A Smart Sterilization Robot System With Chlorine Dioxide for Spray Disinfection

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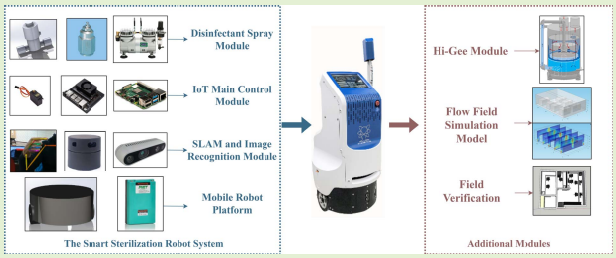
***Abstract*—The highly infectious and serious nature of coronavirus disease 2019 (COVID-19) has highlighted the need for hospital space disinfection technology and the prevention of human exposure to pathogenic environments. This research developed novel chlorine dioxide (ClO_2) sterilization technology to reduce bacteria and viruses in the air and on surfaces. A smart sterilization robot system was also developed to spray disinfectants in operating theaters or patients' rooms, designed according to the results of controlled experiments and the requirements for hospital disinfection. The system was built incorporated a semi-automatic remote-controlled module and an automatic intelligent disinfection function; that is, it could operate independently according to specific epidemic prevention strategies, which were implemented using a combination of Internet of Things (IoT) applications and a gesture recognition function. The elimination of Escherichia coli (*E. coli*) bacteria on sample plates was 99.8 % effective. This paper reviews the evolution of various disinfection technologies and describes a disinfection robot system in detail.**



***Index Terms*—Mobile robots, medical robotics, intelligent systems, robot sensing systems.**

I. Introduction

WITH the rapid development of technology and globalization, human travel and international trade are becoming more frequent. Although infectious diseases in cities may seem remote, they can be transmitted rapidly to other cities around the world through a transportation medium. According to a report by the World Health Organization (WHO) on May 25, 2021, coronavirus disease 2019 (COVID-19) had spread to 220 countries, causing 166,860,081 person-times of illness, including 3,459,996 deaths [1]. Various epidemic situations have also increased the burden and pressure on hospitals, and effective disinfection for general wards, diagnosis rooms, halls, and examination rooms is urgently needed to prevent and control the outbreak of infectious diseases.

The disinfection methods used for various functional rooms in hospitals include manual spraying of disinfectants, ultraviolet (UV) light irradiation, and automatic disinfection robots [2]–[4]. The risk of manual disinfection is that humans may be exposed to potentially contaminated surfaces, causing anxiety, tension, and loss of productivity for medical staff, especially in hospital contagion units. Furthermore, public panic about COVID-19 has led to the popularization of disinfection robots [5]–[7]. Robot disinfection usually can be divided into two categories: UV light irradiation [8]–[10] and chemical disinfection [11], [12]. Most glass and plastics can reduce the intensity of UV radiation; thus, volatile chemical disinfectants perform better in sealed environments [4], [13], [14].

A smart sterilization robot system should be able to carry out various functions, not limited to remote movement and disinfection. Besides achieving effective disinfection, such a system should use sensor data to navigate the surrounding environment and ensure safety according to established disinfection strategies. Traditional disinfection based on human labor is restricted to the available time and attention of operators. Compared to manual disinfection, robot disinfection can be performed around the clock, even at peak times; prevent pathogenic environments or disinfectants from harming humans; and adapt to a variety of working conditions.

Manuscript received June 15, 2021; revised July 26, 2021; accepted July 26, 2021. Date of publication July 30, 2021; date of current version October 1, 2021. This work was supported in part by the Ministry of Science and Technology (MOST) of Taiwan under Grant MOST 109-2221-E-002-074-MY2. The associate editor coordinating the review of this article and approving it for publication was Dr. Eduardo Garcia-Breijo. *(Corresponding author: Han-Pang Huang.)*

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Digital Object Identifier 10.1109/JSEN.2021.3101593

In order to save manpower, reduce the possibility of human exposure to the virus environment, and maximize the disinfection agent utilization efficiency and spraying effectiveness, the robot was designed to be mounted with a disinfectant spraying device and embedded a variety of sensors to sense the environment and ensure the safety of human beings and the robot itself. Finally, the semi-automatic remote-control or automatic intelligent disinfection function can be realized through the cooperation of various sections.

The research objective was to integrate practical technologies into a smart sterilization robot system to achieve the efficient disinfection that is crucial during pandemics. First, the advantages and disadvantages of disinfection methods and the characteristics of various disinfection robots were evaluated to provide the foundation for the design parameters and functionalities of our system. After the system's hardware and software had been identified, the active and passive behaviors of a robot system were defined to underpin the automatic control mechanism. An embedded computer would determine the speed of the robot system and the state of the valve on the robot according to sensor data, recognize a user's gestures, and execute commands using a camera. The robot system was ultimately tested in the field for disinfection verification and evaluation to prove that it could inhibit the growth of *E. coli* bacteria in a hospital environment.

TABLE I
COMPARISON OF SPACE DISINFECTION METHODS

Disinfectant	Principle	Advantages	Disadvantages
UV light	Destroys microbial nucleic acid.	Low cost, no disinfectant consumption.	Insufficient penetration depth, may cause conjunctivitis.
NaClO	Sterilizes by chlorine substitution and oxidation reaction.	Low cost.	Corrosion of metals.
HOCl	Sterilizes by chlorine substitution and oxidation reaction.	Low toxicity, high efficiency.	High pollution, corrosion of metals.
ClO_2	Inactivates enzymes by oxidation reaction.	Low cost, high efficiency, less residue.	Inconvenient storage.
H_2O_2	Inactivates enzymes by oxidation reaction.	Low toxicity, less residue.	Inconvenient storage.
Alcohol	Dehydrates the protein in microorganisms.	Low cost, less residue.	Ineffective against enterovirus, flammable.
O_3	Acts on cell membranes to change permeability.	High efficiency, deodorizing.	High toxicity, high costs.

