CLOUD-CONNECTED UV DISINFECTION ROBOT WITH HMI CONTROL FOR PANDEMIC MITIGATION IN HEALTHCARE

A Project Report

Submitted by

ALBERT THOMAS ABRAHAM	**JEC21EC008**
ANLI JOY	**JEC21EC011**
PRANAV PRASAD	**JEC21EC030**
REMYA P.	**JEC21EC031**

to

APJ Abdul Kalam Technological University

in partial fulfillment of the requirements for the award of the Degree of

Bachelor of Technology (B.Tech)

in

ELECTRONICS & COMMUNICATION ENGINEERING

Under the guidance of

DR. SINDHU S.

JYOTHI ENGINEERING COLLEGE
LEAD KINDLY LIGHT
TET
CREATING TECHNOLOGY
LEADERS OF TOMORROW
ESTD 2002

DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING

Jyothi Engineering College
Reaccredited with NAAC (Grade A) and NBA Programmes*
Approved by AICTE and Affiliated to APJ Abdul Kalam Technological University
A CENTRE OF EXCELLENCE IN SCIENCE AND TECHNOLOGY BY THE CATHOLIC ARCHDIOCESE OF TRICHUR
JYOTHI HILLS, VETTIKATTIRI P.O., CHERUTHURUTHY, THRISSUR, 679531 | Ph. +91 4884 259000 | info@jecc.ac.in | www.jecc.ac.in
*NBA accredited BTech Programmes in Civil Engineering, Computer Science and Engineering, Electronics and Communication Engineering, Electrical and Electronics Engineering and Mechanical Engineering valid till 2025, Mechatronics Engineering valid till 2026

April 2025

DECLARATION

We the undersigned hereby declare that the project report " Cloud-Connected UV Disinfection Robot with HMI Control for Pandemic Mitigation in Healthcare", submitted for partial fulfillment of the requirements for the award of degree of Bachelor of Technology of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by us under supervision of Dr. Sindhu S. This submission represents our ideas in our own words and where ideas or words of others have been included, we have adequately and accurately cited and referenced the original sources. We also declare that we have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in this submission. We understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously used by anybody as a basis for the award of any degree, diploma or similar title of any other University.

ALBERT THOMAS ABRAHAM (JEC21EC008)

ANLI JOY (JEC21EC011)

PRANAV PRASAD (JEC21EC030)

REMYA P. (JEC21EC031)

Place:

Date:

Jyothi Engineering College

NAAC Accredited college with NBA Accredited programmes

DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING

CREATING TECHNOLOGY LEADERS OF TOMORROW

ESTD 2002

CERTIFICATE

This is to certify that the report entitled "**CLOUD-CONNECTED UV DISINFECTION ROBOT WITH HMI CONTROL FOR PANDEMIC MITIGATION IN HEALTHCARE**" submitted by ALBERT THOMAS ABRAHAM (JEC21EC008), ANLI JOY(JEC21EC011), PRANAV PRASAD(JEC21EC030), REMYA P.(JEC21EC031) to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree in Bachelor of Technology in **Electronics & Communication Engineering** is a bonafide record of the project work carried out by them under my guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

Internal Supervisor	**Head of the Department**
Dr. Sindhu S. **Associate Professor**	**Dr. Sindhu S.** **Associate Professor**

ACKNOWLEDGEMENT

We take this opportunity to thank everyone who helped us profusely, for the successful completion of our project work. With prayers, we thank **God Almighty** for his grace and blessings, for without his unseen guidance, this project would have remained only in our dreams.

We thank the **Management** of Jyothi Engineering College and our Principal, **Dr. Jose P. Therattil** for providing all the facilities to carry out this project work. We are grateful to the Head of the Department and Project Guide **Dr. Sindhu S.** for her valuable suggestions, encouragement, support and guidance in the right direction during the entire project work.

We thank our Project Coordinators **Dr. Prajoon P.** & **Dr. Bindhu K Rajan** for their constant encouragement during the entire project work. We extend our gratefulness to all teaching and non teaching staff members who directly or indirectly involved in the successful completion of this project work.

Finally, we take this opportunity to express our gratitude to the parents for their love, care and support and also to our friends who have been constant sources of support and inspiration for completing this project work.

ALBERT THOMAS ABRAHAM (JEC21EC008)
ANLI JOY (JEC21EC011)
PRANAV PRASAD (JEC21EC030)
REMYA P. (JEC21EC031)

VISION OF THE INSTITUTE

Creating eminent and ethical leaders through quality professional education with emphasis on holistic excellence.

MISSION OF THE INSTITUTE

- To emerge as an institution par excellence of global standards by imparting quality Engineering and other professional programmes with state-of-the-art facilities.
- To equip the students with appropriate skills for a meaningful career in the global scenario.
- To inculcate ethical values among students and ignite their passion for holistic excellence through social initiatives.
- To participate in the development of society through technology incubation, entrepreneurship and industry interaction.

VISION OF THE DEPARTMENT

Create eminent and ethical leaders in the field of Electronics and Communication through quality professional education to excel in academia and industry.

MISSION OF THE DEPARTMENT

- To impart comprehensive knowledge and practical skills in the field of Electronics and Communication Engineering.
- To provide an environment that nurtures a culture of innovation and entrepreneurship, to develop solutions to real-world challenges and explore opportunities for technology commercialization.
- To foster socially responsible engineers and ethical leaders who drive positive change through innovative technology and a commitment to the betterment of society.

PROGRAMME EDUCATIONAL OBJECTIVES

PEO 1: Graduates shall have fundamental and advanced knowledge in electronics and communication engineering along with knowledge in mathematics, science and computing and get employed in national or international organizations or government agencies.

PEO 2: Graduates shall have ability in analyzing, designing and creating innovative solutions which lead to a lifelong learning process or higher qualification, making them experts in their profession thus helping to solve electronics & communication engineering and social problems.

PEO 3: Graduates shall have good organizing capability, presentation skills, communicating ability, leadership, teamwork and ethical practices.

PROGRAMME SPECIFIC OUTCOMES

Graduate possess -

PSO 1: Apply theoretical knowledge and practical skills in the field of Electronics and Communication Engineering to analyze, design, and implement electronic systems, communication networks, and signal processing solutions effectively.

PSO 2: To cultivate a culture of innovation and entrepreneurship among students, enabling them to identify and address real-world challenges in electronics and communication.

PSO 3: To instill a sense of social responsibility and ethical awareness in students by preparing them to use their technical expertise for the betterment of society and the environment.

PROGRAMME OUTCOMES

1. **Engineering knowledge:** Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
2. **Problem analysis:** Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
3. **Design/development of solutions:** Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.
4. **Conduct investigations of complex problems:** Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.
5. **Modern tool usage:** Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.
6. **The engineer and society:** Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.
7. **Environment and sustainability:** Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.
8. **Ethics:** Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.
9. **Individual and team work:** Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.
10. **Communication:** Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.
11. **Project management and finance:** Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.
12. **Life-long learning:** Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

COURSE OUTCOMES

COs	Description	Bloom's taxonomy level
CO1	Model and solve real-world problems by applying knowledge across domains.	Applying(P)
CO2	Develop products, processes, or technologies for sustainable and socially relevant applications.	Applying(P)
CO3	Function effectively as an individual and as a leader in diverse teams, and comprehend and execute designated tasks.	Applying(P)
CO4	Plan and execute tasks utilizing available resources within timelines, following ethical and professional norms.	Applying(P)
CO5	Identify technology/research gaps and propose innovative or creative solutions.	Applying(A)
CO6	Organize and communicate technical and scientific findings effectively in written and oral forms.	Applying(P)

CO MAPPING TO POs

	POs											
COs	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12
CO1	2	2	2	3	2	2	2	1	1	1	1	2
CO2	2	2	2		1	3	3	1	1		1	1
CO3									3	2	2	2
CO4					2			3	2	2	3	2
CO5	2	3	3	1	2					1		1
CO6					2			2	1	3	1	2

CO MAPPING TO PSOs

	PSOs		
COs	PSO1	PSO2	PSO3
CO1	2	2	2
CO2	2	2	2
CO3	2	2	1
CO4	2	2	2
CO5	2	2	1
CO6	2	1	2

ABSTRACT

In healthcare and public environments, maintaining hygiene standards is critical to preventing the spread of infections.Traditional disinfection methods are time-consuming, unreliable, and expose workers to harmful pathogens leading to a spread of pandemic.To address these challenges, a cloud-connected UV disinfection robot is introduced, automating surface sterilization using UV-C light to ensure an effective pathogen elimination while minimizing the human exposure.The system integrates a microcontroller, UV-C LEDs, environmental sensors, and navigation modules. By connecting to a cloud-based platform, the robot provides real-time monitoring and control through a human-machine interface, allowing operators to receive performance data. The solution incorporates real time data analysis to optimize disinfection parameters and environmental factors such as temperature, humidity, and air quality ensuring maximum efficiency. The use of UV-C technology, cloud connectivity, and advanced data analysis makes this system effective tool for controlling pandemics.This project also includes an Impact analysis and scoring of the environmental factors on pandemic spread.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVATIONS

HAI	Healthcare-Associated Infection
HMI	Human Machine Interface
I2C	Inter-Integrated Circuit
IDE	Integrated Development Environment
IoT	Internet of Things
LCD	Liquid Crystal Display
RGB LED	Red, Green and Blue Light Emitting Diode
SLAM	Simultaneous Localization and Mapping
UV	Ultra Violet
UVGI	Ultraviolet Germicidal Irradiation
Wi-Fi	Wireless Fidelity

CHAPTER 1

INTRODUCTION

1.1 Overview

The COVID-19 pandemic brought many challenges to healthcare systems worldwide, revealing critical gaps in infection control and disinfection protocols. In healthcare environment where patients are already vulnerable, surface contamination plays a significant role in the transmission of infectious diseases. Pathogens such as Methicillin-resistant Staphylococcus aureus (MRSA), COVID-19, and other harmful microorganisms can survive on surfaces for days, leading to the spread of hospital-acquired infections (HAIs). In the fight against these infections, conventional cleaning methods alone have proven to be insufficient, often leaving behind dangerous residues or missing hard-to-reach areas[1, 2, 3, 4, 5]. There is an increasing need for innovative solutions that can effectively reduce the microbial load on surfaces, especially in environments like hospitals and clinics, where hygiene is paramount.

One of the most promising technologies for addressing these challenges is ultraviolet (UV) disinfection[6, 7, 8, 9, 10]. UV light, particularly in the UVC spectrum, has been proven to kill or inactivate a wide range of microorganisms by disrupting their DNA and RNA, rendering them unable to replicate or spread. In the context of healthcare, UV disinfection provides a non-toxic and residue-free solution to decontaminate surfaces efficiently.It serves as a complementary technology to traditional cleaning methods, ensuring a higher level of disinfection.

Figure 1.1: UV Disinfection System in operation. Source: Atalian CZ

The UV disinfection robot shown in Figure 1.1 has been specifically designed for pandemic mitigation in healthcare settings. While fully autonomous robots offer convenience, this system combines the power of UV disinfection with human-machine interface (HMI) control, giving healthcare workers the flexibility to navigate and control the robot in real-time. This semi-autonomous design ensures that disinfection is thorough, allowing operators to direct the robot to critical areas that require more attention or are difficult for standard cleaning practices to reach.

Healthcare environments, especially during pandemics, are high-risk areas for cross-contamination. Pathogens like MRSA are notorious for their ability to persist on surfaces such as bed rails, medical equipment, and countertops. Hospital-acquired infections contribute to increased patient morbidity, longer hospital stays, and greater healthcare costs. Furthermore, during outbreaks like COVID-19, healthcare facilities become hotspots for viral spread due to the high volume of patient contact, making rigorous and regular disinfection vital.

Research has shown that viruses like SARS-CoV-2, the virus responsible for COVID-19, can survive on surfaces for several hours to days, depending on the material. As a result, maintaining an infection-free environment is a key part of pandemic response in hospitals.

The robot's UV disinfection technology ensures that healthcare facilities can maintain cleaner, safer spaces for patients, medical staff, and visitors[11, 12, 13].

Its semi-autonomous HMI system allows the operator to precisely target high-touch areas, such as door handles, bed rails, and medical devices, without requiring direct human contact. The robot not only minimizes the need for hazardous chemical disinfectants, which can have harmful effects on both people and equipment, but it also reduces the time required for manual cleaning and disinfection tasks.

By integrating advanced UV disinfection technology with a user-friendly HMI system, this robot will be a highly effective tool for pandemic mitigation in healthcare settings. It addresses the pressing need for efficient, scalable disinfection solutions that ensure critical spaces remain safe and sanitary, helping to reduce the risk of infection spread and protect the most vulnerable populations during healthcare crises.

1.2 Motivation

The motivation behind this project stems from the urgent need for improved disinfection protocols in healthcare environments, where effective infection control directly impacts patient outcomes and healthcare safety [6, 7, 8, 9, 10]. The COVID-19 pandemic highlighted critical vulnerabilities in conventional cleaning methods, exposing healthcare workers and patients to increased risks of contamination. While manual cleaning processes are essential, they often fall short in addressing hidden or hard-to-reach areas, leaving gaps in pathogen elimination.

Traditional cleaning agents, especially chemical disinfectants, are effective but come with limitations. They can leave harmful residues, damage sensitive medical equipment, and pose health risks when used frequently in enclosed areas[14, 15]. In contrast, UV disinfection offers a residue-free and non-toxic solution, making it ideal for use in settings that demand high levels of hygiene, such as hospitals and clinics.

The effectiveness of UV-C light in inactivating pathogens like MRSA and SARS-CoV-2 by disrupting their DNA and RNA structures has been well-documented, positioning it as an effective, scalable alternative to support standard cleaning protocols.

The development of a semi-autonomous UV disinfection robot with HMI control addresses both the technological and practical challenges of healthcare disinfection. By allowing for real-time navigation and control, this system enables healthcare workers to precisely target high-risk areas without direct physical interaction, thus reducing exposure to harmful pathogens. This innovation not only contributes to lowering the incidence of hospital-acquired infections but also serves as a proactive solution to pandemic response, offering a scalable and effective method for maintaining cleanliness in critical healthcare spaces.

1.3 Report Outline

This report provides a structured overview of the development of an autonomous robot focused on monitoring critical environmental factors, such as temperature, humidity, and air quality, within healthcare settings.

The initial sections introduce the project, its objectives, and the motivation behind creating a system that enhances safety and infection control in medical environments. Subsequent sections explore relevant studies and background technologies to establish the need for this robotic system. Following this, the report elaborates on the design process, from hardware assembly to the integration of cloud-based software for real-time data visualization. The final sections include a comprehensive analysis of results, highlighting the system's performance in practical scenarios, and a conclusion that encapsulates the project's achievements while outlining the possibilities for future advancements, such as enhanced automation and expanded disinfection capabilities.

CHAPTER 2

LITERATURE SURVEY

Conventional disinfection processes tend to require manual effort and chemical substances, which are time-consuming, labor-intensive, and even harmful to human health. In order to overcome these shortcomings, a UV sanitizing robot capable of independently disinfecting different environments such as hospitals, schools, and public areas is proposed. Prior to discussing the details of this project, an extensive review of current literature is essential. This literature survey will discover and analyze relevant research establish the state of the art regarding the subject proposed project.Also this section lists and explore relevant research studies, technologies, and methodologies relating to UV disinfection and robotic automation.These studies help develop the level of existing knowledge in relation to the subject matter, outline the strengths and weaknesses of existing solutions, and determine likely gaps to be filled that this project aims to fill. Awareness of existing research and technological innovation will make sure the resulting solution leverages winning processes and introduces innovative improvements.

This section also facilitates the determination of any loopholes or weaknesses of existing research. The subsequent section will outline critical analysis of the pertinent scholarly writings. This review will give sound ground for inquiry and lead to knowledge enhancement in this area.

2.1 UV-C Technology

Disinfection involves a variety of methods to eliminate or reduce harmful microorganisms, each suited to different needs and environments. Chemical disinfection uses agents like alcohol, chlorine, and hydrogen peroxide, commonly seen in healthcare and sanitation. Physical methods include heat (like autoclaving or boiling), UV-C light for surface and air disinfection, and filtration using HEPA filters or water filtration systems. Gaseous disinfectants such as ozone, chlorine dioxide, and hydrogen peroxide vapor are effective in air and surface disinfection, often in healthcare and industrial settings. Mechanical disinfection involves manual scrubbing, while nanotechnology introduces antimicrobial surfaces with silver or copper nanoparticles. Emerging approaches like high-pressure systems and cold plasma are expanding the field, especially in areas with strict hygiene requirements. Often, combining methods—such as UV-C with chemical agents or heat with pressure—enhances effectiveness, particularly in high-risk settings like hospitals, food processing, and water treatment.

UV-C technology uses short-wavelength ultraviolet light to inactivate microorganisms like bacteria, viruses, and fungi. This technology has proven highly effective in disinfection and sterilization because UV-C light, with wavelengths between 200-280 nanometers, has germicidal properties that break down the DNA and RNA of pathogens[5]. This damage prevents them from reproducing or causing infections, effectively killing or neutralizing them. When microorganisms are exposed to UV-C light, the radiation penetrates their cell walls and disrupts their genetic material. This process primarily involves creating pyrimidine dimers within the DNA or RNA, which leads to errors in replication and transcription.

When the DNA is damaged this way, microorganisms can no longer replicate, rendering them inactive and harmless. This germicidal mechanism is especially valuable in environments where sterilization is essential, such as hospitals, laboratories, and food processing facilities[7].

UV-C light does not require the use of chemicals, which can be an advantage in sterile or clean environments so this is perfectly apt for this project. Since it relies only on light to inactivate pathogens, it can be a relatively quick process, depending on the power of the UV-C source and the exposure time. This non-contact approach reduces the risk of contamination and can sterilize areas that are hard to reach by traditional cleaning methods.

2.2 Simultaneous localization and mapping(SLAM)

Simultaneous Localization and Mapping (SLAM) and image recognition are foundational technologies that empower robots to operate autonomously in unknown environments. SLAM allows robots to build a map of their surroundings and simultaneously track their position within this map. This capability is essential for tasks requiring precise navigation and obstacle avoidance, as it enables the robot to create an internal representation of the environment and use that map to plan movements. SLAM relies on sensor data, often from a combination of LiDAR, depth cameras, and odometers, to achieve a real-time, evolving understanding of the surroundings. Meanwhile, image recognition adds another dimension, enabling the robot to visually interpret and respond to objects, gestures, and specific features in its environment, a critical function for interaction with human operators or adapting to changes in the environment.

1. **2D SLAM**

   2D SLAM involves creating a flat, two-dimensional map of the environment, which is often sufficient for tasks where navigation primarily occurs at floor level, such as in warehouses, hospitals, or offices[16]. In this process, a Flash LiDAR sensor (such as the Flash LiDAR F4) captures data that represents the distance to objects in the robot's immediate surroundings as shown in Figure 2.1. This data, when processed with a SLAM algorithm like GMapping, produces a 2D occupancy grid map, showing where obstacles exist relative to the robot's position.

   GMapping is based on particle filtering, a probabilistic technique that enables the robot to estimate its position and orientation within the map. The algorithm operates by generating a set of hypothetical positions, known as particles, representing possible states of the robot within the environment. Each particle is assigned a weight based on how well it matches sensor readings, particularly from the LiDAR and odometer.

These weights help refine the robot's understanding of its location, as particles that align closely with sensor data receive higher weights, and those that diverge are discarded.Over time, GMapping uses these particles to continuously update the robot's location and improve map accuracy. This type of mapping is valuable in dynamic environments where the robot needs to adjust its position frequently and in real-time to avoid obstacles like walls or furniture.

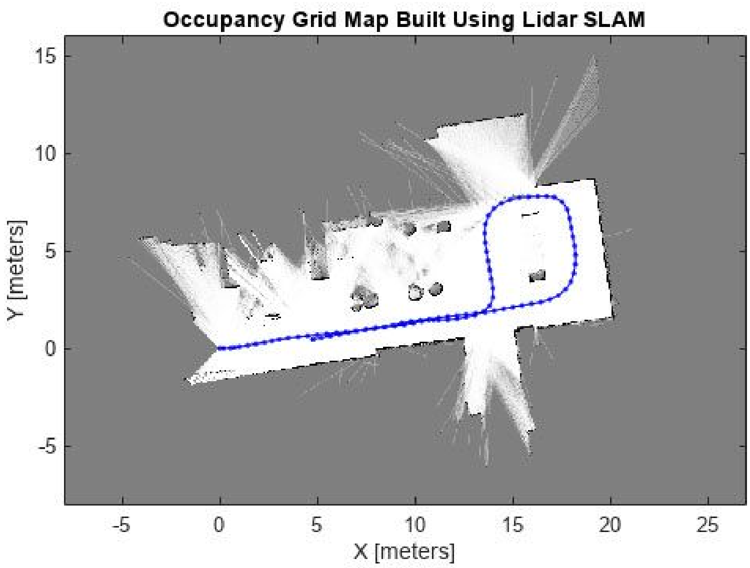

Figure 2.1: SLAM with 2D LiDAR

2. **3D SLAM** For environments that require an understanding of height and depth, such as multilevel buildings or spaces with shelves and tables, 3D SLAM is indispensable. 3D SLAM involves capturing data from a depth-sensing camera (like the Intel RealSense Depth Camera D435i), which provides information on the distance between the robot and objects at various heights. The depth camera allows for a richer, three-dimensional view of the environment, which is necessary when vertical navigation or interaction with raised objects is required as shown in Figure 2.2.

   In this application, ORB-SLAM (Oriented FAST and Rotated BRIEF SLAM) is employed, working alongside the Point Cloud Library (PCL) to construct a 3D map[17]. ORB-SLAM relies on feature detection and matching, where key points within images are identified and tracked across multiple frames to provide depth and spatial information. Using these points, ORB-SLAM can recognize areas the robot has seen before, enabling efficient localization and mapping. PCL is instrumental in processing and structuring the point cloud data collected by the depth camera, forming a more coherent representation of the environment.

This 3D map is particularly valuable for obstacle detection, allowing the robot to detect and avoid complex obstacles, including pedestrians, in real-time.

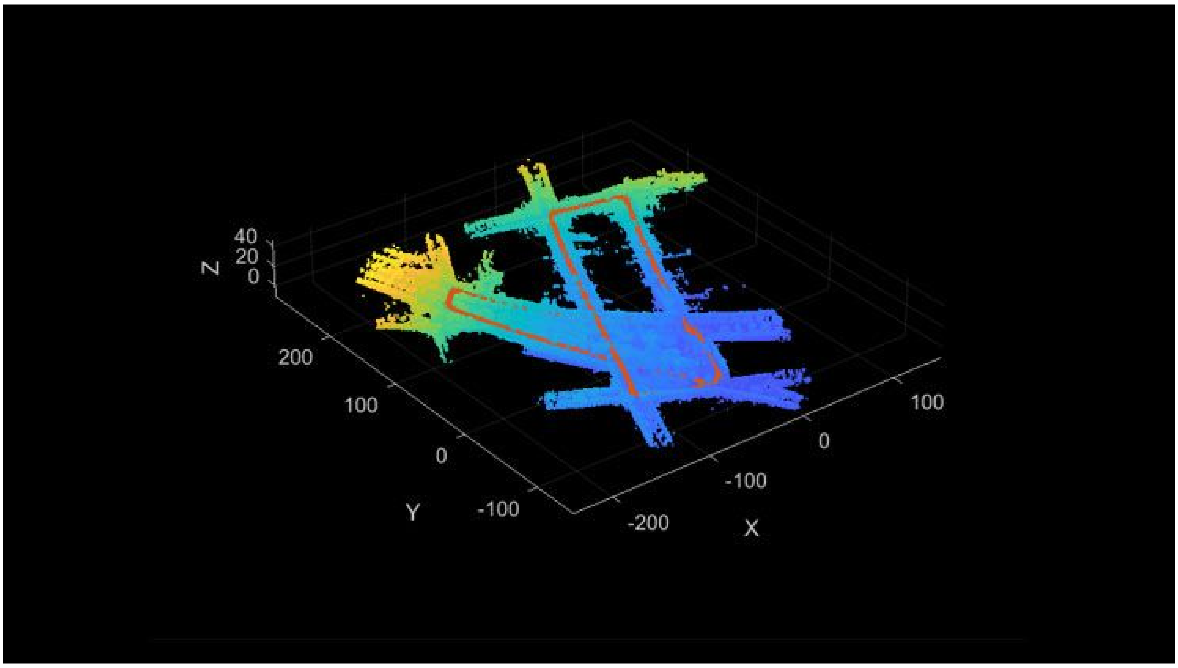

Figure 2.2: SLAM with 3D LiDAR

Despite its advantages, SLAM technology faces several implementation challenges. Processing the vast amounts of data from depth cameras and LiDAR in real-time demands very high computational power, which can be limiting for robots with lower processing capacities.

