UV Disinfecting Robot for Tabletops

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Abstract

Many restaurants find it difficult to keep up with cleaning tables quickly and effectively during busy shifts. Cleanliness is especially important to mitigate the spread of diseases, such as the novel coronavirus (COVID-19). A previous team designed a cleaning solution that cleans mechanically, which can become costly if many units need to be installed and also lead to quicker failure of parts. We have designed an autonomous robot that can maneuver on a tabletop. It emits UVC light that can kill pathogens such as COVID-19. It is more cost-effective since it can be used for multiple tables.

Contents

1 Introduction

The purpose of this chapter is to introduce the problem our design is trying to solve. Giving a basic background of our project is essential to understanding the reasoning behind why we chose certain designs and why we changed aspects of the original design implemented by group 60. We also would like to discuss three overall goals/requirements we focused on during the design process. At the end of this chapter, we give a basic visual of what is to come in the next chapter of this report.

1.1 Problem Statement

When restaurants are extremely busy, employees focus their attention on taking orders and seating customers, not disinfecting tables. Fully disinfecting tables takes a lot of time which some employees might not have. In a study that swabbed ten restaurant tables, E. coli was isolated from 20% of those tables [1].

This issue of not disinfecting surfaces does not only pertain to restaurants—hospital surfaces also have this issue. It was reported that more than 50% of hospitals in the United States have shortages in environmental services personnel, such as custodians [2]. It was also shown that among these personnel there was often confusion about who is responsible for cleaning different areas of the hospital [2]. Industries that must obey strict health guidelines are failing due to the current shortage of people. With the current outbreak of COVID-19, there is going to be a higher need for new disinfection technologies. Without a reliable source that repeatedly disinfects areas, outbreaks such as COVID-19 will be a continuous issue.

Our goal is to design an autonomous robot which will disinfect restaurant tables using UV light. We will be using a bi-wheel robot that a user can place on the corner of the table. This robot will move around the table, ensuring that 95% of the table is hit with UV. We will also ensure that this robot is safe to use around people. We will include sensors that detect when this robot is not on the table so the UV light is deactivated. The robot will also be designed so less than 1 μJ of energy leakage can be detected at 0.3 m away from the device.

A company called UVD robots designs robotic based UV disinfection solutions for hospitals [3]. Although these robots are effective in killing bacteria in hospital rooms, we are aiming to market our design for smaller applications. We hope that small restaurant owners will be able to use our design to disinfect surface areas, such as tables. Our attempt of a UV solution will also be cost-effective compared to similar technologies on the market [3].

Our autonomous robot is essential to alleviate pressure from employees by fully disinfecting tables of bacteria and germs. If an employee only has time to wipe up crumbs and garbage after customers leave, the employee can set our device on the table to finish the disinfecting part of the task.

1.2 Updated Solution

Team 60's design for a self-cleaning table consists of an arm device that will slide across the table to clean crumbs and small spills on the surface of tables. The arm will move across the length of the table via a pair of guide rails and a screw drive on the underside of the table. This device will start its cleaning once motion sensors detect no one is at the table and nothing is detected on the table (napkin dispenser, condiments, etc.). Once the table is cleared, the arm will spray the table with a chemical disinfectant solution, squeegee the table, and then dry the table. Once this task is complete, the arm will retract and will be out of the way for the next customer.

When our team came across this solution, we wanted to improve scalability and reduce mechanical components, since the team discussed mechanical components are the most likely to break. We approached our solution by designing an autonomous vehicle that could potentially be placed on top of any shape surface (our project will focus on rectangular surfaces). This vehicle would also alleviate mechanical issues that guide rails might cause. Our design also stepped away from having any chemical disinfectant solution, eliminating the pump and sprayer, and exchanging it for a UV light. This solution will accomplish the disinfection task of the original solution while also reducing mechanical parts and eliminating the constant need to fill the device with chemical disinfectant solution. With our design, we felt focusing on the disinfecting part of cleaning the table was most important, so we did not include the aspect of the original design that wipes the table of crumbs and spills. However for future projects, this might be an issue we could tackle with our solution.

