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

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1 COMMON DISINFECTION METHODS
The research provides creation of an advanced sterilization system that ensures a safe teaching and learning environment on campus. This UV device incorporates several innovative features on Intelligent Internet of Things (IoT) System, human safety mechanisms, real-time monitoring and notifications, anti-theft measures and the integration of advanced technologies. This system integrates a mobile high-power ultraviolet sterilizer with an intelligent control system, leveraging sensors and the Internet of Things (IoT) supported by big data networking. The system is designed to perform disinfection tasks in unmanned indoor spaces, ensuring that areas can be disinfected at any time without human presence.

A key feature of this system is the emergency shutdown mechanism, which is activated by human body sensors to prevent the risk of UV light exposure to individuals. This is particularly important given the dangers associated with UV-C light, which can cause skin damage, cataracts, or even cancer. The system's intelligent control allows for remote operation using Wi-Fi or NB-IoT, providing flexibility and ease of use. During operation, the system not only uses status indicator lights but also provides voice broadcast reminders to inform users of the ongoing process. After the disinfection process is completed, the system automatically notifies relevant personnel of the status via LINE.

1.1 Types of Disinfection Methods
Since the outbreak of the COVID-19 pandemic in Taiwan, pandemic prevention has become a large-scale campaign, emphasizing mask-wearing, social distancing, and disinfection. Common methods include ethanol, hypochlorous acid, and UV-C light (Sadeghi-Niaraki, 2023). Disinfection times for HClO vary from 20-30 seconds (Ali et al., 2023) to 5-10 minutes (Jan et al., 2022), while UV-C with wavelengths of 200-280 nanometers requires 3-30 minutes
Specifically, UV-C light is the most effective method to deal with the spread of aerosol viruses, and it was the disinfection method used in this system.

1.2 UV Light as Disinfection

UV light, invisible to the naked eye, exists in nature. It has wavelengths, from long to short, are UVA > UVB > UV-C. The shorter the wavelength is, the weaker the penetration but the higher the energy (Fajar et al., 2002). In recent years, high doses of ultraviolet germicidal irradiation (UVGI) technology (≥40,000 W·s/cm²) have become widely used in medical institutions, food hygiene, and office building air conditioning system purification due to its fast germicidal rate, high disinfection rate, and strong sustainability, without derivative secondary pollution (Pathmudi et al., 2023). A team at Columbia University Irving Medical Center in the United States pointed out that far ultraviolet light with a wavelength of 222 nm can safely kill airborne influenza viruses. COVID-19 and influenza viruses belong to the coronavirus family, so the relevant results were expected to be extrapolated to the prevention of the COVID-19 pandemic. The medical team at Columbia University Irving Medical Center used an aerosol irradiation chamber to test the effectiveness of 222-nm far ultraviolet light in inactivating aerosolized human coronaviruses (βHCoV-OC43 and αHCoV-229E). Following the exponential disinfection model, 1.7 mJ/cm² or 1.2 mJ/cm² of 222-nm UV doses inactivated 99.9% of αHCoV-229E and βHCoV-OC43, respectively (Rastegari et al., 2023). The Industrial Technology Research Institute proposed using UV-C instead of traditional disinfection methods and used a UV-C disinfection band of 270 nm–280 nm to purify water. The portable flowing water module (Chiu et al., 2022) developed on this basis had a disinfection efficiency of more than 99.9%. The module was embedded with 18,650 batteries for the power supply, which is not only convenient to carry but also can effectively sterilize and disinfect. It could avoid the shortcomings of traditional mercury lights, which have a large size, are easy to break, and cause harm to the environment and human health.
Viruses must be exposed to UV-C light of a certain dose or more for several seconds before they can be destroyed. According to the medical microbiology research team at Boston University, 99% of COVID-19 viruses can be eliminated at a radiation dose of 5mJ/cm² (Rahayu et al., 2021). Under a UV-C wavelength of 254 nm and a radiation measurement of 3.7 mJ/cm², replication of the SARS-CoV-2 virus was significantly reduced. The UV-C at this dose obviously inhibited the replication of the virus. More importantly, the replication of the virus did not increase over time, proving that the virus was effectively inactivated (Ramadani et al., 2021).
**TEXT S 2**
The followings are previous studies done in line with this topic and this study compares to them:

1. The ultraviolet (UVC) sterilization device can be turned on and off through wireless control or manual control. When the sterilization function is activated through the cloud system, the activation data can be returned to the database and the classroom disinfection history records can be queried online. In addition, the push function of LINE has been integrated, so relevant personnel can be notified of the completion of disinfection in the group.