Additionally, SLAM's accuracy can be impacted by environmental factors such as poor lighting, which can disrupt vision-based SLAM systems.While sensor technology advances and machine learning techniques continue to improve, SLAM systems are expected to become more efficient and robust, addressing current limitations and expanding the potential of SLAM-based navigation, this has not been implemented in this project.

2.3 Boustrophedon Pattern based Path Planning for Disinfection Robots

The boustrophedon pattern is a popular path-planning method in robotics, used for thorough and systematic area coverage. In this approach, a robot moves back and forth in alternating rows, much like mowing a lawn, ensuring minimal overlap while covering the area efficiently. This structured pattern conserves energy and speeds up task completion, which is crucial in settings that require both speed and accuracy[18].

The term ”Boustrophedon” originates from Greek, meaning ”as the ox turns,” describing an ancient farming technique where farmers plowed fields in a zigzag pattern. Robots use this approach to ensure that no part of a designated area is left uncovered, which is critical in applications like UV disinfection, vacuum cleaning, agricultural spraying, and mapping. For example, in UV disinfection, thorough coverage is essential to expose all surfaces to UV light, which deactivates pathogens[19]. In agriculture, robots following this pattern can evenly spray pesticides or fertilizers, reducing missed areas that may affect crop growth.

In complex, real-world environments with obstacles such as furniture in hospital rooms the boustrophedon pattern is adapted with a grid-based approach. The robot divides the space into smaller cells, covering each cell individually before moving to the next, ensuring comprehensive coverage even in irregularly shaped areas. This cell-by-cell approach minimizes missed spots or redundant paths, enhancing efficiency.

This method has become foundational in robotics due to its simplicity and reliability. Whether in healthcare, agriculture, or logistics, the boustrophedon pattern allows robots to achieve consistent, complete coverage, meeting the demands of applications that rely on precision and efficiency.

As robots are increasingly deployed in autonomous roles, this method continues to support their ability to deliver consistent, high-quality performance across various industries. In this project, a basic back-and-forth movement inspired by the boustrophedon approach was considered sufficient for achieving complete area coverage with manual control. This design choice provides a simple but effective navigation strategy suited to environments with relatively straightforward layouts, like hospital corridors or rooms. Advanced grid-based boustrophedon patterns, which adjust paths dynamically around obstacles, is not implemented. Given the processing limitations of the ESP32, a simplified navigation was preferred to conserve power and resources.

2.4 Hydrogen Peroxide Vapour Disinfection

Hydrogen Peroxide Vapor (HPV) disinfection is an efficient technique widely used in healthcare and laboratory environments to sterilize surfaces, air, and hard-to-reach areas. This method as shown in Figure 2.3 disperses vaporized hydrogen peroxide into a sealed environment, allowing it to permeate and cover surfaces, cracks, and crevices. The vapor kills a broad range of pathogens, including bacteria, viruses, fungi, and spores, through a process called oxidation. When hydrogen peroxide is vaporized, it generates reactive oxygen species (ROS) that interact with cell membranes, proteins, and DNA within microorganisms. This oxidative action disrupts cellular structures, leading to pathogen inactivation and achieving a high level of sterilization, particularly valuable in settings such as operating rooms, intensive care units, and pharmaceutical facilities[20].

Figure 2.3: HPV Disinfection in Healthcare

In HPV systems, vapor is released into a space and allowed to dwell for a designated period, ensuring adequate contact with surfaces and the air. Advanced systems often include sensors to monitor hydrogen peroxide concentration in real-time, adjusting the release to maintain effective levels while minimizing waste. The residue-free nature of HPV suits environments requiring the highest sterility standards.

In comparison, this project focuses on UV-C disinfection rather than HPV, emphasizing a non-chemical disinfection method. Unlike HPV, UV-C disinfection uses ultraviolet light at wavelengths between 200-280 nanometers to inactivate pathogens on exposed surfaces. The UV-C radiation damages the DNA or RNA of microorganisms, preventing them from replicating and effectively neutralizing them. One of the main distinctions between UV-C and HPV disinfection lies in the mechanism of inactivation—UV-C physically disrupts genetic material through photodamage, whereas HPV chemically disrupts cellular components through oxidation. UV-C systems, as employed in this project, require line-of-sight exposure, meaning they are limited to surfaces directly reached by the UV light. Shadows or objects that block the light can reduce UV-C's effectiveness, whereas HPV vapor can penetrate these areas, providing more uniform coverage.

The UV-C approach offers advantages in terms of operational simplicity, safety, and maintenance. UV-C does not require a sealed environment, specialized venting, or vapor generation systems, making it straightforward and potentially less costly for disinfection in dynamic spaces. By relying on light rather than chemicals, UV-C disinfection can also reduce the risk of corrosion or material degradation over time. However, UV-C does have limitations addressed more effectively by HPV, particularly regarding surface coverage and pathogen reach. While UV-C is highly effective on surfaces directly exposed to the light, it may not disinfect recessed areas or the undersides of objects as thoroughly as HPV vapor.

2.5 Robotic Disinfection with Structure-Aware Semantic Mapping

In light of the ongoing COVID-19 pandemic, the demand for robots to assist or replace humans in performing critical disinfection tasks in public spaces has increased significantly. Traditional methods of disinfection are labor-intensive and expose workers to potential health risks. As a result, robots are now expected to handle these tasks autonomously and efficiently, especially in high-traffic environments like metro stations, airports, and public transport systems. However, since different areas within these environments have varying levels of infection risk, conventional robot systems equipped with the an advanced SLAM technology may not sufficient. Beyond just navigating a space, these robots must also be capable of recognizing and differentiating between objects and areas in the scene to execute customizable and targeted disinfection tasks.Semantic information (e.g., different categories of points including the door, wall, seat, joint, stanchion in the metro car) is extracted from the raw LiDAR point cloud, given the structure of the scene as prior knowledge[21].

Then such semantic information will be merged to construct a hierarchical semantic map of the scene, which is necessary for customizable disinfection tasks, especially for the disinfection distance and time control.
To address these needs, a LiDAR-based semantic mapping system specifically designed for robotic disinfection tasks is proposed. The system utilizes prior knowledge about the environment's structure to extract multi-level semantic information from raw point cloud data. This allows the robot to not only create an occupancy grid map for navigation but also generate a hierarchical semantic map. This map as shown in Figure 2.4 provides detailed, context-sensitive information, such as navigation waypoints, disinfection distances, and disinfection durations, enabling the robot to perform customizable tasks based on the specific requirements of each area. The project does not incorporate structure-aware semantic mapping, as this feature requires advanced image recognition and real-time processing beyond the capacity of the ESP32.

Instead, a more generalized disinfection approach was selected, focusing on consistent UV-C exposure across all accessible areas. The decision to exclude semantic mapping simplified the robot's design, while still ensuring effective disinfection in standard healthcare environments,analysis of disinfection duration for this project is inspired from this system. The proposed system has been validated in real-world metro disinfection applications, where

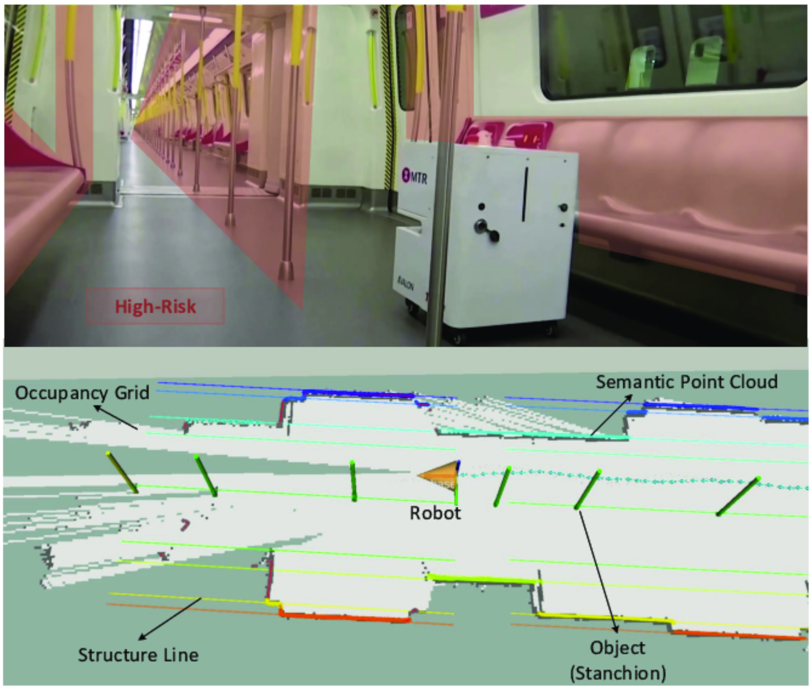

Figure 2.4: Robot with Color-Coded map for Targeted Disinfection

it demonstrated the ability to accurately recognize different areas and adjust its disinfection approach accordingly.

2.6 Autonomous Disinfection Planner based on the Irradiation Map

Many UV-C disinfection approaches utilize stationary light sources, but disinfection of distant areas is often slow due to energy decay with distance. Studies suggest that a mobile light source can disinfect areas more efficiently than a stationary one.An autonomous disinfection robot, therefore, needs to meet several requirements to effectively disinfect an environment. Much like humans, the robot should approach obstacle surfaces as closely as possible to maximize UV-C irradiation, covering all reachable free space and exploring to gather information about the environment. It should also disinfect the space uniformly, ensuring no contaminated areas remain, and operate autonomously, making its own decisions about where to move and when disinfection is complete[22].

To achieve these goals, a high-level planner sequentially selects waypoints in the place. With the waypoints set, the robot's control system adjusts movements through a local trajectory planning strategy, such as the ROS navigation stack. This method relies on a global 2D costmap that starts empty but is updated incrementally as the robot moves Combining data from a 2D SLAM map and 3D local input from RGBD cameras, along with an irradiation Map.The planner guides the robot to move close to obstacle surfaces. The UV-C energy

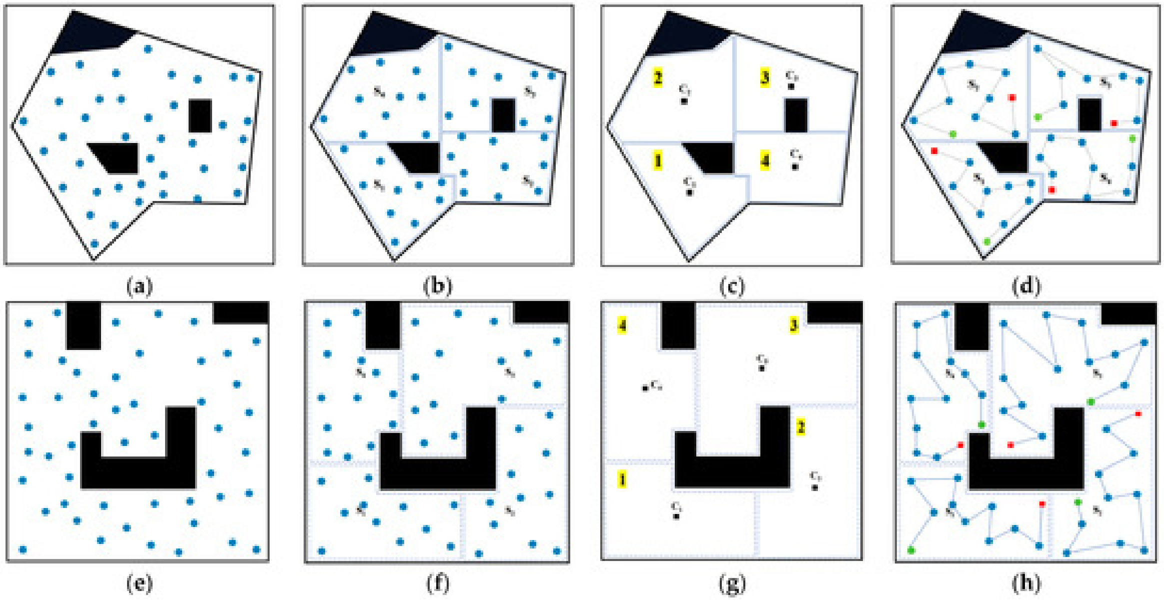

Figure 2.5: Coverage Planning for UVC Irradiation

delivered is highly dependent on distance: the closer the light source is to an obstacle, the higher the dose. To ensure effective disinfection, the robot must move around obstacles within a set distance range, maintaining safe proximity to avoid collisions while maximizing UV-C exposure[23]. Obstacles within the 2D gridmap are expanded by a specified number of cells toward free space chosen based on the smallest safe distance that prevents collisions as shown in Figure2.5. Only cells at the boundary between free space and this expanded zone are selected as waypoints, so the robot primarily moves along these borders, ensuring both safety and effective UV-C delivery.

The robot must cover all reachable free spaces to maximize surface irradiation. As it initially does not know the layout, it must explore to identify accessible areas. Consequently, only areas inaccessible to the robot will remain undisinfected.

The planner directs the robot along the borders of undisinfected obstacles, selecting an initial waypoint and neighboring waypoints in the same direction until the entire boundary is covered. If any border cells remain, the robot will revisit these areas to ensure complete disinfection.

After completing disinfection around one obstacle, the planner guides the robot to the nearest undisinfected border of the next obstacle, ensuring all reachable areas within sensor range are disinfected as a reasonable approach for environments like rooms and offices.

The irradiation map plays an essential role in estimating UV-C dosage, preventing redundant disinfection and highlighting areas that lack adequate exposure.This allows the planner to distribute disinfection evenly across the environment. For example, consider a room with a table in the center. The robot starts disinfecting along the walls, when it returns to the starting point, the irradiation map will show a lower UV-C dose around the table. The planner then guides the robot toward the table to complete the disinfection. This process continues until all accessible surfaces reach the required UV-C dosage for effective disinfection.

2.7 Optimizing Disinfection Parameters through Taguchi Analysis

The objective of the Taguchi analysis in this project centers on optimizing the parameters involved in the disinfection process to achieve maximum sanitization effectiveness. This analysis aims to determine the ideal operational conditions for the robot, ensuring that disinfection is both efficient and thorough.

The first step is to identify the control factors that will be manipulated during testing. In this project, these factors include parameters such as distance between the disinfection source and target surface, the duration of exposure to the UV light, and the speed of the robot's movement. For instance, different distances (e.g., 10 cm, 20 cm, and 30 cm), exposure durations (5 minutes, 10 minutes, and 15 minutes), and varying speeds (slow, medium, and fast) can be tested. Adjusting these parameters provides insight into their effects on disinfection efficacy[24] .

Next, appropriate levels for each control factor are defined to structure the experiments systematically. Using an L27 orthogonal array provides an efficient framework for the experiments, allowing for the examination of 27 unique parameter combinations without requiring an exhaustive number of trials. This structured approach ensures that each factor's impact on disinfection performance is observed while minimizing redundant testing.With the experimental design in place, testing proceeds in a controlled environment, where the robot is configured according to the specified settings in the orthogonal array. After each trial, disinfection effectiveness is assessed, potentially through quantifiable measures like microbial reduction rates.Once the experimental runs are completed, the data is subjected to statistical analysis. The Signal-to-Noise (S/N) ratio for each trial provides a measure of how effectively each configuration promotes disinfection. Utilizing statistical software, the analysis identifies the combinations yielding the highest S/N ratios, pointing to the optimal settings for each parameter.

Following this analysis, the results are visualized to offer accessible insights. A plot—such as a bar chart, line graph, or heatmap—can depict the relationship between various parameters and disinfection effectiveness. For example, a graph might show how exposure duration influences microbial reduction, or a heatmap might reveal optimal settings across all tested variables.

Finally, this visual data is embedded into the project's web interface, where it is available for review. The plot enhances the user experience by providing an intuitive display of the Taguchi analysis results, highlighting the most effective configurations for disinfection and helping users understand how each factor influences the process.

2.8 UV* (UV-Star) Algorithm

The UV* (UV-Star) algorithm is a variation of the well-known A* (A-Star) search algorithm, designed to efficiently navigate and find paths in graph-based search problems, particularly in environments with certain constraints or conditions that need to be addressed. While the traditional A* algorithm is widely used for pathfinding and graph traversal in various applications, the UV* algorithm incorporates unique enhancements that make it suitable for specific scenarios, particularly in robotics, where dynamic obstacles and environmental changes can significantly affect the pathfinding process.The UV* algorithm is capable of adapting to dynamic environments.

It can recalculate paths in real time as new obstacles are detected or as the conditions of the environment change, which is essential for applications in robotics and navigation systems[25]. Similar to A*, UV* utilizes a heuristic cost function to evaluate the desirability of each node in the search space. However, UV* may adjust the heuristic based on environmental factors, such as the density of obstacles or varying terrain, improving the algorithm's efficiency and path optimality.

The algorithm is designed to operate in real-time, making it suitable for scenarios where quick decision-making is critical, such as autonomous vehicles or robotic systems navigating unpredictable environments[26]. The UV* algorithm can incorporate uncertainties in its pathfinding approach, such as unpredictable movements of dynamic obstacles. This is achieved through probabilistic modeling, which allows the algorithm to estimate the likelihood of various paths and make informed decisions based on that information.

UV* often employs improved heuristic functions that are specifically tailored for the characteristics of the environment it operates within, enhancing its ability to find the shortest or most efficient paths compared to the standard A* algorithm.

In scenarios involving multiple robots or agents, UV* can be adapted to coordinate the movements of these entities, ensuring that they do not collide while navigating towards their respective goals. This coordination is vital in environments with shared space constraints.

The UV* algorithm represents a significant advancement over traditional pathfinding methods like A*, particularly in environments characterized by dynamic obstacles and uncertainties. Its adaptive capabilities, real-time performance, and enhanced heuristics make it a valuable tool in fields requiring efficient and effective navigation solutions.
By continuously evolving and responding to changing conditions, the UV* algorithm contribute to the development of smarter and more capable autonomous systems.

2.9 Cloud Technologies in Healthcare Disinfection

Cloud technologies provide a secure, transparent, and reliable framework for data storage and analysis, essential for healthcare environments that prioritize stringent hygiene and regulatory standards[27]. In healthcare disinfection, cloud technology can act as a centralized platform for logging disinfection activities, recording environmental conditions, and tracking operational parameters. This centralized storage allows easy access to data for multiple stakeholders, including hospital administrators and maintenance teams, promoting visibility and accountability in sanitization practices.

In this project, cloud technology has been harnessed to record real-time environmental data, such as temperature, humidity, and air quality, during each disinfection session. By leveraging cloud-based data logging, the project establishes a reliable record of each cycle, ensuring traceable and accessible data for review. This setup, though not decentralized like blockchain, benefits from cloud storage's secure access controls, which safeguard data integrity and ensure that records remain tamper-proof and verifiable. This approach is especially useful in regulated healthcare settings where a reliable log of disinfection activities supports compliance and patient safety.

Another critical feature of cloud technology in healthcare disinfection is automated data collection, which has been incorporated into the project. Through automatic logging at specified intervals, the system builds a continuous, accurate record of disinfection activities. This consistency in record-keeping, achieved through cloud-based data storage, reduces the risk of human error and provides a comprehensive trail of each disinfection session for healthcare personnel to review as needed.

The project also incorporates cloud-inspired transparency by enabling remote access to data via a web interface. In cloud systems, this feature allows multiple stakeholders to view data in real time, supporting coordinated oversight. Similarly, this project's cloud integration facilitates remote access to environmental readings and disinfection status updates, allowing healthcare staff to monitor disinfection progress from any location with internet access.

Although the project does not utilize a decentralized ledger, this transparency feature ensures that disinfection data is accessible and reliable, building trust in the process.Certain advanced features of cloud technology, however, have not been implemented due to practical considerations. For example, cloud-based machine learning for real-time disinfection analytics, while enhancing automation and precision, requires more computational resources and network infrastructure to achieve low latency[28].

This project relies on simpler automation through predefined sensor thresholds rather than complex cloud-based algorithms, optimizing resource usage while still ensuring effective disinfection.Additionally, distributed data replication across multiple cloud regions, common in advanced cloud setups for data resilience, is omitted here to maintain manageable storage requirements.

In summary, this project integrates select cloud technology features—secure data logging, remote accessibility, and automated record-keeping—to support reliable and transparent healthcare disinfection processes. These cloud-inspired elements fulfill the core objectives of secure and traceable disinfection without the added complexity and resource demands associated with more advanced cloud setups, allowing the project to remain focused on efficient data management within healthcare environments.

2.10 Selective Disinfection using Directional UV Irradiation and AI

Selective disinfection using directional UV irradiation and AI addresses the limitations of traditional UV systems that emit omnidirectional radiation, which poses safety concerns due to potential human exposure and requires personnel evacuation during operation. A targeted UV disinfection system has been developed by integrating robotics, laser technology, and deep learning algorithms, allowing for precise application of UV radiation to designated surfaces while avoiding unintended areas such as human occupants. A laser-galvo mechanism and a camera mounted on a two-axis gimbal enhance the system's accuracy in identifying and disinfecting high-touch surfaces. Deep learning algorithms facilitate real-time surface recognition, improving both safety and operational efficiency in disinfection processes[29]. Incorporating advanced oxidation processes can further enhance the effectiveness of UV-based disinfection systems.A UV photocatalytic oxidation-based system generates hydroxyl radicals and negative air ions to inactivate pathogenic microorganisms, effectively addressing shadowed regions where direct UV light penetration is limited. This approach achieves over 95% bacterial inactivation efficiency, ensuring comprehensive sterilization even in some complex environments. Intelligent space sterilization systems that monitor environmental data in real-time and adapt disinfection strategies accordingly play a crucial role in effective pathogen control. An AI-based system utilizing UV-LEDs, complex sensors, wireless communication devices dynamically controls air purification and sterilization mechanisms based on the contamination analysis, optimizing disinfection processes in multi-use spaces, including public transportation and medical facilities[30]. The integration of directional UV irradiation and AI has proven particularly effective in addressing disinfection challenges posed by the COVID-19 pandemic, with selective disinfection systems aimed at mitigating virus transmission through targeted application. These systems combine UV technology with AI to enhance disinfection efficacy during pandemic scenarios, highlighting the potential for widespread implementation in healthcare environments.

The convergence of directional UV irradiation, AI, and advanced oxidation technologies offers a promising avenue for developing intelligent disinfection robots capable of targeted and efficient sterilization.These systems effectively identify and disinfect high-touch surfaces while ensuring safety through dynamic pedestrian avoidance, aligning with cloud-connected solutions for remote disinfection in pandemic healthcare settings and offering a proactive approach to infection control.

2.11 Real-Time Environmental Sensing and Adjusted Disinfection Levels

Integrating real-time environmental sensing is essential to ensure that the robot can maintain optimal conditions for UV-C disinfection efficacy. Environmental factors, such as temperature, humidity, and air quality, play a significant role in the effectiveness of UV-C light against pathogens, as they can directly influence pathogen survival rates and the required UV-C exposure levels to achieve effective disinfection. For instance, increased humidity levels can create favorable conditions for pathogens, necessitating a stronger or prolonged UV-C exposure to counteract the resilience of microorganisms. Similarly, deteriorated air quality may indicate a higher microbial load, thereby requiring intensified disinfection efforts[31].

