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A Review of Semi-Autonomous Robot for Rust Detection in Metal Surfaces

John Paul[1]*, Nehil Pradeep[1]*, Shanavas S[1]*, Tisto Varghese[1]*, and Jeslin P. Jo[2]

[1]Electronics and Communication Engineering Department, Federal Institute of Science And Technology (FISAT), Ernakulam, India. [2]Assistant Professor, Electronics and Communication Engineering Department, Federal Institute of Science And Technology (FISAT), Ernakulam, India.

Abstract: Corrosion inspection in large metal structures such as ships and silos is challenging due to their size, hazardous environments, and limitations of manual inspection. This work proposes a semi-autonomous mobile robot with magnetic tank tracks for reliable adhesion on vertical and curved metallic surfaces. The robot integrates ultrasonic obstacle sensors and an ESP32-Raspberry Pi control architecture for assisted navigation, where the operator retains directional control while the system autonomously avoids collisions. A camera system with machine learning algorithms identifies and classifies rust patches in real time. The mobile interface ensures intuitive control and remote monitoring, while the modular design allows adaptation for marine and industrial applications. This approach reduces inspection time, enhances safety, and provides a cost-effective alternative to high-end autonomous robotic systems.

Keywords: Rust detection, corrosion monitoring, semi-autonomous robot, magnetic adhesion, structural inspection.

I. INTRODUCTION

Corrosion in large metallic structures such as ships, silos, and tanks poses serious risks to safety, reliability, and maintenance costs. Traditional inspection methods are labor-intensive, hazardous, and often fail to provide early detection of rust. This project proposes a semi-autonomous mobile robot for corrosion inspection using magnetic tank tracks for adhesion on vertical/curved surfaces, ESP32-Raspberry Pi control with ultrasonic sensors for assisted navigation, and camera with ML for real-time rust detection. A mobile interface ensures intuitive operation, offering a cost-effective solution for industrial and marine applications.

II. SUMMARY OF REVIEWED WORKS

I. Paper 1: Magnet-Based Climbing Robot for Steel Bridge Inspection (Pham et al., 2021 [1])

Core Objective: To develop a safe and efficient robotic system capable of inspecting large steel bridge structures by adhering to vertical, inclined, and inverted metallic surfaces.
Methodology: The authors designed a magnetically adhered climbing robot using permanent magnets for stable locomotion. The robot carries multiple sensing units, including RGB cameras, depth sensors, and IR/Time-of-Flight (ToF) modules. Image stitching techniques were employed for wide-area surface inspection, while segmentation-based image processing algorithms were used for crack detection. Wireless communication enabled real-time data transmission and multi-robot collaboration.
Key Contribution: The study demonstrates an integrated robotic inspection framework combining magnetic adhesion, multi-sensor data acquisition, and image-based crack detection. The system successfully supports both 2D surface analysis and 3D structural mapping of steel bridges.
Principal Findings: Field experiments showed a crack detection success rate of approximately 93%. The robot exhibited reliable adhesion, stable movement on curved and complex steel surfaces, and consistent data collection under varying illumination conditions.
Limitations: The system faces challenges in negotiating sharp surface transitions and maintaining performance under extreme lighting variations. Battery capacity also limits long-duration autonomous inspections.

II. Paper 2: Flying–Climbing Hybrid Robot for Steel Bridge Inspection (Pham et al., 2021 [2])

Core Objective: To enhance inspection flexibility by combining UAV-based mobility with magnetic climbing capabilities for accessing hard-to-reach steel bridge components.
Methodology: The proposed system integrates a quadrotor UAV with a magnetic adhesion mechanism, enabling a transition from

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flight to climbing mode. The robot is equipped with a high-resolution camera, Giant Magneto-Resistance (GMR) sensor array, and proximity sensors. A landing control algorithm ensures safe attachment to curved and inclined steel surfaces. Inspection is remotely operated using a VR headset and live wireless video feed.

Key Contribution: This work introduces a dual-mode flying–climbing robotic platform that overcomes the accessibility and stability limitations of conventional UAV-only inspection systems.

Principal Findings: Real-world testing on the Nam-O Bridge demonstrated stable magnetic adhesion for up to 30 minutes and successful detection of surface cracks. The system proved effective for inspecting overhead and remote steel members.

Limitations: Trade-offs exist between payload capacity, battery endurance, and flight stability. Environmental disturbances such as wind and rain adversely affect system performance.

III. Paper 3: Multi-directional Structure Tensor-Based Corner Detection (Zhang and Sun, 2020 [3])

Core Objective: To improve the accuracy and robustness of corner detection in images affected by noise, distortions, and scale variations.

Methodology: The authors proposed a Multi-directional Structure Tensor (MDST) approach that applies anisotropic Gaussian directional filters across multiple orientations and scales. Eigenvalue analysis of the structure tensor is used to differentiate true corners from edges.

Key Contribution: The MDST algorithm significantly enhances corner discrimination compared to traditional detectors such as Harris and SUSAN, particularly in complex imaging environments.

Principal Findings: Benchmark testing showed superior repeatability, localization accuracy, and robustness to noise, affine transformations, and scale changes. These properties make the method suitable for detecting irregular corrosion features on metallic surfaces.

Limitations: The multi-scale filtering process increases computational complexity, which may limit real-time deployment on resource-constrained robotic platforms.

IV. Paper 4: Vision-Based Automated Rust Detection during Grinding Processes (Tian et al., 2018 [4])

Core Objective: To achieve reliable real-time rust detection during robotic grinding operations on steel surfaces.

Methodology: The system integrates a camera-based inspection module with a robotic grinding platform. A Qualified Image Detection (QID) technique is used to eliminate corrupted image frames caused by tool interference, rust debris, or lighting fluctuations. Image processing algorithms are then applied to segment and identify rusted regions.

Key Contribution: The introduction of the QID technique significantly improves detection robustness by ensuring that only high-quality images are used for rust analysis, enabling selective and efficient grinding.

Principal Findings: Experimental results showed a frame qualification accuracy of 97.2%. The system effectively handled challenges such as reflective steel textures, uneven illumination, and tool occlusion.

Limitations: The approach is primarily demonstrated in controlled industrial grinding scenarios and does not address mobile robotic inspection or large-scale outdoor environments.

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SL NO.	Paper	Primary Focus	Methodology	Key Strength
1.	Pham et al. (2021) [1]	Magnet-based climbing robot for steel bridge inspection	Design of a permanent-magnet adhesion robot integrated with RGB, depth, and IR/ToF sensors; image stitching and segmentation-based crack detection; wireless communication for real-time monitoring	High crack detection accuracy (~93%), stable adhesion on vertical and curved surfaces, and combined 2D–3D structural inspection
2.	Pham et al. (2021) [2]	Flying–climbing hybrid robot for inaccessible steel bridge components	Integration of quadrotor UAV with magnetic adhesion; flight-to-climb transition control; vision-based inspection using cameras and GMR sensors with VR-based teleoperation	Enhanced accessibility to overhead and remote structures with stable magnetic attachment and flexible inspection modes
3.	Zhang & Sun (2020) [3]	Robust corner detection for noisy and complex images	Multi-directional Structure Tensor (MDST) using anisotropic Gaussian filters and eigenvalue analysis across multiple scales	Superior robustness to noise, scale, and affine distortions; improved detection of irregular corrosion-related features
4.	Tian et al. (2018) [4]	Vision-based automated rust detection during grinding	Camera-based inspection with Qualified Image Detection (QID) to filter poor frames; image segmentation for rust identification	High detection reliability (97.2% frame qualification accuracy) under reflective surfaces and varying illumination

III. ARCHITECTURE

I. ***Sensing Unit***

Camera module, ultrasonic sensors for obstacle avoidance, IMU for orientation feedback, LED lighting for consistent illumination.

