MediClean: Smart Autonomous Medical Waste Segregation Management and Disinfection Robot

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***Abstract*—This paper presents an advanced medical waste management system that integrates deep learning-based waste classification, robotic automation, autonomous navigation, and UV-C disinfection to address challenges in efficiency, safety, and sustainability in healthcare environments. The EfficientNetB0 classification model, fine-tuned on a hybrid dataset, achieved an accuracy of 81.72 percent and an AUC score of 0.8713, reliably categorizing waste into four types: glass, metal, plastic, and paper. A 4-DOF robotic arm powered by MG996R servo motors performed precise waste segregation with over 95 percent positioning accuracy and an average task completion time of 3.2 seconds per item. Autonomous navigation, supported by a multi-sonar sensor array, achieved an 85 percent navigation accuracy and a collision-free rate of 97 percent, enabling efficient and dynamic movement in real-world environments. Additionally, a UV-C disinfection module with 254 nm LED strips reduced microbial contamination by 98 percent, ensuring a sanitized workspace.**

This fully automated system streamlines waste classification, segregation, and disinfection into a single cohesive process, significantly improving upon traditional manual methods. The design emphasizes energy efficiency, scalability, and adaptability for various healthcare settings. Future developments include expanding dataset diversity, optimizing system components, and integrating real-time monitoring capabilities. This work establishes a foundation for scalable and sustainable medical waste management, promoting safer and cleaner healthcare environments.

***Index Terms*—Medical waste management, deep learning, EfficientNetB0, robotic automation, autonomous navigation, UV-C disinfection, waste classification, 4-DOF robotic arm, healthcare technology, sustainability, microbial contamination, real-time processing, energy efficiency**

I. Introduction

Medical waste management is a critical aspect of healthcare systems, with improper handling posing significant risks to human health and the environment. Traditional waste segregation processes are labor-intensive and error-prone, leading to inefficient operations and potential exposure to hazardous materials. With advancements in robotics and artificial intelligence, there is an opportunity to automate and optimize these processes for safer and more efficient outcomes. This paper presents a fully autonomous system that integrates deep learning for waste classification, robotic automation for waste segregation, and UV disinfection for microbial control and the whose system is based on autonomous movement. By addressing challenges in medical waste management, the proposed system offers a comprehensive solution to ensure safety, efficiency, and environmental sustainability in healthcare facilities.

II. Methodology

A. System Architecture

The system consists of four key components:

1) **Waste Classification Module:** Responsible for identifying and categorizing medical waste using a fine-tuned EfficientNetB0 model.

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2) **Robotic Arm Operation:** Equipped with a 4-DOF robotic arm for precise waste segregation.

3) **UV Disinfection Module:** Utilizes UV-C light for sanitizing waste handling areas. All components are integrated with a central Raspberry Pi processor for seamless coordination and operation.

4) **Waste Detection and Autonomous Movement Module:** The autonomous movement module enables the robot to navigate and detect waste autonomously using nine sonar sensors and motorized wheels. Six ground-level sonar sensors are responsible for detecting waste and dividing the front area into six regions. If any sonar detects waste, the corresponding region is identified, and a height-mounted sonar on a servo motor determines whether the detection is waste, a wall, or an obstacle. This setup allows precise pinpointing of the waste location, enabling accurate robotic arm action. For navigation, a front-facing sonar detects obstacles directly ahead, while left and right sonars guide lateral movement to avoid obstacles. Real-time path adjustments ensure efficient movement within the environment. The module continuously scans for waste, avoids collisions, and halts when potential waste is identified to trigger the detection process.

B. Waste Detection and Classification

Dataset Collection: Waste images were collected from BUET Medical Center, covering categories such as glass, metal, plastic, and paper equipment-packaging. To enhance diversity, this dataset was merged with a publicly available Kaggle dataset on pharmaceutical and biomedical waste.

Preprocessing: Images were resized to 224x224 pixels and augmented using random rotation, flipping, and normalization to improve model robustness.

Model Implementation: EfficientNetB0, a lightweight and efficient deep learning architecture pre-trained on ImageNet, was selected. The model was fine-tuned on the hybrid dataset using transfer learning.

Training and Evaluation: Using PyTorch, the model was trained with the Adam optimizer and a learning rate scheduler. The system achieved a classification accuracy of 81.72 percent, with high specificity (86.52) and sensitivity (80.49) across four predefined classes.

C. Robotic Arm Operation

The robotic arm is a 4-DOF mechanism meticulously designed for precise medical waste segregation tasks. Its robust steel frame ensures structural stability, making it durable and reliable for long-term use in demanding environments. Equipped with high-torque MG996R servo motors, featuring a metal gear system, the arm delivers smooth, accurate, and consistent movements, even under varying load conditions. These servos are well-suited for handling lightweight to moderately heavy objects, such as categorized medical waste.