II. FUNDAMENTALS OF THE DISINFECTION ROBOT SYSTEM

A. Disinfection Methods

Disinfection is a process that destroys or otherwise inactivates pathogenic organisms. This outcome may be achieved using different physicochemical treatments, including direct application of thermal energy, UV light irradiation, and/or chemical reagents. UV light and chemical spraying are the most common methods for disinfecting spaces. UV light can be divided into three types with different wavelengths: ultraviolet A (UVA), ultraviolet B (UVB), and ultraviolet C (UVC). UVC (with a wavelength of about 200–280 nm), which is sometimes called deep UV (DUV), is the most effective wavelength for epidemic prevention and disinfection. It destroys the deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) of microorganisms through electric radiation, and then kills biological cells to achieve disinfection and sterilization. UVC is effective against all known coronaviruses [15].

UVC is produced by various types of equipment, including UV lamps, mercury vapor lamps, and UV light-emitting diodes (UV-LEDs). In the past, mercury vapor lamps were often used as UV generators, which caused serious environmental pollution due to their high energy consumption. According to the Minamata Convention on Mercury, vapor lamps are gradually being replaced by UV-LEDs, which have more concentrated energy and lower energy consumption [16], [17]. UVC is used to combat the crisis of increasing multidrug resistant organisms (MDROs) in patients' rooms, bathrooms, operating theaters (OTs), and equipment rooms, and on mobile devices [18]. Some researchers [19], [20] evaluated the efficiency of UVC for disinfection of electronic products, and UVC light effectively eliminated all the pathogenic bacteria on mobile phones.

According to [4], [13], UVC disinfection should not be used alone but could be combined with chemical disinfection. As another common approach, a chemical disinfection system is linked to many devices, including storage tanks, pumps, power supplies, different types of nozzles, and aerosol sprays. Due to the nature of aerosols, any pathogens without physical shielding would be killed. The design of spraying devices and the choice of chemical agents can also undermine the effectiveness of disinfection. According to studies [4], [14], [21]–[23], some chemical agents, such as sodium hypochlorite (NaClO), hypochlorous acid (HOCl), chlorine dioxide (ClO_2), hydrogen peroxide (H_2O_2), alcohol, and ozone (O_3), can be effective sterilizers. A comparison of various space disinfection methods is shown in TABLE I. Most disinfectants are volatile, leave little residue, and are relatively cheap. Compared to UV disinfection, ClO_2 solution particles have stronger disinfection effects. Diffusing and permeable ClO_2 aerosols are good fumigants for disinfecting confined spaces. Fogged ClO_2 disinfectant can effectively eliminate human norovirus (HoV) and feline calicivirus (FCV) on hard-to-reach surfaces [24]. Some studies [23], [25]–[29] indicated that both the aqueous and gaseous forms of ClO_2 demonstrate good sterilization efficiency. Additionally, ClO_2 has the characteristics of low cost, extremely low residue, good sterilization effects, and relative safety. Accordingly, ClO_2 solution is distributed in aerosol and fog states for disinfection.

B. Robot Technologies for Disinfection Systems

In response to the spread of COVID-19, various robots were developed for patient diagnosis and health care, food

and drug delivery, social interaction, and disinfection, which also promoted corresponding robot technologies. Robot technologies consist of communication devices, control modules, path planning tools, simultaneous localization and mapping (SLAM), and behavior monitoring. Robot platforms equipped with epidemic prevention functions usually travel on wheels or bipedal devices. Most of them are designed to complete sterilization work through remote control or a fixed route, which protects operators from harmful disinfectants while satisfying basic disinfection requirements. Some robots with cameras can be controlled to explore enclosed spaces by wireless communication protocols based on the interconnection between internal modules and external modules.

Robots generally employ various sensors, including cameras, light detection and ranging (LIDAR), inertial measurement units (IMUs), temperature sensors, proximity sensors, and humidity sensors, to observe the surrounding environment and calculate the disinfection path. Path planning may differ across types of robots; nevertheless, it is largely similar for robots intended for disinfection purposes with similar pesticide spraying strategies. One of the most common uses of robots is to pick up and place objects, which requires a start point and an end point. Path-following algorithms, such as the A*, AO*, rapidly-exploring random trees (RRTs), and DAO* algorithms, search for the best path and then execute commands accordingly [30]. Since disinfection robots need to traverse whole spaces and spray disinfectants uniformly, the first design task is to construct 2D or 3D metric maps via SLAM, which is used by robots to acquire maps of the surrounding environment and position themselves accordingly. Laser scans or images are combined to form a map based on geometric relationships, which is then decomposed into many blocks with different weightings, enabling the robot to identify obstacles and edges and avoid collisions. Finally, graph traversal is used to plan the robot's motion; for example, simultaneous localization and mapping with moving object tracking and scene prediction (SLAMMOT-SP) is an algorithm that integrates multiple robotics technologies, allowing each robot to actively predict possible changes of views and identify moving objects [31], [32].

