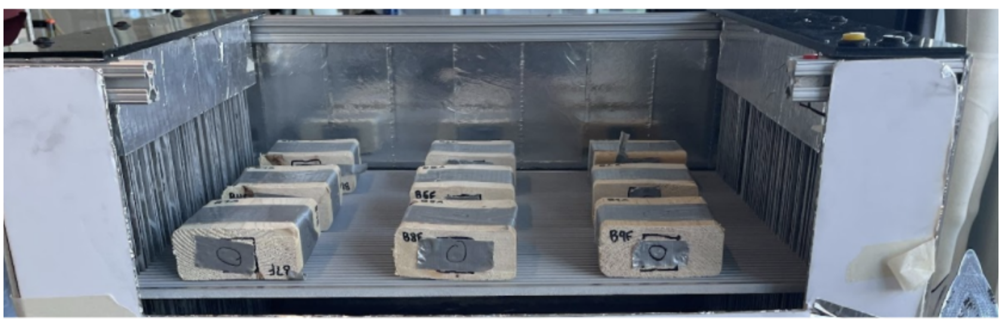
	Top of Sticker	Bottom of Sticker
Stationary Platform		
Moving Platform		

Figure 7.2: Pictures of the stickers after testing on both platforms. While the bottoms are clearly receiving more fluence, color checking reveals that the tops did receive 20 $\frac{mJ}{cm^2}$ during the ten minute run time of the machine. This would lead to a total run time of 70 minutes for the final machine which is reasonable with respect to the technical specifications.

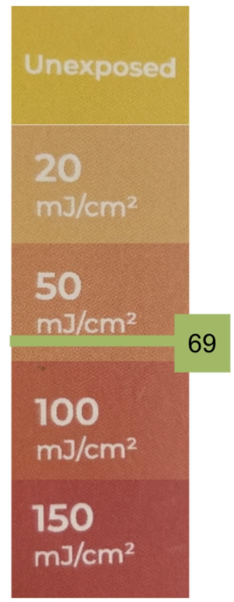
7.2 Prototype 2

7.2.1 Sticker Testing

Once a full mechanically working prototype was built, a deeper exploration into coverage and reflectivity was conducted. The sticker testing was used to ensure that all sides of an object were receiving UV dosage and to characterize the time that the machine would need to run in order to get all sides exposed at the 69 $\frac{mJ}{cm^2}$ level. 9 blocks were placed evenly spaced on the platform as pictured in Figure 7.3a. Six stickers were placed on the center block, one on each side, under the assumption that the center block is the most blocked from light on the sides. Two separate tests were run. Each test mimicked the final working of the machine, where the blocks started on one platform, and halfway through moved to the other for a full second cycle. In the first test, each fluence cycle was 5 minutes of light exposure and in the second there was 20 minutes of exposure. Due to the 50% duty cycle of the lamp, these tests took 20 and 80 minutes respectively.



(a) Block Placements for Sticker and Biological Testing



(b) UVC Dosimeter Color Scale

Figure 7.3: Sticker Testing Setup

In the first test, the stickers on the bottom received approximately 60 $\frac{mJ}{cm^2}$ evenly distributed so that there were no zones that were blocked completely, as can be seen in Figure 7.4. The top and sides of the block received between zero and twenty $\frac{mJ}{cm^2}$, with the top clearly receiving more fluence than the sides. With these results, it was somewhat unclear what the numbers were and if any fluence was truly being received on the sides, and so a longer test was run to get more definitive results.

The second test gave better results, pictured in Figure 7.4. The bottom sticker received

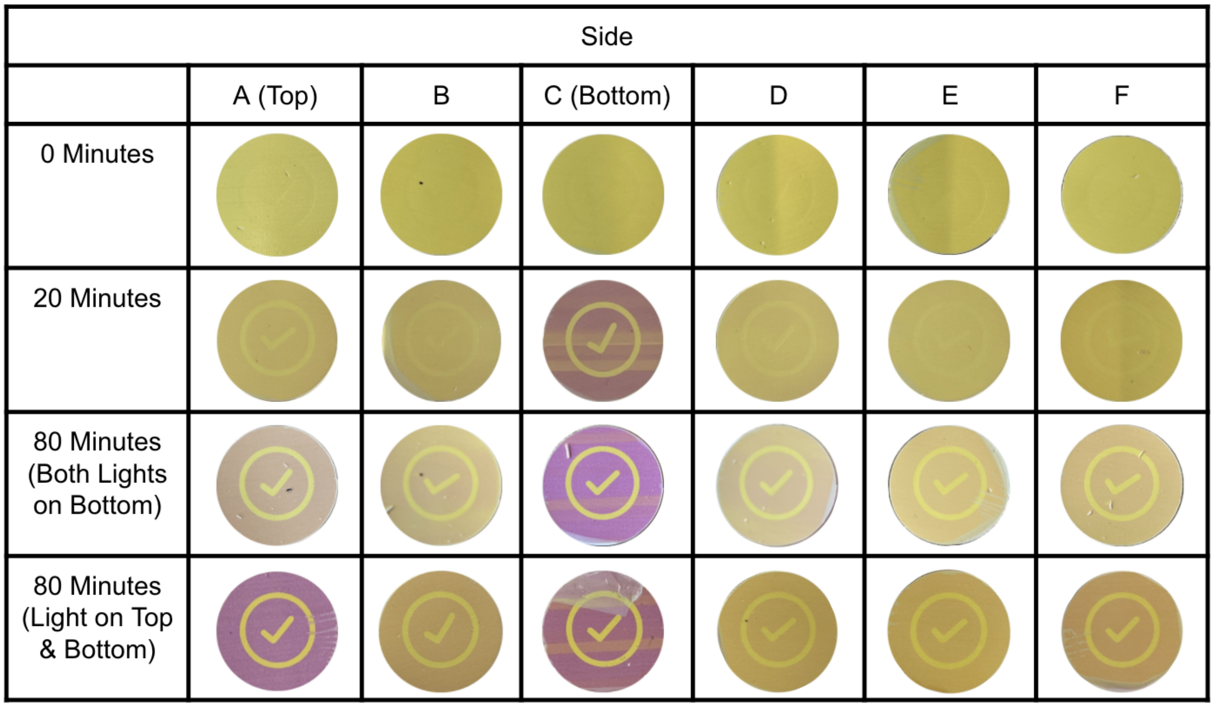


Figure 7.4: Results from sticker testing show that all sides of the blocks are receiving fluence, but at a slower rate than anticipated.

far over 150 $\frac{mJ}{cm^2}$, as it was a color far deeper than any pictured on the card seen in Figure 7.3b. The top received approximately 30-40 $\frac{mJ}{cm^2}$ and the sides received 20 $\frac{mJ}{cm^2}$.

These results mean that the machine would need to run for approximately 280 minutes, which is far over the 60 minute specification that was initially ideated. While this is technically a failure of this prototype, these tests did prove the premise of the machine. The bottom stickers emerged without any unexposed stripes, which means that the hand off between the platforms was smooth and that all parts of the bottoms are being exposed to the light and therefore sanitized. The top and sides are all definitively receiving light, meaning that the aluminum pieces are reflecting the light up and around as they should. This reflection is just leaving the light at a lower intensity, meaning fluence is received at a slower rate than desired. However, if left running for enough time, the machine will work effectively as all sides are receiving UV dosage.

In order to fix the timing issue, the first idea was to move one of the lights. The stickers on the bottom, even with half of the fluence time, are far over exposed compared to those on the tops and sides. A test was run moving one light to the top and leaving one on the bottom, with the results in the last row of Figure 7.4. This test was completed with the same timing, but did not significantly change the results. The sides of each object are receiving approximately the same dosage with both lights on the bottom as they do with one light on top (the small discrepancies can be explained by lighting in the photos taken, in actuality the stickers looked exactly the same). Given these results, the decision was made to leave both lights on the bottom. On the floor, there are several layers of platforms and walls to ensure that no one could ever touch or interfere with the high voltage lighting. With no significant change to the results, leaving the lights in the safer position is the correct decision.

One final test that was run was an 80 minute sticker test but with the reflective aluminum coating covered on as many parts of the machine as possible in order to test whether the reflectivity of the four sides and the lid made a difference in terms of fluence received. For this test, while the 4 side stickers did still receive some fluence, the top sticker looked the exact same as the control sticker: pure unexposed yellow. This proved that having the sides and lid be reflective made a significant difference in the functionality of the machine.

7.2.2 Biological Testing

Once the sticker testing had characterized how long the machine would need to run, biological testing was performed to ensure the efficacy. There were several rounds of testing. Despite repeated tries, no more than 7 colonies of *B. subtilis* were able to survive the time required for the tests to run, even with highly concentrated bacteria. Therefore, despite the original plan to attempt to test a gram-positive and a gram-negative bacteria, due to safety and time constraints the rest of the testing was completed with just *E.coli*.

The first round of testing with *E.coli* used a highly concentrated solution. The solution was smeared using swabs onto the duct tape covered blocks, and samples were taken again after the test was run for 80 minutes. In this test, the bacteria were far over concentrated.

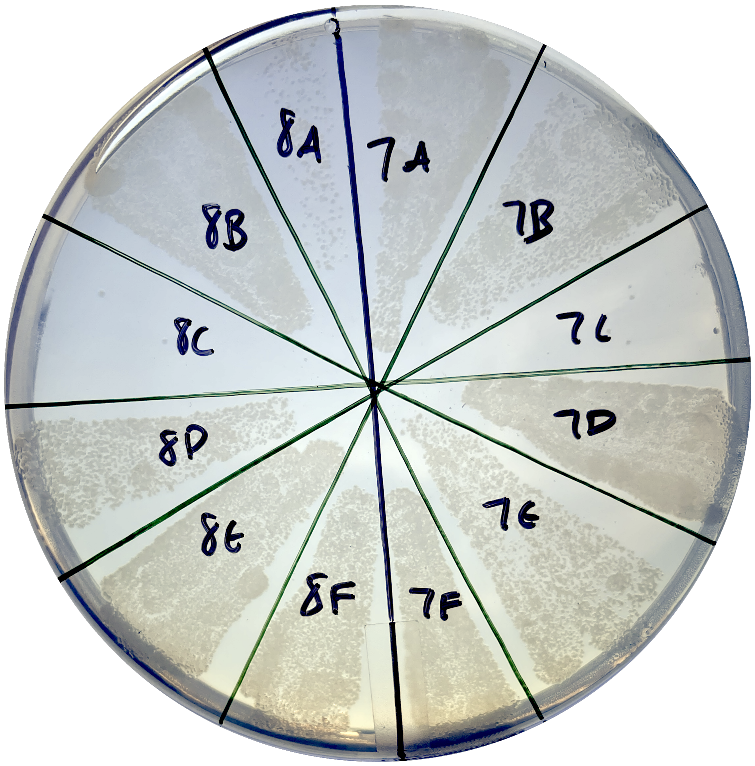


Figure 7.5: Agar Plate from initial biological testing. The sides vary in visible bacteria, but side C (the bottoms of the blocks) have no bacteria left, proving that more light leads to further disinfection.

There was a full rug of bacteria on each of the control sides, as well as most of the experimental areas on the agar plates. There very well may have been a 3, 4, or 5 log reduction in bacteria, but because there were so many bacteria to start you could not see the difference with the human eye or count any colonies. An example of an agar plate from this test is shown in Figure 7.5. The important takeaway from this test is that on each of the experimental plates, side C was completely clear, with no bacteria left, despite the multitude of bacteria on the other sides. From the sticker testing, as you can see in Figure 7.4, side C is the bottom of the blocks, and is far overexposed compared to the other sides, receiving far over 150 $\frac{mJ}{cm^2}$ in the 80 minutes. For these parts to be completely clean compared to the others establishes that with enough time and exposure, this machine can kill all of the bacteria. Any remaining bacteria after a test are not UV resistant, but just have not been exposed to enough light.

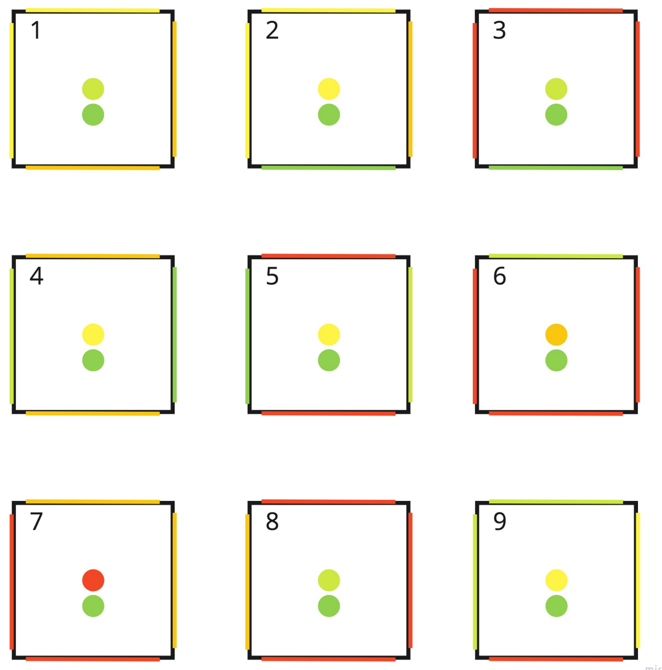


Figure 7.6: Chart marking which sides of blocks had the greatest reduction in bacteria to the eye. The results showed no pattern as to where fluence was or was not being received.

A diagram of the results of this testing is pictured in Figure 7.6. There was no particular pattern as to where the most sanitation was happening and where very little appeared to be happening. It is entirely possible that the differences are completely due to application method and survival factors unrelated to the UV. The only consistent thing is that the bottoms were completely clean and clear. In the chart lime green corresponds to completely clear, and red corresponds to no difference between the control and experimental areas visible to the human eye, with the color scale going in order between the two.

The second round of testing involved finding the right concentration of bacteria to use for the rest of the testing. Another 80 minute test was run. The original solution was found to have an optical density (OD) of 1.484, and 10 microliters of 10, 100, 1000, and 10,000 dilutions of the original solution were swabbed onto two sides of a block. The results from this test can be seen in Figure 7.7. All of the bacteria were gone in the 10,000 and 1000 dilutions, with some left in the other three. The 10,000 times dilution corresponds to placing 1,180 colony forming units (cfu) onto the testing area on each side [42]. For the rest of the testing, the 1/10,000 dilution was used, but the test was run for half of the time, for 40 minutes.