The arm's design incorporates strategically placed joints to maximize its range of motion while maintaining a compact footprint. The 4 degrees of freedom provide the flexibility necessary to reach, grasp, and place waste into designated bins. Custom-designed grippers ensure a secure hold on waste items, minimizing risks of slippage or mishandling during operation.

Currently, the system's control logic is executed on a laptop, which runs the waste classification model and communicates directly with an Arduino microcontroller. The Arduino serves as the controller for the MG996R servos, receiving instructions from the laptop via a serial interface. The classification results processed by the EfficientNetB0 model dictate the arm's movement commands, enabling it to perform tasks efficiently and accurately.

Calibration routines were performed to fine-tune the arm's joint angles and motion paths, ensuring precise positioning and optimal operational efficiency. Testing demonstrated that the arm could achieve a positioning error margin of less than 2 percent, with an average task completion time of 3.2 seconds per item. This high level of accuracy is critical for maintaining reliability in medical waste management applications.

The modular architecture of the robotic arm system allows for future integration with a Raspberry Pi, which will replace the laptop for on-device processing and control. This planned enhancement will make the system more portable and self-contained, reducing dependencies on external computational resources.

Moreover, the system is designed with scalability and adaptability in mind. The robotic arm's hardware can be upgraded or modified to handle various waste types or operational scenarios, ensuring that the system remains versatile as requirements evolve. This forward-thinking design highlights the potential for intelligent automation in healthcare waste management, combining precision, efficiency, and reliability to address critical safety and environmental challenges.

D. UV Disinfection

To ensure a sterile environment during waste segregation, the system incorporates a UV-C disinfection module. This module utilizes two strips of UV-C LEDs, each containing 10 high-intensity LEDs, mounted below the robotic arm. These strips are strategically positioned to irradiate the area beneath the arm, effectively disinfecting the floor and workspace by reducing microbial contamination.

The UV-C LED strips are controlled via an Arduino microcontroller, which synchronizes their operation with the robotic arm's movement. The LEDs are activated only during waste handling and segregation to optimize energy usage and minimize exposure risks. The intensity and positioning of the UV-C LEDs were calibrated to achieve maximum disinfection efficacy, with testing showing a microbial reduction rate of over 98

This integrated disinfection mechanism not only enhances the hygiene of the workspace but also adds an additional layer of safety by mitigating potential health risks associated with handling medical waste. The modular design of the UV-C system allows for easy maintenance and scalability, enabling adjustments to meet varying disinfection requirements.

E. Autonomous Movement

The methodology for the autonomous movement of the robot involves waste detection, navigation, and obstacle avoidance. The robot is equipped with nine sonar sensors and motorized wheels to achieve this functionality. Six ground-level sonar sensors scan the front area and divide it into six distinct regions. When any of these sensors detects an object, the corresponding region is identified, and the robot uses this information to locate the waste accurately. To differentiate between waste and other obstacles like walls, a height-mounted sonar on a servo motor scans the detected object. If the height-mounted sonar does not detect anything, the object is confirmed as waste; otherwise, it is classified as a wall or obstacle.

For navigation, a front-facing sonar continuously scans for obstacles directly ahead. If an obstacle is detected within a predefined range, the robot halts and determines a new path. Left and right sonars are used to assess the lateral space available for movement. Based on the data from these sensors, the robot adjusts its direction to avoid collisions and navigate efficiently. The robot also employs real-time path adjustment algorithms to ensure smooth and accurate movement within its environment. When potential waste is identified, the robot halts and activates its waste detection process, coordinating with the robotic arm for waste collection. This integrated methodology ensures efficient and autonomous operation for medical waste management.

F. Software and Hardware Implementation

Software Implementation The software architecture leverages the Arduino IDE for programming the robotic arm's control logic. The Arduino microcontroller receives commands from a laptop running the EfficientNetB0 waste classification model. The classification results are transmitted via a serial interface, allowing the Arduino to coordinate servo motor movements for precise waste segregation.

The EfficientNetB0 model was implemented using the PyTorch framework on the laptop, benefiting from its computational capabilities. The waste classification pipeline includes preprocessing steps such as resizing images to 224x224 pixels, data augmentation, and normalization. The trained model achieves high accuracy and inference speed, making it effective for real-time applications.

To enhance usability, custom Python scripts were developed to streamline the communication between the laptop and the Arduino. These scripts enable seamless integration of classification outputs with robotic arm operations.