Image recognition and robot behavior are also important functions of disinfection robots. Image recognition is a visual aid system, which should be treated as an auxiliary function requiring operator intervention. Image recognition makes the behaviors of the robots more intelligent and may permit them to work independently.

C. Disinfection Strategies

This section describes different disinfection strategies used to verify the effect of epidemic prevention, with the efficiency of the disinfection method calculated by comparing the number of bioindicators present before and after disinfection. There are many complex factors that affect the death of bioindicators, including measurement methods, disinfection equipment, disinfection times, bioindicator properties, room characteristics, etcetera. The bioindicators used for effectiveness testing, including E. coli, methicillin-resistant Staphylococcus aureus (MRSA), and multidrug resistant Acinetobacter baumannii, are more resistant to disinfection but less harmful than COVID-19.

Due to the time required for biological cultivation and inspection, robots cannot carry out disinfection verification work. Verification can be used to evaluate and improve the efficiency of robots, based on counts of bioindicator populations in professional laboratories. Jinadatha *et al.* [33] showed that UV disinfection improved overall cleanliness and was better than manual cleaning for MRSA and bacterial heterotrophic plate counts (HPC). Fleming *et al.* [34] showed that UV robots had positive effects on disinfection for Clostridium difficile (C. diff).

The effectiveness of disinfection is closely related to disinfection strategies. Robots without disinfection strategies lack the necessary flexibility to deal with emergencies and complex environments, but too little research has investigated disinfection strategies and their related functions; thus, most robots are unable to manually traverse whole spaces and achieve complete sterilization. An appropriate path planning strategy, as presented by [35], is an important way to improve efficiency by calculating the efficient route according to various parameters. Hu *et al.* [36] developed a deep-learning method to distinguish between different areas of potential contamination and assign different weights to guide a robot disinfection system.

III. Materials and Methods

A. Disinfection Experiments

Before configuring the robot, a controlled experiment was performed to determine the sterilization effect of a ClO_2 solution on bioindicators at different concentrations. The ClO_2 solution was prepared by dissolving commercial ClO_2 effervescent tablets (Green Disinfectant, Virashield Asia Limited, Hong Kong, China) in deionized water according to the instructions: one effervescent tablet in 1 l of water produced a 100 ppm ClO_2 solution with a pH value of 2.30.

The selected bioindicator *E. coli*, which has low toxicity and is easy to cultivate, is distinct from other bacteria. Wang *et al.* [37] showed that SARS-CoV is more susceptible to disinfectants than *E. coli*, indicating that *E. coli* was suitable as a biological indicator for coronavirus. The *E. coli* was coated onto porous beads and stored at −80 °C. The beads were then placed on agar plates and incubated at 37 °C for 24 h. The colony density was adjusted to 6.3×10^9 CFU/mL and stored at 4 °C before use. All the petri dishes in the experiment had a diameter of 9 cm and a bottom area of 55 cm^2. The sprayed ClO_2 solution had a concentration of 1,000 ppm. The log reduction and disinfection efficiency for *E. coli* were determined by comparing the survival of the populations with a control group.

The controlled experiments included a negative control and a positive control with dripping solutions at different concentrations, which eliminated most potential confounding variables. The experiments confirmed that the ClO_2 solution has a disinfecting effect on *E. coli*. The number of *E. coli* colonies is shown in TABLE II. The colonies in the two sample petri dishes were counted and marked as X_1, X_2(unit: PCS, same as in TABLE VI). The RPD indicated that the two

TABLE II
THE NUMBER OF *E. Coli* COLONIES (NEGATIVE CONTROL AND POSITIVE CONTROL)

Conditions			Experiments			
Control Type	Concentration	Drop Volume	X_1	X_2	Mean	RPD *
Negative Control	N/A	N/A	610	600	605	1.7 %
Positive Control	10 ppm	1 mL	532	546	539	2.6 %
Positive Control	100 ppm	1 mL	425	328	376.5	25.8 %
Positive Control	1000 ppm	1 mL	0	0	0	0

* Relative percentage difference (RPD) is equal to the absolute value of the difference between X_1 and X_2 divided by the mean of X_1 and X_2, which was used to analyze the similarity of the two sets of data.

TABLE III
THE PSEUDO-CODE FOR THE RRT-CONNECT ALGORITHM

```
connect (S, q)
1  do {
2    S = extend (S, q)
3    } while (S = Advanced)
4  return S;
RRTConnectPlanner( q_init , q_goal )
1  T_a .init(q_init); T_b .init(q_goal)
2  for k = 1 to K do
3    q_rand →randomConfig()
4    if not (extend(T_a,, q_rand , q_new) = Trapped) then
5      if(connect() = Reached) then
6      return path (T_a, T_b)
7    swap (T_a, T_b)
8  return Failure;
```

sets of data were similar and that there were few accidental factors. Thus, the time for effective disinfection could be calculated according to the results of the positive control and the characteristics of the nozzle. The operational parameters and appearance of the robot were customized to ensure that the environment was disinfected and to control the consumption rate of the disinfectant simultaneously.

B. Route Planning

Robot motion planning involves a system configuration space with one or more complicated geometric bodies across which a robot must identify a collision-free path between a given starting point and a goal.

The disinfection robot was designed using a path planning method called Rapidly-Exploring Random Tree Connect (RRT-Connect) [38], which consisted of two rapidly-exploring random trees (RRTs) and a simple greedy heuristic. RRTs were used for the robot's route planning, the aim of which was to select a route from a start position (q_{init}) to a goal position (q_{goal}), preventing the robot from colliding with a target object or obstacles. A set of start-to-goal routes could be obtained using SLAM and image recognition or commands issued by an operator. Two bidirectionally extended RRTs calculated a feasible path based on random sampling, and the heuristic greedy method calculated the local optimal solution and reduced the operation time.