This project addresses these environmental challenges by incorporating dedicated sensors to monitor key parameters: the DHT22 sensor measures temperature and humidity, while the MQ135 sensor assesses air quality in the immediate surroundings. These sensors provide continuous environmental data, allowing the robot to make informed adjustments to its UV-C intensity or exposure duration as conditions fluctuate. For example, if humidity levels rise above a predefined threshold, the robot can automatically extend the UV-C exposure time or amplify its intensity to ensure disinfection effectiveness remains uncompromised, regardless of less-than-ideal environmental conditions[32].

In the context of a healthcare facility, this capability is particularly advantageous as it allows the robot to dynamically respond to variations in environmental conditions commonly experienced in such settings, including HVAC system adjustments or changes in room occupancy. Real-time environmental data is continuously uploaded to Firebase, where it can be stored for future analysis or immediate access by healthcare personnel. By compiling a historical record of environmental and disinfection data, the system provides valuable insights into the correlation between environmental conditions and disinfection outcomes, aiding healthcare staff in identifying patterns or specific conditions that may impact disinfection efficiency. This data-driven approach supports ongoing optimization and fine-tuning of the robot's disinfection protocol, making it adaptable and responsive to the unique environmental conditions encountered in healthcare environments[33].

2.12 Conclusion of Literature Survey

In conclusion, the conducted literature survey has yielded valuable insights into the field of the project. The review of relevant technologies has provided a comprehensive understanding of existing research, advancements, and challenges within the project domain.

Analysis of the literature has identified several advantages of the project, including its focus on real-time monitoring, utilization of resistance values for accurate results, and the portability of the system. These strengths differentiate the project from existing works and offer potential benefits in terms of improved patient care, usability, and efficiency.

The findings from the literature survey provide a strong foundation for the project, offering valuable insights and guidance. The identified gaps and opportunities outlined in the literature will inform future research and development endeavors, enabling the project team to address limitations and further enhance the effectiveness and practicality of the project. Through the literature survey, key advancements and innovations within the project domain have been identified. This includes understanding the latest technologies, methodologies, and best practices that researchers and practitioners have employed. By being aware of these advancements, the project can benefit from the existing knowledge and build upon the work of others. Furthermore, the literature survey has shed light on the challenges and limitations that researchers have encountered in the field. This has provided insights into potential pitfalls and hurdles that the project may face. By understanding these challenges, the project team can develop strategies to overcome them or devise alternative approaches.

In summary, the literature survey presents a comprehensive overview of the existing knowledge and research landscape within the project domain. It guides the project team in understanding the current state-of-the-art, identifying challenges, and exploring potential avenues for innovation. With the knowledge, the project is poised to contribute to the advancement of the field and make a meaningful impact.

CHAPTER 3

METHODOLOGY

This section outlines the comprehensive methodology adopted for the design and the implementation of the UV disinfection robot. The primary objective of this project is to develop an automated system capable of disinfecting surfaces effectively, thereby enhancing hygiene and safety in various environments through the integration of advanced microcontroller technology and a variety of peripheral devices. Central to this system is the ESP32 DevKit ESP32-CAM module, which serves as the main processing unit, coordinating the functionalities of multiple components including the UV LEDs, ultrasonic sensor, temperature and humidity sensor, piezoelectric buzzer, RGB LEDs, motor driver, and relay module.

The methodology is structured into two main segments: the block diagram and the circuit diagram. The block diagram provides a high-level overview of the system architecture, illustrating the interconnections and interactions among various components. This diagram emphasizes how each element collaborates to accomplish the desired disinfection functionality, ensuring the robot navigates its environment while effectively delivering UV light to targeted areas.

Conversely, the circuit diagram which is designed in Fritzing Software presents a detailed examination of the specific electronic connections within the system. This diagram outlines how the components are wired and configured, enabling seamless communication and operation between the microcontroller and the peripherals. Together, these diagrams provide a holistic perspective on the system's design and integration, promoting efficient operation and ease of use. The insights derived from both the block and circuit diagrams underscore the careful planning and collaboration that underpin the development of the UV disinfection robot.

3.1 Block Diagram

The block diagram in Figure3.1 provides an all-encompassing visual overview of the key elements and their interactions in the UV disinfection robot. Each block represents an essential module, showing how data moves among different hardware and software components to provide seamless, autonomous, and cloud-integrated disinfection capability. ESP32 microcontroller acts as the controlling unit, interpreting inputs from the sensors while balancing motor control, UVC lamp switching, real-time data upload, and interaction with the cloud. Being an efficient microcontroller, it sees to it that all the attached modules run without hitches through performing several duties at a go. Its double-core structure coupled with its built-in Wi-Fi functionality makes its integration with the cloud services as well as the remote control interface seamless. The ESP32 accepts inputs from the temperature and humidity sensor, air quality sensor, ultrasonic sensor, and ESP32 CAM, and controls the switching of UV LEDs, motors, and alerting devices like the buzzer and RGB LED.

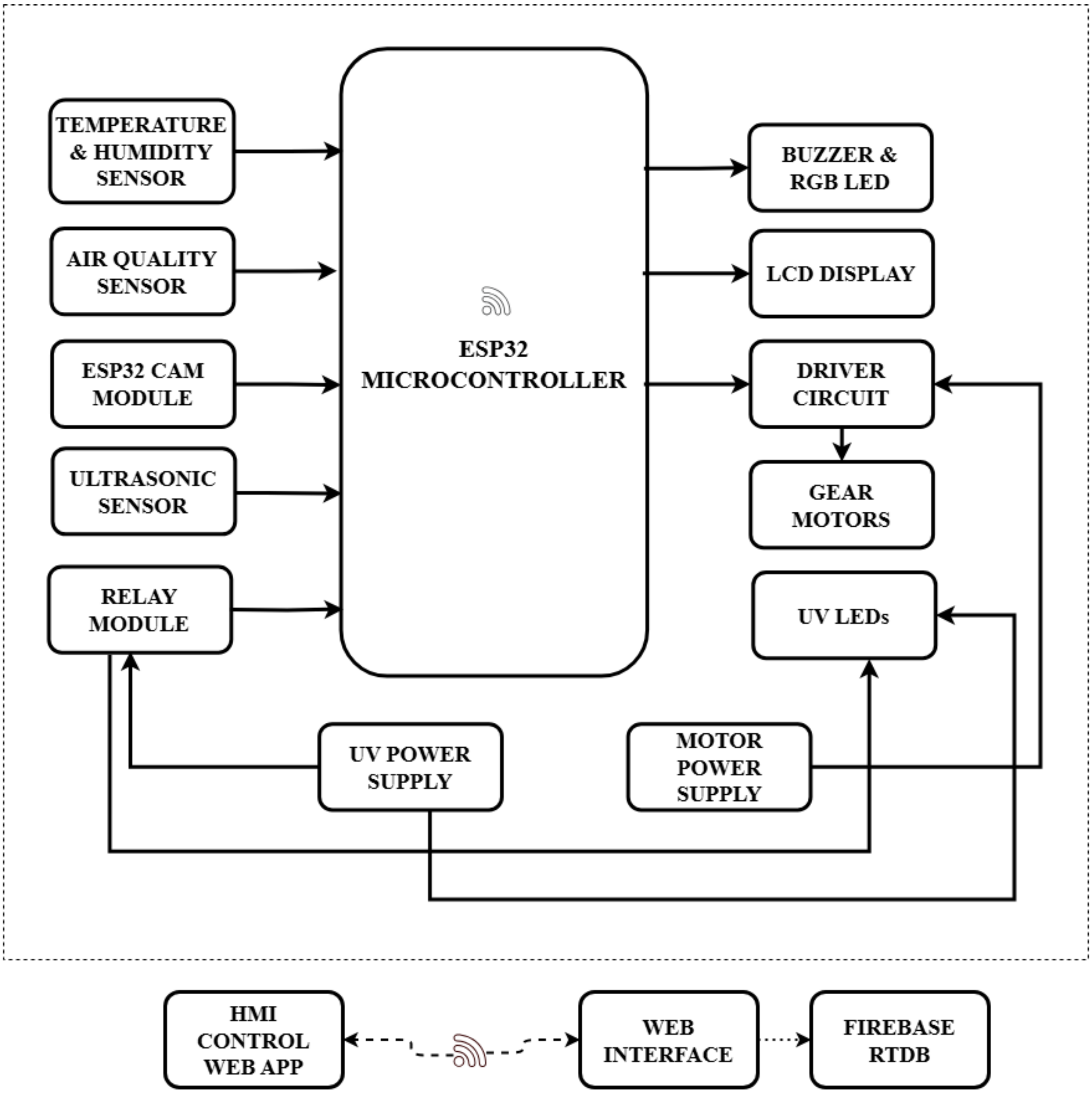

Figure 3.1: Block Diagram for UV Disinfection Robot

The block diagram in Figure 3.1 provides an all-encompassing visual overview of the key elements and their interactions in the UV disinfection robot. Each block represents an essential module, showing how data moves among different hardware and software components to provide seamless, autonomous, and cloud-integrated disinfection capability. ESP32 microcontroller acts as the controlling unit, interpreting inputs from the sensors while balancing motor control, UVC LED switching, real-time data upload, and interaction with the cloud. Being an efficient microcontroller, it sees to it that all the attached modules run without hitches through performing several duties at a go.

Its double-core structure coupled with its built-in Wi-Fi functionality makes its integration with the cloud services as well as the remote control interface seamless. The ESP32 accepts inputs from the temperature and humidity sensor, air quality sensor, ultrasonic sensor, and ESP32 CAM, and controls the switching of UVC LEDs, motors, and alerting devices like the buzzer and RGB LED.

The temperature and humidity sensor is important in achieving efficient disinfection by keeping track of environmental factors that directly affect the intensity and duration of UVC exposure. The real-time data collected by this sensor is processed by the ESP32 so that the system can dynamically control disinfection parameters to provide maximum effectiveness. The air quality sensor checks for the presence of toxic gases or contaminants in the atmosphere so that the air is safe for disinfection. If there is any air quality deviation, the ESP32 sends out alerts via buzzer and RGB LED to inform users of the contaminated environment. This preventive monitoring ensures a secure and controlled environment for disinfection.

The ESP32 CAM module offers real-time video feedback, enabling a remote visual inspection of the disinfection process. This video stream is crucial in monitoring the path of the robot, confirming that the target zone is adequately disinfected, and checking for obstacle-free movement. The ESP32 CAM sends video information to the web interface, which is accessed by users to monitor the live stream and remotely control the robot. The ultrasonic sensor, positioned on the robot strategically, monitors for obstacles along its path by measuring the distance to objects ahead. The ultrasonic sensor data allows the ESP32 to dynamically modify the trajectory of the robot, thereby preventing collisions and providing smooth movements. The use of this sensor is critical for ensuring that the robot is capable of navigating cluttered and changing environments safely.

A relay module is used for controlling the operation and shutdown of the UV LEDs and gear motors by being linked to the ESP32. The relay provides assurance that UV LEDs receive power only when needed, avoiding unnecessary exposure and saving energy. According to programmed conditions or remote user instructions, the ESP32 commands the relay to switch on or off the LEDs to maintain control over the disinfection process. This system provides enhanced operation safety by avoiding inadvertent UVC exposure. The motor control system, driven by a 12V lead-acid battery, is controlled by an L298N motor driver that receives instructions from the ESP32 and controls the gear motors accordingly. Owing to the heavy load and intricate nature of the movement of the robot, pivot or on-the-spot turn is utilized in order to move effectively. The L298N provides stable and smooth movement while keeping the robot's direction and speed under control as it efficiently traverses the target area for disinfection.

Real-time feedback to users is delivered through a piezoelectric buzzer and RGB LED module by producing sound and light signals during decisive moments. The buzzer is designed to produce sound whenever decisive events occur, including task accomplishment, collision, and alterations in air quality. At the same time, the RGB LED dynamically changes color to display the robot's operational status visually. For instance, a green color signifies normal operation, a red color an obstacle or unfavorable environmental condition, and a blue color the robot's standby mode. Such feedback mechanisms help users stay aware of the system status and take necessary action in case of an issue in real time.

An LCD display, connected to the ESP32, gives real-time graphical feedback of important system parameters, such as temperature, humidity, air quality index, and status of the UVC LEDs. The LCD display enables users to see the operation status of the robot visually in real time, so any discrepancies or changes are clearly observable. This graphical feedback adds transparency and reliability to the system, in addition to the cloud interface where data is recorded and processed for long-term analysis.

Power to the whole system is provided by a 12V lead-acid battery, which gives sufficient power to the motors, UV LEDs, sensors, and other parts. The high capacity of the battery guarantees steady performance and long-lasting operation without repeated recharging. Independent power supplies are assigned to the UV LEDs and the motor system, so that each subsystem gets enough power without compromising the other's performance. The relay module acts as a sentinel in controlling this power supply to avoid overloading and ensure stability of the system.

The cloud-connected system is capable of transferring data in real-time and far-end control. The ESP32 talks to a Firebase real-time database (RTDB), logging environmental data, operating parameters, and system states in real time. The information can be retrieved by users from the web interface, which in turn is linked to the HMI (Human-Machine Interface) control web app. The app provides remote monitoring and control of the robot, with features that enable users to initiate or terminate disinfection cycles, monitor live video streams, and receive live alerts regarding the state of the system. The cloud connectivity allows the robot to be accessed and controlled from any location, which increases the usability and flexibility of the system.

In summary, the block diagram clearly illustrates the integration of different hardware and software components that operate harmoniously to provide seamless and autonomous UVC disinfection. Every module, ranging from sensors and actuators to communication interfaces and power management, plays a role to make the robot efficient, safe, and reliable. The interconnected design of these modules guarantees that the robot performs at its best in the dynamic environments, providing an effective solution for pandemic healthcare decontamination with the ability to support remote monitoring and control through cloud integration.

3.2 Circuit Diagram

The circuit diagram for the Cloud-Connected UV disinfection robot, as seen in Figure3.2, carefully displays the complex connections between the various hardware elements working together to control the functionality of the system. The central command of the circuit is the ESP32 microcontroller, a very powerful and adjustable device that controls the core for data processing, command execution, and maintaining co-ordinated activation of all interlinked components. The ESP32 not only controls sensor inputs and motor drive but also performs wireless communication, enabling real-time data transmission and remote control. The addition of the ESP32 CAM greatly extends the capability of the system by providing real-time video feedback, which is important for visually monitoring the disinfection process remotely. The camera provides a live video feed that enables users to watch the path of the robot, confirm the effectiveness of the disinfection process, and confirm whether the environment surrounding the robot has been properly disinfected.

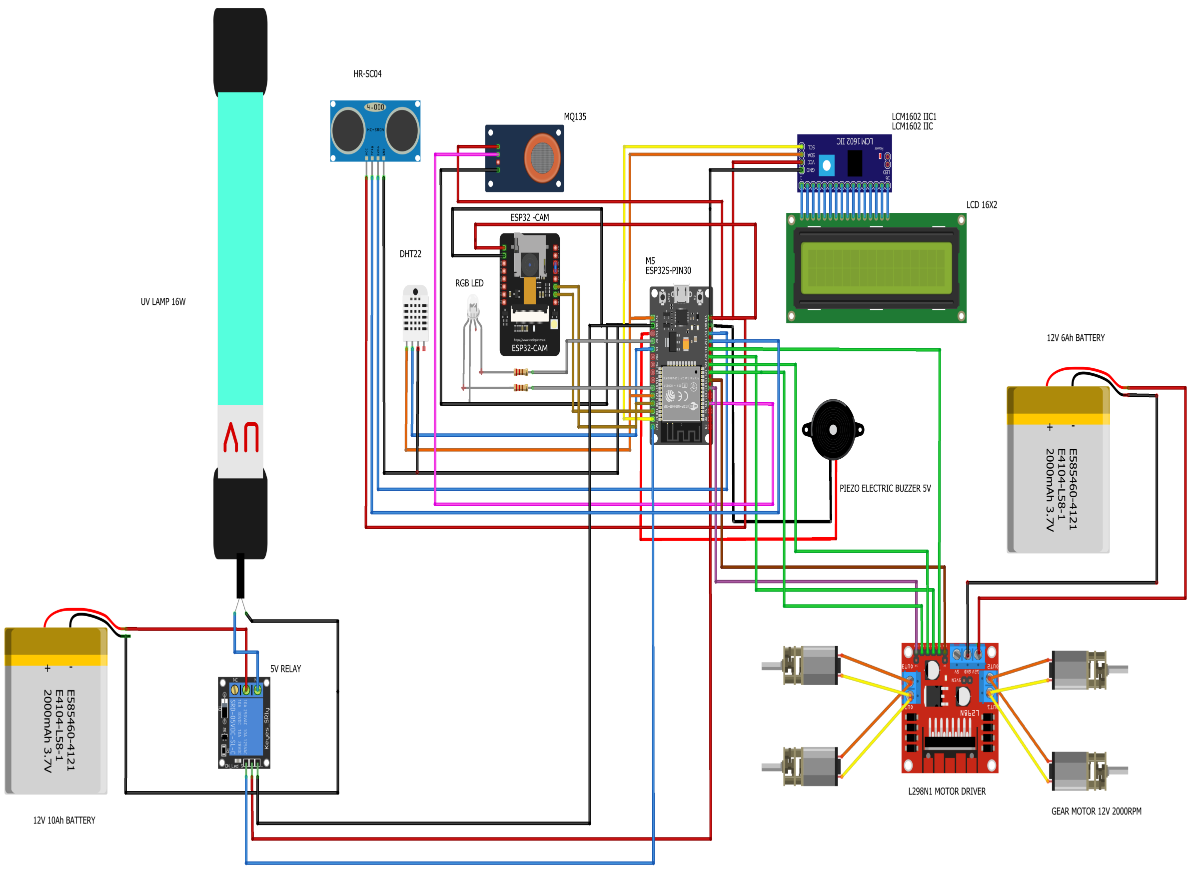

Figure 3.2: Circuit Diagram for UV Disinfection Robot

One important module incorporated in the system is the DHT22 temperature and humidity sensor that is directly plugged into the ESP32 microcontroller. This sensor is instrumental in tracking the environmental factors that have an impact on the effectiveness of UVC disinfection. Real-time temperature and humidity information is recorded and interpreted by the ESP32, enabling the system to adaptively regulate the intensity or duration of exposure to UVC depending on the environment. For example, increased humidity might necessitate longer exposure periods to achieve proper disinfection, and variations in ambient temperature might influence the conduct of airborne pathogens. This dynamic response ensures each disinfection cycle is optimized for peak performance, maximizing overall system reliability.

An HC-SR04 ultrasonic sensor is also added to further improve the autonomous navigation and collision avoidance capabilities of the robot. This sensor identifies obstacles along the path of the robot through the measurement of the time it takes for ultrasonic pulses to reflect off surrounding objects. The information from the ultrasonic sensor is constantly communicated to the ESP32 microcontroller, allowing the robot to adjust its path in real-time, thus preventing collisions. The inclusion of this sensor makes the robot able to navigate through environments with numerous obstacles in a safe manner and continue with uninterrupted and smooth functionality even in heavy or complex conditions.

Apart from environmental scanning and obstacle sensing, the system features an MQ135 air quality sensor, which tests the air condition around the robot. This sensor is extremely sensitive to a series of dangerous gases and pollutants, including ammonia, benzene, and smoke, and is thus an extremely valuable device in ensuring a safe disinfection environment. Through monitoring the air quality at all times, the robot is able to identify any variations that can compromise the efficacy of the disinfection process. If dangerous levels of contaminants are found, the system is able to initiate proper alerts or adjust operation parameters to reduce possible hazards.

In order to implement real-time visual feedback and show important system parameters, an LCD display has been incorporated into the system. The LCD display, which is directly connected to the ESP32 microcontroller, shows fundamental details like real-time temperature and humidity levels, air quality index value, and the condition of the UVC LEDs. While the disinfection is in progress, the LCD displays real-time information regarding the robot's running status, such as task completion, obstacle detection, and air quality status. This visual feedback provides operators with the ability to track the performance of the robot and react promptly to any deviation or environmental changes. The LCD also displays system error or operational warning-related alerts, enhancing situational awareness and improving the overall system reliability.

The circuit also includes an RGB LED on the ESP32 microcontroller, which can be used as a dynamic visual indicator of the status of the robot. The RGB LED is color-coded according to varying operational states and provides a simple and quick means of informing the users of the system condition. Green light shows that the system is operating normally with no obstacles and safe environmental conditions. Red light warns of an obstacle detected in the robot's path or an environmental condition which may influence disinfection. Blue light warns that the robot is waiting or ready to start the next cycle of disinfection. The use of the RGB LED has strengthened the system's capability to present real-time status information to users, supplementing the visual information shown on the LCD screen.

To guarantee effective communication of crucial information to the users, the circuit incorporates a piezoelectric buzzer, which is attached to the ESP32 microcontroller. The buzzer generates sound signals on the basis of particular triggers, like task achievement, alerts concerning poor air quality, or identification of obstacles. The sound alerts guarantee that the users are updated about the operation of the robot and can immediately act in case of an issue. The addition of the buzzer provides an added layer of reliability and safety, ensuring the strength of the system in various operation environments. With the integration of the RGB LED, the buzzer also enhances user perception by giving both visual and auditory indications for important occurrences.

Another important component of the safety and effectiveness of the system is the accurate regulation of power to the UVC LEDs and motors. This operation is controlled by a relay module, acting as a precaution by allowing for controlled switching on and off of the UV LEDs and gear motors. The relay prevents the UV LEDs from turning on unnecessarily, saving energy and avoiding unnecessary exposure. By following pre-programmed conditions or user-defined instructions, the relay module exercises tight control over the operation of the LEDs, improving energy efficiency and operational safety. The relay also prevents power surges or accidental activation, protecting the hardware of the system and prolonging its lifespan.

The robot's movement is controlled by an L298N motor driver, which controls the 12V DC gear motors to provide smooth and accurate control of the robot's speed and direction. The L298N module receives commands from the ESP32 microcontroller and converts them into electrical signals that control the rotation speed and direction of the motors. Due to the high loading and complex movements of the robot, the system uses pivot or on-the-spot turning to move effectively since differential steering alone is not adequate for smooth movement. Through this kind of design, the robot is able to make precise turns and stay stable while in use.

The whole system is powered by a 12V lead-acid battery, which delivers stable and reliable power to all the parts, such as the motors, UVC LEDs, sensors, and control modules. The high capacity of the battery ensures extended operation without requiring frequent recharging, allowing the robot to execute long disinfection operations without breaks. A battery supplies a 12V 2A output to feed peripheral components, with stable voltage levels that protect the reliability of the system.

To enable remote monitoring and control, the ESP32 microcontroller sends data to a cloud database where real-time data are stored and analyzed. This cloud connectivity enables users to view operating data anywhere in the world, allowing for round-the-clock monitoring of environmental conditions, air quality, and the disinfection status. The cloud interface also provides data logging and historical analysis capabilities, providing insights that can be utilized to optimize and improve the disinfection process over time.

In conclusion, the circuit diagram illustrates the advanced network of interconnections that control the robot's functionality. Every device, ranging from sensors and motors to microcontrollers and communication modules, contributes to seamless and autonomous UVC disinfection. The incorporation of the LCD display, RGB LED, and piezoelectric buzzer provides users with real-time information through visual and auditory indicators, which boosts situational awareness and system dependability. By making sure that all hardware components function in perfect harmony, the system ensures high efficiency, safety, and operational resilience, making it an all-around solution for pandemic healthcare disinfection in various environments.