1.3 High-Level Requirements

- The autonomous robot must be able to use sensors to determine when it gets within 5 cm of the edge of the table and change its trajectory to remain on the table.
- The robot must be safe to operate near customers and emit less than 10 uJ at .3 m away from the device.
- The autonomous robot must shine UV light on 95% of a rectangular table.

1.4 Visual Aid

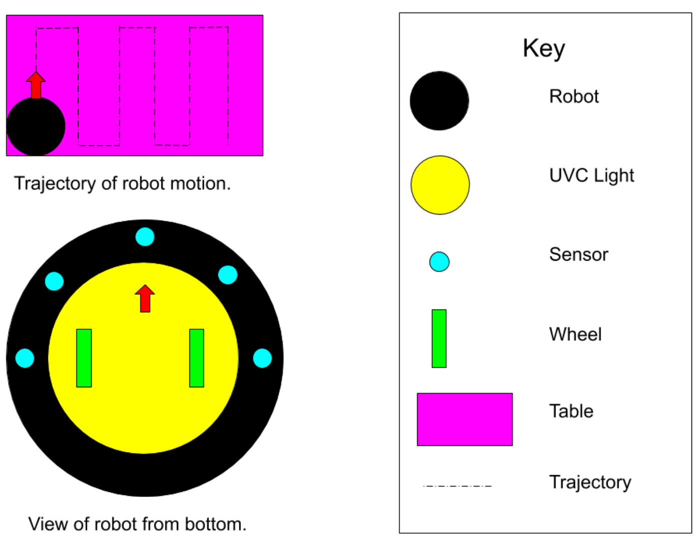

Figure 1: Visual aid.

Figure 1 shows the general trajectory of the robot's motion as well as the positioning of sensors and wheels of the robot. The robot is approximately 30 cm in diameter.

1.5 Block Diagram

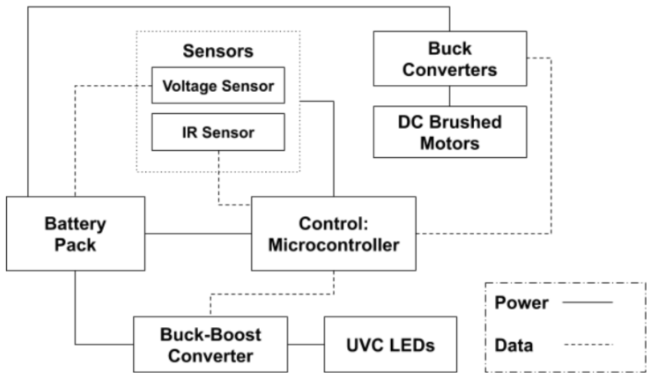

Figure 2: Block diagram.

Figure 2 shows the block diagrams and the interconnections between elements with power and data. Note the sensor block contains both voltage sensors and IR sensors.

2 Project Implementation

In this chapter, we dive deep into the technical work behind our design. We begin with the electrical side of our design where we added an image of our LTspice circuit and explained our circuit simulations. After that, we talk about the traversal algorithm we implemented and a few simulations that were conducted to show the effectiveness of that traversal. Lastly, we share a few images of the CAD design of the robot to give an idea of what our robot would look like.

2.1 Design

2.1.1 Battery Pack

This will be a three-cell Lithium ion pack that will power the device. Since this is a three-cell pack, it will have a voltage range between 9-12.6 V. We are looking at powering ten LED modules, two DC motors, and an Arduino for about an hour. This gives us an estimated capacity of 13 Ah for a worst case scenario. Realistically, the motors will not be running constantly at full throttle, so a more realistic range would be 10-12 Ah.

2.1.2 DC Brush Motors

This is the primary method by which our robot will move. We are using DC Brushed due to their ease of control and their low cost. These will be controlled by the attached Buck Converter, which will allow for precise speed control. These motors are rated for 12 V and 0.3 A.

