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BOARD # 191: Design of An Optical Sensing System in Near-Ultraviolet (UV) Spectrum to Detect Environmental Surface Contamination

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Design of An Optical Sensing System in Near-Ultraviolet (UV) Spectrum to Detect Environmental Surface Contamination

Abstract

This paper presents a multidisciplinary research project to develop an optical sensing system based on hybrid Ultraviolet-Visible (UV-VIS) spectrum image fusion algorithms that can contribute to the technical advances for the automated Ultraviolet Disinfection (UVD) mobile systems. The objectives of the proposed research were twofold: 1) To establish a collaborative project between the Departments of Engineering and Biology to provide training and mentoring opportunities for a diverse group of undergraduate research assistants; and 2) To develop a novel adaptive real-time optical sensing algorithms in near-Ultraviolet (UV) spectrum by combining reflected-UV and UV fluorescence techniques to transform our ability to detect biological surface contaminants, such as saliva, that could potentially contain infectious pathogens. The reflected-UV and UV fluorescence imaging methods are used in various scientific, industrial, and medical optical sensing systems, such as in germicidal irradiation (disinfecting), digital forensics, food/agricultural industries, remote sensing, space science (NASA Perseverance), etc. The recent use of UV light surface disinfection mobile robot platforms and devices has shown promising results in the reduction of harmful microorganisms. These UVD systems have been marketed to reduce the transmission of coronavirus and other pathogens that can live for extended periods on the surfaces of objects and that can subsequently lead to infection. However, for complex environments, e.g. a hospital or office with dozens of rooms and various layouts, questions arise during the operation of UV surface disinfection mobile semi-autonomous or autonomous systems, such as *can the robot unknowingly miss certain areas or not expose the surface to UV light long enough leading to incomplete sterilization and the possibility of unexpected contagion?* The proposed system was developed and implemented by using a FujiFilm X-T1 mirrorless camera as the optical sensor for UV-VIS image data acquisition, a Raspberry Pi Model 3B+ for dual spectrum image fusion, analysis, presentation, and edge-cloud computing algorithms to provide rapid delivery of output data. This project provided the undergraduate Engineering and Biology students an opportunity to apply their existing technical knowledge, improve their time management, communication skills, and work as a team on a real-world problem.

Introduction

The Ultraviolet (UV) light accounts for 10% of the sun's total output but it is completely invisible to the human eye[3,4]. There are three ranges of UV wavelengths, classified as: UV-A, UV-B, and UV-C. Table 1 describes the UV wavelengths and their properties.

Table 1. UV light wavelengths and their properties

Type of Ultraviolet Light	**UV Wavelength**	**Description**
UV-A	320 – 400 nm	Often referred to as 'blacklight', this is the longest wavelength region and lowest energy. Represents the largest portion of natural UV light. Utilized by most UV light fluorescent inspection processes
UV-B	280 – 320 nm	Higher energy than UV-A and often referred to as middle wave or erythemal UV light. Partially blocked by the ozone layer, and largely responsible for sunburn (erythema)
UV-C	100 – 280 nm	Higher energy than UV-A and UV-B. Referred to as shortwave or germicidal UV light. Absorbed by the earth's atmosphere.

Optical imagers encompass imaging systems that operate in the visible, UV-A and UV-B (320 - 400nm), and Infrared segments of the EM spectrum. Full Spectrum digital cameras (sensors) can record reflected energy in all the light spectrums[6]. Figure 1 shows the optical imagers based on their electromagnetic (EM) spectrum, extending from the gamma-ray region to the radio region[6].