TABLE III shows the pseudo-code of the RRT-connect algorithm. Two trees, T_a and T_b, were built from q_{init} and q_{goal}, followed by random sampling K times. Two functions were governed by the RRT connect algorithm: 'Extend' and 'Connect'. 'Extend' created q_{new} from q_{rand} in T_a and extended from T_b to the q_{new} direction of T_a. If q_{new} collided with an obstacle, the Extend function would return empty. 'Connect' made a judgment about whether T_a and T_b were connected as a whole S; if not, the random sampling continued until it failed.

The RRT-Connect algorithm is simple, requires few resources, and can quickly calculate a path, which met our needs. The path could be planned by giving multiple denser goals, enabling the risky environment to be disinfected.

TABLE IV
COMPARISON OF THE DISINFECTION ROBOTS

Disinfection methods	Robot Technologies	Applications	Experimental Effects	Ref.
UVC, 3×19.3 w	Manual navigation	Indoor disinfection	35cm, kill 23/23 S. aureus	[8]
UVC	Automatic navigation, manual navigation	Indoor disinfection	N/A	[9]
UVC, 4×75 w	Automatic navigation, manual navigation	Indoor disinfection	Over 16.9 mJ/cm^2, disinfect 24/24 markers	[10]
Chemical disinfectant	Manual navigation	Indoor disinfection	N/A	[11]
Chemical disinfectant	Automatic navigation, manual navigation	Animal husbandry	N/A	[12]

C. Proposal for the Robot System

TABLE IV shows a comparison of disinfection robots. A robot can be equipped with UVC-LEDs for disinfection, but operators must avoid looking at the LEDs directly because they can cause eye injury in a few seconds. Chanprakon *et al.* [8] designed a UVC disinfection robot system based on Raspberry Pi, which connected to the robot via Wi-Fi to control its movements. However, UV robots have shortcomings: direct UVC exposure can cause damage to the eyes and skin. The LEDs mounted on robots build up heat, but fans and other light-shielding equipment cannot be used for heat dissipation. Even worse, disinfection is time-consuming, and it is difficult to disinfect "dead" corners blocked by obstacles or dust. The robot in this study had three 19.3-watt UV lamps and a height of 1.44 meters. In the experiment, all the *S. aureus* colonies were killed within 8 s of UV light exposure; however, the number of bacteria colonies on the reference plate was 23, and a single control group was not sufficient to ensure accuracy. Tiseni *et al.* [10] developed a novel trajectory planner based on a genetic algorithm that optimized the efficiency of radiation according to the environment. Krishnamoorthy and Tande [39] showed that the effectiveness of UVC germicidal irradiation

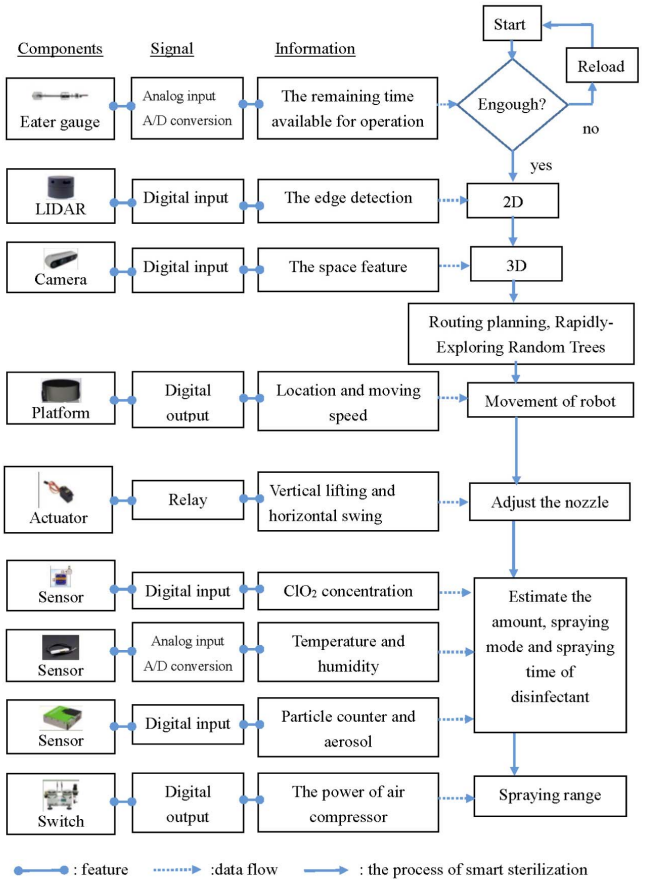

Fig. 1. The flow chart for the smart sterilization robot system.

was improved by a reflective wall coating. Buonanno *et al.* [40] estimated that UVC (at about 222 nm) could kill 99 % of coronavirus in about 16 min at the current regulatory exposure limit (∼3 mJ/cm^2/hour). The robot can also disinfect the environment by spraying disinfectant. Feng and Wang [12] focused on livestock breeding and established a strong flow spraying robot. Comparing various disinfection robot systems enabled us to incorporate the best aspects of architecture design, operational parameters, and various functionalities into the construction of our robot system. Moreover, we addressed deficiencies in the aforementioned studies by designing epidemic prevention strategies and conducting scientific verification of disinfection effects.