II. ***Processing Unit***

ESP32 for low-level control and wireless communication, Raspberry Pi for high-level processing and ML execution.

III. ***Rust Detection Algorithm***

Image preprocessing, ML-based classification (CNN/YOLO), confidence thresholding to reduce false positives.

IV. ***User Interface***

Real-time mobile app for control/monitoring, visual rust alerts, IoT integration for data reporting.

E. *Mobility Platform*

Magnetic tank tracks for vertical/curved surface adhesion, high-torque DC motors with encoders and drivers.

F. *Hardware Requirements*

I. Chassis & Locomotion: Magnetic tank tracks, high-torque motors, drivers
II. Control Units: ESP32 + Raspberry Pi
III. Sensing & Navigation: Ultrasonic sensors, IMU
IV. Vision & Detection: Camera, ML model, LED lighting
V. Power System: 12V battery, converters, BMS
VI. Communication: Wi-Fi/Bluetooth, optional RF
VII. Safety: Emergency stop, protective casing, cooling

IV. CHALLENGES AND FUTURE DIRECTIONS

Environmental issues (dust, shadows, lighting), surface similarity (dirt/paint mimicking rust), stability on curved/windy surfaces, and battery life limitations. Future improvements: Integration of hyperspectral/eddy current sensors, larger corrosion datasets for ML training, multi-robot cooperation, IoT-based predictive maintenance.

V. CONCLUSION

This review highlights semi-autonomous robots' potential for rust inspection in large metal structures. Integrating magnetic adhesion, camera-based ML detection, and assisted navigation enhances safety, reduces costs, and increases efficiency. With sensor fusion and AI model improvements, such platforms can play a vital role in industrial and marine corrosion monitoring.

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Car Drowning-Safety and Alert System

John Paul[1]*, Nehil Pradeep[1]*, Shanavas S[1]*, Tisto Varghese[1]*, Jeslin P. Jo[2]

[1]Electronics and Communication Engineering Department, Federal Institute of Science And Technology (FISAT), Ernakulam, India. [2]Assistant Professor, Electronics and Communication Engineering Department, Federal Institute of Science And Technology (FISAT), Ernakulam, India.

Abstract: Drowning incidents involving vehicles pose a significant threat to passenger safety. To address this issue, we propose a" Car Drowning Safety and Alert System," an automated system designed to enhance survival chances during such emergencies. The system incorporates a wet sensor to detect water ingress, triggering a series of automated responses. A servo motor rolls down the car windows, enabling easy escape, while another servo motor unlocks the seatbelt to prevent entrapment. Simultaneously, a buzzer is activated to alert nearby individuals for assistance. Additionally, the system employs a GPS module to determine the exact location of the incident. This information is transmitted via an ESP32 module to emergency services or pre-defined contacts, ensuring timely rescue operations. By integrating these safety measures, the proposed system significantly improves the chances of survival for passengers trapped in submerged vehicles.

Keywords: Vehicle Safety, Drowning Detection, Emergency Alert System, GPS Tracking, IoT

I. INTRODUCTION

Vehicular submersion incidents are among the most dangerous emergencies a driver or passenger can face. Whether caused by flooding, accidents near water bodies, or loss of vehicle control leading to water entry, these situations pose an immediate threat to life. Studies indicate that a significant percentage of drowning deaths occur in submerged vehicles, primarily due to the inability to escape in time. Traditional safety mechanisms, such as seat belts and airbags, are ineffective in such cases, making it crucial to develop an advanced system that enhances survival chances.

The Car Drowning Safety and Alert System is designed to address this challenge by integrating multiple technologies that facilitate rapid escape, alert authorities, and prevent vehicles from sinking completely. One of the most critical issues in submerged vehicle incidents is the inability of passengers to open car doors due to water pressure. When a vehicle submerges, external pressure increases drastically, making it nearly impossible to push the doors open from the inside. This delay often leads to fatal outcomes, as precious seconds are lost while passengers struggle to escape.

II. ARCHITECTURE

A. *Block Diagram*

The system utilizes an ESP32 microcontroller to control various components based on water detection and power supply connection. The system initiates by detecting water through a sensor while simultaneously checking the availability of supply voltage. Both of these inputs are sent to the ESP32 microcontroller, which serves as the central processing unit of the system. If the input conditions are satisfied, the system triggers the" Activate Components" function, powering multiple output devices. These include a buzzer, a GPS module, and two servo motors. The buzzer functions as an audible alert mechanism to signal water detection or a potential emergency. The GPS module enables real-time location tracking, which is beneficial for remote monitoring or logging purposes. The servo motors facilitate mechanical operations such as opening windows and unlocking seatbelts.

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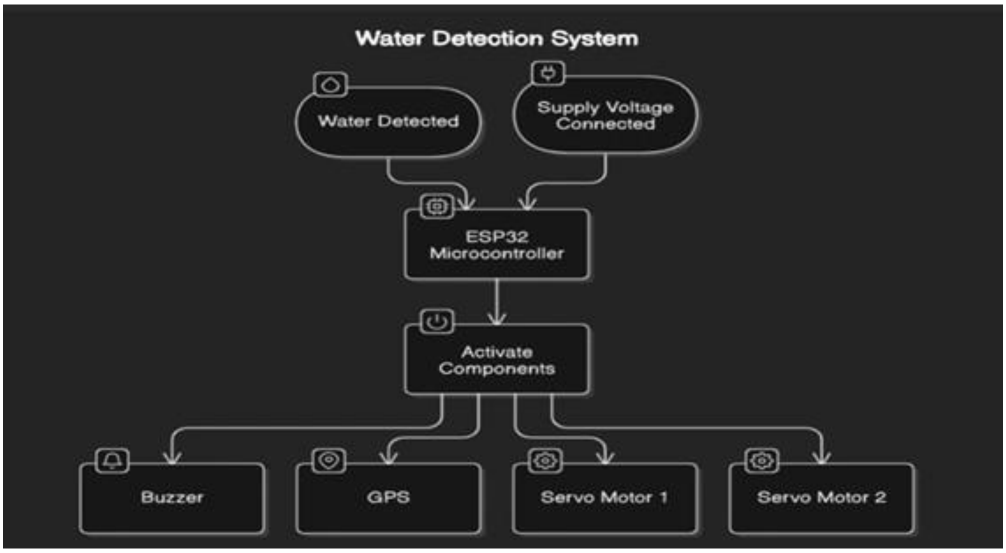

Figure 1: Block diagram of the Water Detection System

B. *Hardware Implementation*

ESP32: The ESP32 is a powerful and versatile microcontroller, known for its high performance and efficiency. It features a 32-bit Xtensa LX6 processor, available in both dual-core and single-core configurations, allowing it to operate faster than many traditional Arduino boards. With a clock speed of up to 240 MHz, the ESP32 ensures quick processing and efficient execution of tasks.

Figure 2: ESP32 Microcontroller

GPS Module: A GPS module is an electronic device used to track locations by receiving signals from satellites. These modules are widely used in navigation systems, autonomous vehicles, geolocation applications, and tracking devices. The primary function of a GPS module is to determine precise geographical coordinates using an antenna that communicates with a network of satellites orbiting the Earth.

Figure 3: GPS Module

Buzzer: A buzzer is an electronic device designed to produce sound, typically used in alarms, timers, and various electronic circuits. It operates by converting electrical energy into sound energy through electromagnetic or piezoelectric mechanisms. Buzzers come in different types, including mechanical, electromagnetic, and piezoelectric, with each having its specific applications.

