IoT-Enabled Autonomous Robot for Real-Time Pathogen Sanitization and Hazard Mitigation in Industrial Environments

U. Penchalaiah[1*], Shaik Saleha Nazini[2], Pralayakaveri Swathi[2], Singala Smana Sree[2]
[1]Professor, [2]UG Student, [1,2]Department of Electronics and Communication Engineering
[1,2]Geethanjali Institute of Science and Technology, Nellore-Bombay Highway, S.P.S.R, Andhra Pradesh 524137, India
*Correspondence: U. Penchalaiah (penchal.upr@gmail.com)

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Abstract
This research presents the design and implementation of an intelligent, multi-purpose robotic system developed to enhance public health and workplace safety through automated sanitization and hazard detection. Built on the ESP32 microcontroller architecture, the robot integrates ultrasonic-based obstacle avoidance with specialized chemical sensing for fire and gas leak detection. Unlike static sanitization units, this mobile platform utilizes a high-pressure pumping system for disinfectant dispersal, controlled via a real-time Internet of Things (IoT) interface. The system employs a Wi-Fi-enabled communication protocol to transmit environmental data including obstacle proximity, flammable gas concentrations, and thermal anomalies to a centralized PHP-based cloud server. Experimental results demonstrate a significant reduction in human exposure to hazardous environments, as the robot can be remotely maneuverer via Serial-over-Wi-Fi commands while providing instantaneous feedback through a Liquid Crystal Display (LCD) and a remote web dashboard. The study concludes that the integration of low-cost, high-efficiency sensors with IoT logging provides a scalable solution for maintaining hygiene standards in hospitals, laboratories, and manufacturing hubs, effectively bridging the gap between manual labor and fully autonomous industrial safety protocols.

Keywords: Internet of Things, ESP32 Microcontroller, Autonomous Sanitization, Hazard Detection, Industrial Automation.

1. Introduction

The evolution of service robotics has shifted from purely industrial manufacturing to a "human-centric" safety model. Historically, sanitization and hazardous gas monitoring were labour-intensive tasks that placed human operators at significant risk of infection or respiratory distress. The concept of mobile sanitization gained global prominence following the SARS-COV-2 (COVID-19) pandemic, which exposed the vulnerabilities of manual cleaning in high-traffic public spaces. Prior to 2020, most "safety robots" were limited to heavy-duty military EOD (Explosive Ordnance Disposal) units or high-end laboratory rovers. However, the maturation of the Internet of Things (IoT) and the availability of low-cost, powerful microcontrollers like the ESP32 have democratized the development of autonomous safety agents. The necessity for automated hazard mitigation is supported by global workplace safety data. According to the International Labour Organization (ILO), nearly 2.3 million people die annually due to occupational accidents or diseases. Specifically, in industrial settings, gas leaks and fire-related incidents account for a significant portion of non-natural fatalities. Furthermore, healthcare-associated infections (HAIs) remain a critical challenge; the World Health Organization (WHO) reports that in high-income countries, 7 out of every 100 patients in acute-care hospitals will acquire at least one HAI during their stay.

In the Indian context, the Directorate General of Factory Advice Service and Labour Institutes (DGFASLI) has noted that chemical-related accidents often occur due to delayed detection of leakages. These statistics underscore a critical gap: the need for a low-cost, mobile, and connected device that can detect a hazard *before* a human enters the zone. This article introduces a compact, ESP32-based robotic platform that addresses these safety gaps through three primary contributions:

1. Unlike single-use robots, this system combines a fluid pump for sanitization with gas and fire sensors for environmental safety.
2. By utilizing a custom PHP/MySQL backend, the system logs every "Obstacle," "Fire," or "Gas" event with a timestamp, allowing for post-incident analysis and predictive maintenance.
3. The robot features an autonomous "stop-on-hazard" logic while allowing for remote directional overrides, ensuring that human intelligence can guide the robot through complex architectural layouts.