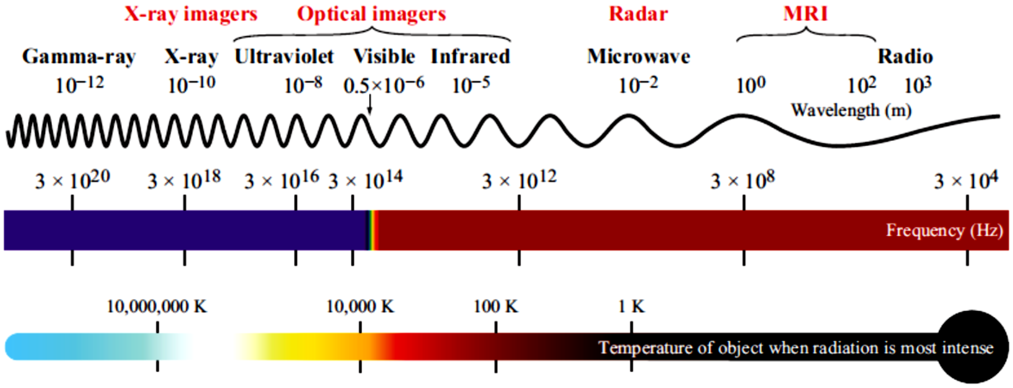


Figure 1. Electromagnetic spectrum[6]

Since the discovery of UV light's germicidal effect in 1878, it has often been applied for microbial control, such as disinfecting drinking water[11,12,13]. In 2003, UV was deployed as a disinfectant against deadly coronavirus particles during the SARS outbreak. During the current pandemic, UV-wielding robots in hospitals, schools, libraries, airplanes, and subway cars have joined a host of technologies being rolled out to disinfect surfaces[11,12,13]. Some of these UV disinfection robots are shown in Figure 2.

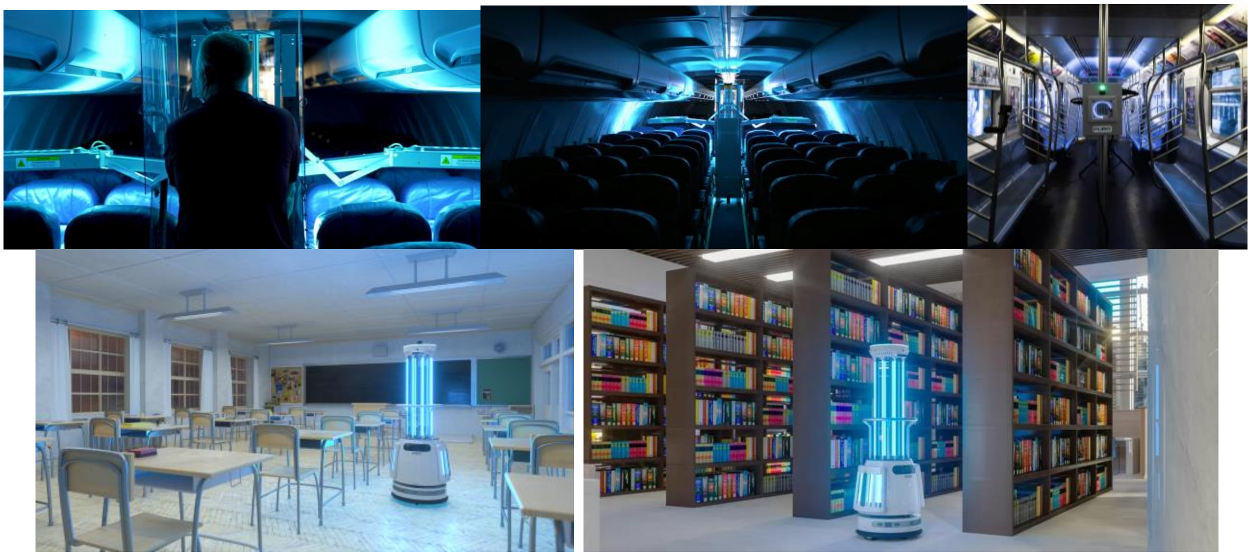
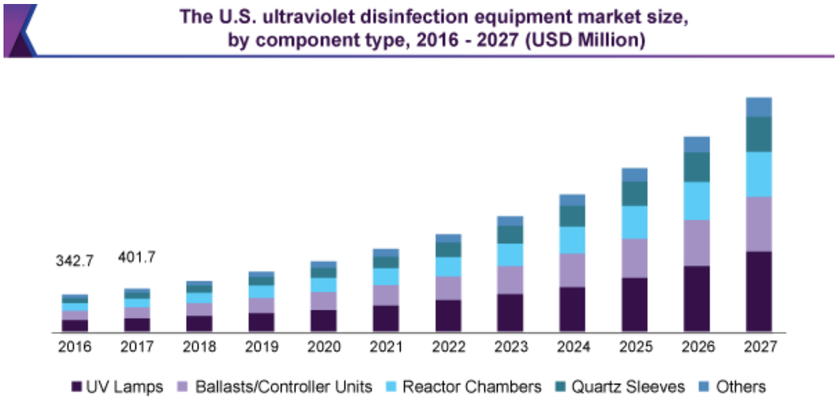