3.3 Framework Design

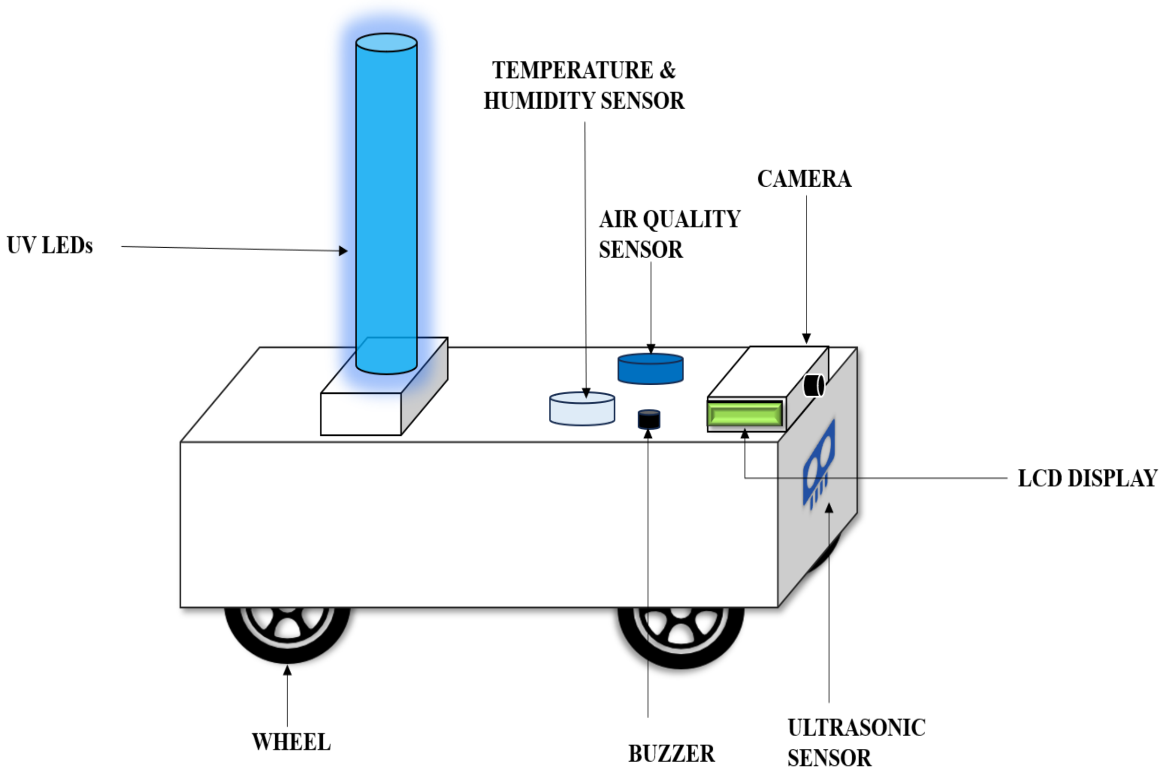

Figure 3.3: Framework Design of Disinfection Robot

The Framework Design of the UV disinfection shown in Figure 3.3 robot incorporates structural parts, sensors, and electronic devices for stability and performance. The robot base is built with a forex sheet combined with a multi-wood framework that offers lightweight protection as well as mechanical stability. The motors, wheels, and battery packs are firmly fixed onto the multi-wood base, guaranteeing smooth movement and load handling.

The motor unit is made up of four motors with a voltage of 12V, RPM of 100, rated torque of 2.9 kg·cm, and stall torque of 11.9 kg·cm. The motors are fixed at the bottom with metal brackets and screws, and there is rubber cushioning between the brackets and the bottom to act as a vibration absorber and improve stability. The motors are attached to the wheels, facilitating smooth movement and pivot turns based on the high weight of the robot.

The erect structure that contains the UVC LEDs and LED strips is mainly made from a PolyVinyl Chloride (PVC) cylindrical pipe with a diameter of 2 inches is employed to keep the UVC LEDs aligned. The erecting structure allows the UVC LEDs to be kept vertically in order to ensure maximum disinfection efficiency by channeling the radiation onto the target surface.In front of the robot, ultrasonic sensors are installed to sense obstacles and offer human presence detection. An RGB LED indicator is also located close to the sensors to show obstacle status—red when detected and green when no obstacle is detected. Cameras, such as an ESP32-CAM for live streaming, are installed in the front to offer real-time monitoring and path tracing. Within the robot, the DHT22 and MQ-135 sensors are safely housed to track temperature, humidity, and air quality readings while in operation.The base houses the battery compartment for two 12V lead-acid batteries (7.2Ah), which are soldered in series to deliver 24V to the UVC LEDs and the LED strips. There is a single battery delivering a 12V 2A output for driving auxiliary devices. The sensor, motor, and LED wires are routed out of the way along the frame and secured with cable ties to avoid entanglement and ensure safe operation.

The end assembly provides a solid and balanced framework incorporating motors, sensors, cameras, and UVC LEDs with great ease. With the union of a safe base, a PVC pipe containing the UVC LEDs, and precisely placed sensors and cameras, stability and performance in the robot are guaranteed when operating.

3.4 UVC Safety Protocols for Protection

In case of deployment of this UV disinfection robot in public spaces, the safety of human beings from exposure to UVC is critical.Protective safety protocols for human beings and the general public need to be initiated. UVC light is both eye and skin harmful, producing erythema and photokeratitis, requiring safe measures against direct or indirect exposure.
Prior to launching the robot, everyone in the area should don the proper Personal Protective Gear (PPE) to protect against UVC exposure. Safety glasses or face shields specifically designed for blocking UVC wavelengths must be used by operators or maintenance personnel at all times. Regular sunglasses or clear safety glasses do nothing against UVC, so using UVC-certified eyewear that provides total protection is very important. Besides, the skin should be covered with long-sleeved garments and gloves made of resistant materials against

Figure 3.4: Warning; Optical radiation

UVC penetration. If prolonged exposure cannot be avoided, wearing UV-blocking face shields and aprons is strongly advisable.

Removing or covering material that can degrade or emit toxic byproducts upon long exposure to UVC is also a vital safety precaution. Some plastics other man-made materials, tend to degrade from UVC irradiation, generating toxic fumes or compromising their structural integrity.
These items would need to be removed prior to starting the disinfection cycle or replaced with equivalent UV-resistant counterparts or wrapped using UVC-proof shields like aluminum foil or industrial UV-blocking coverings. In addition, sensitive surfaces and equipment that can be compromised by UVC exposure should be moved or covered to preserve their operation.

To further reduce risk, rooms in which UVC disinfection is performed should be isolated and posted with obvious signage. Warning signs should alert of active UVC use and limit access during the disinfection cycle. These signs must be installed at all entry points and clearly readable from a distance. Where possible, physical barriers in the form of tape or temporary enclosures can be utilized to discourage unauthorized access into the exposure zone. All persons must be ensured to have cleared the area before starting the robot, and only be re-admitted once they are certain that the UVC cycle is done and the area is safe.

Emergency procedures should also be set up in the event of accidental exposure. First aid steps for UVC exposure involve immediate flushing of the eyes with cool water for at least 15 minutes and seeking medical assistance if symptoms such as eye irritation or skin redness develop. All personnel should be trained to identify the signs of UVC overexposure and respond quickly to avoid damage. Reports on incidents of UVC exposure should be kept in order to enhance safety measures and minimize recurrence.

Through adherence to these protocols, the use of the UV disinfection robot can be conducted safely, thereby reducing the risk of UVC-induced injuries and promoting the health of occupants of public places.

3.5 Conclusion

Finally, the developed system provides a holistic, autonomous UV disinfection solution that directly tackles the need for efficient and dependable sterilization across various settings. Through the inclusion of crucial sensors like the DHT22 to monitor temperature and humidity levels, the MQ135 to detect air quality, and ultrasonic sensors to map out obstacles, the system achieves real-time awareness of the surroundings, which augments the effectiveness of the UV-C disinfection process. Actuators and motor control through the L298N driver facilitate accurate movement and coverage so that the robot will move effectively and cover all spaces without gaps. The ESP32 microcontroller deals with sensor readings and commands for movement and disinfection operations while ensuring continuous working and even output.

Cloud connectivity through Firebase introduces a remote monitoring and also control functionality, where users can modify disinfection parameters and examine historical data in real-time. The ESP32-CAM delivers live video streaming, with situational awareness and efficient path tracking. Moreover, the system's capability to adaptively adjust UV-C intensity or exposure time depending on real-time environmental conditions guarantees optimal disinfection even when environmental factors such as temperature, humidity, or air quality vary.

Through the use of UVC protective measures, the robot deployment can be done safely without causing harm to people and maintaining environmental integrity. Safety precautions like ensuring there is no human presence when operating UV-C, wearing proper personal protective equipment (PPE), and having physical barriers in place avoid accidental exposure. The modular and scalable nature of the system also enables future upgrades, which guarantee flexibility to changing disinfection requirements. Overall, this system provides a strong, effective, and secure solution for ensuring hygiene levels in healthcare and other sensitive settings.

CHAPTER 4

SYSTEM DESIGN

4.1 System Design Overview

This chapter presents the system design of the UV disinfection robot, focusing on the integration of hardware and software elements to create a cohesive and efficient system. The design emphasizes seamless communication for real-time monitoring and control, ensuring that the robot operates effectively in various environments.

The architecture allows for precise movement and control, facilitating the robot's navigation while carrying out its disinfection tasks. Additionally, the software infrastructure is designed to support easy data collection and visualization, enhancing user accessibility and operational efficiency.Overall, this chapter highlights the thoughtful integration of various elements, demonstrating how the system achieves its goals and operates effectively within its intended context.

4.2 Hardware Used

4.2.1 ESP32 DevKit V1 Microcontroller

The ESP32 DevKit V1 microcontroller serves as the central core of this UV disinfection robot, responsible for managing all sensor data, motor control, and communication between the various hardware components. It is chosen due to its capability to handle multiple tasks simultaneously while maintaining reliable performance. Its built-in Wi-Fi and Bluetooth features enable seamless integration with the Firebase cloud server, allowing real-time updates and control through websites developed for this project.

Major Specifications of ESP32 DevKit V1 includes:

1. **ESP32 SoC:** The heart of the module is the ESP32 chip, which integrates a dual-core Xtensa LX6 microprocessor, Wi-Fi and Bluetooth connectivity, and various peripherals. The microprocessor cores operate at a maximum frequency of 240 MHz.

2. **Wi-Fi:** The module supports 2.4 GHz Wi-Fi connectivity, complying with the IEEE 802.11b/g/n standard. It can function as a station (client) or as an access point (AP) for creating its own Wi-Fi network.

3. **Bluetooth:** The ESP32 DevKit V1 supports Bluetooth Classic and Bluetooth Low Energy (BLE). It allows wireless communication with other devices, such as smartphones, tablets, and other IoT devices.

4. **Flash Memory:** The module is equipped with a built-in SPI flash memory for program storage. The available flash memory size varies, but common options include 4MB, 8MB, or 16MB.

5. **RAM:** The ESP32 DevKit V1 provides on-chip RAM for data storage and program execution. The amount of available RAM is typically 520KB or more.

6. **GPIO Pins:** The module offers a range of general-purpose input/output (GPIO) pins that can be used to interface with external components and sensors. The exact number of GPIO pins depends on the specific variant of the module.

7. **Analog-to-Digital Converter (ADC):** The ESP32 DevKit V1 includes a 12-bit SAR ADC with multiple channels, allowing analog sensor readings.

8. **UART, I2C, SPI:** The module supports various communication interfaces, including Universal Asynchronous Receiver-Transmitter (UART), Inter-Integrated Circuit (I2C), and Serial Peripheral Interface (SPI). These interfaces enable communication with external devices and sensors.

9. **Power Management:** The module includes power management features such as voltage regulators and sleep modes, which help optimize power consumption for energy-efficient designs.

10. **Antenna:** The ESP32 DevKit V1 integrates an on-board antenna for Wi-Fi and Bluetooth communication. Some variants may offer an external antenna option for improved range.

The ESP32 DevKit V1 serves as the core control module of the UV disinfection robot, enabling seamless integration of sensor data, motor operations, and communication with the Firebase database. Its robust performance and versatile connectivity ensure the efficient execution of all system processes, making it a critical component in achieving the project's objectives.

4.2.2 ESP32-CAM Module

The ESP32-CAM module is incorporated to facilitate remote surveillance during the disinfection process. It features an onboard ESP32-CAM web server that streams live video directly to the HMI Control interface developed using HTML, enabling real-time monitoring of the robot's surroundings. The compact form factor, combined with its ability to deliver video over Wi-Fi, makes it an ideal choice for integrating real-time visual feedback in this project.

The major specifications of the ESP32-CAM module are listed below.

1. **ESP32 SoC:** The ESP32-CAM features the powerful ESP32 chip, which includes a dual-core Xtensa LX6 microprocessor capable of operating at a frequency of up to 240 MHz. This processing power allows for efficient image processing and real-time data handling.

2. **Camera:** The module is equipped with an OV2640 camera that supports resolutions up to 2MP (1600x1200 pixels). In this project, this camera captures real-time video footage, enabling effective surveillance and monitoring of targeted areas.

3. **Wi-Fi Connectivity:** The ESP32-CAM supports 2.4 GHz Wi-Fi connectivity, compliant with the IEEE 802.11b/g/n standard. It functions as an access point (AP) or as a client, allowing users to remotely access the camera feed from smartphones or computers. This feature is essential for instant monitoring and control.

4. **Bluetooth:** The module supports both Bluetooth Classic and Bluetooth Low Energy (BLE). In this project, Bluetooth can be utilized for local device communication, enabling easy configuration and control from nearby devices.

5. **Flash Memory:** The ESP32-CAM includes built-in SPI flash memory for program storage, typically ranging from 4MB to 16MB. This memory is crucial for storing firmware and logging captured data for later review.

6. **RAM:** With on-chip RAM typically around 520KB, the ESP32-CAM can handle data processing required for image capture and transmission efficiently, ensuring smooth operation of real-time monitoring features.

7. **Communication Interfaces:** The ESP32-CAM supports communication protocols including UART, I2C, and SPI. This flexibility facilitates seamless integration with external devices, enhancing the project's capability for real-time data exchange and control.

8. **Power Management:** The module features efficient power management capabilities, including voltage regulators and sleep modes, making it suitable for battery-powered applications. This is particularly useful for this project, allowing it to operate sustainably in remote locations.

9. **MicroSD Card Slot:** The ESP32-CAM includes a microSD card slot for additional storage, allowing it to save captured images and videos locally.

The ESP32-CAM module has a key function of facilitating remote viewing and monitoring for the UV disinfection robot. Its onboard camera, combined with Wi-Fi capabilities, facilitates real-time streaming of video to the external interface used in monitoring. The processing capability and memory of the module make it ideal for recording and transmitting visual information effectively, which maximizes situational awareness and maintains safe operation in various environments.

4.2.3 UVC LEDs

The UVC LEDs used in the UV disinfection robot are a highly specialized LEDs that provide focused and effective germicidal action for the UV disinfection robot. This module emits at a very specific UV-C wavelength of about 254.7 nm, which has been shown to be very efficient for inactivating a broad spectrum of microorganisms such as bacteria, viruses, and fungi by damaging their DNA and RNA structures. The UVC LEDs are configured in several arrays housed within a well-protected 2-inch diameter PVC cylindrical tube, which directs the emitted UV-C light into the target area of disinfection. The cylindrical structure, as well as the positioning of the LED arrays, provides maximum coverage and improves the sterilization process.

The size and light weight of the UVC LED strips are a perfect fit for this application, in which space and power consumption are of utmost importance. Contrary to traditional UV lamps, which have larger sizes and involve dangerous mercury, UVC LEDs offer a safer and more environmentally friendly solution. Their solid-state construction ensures improved mechanical toughness, which helps them withstand shock and vibration better, a very critical requirement in mobile disinfection use. Their quick response period also guarantees maximum UV-C output immediately, saving warm-up time. This prompt action is well suited in this project where stability and real-time disinfection must be maintained at all times.

The UVC LED strip is powered by the 24V supply from the two 12V lead-acid batteries connected in series, more than enough voltage to hold the optimal LED performance over extended periods. As the UVC LEDs draw relatively low power compared to traditional UV lamps, the energy efficiency of the system is significantly improved, enabling the disinfection robot to run for extended periods of time without the necessity of frequent recharging. The low thermal emission of the UVC LEDs also provides for reduced heat dissipation, enabling continuous operation without any likelihood of overheating or compromising module integrity.

The directional emission of the UVC LEDs also adds to the efficiency of the disinfection process by providing that the UV-C light emitted is focused exactly onto the targeted surface. This directional control also minimizes energy losses and maximizes germicidal effectiveness. In this project, the LED arrays have been designed to offer uniform exposure throughout the specified disinfection area, reducing the likelihood of shadowed or underexposed areas. This controlled delivery of UV-C maximizes the sterilization effect and ensures that the module works with maximum efficiency.

Another essential benefit of utilizing UVC LEDs in this project is their long lifespan, which is longer than that of conventional UV lamps that wear out and need to be replaced frequently. The UVC LED module applied in this project has stable performance over thousands of working hours, saving maintenance cost and providing steady long-term disinfection. The LEDs are designed to maintain steady UV-C output without losing intensity, and this is a critical factor for preserving the efficacy of the disinfection process throughout the robot's lifetime.

The module design of the UVC LED arrays also gives the flexibility to increase the disinfection capability of the robot by adding more LEDs when needed. This scalability means that the system can be readily scaled up for bigger disinfection applications without extensive redesign or component alteration. Moreover, the solid-state nature of the UVC LEDs guarantees mechanical stress resistance, which contributes to the overall robustness and reliability of the module, even under harsh operating conditions.

The performance of the UVC LED module is also improved by its capability to output UV-C with lower voltages. This renders it perfect for battery-operated disinfectant systems like this project, where both power management and working life are of prime importance. By providing a stable and consistent UV-C output, the UVC LED module ensures that the robot consistently produces effective sterilization results, making it an essential part of the successful functioning of the UV disinfection robot.

4.2.4 DHT22 Temperature and Humidity Sensor

The DHT22 Temperature and Humidity Sensor is integrated into the UV disinfection robot to keep track of environmental conditions in the disinfection area for the optimal performance of the UVC LEDs.It is housed within the robot's disinfection chamber, it continuously monitors temperature and humidity, enabling real-time control of the UV disinfection process. The sensor is also directly connected to the ESP32 microcontroller by a single-wire digital interface, which provides easy data reading and low-latency data processing.

The DHT22 in this project offers a temperature reading between -40°C and 80°C with accuracy ±0.5°C as well as measurements of humidity levels between 0% and 100% relative humidity with ±2–5% accuracy. When humidity levels rise above optimal levels, the system automatically prolongs the disinfection cycle to ensure effective sterilization. Similarly, when the temperature drifts outside the normal range, the ESP32 initiates appropriate adjustments to avoid running the UVC LEDs under poor thermal conditions, thus maintaining their longevity and stable operation.

The DHT22 sensor runs on 3.3V and consumes negligible current from the ESP32, making it power-efficient. Its low consumption of power guarantees uninterrupted monitoring of the environment without affecting the system's overall energy consumption significantly. This efficiency is specifically useful in a battery-operated system like the UV disinfection robot, where optimal power management is essential for long-term operation.

In order to shield the DHT22 from direct UV-C radiation, it is located in a protected position within the chamber with precise environmental monitoring. This incorporation ensures that the UVC LEDs can operate consistently in optimal conditions for effective and reliable sterilization across a wide range of operating environments.

4.2.5 MQ-135 Air Quality Sensor

The MQ-135 Air Quality Sensor is built into the UV disinfection robot to detect the Air Quality Index (AQI) in real time and make sure that the disinfection process is performed under safe environmental conditions. The sensor is mounted inside the disinfection chamber and is connected to the ESP32 microcontroller via its analog output pin (AOUT), which sends an analog voltage representing the air quality. The ESP32 detects this voltage through an ADC (Analog-to-Digital Converter) pin and translates it into a calibrated AQI value that represents the concentration of different air pollutants.

In this project, the MQ-135 sensor is calibrated to sense a variety of air pollutants, such as ammonia (NH), nitrogen oxides (NOx), benzene (CH), carbon dioxide (CO), and smoke particles. The sensor works by sensing changes in the resistance of its internal sensing element, which changes depending on the concentration of these pollutants. The sensor's analog voltage is translated by the ESP32 into an AQI value through a calibrated formula that maps the output voltage to pollutant concentration. The sensor can measure gas concentrations between 10 ppm and 1000 ppm, with the AQI threshold calibrated for this project to guarantee that even low-level pollutant concentrations are measured.

For this project, if the AQI is above the predetermined threshold value, meaning poor air quality, the system initiates visual and audio alarms. The LCD shows a poor air quality warning message, and if set, a buzzer is turned on to alert the user. The MQ-135 sensitivity is tuned to react efficiently to even minor changes in pollutant concentration, so any air quality deviation is detected immediately.

The AOUT pin, which is the analog output, is wired to one of the ESP32's ADC pins, where the microcontroller can read the analog voltage and calculate the AQI. DOUT pin is not utilized in the project, as there is always a need for continuous analog data to achieve reliable AQI measurement. Also, the current real-time AQI data are transferred to a real-time cloud-based database and charted on the website developed to monitor air quality trends in real-time continuously.

4.2.6 HC-SR04 Ultrasonic Sensor

The HC-SR04 Ultrasonic Sensor is utilized in the UV disinfection robot to provide safety by sensing any object or human being that enters the robot's working range. Placed at the front of the robot, it constantly scans the environment and senses objects or people within a specified threshold distance of 15 cm. When it senses an obstacle or the presence of humans, the sensor sends data instantly to the ESP32 microcontroller, which sounds a visual warning on the LCD and an auditory warning by energizing the buzzer, thus avoiding unintentional exposure to UVC radiation.

The HC-SR04 sensor works by sending ultrasonic pulses at 40 kHz via its TRIG pin, which then reflect back after colliding with an object and are picked up by the ECHO pin. ESP32 calculates the distance with high accuracy by measuring the time delay of the transmitted and reflected signals. The sensor here is precisely tuned in this project to send warnings if the distance measured is 15 cm so that the system takes prompt cautionary measures.The accurate distance measurement and quick response of the sensor make it perfect for use in applications where real-time human detection and obstacle avoidance are paramount.

Through automatic object or person detection within the safety zone, the system guarantees that the disinfection process is stopped or adjusted accordingly, eliminating any risk of exposure. This feature not only boosts the security of the UVC disinfection process but also enforces conformity to safety standards demanded of autonomous robotic systems utilized in healthcare facilities. The hassle-free integration of the HC-SR04 sensor with the disinfection system attests to the project's focus on reliability, security, and instant response in maintaining a secure operating environment.

4.2.7 5V Piezoelectric Buzzer

The 5V Piezoelectric Buzzer is an essential element embedded in this UV disinfection robot for providing audible feedback in accordance with different environmental conditions as well as system events. The Buzzer has a crucial function of warning people on the basis of clear-cut warning signals whenever certain conditions are fulfilled to maintain safety and operating awareness. The buzzer is activated on the basis of real-time data gathered from the MQ-135 and DHT22 sensors, which measure air quality and temperature, respectively. In cases where poor air quality or unusual temperature readings are found, the buzzer gives an alarm, alerting individuals in the vicinity to possible environmental threats. In addition, the buzzer also triggers whenever an object or human is sensed by the HC-SR04 ultrasonic sensor, giving a timely warning and playing a role in the safety features implemented.

The selection of the 5V Piezoelectric Buzzer is motivated by its low power consumption, simplicity of integration, and capacity to produce loud and clear alerts that effectively convey warnings to people in the vicinity of the robot. Its stable performance and compatibility to run smoothly with the ESP32 microcontroller make it suitable to provide timely feedback without putting a heavy load on the power supply of the system. Also, the buzzer is interfaced with the control system via the ESP32's GPIO pins, allowing real-time activation in response to sensor input and system status.

The presence of the 5V Piezoelectric Buzzer in this project adds to general safety by generating instant audio signals in key situations, avoiding unintended exposure to UVC light and ensuring that the disinfecting process is carried out in a secure setting. Its ability to give predictable and timely alerts renders it an integral component of the safety and monitoring mechanism of the UV disinfection robot.

4.2.8 RGB LEDs

The RGB (Red, Green, Blue) LEDs integrated in the UV disinfection robot are common cathode RGB LEDs, chosen for their ease of control and flexibility. The LEDs are used solely to facilitate visual feedback upon obstacle detection, to ensure operational safety while disinfesting. The RGB LEDs dynamically switch color based on the detection or lack of obstacles or people through the HC-SR04 ultrasonic sensor, enabling users to immediately determine the status of the system.

The RGB LEDs are coded to produce a red light when there is an obstacle or human presence detected within the safety range of 15 cm. This visual warning indicates that the system has sensed a possible hazard, which causes the disinfection process to stop or delay. When no obstacle or human presence is sensed, the RGB LEDs produce a green light, which means that the system is free to continue its operation safely.