Fig. 1 shows the flow chart of the proposed smart sterilization robot system. The smart sterilization process is as follows:

1. The robot confirms whether the stock of disinfectant is sufficient to complete the next task.

2. The robot uses LIDAR and the camera to perform edge detection and spatial image feature discrimination to construct 2D or 3D metric maps via SLAM.

3. The robot plans the route and suggests the best route using the RRT algorithm.

4. Using the best route to reach the destination quickly, the robot recognizes the operator's gesture for a different response.

5. Based on environmental sensing information, the robot evaluates the disinfection dosage, spray mode, and spray direction.

Fig. 2. The hardware for the smart sterilization robot system.

TABLE V
THE PARAMETERS OF THE SMART STERILIZATION ROBOT SYSTEM

Size	440 × 440 × 860 mm
Weight	23 kg
Battery Storage	12 × 2 + 13 Ah
Endurance	Over 1 h
Spray Capacity	5 L/h
Vertical Lifting Range	800 mm–1,000 mm
Horizontal Swing Range	-40°–140°
Disinfectant Cost Estimate	1–3 USD per liter

6. The operator remotely controls the height and elevation of the nozzle for disinfection operation.

7. The ClO_2 concentration determined by the environment sensor will be fed back to control air compressor actuation.

As shown in Fig. 2, the whole system rests on a mobile robot platform, which supports the weight of all the modules. The wheels of the platform can bear a weight of 50 kg and move freely across the flat surface. The left and right motors are driven by 12-volt batteries. Raspberry Pi controls the motors and LIDAR SLAM map generation. The complete robot design parameters are shown in TABLE V. A ClO_2 solution with a concentration of 1,000 ppm costs about 1–3 USD per liter. The robot is also equipped with two computers: a NVIDIA Jetson NX Xavier and an Intel Core i7-9700TE (4 cores @ 1.8GHz), which are respectively used for IoT sensor signal processing and image recognition. Extra computing power and interfaces are reserved for extension of the hardware and software, such as for machine learning and additional sensors.

The graphical user interface (GUI) for the smart sterilization robot system is shown in Fig. 3. The robot can be controlled

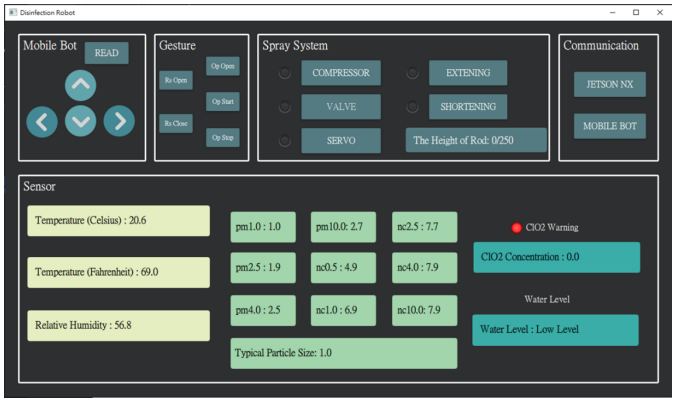

Fig. 3. The graphical user interface (GUI) for the smart sterilization robot system.

and monitored through the GUI, which can be used on an external laptop, or on a computer mounted on the robot. A socket is used for communication inside the robot and is also responsible for the transmission of sensor values and for controlling signals.

IV. Development of Disinfection Robot System

A. IoT Sensors and Control System

The disinfection robot system is equipped with IoT sensors to assess environmental information for surrounding perception, allowing the corresponding disinfection strategies to be designed accordingly. These sensors include a temperature and humidity sensor, a particulate matter (PM) sensor, a ClO_2 concentration sensor, and a water level gauge. The values obtained by these sensors are used for the feedback control of the travel speed, location, and spray unit of the robot platform.

The disinfectant spray module comprises a pressure water tank, a small air compressor, a two-fluid nozzle, motors, and IoT sensors. The motors provide two degrees of freedom (DoFs) for control, allowing the nozzle to move vertically and swing horizontally to increase the spray range. Air compressors and electric valves are also controllable devices. During the test, the actual spray rate was about 1.4 mL per second, the aerosol particle size was about 20 to 30 μm, and the coverage radius was about 1 meter.

This robot system can use multiple disinfectants, but the evaluation showed that ClO_2 is relatively the best choice. ClO_2 disinfectant is a strong oxidant with antimicrobial activity and is expected to serve as an inexpensive option for cleaning and disinfecting hospital environments. Compared with chlorine-based disinfectants that rely on chlorination reactions for disinfection, ClO_2 disinfection products, relying on oxidation reactions, have no carcinogenic effects. Although ClO_2 is inconvenient to store and transport, this is not a concern for a robot system structurally equipped with a Hi-Gee module. The Hi-Gee module—a small high-gravity rotating packed bed for producing ClO_2 gas—can be configured as a standalone product used for disinfection.