Figure 2. UV disinfection technologies to sterilize surfaces in airplanes and subway cars[16]

Germicidal UV technology is now being used to fight the new coronavirus and sterilize surfaces, air and personal protective equipment like N95 masks[11,12,13]. While antiviral drugs and vaccines concentrate on minimizing and repelling infections in the body, the ultraviolet systems being deployed focus on terminating the virus in the environment before it has a chance to infect anyone[11,12,13]. While UV-C light has been used successfully against biological contaminants for more than a century, it’s only recently that researchers have understood why it’s so successful. In DNA’s four-letter alphabet of nucleotides, thymine (T) and cytosine (C) are particularly susceptible to UV. The UV knocks an electron loose and causes two T molecules or two C molecules to bond together, introducing an error into a string of DNA. Humans have genetic self-repair mechanisms, including a molecule called p53. This protein (sometimes referred to as the “guardian of the genome”) patrols DNA strands and looks for just this kind of nucleotide damage. SARS-CoV-2, the virus that causes COVID-19, lacks such sophisticated self-repair mechanisms, and its genetic material is made up of RNA rather than DNA. RNA contains uracil instead of thymine, but the effect of UV-C is essentially the same: Genetic damage accumulates and the virus is destroyed[11,12,13]. The main problem with UV-C light in the 254-nm range is that it penetrates human skin and eyes, leading to skin cancer and cataracts. Thus, due to UV-C's ability to damage DNA, any disinfecting device that utilizes it must be designed to operate either in an unoccupied room or within a self-contained space that humans cannot enter[11,12,13].

While the market for UVC irradiation equipment is growing, as shown in Figure 3, questions about its efficacy have been raised. Its relatively short wavelength makes it most efficient only over short distances and in a direct line with the UV light source. This in turn raises questions about shadowed areas, for example, and surfaces such as those behind furniture or the lavatory.



Source: www.grandviewresearch.com

Figure 3. UV disinfection equipment market size and trend analysis[15]

It is vital to ensure the safety of the UV disinfection system operators while providing an efficient sterilization workflow for biologically contaminated surfaces in the environment.

The *long-term goal of this project* was to provide safe and healthy spaces for humans, by designing fully autonomous surface sterilization robotic systems to acquire and classify the presence of biological contaminants in real-time video obtained by full spectrum cameras. To accomplish this mission, the objectives of the proposed line of research were phased accordingly:

Phase 1: Develop a novel adaptive near-UV imaging algorithm. The goal of this phase was to explore a hybrid reflected and fluorescent UV imaging method in the near-UV spectrum (300-400 nm wavelengths) for machine vision applications.

Phase 2: Integrate the proposed machine vision algorithm into an existing surface disinfection platform. In this phase, the proposed algorithm in phase 1 will be integrated into an existing UV surface disinfection mobile platform to semi-autonomously navigate the environment based on biological residue detection during the sterilization task in real-time.

Phase 3: Build a prototype mobile system. This phase involves building and testing the capabilities of the proposed system developed in phases 1 and 2 as a tool to autonomously detect the presence of biological contaminants in the environment.