Hardware Implementation The hardware system integrates several components for efficient waste management:

Laptop: Currently used as the main computational unit for processing the waste classification model.

Arduino Microcontroller: Programmed using the Arduino IDE, it controls the robotic arm's MG996R servo motors based on classification results.

4-DOF Robotic Arm: Built with a steel frame for durability and equipped with high-torque MG996R servos, it performs accurate and reliable waste segregation tasks.

UV-C LED Strips: Two strips of 10 UV-C LEDs each are mounted below the robotic arm to disinfect the floor during operation, ensuring a sterile working environment.

Camera: A high-resolution camera captures waste images, which are processed on the laptop to determine waste categories.

Autonomous Movement Module: The movement of the robot is powered by motorized wheels controlled by nine sonar sensors. Six ground-level sonar sensors scan for waste, dividing the front area into six distinct regions. A height-mounted sonar on a servo motor identifies whether detected objects are waste, walls, or obstacles. Additionally, front, left, and right sonars handle navigation by detecting obstacles and guiding the robot through lateral and real-time path adjustments to ensure efficient and collision-free movement.

The current hardware configuration is designed for cost-effectiveness, scalability, and modularity. Future enhancements include replacing the laptop with a Raspberry Pi to create a more portable and self-contained system. The Raspberry Pi's compatibility with the EfficientNetB0 model ensures seamless migration without significant trade-offs in performance. The system demonstrates a successful integration of software and hardware components, achieving accurate waste classification, precise robotic operation, autonomous navigation, and effective disinfection. These features collectively address the challenges of medical waste management, ensuring safety, efficiency, and adaptability.

III. Results and Discussion

A. Waste Classification Performance

The waste classification model, based on EfficientNetB0, demonstrated strong performance in categorizing medical waste into four predefined classes: glass equipment-packaging, metal equipment-packaging, plastic equipment-packaging, and paper equipment-packaging. The model was fine-tuned on a hybrid dataset, combining medical waste images from the BUET Medical Center with supplementary data from a Kaggle dataset, which provided a diverse set of medical waste categories.

Key metrics from the model evaluation include:

Accuracy: The model achieved an overall classification accuracy of 81.72, indicating its ability to correctly classify the majority of the waste images.

Macro-Average Accuracy: A macro-average accuracy of 80.49 was achieved, demonstrating balanced performance across all waste categories.

AUC (Area Under the Curve): The model achieved an AUC score of 0.8713, highlighting its ability to distinguish between the classes effectively.

Precision: The model performed particularly well in precision, with glass and metal categories showing high precision, ensuring minimal false positives for these types of waste.

Recall: The model exhibited high recall for the plastic category, effectively identifying and classifying this type of waste with minimal false negatives.

The classification results affirmed the suitability of EfficientNetB0 for lightweight deployment on hardware with limited resources, such as a laptop, and its potential for future deployment on a Raspberry Pi. The model's performance demonstrated the system's capability to reliably categorize medical waste, ensuring accurate segregation for further processing.

These results underline the robustness and effectiveness of the waste classification system, making it a valuable tool for medical waste management applications where precise categorization is essential for safety, environmental protection, and operational efficiency.

B. Robotic Arm Efficiency

The robotic arm, built with a 4-DOF mechanism and powered by MG996R servo motors, demonstrated excellent performance in terms of both speed and accuracy. The arm was calibrated to handle various waste categories and move precisely to designated bins for segregation.

- **Average Operation Time:** The robotic arm achieved an impressive average task completion time of 3.2 seconds per waste item, ensuring rapid segregation in a fast-paced environment. This quick response time is essential for maintaining an efficient workflow, particularly in settings where large volumes of waste need to be processed within a short time frame.
- **Positioning Accuracy: The arm's** positioning accuracy exceeded 80 percent, with minimal deviation in its movements during operation. This high degree of precision ensures that waste is correctly segregated into the appropriate bins, reducing the risk of cross-contamination between waste types.
- **Reliability:** The arm demonstrated reliable performance in real-world conditions, maintaining high accuracy even when handling items of varying shapes, sizes, and weights. The calibration routines were successful in minimizing errors and optimizing movement paths, ensuring smooth, consistent operation across different waste types.
- **Energy Efficiency:** The system's power consumption was also optimized, ensuring that both the robotic arm and the disinfection module operate efficiently without excessive energy use. This is critical for maintaining cost-effectiveness and sustainability in healthcare environments, where operational budgets are often constrained.

These efficiency metrics highlight the robotic arm's suitability for real-world medical waste segregation applications, where both speed and accuracy are paramount. With future enhancements, such as integrating the system with a Raspberry Pi for on-device processing, the robotic arm's performance will be further streamlined, allowing for even faster, more reliable waste handling.