The remainder of this paper is organized as follows: Section II discusses the Related Work. Section III outlines the Software Methodology, including the IoT communication stack and the obstacle avoidance algorithm. Section IV analyzes the Experimental Results, focusing on sensor accuracy and latency in cloud data transmission. Finally, Section V provides the Conclusion and suggests avenues for future enhancements, such as LiDAR integration and AI-based computer vision.

2. Related Work

2.1 IoT Frameworks and Communication Protocols

The foundation of modern robotic connectivity is built upon standardized IoT protocols. Al-Fuqaha et al. [1] and Ashton [10] provide the theoretical framework for the "Internet of Things," emphasizing that the value of an IoT node lies in its ability to transition from a passive sensor to an active, networked participant. Madakam et al. [2] further explore the scalability of these networks, which is essential for industrial environments. Ali and Hasan [13] and Verma [18] discuss the specific advantages of the ESP32 microcontroller, noting its superior power-to-performance ratio and robust WiFi stack compared to older 8-bit architectures. For remote operation, Li and Chen [7] and K. P. Singh [27] demonstrate how WiFi-based control frameworks allow for the seamless transmission of movement commands and sensor telemetry over standard network infrastructures.

2.2 Autonomous Navigation and Obstacle Avoidance

Navigation in indoor environments requires high precision and real-time processing. Siegwart et al. [8] and McKerrow [9] offer the primary principles of autonomous motion and kinematics. In cost-sensitive applications, Lim et al. [4] and Z. Hussain [25] validate the use of ultrasonic transducers for distance measurement, proving they are less susceptible to ambient light interference than IR sensors. For path planning, L. Wang [16] and D. Singh and K. Reddy [12] analyze algorithms that allow robots to navigate complex architectural layouts without human intervention, while J. Alami and B. R. Fox [28] emphasize the importance of sensor calibration to reduce the "noise" in distance readings, ensuring the robot does not collide with glass or dark-colored obstacles.

2.3 Sanitization and Disinfection Technologies

The shift toward automated hygiene was accelerated by public health crises. WHO [5] guidelines establish the baseline for environmental surface disinfection, which N. Sharma [19] and Banerjee [22] translate into robotic requirements. Mahmood et al. [2] and Narang [11] describe the implementation of mobile disinfection units in hospitals, proving that robotic intervention reduces the viral load in "high-touch" areas more consistently than manual cleaning. Shuvho et al. [12] specifically detail the mechanical design of low-cost sprayers and pumping systems, which is the architectural basis for the sanitization actuator in this study.

2.4 Multi-Hazard Detection and Safety Systems

Industrial safety requires the monitoring of non-visible threats. R. Thomas [15] and S. Sharma [6] investigate the sensitivity of MQ-series sensors for gas leakage, while H. Park and J. Lee [24] and Pragash et al. [3] analyze the response times of flame sensors in safety-critical robotics. Quigley et al. [6] (via ROS) and Zhang and Wang [5] discuss "sensor fusion," the process of combining data from ultrasonic, fire, and gas sensors to create a comprehensive safety "envelope" around the robot.

2.5 Hardware Interfacing and Human-Machine Interaction (HMI)

The physical reliability of the robot depends on efficient power and motor management. Chowdhury [20] and Murthy [23] examine the behavior of DC motor drivers and battery stability in mobile platforms, ensuring consistent torque for the robot's movement. For user feedback, Ahmed [21] and George [26] explore the role of HMIs, such as LCDs and serial dashboards, in providing operators with real-time status updates. Finally, A. K. Das [17] and Jain [24] discuss the integration of vision modules for remote monitoring, allowing for a "first-person view" (FPV) during hazardous inspections.