The innovative aspect of this project is that, as the system "*sees*" the surfaces through the full spectrum camera, the robot can learn and optimize its operational mode in motion mapping and UV exposure time for the unknown, complex environments with obstacles present and arbitrary surfaces without having previous knowledge. The mobile robotic systems with this novel real-time UV image processing capability will substantially impact workflow optimization and become the crucial factor in achieving significantly higher efficiency and efficacy in any surface disinfection task thereby reducing opportunities for the spread of disease in the future.

The proposed research will provide training and mentoring opportunities for a diverse group of undergraduate research assistants. The findings and knowledge generated as part of this project will be widely disseminated through professional presentations, publications, and web access. Finally, the research findings have the potential to support our local community through awareness of healthcare, such as public institutions, emergency care facilities, military installations, etc.

Materials and Methods

In Phase 1, the goal of the multidisciplinary research project was to develop and design an efficient optical sensing system based on combinational UV imaging algorithms that can contribute to the technical advances for the automated UV disinfection (UVD) mobile systems. Figure 4 summarized our proposed algorithm development framework, which was implemented by using an edge cloud computing approach. Unlike cloud computing, edge cloud computing allowed us to process our images closer to the source of local computing power, such as using a Raspberry Pi Model 3B+ for dual spectrum image fusion, analysis, presentation, to provide rapid delivery of output data[23]. The image acquisition block was to address the challenges in the UV image capture and collection. A FujiFilm X-T1 IR mirrorless camera was chosen due to its advanced performance in UV, visible and infrared (IR) imaging capabilities in the light spectrum. In addition, this is the only camera that is available to the consumer market without any needed modifications for UV and IR (UVIR) imaging.

