Environmental Disinfection Based on Mobile Intelligent Networking
Highly Efficient Ultraviolet Light Machines

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Abstract

Since 2019, the world has suffered from the outbreak of the "Coronavirus Disease (COVID)-19 pandemic. This study used the principle of Ultraviolet (UV)-C disinfection to produce a mobile high-power UV-C sterilizer. It focused on combining intelligent control systems, human sensors, and Internet of Things (IoT) systems to carry out disinfection tasks in unmanned indoor spaces. Because of its mobile nature, the sterilizer could be moved at any time in various learning, research, and activity rooms for disinfection. In addition to manually controlling the sterilizer, a Wi-Fi or Narrowband (NB)-IoT-enabled remote control was provided to start the disinfection process. In order to prevent ultraviolet light from harming the human body, sensors were employed self-acting to detect the presence of people and turn off the ultraviolet light when people were detected in the area. At the same time, a camera on the sterilizer would capture an image and notify the relevant personnel through a LINE notification, to prevent the human body from being exposed to ultraviolet light, causing harm to the teachers and students on campus. During operation, voice broadcast reminders and a status indicator could provide information about the operation status. After disinfection, users could view the disinfection process through a mobile device application or a webpage, which would automatically notify relevant personnel of the disinfection status.
through a LINE notification. In this way, the disinfection progress could be updated at anytime, anywhere and the current disinfection status in the classroom could be displayed in real-time, allowing teachers and students on campus to carry out teaching and learning in a safe and secure environment.

*Keywords:* UV-C sterilizer, Disinfection, LINE bot, Internet of things.
1 INTRODUCTION

In 2019, the global impact of the COVID-19 pandemic was felt, leading Taiwan to collaboratively combat the virus under the Central Epidemic Command Center. World Health Organization experts warn that the virus can spread through aerosols, posing a significant infection risk. Aerosol particle size plays a crucial role in transmission and deposition in the lungs, with smaller particles having a higher likelihood of causing severe disease with a lower infectious dose (Ehsanifar, 2021). Severe Acute Respiratory Syndrome (SAR)-CoV-2 can remain viable in ambient air for over three hours and replicate through fine aerosols emitted by infected individuals (Yao et al., 2020). Besides, there is a connection between a slight increase in PM$_{2.5}$ levels and a small rise in COVID-19 spread (Chakrabarty et al., 2021). These findings have important implications for managing the COVID-19 pandemic and other cardio-pulmonary diseases during PM pollution events, highlighting the significance of reducing PM pollution in major cities. Another study suggested that an increase of 1 $\mu$g/m$^3$ in PM$_{2.5}$ is associated with a rise in mortality by $10.5 \pm 2.5\%$ in 6 Western Europe countries (France, Germany, Italy, Netherlands, Spain, United Kingdom) during 2020 – 2022 (Renard et al., 2022).

To curb the transmission of this virus, government and numerous enterprises emphasize the significance of indoor disinfection. The demand for disinfecting products, like hand sanitizers, masks, and environmental disinfectants, has surged online, signifying heightened awareness of
epidemic prevention among Taiwanese people (Jaiswal et al., 2023). However, in crowded areas like hospitals, offices, malls, and bus stations, relying solely on manual cleaning methods (e.g., alcohol, bleach) may lead to insufficient disinfection quality and increased labour efforts (Kartikaningsih et al., 2022).

The study introduced a sanitizing and disinfection system that combined a high-power mobile ultraviolet sterilizer with intelligent ultraviolet control and an anti-theft system. It included a human body sensor and IoT technology for unmanned indoor disinfection and anti-theft tasks. The system transmitted real-time disinfection process and surveillance images to LINE, notifying relevant personnel of the area's disinfection status and conducting anti-theft measures. Besides remote control options and an emergency shutdown mechanism protected individuals from UV exposure.

In manual control, a Wi-Fi or NB-IoT-enabled remote control could also be used to start disinfection. The system also provided status indicators, voice reminders, and data recording via a cloud webpage control and mobile app, contributing to a safe and non-toxic campus environment.