2.1.3 UVC LEDs

This is our primary tool for disinfecting a surface. UVC is a high energy ultraviolet radiation that is capable of destroying DNA and RNA [4]. This is what allows the LEDs to kill viruses and bacteria on a surface. The biggest concerns we have would be to make sure that we are both dousing the surface with enough radiation to disinfect and preventing a significant amount for radiation from leaking out. We would be using some control algorithm to ensure surface coverage. To prevent radiation leakage, we would use some sort of covering around the rim of the robot to block the UVC light and prevent it from escaping.

2.1.4 Buck Converters

This is a simple switching converter that allows a DC voltage to be efficiently stepped down to whatever voltage is needed. This is the intermediary between the controller and the DC motor. These converters will be rated to output at least 0-10 V +/- 10% along with being able to supply 1 A +/- 20%.

2.1.5 Buck-Boost Converter

This is used to precisely control the voltage being placed on the LEDs. Two LEDs are placed in series for each stack to improve the efficiency of the device. The problem is that the battery voltage can vary over a fairly large range. This range runs too much current through the LEDs when the battery pack is charged, but the LEDs fail to turn on when the pack is discharged. The Buck-Boost Converter allows for a precise voltage to be placed on the LEDs regardless of what voltage the battery pack is at. These converters will be rated to output at 11 V +/- 10% along with being able to supply a max of 3 A - 20%.

2.1.6 Voltage Sensor

This is used to estimate the energy left in the battery pack and also to adjust converter duty cycles as needed. Is especially important for current control in the LEDs and safely shutting off the robot at the specified voltage minimum.

2.1.7 IR Sensor

This is used to determine the table edges and to judge if the robot is still on the table. We do not want the robot to drive itself off of a table, therefore the IR sensors will be used to detect when the robot is about to drive off the table. We can also use these sensors to determine if the robot has been picked up off of the table. This is important for safety reasons due to the UVC light. By having this information, the robot can shut off the LEDs when it determines that it was picked up off the table. This might be switched with an ultrasonic depending on usability.

2.1.8 Control Microcontroller

This will be implemented with an ATMega or Arduino microcontroller. It will send the controls to the motor, and converters. It will additionally supply power and receive information from the sensors.

2.2 Electrical Design

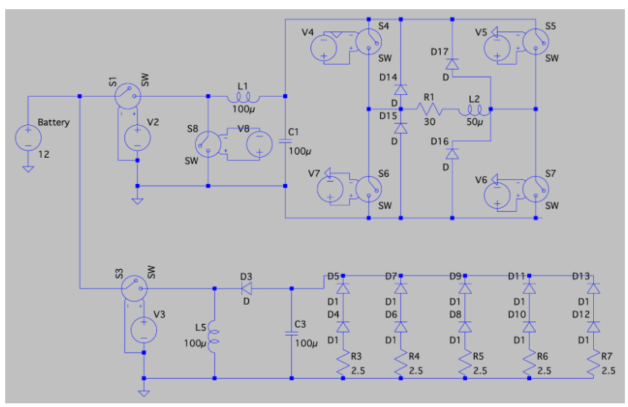

Figure 3: Electrical schematic.

This is the electrical schematic for this design. The top node is the buck converter with H-bridge that drives the motors. Each motor will have its own separate converter to allow independent control of each wheel. The buck converter portion allows for fine voltage control, which can be used to directly control the speed of each motor. The rotational speed of each motor can be directly tracked via the optical encoders in each motor.

The direction of each motor is directly chosen using an H-bridge to control the voltage polarity on the motors. Built into the bridge is a diode loop to prevent an open-circuit condition on the motor. Such a condition can easily cause arcing or high voltage stress due to the inductive component of the motor.

The bottom node is a buck-boost converter that is attached to the LED array. The buck-boost converter allows for fine output voltage control, which is important for power management of LEDs. The LEDs will require about 10 volts to turn on, however the voltage can range from 9 to 12.6 volts. This converter will allow for a more stable voltage to be imposed on the LEDs. This will be accomplished using a feedback loop to stabilise the LED voltage level.

2.3 Traversal Algorithm

We chose to use a zig-zag motion to traverse the table. The robot moves parallel to the edge of a rectangular table, then completes a half-turn and returns in the opposite direction. Figure 4 depicts a typical zig-zag path as described in the paper by Galceran and Caceres [5].