B. SLAM and Image Recognition

Robots without SLAM and image recognition functionality cannot operate independently. SLAM involves two types of

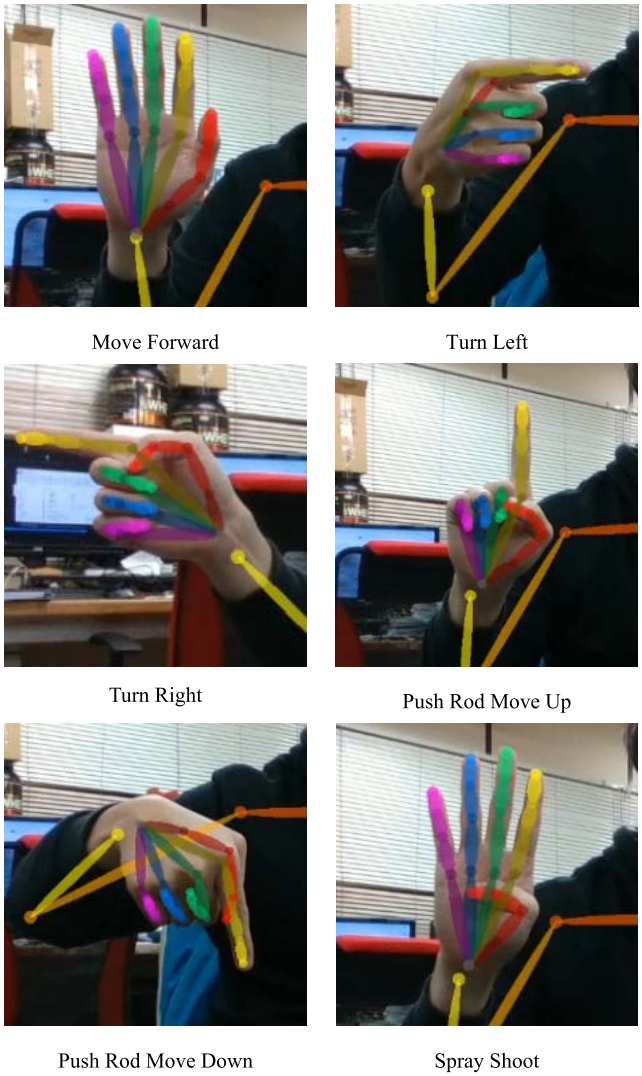

Fig. 4. Hand gestures and corresponding commands.

devices: one is 2D SLAM using Flash LIDAR F4 and the other is 3D SLAM using an Intel RealSense Depth Camera D435i. The 2D SLAM in the system is mainly based on Robot Operating System (ROS) [41] and GMmapping algorithm [42], [43], which is a more reliable and mature algorithm based on LIDAR and odometer solutions. The core of the GMapping algorithm is a particle filter, which helps to calculate the distribution of variables by combining samples with parameter density functions. 3D SLAM, based on ORB-SLAM [44], [45], is combined with Point Cloud Library (PCL) [46] to display the internal structure of the room. During the experiment, the robot could avoid obstacles, including pedestrians, in real time. Due to the error and bias of the odometer and LIDAR or the robot's slipping motion, the robot coordinates estimated by 2D SLAM were not accurate. Sensor fusion was used to correct this error. The matrices of poses calculated by 2D and 3D SLAM are loosely coupled with different weights, which makes the system more accurate and robust.

Image recognition and hand gesture control were developed for the robot system (Fig. 4). The gesture recognition was based on OpenPose [47]. The images from the camera stream are processed into feature vectors, which are used to match

those of defined gestures. The best similarity between multiple consecutive frames is used to make the final judgment. As a result, the robot could be manipulated to perform many tasks, such as displacement, spraying disinfectant, and so on.

C. Disinfection Strategies

Alongside the construction of the body of the robot system, the key to its intelligence lies in the design and implementation of disinfection strategies, which use data returned by IoT sensors for feedback control, image recognition of user gestures, and execution of commands.

Disinfection strategies based on IoT sensors do not require human interaction and are described as follows. Changes in temperature and humidity in the air are the two important factors affecting disinfection effectiveness and were used to determine the optimal exposure time for disinfection. The Occupational Safety and Health Administration (OSHA) suggested the health standard of 0.1 ppm averaged over 8 h of ClO_2 exposure in 2002 [48], and excessive inhalation of ClO_2 gas may cause many problematic symptoms, such as coughing, sore throat, and severe headaches [23]; hence, the robot is equipped with a ClO_2 concentration sensor with a measurement range of 0 to 2 ppm, which can alert the user to avoid over-inhalation. The PM sensor provides data on particle mass concentration and number count. These data serve two useful purposes: 1) Before the disinfection process, the particle concentration of each room can be roughly estimated. The results of [49] showed that COVID-19 aerosols were mainly available in two size ranges: from 0.25 μm to 1.0 μm and over 2.5 μm. Therefore, an epidemic prevention strategy can be planned so that the linear velocity of the robot can be set negatively relative to the PM data. 2) During the disinfection process, the value fluctuation of the PM sensor can indicate changes in the ClO_2 concentration in a room. Finally, the readings of the water level gauge can indicate the remaining capacity of the robot.

Path planning is an important part of intelligent disinfection. All nodes are marked and traversed using a 2D map, and the planned path can be obtained by connecting the nodes. During the experiment, the robot could follow this path to carry out disinfection, ensuring that all the possible "dead" corners were covered with minimal consumption of disinfectant.

Also, since the robot should be able to interact with operators and facial touches are frequent for human beings, it is important to disinfect the operators' hands for epidemic prevention, so we considered and incorporated this feature. The operator uses different hand gestures (shown in Fig. 4) to direct the robot and adjust the height of the nozzle for comfortable operation; thus, the nozzle sprays low-concentration atomized ClO_2 onto the operator's hands and should also be able to spray alcohol.

V. Sterilization Effects Verification

The disinfection experiments were conducted in the Shin Kong Memorial Wu Ho-Su Hospital in Taipei city. The preparation of the ClO_2 solution and *E. coli* petri dishes used in the verification experiment were carried out as in the control experiment.