2 DESIGN, SYSTEM ARCHITECTURE AND MATERIALS

2.1 Design Study

Several types of disinfection methods are mentioned in Text SI 1.1. Ultraviolet light is commonly used for disinfection, destroying DNA (Deoxyribonucleic Acid) and RNA (Ribonucleic Acid) structures in cells. However, it can harm humans. Moreover about UV light as desinfectant
can be found in Text SI 1.2. Current UV-C light disinfection devices detect people and halt the process, requiring manual restart. This study aims to optimize efficient disinfection while ensuring human safety (Hasan, 2018). IoT is a network where digital machines and devices connect and exchange data without human interaction. It spans various sectors like industry, healthcare, and smart environments, involving interconnected objects with sensors and software for data transmission (Kun-Lin Tsai, 2022; Lu et al., 2022).

As shown in Fig. 1a, the system architecture consisted of three main components: (1) a highly efficient mobile intelligent networking ultraviolet light machine with a four-wheel axle aluminium alloy platform for easy mobility between classrooms, (2) a lens module, and (3) a main control center. The UV light machine featured a UV light generation unit, a control unit, and a human body protection mechanism, including an infrared sensor, warning lights, and a voice device. During disinfection, the infrared sensor activated, sending signals to the server and transmitting captured images to a LINE group, ensuring safety, pandemic prevention, and anti-theft information (Rizvi, 2011; Chen et al., 2022; Hawari and Hazwan, 2022; Immonen and Hämäläinen, 2022).

The server's main control center used a Raspberry Pi with Linux, Apache, MySQL (Structured Query Language), PHP (Personal Home Page), MQTT (Message Queuing Telemetry Transport), and Python. Switching the UV machine to Wi-Fi or NB-IoT allowed remote control via a mobile app or webpage. Disinfection data could be queried, and LINE Notify provided timely notifications.
2.2 Sensor and Data Collection

The system utilizes an array of HC-SR501 human infrared sensing modules to detect the presence of individuals within the vicinity of the UV light machine. These sensors are highly sensitive and have adjustable settings for delay and detection distance, allowing them to be fine-tuned for the specific requirements of the environment in which they are deployed. The sensors are strategically placed on all sides of the system to detect motion from any direction, with a set sensing distance of 5 meters to ensure that the UV-C light is deactivated if a person approaches, thereby preventing harmful exposure. When the infrared sensors are triggered, they send a signal to the Espressif System Platform (ESP) WROOM-32 module, which is connected through General Purpose Input/Output (GPIO), and the UV light generation unit is immediately shut down. Additionally, the system incorporates an ESP32 CAM development board equipped with an OV2640 lens module. This board is responsible for capturing images when the infrared sensors are activated, indicating that someone is approaching the disinfection range. The ESP32 CAM board...
is lightweight and supports Wi-Fi and Bluetooth protocols, making it suitable for IoT applications. Upon capturing an image, the system sends an alert through LINE Notify to inform relevant personnel, which also serves as an anti-theft security function.

The data collected by the sensors and the ESP32 CAM board is then transmitted back to a server using MQTT messaging, where it is stored and managed. This allows for real-time monitoring and the ability to respond quickly to any potential safety issues or unauthorized access to the disinfection area. The integration of these sensors and data collection technologies ensures that the UV light machine operates safely and effectively, with minimal risk to humans while maintaining a high level of disinfection efficacy. Furthermore, details of the sensor and data collection are explained in supplementary 2.5.

2.3 Highly Efficient Ultraviolet Light Machines

In Fig. 1b (supplementary), the control unit acted as the sterilizer's brain, managing activation, timing, and other units. The manual switch facilitated operator interaction, while the infrared detection unit ensured safety by detecting people nearby. The warning unit provided visual and auditory alerts in coordination with the disinfection process. The ultraviolet unit followed control unit commands to start or stop disinfection, updating the server database with progress and status information.