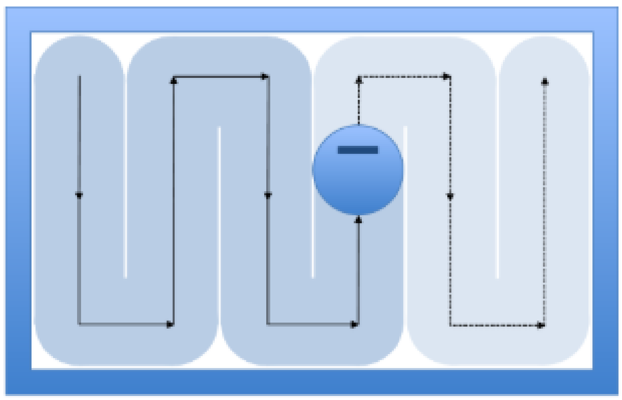

Figure 4: Typical zig-zag path. The robot starts in the darker regions and moves towards the lighter ones. [5]

A state-machine description of the general traversal algorithm can be seen in Figure 5. The next state must depend on the current state. The algorithm should handle most erroneous sensor readings without the robot falling off the table.

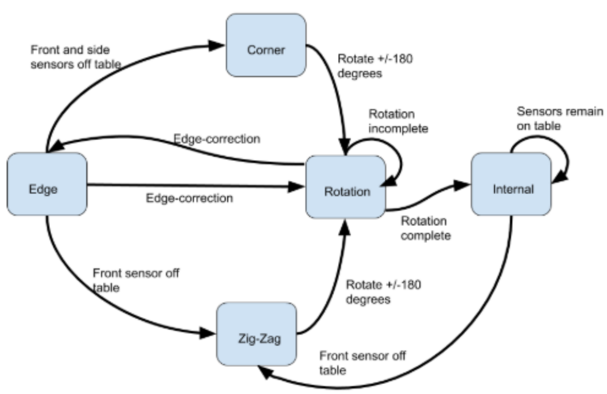

Figure 5: State-machine for traversal algorithm.

2.3.1 Tolerance Analysis

It is imperative that the control microcontroller outputs the correct signal. The controller ensures that the UVC LEDs are only turned on when the robot is securely on the table, and that the robot never falls off the table. It should be able to stop quickly enough when the signal is sent to it. However, sometimes data from the IR sensors can be noisy and not accurately capture the edge of the table. Additionally, the response time of the motor might be slow enough to cause the robot to fall off the edge. Also, the encoder on the motor might only turn it within 1% of the specified amount. In order to test these three situations, we created simulations in Python that used various noise models for the sensor. The results are in Table 1. In most of the simulations, at least 95% of the table was covered, and the robot remained on the table.

Figures 6, 7, and 8 show the simulations run for sensor noise failure rate = 0.1% and the motor rotation error of 0.05 rad. Table 1 shows the mean and standard deviation for 100 runs of different combinations of sensor noise failure rates and motor rotation error. Note that not all of the sets of runs had a mean within 95% coverage. This might be due to our estimates of what the error in the rotation of the robot and sensor would be. Testing would be performed if we had access to the physical sensors and device to get a more fair estimate of what the noise would be. Additionally, the algorithm would be edited slightly for better accuracy. The simulation was developed using the procedure described in 2.3 Traversal Algorithm.

At max speed, the motor travels 180 rev/min and the stopping time at full speed is 0.029 s. Therefore, it would travel about 2.29 cm before coming to a complete stop at full speed. We can prevent the robot from falling off the table by ensuring that there is at least 3 cm between the edge of the wheel and the front of the robot, and always moving the robot backwards about 3 cm when the robot turns around. However, the robot should not be travelling this fast in practice, as it must travel more slowly in order to irradiate the table with the proper amount of light to deactivate viruses.