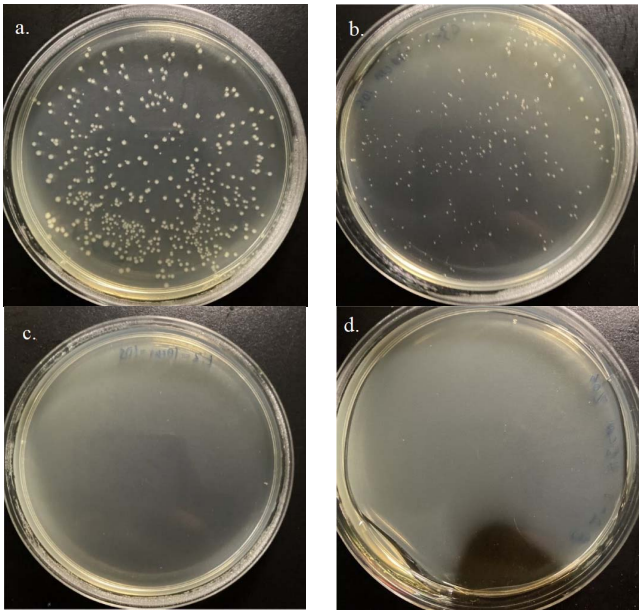

Fig. 5. Images of petri dishes under different conditions: a) negative control; b) placed vertically (vertical distance −10 cm, horizontal distance 40 cm, for10 seconds); c) placed vertically (vertical distance −10 cm, horizontal distance 10 cm, for 10 seconds); d) placed horizontally, (vertical distance −30 cm, horizontal distance 45 cm, for 20 seconds).

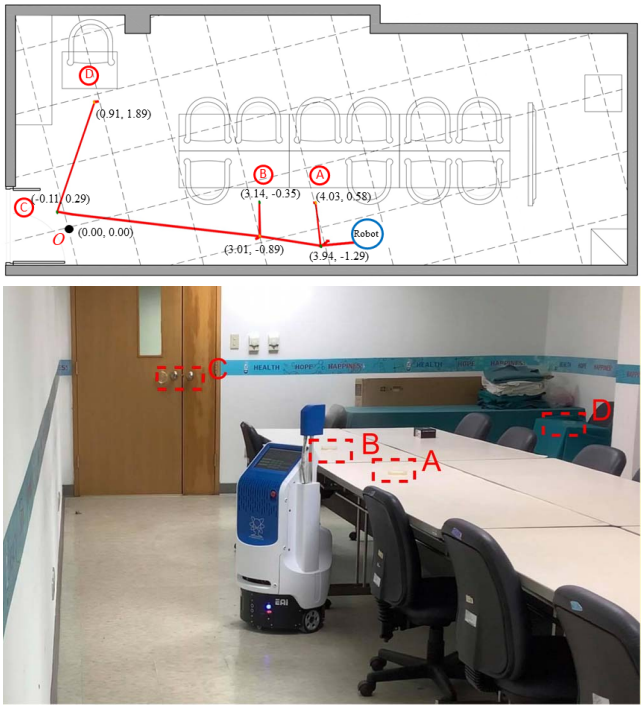

Fig. 6. The demonstration of disinfection process.

Assuming that the solution was sprayed evenly, about 0.01 mL of liquid was sprayed into the petri dish under test every second. Since pathogens can be found in many areas (especially on tables and door handles frequently touched during human activities), we estimated that the best spraying effect could be achieved by aiming the geometric central point of the spray nozzle for about 10 s. To simulate the disinfection of tables and door handles, the experimental objects were

TABLE VI
THE NUMBER OF *E. Coli* COLONIES (EXPERIMENTAL GROUPS)

Conditions				Experiments				
Petri Dish Orientation	Horizontal Distance*	Vertical Distance*	Disinfection Time	X_1	X_2	Mean	RPD**	Sterilization Rate
Negative Control	N/A	N/A	N/A	519	504	511.5	2.9 %	N/A
Horizontal	60 cm	-30 cm	5 s	221	213	217	3.7 %	57.6 %
Horizontal	60 cm	-30 cm	10 s	162	167	164.5	3.0 %	67.8 %
Horizontal	60 cm	-30 cm	20 s	1	0	0.5	200.0 %	99.9 %
Horizontal	45 cm	-30 cm	10 s	68	19	43.5	112.6 %	91.5 %
Horizontal	45 cm	-30 cm	20 s	0	0	0	0.0 %	100.0 %
Vertical	40 cm	-10 cm	10 s	3	3	3	0.0 %	99.4 %
Vertical	40 cm	-25 cm	10 s	72	67	69.5	7.2 %	86.4 %
Vertical	40 cm	-40 cm	10 s	217	230	223.5	5.8 %	56.3 %
Vertical	20 cm	-10 cm	10 s	0	0	0	0.0 %	100.0 %
Vertical	20 cm	-25 cm	10 s	46	43	44.5	6.7 %	91.3 %

*Horizontal distance and vertical distance refer to the distance between the petri dish and the nozzle.
**RPD is equal to the absolute value of the difference between X_1 and X_2 divided by the mean of X_1 and X_2, which was used to analyze the similarity of the two sets of data.