Once the UV machine starts, the control unit awaits signals from the manual switch or network module. An off signal prompts an immediate stop through the UV and infrared units. A start signal
activates the infrared detection unit and timer, along with a voice warning for disinfection (Fig.2). The infrared unit ensures the area is clear, with a default five-second delay for people to leave. The warning unit continues to sound warnings while the infrared detector monitors for any presence. If the set time elapses and the area is clear, disinfection commences. Otherwise, the process repeats until completion (Davis and Clowers, 2023). When the disinfection procedure started, the control unit would activate both the UV light and infrared detection units. The preset disinfection time was 30 minutes, adjustable as needed. Throughout the process, the warning unit displayed a continuous red light to caution against approaching the area. If the human body detection unit detected anyone nearby, it promptly alerted the control unit to stop UV light emission, showing a yellow warning light and issuing a voice warning for evacuation. The unit also transmitted real-time images to the LINE group through LINE Notify, triggering site clearance and restarting disinfection. After completion, the control unit signaled the warning unit to emit a green light, indicating a successful on-site disinfection and uploading the information to the database for teachers' and students' reference.
Fig. 2. Flow chart of the sterilizer system.

The control system activates UV light based on signals: manual or remote start. Human body protection also warns accordingly (Ma and Ding, 2018). The detailed information about the ESP32 module, NB-IoT Module, human body protection mechanism, status warning lights, infrared sensing, server system, lamp server erection and php my admin can be found in the supporting information.
2.4 Mobile Intelligent Networking

2.4.1 Human-Machine Interface Design

The human-machine interface had two components. One allowed remote UV sterilizer control via a mobile app or webpage in Wi-Fi or NBiot mode. The other facilitated real-time query of disinfection results through the app or webpage, displaying data from the database. The mobile app was developed using MIT App Inventor 2, an online Android development environment. The app's interface (Fig. S11) and functionality were designed on the designer page and programmed in the block editor, similar to Scratch. The app integrated UrsPahoMqttClient to connect to the MQTT server, enabling message exchange and historical query of disinfection data from the database (Hakim et al., 2019; Boppana and Bagade, 2023).

The system website was built using Bootstrap, a front-end framework for responsive web design (RWD) adaptable to various devices. Leveraging the widespread use of smartphones and LINE app, the proposed system utilized IFTTT platform (If This Then That) to enable real-time push notifications. By setting up webhooks in the IFTTT platform and integrating with LINE Notify, relevant personnel would receive automated disinfection result messages when triggered, as shown in Fig. S12 (Seetharaman et al., 2022). This allowed convenient and timely updates without the need to open additional webpages or devices.
2.4.2 Message Queuing Telemetry Transport (MQTT)

MQTT, part of the Transmission Control Protocol/Internet Protocol (TCP/IP) protocol suite, enables lightweight message publishing and subscription. The system's communication architecture involves Publishers, Subscribers, Topics, and Agent Brokers (Fig. S9). The proposed system utilizes MQTT for efficient and timely data transmission between the server and UV sterilizer. The operator can start the sterilizer via a mobile app or webpage. When activated, the sterilizer subscribes to MQTT topics on the server, commencing the disinfection process and transmitting relevant information back to the server after completion (Fig. S10).

3 SYSTEM BUILDING AND ACHIEVEMENTS

3.1 Mobile Intelligent Networking Ultraviolet Light Machine with High Efficiency

Fig. 3(a) is the UV sterilizer with an aluminum alloy design, making it lighter and easier to move with four-wheel axles. The 360° high-power annular UV-C light tubes feature a three-section bracket, allowing different directions of sterilization for better disinfection results, as illustrated in Fig. 3(b).
Fig. 3. (a.) Disinfection of 360° high-power circular UV-C light tube (b.) three-section brackets

3.2 Operation Mode of the Ultraviolet Light Machine

The startup mode offers three options that could be controlled through the switch mode button (Fig. 4(a)):

1. Manual mode: Users can start the disinfection program by pressing a button or using a remote control (Fig. 4(b)).

2. Wi-Fi: The UV sterilizer can be remotely activated via a mobile app or webpage, using the MQTT protocol after connecting to Wi-Fi.