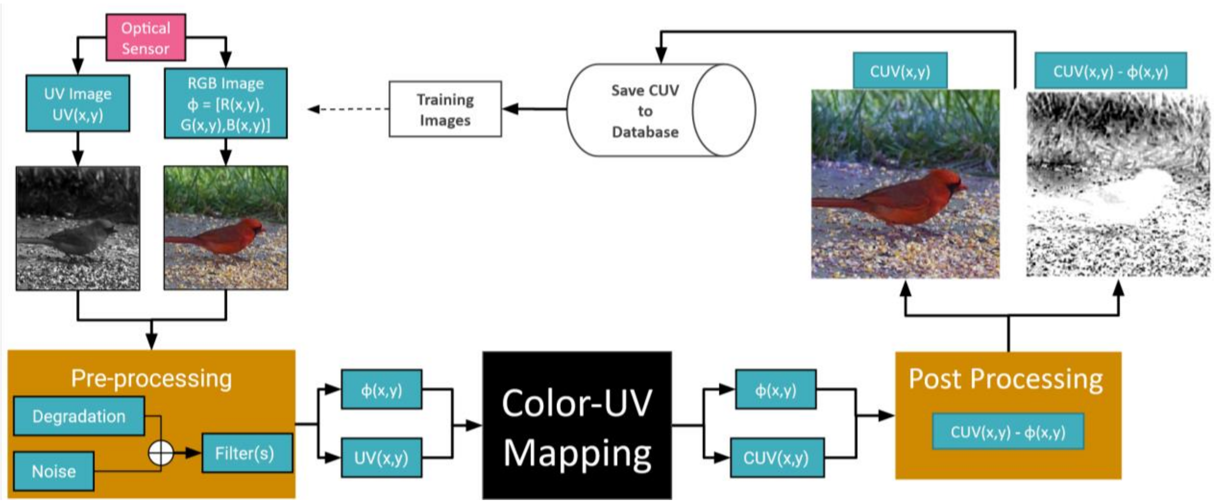


Figure 4. UV image processing framework

The preprocessing block addressed the challenges in the UV and color (RGB) image quality. In this block, the filtering algorithms were developed to obtain clean and detailed images that may have been corrupted by motion blur, noise from the environmental signal interferences. After the preprocessing block, the proposed adaptive hybrid UV algorithm[26] was developed to analyze the UV details from sample images that were acquired from contaminated surfaces with biological matter. UV light itself is not visible, but when a photon of ultraviolet radiation collides with an electron in an atom of a fluorescent material, it elevates the electron to a higher energy level. Subsequently, the excited electron relaxes to a lower level and emits light in the form of a lower-energy photon in the visible (blue) light region. The basic task of the fluorescence microscope is to use an excitation light to irradiate a prepared specimen and then to separate the much weaker radiating fluorescent light from the brighter excitation light. Thus, only the emission light reaches the eye or other detector, such as a full spectrum camera. The controlled experimentation of UV imaged samples, i.e. synthetic human saliva, sun screen, invisible ink, etc., on an environmental surface, such as a classroom desk, was analyzed by the proposed Color-UV mapping process. The samples were excited with a wavelength of 254 and 365 nm by UV light. The high-definition Fujifilm X-T1 mirrorless camera was used to capture the images of marked area. These images were passed onto the post processing stage of the proposed framework in Figure 4.

Results and Discussion

This section presented our results as part of post processing stage, as shown in Figure 4, in which Color-UV (CUV) and RGB images were further analyzed to be combined in spatial image domain to visualize the CUV fused image. A system's cameras, optics, filtering and illumination must be carefully selected according to the UV ranges being imaged. Most of the system design depends on custom-built cameras with modified lenses and UV filters that are relatively expensive to operate, maintain and repair. These optical sensing system specific results require high-definition cameras with multispectral sensitivities. Thus, it is critical to provide an integrated and efficient approach to address the variability of UV based optical sensing systems. The MathWorks' MATLAB[2] software was used to develop the proposed near-ultraviolet spectrum imaging technique. Initial investigation in developing the near-ultraviolet spectrum image processing algorithm was through experimenting with a hyperspectral imaging technique to obtain the electromagnetic spectrum information from the pixels in the UV images to identify the wavelength range. Hyperspectral imaging measures the spatial and spectral characteristics of an object by imaging it at different wavelengths. The wavelength range extends beyond the visible spectrum and covers ultraviolet (UV) to long wave infrared (LWIR) wavelengths.