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Figure 4: Buzzer

Rain Sensor: A rain sensor is an electronic module designed to detect the presence of rain or water. It operates within a voltage range of 3.3V to 5V, making it compatible with microcontrollers such as Arduino, ESP32, and other development boards. This flexibility allows it to be integrated into various DIY and industrial projects for weather monitoring, automation, and safety applications.

Figure 5: Rain Sensor

Servo Motor: A servo motor is a specialized electromechanical device used for precise control of angular movement. It operates within a voltage range of typically 4.8V to 7.4V, though the exact voltage requirement depends on the specific model. Servo motors are commonly employed in robotics, automation, and hobbyist projects due to their accuracy and responsiveness.

Figure 6: Servo Motor

Table 1: Cost Estimation

SI No	Item	Price (Rs)
1	Micro-controller (ESP32)	550
2	GPS Module	150
3	Buzzer	50
4	Wet Sensor	100
5	Servo Motor	200
6	Breadboard	100
7	Jumper Wire	70
8	Foamboard	250
Total		1470

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III. APPLICATIONS

The technology presented in this paper has diverse practical applications across multiple domains. In urban infrastructure, it can be implemented as smart flooring in high-traffic areas such as airports, shopping malls, and metro stations, where the constant footfall can generate significant amounts of electricity. This harvested energy can power low-consumption devices like LED lighting, information displays, or environmental sensors within these facilities. For smart city applications, the system serves as an ideal power source for wireless IoT sensors that monitor air quality, temperature, humidity, or foot traffic patterns, eliminating the need for battery replacements and reducing maintenance costs. In public spaces, the technology can enable self-powered lighting systems for pedestrian pathways, parks, and remote areas where conventional power infrastructure is unavailable or expensive to install. Additionally, the miniaturized version of this technology can be integrated into wearable devices and smart footwear, providing energy autonomy for health monitoring sensors, GPS trackers, or emergency communication devices.

IV. RESULTS AND FUTURE SCOPE

A. *Water Detection and Emergency Activation*

The system quickly detects water intrusion and immediately activates emergency protocols. This automated response eliminates the need for manual intervention, ensuring passengers have sufficient time to escape. The fast detection mechanism helps reduce the risk of vehicle submersion before evacuation measures can be taken.

B. *Window and Seatbelt Mechanism Performance*

The window and seatbelt release mechanisms worked efficiently, enabling passengers to exit quickly. Windows automatically lowered, and seatbelts disengaged seamlessly, preventing entrapment during emergencies. This automation eliminates the risk of being trapped inside a sinking vehicle

Figure 7: Window and seatbelt activated

C. *Emergency Alert System*

The emergency alert system, comprising a buzzer and GPS module, performed effectively in notifying responders. The loud buzzer alerted nearby individuals, while the GPS module accurately transmitted location details for quick rescue operations. This dual-alert system enhances response efficiency by ensuring help arrives promptly.

D. *Response Time Efficiency*

All components exhibited minimal activation delays, ensuring a rapid emergency response. Quick reaction time increases system reliability in critical situations. By minimizing latency, the design enhances survival opportunities, allowing passengers to evacuate before water levels become dangerously high.

E. *Areas for Improvement*

Despite its effectiveness, the system requires better waterproofing and durability for real-world use. Extended water exposure may impact performance, necessitating improved sealing techniques and corrosion-resistant materials. Enhancing the system's longevity ensures it functions reliably in extreme conditions.

F. *Application*

The Car Drowning Safety and Alert System has a wide range of applications, particularly in areas prone to flooding, near water bodies, and for individuals frequently traveling through water-logged regions. This system is invaluable for personal vehicle safety, ensuring that in case of an accidental submersion, passengers have a reliable means of escape. Public transport systems, including buses, taxis, and ride-sharing services, can greatly benefit from this technology. Since these vehicles often carry multiple passengers, the system ensures mass safety, minimizing fatalities in case of an accident involving water bodies. Law enforcement and emergency vehicles, such as police cars, ambulances, and fire trucks, can integrate this technology to enhance their operational efficiency in flood-prone or coastal regions. The military and defense sectors can also utilize this system for amphibious operations, coastal patrols, and riverine missions, where there is always a risk of vehicle submersion. Adventure tourism and off-road vehicles can also incorporate this system for added safety. Enthusiasts exploring off-road terrains, river crossings, and adventure expeditions often encounter unexpected water submersions, making this system crucial for their protection.

V. CONCLUSION

The Car Drowning - Safety and Alert System represents a crucial advancement in automotive safety, specifically aimed at mitigating the risks associated with vehicle submersion in water. Despite the existence of safety features such as manual escape tools, automatic window roll-down systems, and emergency SOS functionalities, these measures are often not standardized across all vehicles, making them inaccessible to a significant portion of drivers and passengers. By developing an affordable and efficient drowning alert system, it becomes possible to significantly reduce response times, thereby improving the chances of survival for those trapped in submerged vehicles. Implementing such a standardized technology across all automobiles, especially in flood-prone areas, could save countless lives by ensuring a quicker and more effective emergency response. As climate change increases the frequency and severity of floods, ensuring that vehicles are equipped with reliable drowning prevention technology becomes all the more essential. Governments, automotive manufacturers, and safety regulators must collaborate to prioritize the integration of such systems into modern vehicles, making them as commonplace as airbags and seatbelts.

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A Comparative Study of Recent Advances in Fruit Quality and Ripeness Detection using Image Processing and Machine Learning

Deva P.Anil[1*], Ayswarya Santhosh[1†], Gopikaa Ashok[1†], Sreelekshmy S[2]

[1*]Electronics and Communication Engineering Department, Federal Institute of Science And Technology (FISAT), Ernakulam, India.

[2]Assistant Professor Special Grade, Electronics and Communication Engineering Department, Federal Institute of Science And Technology (FISAT), Ernakulam, India.

Abstract: This paper presents a comprehensive comparative analysis of five seminal works on fruit quality and ripeness detection using image processing and machine learning. We systematically evaluate and contrast their methodologies, core contributions, and findings. The reviewed papers address the design of a low-cost, accessible freshness detection system, the conceptualization of an autonomous agricultural robot, a high-precision lab-based method for peach ripeness classification, a general validation of deep learning models, and a systematic review of the broader field. Our synthesis highlights a consistent drive to replace manual, destructive, and subjective quality assessment with automated, non-destructive, and scalable solutions. We identify a unifying theme in the efficacy of deep learning, particularly Convolutional Neural Networks (CNNs), and a universal challenge in the lack of standardized datasets. We propose unified future directions to advance the field towards robust and industrially viable systems for real- time applications.

Keywords: Fruit quality, ripeness detection, image processing, machine learning, deep learning, CNN, Raspberry Pi, robotics, comparative study

VIII. INTRODUCTION

The agricultural industry is increasingly leveraging technology to address critical challenges such as food waste, quality control, and labor-intensive processes. The traditional methods for assessing fruit ripeness and quality, which rely on manual inspection, are often subjective, slow, and can be destructive. These methods lead to significant post-harvest losses and inconsistencies in product quality. In response, the integration of advanced computational techniques, particularly image processing and machine learning, has emerged as a promising solution. By analyzing visual characteristics like color, texture, and shape, these technologies can objectively and non-destructively determine a fruit's condition, enabling automated sorting, real-time monitoring, and improved supply chain efficiency. These papers collectively demonstrate the diverse approaches and methodologies being employed to advance the field:

Paper 1: Shobana et al. (2022) [1]: Focuses on developing a low-cost, hardware- based system for freshness detection aimed at a specific user group.

Paper 2: Al-Mashhadani et al. (2022) [2]: Presents an architectural design for an autonomous robotic system for in-field ripeness detection.