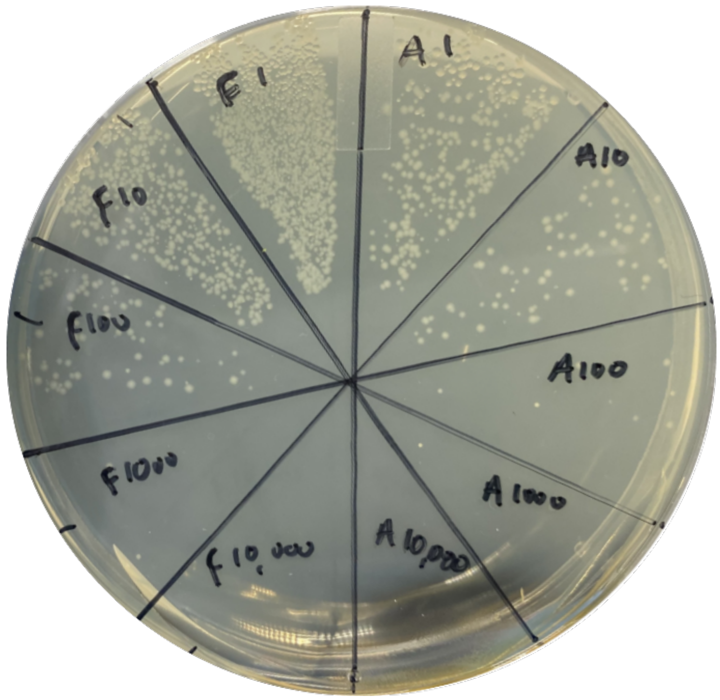


Figure 7.7: Agar plate showing the original solution down to a 10,000x dilution of that solution after an 80 minute test. The solutions were placed on two of the sides that were receiving the least dosage in the previous test.

The results of the sticker testing showed that the parts of the block receiving the least intense light were receiving 20 $\frac{mJ}{cm^2}$ in 80 minutes. The biological testing used *E.coli*, which from Table 6.1 requires 9.1 $\frac{mJ}{cm^2}$ to ensure a 3 log reduction in bacteria. Therefore for this testing the device was run for 40 minutes, in order to ensure delivery of 10 $\frac{mJ}{cm^2}$. *E.coli* and most of the other bacteria, viruses, and fungi researched will have a huge margin of safety in terms of dosage received by the device. However, if *E.coli* had been way overdosed, it would not be possible to claim that running the exact fluence dosage decided upon would be effective against the bacteria that requires that dosage.

Two tests were run under these conditions. With nine experimental blocks each time and three control blocks each time, this led to N=108 total experimental sides and N=36 control sides from which to collect data. An example agar plate from this test can be seen in Figure 7.8. There are clearly many more living colonies in the control half of the agar plate compared to the experimental half.

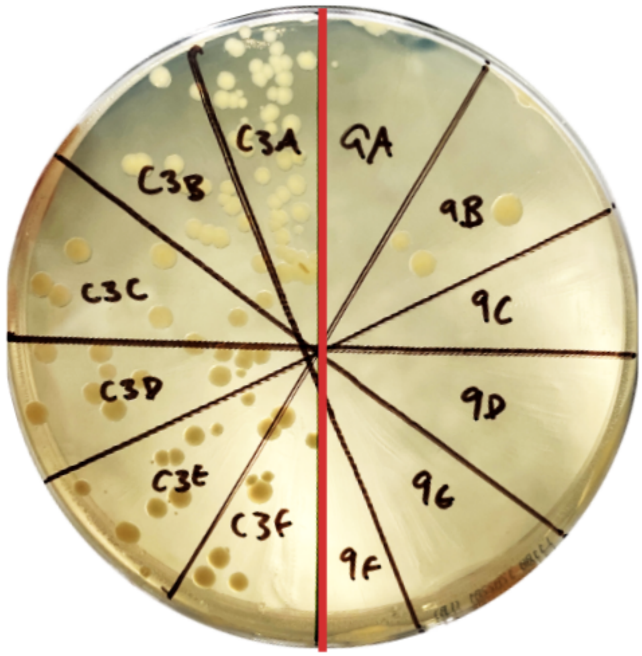


Figure 7.8: Example agar plate from final testing. The 6 sides of the control block, on the left, have far more bacterial colonies than the 6 sides of the experimental block, on the right.

For this final bacterial testing, the goal was to have at least 15 colony forming units per centimeter squared ($\frac{cfu}{cm^2}$). The testing areas on each side of the blocks were approximately one cm^2, so this corresponded to at least 15 control cfu per side. This is because Ibfelt et al. found that the maximum number of *E.coli* $\frac{cfu}{cm^2}$ found on toys was $15 \pm 2.3 \frac{cfu}{cm^2}$ [43]. The goal was then to eradicate 99.9% of these bacteria to meet the technical specifications for this project.

Between the two tests, it was found that on average for the control there were 35.275 $\frac{cfu}{cm^2}$. 1,180 were plated on each side, but 35.275 survived the process. This is within the same order of magnitude as the above goal value, showing that this test did replicate the number of bacteria one might actually find on a toy. The average number of experimental colonies per side was 0.777 ± 0.306 $\frac{cfu}{cm^2}$for a 95% confidence interval of 0.471 to 1.083. This corresponds to a 97.8% reduction.

While a 97.8% reduction is not a 99.9% reduction, this is not a failure of the machine. This test was run right on the margin in terms of time, with no factor of safety beyond what the research said was needed for a 3-log reduction. Every testing environment and machine is different. The first test run proved that these bacteria are not just resistant to UV completely, but that more UV dosage does in fact just keep killing the bacteria. In order to make that jump from 97.8 to 99.9, the machine just needs to run longer. Further testing can discover what that exact length of time is.

7.3 Evaluation Against Technical Specifications

Table 7.1: Technical Specification Evaluation

Specification	Metric
1. Solution must create 3-log reduction against *B. subtilis* and *E. coli*.	99.9%, achieved using 69 mJ/cm^2
2. All external surfaces must exhibit 3-log reduction in contamination.	99.9%, achieved using 69 mJ/cm^2
3. Solution uses Kr-Cl Excimer lamp.	222 nm
4. Solution must fit in a classroom.	<6 cu. ft.
5. Solution must be quick.	<1 hr.
6. Device must be safe to exist in preschool classrooms.	No reachable sharp parts, or pinching hazards.
7. Device must not disrupt classroom environment.	<52 db
8. Solution able to be loaded and unloaded quickly.	<10 seconds
9. Sanitation Machine must accommodate toys of a range of sizes.	Minimum: 2.5 cm^2 Maximum: 3500 cm^2
10. Solution powered through a typical wall-outlet.	120V
11. Solution requires no human interaction between start and finish.	-

All of the completed testing allows evaluation of the final device against the original technical specifications. The critical specifications for this device are numbers one and two: the solution must create a 3-log reduction against the target bacteria on all external surfaces. Specification 1 is colored yellow, which is defined to mean that the spirit of the specification is met, if not the exact original definition. From the biological testing, *B.subtilis* was not able to be tested, and a 97.8% reduction in *E.coli* was observed. However, from the testing with extremely concentrated bacteria it was possible to conclude that with extra time, further sanitation would occur. Therefore, the spirit of this specification is met because if the machine is run for enough time, a 99.9% reduction can be achieved. Further testing is required in order to find out the exact amount of time the machine needs to be run. The second specification has to deal with all external surfaces exhibiting this 99.9% reduction, and this specification was met. The sticker and biological testing both demonstrated that all sides of objects placed in different parts of the machine were being fully sanitized.

The rest of the specifications have less to do with core machine functionality and more to do with usability as a consumer product. The device does use a 222 nm Kr-Cl excimer lamp, which emits wavelengths that are safe for human skin and eye exposure should they somehow become exposed. Specification 4 is again yellow, as while the solution still clearly fits within a classroom, it is slightly larger than it was originally planned to be. The height of the machine had to be increased in order to account for the results of the shadow testing and make sure the device would be effective. Specification 5 is the only specification that is currently really not being met. The original intention was for the machine to be usable within an hour, so that a teacher could run it between classes, or while the children are at recess etc. Currently, the data suggests that it would take between five and eight hours for the machine to run successfully. This takes it from being a during the day activity to an overnight one. However, the machine is very scalable. It can still function effectively overnight by being much larger and installed in a back room where all of the teachers could use it concurrently overnight.

The power safety shut off button keeps the machine safe by not allowing the lights to be on or any part of the machinery to move unless the lid is on and the box is enclosed, satisfying specification six. The next specification has to do with noise. The original specification was based off of the average sound of a dishwasher, at 52 db. However, it was discovered that the Active Learning Labs HVAC system leaves that room at 62 db at its quietest. My machine working increased this sound level to an average of 70 db. However, the walls of the machine are currently made of foam core attached to a metal frame. If the internal parts had been placed in a complete airtight box, the overall noise would have been dampened significantly. Furthermore, the sound specification was used mainly within the pugh matrix to aid in deciding on what mechanism to use to move the toys. The one chosen was one of the quietest of all the ideated designs.

The solution is able to be loaded and unloaded quickly, as the wire mesh guards attached to the moving platform prevent any toys from falling into the bowels of the machine. The machine also can fit toys of a range of sizes. It was designed around a 4-dot Lego, to make sure that small toys would not fit through the slats, and this specification was met. The platform size was based off of being able to fit 15 plush toys. In hindsight, a platform of that size with the full device still being beneath 6 cu. ft. is virtually impossible. The platform still does fit larger toys, and has an area of 2100 cm^2. Finally, the solution is powered through a typical wall outlet which gives it much versatility, and it requires zero human interaction between start and finish.

Chapter 8

Conclusions

As seen above, this device satisfies the vast majority of the specifications set out for it. Every detail of the design has been thoroughly thought through and implemented with care. Besides time, which is a usability constraint, every other specification has been reasonably met. This machine improves upon the existing devices by making sure to accurately sanitize all sides of an object. Furthermore, it is easy to use for teachers, and cuts down on the time that they have to spend every day sanitizing toys. This device improves the lives of teachers, children, and their parents. Overall, it is safe, useful, and effective in the way that it was intended to be.

8.1 Future Work

There are two categories of future work that are important for this machine. First, further biological testing is required in order to know the exact run time of the machine needed in order to achieve a 99.9% reduction in relevant bacteria, fungi, and viruses. The vast majority of the microbes researched require far less than 69 $\frac{mJ}{cm^2}$ and have a significant safety factor in the machine, but the microbes with high fluence requirements need to be tested in order to ensure the machine is effective with all of the target microbes.

The other large category of future work goes into reducing the run time of the machine.

Figure 8.1: LED Testing Setup within the Device

There are several solutions here. The two 222 nm Kr-Cl Excimer lamps that were used were a donation from Ushio America. If more of these lamps had been available they could have been installed in additional locations in order to increase the total fluence being received by objects at any given time, reducing the cycle time.

Furthermore, germicidal UV LED's exist in several other common wavelengths, including 254 nm. The vast majority of the research into 222 nm technology has been completed since 2018, so it is a reasonable assumption that 222 nm UV LEDs will exist in the near future.

In order to investigate the effects of adding LED lights, an experiment was run with visual light LEDs, as seen in Figure 8.1. An online calculator was able to convert lux at 555 nm to $\frac{mJ}{cm^2}$, removing concerns about the energy of different wavelengths [44]. 555 nm corresponds to green light. Two rows of LED's were installed in the machine to add light intensity. Measurements were made with a lux meter. In order to meet the specification, there must be 69 $\frac{mJ}{cm^2}$ delivered in 60 minutes, or 1.17 $\frac{mJ}{cm^2}$ per minute. The worst case scenario with the current lights is 20 $\frac{mJ}{cm^2}$ in 80 minutes, or 0.25 $\frac{mJ}{cm^2}$ per minute. This meant the desired added amount of fluence in order to meet the spec was 0.92 $\frac{mJ}{cm^2}$ per minute, or .000015278 W, which corresponds to 104.34 lux [44]. Of all of the measurements taken with the lux meter at different angles and in different positions, all of the measurements were far above this threshold, with the lowest measured flux being 115 lux. This testing further proved that once 222 nm UV LEDs are available, the machine run time will be able to be brought down to within the specification range fairly easily.

8.2 Impact

The sanitation machines already on the market are not adequately accessible, effective, or easy to use. My machine does not leave any residues on the toys, nor does it leave any portion of the toys unsanitized. It solves all of the problems presented by previous iterations of UV boxes. It is easy to use, and requires extremely little interaction from the busy teachers throughout their day. This machine would be extremely useful in preschools and daycares around the world. Children need to be healthy in order to learn, and this machine helps them do that. Overall, Good Clean Fun is a safe, useful and effective solution to the problem it was designed to solve.

Appendices

Appendix A

Existing Product Examples

Table A.1: Existing Product and Service Examples

Product Example	Key Characteristics	Reference
ZONO Disinfecting and Sanitizing Cabinets	36 sq. ft. UV and Ozone disinfection cabinet. 99.99% kill rate of common bacteria and viruses in 30 minutes. Price available upon request.	[17]
JJ CARE UV Sanitizer Box	1 sq. foot, and able to be folded for easy storage. Reflective tin foil interior. Uses UV light to sanitize.	[14]
Munchkin Nursery and Toy UV Sterilizer Bag	1 sq. foot, meant for one toy at a time or small items such as sunglasses. Uses UV leds. Market leader for portable sanitizers.	[15]
Wabi Baby Touch-Panel Dual-Function UV-C Sanitizer Sterilizer & Dryer	1.5 sq. feet, meant for baby bottles. Eliminates 99.9% of bacteria. Has a drying mechanism too, meant for sanitization after washing.	[16]
Spraygenix Disinfecting Atomizer With Nano UV Light	Uses UV and disinfectant spray. 99.9% disinfection rate. Handheld.	[20]
Victory Cordless Electrostatic Backpack Sprayer	Backpack that uses disinfectant spray. $2500.	[19]
SaniCart	Fog machine that fogs disinfectant into a room to cover all surfaces. Room must be evacuated for use.	[18]

Product Example	Key Characteristics	Reference
Corvus Janitorial	Service for hire to come clean toys in preschools and daycares overnight.	[21]
Germinator	Service for hire to come clean toys in preschools and daycares overnight.	[22]

Appendix B

Bill of Materials

Table B.1: Source Parts and Purchased Materials

Part Name	Part Number	Link	Quantity	Cost per Item
Nema 17 Stepper Motor	n/a	Amazon	2	29.99
Stepper Motor Driver	A4988	Amazon	1 pack of 5	10.99
400 mm Tr8x8 Lead Screw	n/a	Amazon	1 pack of 2	15.59
Linear Motion Shaft	6112K46	McMaster Carr	4	22.16
Linear Bearings	n/a	Amazon	1 pack of 12	10.95
Aluminum Plate($\frac{1}{4}in$)	88895K111	McMaster Carr	1	124.30
Aluminum Plates ($\frac{1}{16}in$)	8973K604	McMaster Carr	3	37.78
Wire Mesh	9217T31	McMaster Carr	1 ft.	1.26
Lid Corner Brackets	1556A24	McMaster Carr	2	0.67
Lid Handle	1645A2	McMaster Carr	1	1.60
Momentary Buttons	n/a	Amazon	1 pack of 5	8.99
Aluminum Tape	7616A31	McMaster Carr	1	21.44
Limit Switches	SS-5GLT	Digi-Key	2	2.61
ACDC Converter	n/a	Amazon	1	20.99
UVC Dosimeter Stickers	n/a	Prolamp Sales	35	3.50
Total Spent:				**$607.13**