3. NB-IoT: With a SIM card and telecom base station connection, the UV sterilizer can be remotely activated via a mobile app or webpage, using the MQTT protocol. For Wi-Fi and NB-IoT modes, users can press the start button on the mobile app (Fig. 4(c)) or webpage (Fig. S13(a)) to initiate the disinfection process. The webpage, designed with RWD, allows
convenient browsing on different interfaces (Fig. S13(b)). The interface displays the UV sterilizer's status, start button, and query button for real-time process viewing, providing a reference for teachers and students.

![Interface Image](image)

**(a)** Mode switching button (b) manual start button and remote controller (c) app interface of the mobile device.

**3.3 Ultraviolet Light Machine Sensing Device and Control**

When the UV light was activated, the ESP32-WROOM 32 model immediately activated the infrared detection unit. In Wi-Fi mode, it connected to the wireless base station, while in NB-IoT mode, it connected to Telecom's base station. Upon connection, it subscribed to MQTT topics and awaited disinfection commands from the server. The DFPlayer (Dragonfly Player) Mini would announce safety precautions before starting the 30-minute UV-C light timer (Fig. 5). A red warning light indicated danger during UV-C light operation (Fig. S14(a)), and a green light signified safety upon completion (Fig. S14(b)). The system transmitted completion data to the server through MQTT. If the infrared sensor detected someone approaching, the UV-C light stopped, and the DFPlayer Mini issued warnings (Fig. S14(c)). The ESP32 CAM lens module captured and
transmitted images through LINE Notify (Fig. S15(a) and Fig. S15(b)), restarting detection and
timing after the person left.

![Image](image.jpg)

**Fig. 5** The ultraviolet light machine in use.

### 3.4 Ultraviolet Light Tube Test

The germicidal light tube used in this system was a Sankyo Denki 20 W UV-C T8 light tube. The ultraviolet germicidal ability depended on the irradiation intensity and irradiation time, as shown in Eq. (1). This experiment was based on the fact that the cumulative radiation dose of 5 mJ/cm² can inactivate 99% of COVID-19 viruses, according to the medical microbiology research team of Boston University.

\[
K(\text{disinfection dose}) = I(\text{irradiation intensity}) \times t(\text{irradiation time}) \
\]

(Eq. 1)

When the light tube was 20 W and a UV-C illuminance instrument was used, the UV-C irradiance intensity was 33 µW/cm² at a distance of 100 cm, 4 µW/cm² at a distance of 300 cm, and less than 1 µW/cm² at a distance of 500 cm, 2 minutes and 31 seconds at a distance of 100 cm,
and 20 minutes and 5 seconds at a distance of 300 cm. The power at 500 cm was insufficient and
could not be calculated, as shown in Table 1.

Table 1. Test data of ultraviolet disinfection light tube at various power

<table>
<thead>
<tr>
<th>Power</th>
<th>20 W</th>
<th>40 W</th>
<th>80 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>Irradiance Intensity</td>
<td>Time</td>
<td>Irradiance Intensity</td>
</tr>
<tr>
<td>100 cm</td>
<td>33 µW/cm²</td>
<td>2 minutes and 31 seconds</td>
<td>124 µW/cm²</td>
</tr>
<tr>
<td>300 cm</td>
<td>4 µW/cm²</td>
<td>20 minutes and 5 seconds</td>
<td>15 µW/cm²</td>
</tr>
<tr>
<td>500 cm</td>
<td>&gt;1 µW/cm²</td>
<td>-</td>
<td>5 µW/cm²</td>
</tr>
</tbody>
</table>