To achieve normal functioning and avoid damaging the LEDs, specific resistors are applied to the red and green terminals. A 220-ohm resistor is placed in the red terminal, while a 100-ohm resistor is placed in the green terminal. These resistors control the amount of current going through the LEDs, ensuring steady brightness and increasing their lifespan. The various resistor levels are used to ensure that the intensity of the red and green light components is kept in balance, avoiding excessive current that might destroy the LEDs.

The choice of using common cathode RGB LEDs in this project was influenced by their capacity for multiple color output from a single module, resulting in a compact and efficient visual alert system. Their reliability, low power needs, and potential to convey system status through differing color changes give them the optimal position for implementation in the field of improving safety and facilitating a smooth operation for the disinfection system.

4.2.9 16x2 LCD Module with I2C Interface

The 16x2 LCD (Liquid Crystal Display) module with I2C (Inter-Integrated Circuit) interface is incorporated into the UV disinfection robot to show real-time visual feedback of system status and sensor data. The LCD efficiently displays vital messages like "UV Disinfection Robot Turned On," "Obstacle Detected," "Temperature Low," and "Poor Air

Quality," keeping users updated regarding the operational condition of the robot. This real-time feedback loop increases safety and operational situational awareness by allowing for real-time monitoring and immediate response to environmental changes.The 16x2 LCD is capable of displaying 16 characters on each line spread over 2 lines, which is a perfect option to provide short and essential information. The LCD also features adjustable display contrast for maximum visibility in any type of lighting.

The choice of the 16x2 LCD with I2C communication was motivated by the requirement for a clean and efficient interface with the ESP32 microcontroller. Traditional LCD modules usually need several GPIO pins for parallel communication, which greatly complicates wiring and takes up precious microcontroller resources. By having an I2C interface, the LCD only needs to use two lines SDA (Serial Data Line) and SCL (Serial Clock Line)which highly minimizes the hardware configuration and decreases the overall wiring load. This pin-efficient method not only maximizes the utilization of GPIO resources but also leaves the remaining pins free to be used by other essential parts like sensors and actuators.

In this project, the 16x2 LCD is solely utilized to display real-time feedback from several sensors that are part of the system. It shows air quality index (AQI) levels from the MQ-135 sensor, temperature and humidity readings from the DHT22 sensor, and obstacle detection warnings from the HC-SR04 ultrasonic sensor. In safety-critical conditions, as in the identification of a human or an object within the designated 15 cm range, the LCD gives out instant warnings to alert users and allow proper response to be implemented in a timely manner. In addition, the LCD updates dynamically according to varied environmental conditions such that real-time information is perpetually displayed for users.

The selection of the I2C-enabled 16x2 LCD module is strategically made to optimize system efficiency, reduce hardware complexity, and offer a safe visual interface in monitoring the operation of the disinfection robot. Its capability to deliver real-time feedback while keeping hardware requirements to a minimum makes it a crucial element in guaranteeing the safe and efficient operation of the UV disinfection system.

The 16x2 LCD's real-time display capabilities, coupled with its I2C interface, provide a user-friendly control interface. This ensures that users can easily monitor the robot's operation and respond appropriately to any changes, enhancing the overall usability and operational transparency of the UV disinfection system.

4.2.10 12V 100 RPM Gear Motor

The 12V 100 RPM DC motors utilized in this UV disinfection robot were carefully selected to provide stable, accurate, and controlled motion while holding up the load of important elements like UVC LEDs, sensors, and the mechanical structure. Every motor features a high-precision gearbox to lower the revolution speed but provide greater torque output, enabling it to manage the robot's considerable load effectively. The major reason for choosing these motors is that they can deliver high torque at low speeds, which is necessary to provide smooth motion over different surfaces such as tiles, carpets, and uneven floors without producing jerks or instability.

These motors provide a consistent speed to the robot during disinfection, which is necessary to achieve even exposure to UVC radiation over the target surface. Because the disinfection robot has to traverse certain areas without leaving out any spots, the 100 RPM controlled speed enables it to keep up a constant pace without overshooting or lasting too long in one spot. The motors also have sufficient torque to support the structure weight of the robot, such as the vertical BI-V design comprised of multi-wood and forex sheet, so the robot can move efficiently even when weighed down.

One of the most important considerations in deciding to utilize these motors is that they can pivot turn or on-the-spot rotate without speed control. Because the robot uses pivot turning to move around, the 100 RPM motors provide the capability for the robot to reverse direction effectively without sudden stops or skidding. Also, the 12V operating voltage is ideal for the power needs of the system since one of the 12V lead-acid batteries provides power directly to these motors without any extra circuitry or DC-DC converters, making the electrical design simple and energy efficient.

Through the use of these motors, the UV disinfection robot has smooth, controlled, and stable movement while disinfecting. Their torque capability is high, and thus the robot maintains a steady motion even when passing through narrow passages or over slight obstacles, a necessity for upholding the effectiveness of UVC exposure and proper disinfection.

4.2.11 L298N Motor Driver

The L298N motor driver is used in this UV disinfection robot for driving the robot's forward, backward, left, and right movements with the help of the Human-Machine Interface (HMI) designed for the project. The joystick provided in the web-based control interface sends movement commands to the ESP32 microcontroller, which interprets these commands and transfers suitable signals to the L298N motor driver. The motor driver then translates these signals and switches on the relevant motors, which enables accurate control of the movement of the robot on various surfaces. This mechanism of control enables smooth and efficient maneuverability, which is a necessity for complete disinfection.

The L298N is specifically used in this project because it has the ability to drive four 12V 100 RPM DC motors at once, as required by the torque and speed of the robot. In contrast to other motor drivers that may be limited to controlling only two motors or offering minimal current handling capability, the L298N is capable of dual H-bridge operation, enabling independent control of each side of the robot drive system. This is perfect for the robot's pivot turns and direction changes on the spot, maximizing operational efficiency without the necessity of extra circuitry.

The second primary reason for choosing the L298N motor driver is that it supports continuous current of up to 2A per channel, which matches the power usage and torque demand of the four DC motors employed in this project.

The in-built protection mechanisms, including thermal shutdown and back EMF protection, also help in the reliability of the system by making the motor driver operational even under abrupt motor direction or load changes. The L298N motor driver includes two H-bridges that are fed by the ESP32 microcontroller.The IN1, IN2, IN3, and IN4 pins are attached to the microcontroller so that direction of rotation of the motors can be controlled. The ENA and ENB pins that control enabling/disabling motor channels are kept at a HIGH level so that motor operation is always continuous without the necessity of speed modulation. This arrangement allows for easy control of the robot's motion, which permits accurate movement through tight spaces as well as comprehensive coverage of spaces when disinfecting.The choice to implement the L298N as compared to other motor drivers was motivated by its suitability to handle the necessary motor requirements efficiently and with better control and protection capabilities.Its strong construction, along with its capacity to accommodate multiple motors and function well under dynamic conditions, makes it an ideal choice for the UV disinfection robot.

4.2.12 Relay Module

The single-channel relay module 5V utilized in this UV disinfection robot is basically responsible for switching the on/off control of the UV-C LEDs using an HMI (Human-Machine Interface) control interface we have developed. The HMI interface includes a toggle switch enabling manual on/off switching of the UV LEDs by the user. When the toggle switch is flipped, the web application data is relayed to the ESP32 microcontroller, which then activates the relay to switch off or supply power to the UV LEDs. This uninterrupted control allows for smooth regulation of the disinfection process with little delay, improving the overall efficiency and safety of the system.

The selection of a 5V relay module was based on its compatibility with the ESP32 microcontroller, which is able to drive a 5V relay efficiently using its GPIO pins. This relay module features opto-isolation between the control side and the high-voltage load side, protecting the microcontroller from any voltage spikes that might harm the system. The relay works by being activated with a low-voltage control signal from the ESP32, which powers its internal coil and switches on or off the switch, thus permitting or blocking the current flow to the UV-C LEDs.

The relay module used within this project has a Normally Open (NO) and Normally Closed (NC) contact type, allowing it to efficiently perform the on/off switching of the UV LEDs. When the system is able to detect any human or obstacle using the HC-SR04 ultrasonic sensor, the relay will switch off the UV LEDs automatically in order to avoid accidental exposure to dangerous UV radiation. This feature is an essential safety feature installed to make sure that the process of disinfection stops instantly if there is the presence of human beings or obstacles.

A 5V relay is used because it is reliable, simple to integrate into the ESP32, and would meet the switching needs of the UV LEDs without adding delays or distorting the signal. The working pins on this relay module are the VCC pin that serves as power input, the GND pin for grounding, and the IN pin for getting control signals from the ESP32. The output side includes the COM (common), NO (normally open), and NC (normally closed) contacts, which are utilized to drive the electrical connection to the UV LEDs.

A single-channel electromagnetic relay is selected for this project due to its durability, small size, and high switching rate, which qualifies it as the best component for controlling the UV disinfection system. Its responsiveness in providing real-time control over the UV LEDs, along with its opto-isolation and safety features built into the component, makes it an effective and efficient means of ensuring safe and effective disinfection operations.

4.2.13 Robot Wheels

The 70mm x 40mm wheels utilized in this UV disinfection robot are specially selected to provide maximum mobility and maneuverability in various environments. The wheels are crafted out of long-lasting materials, featuring high-quality rubber that provides the best traction and ensures durability even with extended use. Their size—70mm in diameter and 40mm in width—provides an optimal balance of size and stability, hence being extremely compatible with robotic platforms that need steady and accurate movement.

The tread pattern of these wheels is designed to offer greater traction on different surfaces, such as smooth tiles, carpets, and rough floors, which is vital for controlling and stabilizing during disinfection processes. The light weight of these wheels does not allow for any excessive loading on the 12V 100 RPM DC motors, helping to ensure efficient battery consumption and extend the total operating runtime of the system. Their small dimensions also allow the robot to move freely within small spaces, so it can reach difficult-to-reach places and achieve its highest disinfection area.

For the purpose of this project, the 70mm x 40mm wheels are essential in guaranteeing that the UV disinfection robot is able to move within its environment easily while staying stable. Their smooth movement across various surfaces guarantees that the robot can carry out uniform disinfection without interruption. Moreover, the light weight of the wheels reduces motor load, avoiding unnecessary power consumption and increasing the battery life, thus adding to the overall efficiency of the robot in operation.

The choice of these wheels was motivated by the need to realize a compromise between stability, traction, and operational effectiveness, which makes them the best fit for the UV disinfection robot. Their performance profile is completely compatible with the project.

4.2.14 12V 7.2 Ah Battery (2 Nos)

The two 12V 7.2Ah rechargeable lead-acid batteries are integrated into this UV disinfection robot for different power applications in the system. The batteries are important because they provide a stable and dependable power supply to the different components of the robot. The 12V 7.2Ah battery supplies power to the L298N motor driver that drives the four gear motors utilized for the mobility of the robot. The reliable 12V supply provides the motors with a steady power, allowing for smooth and controlled movement on various surfaces during disinfection. As the L298N can function well under 12V, the application of this battery avoids the necessity for further voltage regulation.

The second 12V 7.2Ah battery is coupled in series with the initial battery, which yields a total output of 24V. This 24V power supply is utilized to power the UVC LEDs, such that the LEDs are powered with enough intensity to provide effective disinfection. The use of 12V 7.2Ah batteries was considered because they are highly reliable, economical, and can provide sustained power for long durations. The 7.2Ah rating guarantees that the robot can complete extended disinfection operations without having to be constantly recharged, which makes it suitable for tasks where there's a need for continuous operation. Lead-acid batteries were used because they've been proven to be long-lasting, easy to recharge, and compatible with the power requirements of the system.

Though heavier than lithium-ion options, their consistent power supply and capacity to withstand multiple charge and discharge cycles render them a sensible option for this project. The use of two 12V 7.2Ah batteries, in series to provide 24V, and with one used to offer 12V for motor control, optimizes the distribution of energy while preserving the performance and safety of the robot during the disinfection procedure.

4.3 Software Used

4.3.1 Google Firebase

In this UV disinfection robot, Google Firebase is aptly integrated to control real-time collection of data, storage, and visualization of sensor data to facilitate smooth and effective operation. Firebase is a robust cloud server where the ESP32 microcontroller data, temperature, humidity, and air quality data, are broadcast in real-time. This real-time database feature guarantees that all sensor data are updated dynamically and remain accessible, with real-time feedback throughout the disinfection process.

One of the main reasons that Google Firebase is chosen over others is its greater real-time synchronizing capability that allows for sensor values to appear on the Disinfection Interface website created within this project instantaneously. It plots live environmental charts, which provide users a graphical representation of the disinfecting environment as it happens. Firebase cloud storage makes the data that is obtained safe to store and retrieve for analysis at a later time, adding to system efficiency.

The inclusion of Firebase not only increases the functionality of the UV disinfection robot but also makes monitoring of essential environmental parameters accurate via an easy-to-use interface. Through the integration of Firebase, we have created a solid data management system that enables users to effectively interact with the system while having real-time access to operational conditions. The smooth data exchange between the robot, Firebase, and the interface ensures that the system runs with optimal reliability and efficiency, ultimately leading to the success of the disinfection process.

4.3.2 Visual Studio Code

For this UV disinfection robot project, Visual Studio Code (VS Code) is used as one of the main integrated development environment (IDE) for the development and design of both the front-end and back-end of the disinfection interface. The front-end is implemented using a blend of HTML, CSS, and JavaScript to produce a responsive, interactive, and user-friendly interface that properly shows real-time sensor information and controls. HTML and CSS were utilized for structural and visual design, whereas JavaScript is implemented to facilitate dynamic features like real-time updates, interactive widgets, and responsive user interaction. Python and Flask were used for coding the back-end, allowing for seamless communication between the ESP32 microcontroller and the cloud database to ensure that sensor readings like temperature, humidity, and air quality were correctly displayed on the interface.

VS Code is selected because it could support multiple languages and frameworks employed in this project with ease. Its flexibility enabled easy development of the interface templates and interactive widgets that graphed live sensor data through Chart.js.The integration with Git was smooth through its built-in feature, and its rich extension library gave it extra tools that made debugging, back-end coding, and real-time web development easier.

Choosing VS Code greatly improved the development process by allowing the effective management of various technologies involved in this project. Its flexibility and extensive set of features provided assurance that all aspects, ranging from data visualization in real-time to HMI controls, were successfully implemented, which supported the overall functionality and usability of the UV disinfection robot.

4.3.3 Arduino IDE

Throughout this entire project, the Arduino IDE is heavily utilized for the development, compilation, and upload of firmware responsible for programming the ESP32-CAM along with other pieces of hardware. Arduino IDE allowed for an easy and effective medium to create and debug code to control many functionalities of the system, such as obtaining sensor values, moving the motor, and creating wireless connections between the robot and cloud server. It served a major function in making sure that the data from the sensor received by the DHT22 and MQ135 is processed appropriately and sent to Google Firebase to facilitate real-time updates to the disinfection interface.

The Arduino IDE was selected for use in this project because it is compatible with the ESP32-CAM and it has a wide library ecosystem that allowed for easy integration of the different modules and sensors used in the system. The capability to rapidly troubleshoot with the onboard serial monitor and debugging facilities made testing and validation of firmware easier, with all hardware components working as expected. The simple interface of the IDE facilitated rapid iteration and deployment of code, making it possible to fine-tune the performance of the robot while in development.

Secondly, the Arduino IDE allowed smooth integration with the wireless communication protocols so that accurate and continuous real-time sensor data is transmitted to the external web interface. It is an excellent choice for embedded system development due to its ease of use and large support base, playing a major role in the overall reliability and functionality of the UV disinfection robot.

CHAPTER 5

RESULTS & DISCUSSION

5.1 Introduction

The development of the pandemic mitigation system, targeted towards healthcare domain, involved creating a digital monitoring system that gathers and displays essential environmental data. This system was designed to provide healthcare administrators with real-time insights into air quality, temperature, and humidity levels within healthcare facilities, enabling timely adjustments to minimize the risk of airborne pathogen transmission, such as those seen in COVID-19. The aim was to develop an autonomous environmental quality-monitoring robot that would support proactive infection control.

5.2 Hardware Setup

The hardware setup of the Cloud-Connected UV Disinfection Robot was meticulously executed to integrate all the parts seamlessly, starting with the cautious hardware procurement and moving through soldering, sensor placements, motor installations, and full assembly of the mechanical frame. The installation started by putting together the central control system around the ESP32 microcontroller, which controls all autonomous functions, environmental detection, and disinfection operations. ESP32-CAM module was also included in the system to support real-time video streaming, increasing remote monitoring ability. DHT22 sensor, for temperature and humidity measurement, and MQ-135 sensor, used to detect air quality and harmful gases, were individually tested to confirm their accuracy and sensitivity prior to soldering them on the PCB. The ultrasonic sensor was calibrated so that it could pick up objects correctly within the specified range so that collisions could be avoided, and it was placed exactly at the front of the robot at 10 cm to achieve the best obstacle detection. The buzzer and RGB LED were set up and connected to offer both visual and sound alerts, where the LED lit red and the buzzer sounded three warning beeps if air quality fell below the specified threshold.

After completing individual component testing, soldering and wiring started. All the modules and sensors were soldered onto a custom-designed PCB so that they were securely and dependably connected. The wiring was carefully insulated with heat shrink tubing to avoid accidental short circuits and ensure safety. The ESP32 microcontroller was wired to the L298N motor driver, which powered the four 12V, 100 RPM gear motors, each rated for 2.9 kg·cm torque, for smooth and stable motion. These motors were fitted to the multi-wood base, and 70mm x 40mm wheels were fitted with the help of metal shafts to enable durability and stability across different surfaces. A pivot-turn mechanism was used to facilitate that the robot would turn on the spot without needing differential steering, hence minimizing stress on the motors and increasing maneuverability. The motor and motor driver were supplied by one of the two 12V, 7.2 Ah lead-acid batteries in order to provide smooth power supply while running. The hardware setup is shown in Figure 5.1. The UV-C disinfection system was supplied by the second battery and was comprised of 12V UV-C LED strips mounted on the lower frame so that maximum exposure was provided to surfaces being disinfected.

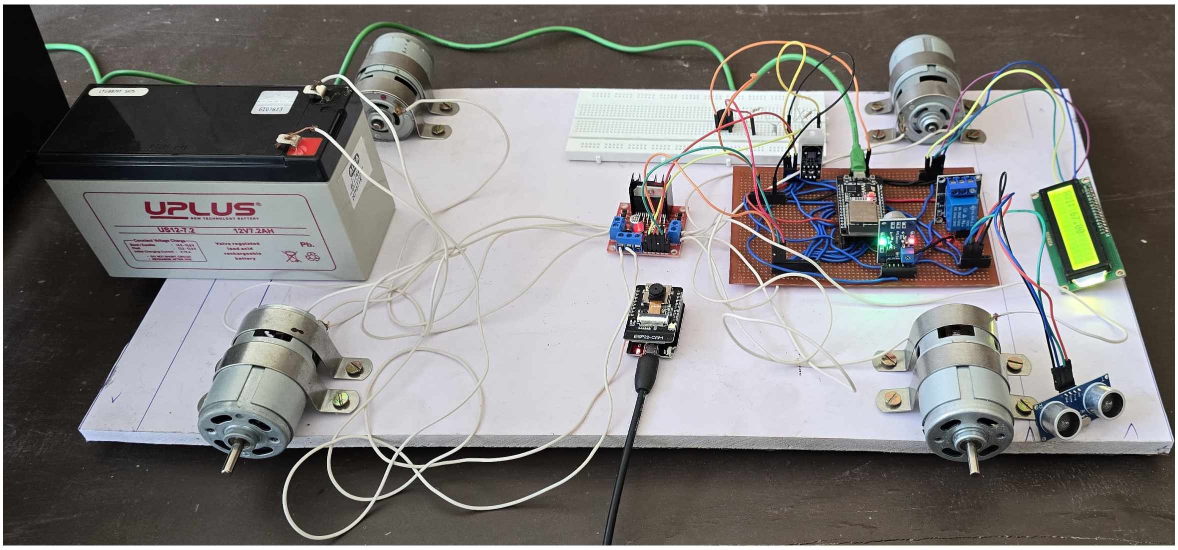

Figure 5.1: Hardware Setup

The UV-C LED strips were mounted onto a 2-inch diameter PVC cylindrical pipe with caution, placed in a manner to ensure 360-degree coverage for thorough disinfection. The strips were fixed using heat-resistant adhesive and zip ties to avoid movement and displacement. The whole UV-C assembly was covered in a PVC protective casing to avoid accidental exposure and damage while ensuring the best disinfection performance. The relay module, responsible for the on/off control of the UV-C LEDs, was built in to avoid unnecessary power drain, extending the life of the LEDs. Ventilation was built into the case to avoid overheating, maintaining the efficiency and longevity of the disinfection system.

The air quality monitoring system was carefully designed, where the MQ-135 sensor was housed within a vented compartment on the top of the robot to enable free airflow and precise AQI measurement. Next to it, the DHT22 sensor was mounted to give real-time temperature and humidity values. The ultrasonic sensor was held in place on the front panel of the robot with a 3D-printed bracket that ensured accurate alignment for consistent and precise detection of obstacles. The RGB LED and buzzer were attached to the top panel to maximize visibility and audibility of the alerts, offering both visual and auditory feedback. The ESP32 filtered all sensor inputs and presented them on an LCD display, providing real-time feedback on environmental parameters. This data was also sent to Firebase, enabling real-time monitoring via a web interface where temperature, humidity, and AQI patterns could be graphed and tracked over time.

The mechanical build comprised the careful fabrication of the robot's frame with a mix of multi-wood and forex sheets. The bottom frame was designed from multi-wood to give structural support and a solid foundation for the mounted parts. The outer casing was made from forex sheets, which were selected due to their light but tough characteristics, keeping the internal hardware safe while keeping the overall weight of the robot at an optimal value. The housing was carefully engineered with points of ventilation to avoid the accumulation of heat, thus safeguarding delicate electronic devices against heat damage. The 2-inch PVC cylindrical pipe encasing the UV-C LEDs was firmly attached to the bottom frame of the robot through specialized brackets that positioned it firmly without causing any movement, ensuring the disinfection light was distributed uniformly across surfaces.

Figure 5.2: Final Product

The motor assembly was done with care to ensure balance and stability in movement. The motors were fixed on metal brackets to ensure that they were securely attached to the frame, even for prolonged operations. The wheels, measuring 70mm x 40mm, were fixed on the motors with strong metal shafts to ensure smooth and uniform movement on different surfaces. The L298N motor driver was placed in the middle of the frame to reduce wire length and distribute power optimally. Power distribution was managed properly so that the motors and UV-C LEDs worked in isolation from each other, each powered by separate power supplies from the two 12V batteries to avoid power drain during continuous use.

The integration process completed was prolonged testing of all systems to make sure they functioned as desired. The ESP32 was programmed to manage all of the functions such as acquiring sensor data, motor control, UV-C disinfection, and real-time data uploading to Firebase. Calibration testing was conducted to ensure the accuracy of the MQ-135 and DHT22 sensors and the ultrasonic sensor was tested in diverse environments to ensure reliable obstacle detection. The UV-C LED strips were evaluated for uniform dispersion of light and effective coverage of disinfection, to ensure the system adequately neutralized the pathogens on the exposed surfaces. The ESP32-CAM module was evaluated to ensure quality of live video feedback for better remote surveillance and control. Two individual web interfaces were implemented—one to monitor real-time environmental conditions and another for controlling the robot's movement and disinfection schedule.

With all the elements successfully integrated and tested, the robot underwent a series of performance tests to ensure its reliability, safety, and efficiency in actual operating conditions. The final hardware configuration and mechanical assembly as shown in Figure 5.2 yielded a strong, modular, and efficient solution for autonomous UV disinfection, providing improved environmental safety in healthcare and high-traffic public spaces.

5.3 Website Development and Firebase Integration

To support remote monitoring and remote control of the UV disinfection robot two custom-designed websites were implemented: the **Disinfection Interface Website** and the **HMI-Controlled Website**. The two websites are key parts of the project, supporting real-time data visualization and robot control.