Table B.2: Fabricated and Donated Parts and Materials

Part Name	Material	Fabrication Method	Quantity	Material Source
1x1 80-20	Aluminum	Cut to Length	5 24in 2 22in 2 4in 2 18 in 2 16 in	ALL
47065T236 Silver Corner Bracket	Aluminum	n/a	16	ALL
3136N157 Outside Corner Bracket	Aluminum	n/a	4	ALL
Floor	$\frac{1}{4}in$ Acrylic	Laser Cutter	1	ALL
Front Side	Foam Core	Laser Cutter	1	ALL
Back Side	Foam Core	Laser Cutter	1	ALL
Side Sides	Foam Core	Laser Cutter	2	ALL
Top Flap	$\frac{1}{4}in$ Acrylic	Laser Cutter	2	ALL
Lid Top	$\frac{1}{4}in$ Acrylic	Laser Cutter	1	ALL
Lid Front	$\frac{1}{4}in$ Acrylic	Laser Cutter	1	ALL
Moving Platform	$\frac{1}{4}in$ Aluminum	Water Jet	1	Purchased
Stationary Upright	$\frac{1}{16}in$ Aluminum	Water Jet	104	Purchased
Stationary Length	$\frac{1}{16}in$ Aluminum	Water Jet	52	Purchased
Motor Mount	3D Print	3D Print	2	ALL
Motor Mount Lid	3D Print	3D Print	2	ALL
Shaft Mount	3D Print	3D Print	4	ALL
Shaft Top Stabilizer	3D Print	3D Print	4	ALL
Bearing Holders	3D Print	3D Print	4	ALL
Bottom Stationary Platform Support	3D Print	3D Print	4	ALL
Top Stationary Platform Support	3D Print	3D Print	4	ALL
Spacer Supports	3D Print	3D Print	4	ALL
Light Mount	3D Print	3D Print	2	ALL
Floor Brackets	3D Print	3D Print	9	ALL
Arduino MKRZero	n/a	n/a	1	ALL
222 nm UVC Lights and Inverters	n/a	n/a	2	Ushio America

Appendix C

Arduino Code

```
/*
Katie Barkin Thesis Code

When loaded on the arduino, this code runs the Good Clean Fun machine
  autonomously at the input of the mechanical buttons.
*/
const boolean debug = false;
const int stepPin = 5;
const int dirPin = 4;
const int stepPin2 = 14;
const int dirPin2 = 13;
const int downPin = 11;
const int upPin = 12;
const int psobutton = 10;
const int startpin = A2;
const int resetpin = 6;
const int lswitchup = 8;
const int lswitchdown = 9;
const int lighttrigger = 2;
const int lightmonitor1 = 1;
const int lightmonitor2 = 0;
int psobuttonState;
int downbuttonState;
int downlastbuttonState;
int upbuttonState;
int uplastbuttonState;
int resetbuttonState;
```

```
int CurState;
int counter;
volatile boolean Lid;
volatile boolean Start;
volatile boolean reset;
unsigned long StartTime = 0;
volatile boolean done;
const int cyclesperfluence = 2;
const int redpin = A4;
const int bluepin = A3;

void setup() {
  pinMode(stepPin,OUTPUT);
  pinMode(stepPin2,OUTPUT);
  pinMode(dirPin,OUTPUT);
  pinMode(dirPin2,OUTPUT);
  pinMode(bluepin,OUTPUT);
  pinMode(redpin,OUTPUT);
  pinMode(upPin, INPUT);
  pinMode(downPin,INPUT);
  pinMode(psobutton, INPUT_PULLUP);
  pinMode(startpin,INPUT_PULLUP);
  pinMode(lswitchup,INPUT_PULLUP);
  pinMode(lswitchdown,INPUT_PULLUP);
  pinMode(resetpin, INPUT_PULLUP);
  pinMode(lighttrigger,OUTPUT);
  pinMode(lightmonitor1, INPUT_PULLUP);
  pinMode(lightmonitor2, INPUT_PULLUP);
  psobuttonState = 0;
  downbuttonState = 0;
  downlastbuttonState = 0;
  upbuttonState = 0;
  uplastbuttonState = 0;
  resetbuttonState = 0;
  attachInterrupt(digitalPinToInterrupt(startpin), change, RISING);
  attachInterrupt(digitalPinToInterrupt(resetpin), changer, RISING);
  for (int j = 0;j<5;j++){//When power is turned on, indicator light should blink for 10 seconds.
    //This is in order to delay the loop from starting as the current inrush can overwhelm the mechanical
    //switches and start things inadvertently.
    digitalWrite(redpin,HIGH);
    digitalWrite(bluepin,LOW);//blue light on
```

```
    delay(1000);
    digitalWrite(bluepin,HIGH);//blue light off
    delay(1000);}
  reset = false;
  CurState = 1;}

void StartTimer() {//when called records the time so that calculations about elapsed time can occur
  StartTime = millis();}

void change(){//when isr is flagged changes variable to true
  Start = true;}

void changer(){//when isr is flagged changes variable to true for reset button
  reset = true;
}

bool checkStart(){//checks to see if isr variable is true, if it is then resets it otherwise returns value
  if (Start == true){
    Start = false;
    return true;}
  else{
    return false;}}

bool checkReset(){//checks to see if isr variable is true, if it is then resets it otherwise returns value
  if (reset == true){
    reset = false;
    return true;}
  else{
    return false;}
  }


void up(void){//moves both motors up 10 steps (18 degree turn)
  digitalWrite(dirPin,LOW);
  digitalWrite(dirPin2,LOW);
  for (int y=0;y<10;y++){
    digitalWrite(stepPin,HIGH);
    digitalWrite(stepPin2,HIGH);
    delay(1);
    digitalWrite(stepPin,LOW);
    digitalWrite(stepPin2,LOW);
```

```
    delay(1);}
  return;}

void down(void){//moves both motors down 10 steps (lead screw 18 degree turn)
  digitalWrite(dirPin,HIGH);
  digitalWrite(dirPin2,HIGH);
  for (int y=0;y<10;y++){
    digitalWrite(stepPin,HIGH);
    digitalWrite(stepPin2,HIGH);
    delay(1);
    digitalWrite(stepPin,LOW);
    digitalWrite(stepPin2,LOW);
    delay(1);}
  return;}
void lighton(void){//turns on light using signal wire
  digitalWrite(lighttrigger,HIGH);
  return;}
void lightoff(void){//turns off light using signal wire
  digitalWrite(lighttrigger,LOW);
  return;}
void red(void){//turns indicator LED red
  digitalWrite(redpin,LOW);
  digitalWrite(bluepin,HIGH);}
void blue(void){//turns indicator LED blue
  digitalWrite(redpin,HIGH);
  digitalWrite(bluepin,LOW);}
void purple(void){//turns indicator LED purple
  digitalWrite(redpin,LOW);
  digitalWrite(bluepin,LOW);}


void loop() {
  if (debug)   { //some important variables to help orient in the case something isnt working
      Serial.print("Current State = ");
      Serial.println(CurState);
      Serial.println(Start);
      Serial.println(psobuttonState);
  }
  checkStart();//makes sure start is not triggered
  psobuttonState = digitalRead(psobutton);//checks power shut off button state
  switch (CurState) {
    case 1://standby mode
```

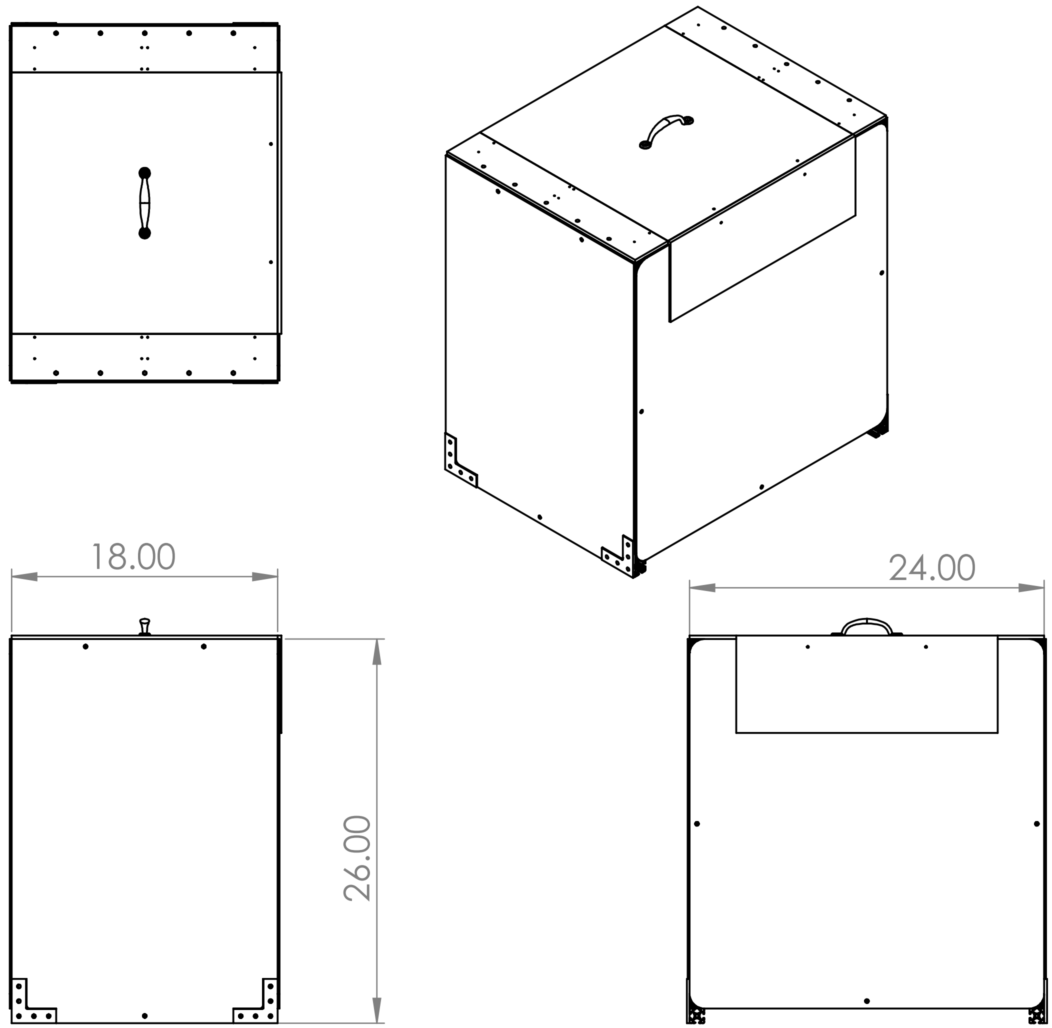
```
      blue();
      if (psobuttonState == LOW){//if lid is on
        resetbuttonState = digitalRead(resetpin);//check states and define variables
        if (checkStart()){//if start button has been pressed initialize counter and go to state 2
          checkStart();
          counter = 1;
          CurState = 2;}
        else if (checkReset()){//if reset button has been pressed go to state 6 to reset
          CurState = 6;}
        else{
          CurState = 1;}}//otherwise stay in state 1
      else{
        CurState = 1;}
      break;
    case 2:
      purple();//program is running so light should be purple
      checkStart();
      if (psobuttonState == LOW){//if lid is still on
        if (digitalRead(lswitchdown) == HIGH){//if light is not at the bottom yet go down
          down();//go down a tiny bit then go back through to make sure lid is still on
          CurState = 2;}
        else{
          CurState = 3;}}//once light gets to the bottom go to state 3
      else{
        CurState = 1;}//if lid is taken off exit to state 1
      break;
    case 3:
      purple();//program running so light is purple
      checkStart();
      if (psobuttonState == LOW){//if lid is on
        lighton();//turn on light
        StartTimer();
        CurState = 4;}//move on
      else{
        CurState = 1;}//if lid is taken off exit to state 1
      break;
    case 4:
      checkStart();
      if (psobuttonState == LOW){//if lid is on
```

```
      unsigned long elapsedTime = millis()-StartTime;//define how much time has passed
      if ((elapsedTime >= 10000) && (elapsedTime <= 300000)){//if that time is long enough for light monitors to be on
        if (lightmonitor1 == LOW){//check monitors to make sure no malfunction with the light
          if (lightmonitor2 == LOW){
            purple();
            CurState = 4;}//stay here with light on
          else{
            CurState = 1;}}//if there is malfunction with the lights exit to state 1
        else{
          CurState = 1;}}//if there is a malfunction with the lights exit to state 1
      else if ((elapsedTime >= 300000) && (elapsedTime <= 600000)){//once the five minutes have passed,
        //the light should turn off and wait for another five minutes to pass the duty cycle
        purple();
        lightoff();
        CurState = 4;}
      else if (elapsedTime >= 600000){//once the full ten minutes have passed
        if (counter >= cyclesperfluence){//if enough cycles have run
          if (digitalRead(lswitchup) == HIGH){//check if the platform is at the top or not
            CurState = 5;}//if its not at the top raise it up
          else{
            done = true;//if it was at the top that means that was the second cycle and so its done,
            CurState = 1;}}//exit out to standby state 1
        else{
          counter++;//if enough cycles have not run increase the counter and turn the light back on
          CurState = 3;}}
      else{//if ten seconds hasnt passed yet just stay there, monitors are not reliable unitl 10 seconds
        purple();
        CurState = 4;}}
    else{
      lightoff();//if the lid is taken off turn the light off and exit to state 1
```

```
        CurState = 1;}
      break;
    case 5:
      purple();//program is running so indicator is purple
      checkStart();
      if (psobuttonState == LOW){//if lid is on
        if (digitalRead(lswitchup) == HIGH){//if platform is not yet at the top
          up();//lift it up
          CurState = 5;}//return here so it checks every few milliseconds while raising
        else{
          counter = 1;//once it gets to the top reset the cycle counter and start the process over
          CurState = 3;}}//turn on light
      else{
        CurState = 1;}//if lid is taken off exit to state 1
      break;
    case 6:
      red();//turn red while reset program is running
      checkReset();//make sure reset isr is reset
      if (psobuttonState == LOW){//if lid is on
        if (digitalRead(lswitchup) == HIGH){//if platform is not all the way up
            up();//go up
            CurState = 6;}//come back here checking lid status on the way
          else{
            CurState = 1;}}//if it gets to the top this is over exit to state 1
       else{
        CurState = 1;}//if lid is taken off exit to state 1
    }}
```