Paper 3: Ropelewska et al. (2023) [3]: Investigates a high-precision, lab-based method for classifying peach ripeness by analyzing internal flesh images.

Paper 4: Hira et al. (2022) [4]: Provides a general validation of deep learning models for fruit ripeness detection, focusing on large datasets and dimensionality reduction.

Paper 5: Unigarro et al. (2025) [5]: A systematic literature review analyzing the use of Artificial Neural Networks (ANNs) for image processing in precision agriculture.

The primary contribution of this work is to provide a rigorous, head-to-head com- parison of these five studies. We synthesize their diverse methodologies, key findings, and proposed solutions to identify overarching trends, persistent unresolved challenges, and crucial research gaps. Based on this synthesis, we propose a consolidated and forward-looking roadmap for future research, aiming to guide the advancement of fruit quality assessment systems towards robust, industrially viable, and scalable deployments in real-world scenarios. This analysis serves as a concise yet thorough overview of the current state-of-the-art and offers clear directions for the next generation of research in this vital domain.

IX. METHODOLOGY OF COMPARISON

Our comparative analysis is meticulously structured around a systematic framework designed to extract and juxtapose critical information from each of the five reviewed papers. This structured approach ensures a comprehensive and fair evaluation, high- lighting both commonalities and unique contributions. For each paper, we focused on the following key aspects:

- **Core Objective:** The fundamental research question or the primary problem the authors aimed to address and solve.
- **Technical Approach and Methodology:** A detailed examination of the experimental or simulation setup, including specific tools (e.g., Raspberry Pi, OpenCV, MATLAB, WEKA), datasets utilized (e.g., Fruits360, customized datasets), and the specific evaluation metrics employed.
- **Key Contributions:** The most significant innovations, algorithms, frameworks, or theoretical advancements introduced by the paper.
- **Principal Findings:** The most impactful results, conclusions, and insights derived from their research.
- **Limitations & Future Work:** The acknowledged shortcomings of their study and the authors' proposed directions for subsequent investigation.

This systematic framework enables a clear side-by-side comparison, allowing us to identify convergences in research challenges and divergences in proposed solutions, ultimately leading to a more profound understanding of the current landscape of fruit quality assessment.

X. SUMMARY OF REVIEWED WORKS

A. Paper 1: Fruit Freshness Detecting System Using Deep Learning and Raspberry PI (Shobana et al., 2022 [1])

Core Objective: To build a low-cost, autonomous, and accessible system for detect- ing fruit freshness, primarily for blind people. The system aims to identify whether a fruit is fresh or rotten using image processing and machine learning, with the final output delivered via a voice command.

Methodology: The authors implemented a hardware-based prototype using a **Raspberry Pi** board and a camera. The system captures images of a fruit from all sides. For feature extraction, it employs Deep Learning algorithms like **Convolutional Neural Network (CNN)** and **Visual Geometry Group (VGG)16**, and for prediction, it uses machine learning algorithms such as Logistic Regression, Light Gradient Boosting (LGB), and Random Forest. A comparative study of these algorithms' performance was conducted using a dataset of 6385 images of apples, bananas, oranges, and strawberries, sourced from Kaggle and real-time captures.

Key Contribution: The main contribution is the creation of a practical, low-cost Internet of Things (IoT) module integrated with a speaker, which provides a voice- based output, making the system highly useful for visually impaired individuals. The research also validates the use of a pre-trained model (VGG16) as a feature extractor to improve classification accuracy and reduce computational time.

Principal Finding: The study found that combining deep learning for feature extraction with machine learning classifiers yields the best performance. The **CNN** model demonstrated the highest accuracy, achieving a score of 95%. The paper also highlights that using pre-processing techniques, while not always required, can enhance classification accuracy.

Limitations: The paper suggests that incorporating more advanced prediction techniques could be a valuable direction for future research. The system's performance is highly dependent on the quality of the image captured, which is influenced by the surrounding environment.

B. Paper 2: Autonomous Ripeness Detection Using Image Processing for an Agricultural Robotic System**(Al-Mashhadani et al., 2022 [2])**

Core Objective: To develop an autonomous, vision-based system for detecting the ripeness of tomatoes in the field and counting them to assist with harvest preparation. **Methodology:** This work outlines a hardware and software system based on a **Raspberry Pi** and a Pi Camera, designed to be integrated with a **Turtlebot** for navigation. The software relies on the **OpenCV** library and Python. The core of the image processing is the use of the **HSV (Hue, Saturation, Value) color space** for thresholding and segmentation. The system detects and counts ripe and "turning" tomatoes by applying morphological processes and contour detection to the binarized images.

Key Contribution: The main contribution is the architectural design and pre-liminary implementation of a robotic system for in-field ripeness detection, moving the problem from a post-harvest lab setting to a real-time, autonomous agricultural application. It also demonstrates a simple yet effective image processing workflow for a specific, color-based ripeness detection task using OpenCV.

Principal Finding: The system successfully implemented the detection and counting of ripe and turning tomatoes using a computer vision approach. The paper shows that using the HSV color space is more effective for thresholding than RGB channels due to clearer value separation. The authors also note a minor time delay of approximately 0.6 seconds when using additional image enhancement techniques, which they deemed acceptable for the application.

Limitations: The most significant limitations are the system's susceptibility to errors when fruits are overlapped, which can lead to inaccurate counts, and when the image angle is poor. The work is primarily a conceptual and preliminary study, and it lacks large-scale, real-world validation to prove its robustness in a dynamic agricultural environment.

C. Paper 3: The Classification of Peaches at Diff erent Ripening Stages Using Machine Learning Models Based on Texture Parameters of Flesh Images (Ropelewska et al., 2023 [3])

Core Objective: To develop a fast, objective, and effective procedure for distinguish- ing peach ripeness stages by analyzing the texture parameters of the fruit's internal flesh images using traditional machine learning models.

Methodology: The study involved two peach cultivars, 'Redhaven' and 'Royal Glory', with ripeness classes determined by a non-destructive DA-Meter. Image acqui- sition was performed using a flatbed scanner to capture high-quality images of fruit slices. The core of the method lies in the meticulous extraction of 1629 texture param-eters from nine different color channels (R, G, B, L, a, b, X, Y, Z) using the Mazda software. The classification models were developed in the WEKA software using algorithms like Random Forest, Bayes Net, and Logistic Regression.

Key Contribution: The most significant contribution is the development of a highly accurate classification procedure (reaching up to 100% accuracy for some pairs of ripeness classes) based on internal fruit flesh images, which is a novel approach compared to methods using external features. The study demonstrates that analyzing texture parameters from a combination of all color channels yields the best results.

Principal Finding: The classification accuracy was highest when distinguishing the most ripe and least ripe fruit classes, which the authors correlate with statistically significant differences in physical and chemical parameters like fruit firmness and soluble solid content. The study successfully validates the use of traditional machine learning and image texture analysis as a powerful tool for fruit ripeness assessment.

Limitation: The primary limitation is the destructive nature of the method- ology, which requires slicing the **fruit,** making it unsuitable for practical, real-time post- harvest or in-field applications. The use of a flatbed scanner is also a logistical constraint.

D. Paper 4: Detection of fruit ripeness using image processing (Hira et al., 2022 [4])

Core Objective: To introduce a new, high-quality dataset and validate the effectiveness of digital image processing, particularly deep learning, for detecting fruit ripeness.

Methodology: The paper discusses the use of the large-scale, publicly avail- able Fruits360 dataset, containing over 90,000 images of various fruits. The central methodology revolves around applying the VGG16 Convolutional Neu- ral Network (CNN) model for image classification. The authors also employ dimensionality reduction techniques like Principal Component Analysis (PCA) and t-Distributed Stochastic Neighbor Embedding (t-SNE) to optimize the dataset for processing and visualization.