When two light tubes were 40 W and a UV-C illuminance instrument was used, the UV-C
irradiance intensity was 52 µW/cm² at a distance of 100 cm, 10 µW/cm² at a distance of 300 cm, 3
µW/cm² at a distance of 500 cm, 1 minute 36 seconds at a distance of 100 cm, 7 minutes 08 seconds
at a distance of 300 cm, and 27 minutes 46 seconds at a distance of 500 cm. When four light tubes
were 80 W and a UV-C illuminance instrument was used, the UV-C irradiance intensity was 124
µW/cm² at a distance of 100 cm, 15 µW/cm² at a distance of 300 cm, 5 µW/cm² at a distance of
500 cm, 40 seconds at a distance of 100 cm, 5 minutes and 33 seconds at a distance of 300 cm, and
16 minutes and 40 seconds at a distance of 500 cm, as shown in Table 1. According to the research
results of Biasin et al., the COVID-19 virus will stop replicating obviously only when the radiation
dose is 3.7 mJ/cm², so the irradiance time was set as 30 minutes for classrooms sized 20–30 m².
3.5 Comparison of the Specifications of Commercially Available Products

The comparison of common UV sterilizers on the market (Cheng-Ta Chiang, 2020) involved coded devices. Product A and Product B, with specific parameters (e.g., wattage, UV wavelength, operation mode, etc.). The system developed in this study surpassed Products A and B by featuring remote control, real-time operation history uploads, and display on a webpage or app. This enhanced utilization efficiency, saving time for observers through remote control and message push notifications, reducing response time and minimizing personnel waste (as shown in Table 2). Products A and B lacked these functions, making the UV-C disinfection system of this study more effective in improving efficiency.

<table>
<thead>
<tr>
<th>Item</th>
<th>This System</th>
<th>Product A</th>
<th>Product B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wattage</td>
<td>80 W</td>
<td>24 W</td>
<td>40 W</td>
</tr>
<tr>
<td>Operation distance</td>
<td>Unlimited</td>
<td>&lt;0 m (close range)</td>
<td>5 - 10 m</td>
</tr>
<tr>
<td>Moving mode</td>
<td>Axle movement</td>
<td>Manual handling</td>
<td>Axle movement</td>
</tr>
<tr>
<td>Status indicator light</td>
<td>Diversified functions</td>
<td>Single function</td>
<td>Single function</td>
</tr>
<tr>
<td>Voice broadcast system</td>
<td>Yes</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Human body sensing function</td>
<td>Yes</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>LINE push notification</td>
<td>Yes</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>History record</td>
<td>Yes (cloud)</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS AND FUTURE DIRECTIONS

The study successfully developed an intelligent Internet of Things (IoT) system applied to a high-power mobile ultraviolet light disinfection device, effectively improving its efficiency. Amidst the ongoing COVID-19 pandemic and the prevalence of unseen viruses and bacteria, the importance of effective disinfection methods cannot be overstated. UV-C light has emerged as one
of the swiftest and most efficient methods available; however, direct exposure to UV-C rays poses
disadvantages to human health. Meanwhile, concerns about residue and pollution surround chemical
disinfectants. Within this context, the study's UV sterilizer addressed these challenges through the
incorporation of a high-power UV-C light bulb and an IoT system. This system allowed for remote
control wirelessly or manually via remote, an app, or a webpage. Notably, the device integrated a
protective mechanism for human safety, featuring audible and visual warnings and an automatic
shut-off of the UV-C light when someone approached. Real-time image transmission to a LINE
group ensured comprehensive protection throughout the process. Following disinfection, data was
automatically transmitted to the server, with results subsequently shared on the LINE group
through IFTTT, alerting relevant personnel. By the cloud system enabled data tracking and online
query of disinfection history, with LINE notifications for completion alerts. Users had the
capability to monitor the disinfection progress in real-time using the app or webpage. Infrared
sensors detected people (within 5 meters) to control UV light activation, accompanied by a buzzer
reminder. Furthermore, the study seamlessly integrated a potent mobile UV germicidal light with
an IoT system, sensors, and anti-theft measures to effectively address manual disinfection
challenges. The IoT system facilitated remote monitoring, environmental checks, and automated
restarts following safety stops. UV light activation included red warning lights, voice prompts, and
an automatic shutdown if someone approached, with a restart if interrupted then green light
indicated completion. Additionally, it stored time records in the cloud to prevent redundant operations. The mobile system with four-wheel axles allowed convenient operation and a three-section design improved disinfection angles and effectiveness. The study also provided a comprehensive comparison with existing market products.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest to report regarding the present study.

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