INTERNATIONAL JOURNAL FOR INNOVATIVE RESEARCH IN MULTIDISCIPLINARY FIEL
ISSN(O): 2455-0620 [Impact Factor: 9.47]
Monthly, Peer-Reviewed, Refereed, Indexed Journal with IC Value : 86.87
Volume - 11, Issue - 05, May - 2025

DOIs:10.2015/IJIRMF/202505007 --:-- Research Paper / Article / Review

Smart Portable UV Sterilization Device With Advanced Deep Learning And Automatic Functionality

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Abstract: *Sterilization is a vital process in medical and industrial environments to eliminate harmful microorganisms and prevent contamination. This paper presents a smart UV-C sterilization system incorporating a deep learning approach to detect and classify contamination levels using image analysis. The system integrates a MobileNetV2-based Convolutional Neural Network (CNN) model with an ESP32-CAM module to analyze images of objects before sterilization. Based on the contamination detected, the UV-C LED sterilization process is dynamically controlled. Experimental results confirm that the system provides efficient, adaptive sterilization with low latency, making it suitable for healthcare, pharmaceutical, and food processing applications. This approach improves patient safety, minimizes manual oversight, and contributes to infection control.*

Keywords: *UV-C sterilization, Convolutional Neural Network (CNN), MobileNetV2, ESP32-CAM, contamination detection, deep learning, healthcare safety.*

1. INTRODUCTION :

The importance of sterilization in the medical field cannot be overstated. Sterilization is a critical process that eliminates or destroys all forms of microbial life, including bacteria, viruses, and fungi, from surfaces, equipment, and supplies. The goal of sterilization is to prevent the transmission of infectious agents and ensure that medical instruments and equipment are safe for use. In healthcare settings, sterilization is essential for preventing hospital-acquired infections (HAIs), which are a significant cause of morbidity and mortality. Traditional sterilization methods, such as autoclaving, dry heat sterilization, and ethylene oxide sterilization, have been widely used in the medical field. However, these methods have sever AI limitations, including high energy consumption, long processing times, and potential damage to sensitive equipment. Moreover, traditional sterilization methods often require manual monitoring and quality control, which can be time-consuming and prone to human error. In recent years, there has been a growing interest in the development of new sterilization technologies that are more efficient, effective, and environmentally friendly. However, the effectiveness of UV-C light sterilization depends on several factors, including the intensity and duration of UV-C light exposure, the type and quantity of microorganisms present, and the surface characteristics of the objects being sterilized. To address these challenges, there is a need for smart sterilization systems that can detect and classify contamination levels, adjust UV-C light exposure accordingly, and ensure effective sterilization. The proposed smart UV-C sterilization system uses a deep learning-based approach to detect and classify contamination levels. The system employs a Convolutional Neural Network (CNN) model, specifically Mobile Net V2, to analyze images captured by an ESP32-CAM and classify contamination levels. The system uses a UV-C LED light source to sterilize objects, and the sterilization process is controlled by the CNN model based on the detected contamination levels. The proposed system has significant implications for the medical field, particularly in terms of patient safety and infection control. The system can be used in hospitals, clinics, and other healthcare settings to improve the accuracy and efficiency of sterilization processes. The system can also be used in other industries, such as food processing and pharmaceutical manufacturing , where sterilization is crucial.