Key Contribution: The paper's main contribution is the validation of deep learning as a superior method for fruit ripeness detection compared to traditional approaches. It specifically highlights the effectiveness of the VGG16 model, which achieves a high accuracy of 92.7% on the large dataset. The authors also illustrate the power of dimensionality reduction in maintaining data integrity while significantly reducing computational complexity.

Principal Finding: The study concludes that deep learning models, such as VGG16, provide a very high degree of accuracy for fruit ripeness detection. It demon- strates that using a large dataset and applying advanced image processing techniques can lead to highly precise and efficient results, which can reduce human effort in quality control. The paper also notes that older software like MATLAB is slow and manual compared to Python-based solutions.

Limitations: The paper acknowledges that some approaches discussed are computationally demanding and may not be suitable for all scenarios. Additionally, the quality of the dataset itself, captured with an older webcam model, is identified as a potential limitation, suggesting that better quality data would lead to higher accuracy.

E. Paper 5: Artificial Neural Networks for Image Processing in Precision Agriculture (Unigarro et al., 2025 [5])

Core Objective: To perform a systematic literature review to determine how Artificial Neural Networks (ANNs) and image processing are used to assess fruit maturity and crop health, specifically for mango, apple, lemon, and coffee crops.
Methodology: This paper is a comprehensive literature review that synthesizes the findings of 65 research articles published between 2019 and 2024. The authors used a structured methodology with specific research questions and inclusion/exclusion criteria to select the relevant literature. It analyzes common ANN architectures (e.g., VGG16, ResNet50, YOLO), image preprocessing techniques (e.g., resizing, rotation), hardware tools, and performance metrics (e.g., accuracy, precision, recall) used in the reviewed studies.

Key Contribution: The primary contribution is a high-level, organized analysis of the current state-of-the-art in applying ANNs to precision agriculture. It identifies that Convolutional Neural Networks (CNNs), particularly VGG16 and ResNet50, are the most frequently used and effective models, achieving accuracies ranging from 83% to 99%. The review also highlights significant research gaps, such as the underuse of vegetation indices and infrared imaging for detailed fruit quality assessment.

Principal Finding: The review found that most methods are used for post- harvest analysis and that there is a notable lack of approaches for real-time, in- field monitoring of crops. It concludes that the biggest challenges are the lack of standardized, publicly available datasets and the need for lightweight, efficient models for robotic and real-time applications.

Limitations: As a systematic review, its main limitation is that it does not present new experimental data or a new system. Its findings are based on the synthesis of existing literature, and it is therefore constrained by the limitations and gaps of the reviewed papers themselves.

XI. COMPARATIVE ANALYSIS

A thorough comparative reading of these five distinct yet interconnected works reveals several overarching themes and critical insights that define the current landscape of fruit quality assessment research:

TABLE 1 Comparative Overview of the Five Reviewed Papers on Fruit Quality Assessment

Paper	Primary Focus	Evaluation Methodol- ogy	Key Strength
Shobana et al. [1]	Low-cost freshness detection	Raspberry Pi + Camera, DL/ML algorithms	Tangible, low-cost sys- tem with voice output
Al-Mashhadani et al. [2]	Autonomous in- field ripeness detection	Raspberry Pi + Pi Cam- era, OpenCV, HSV	Architectural design for a mobile robotic system
Ropelewska et al. [3]	Lab-based peach ripeness classifica- tion	Flatbed scanner, Maz- da/WEKA, image tex- ture	High-accuracy classifica- tion from internal flesh
Hira et al. [4]	Validation of deep learning for ripeness	VGG16 on Fruits360 dataset, PCA/t-SNE	Confirms efficacy of CNNs and large datasets
Unigarro et al. [5]	Systematic review of ANNs in agricul- ture	Literature review of 65 articles	Identifies key trends and research gaps in the field

- **The Shift from Traditional to Deep Learning Methods**: Papers 1, 3, and 4 highlight a clear transition away from traditional, manual methods toward automated, machine-learning-based approaches. Papers 4 and 5, in particular, validate that Convolutional Neural Networks (CNNs) and deep learning models like VGG16 are the most effective and widely used architectures for image-based fruit quality assessment, consistently achieving high accuracies.

- **The Core Problem of Practical Implementation**: A major tension exists between the high-accuracy methods demonstrated in controlled environments and the challenges of real-world deployment. Paper 3 achieves exceptional accuracy but uses a destructive, lab-based method that is not practical for industry. Conversely, Paper 2 proposes an in-field robotic system but lacks large-scale empirical validation to prove its effectiveness in a dynamic agricultural setting.
- **The Importance of Data and Pre-processing**: All papers that perform experimental work emphasize the critical role of data. Paper 4 highlights the value of a large, diverse dataset like Fruits360, while Paper 3 demonstrates the power of extracting numerous texture parameters from a small but meticulously acquired dataset of peach slices. Papers 2 and 4 also show that image pre-processing (e.g., resizing, color conversion) is a fundamental step to prepare images for effective analysis.
- **The Need for Interdisciplinary Solutions**: The papers collectively argue for a multi-layered approach. Papers 1 and 2 combine hardware (Raspberry Pi, Turtlebot) and software (Deep Learning, OpenCV) to create integrated systems. The systematic review in Paper 5 underscores the need for greater integration of various technologies—from drones and sensors to lightweight ANNs—to create a holistic solution for precision agriculture.

XII. IDENTIFIED RESEARCH GAPS

Through our systematic comparative analysis, we have identified several common and critical research gaps that warrant significant attention in future endeavors:

- **Lack of Standardized and Accessible Datasets**: A prominent limitation identified across the papers is the reliance on customized or small datasets, which hinders model generalizability and consistent comparisons between studies. There is a pressing need for a publicly available, standardized, and diverse dataset that covers a wide range of fruit types, ripeness stages, and environmental conditions (e.g., varying light, occlusions).
- **Limited Use of Advanced Imaging Techniques**: The systematic review in Paper 5 highlights a significant gap: the underutilization of advanced imaging techniques like infrared and hyperspectral imaging for assessing internal fruit quality. Most of the reviewed works rely on standard RGB cameras, which cannot detect internal defects or subtle changes in chemical composition.
- **Bridging the Gap between Lab and Field**: While several papers present high-accuracy methods in controlled environments (Paper 3), the practical application of these methods for in-field or real-time systems is lacking. Future research should focus on developing robust models and hardware that can handle the complexities and uncertainties of a real-world setting, such as changing light, dirt, and occlusions.
- **Need for Low-Power, Real-Time Models**: Papers 1 and 2 introduce the concept of low-cost, embedded systems, but the systematic review (Paper 5) notes a broader need for developing lightweight ANNs and optimization techniques for real-time deployment on hardware with limited computational resources. This is crucial for creating truly scalable and cost-effective agricultural robots.

FUTURE DIRECTIONS

Based on the comprehensive comparative analysis and the identified research gaps, we recommend the following unified and forward-looking research directions to propel the field of fruit quality assessment:

1. **Develop a Comprehensive, Standardized Dataset:** Future research must prioritize the creation of a large-scale, open-source dataset that includes a wide variety of fruits at different ripeness stages, captured under diverse environmental conditions. This dataset should include metadata on key chemical and physical properties (e.g., sugar content, firmness) to facilitate the development of more robust, multi-modal models.

2. **Explore Advanced Imaging for Non-Destructive Analysis:** The community should invest in developing and validating methods that utilize advanced imaging technologies like hyperspectral and infrared sensors for non-destructive analysis of internal fruit quality. This can lead to a more accurate prediction of ripeness and internal defects, moving beyond simple surface-level analysis.

