Low Cost Smart Uv-Sterilization Cabinet for Clinical Use

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Abstract—**Hospital-acquired infections remain a major concern in clinical environments due to improper sterilization of frequently handled medical accessories. Conventional sterilization methods such as autoclaving and chemical disinfection are often time-consuming, expensive, and unsuitable for heat-sensitive equipment. This paper presents a low-cost smart UV-C sterilization cabinet designed for safe and automated disinfection of small medical instruments. The system utilizes ultraviolet radiation at 254 nm to inactivate microorganisms without heat or chemical exposure. A microcontroller-based control unit manages sterilization timing, door-interlock safety, and exposure uniformity using a motorized rotating tray. The safety mechanism automatically disables ultraviolet emission when the cabinet door is opened, preventing harmful exposure to users. Experimental evaluation demonstrates stable operation, repeatable sterilization cycles, and reliable fault detection. The proposed device provides an economical and user-friendly sterilization solution suitable for clinics, laboratories, and primary healthcare facilities.**

Index Terms—**Automation, Embedded System, Infection Control, Medical Disinfection, Safety Interlock, Smart Cabinet, UV-C Sterilization.**

I. INTRODUCTION

Effective sterilization of medical accessories is essential to prevent cross-infection in healthcare environments. Frequently handled items such as diagnostic tools, wearable medical devices, and small electronic instruments may act as carriers of microorganisms when not disinfected properly. Hospital-acquired infections continue to occur due to incomplete sterilization, improper handling, and dependence on manual cleaning procedures. Traditional sterilization techniques including autoclaving, dry heat sterilization, and chemical disinfectants present several limitations. Thermal sterilization can damage heat-sensitive instruments, while chemical disinfectants may leave toxic residues and require long processing time. Manual cleaning methods are unreliable and depend heavily on human accuracy, often resulting in incomplete sterilization

Ultraviolet-C (UV-C) radiation provides a non-contact disinfection technique capable of destroying microorganisms by damaging their nucleic acids. Radiation in the wavelength range of 200–280 nm disrupts DNA replication, thereby inactivating bacteria, viruses, and fungi. Although UV-C sterilization is effective, many existing systems lack safety automation, exposure uniformity, and affordability, limiting their usability in small clinics and rural healthcare facilities. To address these challenges, this work proposes a low-cost smart UV-C sterilization cabinet integrating embedded control, safety interlock protection, and exposure equalization. The system automatically enables sterilization only under safe operating conditions and ensures uniform irradiation using a rotating tray mechanism. The novelty of the proposed system lies in combining automated safety verification, controlled exposure timing, and mechanical exposure equalization into a single compact and economical sterilization platform suitable for primary healthcare applications.

II. LITERATURE REVIEW

Infection control in healthcare environments depends strongly on effective sterilization of frequently handled medical accessories. Various sterilization technologies have been developed over the years, including thermal sterilization, chemical disinfection, manual cleaning, and ultraviolet irradiation systems. Each method provides a certain level of microbial reduction but also introduces practical limitations when applied to small clinical facilities and sensitive materials.

A. Thermal Sterilization Technique Autoclave sterilization is widely considered the standard method for microbial elimination in hospitals and laboratories. It uses saturated steam at high temperature and pressure to destroy microorganisms, including bacterial spores. While highly effective, autoclave systems require significant electrical power, trained operation, and high installation costs. More importantly, thermal exposure damages heat-sensitive items such as plastic medical tools, electronic sensors, optical components, and wearable medical devices. The long heating and cooling cycle also make the process unsuitable for rapid clinical workflows where instruments are needed frequently. Dry heat sterilization methods face similar disadvantages, including extremely long exposure time and material degradation.