Table 1: Results of 100 trials of motion simulation

Motor Error (rad.)	Sensor Error (%fail)	Mean (% covered)	Std.
0.01	0.01	96.6497	1.0886
0.05	0.01	93.1326	6.0236
0.01	0.1	94.1353	3.8623
0.05	0.1	90.3016	5.875

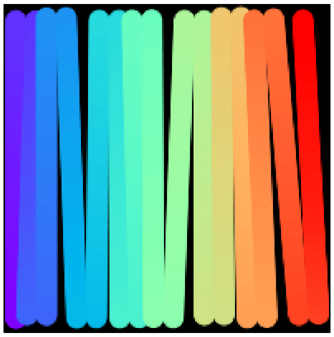

Figure 6: Output of simulation with 0.05 rad motor error, error of 0.01%

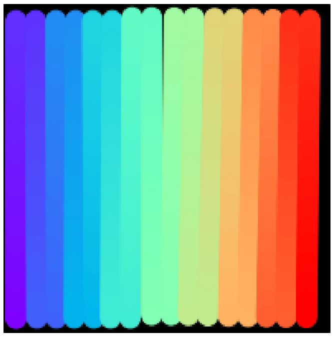

Figure 7: Output of simulation with 0.05 rad motor error, error of 0.01%

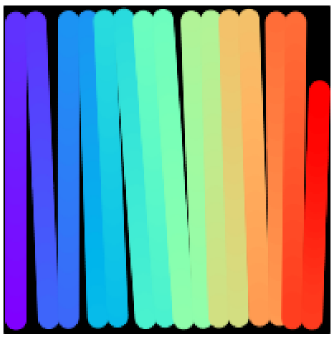

Figure 8: Output of simulation with 0.01 rad motor error, error of 0.1%

2.4 CAD Design

Below are photos for the CAD of robot. We took inspiration from the Roomba design for the external shell. This design serves two purposes in that it is a structurally stable shape and it is a very recognizable shape for its purpose. The structural stability helps to keep the robot intact despite minor impacts and the recognizable shape helps to immediately inform people on the robot's purpose.

The robot contains four main internal sections. The controller section, the motor section, the battery section, and the sensor section.

The controller section contains all the micro-controllers and converters. The micro-controller can be mounted underneath the top plate as it should be producing minimal heat. It should be able to safely cool itself with minimal air flow. The converters, which are expected to produce substantial heat, will be mounted on top of the front plate. The combination of front holes and more space above it should help thermals.

The motor section contains the mounts that the motors will be attached to. This holds the motors in place and contains holes nearby for the wheels.

The battery section contains space for all the batteries to be installed. We are looking at utilizing nine batteries with three in series per stack and three stacks in parallel. This will provide the required capacity while delivering the required the 9 to 12.6 V.

The last section is the sensor section. This section is spread around the bottom of the robot. This section is purely made to provide the necessary space for sensors. The PCBs or sensors could then be mounted through those holes.

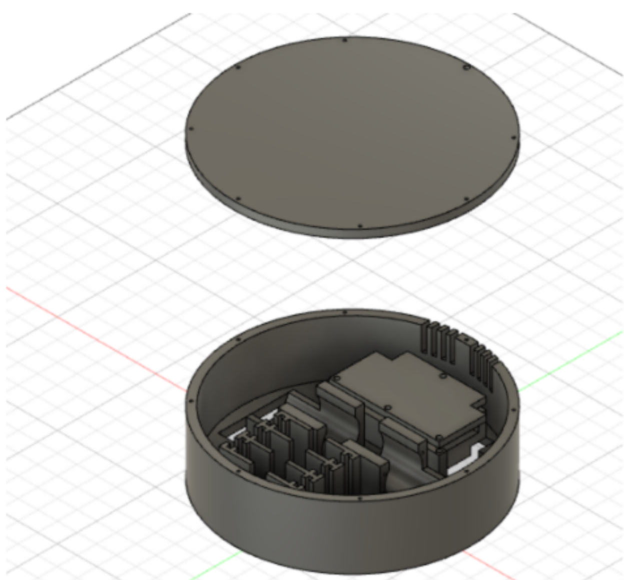

Figure 9: Iso view of the general layout of the robot.