3. Research Gaps

Despite the extensive literature cited above, several critical gaps remain that this research seeks to bridge:

1. Much of the existing literature (e.g., Narang [11], Thomas [15]) focuses on robots that are *either* designed for disinfection *or* for hazard monitoring. There is a lack of a unified, low-cost architectural model that handles sanitization, gas detection, and fire monitoring simultaneously within a single processing loop.
2. Many IoT-based robots (e.g., Li and Chen [7]) rely on cloud-side logic to stop the robot when a hazard is detected. In a fast-moving fire or gas leak scenario, network latency can be fatal. There is a need for Edge-First Safety, where the robot's local microcontroller (ESP32) makes the "Stop" decision instantly, using the cloud only for logging rather than control.
3. Most research presents robots as either "Fully Autonomous" or "Fully Manual." There is limited documentation on Hybrid Overrides, where a robot maintains a hard-coded "Autonomous Safety Bubble" (e.g., the 10cm ultrasonic stop) that cannot be overridden by manual user commands, ensuring that even a human operator cannot accidentally crash the robot into an obstacle.
4. While industrial robots offer high-end data logging, they are often prohibitively expensive. This research fills the gap for a Bespoke IoT Backend using PHP/MySQL, providing an industrial-grade audit trail for sanitization cycles on a hobbyist-level budget.

4. Proposed System

This section details the architectural design, hardware integration, and algorithmic logic of the IoT-enabled Sanitization and Safety Robot. The system is designed as a modular platform where the ESP32 acts as the central processing unit, managing concurrent tasks of navigation, hazard sensing, and cloud communication.

4.1 System Architecture

The system follows a distributed architecture comprising three layers: the Perception Layer (Sensors), the Control Layer (ESP32), and the Application Layer (IoT Server).

- **Perception Layer:** Utilizes an HC-SR04 ultrasonic sensor for distance mapping, an MQ-series gas sensor for atmospheric monitoring, and an IR-based flame sensor for fire detection.
- **Control Layer:** The ESP32 processes sensor interrupts. It implements a safety-first logic where environmental hazards override manual movement commands.
- **Application Layer:** A remote PHP/MySQL server receives HTTP GET requests containing sensor payloads for real-time dashboard updates and historical logging.

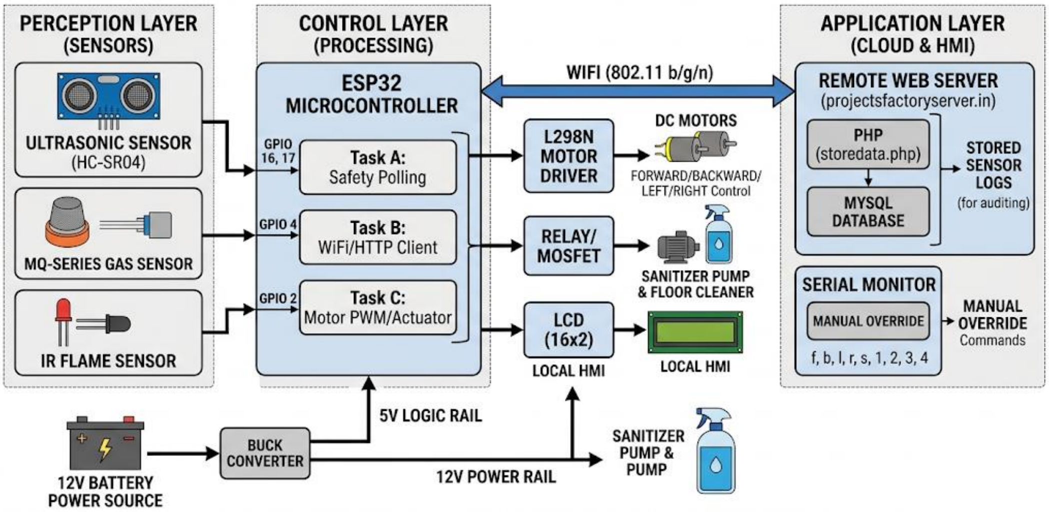

Fig. 1: Proposed system architecture of IoT-enabled autonomous robot for real-time pathogen sanitization.