Appendix D

Engineering Drawings



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

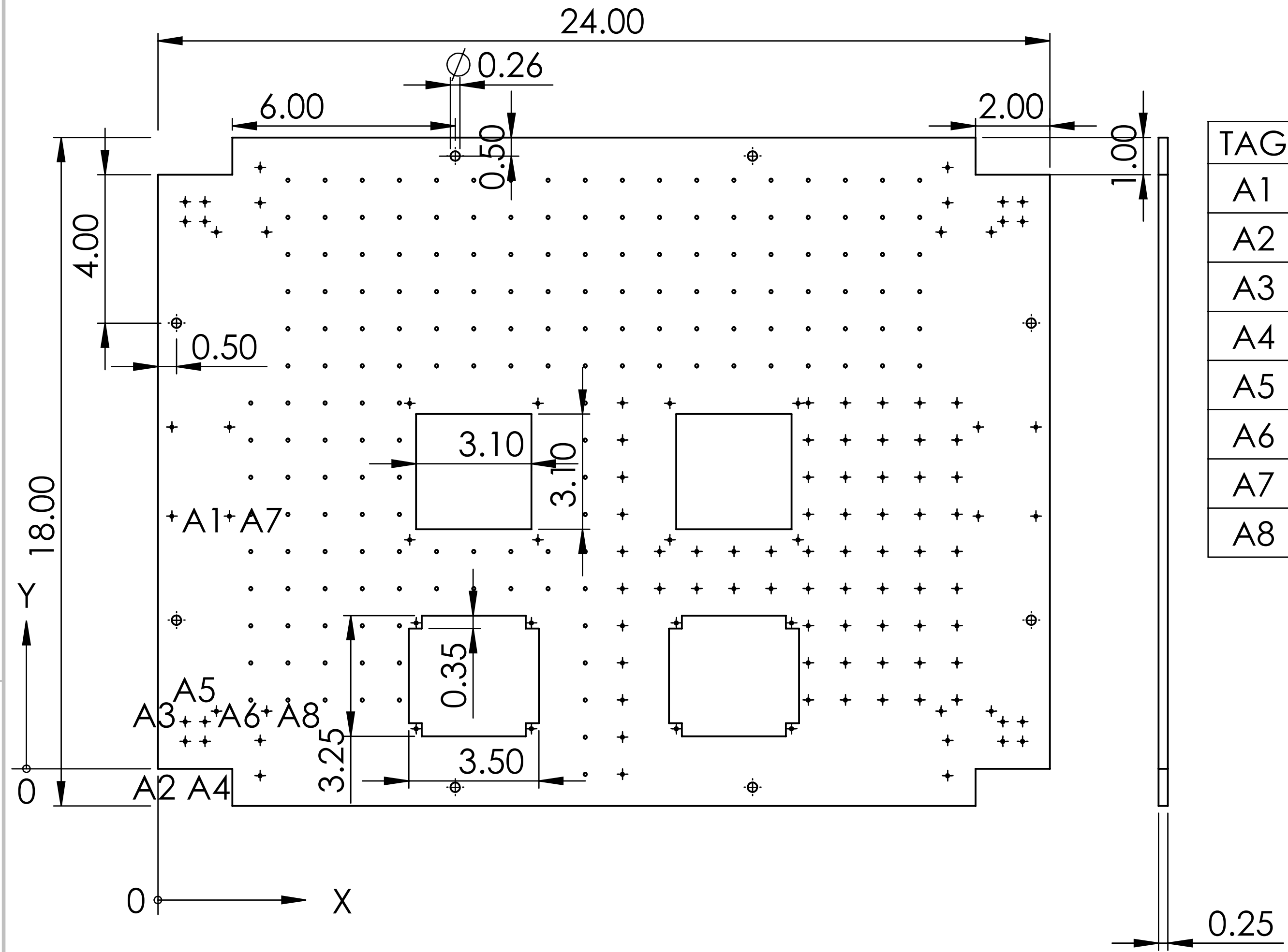
NEXT ASSY	USED ON
APPLICATION	

Katie Barkin

TITLE:

Full Build Assembly

SIZE	DWG. NO.	REV
A		
SCALE: 1:20	WEIGHT:	SHEET 1 OF 1



TAG	X LOC	Y LOC	SIZE
A1	0.38	6.80	Ø0.09 THRU
A2	0.73	0.73	Ø0.09 THRU
A3	0.73	1.27	Ø0.09 THRU
A4	1.27	0.73	Ø0.09 THRU
A5	1.27	1.27	Ø0.09 THRU
A6	1.58	1.55	Ø0.09 THRU
A7	1.93	6.80	Ø0.09 THRU
A8	2.93	1.55	Ø0.09 THRU

NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

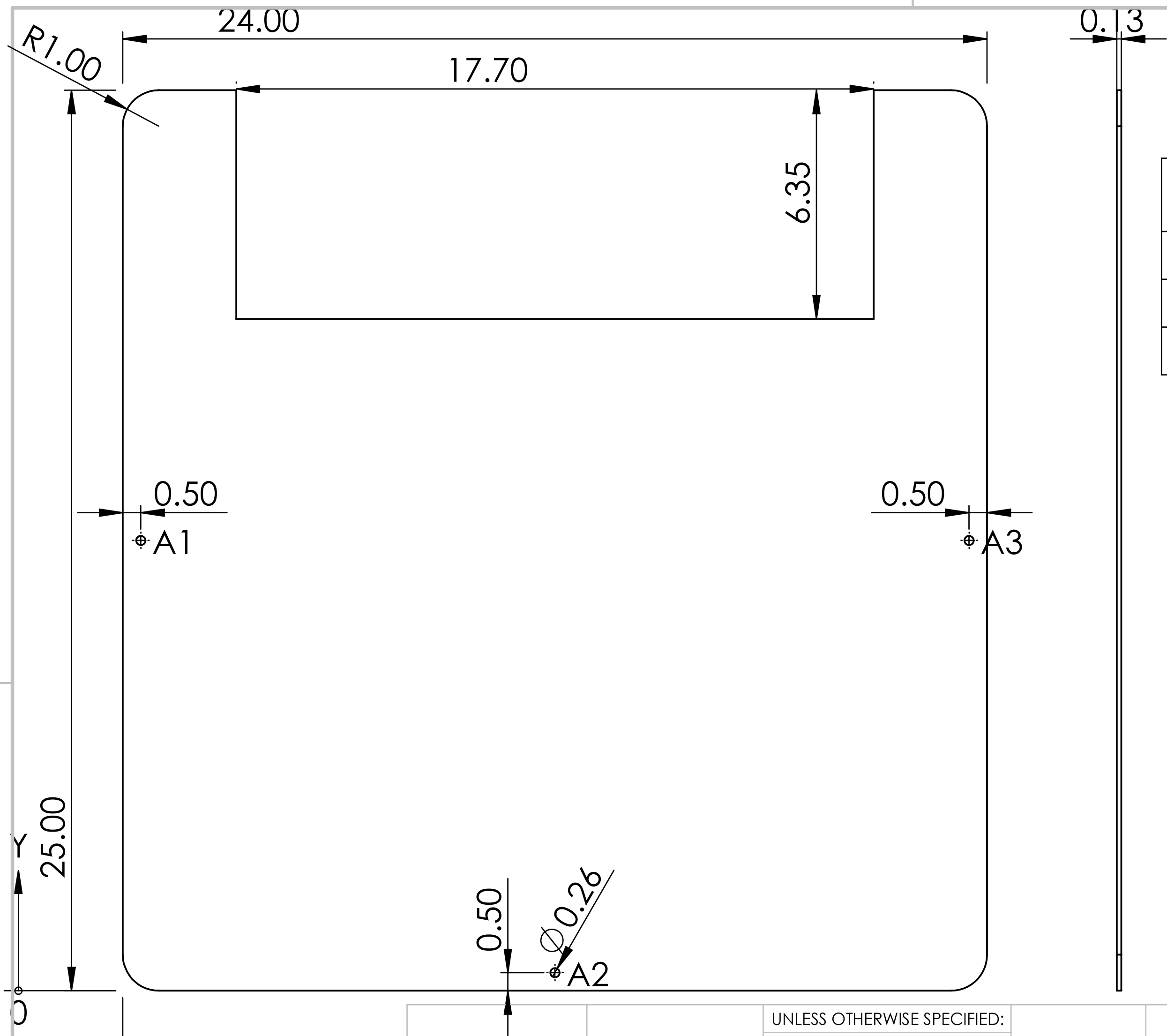
Katie Barkin

TITLE:

Floor

SIZE A | DWG. NO. | REV

SCALE: 1:10 | WEIGHT: | SHEET 1 OF 1



TAG	X LOC	Y LOC	SIZE
A1	0.50	12.50	Ø0.26 THRU
A2	12.00	0.50	Ø0.26 THRU
A3	23.50	12.50	Ø0.26 THRU

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

NEXT ASSY | USED ON

APPLICATION

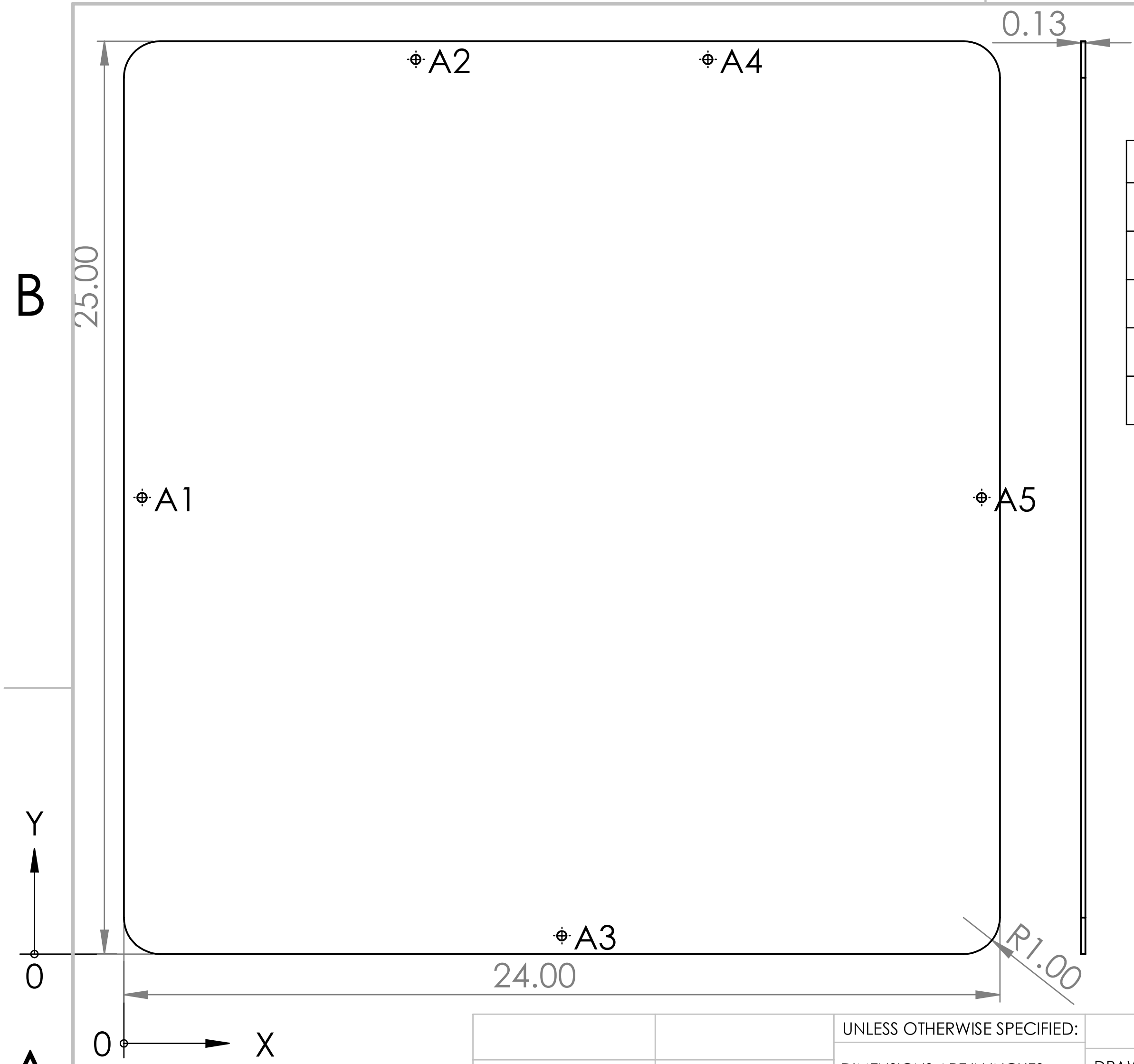
Katie Barkin

TITLE:

Front Side

SIZE A | DWG. NO. | REV

SCALE: 1:10 | WEIGHT: | SHEET 1 OF 1



TAG	X LOC	Y LOC	SIZE
A1	0.50	12.50	∅0.26 THRU
A2	8.00	24.50	∅0.26 THRU
A3	12.00	0.50	∅0.26 THRU
A4	16.00	24.50	∅0.26 THRU
A5	23.50	12.50	∅0.26 THRU

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

NEXT ASSY | USED ON
APPLICATION

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

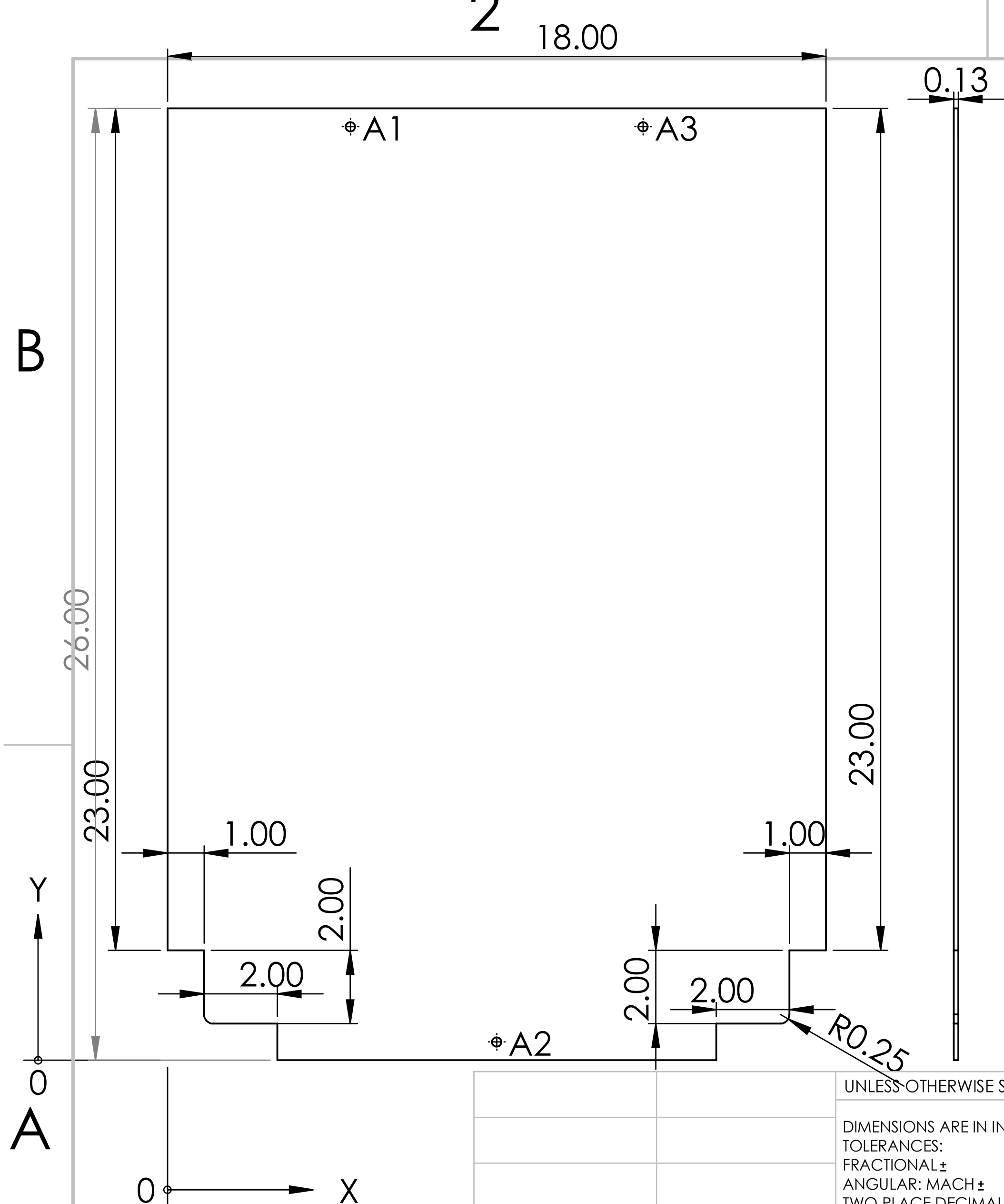
Katie Barkin

TITLE:

Back Side

SIZE A | DWG. NO. | REV

SCALE: 1:10 | WEIGHT: | SHEET 1 OF 1



TAG	X LOC	Y LOC	SIZE
A1	5.00	25.50	∅0.26 THRU
A2	9.00	0.50	∅0.26 THRU
A3	13.00	25.50	∅0.26 THRU

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

NEXT ASSY	USED ON

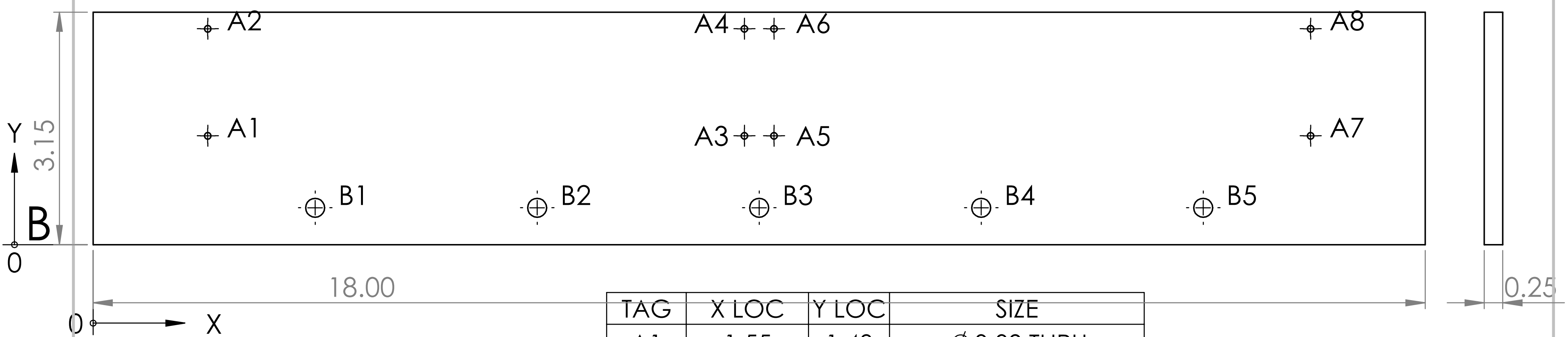
APPLICATION

Katie Barkin

TITLE:

SIZE A | DWG. NO. Side Side | REV

SCALE: 1:10 | WEIGHT: | SHEET 1 OF 1



TAG	X LOC	Y LOC	SIZE
A1	1.55	1.48	∅0.09 THRU
A2	1.55	2.93	∅0.09 THRU
A3	8.80	1.48	∅0.09 THRU
A4	8.80	2.93	∅0.09 THRU
A5	9.20	1.48	∅0.09 THRU
A6	9.20	2.93	∅0.09 THRU
A7	16.45	1.48	∅0.09 THRU
A8	16.45	2.93	∅0.09 THRU
B1	3.00	0.50	∅0.26 THRU
B2	6.00	0.50	∅0.26 THRU
B3	9.00	0.50	∅0.26 THRU
B4	12.00	0.50	∅0.26 THRU
B5	15.00	0.50	∅0.26 THRU

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

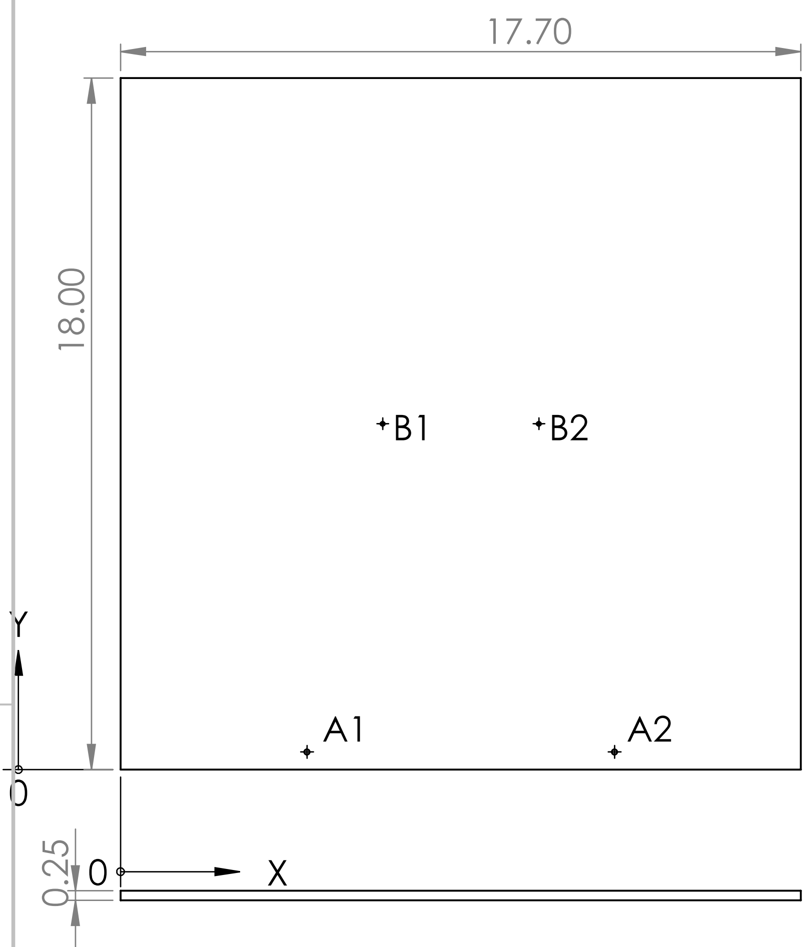
Katie Barkin

TITLE:

Top Flap

SIZE A | DWG. NO. | REV

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



TAG	X LOC	Y LOC	SIZE
A1	4.85	0.46	∅0.14 THRU
A2	12.85	0.46	∅0.14 THRU
B1	6.82	9.00	∅0.11 THRU
B2	10.88	9.00	∅0.11 THRU

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

NEXT ASSY | USED ON

APPLICATION

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Katie Barkin

TITLE:

Lid Top

SIZE A | DWG. NO. | REV

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

TAG	X LOC	Y LOC	SIZE
A1	4.85	0.77	∅0.14 THRU
A2	12.85	0.77	∅0.14 THRU

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

NEXT ASSY | USED ON

APPLICATION

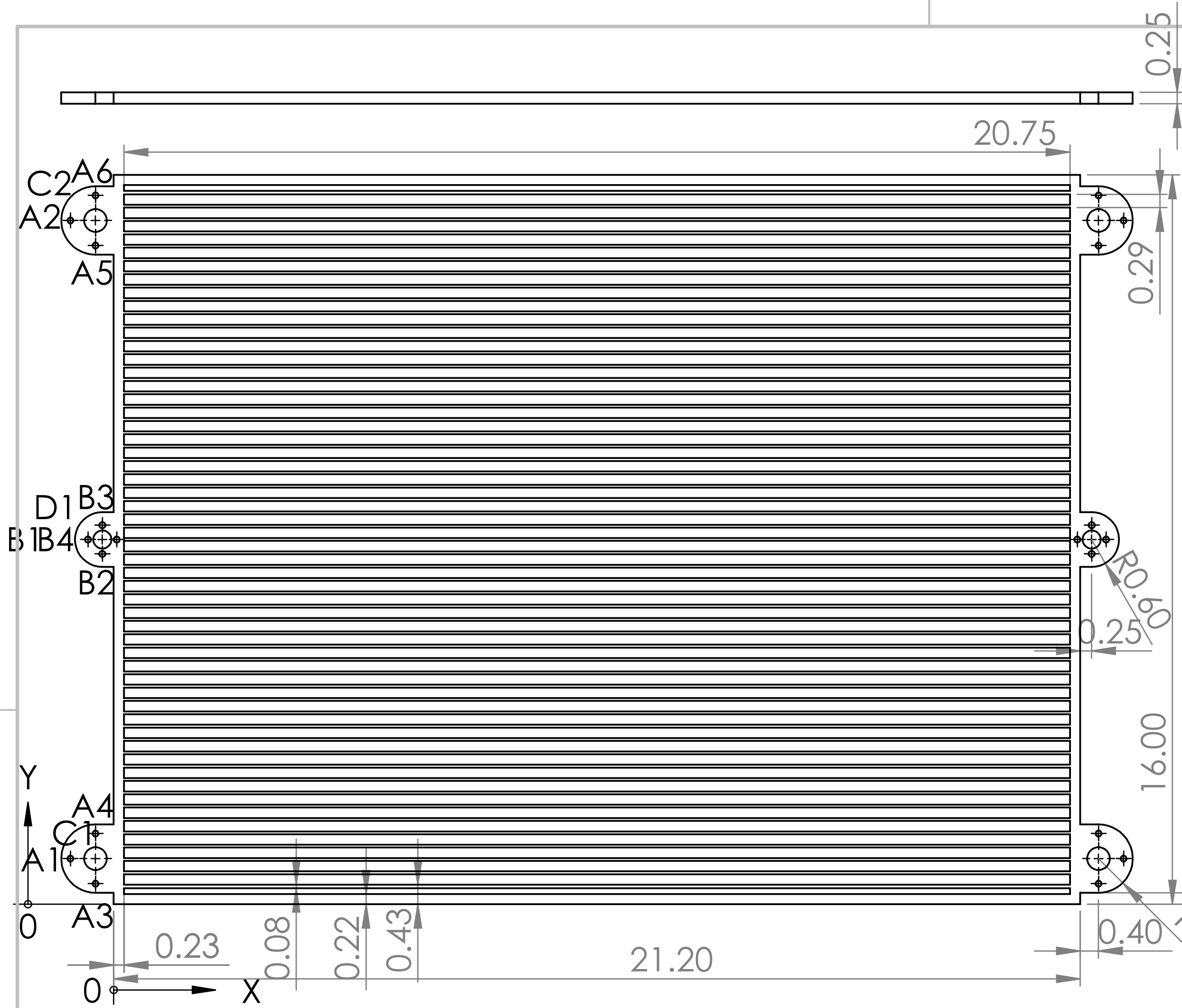
Katie Barkin

TITLE:

Lid Front

SIZE A | DWG. NO. | REV

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



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A2	-0.95	15.00	∅0.13 THRU
A3	-0.40	0.45	∅0.13 THRU
A4	-0.40	1.55	∅0.13 THRU
A5	-0.40	14.45	∅0.13 THRU
A6	-0.40	15.55	∅0.13 THRU
B1	-0.56	8.00	∅0.13 THRU
B2	-0.25	7.69	∅0.13 THRU
B3	-0.25	8.31	∅0.13 THRU
B4	0.06	8.00	∅0.13 THRU
C1	-0.40	1.00	∅0.50 THRU
C2	-0.40	15.00	∅0.50 THRU
D1	-0.25	8.00	∅0.40 THRU

NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

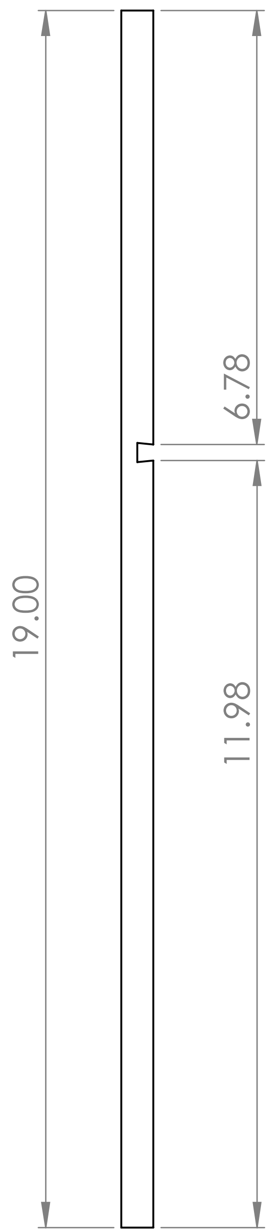
Katie Barkin

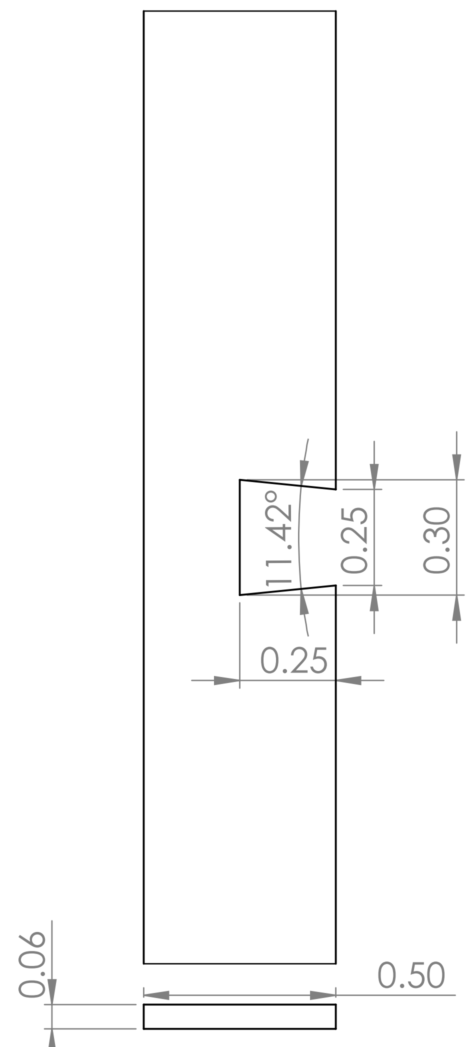
TITLE:

Moving Platform

SIZE A | DWG. NO. | REV

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





PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

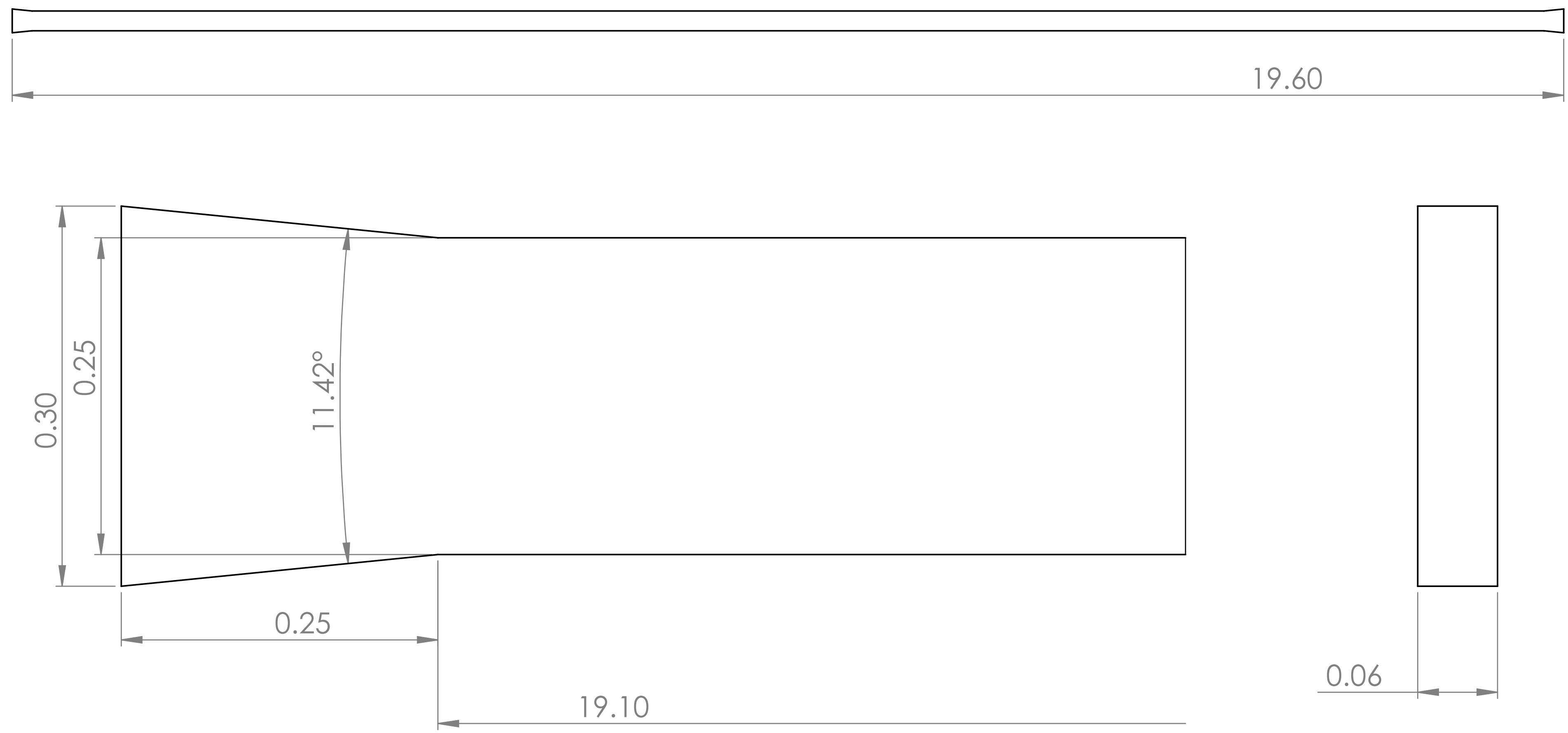
Katie Barkin

TITLE:

Stationary Upright

SIZE	DWG. NO.	REV
A		

SCALE: 1:5 WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Katie Barkin

TITLE:

Stationary Length

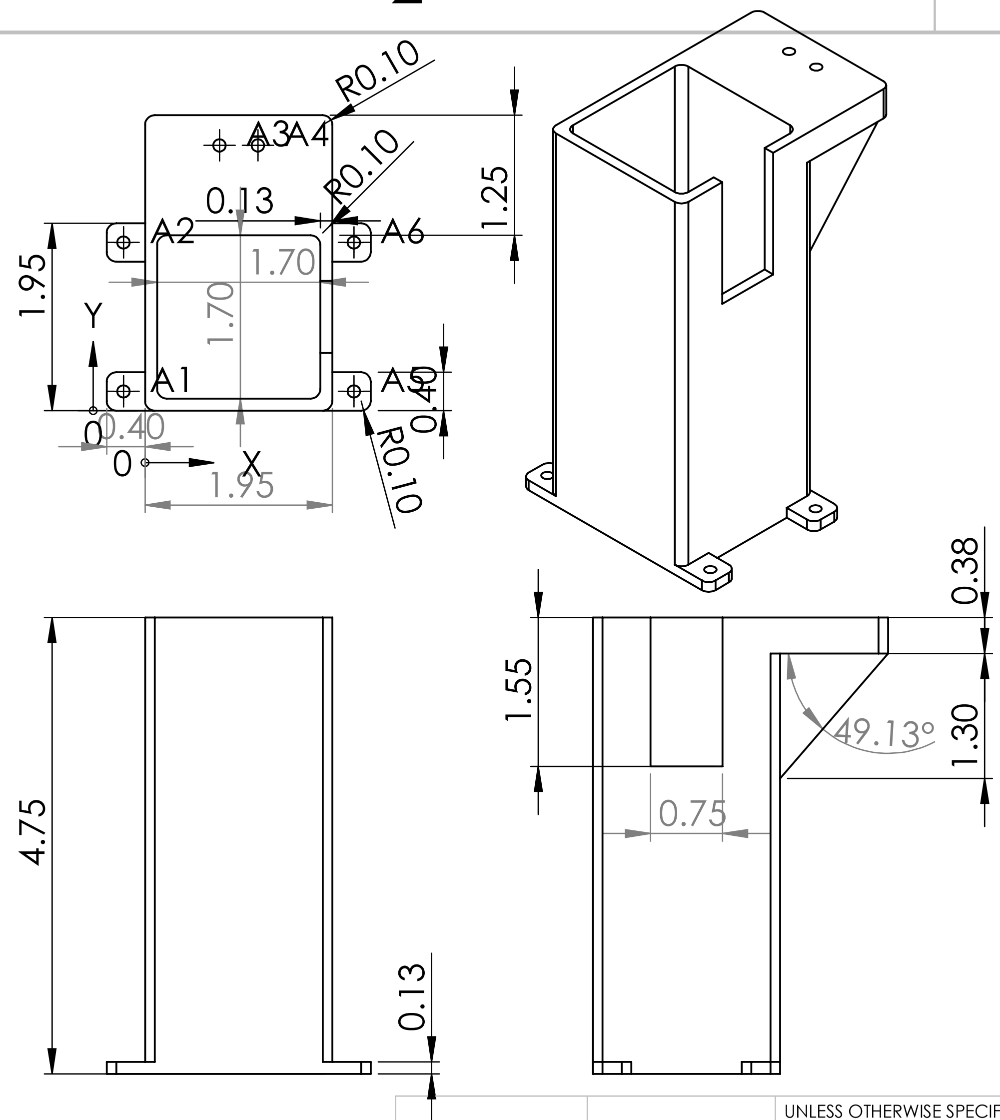
SIZE A | DWG. NO. | REV

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

NEXT ASSY | USED ON

APPLICATION

DO NOT SCALE DRAWING



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A2	-0.23	1.75	∅0.13 THRU
A3	0.78	2.76	∅0.13 THRU
A4	1.18	2.76	∅0.13 THRU
A5	2.18	0.20	∅0.13 THRU
A6	2.18	1.75	∅0.13 THRU

NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

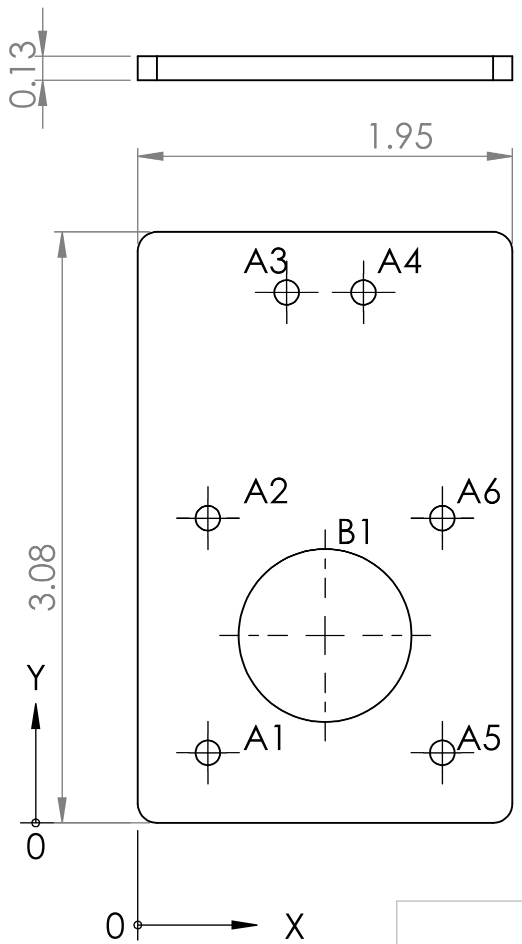
Katie Barkin

TITLE:

Motor Mount

SIZE A | DWG. NO. | REV

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



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A2	0.36	1.59	∅0.13 THRU
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A4	1.18	2.76	∅0.13 THRU
A5	1.59	0.36	∅0.13 THRU
A6	1.59	1.59	∅0.13 THRU
B1	0.98	0.98	∅0.90 THRU

NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

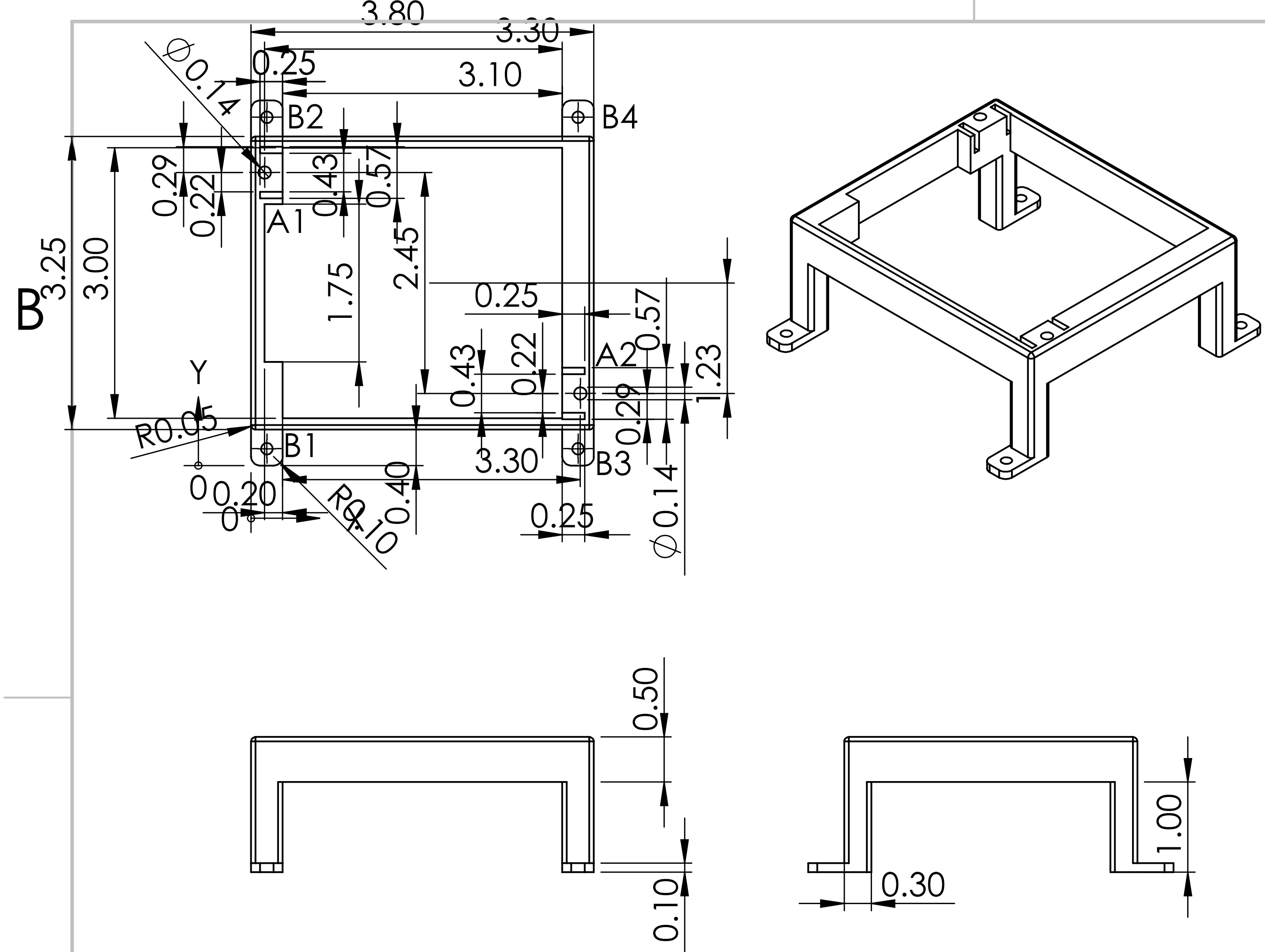
Katie Barkin

TITLE:

Motor Mount Lid

SIZE A | DWG. NO. | REV

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



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A2	3.65	0.80	Ø0.14 THRU
B1	0.18	0.19	Ø0.13 THRU
B2	0.18	3.86	Ø0.13 THRU
B3	3.63	0.19	Ø0.13 THRU
B4	3.63	3.86	Ø0.13 THRU

NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

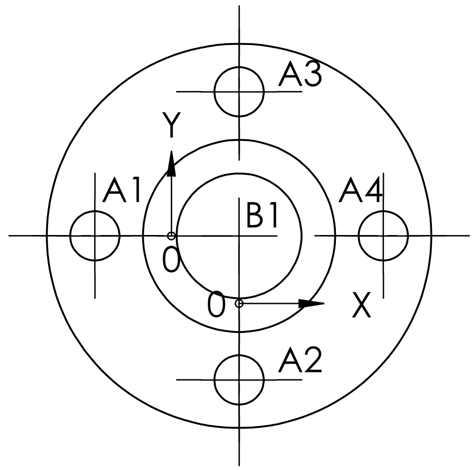
COMMENTS:

Katie Barkin

TITLE:

Light Mount

SIZE A | DWG. NO. | REV
SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1



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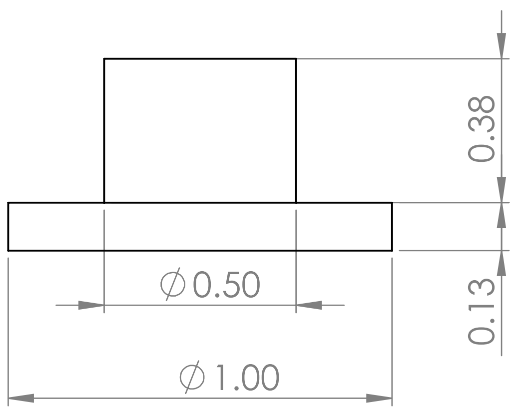
A2	0.00	-0.38	∅0.13 THRU
A3	0.00	0.38	∅0.13 THRU
A4	0.38	0.00	∅0.13 THRU
B1	0.00	-0.00	∅0.33 THRU



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

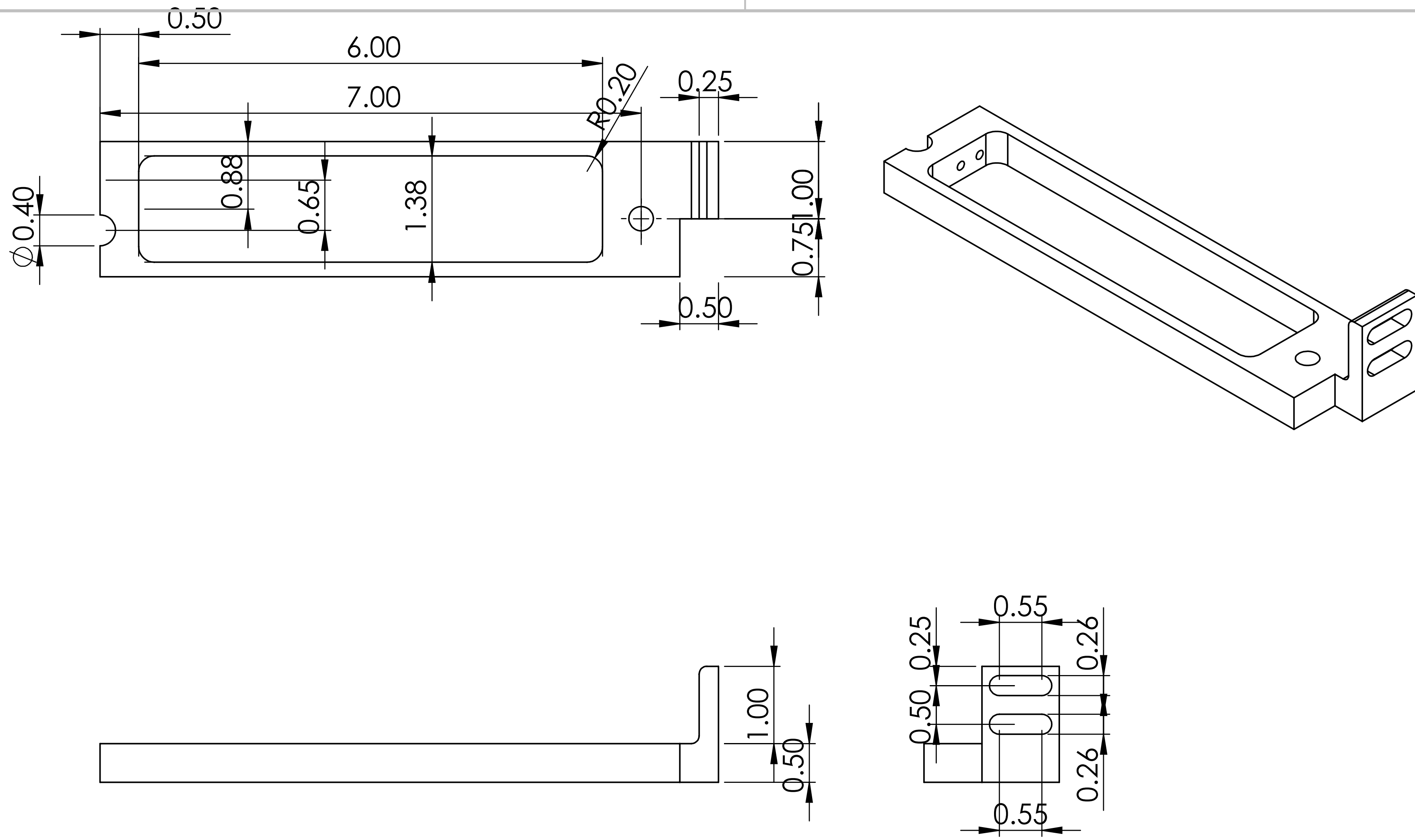
Katie Barkin

TITLE:

Shaft Mount

SIZE A | DWG. NO. | REV

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



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Katie Barkin
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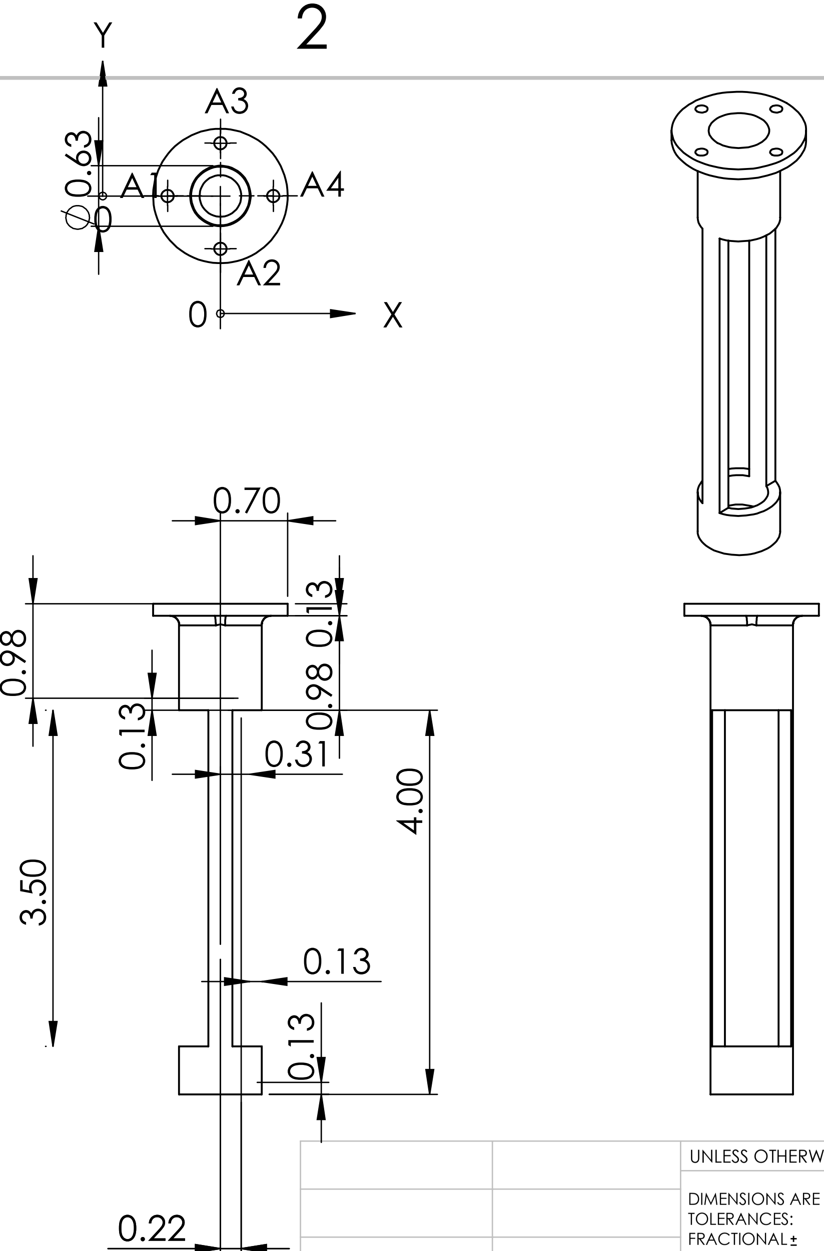
			CHECKED			Shaft Stabilizer
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL	COMMENTS:			SIZE A / DWG. NO. / REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:2 / WEIGHT: / SHEET 1 OF 1



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A2	0.00	-0.55	$\varnothing$0.13 THRU
A3	0.00	0.55	$\varnothing$0.13 THRU
A4	0.55	0.00	$\varnothing$0.13 THRU

NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

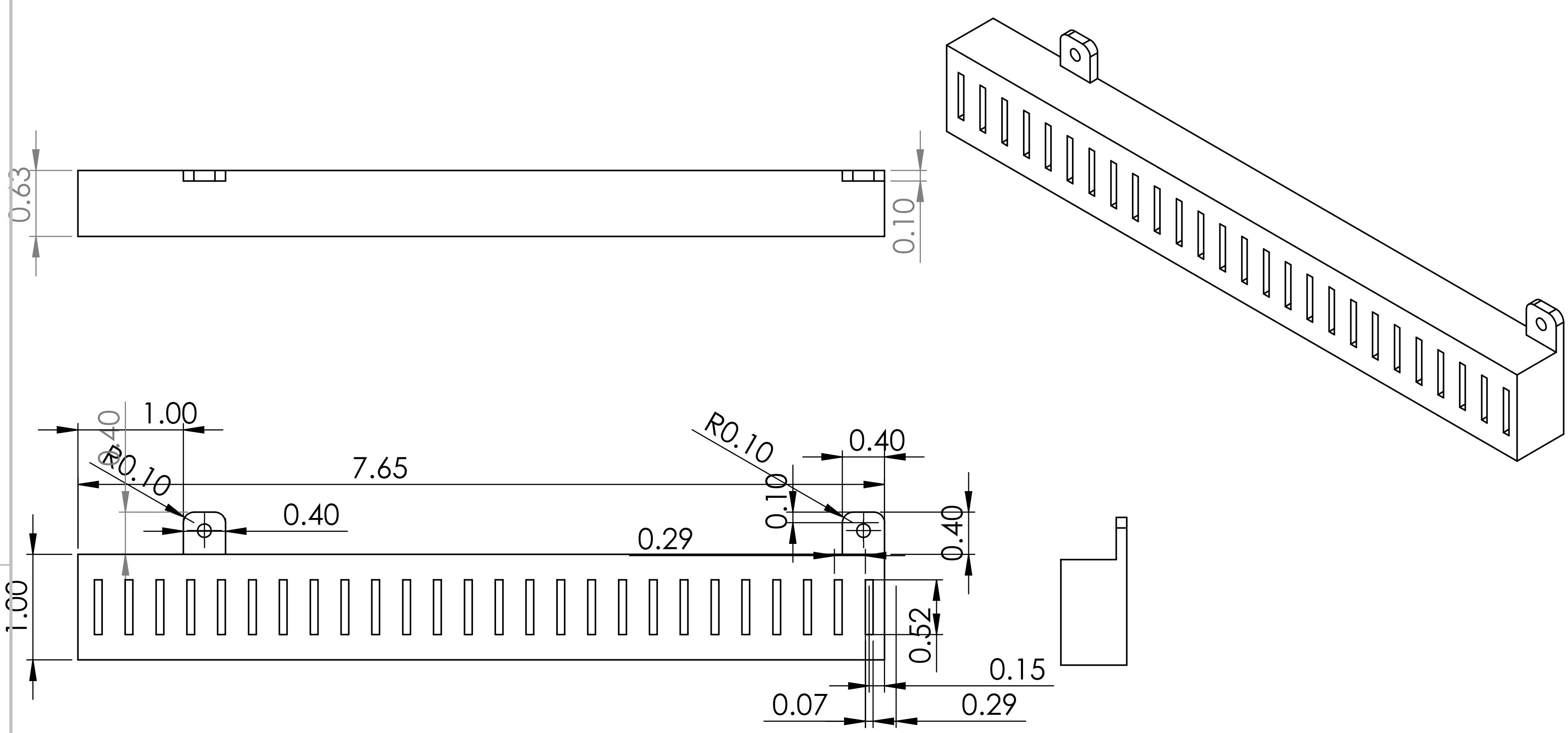
Katie Barkin

TITLE:

Bearing Holder

SIZE A | DWG. NO. | REV

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



PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

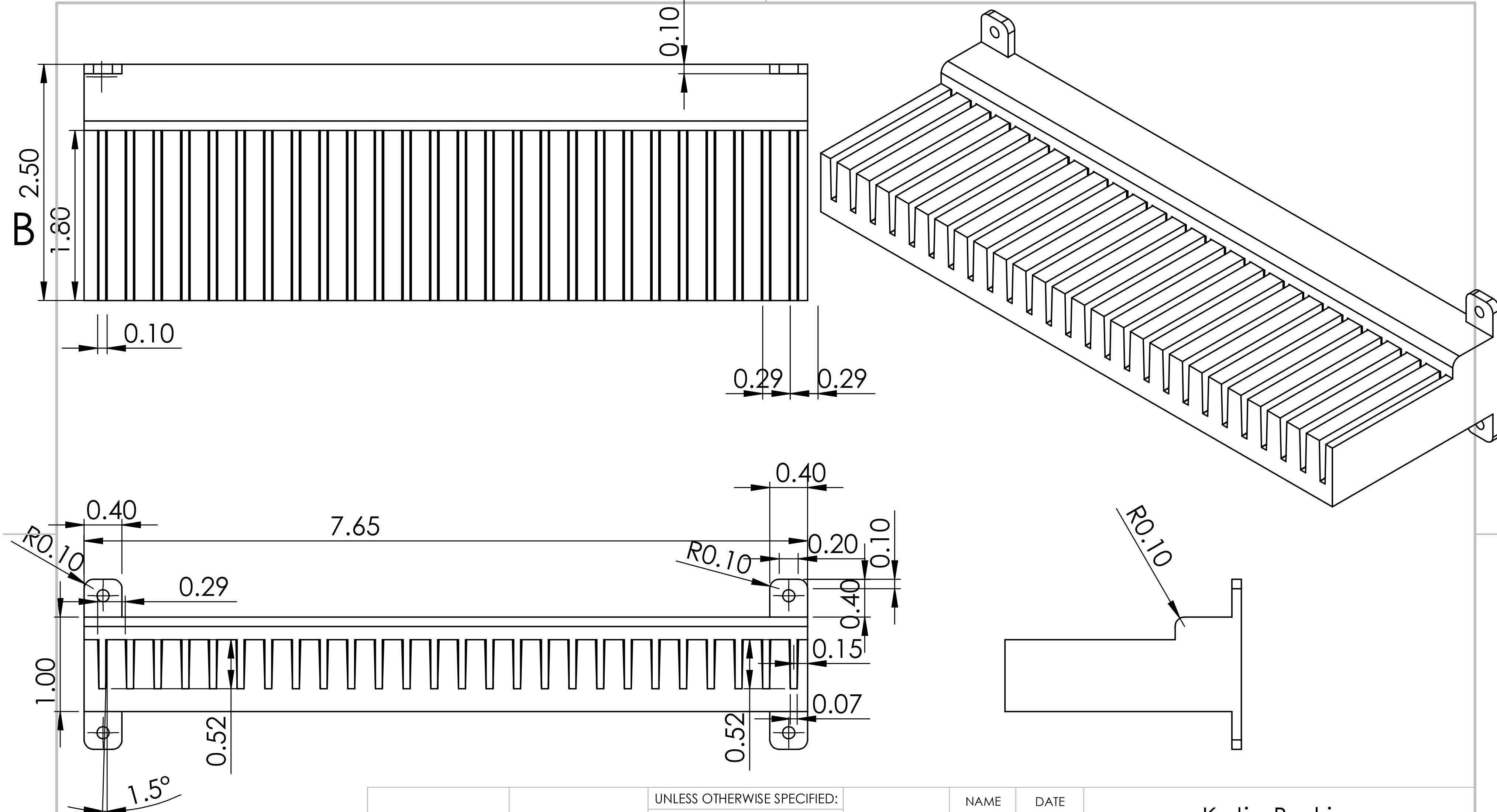
				NAME	DATE
		UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