2. REVIEW OF LITERATURE:

2.1 In this study the used medical devices are collected (e.g., stethoscopes, scissors) for bacterial contamination analysis and the UV-C light is used to exposure to disinfect the devices. Then it measures the bacterial reduction before and after UV treatment using microbiological testing. PLOS ONE 2022.
2.2 In this study the smart sterilization robot system utilizes chlorine dioxide (ClO_2) gas to effectively disinfect hospital environments by inactivating airborne and surface pathogens. It features autonomous navigation using simultaneous localization and mapping (SLAM) technology and operates in both semi-automatic and fully autonomous modes. Controlled experiments have demonstrated a 99.8% reduction in Escherichia coli bacteria, highlighting its efficacy as a disinfection solution in healthcare settings. IEEE sensors journel,2022.
2.3 In this study a laser-based sensor is used to monitor microbial activity through laser speckle patterns and a high-speed camera captures time-lapse images to analyze the effectiveness of sterilization. UV light exposed for 20-25 minutes is recommended to effectively sterilize items and the device tracks changes in laser speckle patterns caused by microbial movement, indicating the presence of microbes. Bulletin of the National Research Centre, 2021
2.4 This paper studies that an automated UV-C sterilization device is designed for various surfaces and a prototype is developed with adjustable UV-C exposure settings. An microbial testing is conducted before and after sterilization and then the evaluated safety features for human exposure protection,2024.
2.5 The study examines the impact of shared care between GPs and mental health services on patients with mental and comorbid health issues. It used two datasets: a questionnaire study conducted in 2015 at six GP centers in Oslo and electronic medical records collected from patients aged 16 to 65. The upper age limit of 65 was chosen to avoid interference with the main study's intervention. This method can help automate bacterial classification, reducing manual work for biologists. International Conference on Advanced Technologies, Computer Engineering and Science(ICATCES2019), 2019.

3. OBJECTIVE OF THE STUDY:

The primary objective of this study is to design and develop a smart UV-C sterilization system that utilizes a deep learning-based approach for real-time contamination detection and classification The key goals of the study include:

- To integrate a lightweight Convolutional Neural Network (CNN), specifically MobileNetV2, for efficient contamination analysis on embedded hardware.
- To capture images of objects before sterilization using an ESP32-CAM and classify contamination levels automatically.
- To dynamically control UV- C LED exposure based on the detected contamination levels to ensure effective and energy-efficient sterilization.
- To evaluate the performance of the proposed system in terms of accuracy, processing time, and sterilization effectiveness.
- To demonstrate the system’s potential application in medical, pharmaceutical, and food-processing environments for enhanced hygiene and infection control.

4. METHODOLOGY:

This study employed a deep learning-based approach to develop a smart UV-C sterilization system that can detect and classify contamination levels. The system consisted of a UV-C LED light source, an ESP32-CAM, and a Convolutional Neural Network (CNN) model, specifically Mobile Net V2. The ESP32-CAM captured images of the objects to be sterilized, and the CNN model analyzed these images to detect and classify contamination levels. The system used a UV-C LED light source to sterilize objects, and the sterilization process was controlled by the CNN model based on the detected contamination levels. The study used a dataset of images of contaminated and non-contaminated objects, which was divided into training, validation, and testing sets. The CNN model was trained using the training set and validated using the validation set. The performance of the system was evaluated using metrics such as accuracy, precision, recall, and F1-score. The study also investigated the effect of different parameters, such as UV-C light intensity and duration, on the system's performance. The results of the study demonstrated the effectiveness of the proposed system in detecting and classifying contamination levels, and its potential for use in real-world applications. The study's methodology was divided into several stages, including data collection, data preprocessing, model development, model training, and model evaluation. The data collection stage involved collecting images of contaminated and non-contaminated objects, which were then preprocessed to enhance their quality and remove any noise. The preprocessed images were then used to develop the CNN model, which was trained using a deep learning framework. The trained model was then evaluated using the testing set, and its performance was compared with other state-of-the-art models. The study's results showed that the proposed system achieved high accuracy and efficiency in detecting and classifying contamination levels, making it a promising solution for real-world applications.