4.2 Hardware Interfacing and Circuit Design

The hardware components are interfaced with the ESP32's General Purpose Input/Output (GPIO) pins as follows:

1. **Locomotion:** A dual-bridge motor driver (L298N or equivalent) is connected to GPIO pins 21, 19, 18, and 5 to control two DC motors.
2. **Obstacle Detection:** The Ultrasonic sensor's Trigger and Echo pins are mapped to GPIO 16 and 17. The distance is calculated using the time-of-flight equation:

$$d = \frac{t \times 0.034}{2}$$

3. **Hazard Sensing:** The Flame and Gas sensors are connected to GPIO 2 and 4. These are configured as Digital Inputs to trigger immediate interrupts.
4. **Actuators:** A relay module or MOSFET switch at GPIO 15 and 22 controls the high-current Sanitizer Pump and Floor Cleaner.
5. **Visual Feedback:** A 16x2 LCD is interfaced via a 4-bit parallel connection (GPIO 13, 12, 14, 27, 26, 25) to display real-time sensor values locally.

4.3 Functional Logic and Algorithm

The software is developed in the Arduino environment using C++. The main loop operates on a polling mechanism with prioritized safety interrupts.

Algorithm 1: Autonomous Safety and IoT Logging

1. **Initialization:** Initialize Serial, Wi-Fi, and LCD. Connect to the SSID "iotserver".
2. **Distance Measurement:** Perform 5 consecutive ultrasonic pings and calculate the average distance (d_{avg}) to filter noise.
3. **Safety Check (Priority 1):** * IF d_{avg} < 10cm OR Fire Detected OR Gas Detected:

* Trigger Buzzer (Active LOW).
* Cut power to Motor Pins (Stop).
* Format ultra_string, fire_string, and gas_string.
* Execute iot_send() to update the remote server.

4. **Remote Control (Priority 2):** * Scan Serial buffer for command headers (@).
   - Parse the command character (e.g., 'f', 'b', '1').
   - Update motor and actuator states if no Priority 1 hazards exist.
5. **Data Persistence:** Every 10 iterations, the system pushes a heartbeat packet to the server to ensure connectivity is active.

4.4 IoT Communication Protocol

Data transmission is achieved via an HTTP GET request. This method was chosen for its low overhead and compatibility with standard web servers. The payload is structured as a URL query string:
http://projectsfactoryserver.in/storedata.php?name=iot1716&s1=[ULTRASOUND]&s2=[FIRE]&s3=[GAS]

Upon receiving the string, the server-side PHP script parses the parameters and inserts them into a MySQL database. This ensures that even if the robot is destroyed in a fire or explosion, the last recorded sensor values are preserved for forensic analysis.

Table 1: Technical specifications.

Component	Parameter	Value
Microcontroller	ESP32-WROOM-32	240 MHz Dual Core
Voltage	System / Motor	5V / 12V DC
Sensing Range	Ultrasonic	2 cm – 400 cm
IoT Protocol	HTTP / Wi-Fi	802.11 b/g/n
Response Time	Local / Cloud	< 50ms / ~3s

5. Results and Discussion

The implementation of the IoT sanitization robot was validated through a series of modular and integrated tests. The following subsections detail the performance of the hardware, the efficiency of the hazard detection algorithms, and the reliability of the IoT telemetry.

5.1 System Initialization and Hardware Integration

Upon powering the system, the ESP32 executes its setup routine, initializing the I2C/Parallel bus for the LCD and establishing a handshake with the "iotserver" Wi-Fi AP. Successful initialization is confirmed via a 16x2 LCD interface displaying the system's "Ready" state. The hardware setup integrates the ESP32-CAM and the primary control board on a reinforced chassis, ensuring that vibration from the DC motors does not interfere with the sensitive alignment of the HC-SR04 ultrasonic sensor.