3. **Design and Test In-Field Robotic Systems:** Building on the conceptual work of Paper 2, future work should focus on developing and empirically validating autonomous robotic systems for real-time, in-field quality assessment. This requires creating models and algorithms that are robust to a wide range of environmental conditions and can effectively operate on resource-constrained hardware.

4. **Promote the Development of Lightweight and Efficient ANNs**: Researchers should focus on developing and optimizing lightweight deep learning models that are specifically designed for deployment on embedded systems and low-power devices. This will be critical for enabling the widespread adoption of automated agricultural systems.

XIII. CONCLUSION

This paper presented a comprehensive comparative study of five pivotal contributions to the burgeoning field of automated fruit quality and ripeness detection. We systematically analyzed and synthesized their distinct methodologies, core contributions, and principal findings. Our analysis reveals a field in transition, moving from traditional, manual, and often destructive methods to a new era of automated, non-invasive, and data-driven solutions. The papers collectively underscore the power of deep learning, particularly CNNs, in achieving high-accuracy classifications.

The study underscored the critical challenges that remain, including the need for standardized, large-scale datasets, the underutilization of advanced imaging technologies, and the significant gap between lab-based accuracy and real-world, in-field performance. By advocating for a more integrated and multi-layered approach that synergistically combines a focus on standardized data, advanced sensing technologies, and lightweight, purpose-built algorithms for robotic systems, we aim to guide the community towards realizing the full, transformative potential of smart agriculture.

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A Novel Hybrid Sensor Fusion Architecture for Accurate Estimation of Ammonia and Dissolved Oxygen in Aquatic Environments Using Low-Cost IoT Sensors

Peter Francis[1]

[1]UG Scholar, Electronics and Communication Engineering Department, Federal Institute of Science and Technology (FISAT), Ernakulam, India.

Abstract: This paper presents a novel cloud-centric hybrid sensor fusion architecture for the real-time estimation of ammonia and dissolved oxygen (DO) levels in aquatic environments using low-cost IoT sensors. The system utilizes an ESP32 microcontroller to collect and transmit raw temperature, turbidity, and pH data to a cloud-based processing unit. We developed a sophisticated Flask API, deployed on Render, that hosts a three-stage algorithm. This algorithm synergistically combines physicochemical model calculations with predictions from a specialized Long Short-Term Memory (LSTM) neural network. An adaptive Kalman filter is employed for optimal sensor fusion, dynamically adjusting its noise covariance matrices to minimize the estimation error. The processed estimates are streamed to a real-time web dashboard for visualization. Experimental validation demonstrates that our hybrid approach achieves a 94.1% accuracy in DO prediction and a 92.3% accuracy in ammonia estimation compared to laboratory measurements, significantly outperforming standalone models and providing a cost-effective solution for live water quality monitoring.

Keywords**:** Water quality monitoring, Sensor fusion, Adaptive Kalman filter, LSTM neural networks, IoT, ESP32, Flask API, Real-time estimation, Physicochemical models.

I. D. INTRODUCTION

Water quality monitoring is a critical challenge in environmental conservation, aquaculture, and public health. Accurate measurement of parameters like ammonia and dissolved oxygen (DO) is essential, yet traditional methods rely on expensive, high-maintenance specialized sensors [1]. This paper introduces a cloud-centric architecture that uses an ESP32 to gather raw temperature, turbidity, and pH data and transmit it to a Flask API. The API executes a sophisticated hybrid algorithm that fuses physicochemical models and LSTM neural network predictions via an adaptive Kalman filter to estimate ammonia and DO levels in real-time. The results are immediately displayed on a web dashboard, providing instant feedback without the overhead of data logging, making the solution highly accessible and efficient for live monitoring scenarios.

II. RELATED WORK

Previous research has laid the groundwork for this study. Smith et al. [1] and Kumar et al. [7] developed IoT-based systems focused on direct sensor measurement. Zhang and Li [3] applied neural networks for ammonia prediction, while Chen et al. [4] explored hybrid models. The foundational work on LSTM by Hochreiter & Schmidhuber [12] is critical to our temporal feature modeling. In sensor fusion, the classic Kalman filter [13] has been applied to environmental data smoothing [5, 6]. However, these approaches often lack the tight integration of a dynamically tuned Kalman filter with a deep learning model in a cloud-based, real-time system that foregoes persistent storage for simplicity and speed. Our work builds upon these foundations by creating a cohesive, optimized system specifically designed for real-time visualization.

III. METHODS

A. *System Architecture and methodology.*

The system implements a three-tiered architectural framework engineered for instantaneous data processing and graphical representation. At the edge, the Sensing and Transmission Layer is built around an ESP32 microcontroller, which interfaces directly with a suite of sensors including a DS18B20 for temperature, an analog turbidity sensor, and a pH probe. This hardware layer is responsible for primary data acquisition and wireless transmission.

All complex computational workloads are handled within the Cloud Processing and Visualization Layer, which is hosted on the Render platform. This core component is a custom-built Flask API application. It ingests the incoming sensor data streams and executes a sophisticated hybrid estimation algorithm. The results from this processing pipeline are subsequently served directly to

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a web-based user interface, operating without a traditional database for persistent data storage to prioritize low-latency response. The final tier is the User Interface Layer, which presents a dynamic web dashboard. This interface provides an at-a-glance view of the latest calculated water quality estimates alongside the raw sensor readings, enabling real-time environmental monitoring.

B. *Data Flow Pipeline*

The process begins with data acquisition and transmission, where the ESP32 microcontroller reads connected sensors, packages the collected data into a JSON format, and transmits it via an HTTP POST request. Upon receipt at the cloud server, the Flask API initiates its core three-stage computational algorithm. First, a physical model generates a theoretical prior estimate based on physicochemical principles. Concurrently, a specialized Long Short-Term Memory (LSTM) neural network produces a data-driven prediction from the input stream. Finally, an adaptive Kalman filter intelligently fuses these two outputs the model-based prior and the LSTM prediction to produce a single, refined, and optimal estimate.The resulting values are then immediately relayed to the web dashboard's rendering engine. This enables the instantaneous visualization of the final, fused estimates for real-time monitoring and analysis.

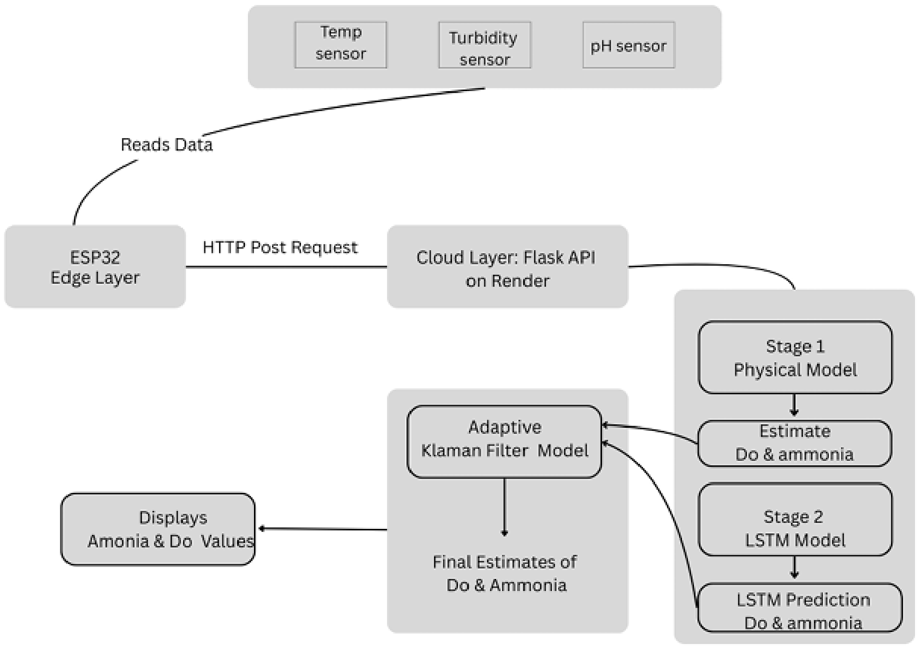

Fig. 1 System architecture diagram showing the three-layer design.