Katie Barkin

TITLE:

Bottom Stationary Suppor

SIZE	DWG. NO.	REV
A		
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1



PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±		
APPLICATION		INTERPRET GEOMETRIC TOLERANCING PER:		
		MATERIAL		
		FINISH		
		DO NOT SCALE DRAWING		

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

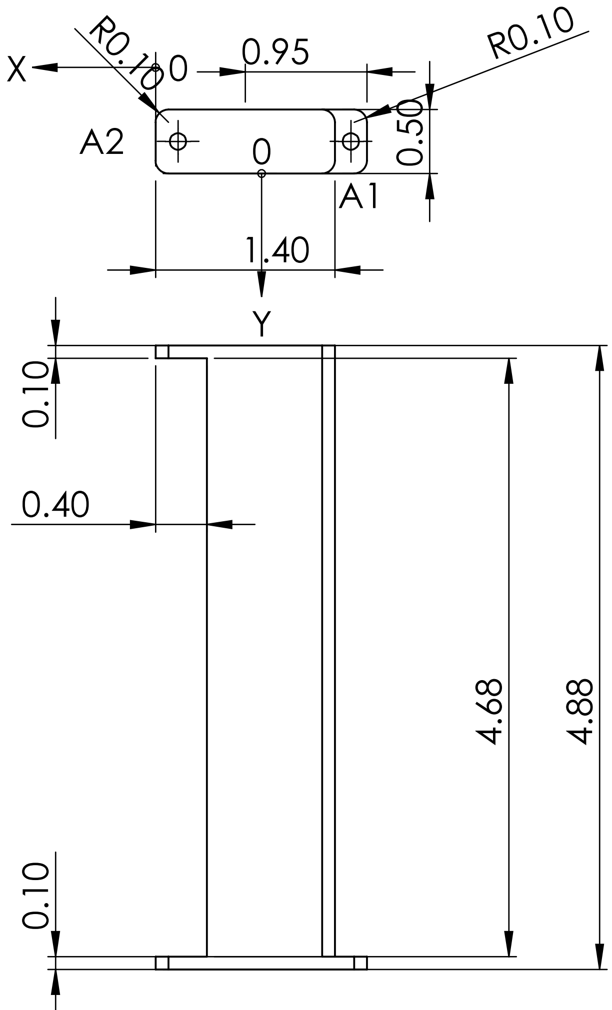
Katie Barkin

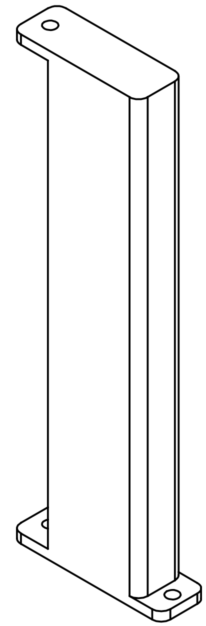
TITLE:

Top Stationary Support

SIZE	DWG. NO.	REV
A		

SCALE: 1:2 WEIGHT: SHEET 1 OF 1





TAG	X LOC	Y LOC	SIZE
A1	-1.53	-0.25	∅0.13 THRU
A2	-0.18	-0.25	∅0.13 THRU

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

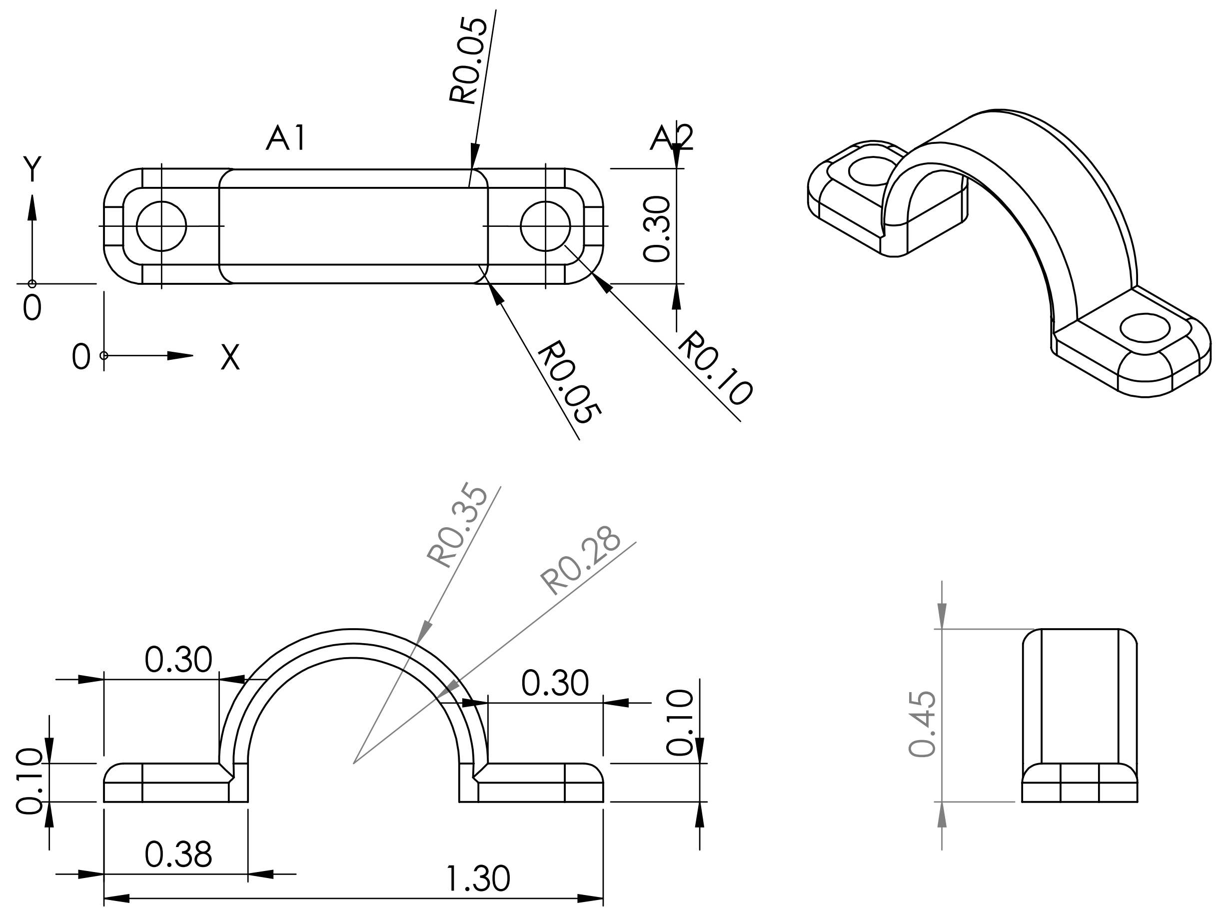
Katie Barkin

TITLE:

Spacer Support

SIZE A | DWG. NO. | REV

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



TAG	X LOC	Y LOC	SIZE
A1	0.15	0.15	∅0.13 THRU
A2	1.15	0.15	∅0.13 THRU

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Katie Barkin

TITLE:

Floor Bracket

SIZE A | DWG. NO. | REV

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

Appendix E

Important Component Specification Sheets

When Ushio America kindly donated the 222 nm Krypton Chloride Excimer Lamps, they requested that the Specification sheet not be shared publicly. If you need access to those specifications, please contact Ushio America directly.

The specification sheet for the NEMA 17 motor is included below.

Quick Reference

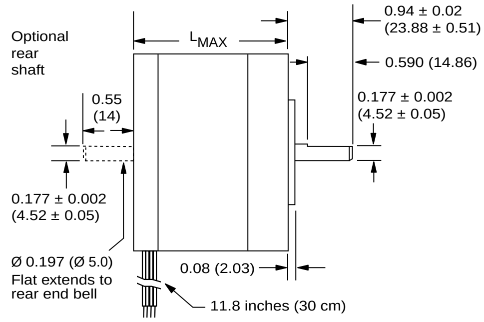
NEMA size 17 1.8° 2-phase stepper motor

INTELLIGENT MOTION SYSTEMS, INC.

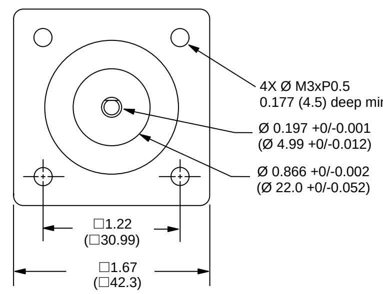
Schneider Electric

Mechanical Specifications

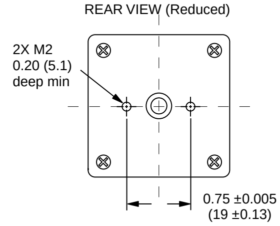
Dimensions in inches (mm)



FRONT VIEW



REAR VIEW (Reduced)



Motor stack length inches (mm)	Single	Double	Triple
LMAX	1.34 (34.0)	1.57 (40)	1.89 (48)

Notes and Warnings

Installation, configuration and maintenance must be carried out by qualified technicians only. You must have detailed information to be able to carry out this work.

- Unexpected dangers may be encountered when working with this product!
- Incorrect use may destroy this product and connected components!

For more information, go to www.imshome.com

Specifications

1.5 Amp motors		Single length	Double length	Triple length
Part number		**M-1713-1.5 •** *(1)*	**M-1715-1.5 •** *(1)*	**M-1719-1.5 •** *(1)*
Holding torque	oz-in	32	60	75
	N-cm	23	42	53
Detent torque	oz-in	1.7	2.1	3.5
	N-cm	1.2	1.5	2.5
Rotor inertia	oz-in-sec^2	0.000538	0.0008037	0.0011562
	kg-cm^2	0.038	0.057	0.082
Weight	oz	7.4	8.1	12.7
	grams	210	230	360
Phase current	amps	1.5	1.5	1.5
Phase resistance	ohms	1.3	2.1	2.0
Phase inductance	mH	2.1	5.0	3.85

(1) Indicate S for single-shaft or D for double-shaft. Example M-1713-1.5S

Wiring and Connections

Signals and wire colors	
Phase A	Red
Phase /A	Blue
Phase B	Green
Phase /B	Black

Part Numbers

Example:	**M - 1 7 1 3 - 1 . 5 S**
Stepper motor frame size **M-17** = NEMA 17 (1.7"/42 mm)	**M - 1 7** 1 3 - 1 . 5 S
Motor length **13-** = single stack **15-** = double stack **19-** = triple stack	M - 1 7 **1 3** 1 . 5 S
Phase current **1.5** = 1.5 Amps	M - 1 7 1 3 - **1 . 5** S
Shaft **S** = single, front shaft only **D** = double, front and rear shafts	M - 1 7 1 3 - 1 . 5 **S**
Optional optical encoder *(1)* **ES** = Single-end **ED** = Differential **Line count** 100, 200, 250, 400, 500 or 1000 *(2)*	M - 1 7 1 3 - 1 . 5 **E S 1 0 0**

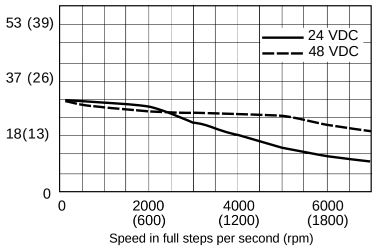
(1) An encoder replaces the shaft designator in the part number.
(2) All encoders have an index mark, except the 1000 line count version.

Torque-speed performance

Measured at 1.5 Amps RMS

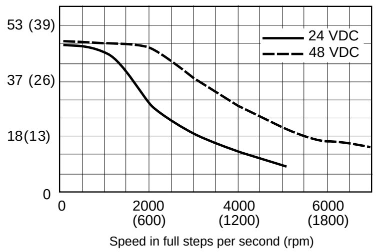
M-1713-1.5

Torque in oz-in (N-cm)



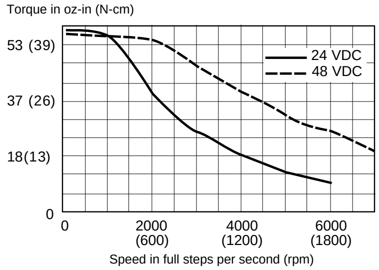
M-1715-1.5

Torque in oz-in (N-cm)



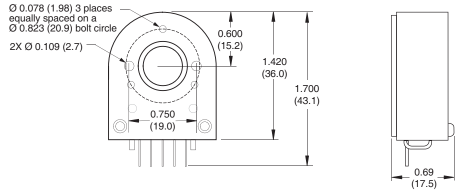
M-1719-1.5

Torque in oz-in (N-cm)



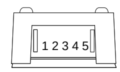
Optical Encoder Option

Dimensions in inches (mm)



Connectivity

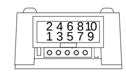
single-end encoder



	wire	*function*
1	Brown	Ground
2	Violet	Index
3	Blue	Channel A
4	Orange	+5 VDC input
5	Yellow	Channel B

optional interface cable available: ES-CABLE-2

differential encoder

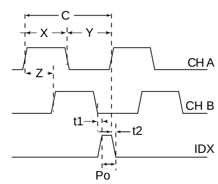


pin	*function*	*pin*	*function*
1	no connect	6	Channel A+
2	+5 VDC input	7	Channel B –
3	Ground	8	Channel B+
4	no connect	9	Index –
5	Channel A –	10	Index +

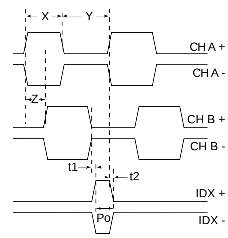
interface cable included

Timing

single-end encoder



differential encoder



Parameter	Symbol	Min	Typ	Max	Units
Cycle error			3	5.5	ºe
Symmetry		130	180	230	ºe
Quadrature		40	90	140	ºe
Index pulse width	Po	60	90	120	ºe
Index rise (after Ch A or B rise)	t1	-300	100	250	ns
Index fall (after Ch A or B fall)	t2	70	150	1000	ns

C One cycle: 360 electrical degrees (ºe).
X/Y Symmetry: the measure of the relationship between X and Y, nominally 180ºe.
Z Quadrature: the phase lead or lag between channels A and B, nominally 90ºe.
Po Index pulse width, nominally 90 ºe.
NOTE: Rotation is as viewed from the cover side of the encoder.

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