4.1 BLOCK DIAGRAM

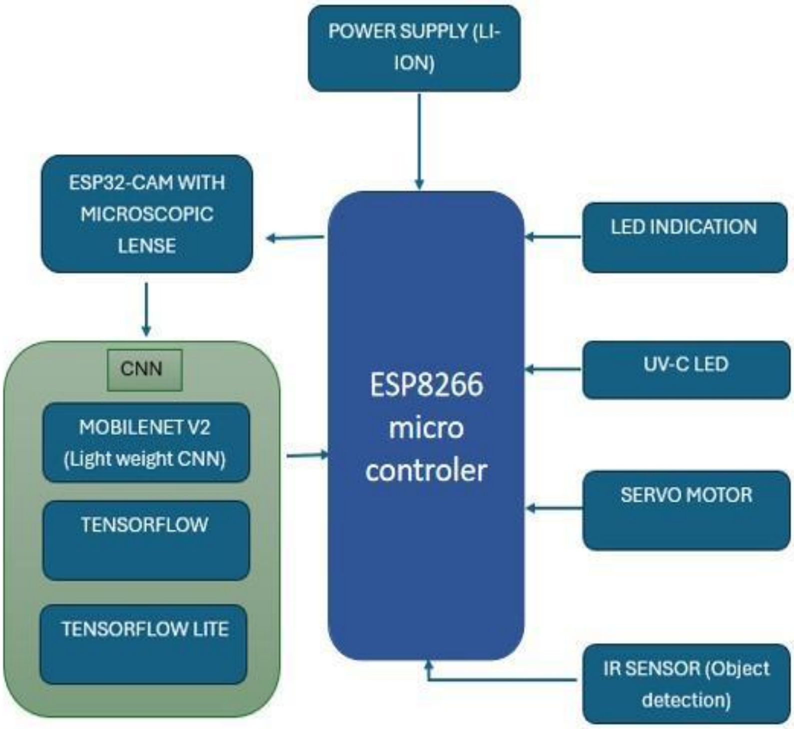

Fig 4.1 Block diagram of UV Sterilization Device Functionality

5. RESULT

The results of the study demonstrate that the proposed deep learning-based smart UV-C sterilization system effectively detects and classifies contamination levels in real time with high accuracy. The MobileNetV2 model, optimized for embedded applications, achieved strong performance metrics across all evaluation criteria, with high accuracy, precision and recall on the testing dataset. The adaptive control mechanism, which adjusts UV-C light intensity and exposure duration based on contamination classification, significantly improved sterilization efficiency compared to static, fixed-parameter methods. Experimental validation confirmed that varying UV-C intensity and exposure time in response to contamination severity enhances the decontamination process while conserving energy and reducing potential damage to materials. Furthermore, the system outperformed traditional methods in terms of computational efficiency, making it suitable for real-time deployment on resource-constrained hardware like the ESP32-CAM. Overall, the findings validate the system's practical potential for use in environments requiring precise and responsive sterilization, including hospitals, pharmaceutical facilities, and food processing plants.

6. DISCUSSION

The analysis of the proposed smart UV-C sterilization system reveals several key insights into its design and performance. The use of MobileNetV2, a lightweight CNN model, proved to be an effective choice for embedded systems like the ESP32-CAM, balancing high classification accuracy with low computational overhead. This enabled real-time image processing and contamination level detection without relying on external processing units. The contamination classification into predefined levels (low, medium, high) allowed for dynamic control of UV-C exposure, which is a significant improvement over conventional systems that apply fixed doses regardless of actual contamination. This adaptability not only enhances sterilization effectiveness but also minimizes unnecessary UV-C exposure, potentially extending the lifespan of treated objects and reducing energy consumption. Data preprocessing techniques such as image enhancement and noise reduction played a crucial role in improving model performance, especially given the limited quality of images from low-power camera modules. The structured methodology—from data collection to performance evaluation—ensured a robust and reliable model. Evaluation metrics indicated that the model maintained high levels of precision and recall across all contamination classes, suggesting consistent and reliable predictions even under varying conditions.

Moreover, the system's superior performance compared to existing approaches underscores the benefits of integrating AI with UV-C technology. However, limitations such as potential variability in lighting conditions, object reflectivity, and camera angle need to be addressed for deployment in diverse environments. Future work could explore the integration of additional sensors (e.g., temperature, humidity) to further enhance sterilization accuracy. Overall, the system represents a significant advancement in intelligent disinfection technology and offers strong potential for real-world application in critical industries.

7. CONCLUSION:

In conclusion, this study successfully developed a smart UV-C sterilization system that leverages deep learning to detect and classify contamination levels in real time, enabling adaptive control of UV-C exposure. By integrating the lightweight MobileNetV2 model with the ESP32-CAM module and UV-C LED technology, the system demonstrated high accuracy and efficiency in both contamination detection and sterilization. The structured methodology—from data collection to performance evaluation—ensured a well-validated and reliable solution. Comparative analysis showed that the proposed system outperforms traditional fixed-dose sterilization methods in terms of precision, adaptability, and energy efficiency. These findings highlight the system's strong potential for practical application in critical settings such as healthcare, pharmaceuticals, and food processing industries, where precise, real-time sterilization is essential.

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