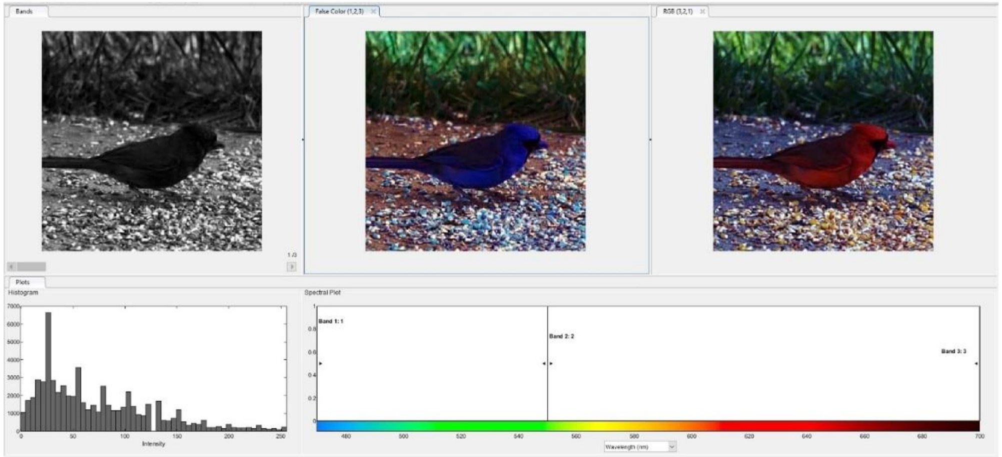


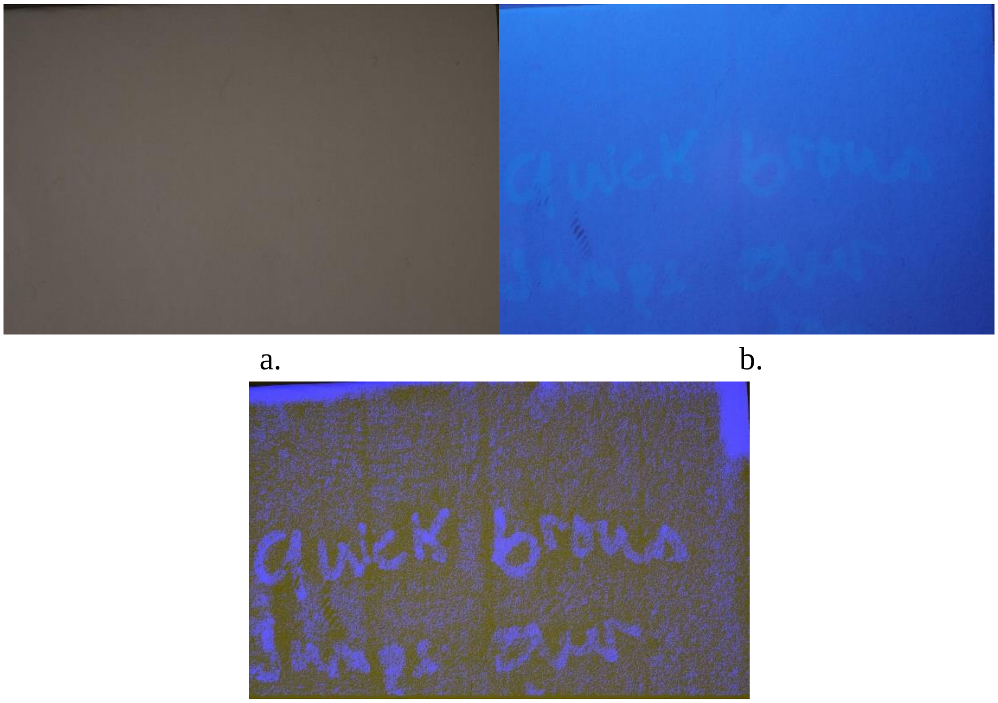
Figure 5. Hyperspectral analysis of an UV Image.

In Figure 5, three stages in identification of the wavelengths in the EM spectrum were displayed. First image in the figure above was the UV image. Second image was the False Color generated by using hyperspectral imaging technique to analyze the UV image to identify the wavelength range (380 nm, 550 nm, 680 nm respectively). The third image was the CUV composite that was generated based on the information gathered from the UV and False Color images to switch and replace the appropriate RGB layers for the output.

(a) (b) (c)

Figure 6: (a) Original RGB image, (b) Color-UV (CUV) composite image, (c) Difference between the original and CUV composite image

Figure 6 (c) showed the difference between the original RGB image and CUV composite to identify the details that are not visible in the original image. In the "Cardinal" image, it was shown that cardinal is reflecting lots of UV light that could be perceived to prevent the bird from overheating. On the other hand, the ground, some of the background green and seeds absorbed red and blue light. The difference illustrated the details of the UV lights reflected and fluorescent attributes in this example. The developed fusion algorithm between RGB and UV provided successful results that the proposed algorithm was further tested on various UV images that were acquired as contaminations on surfaces in a laboratory setting. Figure 7 showed one of those test images.



a. b.

c.

Figure 7. (a) Stainless steel surface with invisible ink under visible light, (b) Under UV light with 254 nm, (c) CUV composite image after processing

There were about 500 images used in this research with various types of biological and non-biological specimens. Some of these test samples were olive oil, sunscreen, chicken blood, invisible ink, glow powder, yeast, *Escherichia coli* (*E. coli*), and *Candida albicans* (*C. albicans*).

Conclusions

The purpose of this collaborative research project was to provide the undergraduate Engineering and Biology students an opportunity to apply their existing technical knowledge, improve their time management, communication skills, and work as a team on a real-world problem. The project timeline was illustrated in Figure 8. This one year long project was divided into three stages that were planning, development, and final deliverable preparation.