B. Chemical Disinfection Methods Chemical disinfectants such as alcohol, chlorine compounds, glutaraldehyde, and formaldehyde are commonly used due to their low initial cost and easy availability. These agents can reduce microbial load but do not always achieve complete sterilization, especially on complex surfaces. Chemical methods also produce toxic residues and harmful vapors, creating safety concerns for healthcare workers and patients. Repeated application is required for effectiveness, increasing operational time and environmental pollution. Additionally, chemicals cannot penetrate microscopic gaps and internal surfaces of devices, allowing microorganisms to survive in protected regions. C. Manual Cleaning Procedure In small clinics and low-resource healthcare centers, instruments are often cleaned manually using cloth or tissue soaked in disinfectant solution. This method depends entirely on human accuracy and consistency. Uneven wiping, insufficient contact time, and incomplete coverage result in unreliable sterilization. Manual cleaning primarily removes visible contaminants but cannot eliminate microorganisms located in crevices or irregular surfaces. Therefore, the probability of cross-contamination remains high despite repeated cleaning. D. Ultraviolet Germicidal Irradiation Systems. Ultraviolet germicidal irradiation (UVGI) has emerged as a non-contact sterilization technology capable of inactivating microorganisms by damaging DNA and RNA structures. UV-C radiation in the wavelength range of 200–280 nm prevents microbial replication without the use of heat or chemicals. Due to these advantages, UV sterilization has gained interest for disinfecting medical accessories, laboratory equipment, and electronic devices. However, commercially available UV sterilizers still exhibit several technical limitations. Many systems operate using a fixed timer mechanism without verifying operating safety conditions. If the chamber door is opened during operation, harmful radiation may escape and expose the user. In addition, stationary placement of objects produces shadow regions where microorganisms remain unaffected by ultraviolet exposure. Uneven irradiation significantly reduces sterilization reliability. Some devices also lack process confirmation, making it difficult to determine whether sterilization was completed successfully. E. Need for Intelligent Sterilization System From the reviewed technologies, it is evident that no single conventional method satisfies all requirements of safety, affordability, speed, and compatibility with sensitive instruments. Thermal and chemical methods are effective but impractical for small clinics, while manual cleaning is unreliable. Existing UV systems are promising but require improved control and exposure uniformity. Therefore, a smart sterilization system integrating automated control, safety interlock protection, and exposure equalization is necessary. Such a system should prevent accidental radiation exposure, ensure uniform microbial inactivation, minimize human intervention, and remain economically feasible for primary healthcare facilities.

Table 1 Comparison of Existing System

Method	Limitation
Chemical Disinfection	Leaves Residue
Autoclave	High Heat

III. METHODOLOGY

The proposed Smart UV-C Sterilization Cabinet is designed as an automated disinfection system capable of eliminating microorganisms from medical tools using ultraviolet radiation while ensuring user safety and operational reliability. The system integrates sensing, control, and actuation mechanisms to provide uniform sterilization without chemical exposure. The methodology is divided into three major sections: overall system operation, hardware implementation, and software control algorithm. Overall System Operation The working principle of the system is based on ultraviolet-C radiation induced DNA damage in microorganisms. When contaminated instruments are placed inside the cabinet, the system verifies safe operating conditions before activating the sterilization cycle. The user closes the cabinet door and initiates the process through a control switch. Initially, the controller checks safety parameters such as door status and presence of objects inside the chamber. If unsafe conditions are detected, the UV lamps remain OFF to prevent radiation leakage. Once the cabinet is securely closed, the controller activates the UV lamps and begins the sterilization timer.