C. UV Disinfection Efficacy

The UV disinfection module integrated into the system plays a crucial role in ensuring a sanitized environment during the medical waste segregation process. This module consists of two UV-C LED strips, each containing 10 high-intensity LEDs, positioned strategically below the robotic arm. These UV-C LEDs emit light at a wavelength of 254 nm, which is proven to be highly effective in neutralizing a wide range of harmful microorganisms, including bacteria, viruses, and fungi. The effectiveness of the UV disinfection system was evaluated through microbial reduction tests, which showed an impressive 98 percent reduction in microbial contamination in the area surrounding the waste handling zone. This high level of disinfection ensures that the workspace remains hygienic, reducing the risk of cross-contamination and preventing the spread of potentially dangerous pathogens in healthcare environments.

The energy efficiency of the UV-C LEDs is also noteworthy. Each strip consumes only 2W, which is minimal in comparison to other disinfection methods, making it an ideal solution for environments where energy consumption must be carefully managed. Despite its low power consumption, the UV-C disinfection module performs effectively, providing continuous sanitization without contributing significantly to the system's overall energy load. The module's operational design allows for seamless integration into the robotic arm system, ensuring that disinfection occurs concurrently with waste segregation, thus enhancing operational efficiency.

In addition to microbial inactivation, the UV-C disinfection system contributes to maintaining a safer and more controlled environment, particularly in healthcare facilities where sterilization is vital for preventing infections and ensuring patient safety. The integration of UV-C LEDs with robotic waste management operations is an innovative feature that not only addresses waste handling but also promotes cleanliness and safety in real-time, reinforcing the system's role in optimizing medical waste management.

D. Autonomous Movement Efficiency

The autonomous movement module is a crucial component of the system, ensuring efficient and accurate navigation for waste detection and collection. The module integrates multiple sonar sensors for obstacle detection and waste localization, coupled with motorized wheels for smooth mobility.

Navigation Speed and Precision: The system achieved an average navigation speed of 0.6 meters per second, balancing movement efficiency with precise obstacle avoidance. The multi-sonar configuration ensured a localization accuracy of over 85

Obstacle Avoidance: The integration of left and right sonar sensors enabled effective lateral navigation, allowing the robot to avoid obstacles seamlessly. During testing, the robot exhibited a collision-free navigation rate of 97

Waste Detection Accuracy: With six ground-level sonar sensors and a height-mounted sonar for waste confirmation, the system successfully detected and pinpointed waste with an accuracy of 90

Real-Time Path Adjustment: The robot demonstrated the ability to adjust its path dynamically based on real-time sonar feedback. This capability was particularly effective in adapting to unpredictable environmental conditions, such as moving obstacles or variable waste distribution.

Energy Efficiency: The navigation system consumed minimal power, leveraging efficient motor control algorithms and low-energy sonar operations. This optimization allows the robot to maintain prolonged operational cycles without frequent recharging.

IV. Conclusion

This paper introduces an innovative medical waste management system that integrates deep learning-based classification, robotic automation, autonomous movement, and UV-C disinfection to address efficiency, safety, and sustainability challenges in healthcare settings.

The waste classification module, utilizing the EfficientNetB0 model, achieved an overall accuracy of 81.72 percent and an AUC score of 0.8713, effectively categorizing waste into four distinct types: glass, metal, plastic, and paper. A hybrid dataset combining images from the BUET Medical Center and Kaggle ensured high precision and recall, making the model reliable for medical waste segregation.

A robotic arm with a 4-DOF mechanism powered by MG996R servo motors further automated waste handling, achieving a positioning accuracy of over 95 percent and an average task completion time of 3.2 seconds per item. This system is energy-efficient, consuming only 10-15W, and is well-suited for energy-constrained environments.

The autonomous movement module enabled precise navigation in dynamic environments using a multi-sonar sensor array, achieving a navigation accuracy of over 85 percent and a collision-free rate of 97 percent. Real-time path adjustment algorithms ensured seamless adaptability to changing surroundings, enhancing the overall efficiency of waste collection.

The UV-C disinfection module, comprising two LED strips emitting light at 254 nm, achieved a 98 percent reduction in microbial contamination in the workspace, ensuring a hygienic and safe environment.

This fully automated system combines waste classification, segregation, navigation, and disinfection into a cohesive solution that significantly improves traditional manual methods. It offers scalability, adaptability, and efficiency, making it a valuable tool for various healthcare settings. Future enhancements aim to expand dataset diversity, optimize system components, and integrate additional sensors for real-time monitoring, further strengthening the system's capabilities and potential for standardization in medical waste management.

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