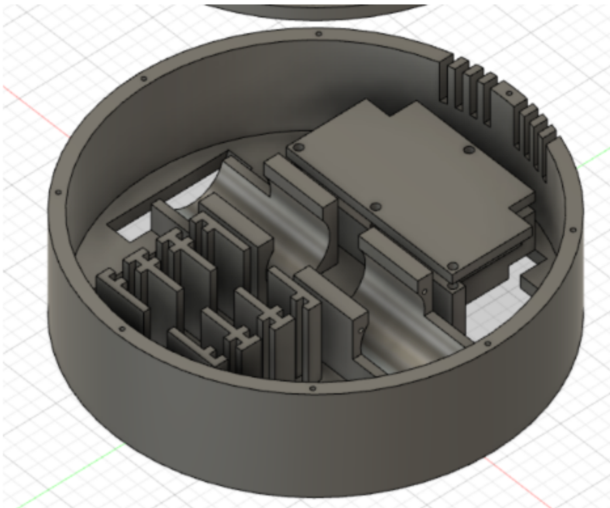

Figure 10: Closer iso view of design.

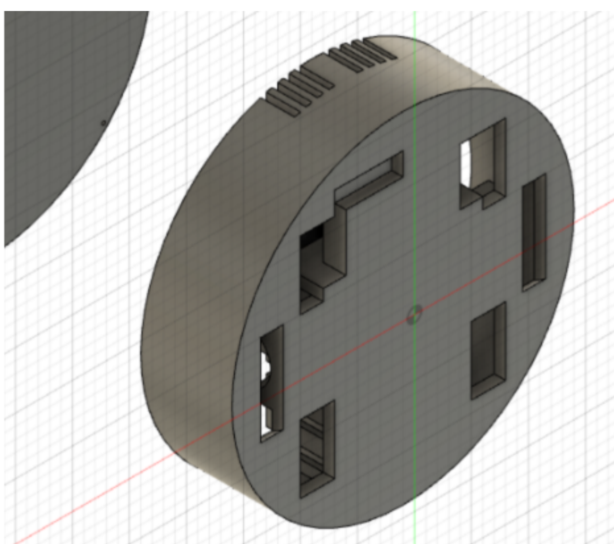

Figure 11: Bottom view, which shows the holes for sensors/wheels etc.

2.5 Costs

2.5.1 Labor Costs

Table 2: Labor Costs for each Team Member

Member	Hourly rate	Hours	Total
Antonio	$50	300	$15,000
Anabel	$50	300	$15,000
Eros	$50	300	$15,000
		Total:	$45,000

2.5.2 Parts Costs

Table 3: Parts Cost

Description	Part	Quantity	Unit Cost	Purchasing Cost
Mosfet	PSMN022-30PL,127	4	$.76	$3.04
Mosfet	296-35012-ND	3	$1.65	$4.95
Gate Driver	IRS2011PBF	30	$1.90	$57
Inductor	22R103C	3	$.96	$2.88
Inductor	SH50C-3.0-100	3	$6.32	$18.96
Motor	996	2	$15.95	$31.90
Resistor		10	$2.37	$23.70
Diode	1N5820-E3/54	8	$.45	$3.60
Diode	SB520	4	$.46	$1.84
Capacitor	FG11X7R1C226MRT06	40	$.86	$34.40
Capacitor	C315C104M5U5TA7303	6	$.24	$1.44
Capacitor	C333C105M5U5TA7301	6	$.49	$2.94
LED	L944-MUV265-4	10	$17.94	$179.40
Total:				$366.05

3 Project Conclusion

In this chapter, we discuss the design process overall. We focus on certain areas of the project that were unknown until we started the design. We discuss certain tasks that we could not accomplish due to the lack of equipment. Then we give a background in the ethics behind our design and how it's important to consider when designing technology. To conclude this paper, we discussed further improvements we would like to add to our design for the future.

3.1 Implementation Summary

We were able to accomplish working simulations for our design on our autonomous robot. We specifically did simulations on our traversal algorithm (completed by Anabel) and electrical circuit (completed by Antonio). These simulations will allow us to build our physical design with reduced errors to start. Our accomplishments in chapter two will set us on a stronger path to complete a physical autonomous robot that will cover all the high-level requirements.