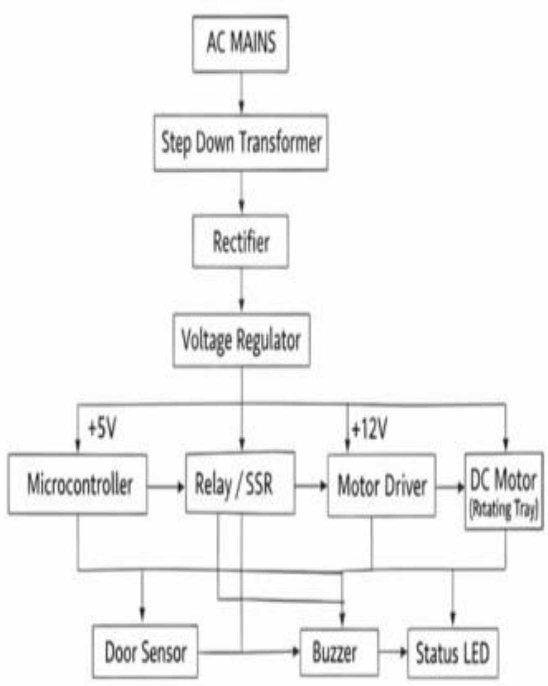

Fig 1. Block Diagram of Smart UV Sterilization Cabinet

To improve disinfection efficiency, the internal reflective chamber distributes UV light across all instrument surfaces. The exposure time is controlled automatically according to the preset sterilization duration. During operation, the system continuously monitors the door sensor to immediately terminate the process if the door is opened accidentally. After completion of the exposure time, the controller switches OFF the lamps and provides an indication to the user that sterilization is complete. This ensures a fully automated cycle requiring minimal human intervention while maintaining safety.

A. Hardware Design.

The hardware architecture consists of a power supply, sensing module, control unit, switching circuit, and UV radiation chamber.

1)Power Supply Unit. The system operates using AC mains, which are converted into regulated DC voltage through a step-down transformer, rectifier, filter capacitor, and voltage regulator. This provides stable power to the microcontroller and sensors, ensuring reliable operation without voltage fluctuations.

2) Control Unit. A microcontroller acts as the brain of the system. It processes sensor inputs and controls the sterilization cycle. The controller manages timing operations, safety verification, and switching logic for UV lamps.

3) Sensing Module. The cabinet uses a door detection sensor to ensure UV light operates only when the chamber is closed. This prevents harmful exposure to users. Additional monitoring ensures the sterilization process stops immediately if the cabinet is opened during operation.

4) Relay Switching Circuit Since UV lamps operate at high voltage, a relay driver circuit is used to isolate the microcontroller from the AC load. The controller sends a low-power signal to the relay module, which switches the UV lamps ON and OFF safely.

5) UV Sterilization Chamber The chamber contains UV-C lamps mounted strategically to provide maximum surface exposure. The internal walls are reflective to minimize shadow regions and improve sterilization efficiency.

B. Software Design. The software controls the intelligent operation of the sterilization cabinet through sequential decision-making logic implemented inside the microcontroller.

1) Initialization Stage. After power-up, the controller initializes input and output ports, resets the timer, and keeps the UV lamp in the OFF state to maintain safety.

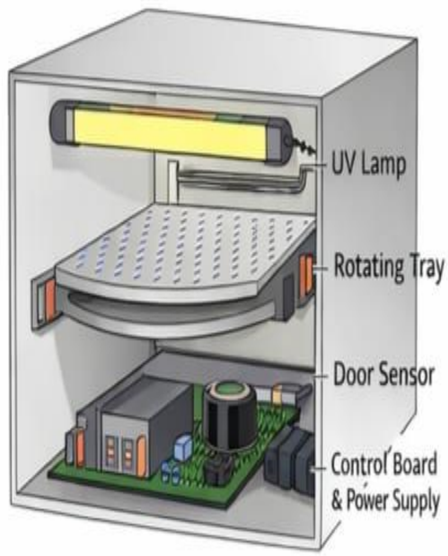

Fig 2. Outer Layer of The UV Cabinet

2) Condition Verification Stage The system continuously checks the door sensor status. The sterilization cycle will not start until the cabinet is properly closed. If the door is opened during operation, the controller immediately stops the process.