2. Use infrared rays to detect (default 5M) whether there are human activities in the place to control the turning on and off of the ultraviolet lamp, and use a buzzer to remind users and people in the disinfection space to carry out disinfection. When the UV machine device starts the disinfection process, the red warning light will light up after starting, and at the same time the voice prompts: "Ultraviolet light disinfection is in progress, please keep people away." Turn on the UV power for 30 minutes. If anyone approaches during the process, it will turn off immediately. UV power supply, the yellow warning light lights up, and the voice prompts: "Personnel approaching, pause disinfection". If someone approaches during the period, the calculation will restart. If the timer is completed, the red warning light goes out, the green warning light lights up, and the voice prompts: " UV disinfection completed.

3. The UV sterilization system is built as a mobile device, equipped with four-wheel axles, which is convenient for users to operate. Therefore, the convenient mobility can improve the utilization rate of this system. The bracket of the UV lamp on the device also adopts a three-section design, which allows the UV lamp to irradiate outward when it is in the folded state, and at the same time allows the UV lamp to irradiate diagonally downward when it is
in the unfolded state. It can sterilize the space from different directions. The floors and desktops that are most susceptible to contamination will further enhance the sterilization effect of the ultraviolet sterilization device. The lens module can use the infrared sensor to determine whether there are people approaching the disinfection area during UV machine disinfection, and send the shooting results to the group through LINE NOTIFY to remind relevant personnel that someone is currently approaching the disinfection area. In the scope, you can know whether there are people approaching the disinfection scope, ensuring the safety of personnel in the sterilization scope and also preventing theft.

2 SYSTEM BUILDING AND ACHIEVEMENTS
The mobile smart networked high-efficiency UV machine includes a movable platform, which is made of aluminum alloy and four-wheel axles, making the platform easy to move, which is conducive to movement between classrooms. The system is equipped with an ultraviolet generating unit, a control unit and a human body protection mechanism. It is installed on the movable platform and is electrically connected to the ultraviolet generating unit to generate ultraviolet rays for sterilization. Human body protection mechanisms include infrared sensors, status warning lights, voice alarms, etc. to generate several warning signals.

When the UV machine is sterilizing, the lens module detects through the infrared sensor on the UV machine. If someone approaches, a signal will be sent to the server to notify the lens module to take a picture and immediately send the picture to LINE Group to ensure the safety of the sterilization area, control epidemic prevention and theft prevention.

2.1 ESP32 Module
The ESP32 module, developed by Espressif Systems, is a low-power single-chip microcontroller that combines Wi-Fi and Bluetooth modules into one unit. It supports the IEEE 802.11 b/g/n standards and the v4.2 BR/EDR/BLE protocols. With rich I/O ports and multi-protocol connection functions, the ESP32 module can integrate numerous sensors and other application devices. It is inexpensive and supports multiple development tools, such as Arduino
IDE, Mongoose OS, and MicroPython. At the same time, it has dual Wi-Fi and Bluetooth modules, so it can be developed directly without installing other modules on the board.

This system mainly used the ESP-WROOM (Espressif Wireless Room) 32 module as the control core of the ultraviolet disinfection device and is developed in the Arduino IDE environment. Arduino IDE is an integrated development environment that can be used on a variety of system platforms, such as Windows, MacOS, and Linux. Programs can be developed on the Arduino IDE, with an additional development version added to the configuration. The main purpose of the system was to process mode switch buttons, manual and remote-control switches, infrared sensors, status warning lights, voice warning devices, and the Narrowband Internet of Things (NB-IoT) module. The system had a Wi-Fi function, and after the ultraviolet light machine was turned on and the mode was switched to Wi-Fi, it could automatically connect to the Wi-Fi sharer and the server to wait for the disinfection signal.

### 2.2 NB-IoT Module

Narrowband Internet of Things (NB-IoT) is a transmission mode that supports low-power devices to connect via cellular data through a WAN built on the existing cellular network. The narrowband signal refers to a signal occupying a narrow frequency range or a small fractional bandwidth, and the NB-IoT only consumes about 180 kHz of bandwidth. It can be directly deployed in a GSM network, UMTS network, or LTE network and there is no need to rebuild the network, thus reducing deployment costs. Besides, NB-IoT has the advantages of strong connection, high coverage, low power consumption, and low costs.

This system used an SIM7020C NB-IoT module, as shown in Fig. S1. It supported the TCP, UDP, LWM2M, HTTP, and MQTT network protocols. It carried a SIM card slot and could support NB-IoT special cards. After installing the NB-IoT card and antenna through the SIM7020C NB-IoT module, it connected to the ESP-WROOM 32 module through the UART transmission mode. When switched to the NB-IoT mode, it could automatically connect to the
base station of ChungHwa Telecom and then connect to the server and use the MQTT transmission protocol to achieve remote control functions (Kamboj et al., 2021).