Websites are integrated with Firebase, Google's cloud-based backend platform, to capture and fetch the sensor data. The environmental parameters captured — Temperature, Humidity and AQI — are sent to Firebase in real-time. The web integration with Firebase is done by utilizing a JSON file and a private key for firebase and a Python Flask backend, to ensure constant updation of the data with no delay.

5.3.1 Disinfection Interface Website

The **Disinfection Interface** shown in Figure 5.3 is meant to track real-time environmental parameters. It gives healthcare administrators and facility managers live information, enabling them to evaluate air quality and temperature in the area of operation of the robot.

Features and Functionalities

- **Real-Time Data Display:** The website retrieves live data directly from Firebase. Temperature, humidity, and AQI readings are updated continuously without the need for manual page refreshes.

- **Graphical Representation:** Data is displayed graphically with real-time using Chart.js, a JavaScript library. There are three interactive dynamic graphs displayed by the interface.The x-axis indicates the time stamp of each update, whereas the y-axis represents the respective sensor values. The feature enables users to see trends and detect sudden changes in environmental conditions.
- **User Interface Design:** The site utilizes contemporary design principles and icons. The design is minimal and clean, with clear color schemes for temperature, humidity, and AQI pages. Buttons and menus are formatted for easy navigation.
- **Firebase Connectivity:** The backend, created with Python Flask, connects to Firebase. Data is exchanged in JSON form, allowing for smooth synchronization between the Firebase database and the live interface.

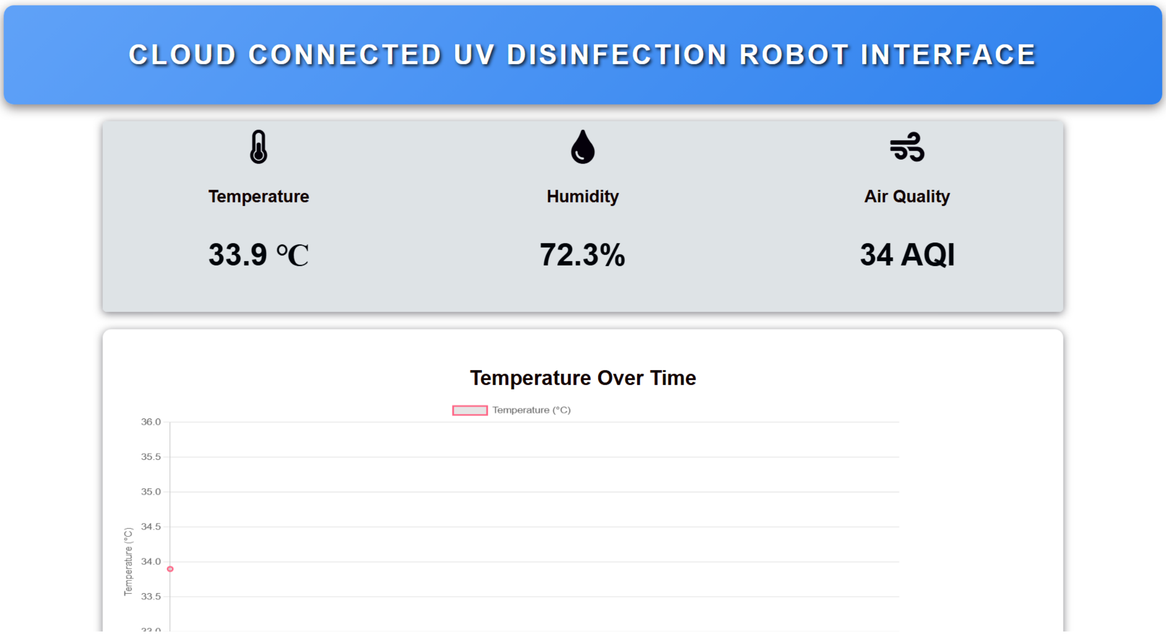

Figure 5.3: Disinfection Interface

The website interface, fulfills its purpose by providing clear visualizations of temperature, humidity, and AQI readings, with minimal delays of Firebase's real-time capabilities.

5.3.2 HMI-Controlled Website

The **HMI-Controlled Website** handles the movement of the robot, UV disinfection control, and live monitoring. It is an interactive web interface for remote operation as shown in FigureB.1.

Features and Functionalities

- **Live Camera Streaming:** A ESP32-CAM module is mounted on the robot and streams live images of the environment. This camera image is embedded on the website using an iframe so that it allows real-time streaming of the video. This capability is very important for surveillance and tracking the path.
- **Robot Control Panel:** There is a virtual joystick for the navigation of robots on the site, providing clear control of robot movement.
- **UV Disinfection Controls:** A toggle button allow operators to switch the robot's UV-C LEDs on and off. The status of the UV lights is visually represented, so operators know whether or not disinfection is occurring.
- **Backend Integration:** The site employs Flask to process commands, which are forwarded to the robot's control system through HTTP requests. The ESP32-CAM forwards live video streams to the Flask server, which refreshes the site in real time.
- **User Interface Design:** Responsive design provides compatibility with desktops, tablets, and smartphones. The interface is clean and functional with an emphasis on basic controls and live video streaming.

The HMI website gives operators immediate control and visual feedback by combining live video streaming and real-time robot control into a single interface.

5.3.3 Challenges Faced

Throughout the development process, several challenges emerged, particularly in relation to sensor calibration, data accuracy, component assembly, and interface development. Sensor calibration proved to be especially complex, notably with the MQ135 air quality sensor, which required precise adjustments to be suitable for healthcare environments. Ensuring that air quality readings accurately distinguished between safe and unsafe conditions was critical, as even slight deviations could compromise environmental assessments. Achieving reliable calibration involved numerous testing cycles and adjustments, especially considering the sensor's sensitivity to varied environmental conditions.

The physical assembling and soldering of components also presented challenges, as each sensor and module required secure placement within the board for optimal stability and data accuracy. During assembly, ensuring firm connections between sensors and the main control board was crucial to prevent disruptions in data flow. The soldering process required precision to maintain the integrity of connections, as poor soldering could lead to intermittent data transfer or inaccurate readings. Given the confined space within the zero pcb board, arranging the components to avoid signal interference and mechanical obstructions

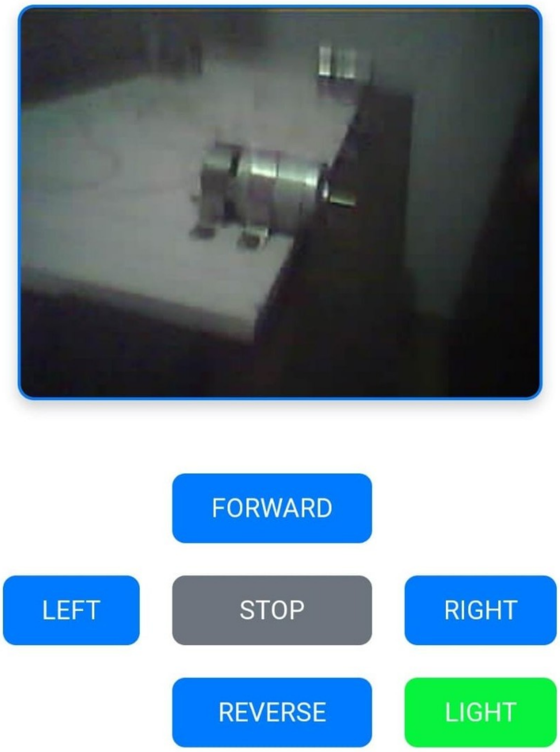

Figure 5.4: HMI Control Website Interface

added further complexity.Interface development for the system's initial display also posed challenges. Designing a responsive interface that accurately reflected real-time sensor data while remaining intuitive for healthcare personnel was essential. The interface needed to display environmental metrics like temperature, humidity, and air quality clearly, with visual alerts for any parameter reaching unsafe levels. Achieving an optimal layout required balancing functionality with clarity, ensuring that essential data could be quickly understood by users without additional navigation. Furthermore, minor delays in data refresh rates necessitated adjustments in the display logic to synchronize updates effectively, creating a smooth user experience.

Environmental variability during testing, such as fluctuating temperatures and also air circulation impacted initial sensor readings, highlighting the need for adaptable data smoothing techniques within the software. These techniques were vital to account for transient fluctuations in readings and maintain consistent data accuracy. Stability was also a priority in configuring the sensors within the framework to minimize movement, as any minor shifts could influence readings and reduce the reliability of data.

Overall, the project encountered a range of technical and design challenges that underscored the importance of a thorough design process, precise calibration, and thoughtful interface design. Addressing these issues has built a solid foundation for future advancements in the system, ensuring that it remains functional, reliable, and user-friendly in a healthcare environment.

5.4 Analysis Framework and Quantitative Insights

This section delves into the analysis of environmental factors influencing the spread of infections, particularly in relation to the effectiveness of UV-C disinfection robot. The framework integrates a threshold-based scoring approach alongside normalization to calculate the impact of each environmental variable on pandemic dynamics, with a special emphasis on its role in UV-C disinfection and environmental conditions in India. Quantitative insights are drawn from epidemiological models, studies on infection rates, and atmospheric studies to inform the model's predictions.

5.4.1 Selection of Impact Scores

Impact scores assigned to each environmental factor were based on the literature available, epidemiological studies, and expert consultations. The scoring is achieved by a range from 3 to 9, showing the comparative difference that the factor presents in influencing pandemic spread.A progressive incremental gap of two units is used in the selection of 3, 5, 7, and 9 offering a balanced step size that guarantees significant contrast between impact levels. Larger gaps, like 3, could oversimplify the scoring system, decreasing granularity and interpretability, while smaller gaps, like 1, could lead to inadequate separation, making the thresholds less effective in differentiating across groups. The two-point increment ensures that the scale is both intuitive and sensitive to changes in the factors under analysis by striking a balance between clarity and resolution.Since lower threshold values like 1 and 2 suggest minimal or inconsequential effects, which are at odds with the environmental components under analysis, they were avoided. The rationale for scores is as follows:

- Temperature (T): Research indicates that lower temperatures increase the survival of viruses and their transmission through aerosols . Hence, scores of 7, 5, and 3 were given to low, moderate, and high temperatures respectively as given in the equation (5.1) respectively, to indicate their effects on the dynamics of transmission.

- Humidity (H): Droplets survive longer at lower humidity values ($< 40\%$). An optimal humidity for droplet stability lies within $40\% - 60\%$. At high humidity ($> 60\%$), coalescence and settling become enhanced factors reducing the transmission of disease. The humidity levels and their impact scores are given in equation (5.2).

- Wind speed (W): According to the equation (5.3), low air movement ($< 1.5\,\text{m/s}$) enhances the stagnation of virus-laden particles, whereas stronger winds ($> 5\,\text{m/s}$) spread and dilute the airborne particles. Therefore, the lower wind speed was rated as higher to indicate higher risk.

- Air Quality Index (AQI): Poor air quality, especially the AQI values that are more than 150, worsens respiratory problems and risks the vulnerabilities to infections, thus justifying the more significant score . Lower AQI values (< 50) correspond to conditions that are healthier and less risky.The detailed AQI levels along with their impact scores are shown in equation (5.4).

5.4.2 Environmental Factors and Thresholds

The environmental factors and their thresholds were calibrated in the following manner:

- Temperature (T):

$$S_T = \begin{cases} 9 & \text{if } T < 10^\circ C \\ 7 & \text{if } 10^\circ C \leqslant T \leqslant 20^\circ C \\ 5 & \text{if } 20^\circ C \leqslant T \leqslant 30^\circ C \\ 3 & \text{if } T > 30^\circ C \end{cases} \tag{5.1}$$

- Humidity (H):

$$S_H = \begin{cases} 9 & \text{if } H < 30\% \\ 7 & \text{if } 30\% \leqslant H \leqslant 40\% \\ 5 & \text{if } 40\% \leqslant H \leqslant 60\% \\ 3 & \text{if } H > 60\% \end{cases} \tag{5.2}$$

- Wind Speed (W):

$$S_W = \begin{cases} 7 & \text{if } W < 1.5\,\text{m/s} \\ 5 & \text{if } 1.5\,\text{m/s} \leqslant W \leqslant 3\,\text{m/s} \\ 3 & \text{if } W > 5\,\text{m/s} \end{cases} \tag{5.3}$$

- Air Quality Index (AQI):

$$S_{AQI} = \begin{cases} 3 & \text{if } AQI < 50 \\ 5 & \text{if } 50 \leqslant AQI \leqslant 100 \\ 7 & \text{if } AQI > 100 \\ 9 & \text{if } AQI > 150 \end{cases} \tag{5.4}$$

5.4.3 Normalization and Impact Percentage

To emphasize the relative contributions of environmental elements, impact scores are normalized. Clear comparisons of influence on pandemic propagation are not possible with direct summarization.The process of normalization facilitates comprehension.

By converting raw scores into percentages, the impact of each component is accurately analysed.Absolute values lack a clear reference in the absence of normalization, which makes meaningful comparisons challenging. In addition to facilitating organized evaluation and avoiding distortions from differences in score ranges or measurement units, this approach maintains linkages among components while eliminating the dependencies on the original scales. Normalization is crucial for assessing environmental impacts on pandemic dynamics because it improves clarity, comparability and also interpretability.The raw impact scores (S) are normalized to compute impact percentages:

$$P_i = \left(\frac{S_i}{\sum_{i=1}^{n} S_i} \right) \times 100 \tag{5.5}$$

Where:

- P_i: Impact percentage of the i^{th} factor.
- S_i: Score of the i^{th} factor.
- n: Total number of factors.

According to equation (5.5) the impact percentage of the environmental factors are calculated.

Table 5.1 shows the key environmental factors affecting the effectiveness of pandemic mitigation by UV-C disinfection calculated as per equation (5.5). It reports typical values for temperature, humidity, wind speed, and AQI in the environment under test. A corresponding score S_i based on predefined thresholds is calculated and normalized with the help of percentage P_i.

Table 5.1: Environmental Factors and Their Impact in Local Region

Factor	**Value**	**Score** (S_i)	**Impact %** (P_i)
Temperature (T)	31°C	3	18.8%
Humidity (H)	74%	3	18.8%
Wind Speed (W)	1.5–3 m/s	5	31.25%
AQI	58	5	31.25%

The data shown in Table 5.1 summarily captures the impact of several environmental variables on airborne virus transmission, with special reference to pandemics. The variables considered are temperature, humidity, wind speed, and air quality, respectively given a score with an associated impact percentage representing relative significance to germ transmission behavior.The inferences derived from these parameters are analyzed below.31°C is the observed temperature that relates to a rating of 3, which carries an 18.8% contribution to the net effect on the spread of germs. When the temperature reaches this level, viral activity decreases relative to other temperatures, so transmission risk drops. Yet still, moderate virus spread can prevail in confined spaces or poorly ventilated rooms where environmental conditions can fail to stop viral survival effectively. This calls for proper ventilation and crowd control in buildings in order to eliminate or reduce such risks, even in warmer conditions.

At a humidity of 74%, the score assigned is 3, with an impact percentage of 18.8%. High humidity decreases airborne suspension of viral particles by facilitating droplet settling, thus decreasing the risk of aerosol-based transmission. Excessive humidity, however, can increase surface contamination since viral particles settle more quickly on surfaces. This dual effect suggests the importance of maintaining moderate humidity levels between 40–60%, which can help balance the reduction of airborne transmission while minimizing surface contamination risks.

Wind velocity, ranging from 1.5 to 3 m/s, is linked with the maximum score of 5, with an impact of 31.25% in the overall effect on the spread of the pandemic. Increased wind velocity increases the dispersion and dilution of airborne particles, thus lowering the concentration of viral aerosols in the outdoors. In open settings, though, this also contributes to the broader dissemination of viral particles across larger distances, which could further enhance the potential for transmission in highly populated regions. Low wind speeds or stagnant air, on the other hand, can worsen the spread of viral particles, especially within closed spaces, underscoring the need to ensure proper air circulation inside buildings.

The measured AQI value of 58 is moderate and has a score of 5, which accounts for 31.25% of the total effect. Moderate air quality also has a risk of viral transmission, particularly in poorly ventilated or high particulate matter environments. Viral particles will be suspended for longer in dirty environments, making inhalation and infection more likely. Safeguarding enhanced air quality, ensuring proper ventilation, and diminishing pollutant amounts in indoor areas is crucial for reducing airborne risk of transmission.

The composite effect of all these environmental considerations indicates that the speed of the wind and the air quality significantly impact the pandemics spread dynamics, both of which factor more than 31.25% of the total effect. Humidity and temperature, while moderate players, remain important factors in managing viral transmission through influencing particle suspension and surface contamination. These discoveries highlight the value of maximizing environmental conditions, such as increasing air circulation, using optimal humidity levels, and maintaining better air quality, to combat the spread of infections in open areas.

Figure 5.5 displays a graph that compares the scores given to each environmental factor: temperature, humidity, wind speed, and AQI. The bar chart format helps emphasize the relative weight of each factor so that one can easily determine the dominant contributors.

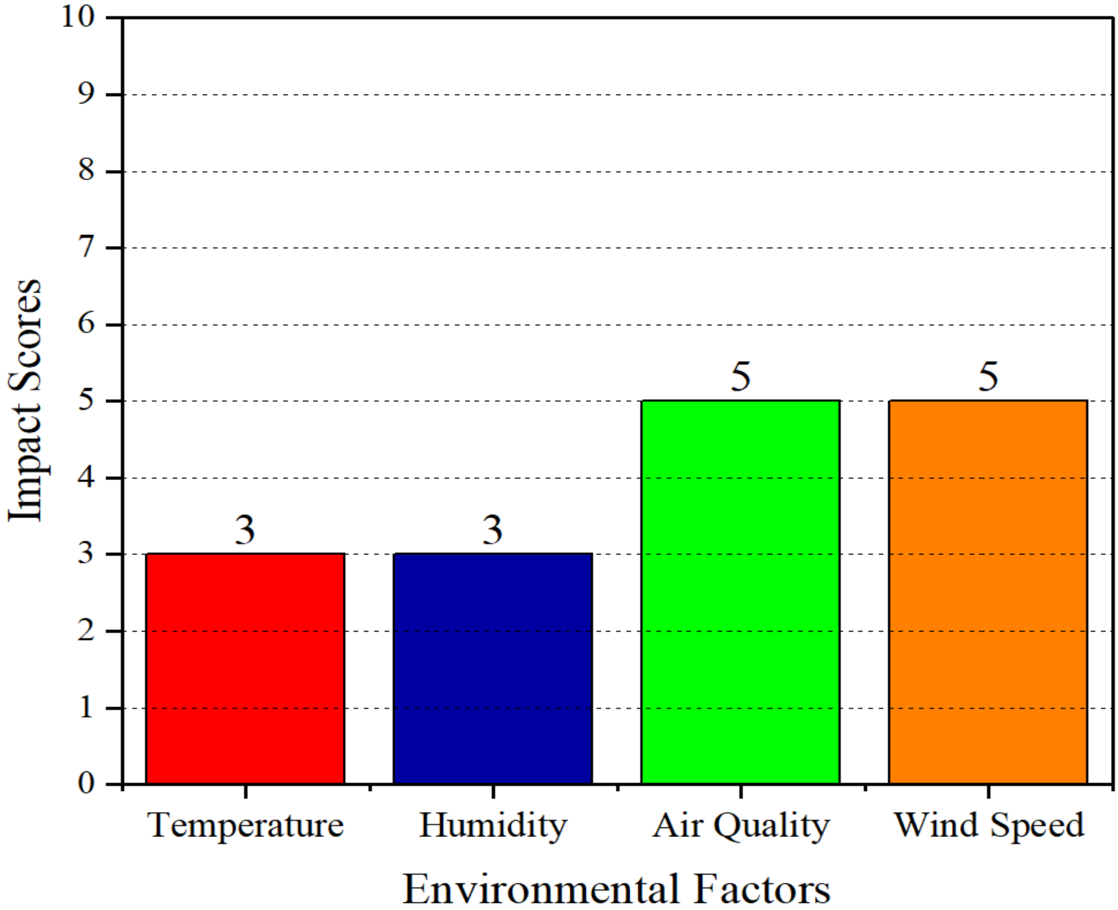

Figure 5.5: Environmental Factors and their Respective Scores

5.4.4 Score Distribution

Environmental factors affecting pandemic dynamics were analyzed based on a scoring framework using threshold values derived from relevant studies. The highest scores are given to wind speed and AQI as 5, due to their leading roles in the spread of viruses and effectiveness of mitigation. These factors significantly affect the dispersion of airborne pathogens. High wind speeds contribute to both increased transmission in crowded areas and rapid dispersion in open environments, which can potentially reduce localized viral load. Similarly, elevated AQI values, which are associated with poor air quality, are correlated with higher respiratory vulnerability, thereby increasing infection risks. Temperature and humidity scored a moderate score of 3, meaning it is a secondary yet notable influence. Although their effects on transmission are less direct than those of wind speed and AQI, research indicates that extreme temperature fluctuations and humidity can influence the survival rates of viruses and their potential for transmission. For example, low humidity has been linked to increased stability of viral aerosols, which increases the chances of airborne transmission, while higher humidity may promote droplet settling, thus reducing airborne persistence. Temperature fluctuations may have indirect impacts upon host immune functions, hence infection rates also. The ranking system is provided with a numeral basis of measurement to interpret ecological contributions toward trends in the outbreak, further calling for focused targeted mitigation measures responsive to predominant agents.

5.4.5 Visual Insights from Bar Chart

Figure 5.5 clearly plots the hierarchy of these environmental factors. Comparing the wider bars for wind speed and AQI with shorter bars for temperature and humidity gives an idea that former two play more dominant roles in pandemic dynamics. This intuitive visualization clearly reveals that wind speed and air quality need to be focused upon much more in health policy. With all this visualization enabled, furthermore trend identification is possible as well as comparison with others. With historical data as well as comparing it to present time, patterns or differences through seasons and space may also bring out, resulting in refinement towards predictive models that could possibly show better insights during the coming next pandemics with a strategy evolved based on upcoming trends.

5.4.6 Strategic Implications

The analysis identifies the most important environmental factors that need to be monitored and controlled to optimize pandemic response strategies in real world.Wind speed and AQI should be closely monitored using sensor networks and AI-driven predictive analytics. Policy recommendations include real-time air quality alerts, enforcement of pollution control measures, and adjustment of public safety guidelines based on wind conditions, such as restricting outdoor gatherings in high-wind, high-AQI scenarios. Secondary factors include temperature and humidity. These seem minor, but they are essential for extreme weather conditions. For instance, in low-humidity environments, enhanced indoor air regulation strategies such as humidification in hospitals and public spaces could mitigate the risks of transmission.

This could similarly apply through adapting responses such as modifying Heating, Ventilation, and Air Conditioning (HVAC) settings based on seasonal variations to enhance comfort and reduce viral spread by improving indoor air quality.

The normalized impact percentages ($\mathtt{P_i}$) of the environmental elements, divided into proportionate portions, are added to the graph in Figure 5.6. It allows for a complete and intuitive comprehension of each factor's contribution to the overall influence.