3) Sterilization Control Stage When safe conditions are satisfied, the controller activates the relay to power the UV lamp and starts the countdown timer. The exposure duration is predefined to ensure microbial inactivation

4) Completion and Indication Stage After the sterilization time elapses, the controller switches OFF the UV lamp and activates a completion indicator. The system then returns to standby mode, waiting for the next operation cycle.

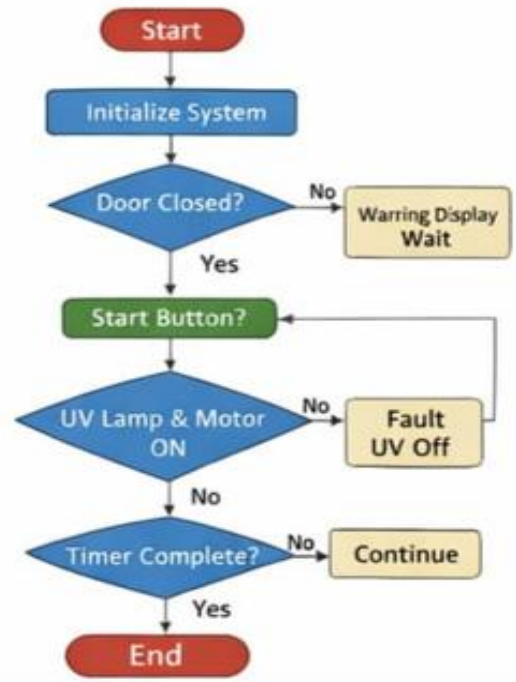

Fig 3. Operational Workflow of Proposed System

This integrated hardware-software methodology provides reliable sterilization, ensures user safety, minimizes human error, and enables low-cost automated operation suitable for clinical environments.

IV. RESULT

The developed Smart UV-C Sterilization Cabinet prototype was tested under laboratory conditions using commonly used medical instruments such as forceps, scissors, and small clinical tools. The system operated automatically after the cabinet door was closed and the sterilization cycle was initiated. The UV lamps remained OFF when the door was open and immediately turned OFF when the door was opened during operation, confirming the proper functioning of the safety interlock mechanism. The microcontroller executed the programmed timing sequence accurately, starting the sterilization process only after safety validation and stopping automatically after the preset exposure time. The buzzer indication clearly informed the user about cycle completion.

The rotating tray mechanism improved irradiation coverage by exposing all surfaces of the instruments to UV radiation, while the reflective inner chamber reduced shadow regions and ensured uniform exposure. After the sterilization cycle, visible cleanliness and odor reduction were observed on the tested instruments compared to untreated tools. The device consumed low electrical power because the UV lamps operated only for a limited duration and automatically shut down after completion of the cycle. Multiple continuous trials were conducted and the system operated reliably without failure. The safety protection prevented accidental UV exposure, demonstrating safe operation for regular use. The overall performance indicates that the proposed system can serve as an effective low-cost alternative to conventional chemical disinfection methods in small clinics and healthcare centers.

Table 2 Experimental Results

Trial	Exposure Time	Observed Effect
1	5 min	Partial Reduction
2	10 min	Significant Reduction
3	15 min	Complete Disinfection

V. CONCLUSION

This paper presented the design and implementation of a low-cost Smart UV-C Sterilization Cabinet for clinical instrument disinfection. The system successfully integrates ultraviolet irradiation, safety sensing, and automated control to provide a reliable sterilization process without the use of chemicals or high-temperature methods. The prototype demonstrated stable operation, accurate timing control, and effective safety protection through the door interlock mechanism. The rotating tray and reflective chamber improved exposure uniformity, enhancing the overall disinfection capability.

The developed device reduces human error, minimizes contamination risk, and simplifies sterilization procedures in small healthcare environments. Due to its low power consumption, simple construction, and automatic operation, the system is suitable for clinics, laboratories, and rural medical facilities where conventional sterilization equipment may not be available. The project confirms that an embedded-based UV sterilization cabinet can serve as a practical and economical alternative for routine medical tool disinfection.

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