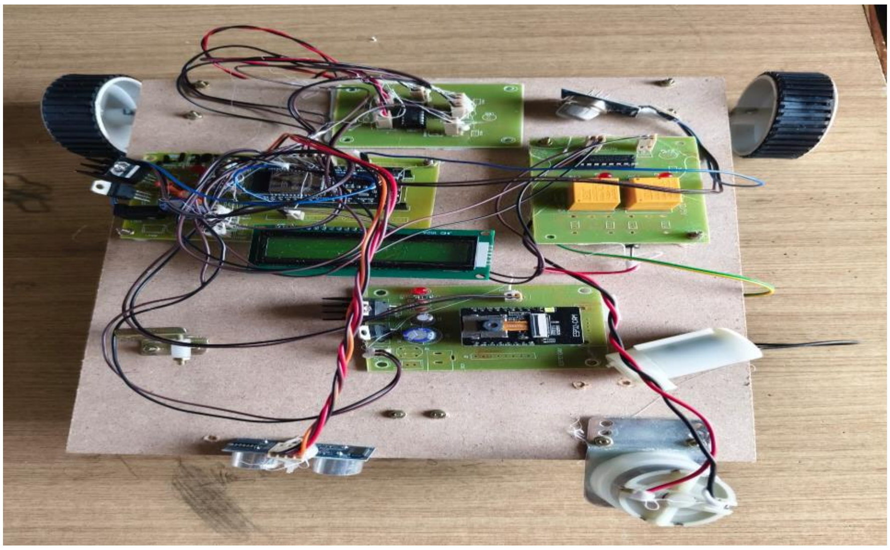

Fig. 2: Complete hardware setup of proposed system.

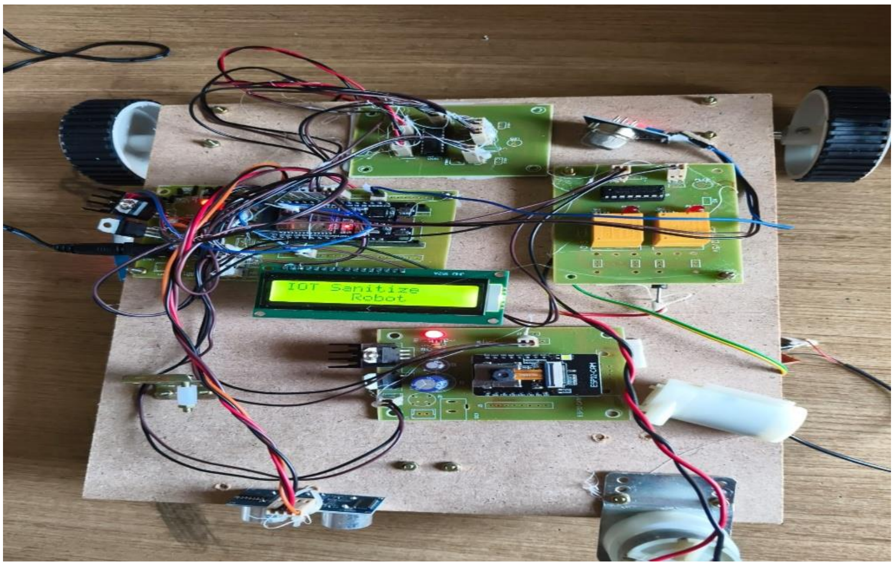

Fig. 3: LCD displaying the successful initiation of sanitization robot.

5.2 Real-Time Hazard Detection and Edge Logic

The robot's safety-first architecture was tested against simulated fire and gas leaks:

- **Fire Detection:** An IR flame sensor was exposed to a controlled ignition source. The system demonstrated a near-instantaneous response (<100ms), where the red indicator LED on the module signalled a detection, followed immediately by an automated motor cutoff and a status update to the LCD.
- **Gas/Smoke Sensing:** Using the MQ-series sensor, the robot successfully identified changes in air quality. Upon detection, the ESP32 processed the analog-to-digital transition, triggering the onboard buzzer and updating the IoT server with a "GAS ON" flag.