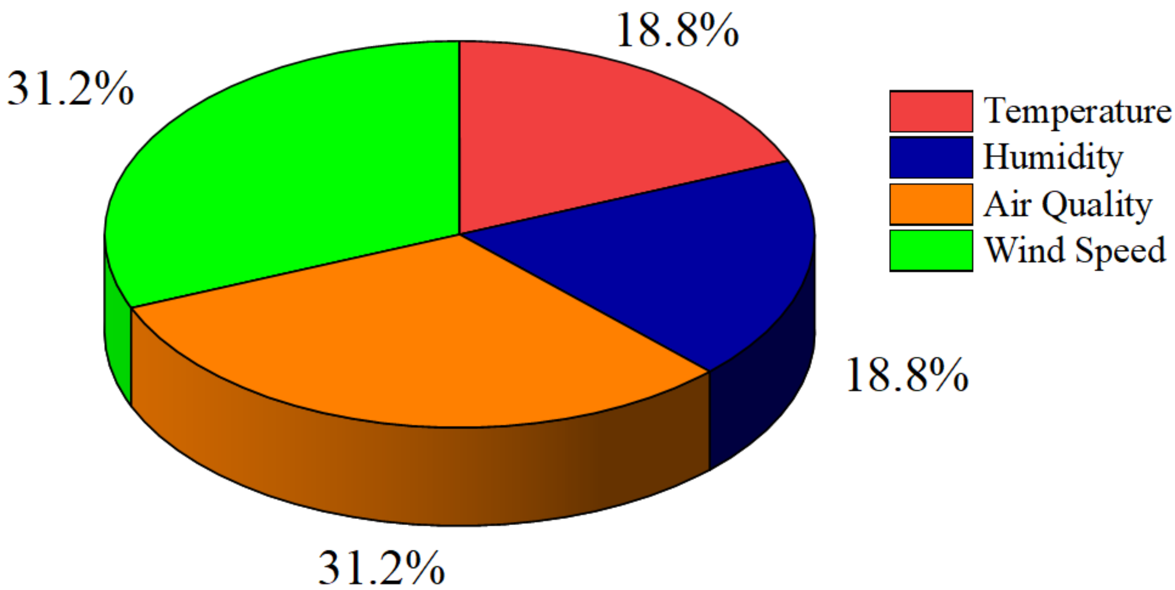

Figure 5.6: Impact Percentage Distribution of Environmental Factors

5.4.7 Proportional Contributions

A proportional breakdown of environmental factors influencing pandemic dynamics reveals that wind speed and AQI each account for 31.25% of the total impact of the influencing factors. These two parameters are dominant in deciding airborne pathogen dispersion and inhalation risks.They generally align with established epidemiological studies that conclude direct transmission with relation to poor air quality and associated high wind speeds.In contrast, temperature and humidity each account for 18.8%, which comprises the residual portion of environmental influence. Although these values are relatively less, their impact is significant. Even small fluctuations in these parameters can affect the stability of virus, immune response of the host, and overall transmission risk. Research studies show that under extreme climatic conditions, the sum effect of temperature and humidity variations enhances viral persistence, thereby validating their status as key secondary parameters in the design of pandemic control measures.The weighted contribution of each factor, as described in Figure 5.6, further reinforces a data-driven decision-making approach, allowing targeted interventions based on environmental risk assessments.

5.4.8 Visual Insights from Pie Chart

The Figure 5.6 shows proportionately the relative role of these factors in controlling the pandemic. The close parity in distribution for wind speed and AQI indicates a co-dominant effect, and consequently, measures to prevent the pandemic should encompass both concurrent observation and control to minimize the chances of transmission by the air. Even if the portions are smaller, temperature and humidity still play a significant role in environmental impact assessment, affecting the survival rates and disease transmission characteristics of airborne pathogens. Temperature also determines virus stability and viability, while humidity determines the size of droplets and the range over which pathogens can travel through the air. High humidity can enhance particle agglomeration, decreasing airborne dispersal, while low humidity will extend the airborne persistence of some pathogens, hence enhancing transmission risk. The graphical representation helps interpret relative significance and policy prioritization by highlighting those that require more emphasis. This data can then be further enriched by merging time-series data with geospatial mapping to build dynamic environmental risk models, facilitating real-time re-adjustments of mitigation measures as a function of changing environmental circumstances. For example, merging temporal data with geospatial heatmaps can enable visualization of infection patterns across geographical regions, providing insights into environmental factor-infection surge correlation. By correlating previous trends with spikes in infections, predictive models can be calibrated to predict future hotspots so that interventions can be made ahead of an increase in outbreaks. The approach enhances situational awareness and enables health authorities to implement timely and geographically targeted pandemic control measures. In addition, integrating machine learning algorithms that constantly monitor environmental data along with infection patterns can improve these predictive models over time, making them more accurate and reliable. In addition, integrating IoT-based environmental monitoring sensors with cloud-connected analytical platforms can enable real-time data acquisition, enabling constant updates and adaptive countermeasures to evolving environmental parameters, making sure that mitigation efforts remain responsive and effective.

CHAPTER 6

CONCLUSION & FUTURE SCOPE

6.1 Conclusion

All of the objectives that were set out for this work, which included developing, analyzing, and implementing a cloud-enabled UV disinfection robot, was completed. The system was designed with functionalities such as UV-C based disinfection, real-time environmental monitoring of temperature, humidity, and air quality, camera surveillance, and HMI control. The given environmental parameters were analyzed graphically for comprehensive impact analysis and performance optimization.The developed system is a wide progress in the current disinfection technologies as it incorporates IoT-enabled cloud connectivity to gain access and control from remote locations, increasing precision, efficiency, and adaptability. This differs from conventional UV disinfection systems, which do not have real-time monitoring and mechanical adaptation. Since this system dynamically responds to environmental factors that determine its optimal effectiveness. The analytical framework applied in this work further reinforces its effectiveness, as the impact analysis revealed that environmental factors such as wind speed and AQI were significant determinants of the disinfection efficiency. Temperature and humidity, although not significant under normal conditions, become crucial determinants when extremes occur and demand optimal deployment strategies to sustain performance. Future development of the system may continue to be channeled to further enhance automation by AI. The focus remains on improving its efficiency with environmental predictive modeling and, eventually, its integration into advanced robotics capable of autonomous navigation and AI decision-making for broader application in more diverse healthcare settings and public infrastructures. Its potential may even be extended toward incorporating high-resolution environmental mapping for better AI-driven analytics in making it possible for a more robust mechanism for determining disinfection efficiency. Being a robust framework and all-encompassing analytics approach, this system has rightly positioned itself for deployment in the real world. In addition to the present need for immediate healthcare sanitization, this solution answers more expansive purposes for applying its scalable approach to pandemics, industrial hygiene, and smart city infrastructure, bringing safer, sustainable environments.

6.2 Future Scope

The potential for further development in this project is immense, especially as rapid advancements continue to shape the fields of IoT, robotics, artificial intelligence, and healthcare management. With the integration of cutting-edge technologies and innovative techniques, this system could evolve beyond its current monitoring capabilities into a fully autonomous, predictive, and preventive tool for pandemic control and healthcare safety. As healthcare demands increase and the importance of proactive infection control measures becomes more pronounced, this project stands poised to incorporate sophisticated functionalities that could transform disinfection and environmental monitoring within healthcare settings. Enhanced automation, data-driven predictive insights, and adaptable responses to fluctuating environmental conditions are just a few areas where future developments could make a significant impact, positioning this system as a critical asset in maintaining healthcare hygiene and safety standards. Here are some of the envisioned future advancements for this project.

Enhanced AI-powered navigation and decision-making will enable advanced autonomous disinfection based on real-time sensor data, utilizing LIDAR and advanced visual processing for dynamic route optimization. Future iterations may incorporate safer UV-C, pulsed xenon, or far-UVC light, along with emerging disinfection methods like plasma and ozone-based technologies. AR-powered HMIs could provide real-time overlays of infection-prone zones and system diagnostics also alerts via smart glasses or tablets. AI-driven predictive analytics will identify high-risk areas based on historical and real-time data, allowing for proactive infection control and automatic disinfection activation. Integration of CO_2, VOC, PM, and biosensors will enable comprehensive monitoring of air quality and pathogen presence for enhanced risk assessment.

Secure and tamper-proof data integration with global health networks via blockchain will facilitate real-time epidemiological insights and predictive outbreak models. Implementation of solar panels, kinetic energy capture, and advanced battery technologies will support continuous operation in resource-constrained environments. Seamless connectivity with smartwatches and mobile apps will provide real-time alerts and voice-activated control for healthcare personnel. Future applications of quantum algorithms will enhance real-time optimization of disinfection routines, sensor calibration, and data analytics. Modular and adaptable system configurations will allow deployment across diverse healthcare settings, from small clinics to large hospitals, ensuring suitability for routine and emergency responses.

These advancements will transform the system into an intelligent, autonomous solution for infection prevention, reinforcing healthcare infrastructure resilience against emerging health threats. With these forward-looking advancements, the pandemic mitigation system has the potential to evolve into a holistic infection prevention tool, adaptable to a range of pathogens and healthcare environments. As the world continues to face new and emerging health threats, the system could serve as a model for smart, data-driven healthcare solutions that prioritize both patient and staff safety. The vision for this project encompasses a future where healthcare facilities are equipped with intelligent, autonomous systems that actively prevent infection and contribute to a safer, more resilient healthcare infrastructure.

REFERENCES

[1] S. Dogru and L. Marques, "Path and trajectory planning for uv-c disinfection robots," *IEEE Robotics and Automation Letters*, vol. 8, no. 7, pp. 4099–4106, 2023. DOI: 10.1109/LRA.2023.3304259.

[2] S. Luo *et al.*, "Uv*: A boustrophedon pattern-based path planning and optimization strategy for an ultraviolet disinfection robot," *IEEE Access*, vol. 11, pp. 52603–52613, 2023. DOI: 10.1109/ACCESS.2023.3295393.

[3] A. Di Lallo *et al.*, "Medical robots for infectious diseases: lessons and challenges from the covid-19 pandemic," *IEEE Robotics & Automation Magazine*, vol. 28, no. 1, pp. 18–27, 2021. DOI: 10.1109/MRA.2021.3066043.

[4] J. Kim *et al.*, "Deep learning for uv-c surface disinfection robots: Efficiency and path optimization," *IEEE Robotics and Automation Letters*, vol. 7, no. 5, pp. 5123–5131, 2022. DOI: 10.1109/LRA.2022.3200272.

[5] W. Chang *et al.*, "Uv-c disinfection strategies for robotic systems in public transportation," *IEEE Transactions on Automation Science and Engineering*, vol. 19, no. 4, pp. 834–843, 2022. DOI: 10.1109/TASE.2022.3162345.

[6] T. Tazrin, M. M. Fouda, Z. M. Fadlullah, and N. Nasser, "Uv-cds: An energy-efficient scheduling of uavs for premises sterilization," *IEEE Transactions on Green Communications and Networking*, vol. 5, no. 3, pp. 1191–1201, 2021. DOI: 10.1109/TGCN.2021.3074536.

[7] A. Zaman *et al.*, "Uvc-purge: A novel cost-effective disinfection robot for combating covid-19 pandemic," *IEEE Access*, vol. 10, pp. 37613–37634, 2022. DOI: 10.1109/ACCESS.2022.3152758.

[8] Z. Xiang and J. Su, "Towards customizable robotic disinfection with structure-aware semantic mapping," *IEEE Access*, vol. 9, pp. 35477–35486, 2021. DOI: 10.1109/ACCESS.2021.3063653.

[9] M. Mantelli *et al.*, "Autonomous environment disinfection based on dynamic uv-c irradiation map," *IEEE Robotics and Automation Letters*, vol. 7, no. 2, pp. 4789–4796, 2022. DOI: 10.1109/LRA.2022.3148263.

[10] Y.-L. Zhao *et al.*, "A smart sterilization robot system with chlorine dioxide for spray disinfection," *IEEE Sensors Journal*, vol. 21, no. 19, pp. 22047–22057, 2021. DOI: 10.1109/JSEN.2021.3072533.

[11] N. Rao *et al.*, “Advanced robotics in autonomous disinfection with multi-agent systems,” *IEEE Transactions on Automation Science and Engineering*, vol. 10, no. 6, pp. 1023–1034, 2023. DOI: 10.1109/TASE.2023.3317885.

[12] Y. Shen *et al.*, “Ai in uv-c disinfection: Enhancing effectiveness and efficiency in real-time scenarios,” *IEEE Access*, vol. 11, pp. 32050–32065, 2023. DOI: 10.1109/ACCESS.2023.3281234.

[13] X. Miao *et al.*, “Multi-cleaning robots using cleaning distribution method based on map decomposition in large environments,” *IEEE Access*, vol. 8, pp. 97873–97889, 2020. DOI: 10.1109/ACCESS.2020.2996537.

[14] R. Gonzalez *et al.*, “Safety standards and protocols for uv-c disinfection in autonomous robots,” *IEEE Robotics and Automation Letters*, vol. 7, no. 4, pp. 5055–5061, 2022. DOI: 10.1109/LRA.2022.3190056.

[15] Y. Guan *et al.*, “Enhanced autonomous operation for uv-c disinfection robots using machine learning,” *IEEE Access*, vol. 10, pp. 84052–84063, 2022. DOI: 10.1109/ACCESS.2022.3185206.

[16] L. Xu *et al.*, “Adaptive control mechanisms in mobile robots for disinfection applications,” *IEEE Transactions on Robotics*, vol. 37, no. 3, pp. 642–650, 2021. DOI: 10.1109/TRO.2021.3056232.

[17] W. Jones *et al.*, “Uav-based uv disinfection system for high-ceiling indoor spaces,” *IEEE Transactions on Green Communications and Networking*, vol. 6, no. 2, pp. 1401–1412, 2023. DOI: 10.1109/TGCN.2023.3247511.

[18] R. Pandey *et al.*, “Path optimization and sensor integration for enhanced uv-c robot navigation,” *IEEE Access*, vol. 11, pp. 62013–62026, 2023. DOI: 10.1109/ACCESS.2023.3307809.

[19] I. Chio *et al.*, “Design and autonomous navigation of a new indoor disinfection robot based on disinfection modeling,” *IEEE Transactions on Automation Science and Engineering*, vol. 20, no. 1, pp. 649–661, 2022. DOI: 10.1109/TASE.2021.3089186.

[20] F. Zheng *et al.*, “Sterilization strategies for autonomous robots in diverse environmental conditions,” *IEEE Transactions on Robotics*, vol. 38, no. 8, pp. 2304–2313, 2022. DOI: 10.1109/TRO.2022.3166047.

[21] H. Liu *et al.*, “Real-time uv-c disinfection modeling and adaptation in hospital environments,” *IEEE Sensors Journal*, vol. 21, no. 18, pp. 30210–30218, 2021. DOI: 10.1109/JSEN.2021.3102452.

[22] H. Cai *et al.*, “A systematic approach to autonomous navigation in complex indoor environments for disinfection robots,” *IEEE Access*, vol. 11, pp. 37562–37578, 2023. DOI: 10.1109/ACCESS.2023.3289735.

[23] L. Gong *et al.*, “Comparative study of path planning algorithms for mobile disinfection robots,” *IEEE Robotics and Automation Letters*, vol. 7, no. 5, pp. 5542–5550, 2022. DOI: 10.1109/LRA.2022.3199807.

[24] J. Lam *et al.*, “Performance evaluation of uv-c disinfection robots in various environments,” *IEEE Transactions on Automation Science and Engineering*, vol. 21, no. 1, pp. 123–134, 2024. DOI: 10.1109/TASE.2024.3310598.

[25] R. Chand *et al.*, “Deep reinforcement learning for path planning in uv-c disinfection robots,” *IEEE Robotics and Automation Letters*, vol. 8, no. 3, pp. 4981–4988, 2023. DOI: 10.1109/LRA.2023.3274821.

[26] X. Chen *et al.*, “Optimal control for uv-c disinfection robots based on path minimization,” *IEEE Robotics and Automation Letters*, vol. 8, no. 4, pp. 6060–6067, 2023. DOI: 10.1109/LRA.2023.3295897.

[27] M. Hoang *et al.*, “Indoor localization techniques for uv disinfection robots in complex environments,” *IEEE Access*, vol. 12, pp. 1020–1030, 2024. DOI: 10.1109/ACCESS.2024.3320198.

[28] M. Alavi *et al.*, “Hybrid control strategies for adaptive uv-c disinfection robots,” *IEEE Transactions on Robotics*, vol. 40, no. 1, pp. 97–108, 2024. DOI: 10.1109/TRO.2024.3256097.

[29] P. Bawane, L. Zhang, and A. Gupta, “Performance assessment of uv-c disinfection systems for surface sterilization,” *IEEE Transactions on Industrial Electronics*, vol. 69, no. 10, pp. 11307–11316, 2022. DOI: 10.1109/TIE.2022.3168945.

[30] X. Zhang, C. Lee, and Q. Yang, “Multi-agent coordination for uv-c disinfection in large environments,” *IEEE Access*, vol. 12, pp. 22012–22025, 2024. DOI: 10.1109/ACCESS.2024.3321024.

[31] K. Nishimura *et al.*, “Study on uv-c path optimization for robotic disinfection in school settings,” *IEEE Access*, vol. 10, pp. 17430–17442, 2022. DOI: 10.1109/ACCESS.2022.3152028.

[32] L. Yi *et al.*, “A review of uvc robot design and implementation strategies for surface disinfection,” *IEEE Robotics and Automation Magazine*, vol. 31, no. 2, pp. 82–95, 2024. DOI: 10.1109/MRA.2024.3241234.

[33] C. Li *et al.*, “Development of a mobile robot for autonomous surface sterilization in public spaces,” *IEEE Transactions on Automation Science and Engineering*, vol. 18, no. 5, pp. 1025–1034, 2021. DOI: 10.1109/TASE.2021.3067007.

[6] [1] [7] [8] [9] [10] [13] [2] [19] [3] [11] [4] [22] [21] [17] [20] [5] [31] [32] [16] [14] [12] [25] [26] [27] [33] [23] [24] [18] [15] [28] [29] [30]