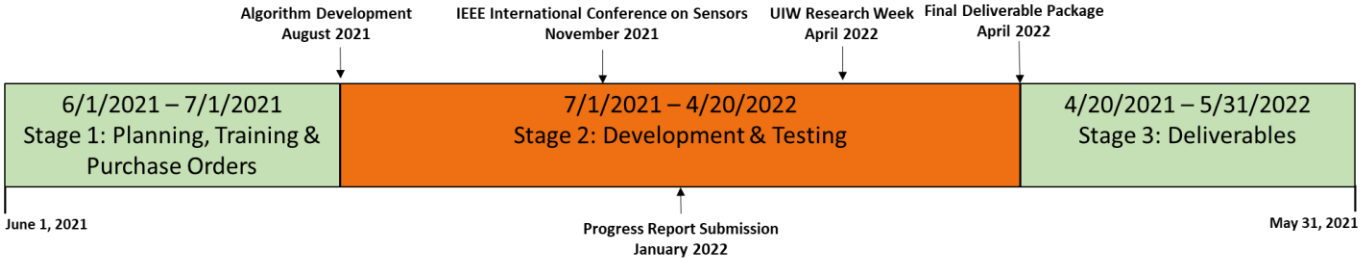


Figure 8. Phase 1 timeline

In the first stage of the project, the authors trained the research assistants in the areas of UV image capturing and processing. Stage 2 consisted of the proposed algorithm development and testing in a laboratory setting. In the third stage, the authors prepared the final report and presentation to be submitted to the Office of Research and Graduate Studies at the university.

Student Experience

This collaborative project provided a multidisciplinary student experience for undergraduate students in the fields of engineering and biology. It served as an innovative approach to develop students' professional skill sets beyond the traditional curriculum of their respective degree programs, including soft and technical skills. From the start of the project, the student team proposed their own multistage project planning as described by the authors in Figure 8. As it is a challenging task in project management, students scheduled their laboratory meetings around their full-time course work in both Fall and Spring semesters. By using a Gantt chart, their time management approach allowed them to stay current on their tasks and to keep track of delegated work within the members. Transferable soft skills that students developed during this project included communication, work ethic, and leadership. One important aspect of this project design was the interdisciplinary approach where engineering students worked closely with biology faculty and students, and vice versa. A sample post project reflective questionnaire and students' responses about the collaboration between the Departments of Engineering and Biology were presented in the following table:

Table 2. A sample of students’ responses to a reflective question on the collaborative project

Question: What was one or more important take aways from completing the interdisciplinary (engineering and biology combined) project?
Student 1: *“One important takeaway is the ability to work effectively in a team with diverse skill sets and backgrounds. Communication skills and understanding are vital when working on interdisciplinary projects. Another takeaway is the value of interdisciplinary collaboration in developing innovative solutions to complex problems. Combining the knowledge and skills from both engineering and biology leads to unique procedures and results.”* **Student 2:** *“I knew from the start that the project would be a challenge compared to previous ones I have done. For instance, scheduling with the biology department to procure supplies and plan follow up meetings with my teammates required me to balance their limited time as well as the professors. The project being interdisciplinary was extremely fun and complex as I had to understand the biological entities and relate them to physics through programming. As I had to combine what I cannot see (UV) with what we can see (Visible). With more time, I wanted to go over the irregularities encountered during the project, such as UV under different shades of darkness or under different magnitudes of light (sunrise vs sunset). I had planned on expanding this idea through video; however it was not possible with the given time we had.”*

The benefits of this approach are that it demonstrates the importance of collaboration between scientists of various fields for the development and implementation of innovation solutions and prepares students for careers that bridge sections of the STEM field. For example, engineering students were exposed to microbiological techniques, such as cell culturing, biohazardous waste handling, and aseptic techniques which are traditionally not part of the engineering core competencies but essential skills for researchers in the field of biomedical or biomaterial engineering. Another sample post project reflective questionnaire and student response about the project conclusion were presented in Table 3:

Table 3. A sample of students’ responses to a reflective question on the conclusion of the project

Question: How will this experience help you achieve your future career goals?
Student 1: *“Completing an interdisciplinary project combining engineering and biology creates valuable work experience for an engineering graduate looking to pursue a career in a related field. It demonstrates an ability to work in multidisciplinary teams, which is increasingly important in industries such as biotechnology, medical devices, and pharmaceuticals. This experience really improved my ability to think outside the box and develop innovative solutions to complex problems.”* **Student 2:** *“Through this project, I have learned that creating a coordinated schedule with each team member and all associated professors will make it easier to coordinate schedules. This experience was beneficial as it helped me achieve a job after the project and provided the knowledge necessary to lead a coordinated team. After this project, I can more thoroughly*

research and dig for relevant data, concepts, and processes in scholarly literature. If I ever get to have the chance in the future to lead a project similar to this, I would do so in a heartbeat!"

The authors strongly believe that the takeaway from this proposed undergraduate research was the importance of opportunities to develop not only basic skills, but also understanding, such that students learn to direct their own work. Mentors should allow students to see their uncertainty and provide support responsively but gradually transfer responsibility to the student. This fosters a sense of ownership, competency and belonging that allows students to grow further as they enter new research experiences[27, 28, 29].

Future Work

One of the goals of this project was to establish a collaborative project between the Departments of Engineering and Biology to provide training and mentoring opportunities for a diverse group of undergraduate research assistants. Based on the student outcomes and interests the authors planned to continue the collaboration as described in the project phases 2 and 3 by building a prototype as rendered in Figure 9.

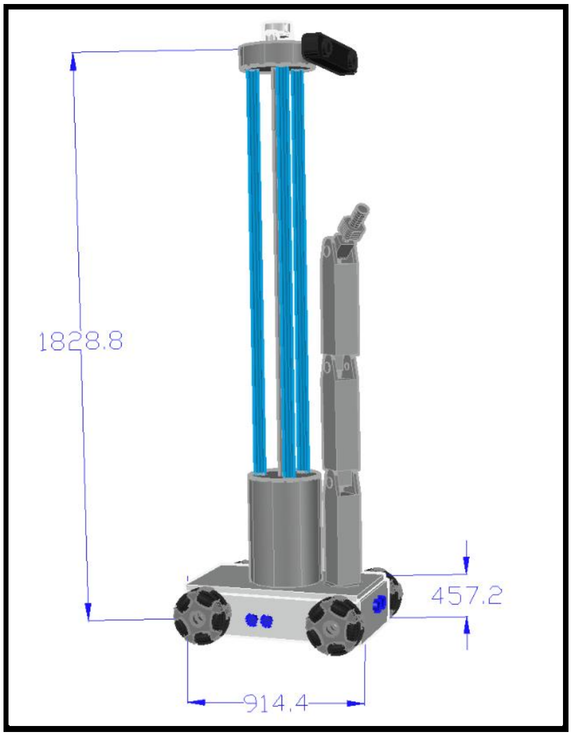


Figure 9. An AutoCAD design for proposed UVD system

The design is based on utilizing multiple cameras that can capture RGB and UVIR images simultaneously. One of these cameras is planned to be the StereoPi v2 for navigational purposes[25]. StereoPi v2 is an open-source stereoscopic camera based on Raspberry Pi with Wi-Fi, Bluetooth, and an advanced powering system[25]. With the integrated spatial AI, people and objects will be identified. Once people are identified the UVD will stop moving and wait for human interaction through the application. The arm will house the FujiFilm X-T1 IR mirrorless camera to capture surface images. The proposed UVD system will be powered by a 500W inverter due to the need for both direct and alternating current.

The long-term goals for the proposed project phase 2 and 3 are twofold: 1) to provide opportunities for students to engage meaningfully with scientific method and engineering design, i.e. by solving design challenges that emerge in the construction of scientific ideas; 2) to establish a learning community that deepens collective knowledge, promotes industrial and professional networking opportunities.

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