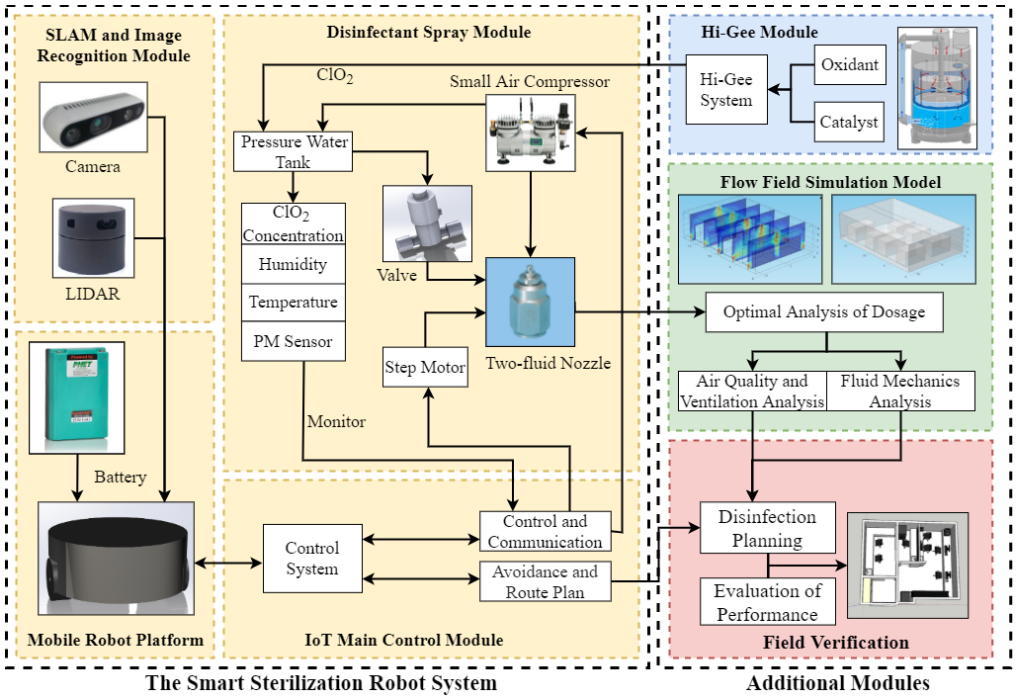

Fig. 7. The final structure of the smart sterilization robot system and additional modules.

divided into two categories: horizontal groups and vertical groups, respectively. For the horizontal groups, the nozzle was fixed at a height of 100 cm from ground level, and the petri dishes were placed on a table 30 cm lower. The control variables were disinfection time and horizontal distance. For the vertical groups, the petri dish was placed upright, and the control variables were disinfection time and the relative vertical and horizontal distances. Fig. 5 shows some examples of *E. coli* experimental groups in the petri dishes being effectively eliminated. TABLE VI shows the numbers of *E. coli* bacteria in the colonies. The sterilization rate was equal to the mean of X_1 and X_2 minus the mean of the negative control (the number of *E. coli* theoretically killed) divided by the mean of X_1 and X_2. The Experimental results showed that the disinfection robot can achieve effective disinfection with a sterilization efficiency above 99.8 % (510/511). Fig. 6 illustrates a demonstration of the disinfection process in the hospital. The coordinates of the goals were entered into the RRT-Connect algorithm to determine the robot's trajectory, which is marked by the red line. Point *O* is the origin of

the map when building the map, so the coordinates are (0.00, 0.00) to extend the grid line, and the unit is a meter. The robot followed the route and disinfected the petri dishes in alphabetical order. Dishes A and B were placed horizontally on the table; Dish C, simulating the disinfection of a door handle, was placed vertically; and Dish D represented the disinfection of a seat.

VI. Challenges and Prospects

To respond to the outbreak of the COVID-19 pandemic and carry out prevention work, the main challenge was to rapidly develop a smart sterilization robot to satisfy the disinfection demands of hospitals. The proposed system includes hardware, software, a GUI, and disinfection strategies to achieve this. The secondary challenge was to verify the effectiveness of the robot system in a hospital. Scientific experiments facilitated the identification of the best system design and configuration to achieve ultimate disinfection efficiency.

This paper proposes a smart sterilization robot system to efficiently and stably disinfect spaces that may contain pathogenic microorganisms. The robot system incorporates multiple technologies, including IoT, aerosol disinfection, SLAM, image recognition, a control system, route planning and navigation, etc. The proposed disinfection strategy enables the robot to automatically complete disinfection throughout any target environment, thereby ensuring human safety and reducing the labor involved in manual disinfection.

Fig. 7 shows the final architecture of the smart sterilization robot system and additional modules that could be employed. The Hi-Gee module and field verification will be included in the robot system for disinfection and to analyze efficiency, respectively. Also, a simulation model of the flow field in the space should be included in the robot system as a part of the disinfection strategy. In summary, future work could include adding new sensors, such as a carbon dioxide sensor, through the reserved sensor interface to monitor human activities, and adjusting the disinfection time for different environmental conditions to enhance disinfection efficacy. Combined with the high-precision ClO_2 sensor, more disinfection experiments should be carried out to obtain accurate parameters for the robot. Furthermore, for the disinfection of various objects in a given space, such as tables, door handles, and mice, object recognition in real time could be integrated into the system to make the robot system more intelligent.

Acknowledgment

The authors would like to thank Chih-Hung Huang with the National Taipei University of Technology for providing disinfectant and petri dishes for us. Gratitude is also extended to the field support personnel from Shin Kong Memorial Wu Ho-Su Hospital and for the instruction of Cheng-Yun Cheng and Po-Lin Yang at the National Taiwan University Robotics Laboratory.

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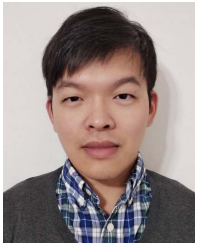

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