![SIM7020C NB-IoT module](image)

**Fig. S 1. SIM7020C NB-IoT module.**

### 2.3 Human Body Protection Mechanism

Because UV-C light is dangerous and can damage the skin and cause cataracts or cancer, it was necessary to install a human protection and warning mechanism on this system. When the sterilizer was started, it would start the infrared detection unit and present a voice warning after receiving the start command. If nobody was detected near the infrared detection unit, the UV light generation unit would start, and a red warning light would be displayed. The disinfection would last 30 minutes. When the time was up, the starting and stopping data would be returned to the database, and a green indicator light would be displayed. At the same time, a voice prompt would indicate that the disinfection was completed. On the contrary, if the time was not complete and the infrared detection unit detected someone approaching, the sterilizer would turn off the ultraviolet light generation unit, capture a scene image through the lens module and transmit it to the LINE group, and display a yellow indicator light. At the same time, a voice warning would remind the person to keep away. Once the infrared detection unit could no longer detect a person, it would restart the timing and disinfection process. Fig. S2 shows the description of the keys and warning lights of the ultraviolet pandemic prevention machine.
2.4 Status Warning Lights

At present, most of the UV-C sterilizers sold in the market are not equipped with status warning lights, or the machine functions are monotonous with little variation, making it difficult for users and people nearby to judge the current status of the ultraviolet sterilizers. People who accidentally enter the area may be in danger. Warning lights, such as traffic lights, lights on police cars, warning lights in factories, and lights on automobile dashboards, are common in daily life. Different colors have different wavelengths that play different roles in human consciousness:

1. Red usually refers to an emergency, indicating prohibition, stop, danger, and firefighting.
2. Yellow usually refers to abnormal conditions, indicating caution, danger, and warnings.
3. Green usually refers to normal conditions, indicating permission to pass, safety, and stability.

The status warning lights of this system had three colors in total. The EPS WROOM32 module was connected through a general-purpose input/output (GPIO) pin to warn people nearby about the current status of the sterilizer. The three colors represented three different statuses:
1. The red light referred to the disinfection process, representing prohibition, stop, and danger. It indicated that the ultraviolet was currently disinfecting the area and that people should keep away.

2. The green light referred to the completion of disinfection, indicating safety. At this time, the UV-C sterilizer had completed disinfection and the site was safe to enter.

3. The yellow light referred to someone approaching, indicating caution, danger, and warning. UV-C light is dangerous to human bodies. Therefore, when the UV-C light was activated, nearby people should keep away.

With the innovation of technology, voice warnings have been upgraded from the traditional passive operation mode to a more intelligent working mode. Equipment with more guaranteed performance will bring more convenience in the future. At present, there are specific applications for many occasions. The voice warning device has been tested in daily work on these occasions, which proves that it is indeed an effective help for the orderly development of modern society and an indispensable part of daily work and life.

The voice warning device of this system used a DFPlayer Mini MP3 module. After connecting to the ESP WROOM 32 module through the UART mode, it could read MP3 audio files in the memory card and output the sound through an 8 Ω 2 W speaker. Three kinds of music files were stored in the memory card.

2.5 Infrared Sensing

Infrared sensing technology is usually applied to lights and alarms in factories, roadsides, shopping malls, toilets, and corridors. If someone passes, the lights will start immediately. The HC-SR501 (a type of passive infrared (PIR) sensor module commonly used in electronics projects, particularly for motion detection) human infrared sensing module is an automatic control module based on infrared technology. Because of its high sensitivity, low power consumption, low voltage, and high reliability, it has been widely used in various automatic induction equipment. The module is equipped with two knobs: one that adjusts the delay, which
can be as short as five seconds and as long as 300 seconds for each trigger, and one that adjusts the detection distance, which can be as short as 3 meters and as long as 7 meters.

The human infrared sensing module, shown in Fig. S3, served as a system protection mechanism. To ensure that each direction could be detected, a human infrared sensor was installed on the front, back, left, and right of the system and connected to the ESP WROOM 32 module through GPIO (General Purpose Input/Output). The sensing distance was set at 5 meters to effectively ensure that when the UV-C light was activated, people could be detected when approaching from any direction. When any one of the sensors detected a person, the UV light generation unit would immediately be closed.

Fig. S 3 HC-SR501 diagram and infrared sensors.