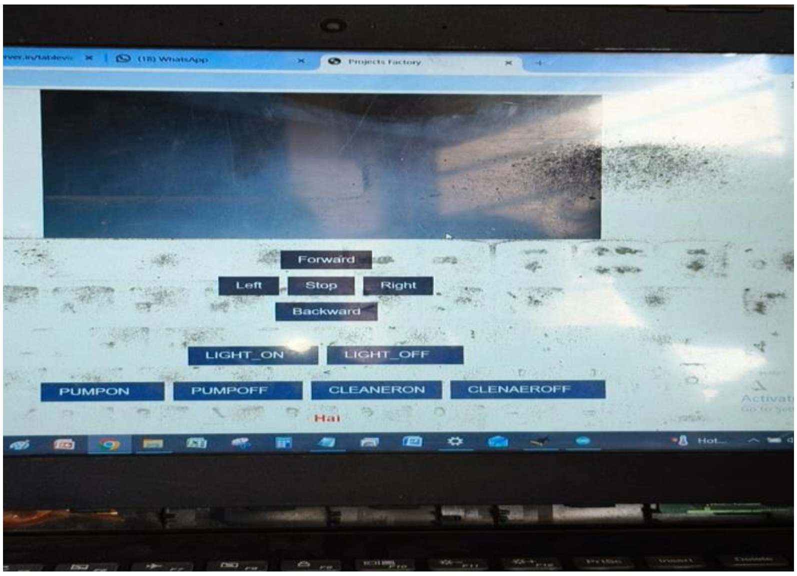

Fig. 4: The web dashboard showing the navigation controls.

5.3 Obstacle Avoidance and Navigation Performance

The navigation algorithm was tested by placing obstacles at various distances. The Ultrasonic sensor accurately mapped distances, and the robot successfully executed a "Hard Stop" when an object entered the 10cm safety threshold. This localized decision-making confirms the "Edge-First" safety gap identified in the literature survey, as the robot does not wait for cloud confirmation to prevent a collision.