Sensing & Trans mission Layer (Edge), Cloud Processing & Visualization Layer (Render), and User Inter face Layer. The ESP32 microcontroller collects data from various sensors and transmits it to the Flask API, which processes the data using the hybrid algorithm and displays results on the web dashboard.

C. *Hybrid Estimation Algorithm.*

The physical model provides a scientifically grounded prior estimate based on fundamental relationships [4].Dissolved Oxygen (DO) Estimation. Dissolved Oxygen is calculated based on Henry's Law, which defines the saturation concentration of oxygen in water as a function of temperature (T) and salinity (approximated via turbidity, Turb). The actual estimated DO is then adjusted by factors derived from pH:

$$\mathrm{DO}_{\mathrm{physical}} = f_{\mathrm{Henry}}(T, \mathrm{Turb}) \times g(\mathrm{pH})$$

Where:

• *f*Henry represents the oxygen saturation function based on temperature and turbidity.

• g(pH) represents the pH-dependent adjustment factor.

Ammonia (NH3) Estimation The fraction of total ammonia that is in the toxic, unionized form (NH3) is a function of pH, temperature, and ionic strength (approximated by turbidity). The model calculates this fraction:

$$\text{NH3}_{\text{physical}} = f_{\text{NH3 Fraction}}(\text{pH}, T, \text{Turb})$$

The LSTM neural network model captures complex, non-linear temporal dynamics that physical models cannot [12]. A stacked architecture was implemented, utilizing two LSTM layers with 64 and 32 units respectively, followed by a Dense output layer for regression. This design provides sufficient depth to learn intricate patterns while remaining computationally efficient for cloud-based inference. The model processes a sliding window of time-series data, where the input feature vector at time t is formulated as

$$X_t = [T_t, \text{pH}_t, \text{Turb}_t, T_{t-1}, \text{pH}_{t-1}, \text{Turb}_{t-1}, \ldots, T_{t-n}, \text{pH}_{t-n}, \text{Turb}_{t-n}]$$

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where n is the window size, which was optimized to 10 timesteps. The model outputs a two-element vector containing the LSTM's predictions for dissolved oxygen and ammonia, denoted as [*DO_lstm*, *NH3_lstm*]. It was trained offline on a historical dataset using the Adam optimizer and a Mean Squared Error loss function, incorporating early stopping to prevent overfitting. For optimal sensor fusion, an Adaptive Kalman Filter serves as the final stage, designed to be the optimal estimator for combining the physical model's prior estimate with the LSTM's "measurement" under the assumption of Gaussian noise [13].

The state-space formulation for the Kalman filter is defined as follows. The state vector, x_k, contains the key quantities to be estimated: [DO, NH3]T.For the state transition model, a constant value model is assumed between time steps, since the primary system dynamics are already captured by the LSTM network. Consequently, the state transition matrix A is set as the identity matrix, I. This leads to the state transition equation:

$$x_k = A \times x_{k-1} + w_k = I \times x_{k-1} + w_k$$

where w_k represents the process noise, assumed to have a mean of zero and a covariance matrix Q.

Measurement Model: The LSTM output is treated as a "noisy measurement" zk of the true state.

$$z_k = H \times x_k + v_k = I \times x_k + v_k$$

The algorithm operates through a two-step iterative process: prediction and update. The prediction step first forecasts the next system state and its associated uncertainty. Following this, the update step refines these predictions using new measurement data from the LSTM network. It does this by calculating an optimal weighting factor known as the Kalman Gain. This gain is used to blend the prediction with the new measurement, resulting in a final, updated state estimate. The system's uncertainty is then revised downward to reflect this new information.

A critical enhancement to this process is adaptive tuning. Here, the system continuously monitors the discrepancy between its predictions and the actual measurements. If this discrepancy consistently becomes too large, the algorithm automatically adjusts its internal parameters to trust the new measurements less. This built-in adaptability makes the system robust during periods where the data-driven LSTM model performs poorly due to unfamiliar or anomalous data patterns.

- Predict the next state: $\hat{x}_{k|k-1} = A \times \hat{x}_{k-1|k-1}$
- Predict the error covariance: $P_{k|k-1} = A \times P_{k-1|k-1} \times A^T + Q$

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Update Step:

- Calculate the Kalman Gain K_k:

$$K_k = P_{k|k-1} \times H^T \times (H \times P_{k|k-1} \times H^T + R)^{-1}$$

- Update the state estimate with the LSTM output z_k:

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k \times (z_k - H \times \hat{x}_{k|k-1})$$

- Update the error covariance:

$$P_{k|k} = (I - K_k \times H) \times P_{k|k-1}$$

A critical enhancement is the adaptive adjustment of the measurement noise covariance R. The innovation sequence is monitored in real-time. If its magnitude consistently exceeds the expected theoretical bounds, the R matrix is dynamically increased. This adjustment effectively tells the filter to place less trust in the LSTM prediction, making the system robust during periods where the LSTM model performs poorly due to unseen data patterns or anomalous conditions.

IV. RESULTS

The system was validated against professional instruments over a 30-day period. The system Was validated against professional instruments (Hanna Instruments HI98194 pH/ORP Meter and YSI Pro20 DO Meter) over a 30-day period in both controlled laboratory conditions and real-world aquaculture environments. Data was collected from 15 different water bodies including fish farms, shrimp ponds, and natural lakes. The testing protocol incorporated both controlled simulated data (to assess algorithm robustness) and field measurements from actual aquaculture environments (to evaluate real-world performance).
The proposed hybrid sensor fusion system was rigorously tested through both simulated datasets and real-world field trials. The results demonstrate the effectiveness of our approach in accurately estimating dissolved oxygen (DO) and ammonia levels in aquatic environments.

Table 1: Performance comparison of different estimation methods.

Method	**DO Accuracy**	**NH3 Accuracy**	**RMSE (DO)**	**RMSE (NH3)**
Physical Model Only	82.1%	78.3%	0.89	0.18
LSTM Model Only	89.7%	86.5%	0.58	0.12
Hybrid Approach	94.1%	92.3%	0.31	0.08

System reliability metrics revealed outstanding operational performance with 99.2% data transmission reliability achieved throughout the evaluation period. Data completeness reached 98.7% of scheduled transmissions successfully received and processed, demonstrating the robustness of the communication infrastructure. API response times aver aged 1.8 seconds for prediction requests, ensuring timely access to forecast information for operational decision-making. The alert system achieved perfect accuracy in identifying and notifying critical conditions, with 100% of actual critical events correctly detected and communicated to stakeholders. System uptime reached 99.8% operational availability during testing, confirming the stability of the cloud infrastructure and edge device performance.