The monitoring system was developed using an ESP32 CAM development board and an OV2640 lens module. ESP32CAM is a development board made of ESP32. It is lightweight and utilizes the Wi-Fi 802.11b/g/n/e/i and Bluetooth 4.2 protocols (M. M. Machado, 2018), which are widely used in IoT devices, as shown in Fig. S4. After the ESP32CAM board started, it would connect to the wireless access point and subscribe to topics of the MQTT broker of the server. If the infrared sensors on the UV light machine were triggered and an MQTT message was published to the server, the ESP32CAM board would receive a command to capture an image, immediately turn on the camera and flash to capture an image, and send the results to the group through LINE Notify to notify relevant personnel that someone was approaching the disinfection range. This action also provided the function of anti-theft security.
2.6 Server system
The server system in this study was built on a Raspberry Pi 3 Model B. Raspberry Pi is a single-chip computer based on Linux (Elbeheiry & Balog, 2023), and it allows the Linux operating system to be put on an SD card. It has a four-core 1.2 GHz Broadcom BCM2837 64bit CPU processor, its own Ethernet port, USB hub, HDMI, Composite RCA, 802.11n, and GPIO connector (Saha et al., 2022), as shown in Fig. S5. The LAMP architecture was used for the database system. In LAMP, L represents the Linux operating system; A represents the Apache web server; M represents the database, for which, MySQL or mariaDB can be used; P represents PHP, a programming language that can be used to create dynamic pages. All of these can be integrated into a database system. After the establishment of the LAMP database system, phpMyAdmin was installed. phpMyAdmin is a free software tool for writing PHP. It can manage MySQL or MariaDB databases through a web interface. Through phpMyAdmin, the databases and tables on a webpage can be easily added, deleted, modified, and queried. In addition, the MQTT server acted as a communication bridge between the user interface and the ultraviolet sterilizer, with little data transmission between the two. MQTT is a lightweight communication protocol. The MQTT protocol is used for data transmission, which can also respond in real-time with less performance burden. After the disinfection data was returned, the disinfection process would be returned to the database data table through a Python program, and the information would be sent to the group through LINE Notify in real-time through IFTTT. The server architecture is shown in Fig. S6.
2.7 LAMP Server Erection
Before installing the LAMP architecture, the Raspberry Pi needed to be updated. The Apache was first installed, and then the command was executed to start the Apache web server. The IP address was entered into a browser on the Raspberry Pi to confirm whether the Apache web server had been successfully started and was operating normally, as shown in Fig. S7.
Installing the PHP and package modules could help the PHP program code to execute on the Apache web server and connect to the MySQL database. After installation, it was necessary to enter the root directory of the webpage/var/www/html to create phpinfo.php to call the built-in function phpinfo() in PHP. The page could clearly display the PHP version, server environment, HTTP headers, PHP license, and other related environment configuration messages. Installing the MySQL database and PHP-related packages could allow the PHP program code to access the MySQL database so that the PHP program code can directly access database data for usage. After installation, the operator could enter the MySQL database environment and execute actions, such as adding, deleting, modifying, and querying databases and data tables.

2.8 PhpMyAdmin

After installing the LAMP database architecture, the phpMyAdmin platform needed to be installed, and then the PHP MySQL module could be started and the Apache server restarted so that phpMyAdmin could directly add databases and data tables to the database. Entering
Server IP/phpmyadmin on the browser would bring up the login page of the phpMyAdmin platform, as shown in Fig. S8. After logging in, the operator could directly add databases and data tables on the phpMyAdmin platform, making it easy to perform the actions of adding, deleting, modifying, and querying. For the establishment of a database system, the time for database establishment can be shortened.

![Login page of phpMyAdmin platform.](image)

**Fig. S 8** Login page of phpMyAdmin platform.

![MQTT architecture.](image)

**Fig. S 9** MQTT architecture.
Fig. S 10 Subscription to the MQTT topics of the UV light machine.

Fig. S 11 Information display interface of mobile device app.

Fig. S 12 IFTTT serial connection.
Fig. S 13 (a) Web page interface (b) RWD design.

Fig. S 14 (a) Red warning light during disinfection (b) green warning light after disinfection (c) yellow warning light indicating someone approaching.

Fig. S 15 (a) LINE group emergency notification (b) LINE Bot notice.
The ultraviolet sterilization device used in this research institute uses high-power UV-C, and combined with the Internet of Things system developed by this research institute, the ultraviolet sterilization machine can be remotely activated through manual remote control or human-machine interface mobile device APP or web page. At the same time, a human body protection mechanism is added to provide warning sound and light signals in different states, and an enhanced protection mechanism of automatic closing is added. When a person approaches, the system uses the infrared sensor to emergency turn off the UV-C ultraviolet light, and the lens module promptly transmits the image to the LINE group to establish a complete protection mechanism. When the disinfection is completed, the information will be automatically transmitted to the server. The results will be sent to the LINE group in real time through IFTTT, notifying relevant personnel that the sterilization is completed. Through the human-machine interface mobile device APP or web browsing, all sterilization processes can be learned efficiently and in real time.

REFERENCES