APPENDIX A
PROGRAM

A.1 Complete Hardware Code

```
#include <WiFi.h>
#include <Wire.h>
#include <WebServer.h>
#include <LiquidCrystal_I2C.h>
#include <DHT.h>  // Include the Adafruit DHT library
#include <Firebase_ESP_Client.h>

// Pin Definitions
#define DHTPIN 27        // DHT22 sensor pin
#define DHTTYPE DHT22    // Define the type of DHT sensor
#define MQ135_PIN 36     // MQ135 sensor pin (Analog)
#define BUZZER_PIN 15    // Buzzer pin
#define RED_PIN 2       // RGB LED Red pin
#define GREEN_PIN 4     // RGB LED Green pin
#define TRIG_PIN 12      // Ultrasonic sensor Trig pin
#define ECHO_PIN 13      // Ultrasonic sensor Echo pin
#define RELAY_PIN 25      // Relay control pin
#define RELAY_PIN_2 26

// I2C Pin Definitions for ESP32
#define SDA_PIN 21       // I2C SDA pin
#define SCL_PIN 22       // I2C SCL pin

int motor1Pin1 = 33;
int motor1Pin2 = 32;
int enable1Pin = 18;

// Motor 2 Pins
int motor2Pin1 = 35;
int motor2Pin2 = 34;
int enable2Pin = 19;

// Initialize DHT sensor
```

```
DHT dht(DHTPIN, DHTTYPE);  // Create a DHT object

// Initialize LCD (address 0x27, 16 chars, 2 lines)
LiquidCrystal_I2C lcd(0x27, 16, 2);
#include "addons/TokenHelper.h"
#include "addons/RTDBHelper.h"
// Insert your network credentials
#define WIFI_SSID "Redmi Note 9 Pro"
#define WIFI_PASSWORD "12345678p"

// Insert Firebase project API Key
#define API_KEY "AIzaSyBEcSJNhI9juvY-yHi7oYtcu0fFcE9PuEo"

// Insert RTDB URLefine the RTDB URL */
#define DATABASE_URL
"https://uv-disinfection-robot-default-rtdb.asia-southeast1.
firebasedatabase.app/"

//Define Firebase Data object
FirebaseData fbdo;

FirebaseAuth auth;
FirebaseConfig config;

WebServer server(80);

unsigned long sendDataPrevMillis = 0;
int count = 0;
bool signupOK = true;

const int freq = 30000;
const int resolution = 8;
int dutyCycle = 0;
String valueString = String(0);

void handleRoot() {
const char html[] PROGMEM = R"rawliteral(
<!DOCTYPE HTML>
```

```
<html>
<head>
<meta name="viewport" content="width=device-width
, initial-scale=1">
<link rel="icon" href="data:,">
<style>
body {
font-family: Arial, sans-serif;
display: flex;
flex-direction: column;
align-items: center;
justify-content: flex-start;
height: 100vh;
margin: 0;
background-color: #fff; /* White background */
color: #000;}
h1 {
margin-top: 15px;
font-size: 1.8rem;
color: #000;
padding: 10px 20px;
border-radius: 5px;
background-color: #f4f4f4;
box-shadow: 0 2px 4px rgba(0, 0, 0, 0.1);}
.button {
background-color: #007bff; /* Blue button */
border: none;
color: white;
padding: 12px 24px;
font-size: 16px;
margin: 5px;
cursor: pointer;
border-radius: 8px;
transition: background-color 0.3s ease;}
.button:hover {
background-color: #0056b3; /* Darker blue on hover */}
.button2 {
background-color: #6c757d; /* Gray button */}
```

```
.button3 {
background-color: #06f43d; /* Gray button */}
.button2:hover {
background-color: #5a6268; /* Darker gray on hover */}
.camera-frame {
border: 2px solid #007bff; /* Blue border */
border-radius: 10px;
overflow: hidden;
width: 320px;
height: 240px;
margin: 20px auto;
box-shadow: 0 4px 8px rgba(0, 0, 0, 0.2);}
.camera-frame img {
width: 100%;
height: 100%;
object-fit: cover;}
.joystick {
display: grid;
grid-template-areas:
". forward ."
"left stop right"
". reverse uv";
grid-gap: 10px;
justify-content: center;
align-items: center;
margin: 20px auto;
width: 240px;}
.joystick button {
grid-area: auto;}
.joystick .forward {
grid-area: forward;}
.joystick .left {
grid-area: left;}
.joystick .stop {
grid-area: stop;}
.joystick .right {
grid-area: right;}
.joystick .reverse {
```

```
grid-area: reverse;}
.joystick .uv {
grid-area: uv;}
input[type="range"] {
width: 100%;
max-width: 300px;
margin: 10px auto;}
</style>
<script>
function moveForward() {
fetch("/forward");}
function moveLeft() {
fetch("/left");}
function stopRobot() {
fetch("/stop");}
function moveRight() {
fetch("/right");}
function moveReverse() {
fetch("/reverse");}
function updateMotorSpeed(pos) {
document.getElementById("motorSpeed").innerHTML = pos;
fetch(`/speed?value=${pos}`);}
let uvLightState = false; // UV light state
function toggleUVLight() {
uvLightState = !uvLightState;
const action = uvLightState ? "on" : "off";
document.getElementById("uvButton").innerHTML =
`LIGHT ${action.toUpperCase()}`;
fetch(`/uv?state=${action}`);
}
</script>
</head>
<body>
<h1>HMI CONTROL FOR DISINFECTION ROBOT</h1>
<!-- Camera Frame -->
<div class="camera-frame">
<img id="stream" src=
"http://192.168.9.92:81/stream" crossorigin="">
```

```
</div>
<!-- Joystick Control -->
<div class="joystick">
<button class="button forward"
onclick="moveForward()">FORWARD</button>
<button class="button left" onclick="moveLeft()
">LEFT</button>
<button class="button button2 stop" onclick="stopRobot()"
>STOP</button>
<button class="button right" onclick="moveRight()"
>RIGHT</button>
<button class="button reverse" onclick="moveReverse()"
>REVERSE</button>
<button class="button button3 uv" id="uvButton"
onclick="toggleUVLight()"
>LIGHT</button>
</div>
<p>Motor Speed: <span id="motorSpeed">0</span></p>
<input
type="range"
min="0"
max="100"
step="25"
id="motorSlider"
oninput="updateMotorSpeed(this.value)"
value="0"
/>
</body>
</html>)rawliteral";
server.send(200, "text/html", html);}

void handleForward() {
Serial.println("Forward");
digitalWrite(motor1Pin1, HIGH);
digitalWrite(motor1Pin2, LOW);
digitalWrite(motor2Pin1, HIGH);
digitalWrite(motor2Pin2, LOW);
ledcWrite(enable1Pin, dutyCycle);
```

```
ledcWrite(enable2Pin, dutyCycle);
server.send(200);}

void handleLeft() {
Serial.println("Left");
digitalWrite(motor1Pin1, LOW);
digitalWrite(motor1Pin2, HIGH);
digitalWrite(motor2Pin1, HIGH);
digitalWrite(motor2Pin2, LOW);
ledcWrite(enable1Pin, dutyCycle);
ledcWrite(enable2Pin, dutyCycle);
server.send(200);}

void handleStop() {
Serial.println("Stop");
digitalWrite(motor1Pin1, LOW);
digitalWrite(motor1Pin2, LOW);
digitalWrite(motor2Pin1, LOW);
digitalWrite(motor2Pin2, LOW);
ledcWrite(enable1Pin, 0);
ledcWrite(enable2Pin, 0);
server.send(200);}

void handleRight() {
Serial.println("Right");
digitalWrite(motor1Pin1, HIGH);
digitalWrite(motor1Pin2, LOW);
digitalWrite(motor2Pin1, LOW);
digitalWrite(motor2Pin2, HIGH);
ledcWrite(enable1Pin, dutyCycle);
ledcWrite(enable2Pin, dutyCycle);
server.send(200);}

void handleReverse() {
Serial.println("Reverse");
digitalWrite(motor1Pin1, LOW);
digitalWrite(motor1Pin2, HIGH);
digitalWrite(motor2Pin1, LOW);
```

```
digitalWrite(motor2Pin2, HIGH);
ledcWrite(enable1Pin, dutyCycle);
ledcWrite(enable2Pin, dutyCycle);
server.send(200);}

void handleUVOn() {
Serial.println("UV Light ON");
digitalWrite(RELAY_PIN, HIGH);
server.send(200);}

void handleUVOff() {
Serial.println("UV Light OFF");
digitalWrite(RELAY_PIN, LOW);
server.send(200);}

void handleSpeed() {
if (server.hasArg("value")) {
valueString = server.arg("value");
int value = valueString.toInt();
if (value == 0) {
ledcWrite(enable1Pin, 0);
ledcWrite(enable2Pin, 0);
digitalWrite(motor1Pin1, LOW);
digitalWrite(motor1Pin2, LOW);
digitalWrite(motor2Pin1, LOW);
digitalWrite(motor2Pin2, LOW);
} else {
dutyCycle = map(value, 25, 100, 200, 255);
ledcWrite(enable1Pin, dutyCycle);
ledcWrite(enable2Pin, dutyCycle);
Serial.println("Motor speed set to " + String(value));
}}
server.send(200);}
void setup() {
Serial.begin(500000);

// Set the Motor pins as outputs
pinMode(motor1Pin1, OUTPUT);
```

```
pinMode(motor1Pin2, OUTPUT);
pinMode(motor2Pin1, OUTPUT);
pinMode(motor2Pin2, OUTPUT);
pinMode(BUZZER_PIN, OUTPUT);
pinMode(RED_PIN, OUTPUT);
pinMode(GREEN_PIN, OUTPUT);
pinMode(TRIG_PIN, OUTPUT);
pinMode(ECHO_PIN, INPUT);
pinMode(RELAY_PIN, OUTPUT);
pinMode(MQ135_PIN, INPUT);
digitalWrite(RELAY_PIN, HIGH);
digitalWrite(motor1Pin1, LOW);
digitalWrite(motor1Pin2, LOW);
digitalWrite(motor2Pin1, LOW);
digitalWrite(motor2Pin2, LOW);
Serial.begin(500000);

// Configure PWM Pins
ledcAttach(enable1Pin, freq, resolution);
ledcAttach(enable2Pin, freq, resolution);
ledcWrite(enable1Pin, 0);
ledcWrite(enable2Pin, 0);

// Connect to Wi-Fi
Serial.print("Connecting to ");
Serial.println(WIFI_SSID);
WiFi.begin(WIFI_SSID, WIFI_PASSWORD);
while (WiFi.status() != WL_CONNECTED) {
delay(500);
Serial.print(".");
}
Serial.println("");
Serial.println("WiFi connected.");
Serial.println("IP address: ");
Serial.println(WiFi.localIP());

// Define routes
server.on("/", handleRoot);
```

```
server.on("/forward", handleForward);
server.on("/left", handleLeft);
server.on("/stop", handleStop);
server.on("/right", handleRight);
server.on("/reverse", handleReverse);
server.on("/speed", handleSpeed);
server.on("/uv/on", handleUVOn);
server.on("/uv/off", handleUVOff);

server.on("/uv", []() {
if (server.hasArg("state")) {
String state = server.arg("state");
if (state == "on") {
handleUVOn();
} else if (state == "off") {
handleUVOff();
}}});

// Start the server
server.begin();
// Start Serial communication for debugging
Serial.begin(500000);

// Initialize I2C with defined SDA and SCL pins for ESP32
Wire.begin(SDA_PIN, SCL_PIN);

// Initialize LCD
lcd.init();          // Initialize the LCD
lcd.backlight();     // Turn on the backlight

// Initialize DHT sensor
dht.begin();

// Set pin modes
pinMode(BUZZER_PIN, OUTPUT);
pinMode(RED_PIN, OUTPUT);
pinMode(GREEN_PIN, OUTPUT);
pinMode(TRIG_PIN, OUTPUT);
```

```
pinMode(ECHO_PIN, INPUT);
pinMode(RELAY_PIN, OUTPUT);
pinMode(MQ135_PIN, INPUT);

// Initial display message on LCD
lcd.setCursor(0, 0);
lcd.print("UV Disinfection");
lcd.setCursor(0, 1);
lcd.print("Robot Turned ON");
delay(2000);  // Display for 5 seconds
lcd.clear();
// Relay ON by default
digitalWrite(RELAY_PIN, LOW);  // Turn ON relay initially
dht.begin();
Serial.begin(500000);
WiFi.begin(WIFI_SSID, WIFI_PASSWORD);
Serial.print("Connecting to Wi-Fi");
while (WiFi.status() != WL_CONNECTED){
Serial.print(".");
delay(300);
}
Serial.println();
Serial.print("Connected with IP: ");
Serial.println(WiFi.localIP());
Serial.println();
/* Assign the api key (required) */
config.api_key = API_KEY;
/* Assign the RTDB URL (required) */
config.database_url = DATABASE_URL;
/* Sign up */
if (Firebase.signUp(&config, &auth, "", "")){
Serial.println("ok");
signupOK = true;
}
else{
Serial.printf("%s\n", config.signer.signupError
.message.c_str());}
config.token_status_callback = tokenStatusCallback;
```

```
//see addons/TokenHelper.h

Firebase.begin(&config, &auth);
Firebase.reconnectWiFi(true);}

void loop() {
// Read temperature and humidity from DHT22
server.handleClient();
float temperature = dht.readTemperature();
float humidity = dht.readHumidity();

// Read air quality from MQ135 sensor (Analog read)
float airQuality = analogRead(MQ135_PIN);
// Display temperature and humidity on LCD
lcd.clear();
lcd.setCursor(0, 0);
lcd.print("Temp: ");
lcd.print(temperature);
lcd.print("C");
lcd.setCursor(0, 1);
lcd.print("Humidity: ");
lcd.print(humidity);
lcd.print("%");
delay(1000);  // Update every 1 second

// Display air quality value on LCD
lcd.clear();
lcd.setCursor(0, 0);
lcd.print("AQI: ");
lcd.print(airQuality);
delay(2000);  // Update every 2 seconds

// Check air quality and trigger buzzer if it's above threshold
if (temperature > 40) {
lcd.clear();
lcd.setCursor(0, 0);
lcd.print("Temperature High");
}
```

```
if (airQuality > 100) {
lcd.clear();
lcd.setCursor(0, 0);
lcd.print("Poor AQI");

// Buzzer beeps 3 times
for (int i = 0; i < 3; i++) {
digitalWrite(BUZZER_PIN, HIGH);
delay(250);
digitalWrite(BUZZER_PIN, LOW);
delay(250);
}}
// Ultrasonic sensor to detect motion
digitalWrite(TRIG_PIN, LOW);
delayMicroseconds(2);
digitalWrite(TRIG_PIN, HIGH);
delayMicroseconds(10);
digitalWrite(TRIG_PIN, LOW);

long duration = pulseIn(ECHO_PIN, HIGH);
float distance = (duration * 0.0343) / 2;
// Calculate distance in cm
// Check if motion is detected
// Check if motion/object is detected within a certain range
if (distance > 0 && distance < 10) {
// Motion detected
digitalWrite(RED_PIN, HIGH);      // Turn on Red LED
digitalWrite(GREEN_PIN, LOW);     // Turn off Green LED
digitalWrite(BUZZER_PIN, HIGH);   // Activate buzzer
digitalWrite(RELAY_PIN, HIGH);    // Turn OFF relay
// Display motion alert on LCD
lcd.clear();
lcd.setCursor(0, 0);
lcd.print("Object Detected");
delay(50);  // Wait for a second
} else {
// No motion detected
digitalWrite(RED_PIN, LOW);      // Turn off Red LED
```

```
digitalWrite(GREEN_PIN, HIGH);  // Turn on Green LED
digitalWrite(BUZZER_PIN, LOW);  // Deactivate buzzer
}
delay(50);  // Small delay before the next loop iteration
if (Firebase.ready() && signupOK
&& (millis() - sendDataPrevMillis > 1000
|| sendDataPrevMillis == 0)){
//since we want the data to be updated every second
sendDataPrevMillis = millis();
// Enter Temperature in to the DHT_11 Table
if (Firebase.RTDB.setInt(&fbdo, "DHT_11/Temperature"
, temperature)){
Serial.printf("Temperature: %f\n", temperature); }
else {
Serial.println("Failed to Read from the Sensor");
Serial.println("REASON: " + fbdo.errorReason());}
// Enter Humidity in to the DHT_11 Table
if (Firebase.RTDB.setFloat(&fbdo, "DHT_11/Humidity", humidity)){
Serial.printf("Humidity: %f\n", humidity);}
else {
Serial.println("Failed to Read from the Sensor");
Serial.println("REASON: " + fbdo.errorReason());}
if (Firebase.RTDB.setFloat(&fbdo, "DHT_11/AQI", airQuality)){
Serial.printf("AQI: %f\n", airQuality);}
else {
Serial.println("Failed to Read from the Sensor");
Serial.println("REASON: " + fbdo.errorReason());
}}}
```

A.2 Website Frontend Code

```
<!DOCTYPE html>
<html lang="en">
<head>
<meta charset="UTF-8">
<meta name="viewport" content="width=device-width,
initial-scale=1.0">
<title>Cloud-Connected UV Disinfection Robot</title>
```

```
<link rel="stylesheet" href="https://cdnjs.cloudflare.com/ajax
/libs/font-awesome/5.15.4/css/all.min.css">
<script src="https://cdn.jsdelivr.net/npm/chart.js">
</script>
<script src="https://www.gstatic.com/
firebasejs/8.6.8/firebase-app.js">
</script>
<script src="https://www.gstatic.com/
firebasejs/8.6.8/firebase-database.js">
</script>
<style>
body {
background-color: #ffff;
color:rgb(17, 1, 1);
font-family: ’Roboto’, sans-serif;
margin: 10px;
padding: 0;
}
.data-head {
text-align: center;
padding: 40px 15px;
background:
linear-gradient(135deg,rgb(96, 162, 248),rgb(46, 129, 238));
color: white;
margin-bottom: 20px;
border-radius: 12px;
box-shadow: 0 4px 12px rgba(14, 1, 1, 0.5);
font-size: 2em;
font-weight: bold;
text-transform: uppercase;
letter-spacing: 3px;
text-shadow: 2px 2px 4px rgba(0, 0, 0, 0.8)
}
.data-container {
margin: 20px auto;
padding: 10px 20px;
background-color:rgba(212, 218, 223, 0.76);
box-shadow: 0 2px 10px rgba(3, 1, 14, 0.5);
```

```
border-radius: 5px;
width: 80%;
display: flex;
justify-content: space-between;
}
.data-item {
text-align: center;
width: 30%;
}
.data-item h2 {
font-size: 20px;
font-weight: bold;
}
.data-item p {
font-size: 36px;
font-weight: bold;
color:rgb(0, 5, 10);
}
.icon {
font-size: 40px;
color:rgb(4, 0, 10);
margin-bottom: 10px;
}
.chart-container {
margin: 20px auto;
padding: 20px;
font color: rgb(0, 14, 15)
background-color:rgb(240, 247, 248);
box-shadow: 0 2px 10px rgba(3, 0, 12, 0.5);
border-radius: 10px;
width: 80%;
}
.chart-container h3 {
text-align: center;
font-size: 24px;
margin-bottom: 10px;
}
canvas {
```

```
max-width: 100%;
height: 400px !important;
}
footer {
margin-top: 20px;
padding: 10px;
text-align: center;
background-color: #1F1F1F;
color: #CCCCCC;
font-size: 14px;
}
/* Caution Box */
.caution-box {
margin: 40px 100px;
padding: 15px;
border-radius: 5px;
background: linear-gradient(135deg, #ff4f4f, #ff6666);
color: white;
text-align: center;
box-shadow: 0 4px 5px rgba(233, 80, 80, 0.3);
}
.caution-box h2 {
font-size: 0.8 em;
color: white;
margin-bottom: 5px;
}
.caution-box p {
font-size: 0.5 em;
font-weight: bold;
}
.caution-box i {
font-size: 1em;
margin-bottom: 5px;
}
</style>
</head>
<body>
<!-- Header -->
```

```
<div class="data-head">
CLOUD CONNECTED UV DISINFECTION ROBOT INTERFACE</div>
<!-- Real-time Data Section -->
<div class="data-container">
<div class="data-item">
<i class="fas fa-thermometer-half icon"></i>
<h2>Temperature</h2>
<p class="value" id="temperature">-- &#8451;</p>
</div>
<div class="data-item">
<i class="fas fa-tint icon"></i>
<h2>Humidity</h2>
<p class="value" id="humidity">--%</p>
</div>
<div class="data-item">
<i class="fas fa-wind icon"></i>
<h2>Air Quality</h2>
<p class="value" id="air-quality">-- AQI</p>
</div>
</div>
<!-- Chart Section -->
<div class="chart-container">
<h3>Temperature Over Time</h3>
<canvas id="temperatureChart"></canvas>
</div>
<div class="chart-container">
<h3>Humidity Over Time</h3>
<canvas id="humidityChart"></canvas>
</div>
<div class="chart-container">
<h3>Air Quality Over Time</h3>
<canvas id="airQualityChart"></canvas>
</div>
<!-- Caution Box -->
<div class="caution-box">
<i class="fas fa-exclamation-triangle"></i>
<h2>Safety First!</h2>
<p>This robot uses UV-C technology to sanitize spaces.
```

```
Always avoid direct exposure to UV light.</p>
<p>Learn more about <a href="https://en.wikipedia.org/wiki
/Ultraviolet_germicidal_irradiation"
target="_blank" style="color:
white; text-decoration: underline;"
>UV Disinfection</a></p>
<p>Air Quality and pandemic spread
<a href="https://media.springernature.com
/full/springer-static
/image/art%3A10.1186%2Fs12302-021-00575-y
/MediaObjects/12302_2021_575_Fig2_HTML.png?
as=webp" target="_blank" style="color:
white; text-decoration: underline;">AQI Ranges</a></p>
<p>Impact Analysis <a href="C:\Users\PRANAV\OneDrive
\Documents\Desktop
\Project 2024\project.png"
target"_blank" style="color: white; text-decoration: underline;"
>Analysis Section</a></p>
</div>
</div>
<!-- Footer -->
<footer>
Group 8 S8 ECE | <a href="https://192.168.39.125"
style="color: #6EB7FF; text-decoration: none;"
>Robot Control</a>
</footer>

<script>
// Firebase configuration
var firebaseConfig = {
apiKey: "AIzaSyBEcSJNhI9juvY-yHi7oYtcu0fFcE9PuEo",
authDomain: "uv-disinfection-robot.firebaseapp.com",
databaseURL: "https://uv-disinfection-robot
-default-rtdb.asia-southeast1.firebasedatabase.app",
projectId: "uv-disinfection-robot",
storageBucket: "uv-disinfection-robot.appspot.com",
messagingSenderId: "763803111689",
appId: "1:763803111689:web:653321ba0c4f65493d83d8",
```

```
measurementId: "G-S7JLLXFLCJ"
};
firebase.initializeApp(firebaseConfig);
var database = firebase.database();
var tempRef = database.ref('DHT_11/Temperature');
var humidityRef = database.ref('DHT_11/Humidity');
var airQualityRef = database.ref('DHT_11/AQI');
// Update temperature, humidity, and air quality values
tempRef.on('value', (snapshot) => {
document.getElementById('temperature')
.innerHTML = snapshot.val() + " &#8451;";
});
humidityRef.on('value', (snapshot) => {
document.getElementById('humidity').innerHTML =
snapshot.val() + "%";
});
airQualityRef.on('value', (snapshot) => {
document.getElementById('air-quality').innerHTML =
snapshot.val() + " AQI";
});
// Chart.js setup
const tempCtx = document.getElementById('temperatureChart').
getContext('2d');
const humidityCtx = document.getElementById('humidityChart').
getContext('2d');
const airQualityCtx = document.getElementById('airQualityChart').
getContext('2d');
const temperatureChart = new Chart(tempCtx, {
type: 'line',
data: {
labels: [],
datasets: [{
label: 'Temperature (°C)',
data: [],
borderColor: '#FF6384',
borderWidth: 2,
fill: false
}]},
```

```
options: {
scales: {
x: { title: { display: true, text: 'Time' } },
y: { title: { display: true, text: 'Temperature (°C)' } }
}}});
const humidityChart = new Chart(humidityCtx, {
type: 'line',
data: {
labels: [],
datasets: [{
label: 'Humidity (%)',
data: [],
borderColor: '#36A2EB',
borderWidth: 2,
fill: false
}]},
options: {
scales: {
x: { title: { display: true, text: 'Time' } },
y: { title: { display: true, text: 'Humidity (%)' } }
}}});
const airQualityChart = new Chart(airQualityCtx, {
type: 'line',
data: {
labels: [],
datasets: [{
label: 'Air Quality (AQI)',
data: [],
borderColor: '#FFCE56',
borderWidth: 2,
fill: false
}]},
options: {
scales: {
x: { title: { display: true, text: 'Time' } },
y: { title: { display: true, text: 'AQI' } }
}}});
const updateChart = (chart, label, value) => {
```

```
chart.data.labels.push(label);
chart.data.datasets[0].data.push(value);
if (chart.data.labels.length > 20) {
chart.data.labels.shift();
chart.data.datasets[0].data.shift();
}chart.update();
};
tempRef.on('value', (snapshot) => {
const tempValue = snapshot.val();
const currentTime = new Date().toLocaleTimeString();
updateChart(temperatureChart, currentTime, tempValue);
});
humidityRef.on('value', (snapshot) => {
const humidityValue = snapshot.val();
const currentTime = new Date().toLocaleTimeString();
updateChart(humidityChart, currentTime, humidityValue);
});
airQualityRef.on('value', (snapshot) => {
const airQualityValue = snapshot.val();
const currentTime = new Date().toLocaleTimeString();
updateChart(airQualityChart, currentTime, airQualityValue);
});
</script>
</body>
</html>
```

A.3 Website Backend Code

```
from flask import Flask, jsonify, render_template
import firebase_admin
from firebase_admin import db, credentials
from flask_cors import CORS
import os
# Initialize Firebase
cred = credentials.Certificate
("C:\\Users\\PRANAV\\OneDrive\\Documents\\Desktop
\\Project 2024\\
Disinfection Interface\\uv-disinfection-robot-firebase-adminsdk
-9ziuz-095bf9f6e2.json")
```

```
firebase_admin.initialize_app
(cred, {"databaseURL":
"https://uv-disinfection-robot-default-rtdb.asia
-southeast1.firebasedatabase.app/"})
app = Flask(__name__)
CORS(app)  # Enable CORS for fetch requests
# Serve the HTML page
@app.route('/')
def index():
return render_template('web.html')
# Fetch temperature and humidity data from Firebase
@app.route('/DHT_11')
def get_data():
try:
ref = db.reference('/DHT_11')
data = ref.get()
if data:
return jsonify(data)
else:
return jsonify({'error': 'No data found'}), 404
except Exception as e:
return jsonify({'error': str(e)}), 500
if __name__ == '__main__':
app.run(debug=True)
```

APPENDIX B
PUBLICATIONS

Cloud-Enabled UV Disinfection System for Remote Healthcare Sanitization during Pandemics

CLOUD-ENABLED UV DISINFECTION SYSTEM FOR REMOTE HEALTHCARE SANITIZATION DURING PANDEMICS

Pranav Prasad
Dept.Electronics and Communication
Jyothi Engineering College
Kerala, India
pranavprasad8713@gmail.com

Anli Joy
Dept.Electronics and Communication
Jyothi Engineering College
Kerala, India
anlipanakkal04@gmail.com

Remya P.
Dept.Electronics and Communication
Jyothi Engineering College
Kerala, India
remya1562@gmail.com

Albert Thomas Abraham
Dept.Electronics and Communication
Jyothi Engineering College
Kerala, India
albertthomasabraham200@gmail.com

Sindhu S.
Senior IEEE Member
Dept.Electronics and Communication
Jyothi Engineering College
Kerala, India
sindhus@jecc.ac.in

***Abstract*—In healthcare and public environments, maintaining hygiene standards is critical to preventing the spread of infections. Traditional disinfection methods are time-consuming, unreliable, and expose workers to harmful pathogens. To address these challenges, a cloud-connected UV disinfection robot is introduced, automating surface sterilization using UV-C light to ensure effective pathogen elimination while minimizing human exposure. The system integrates microcontroller, UV-C LEDs, environmental sensors, and navigation modules. By connecting to a cloud-based platform, the robot provides real-time monitoring and control through a human-machine interface, allowing operators to receive performance data. The solution incorporates real time data analysis to optimize disinfection parameters and environmental factors such as temperature, humidity, and air quality ensuring maximum efficiency. The use of UV-C technology, cloud connectivity, and advanced data analysis makes this system effective tool for controlling pandemics.This work also includes an Impact analysis and scoring of the environmental factors on pandemic spread.**

***Index Terms*—AQI, HMI, IoT, Real Time Database, UV-C, UV Disinfection**

I. INTRODUCTION

The COVID-19 epidemic had glaring effect of illuminating grave flaws in the control mechanisms of infections and disinfections in health systems worldwide. Contamination from surfaces of all locations where patients have high exposures is known to hugely boost the spreading of infectious illnesses [1]. It is suspected from studies that dangerous bacteria including Methicillin-Resistant Staphylococcus Aureus (MRSA) and others with long survival rates such as Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) cause spread of Healthcare-Associated Infection (HAI) due to such longevity on surfaces. Fig.1 illustrates the need for enhanced disinfection procedures to lower mortality and stop the spread of diseases based on an examination of fatality rates from prior virus outbreaks.

Although conventional cleaning methods are necessary, it fails to address these concerns because residues are left on surfaces or fails to decontaminate areas of unreachable regions [2]–[7]. In high risk environment such as hospitals, and clinics, where cleanness is a must have, this highlights the emergent need for innovative methods of disinfection that would perhaps successfully reduce microbial burden.

One of the prospective answers to these problems lies in UltraViolet (UV) disinfection methods [8]–[10]. Because the UltraViolet C (UVC) radiation damages DeoxyriboNucleic Acid (DNA) and RiboNucleic Acid (RNA) configurations of many types of bacteria, it has been shown that they are effective for killing or denaturing them, thus preventing their replication and transmission. UV disinfection presents a non-toxic residue-free alternative that is more suitable for health-care facilities compared to chemical disinfectants. The use of UV-C technology in conjunction with traditional cleaning methods ensures higher disinfection levels.

In this context, the designing of an Human Machine Interface (HMI)-managed, semi-autonomous UV disinfection robot is the most significant innovation in techniques for pandemic mitigation [11]. Such a robot, unlike fully autonomous systems, allows its operators to accurately navigate through and disinfect critical areas with high touch points in real-time, ensuring perfect disinfection even in impossible-to-reach places that are inaccessible for traditional disinfection methods [12].

979-8-3315-0537-0/25/$31.00 © 2025 IEEE

Figure B.1: Opening Page of Accepted Conference Paper

Authors: Pranav Prasad, Anli Joy, Remya P., Albert Thomas Abraham, Dr. Sindhu S.

Conference: 22nd International Conference on Trends in Engineering Systems and Technology (IC-TEST 2025)

Organizing Institution: Govt Model Engineering College, Thrikkakara, Cochin, India

Status: Accepted for presentation at IC-TEST 2025, March 2025