3.2 Unknowns, Uncertainties, testing needed

Since we did not have access to the lab, we were not able to build a physical product of our design. However, we created simulations to represent our design. We did not have access to oscilloscopes or multimeters, so we simulated our circuit on LTspice to get a general idea of how our design would act electrically. We also created a traversal simulation in Python to test our algorithm with the specifications of our robot (size, size of wheel, etc.). In this traversal simulation, we added noise to simulate motors; however we do not precisely know the exact way our design will behave. Although we are unaware of the exact behavior of the robot, we can get estimates of how individual parts of our design might act.

By going through these simulations first, we realize how important it is to the overall design process. These simulations would reduce time and money spent on projects. We would be able to pinpoint a possible error in our design before ordering a certain part or assembling it.

3.3 Ethics and Safety

The safety aspects that are the most concerning with this project are unintentional exposure to UV radiation, exposure to ozone, and incomplete removal of viruses and bacteria.

As engineers, we must protect the public from known hazards; UV light poses many health risks [6]. There are three types of UV light: UVA, UVB, and UVC. Each operates at a different wavelength range, and UVC has the highest potential of hazard. All types can harm humans when exposure is sufficiently high. UVC light in particular can cause photokeratitis, an inflammation of the eye, and erythema, a burning of the skin [7]. Repeated exposure can lead to cancer as well. According to the World Health Organization, the best way to limit damage caused by UV light is to wear personal protective equipment (PPE), which includes UV-resistant clothing, goggles, and face shields, and have robust engineering controls and training [8]. Since our project will contain UVC LEDs, it is imperative that engineers working on the project are sufficiently protected with PPE. The robot itself should also have a mechanism to block the light from the nearby area or concentrate it only directly beneath the device. Additionally, it is necessary to place a warning label on the device clearly explaining that it emits UV light which poses hazards [9].

One of the major challenges with our design is that it is difficult to calculate how much radiation that a person may be exposed to if they are nearby. We can come up with an upper limit assuming direct exposure and a quadratic decay over distance, but this is far from the real life scenario. The real device would have the light pointed away from individuals and would have a brush to help block it. To confirm that the level of UV radiation is safe, we would use a UV sensor at various distances and locations around the robot. We would make changes to the brush as needed to reduce leaked UV radiation below safe levels.

We must hold the health of our users in high regard [6]. Ozone is highly reactive in the respiratory tract and can lead to degradation of the lungs and airways if inhaled, and overall is associated with increased mortality, according to the EPA [10]. Ozone can be generated from UV lights that emit light at a wavelength below 250 nm [11]. Therefore, it is imperative that our device does not emit light of that nature to minimize the amount of ozone the user is exposed to. It would be beneficial to advise the user to remain as distant from the robot while operating when possible to mitigate these negative effects.

According to the IEEE Code of Ethics, we must ensure that we are realistic when stating claims or estimates of the performance of our device [6]. The user must understand that no method of disinfection can remove 100% of pathogens, germs, viruses, or bacteria. Typically, ultraviolet germicidal irradiation (UVGI) measures reduction on the log-reduction scale. For example, a 3-log reduction would make the number of microbes 10^3 times smaller, or remove 99.9% of microbes [12]. Given current research on UVGI, we believe that we could reduce microbes with at least a 2-log reduction [13]. While a 99% reduction in microbes is certainly better than none, the user would need to understand the risk of possibly becoming infected with the stated targeted pathogens even after using our device.

3.4 Project Improvements

Our robot was designed with scalability in mind. The traversal algorithm for this iteration of the robot only focuses on rectangular tables. Most restaurants will have multiple shapes of tables and we want one design to traverse any of them. This would effectively reduce cost for each restaurant, since the restaurant would only need to purchase one robot. Since our robot was mechanically and electrically designed to tackle a table of any shape, all we would have to do is improve the traversal algorithm to complete this goal.

Our design focused on disinfecting a table. The other group had a design that would wipe the table of spills and crumbs. For a future goal, our group would like to add a mechanical cleaning aspect. Future considerations would be to include a vacuum system or a squeegee system, like the original design.

We would also like to add simple upgrades to our design that would make it more presentable to a consumer. Ideas include: adding a dockable rechargeable battery system, adding a user interface to pick different settings, and a data collection system to keep track of how many tables were cleaned.