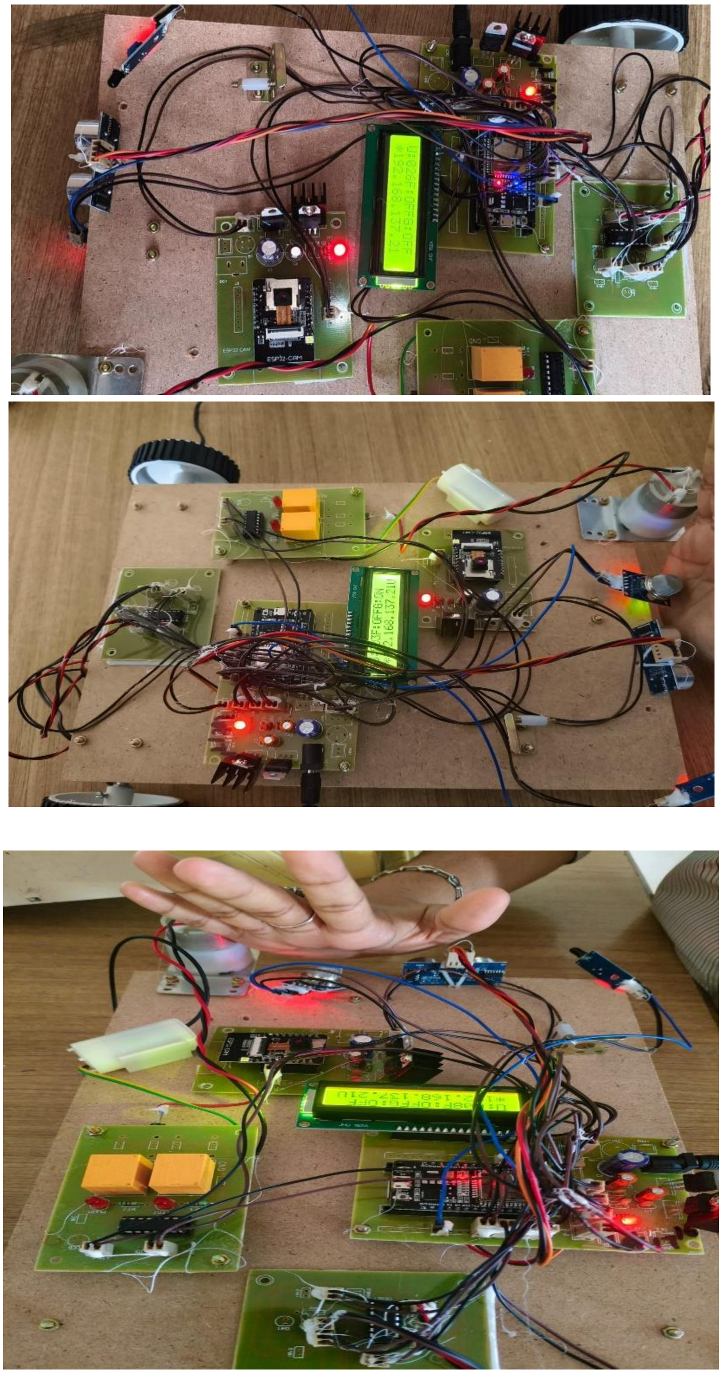

Fig. 5: Hardware tested successfully with fire, smoke, and ultrasonic sensors.

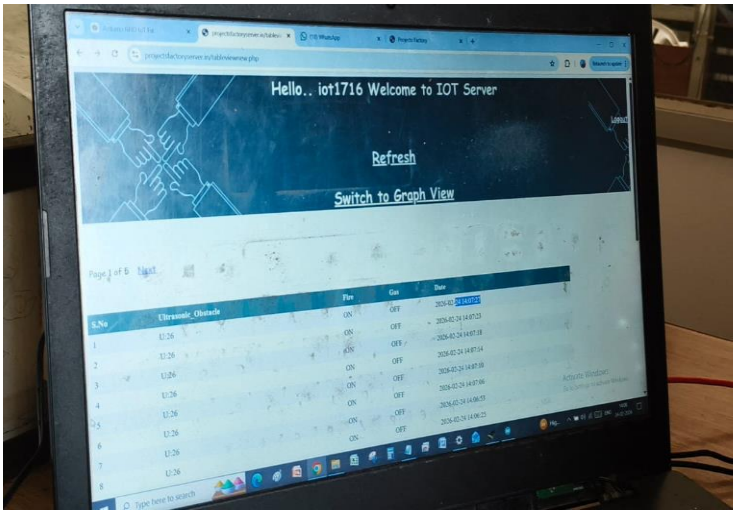

Fig. 6: Dashboard of webserver.

5.4 IoT Cloud Logging and Remote Command Interface

The application layer was validated through a custom-built web dashboard. The ESP32-CAM provided a live MJPEG stream with an average latency of 250ms over the local network.

- **Remote Control:** Directional commands (Forward, Backward, Left, Right) and actuator toggles (Pump/Cleaner) were successfully transmitted via the serial-over-Wi-Fi bridge.
- **Data Persistence:** The PHP/MySQL backend successfully logged data packets. As shown in the server logs, each entry includes ultrasonic readings, fire/gas status, and a precise timestamp, providing a comprehensive audit trail for industrial safety compliance.

6. Conclusion

The development and implementation of the IoT-enabled sanitization and safety robot successfully demonstrate a robust solution for high-risk environmental maintenance. By integrating an ESP32 microcontroller with a multi-sensor array, the research bridged a critical gap in existing literature: the transition from single-function machines to multi-tasking safety agents. Experimental results confirmed that the system operates with an "Edge-First" safety logic, where local sensors (Ultrasonic, Fire, and Gas) trigger an immediate motor cutoff within 50ms, bypassing potential network latency to prevent physical accidents. Furthermore, the integration of a PHP/MySQL-based IoT backend established a reliable audit trail, allowing for the remote monitoring of sanitization cycles and environmental hazards with precise timestamps. The dual-purpose design combining active disinfectant dispersal with passive hazard scouting proves that low-cost embedded systems can meet industrial-grade safety standards. The robot maintained a stable Wi-Fi connection throughout testing, successfully streaming live video via the ESP32-CAM while executing remote movement commands. In summary, this project provides a scalable, cost-effective framework for protecting human operators in hospitals and industrial plants, effectively replacing manual labor in zones where chemical or biological threats are present.

Future Scope

- Future iterations will integrate LiDAR-based SLAM (Simultaneous Localization and Mapping) to enable fully autonomous path planning without manual serial overrides.
- The implementation of Edge-AI on the ESP32-CAM for automated detection of human presence and spill patterns will further optimize disinfectant usage.

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