Appendix A Requirement and Verification Table

Table 4: Battery Pack

Requirement	Verification	Verification status (Y or N)
(a) Rated to deliver 3 A on average, and no more than 6 A. (b) Needs to have at least 3 Ah. (c) Battery does not leave range of 9 to 12.6 V.	(a) Attach 3W electronic load to batteries.Measure current at load using ammeter in series and verify current is ¡ 6 A. (b) Run battery pack with 3 A drain and ensure the batteries can run for 60 minutes. (c) Measure voltage at load using voltmeter and ensure voltage is within 9-12.6 V range for the entire stack.	Y

Table 5: Motor Drive

Requirement	Verification	Verification status (Y or N)
(a) Supply voltage to the motors within the range of 0–12V - 20%. (b) Must be able to withstand current draw from motors of an average .3A and a peak of 0.6A +/- 20%. (c) Manage thermals by preventing the converter from exceeding 100 C. (d) Can switch the voltage polarity without incurring voltage/current spike more than twice the normal ratings. Voltage will not exceed 24 v and current will not exceed 1.2 A.	(a) Probe the output of the converter while the motor is plugged and confirm that the voltage can reach the appropriate range. (b) Using a hall effect sensor, scope the current being supplied to the motor to ensure that it is within specs. (c) Use an infrared thermometer to ensure that the temperature of each of the components is below 100 C. The temperature of every component should be stable within the load range. (d) Probe the output of the converter while the motor is plugged and switch the direction of the motor. Also, we would probe the inputs to the motor to	Y

Table 6: Buck-boost to LEDs

Requirement	Verification	Verification status (Y or N)
(a) Supply voltage to the LEDs within the range of 10–15V - 20%. (b) Withstand current draw from LEDs of an average of 3 A - 20%. (c) Prevent the converter from exceeding 100 C.	(a) Probe the output of the converter while the motor is plugged in and confirm that the voltage can reach the appropriate range. (b) Using a hall effect sensor, scope the current supplied to the LEDs to ensure that it is within specs. (c) Use an infrared thermometer to ensure the temperature of each of the components is below 100 C.	Y

Table 7: Control Microcontroller

Requirement	Verification	Verification status (Y or N)
(a) Turn around when the robot is within 5 cm of the edge of the table at least 95% of the time. (b) Output correct signals to change the duty cycle of LEDs and their power. Ensure the signal for the LED's duty cycle can change the output voltage to the LED to zero within 1 ms. (c) Stop the robot if it is closer than 3 cm to the edge of the table at least 95% of the time.	(a) Create a short program that drives the robot towards the edge of the table. When the robot is within 5 cm of the edge of the table, the robot should turn around. Test this process 100 times. Our design should have at least a 95% pass rate for this test. (b) Simulate an abrupt change of sensors on to off the table. Use an oscilloscope to measure the duty cycle signal and ensure that it drops to zero within 1 ms. (c) Create a short program that drives the robot towards the edge of the table. When the robot is within 3cm of the edge of the table, the robot should stop. Test this process 100 times. Our design should have at least a 95% pass rate for this test.	Y

Appendix B Design

B.1 Determining Speed of Robot

We must ensure that the robot can pass over all areas of the table slowly enough to emit enough energy to deactivate a virus such as COVID-19 or SARS. According to a recent report about inactivation of viruses with UVC light, it takes 0.2 J/cm^2 to deactivate SARS-CoV with grater than 3.4 log reduction [13]. Our LEDS will be operating at 7 V and at 150 mA, which leads to about 1 W of energy. Therefore, in order to deactivate the virus, one of the UVC LEDs we chose would be able to sanitize 5 cm^2/s. Our ten LEDs can sanitize 50 cm^2/s.

$$A = \pi r^2 = 706.86cm^2$$

Therefore, it would take $\frac{700}{50} = 14.1$s of exposure of the table to the entirety f the robot to safely clean the surface directly below the robot.

Within five minutes, the robot would be able to clean 1.4 m^2, which is a table large enough to seat about four people. Assuming a square table, this means the robot would be moving around 0.02 m/s.

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