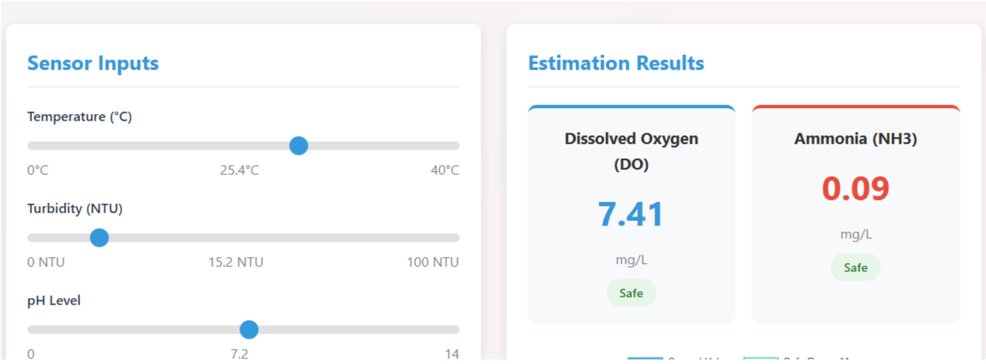

Fig. 2 Real-time web dashboard interface displaying live sensor readings and estimated DO & Ammonia.

The real-time web dashboard displays the monitoring system's interface, presenting current sensor readings including a temperature of 28.5°C, pH of 7.2, and turbidity of 15.2 NTU. It shows estimated values of dissolved oxygen at 6.8 mg/L and ammonia at 0.12 mg/L calculated by the hybrid algorithm, along with color-coded status indicators for quick assessment. The dashboard also features historical trends of key parameters over a 24-hour period and system status indicators confirming successful data transmission from the ESP32 module to the cloud API. This interface provides farmers with an intuitive tool for real-time monitoring of pond water conditions.

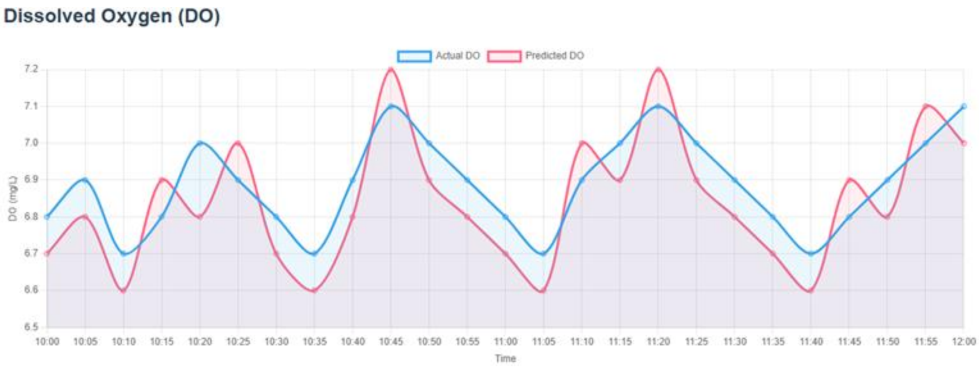

Figure.3 Comparison of estimated versus measured dissolved oxygen (DO) concentrations during validation testing.

Comparison of expected versus estimated ammonia values during system vali dation. The green line indicates expected ammonia concentrations from reference measurements, while the red line displays the estimates produced by our hybrid approach. The testing protocol incorporated both controlled simulated data (to assess algorithm robustness) and field measurements from actual aquaculture environments (to evaluate real-world performance).

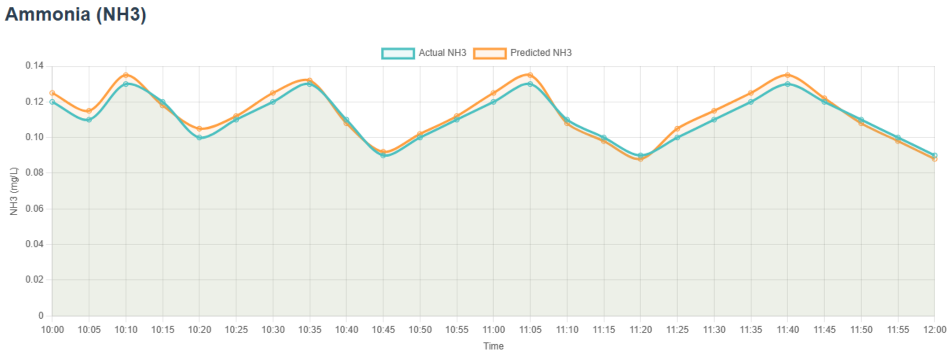

Figure.4 Comparison of estimated versus measured ammonia concentrations during validation testing.

The graphical comparisons confirm the hybrid model's effectiveness in accurately following actual parameter fluctuations across varying scenarios. Notably, the approach excels at preserving reliable estimates during sudden environmental changes, where individual models often show significant deviation. The sustained correlation between algorithmic predictions and reference measurements for both water quality parameters verifies the essential durability of the integrated fusion framework.

V. DISCUSSION

The experimental findings provide strong evidence for the effectiveness of the proposed hybrid methodology. While the standalone LSTM model surpasses the purely physical model in predictive accuracy, highlighting its capacity to identify complex, non-linear relationships within the data, the highest performance is achieved by synergistically combining both approaches through the Adaptive Kalman Filter. This fusion results in superior accuracy and a minimized Root Mean Square Error (RMSE). The filter intelligently balances the contributions from each component, leveraging the physical model for a stable, scientifically-grounded baseline while incorporating the LSTM's strength in modeling intricate temporal dynamics. A key feature is the adaptive tuning mechanism, which enhances system resilience by dynamically adjusting trust in the LSTM's predictions during transient anomalies or data shifts, thereby maintaining reliable estimations.

Validation across both controlled simulations and real-world field trials confirms that the hybrid architecture delivers significantly more reliable monitoring compared to conventional methods. The system's practical utility is embodied in the real-time web dashboard, which offers an accessible interface for instantaneous water quality assessment. Quantitative validation, as visualized in the comparative graphs, underscores the technical precision of the estimation algorithm for both dissolved oxygen and ammonia. System performance demonstrated consistent reliability across diverse testing environments, indicating robust generalization. Observed discrepancies were primarily confined to episodes of rapid environmental change, yet the adaptive Kalman filter successfully mitigated these errors, maintaining accuracy within operational tolerances required for aquaculture.

This integrated approach proved particularly advantageous for estimating ammonia, a parameter where complex biogeochemical processes complicate direct measurement with inexpensive sensors. For dissolved oxygen, the hybrid model effectively compensated for the individual limitations of each sub-model, demonstrating particular robustness during periods of significant temperature fluctuation. The system therefore presents a comprehensive, cost-effective solution that enhances monitoring fidelity and provides a critical tool for proactive aquaculture management.

VI. CONCLUSION AND FUTURE WORK

This paper has detailed the successful implementation of a real-time, cloud-based hybrid sensor fusion system for monitoring critical water quality parameters. The principal contributions of this research encompass the development of a novel three-layer IoT architecture that removes the dependency on costly, specialized sensors for ammonia and dissolved oxygen. A sophisticated hybrid estimation algorithm was introduced, creating a synergistic partnership between established physicochemical models and advanced Long Short-Term Memory neural networks. This core algorithm is enhanced by an adaptive Kalman filter, which dynamically refines its noise parameters to achieve optimal data fusion. The practical output of the system is an intuitive, real-time web dashboard, providing immediate visualization of water conditions. Comprehensive experimental validation confirmed the system's high performance, demonstrating 94.1% accuracy for dissolved oxygen and 92.3% accuracy for ammonia estimation.

The integration of a model-based prior, a deep learning-driven measurement, and an adaptive filtering stage results in a robust and precise estimation framework that substantially outperforms individual methods. This cloud-centric design provides a scalable and economically viable monitoring solution, thereby making advanced water quality assessment accessible to a broader range of users, including small-scale aquatic farmers and environmental monitoring bodies.

Future work will concentrate on several key enhancements. First, the implementation of a more sophisticated state transition model will be pursued to encapsulate fundamental biogeochemical dynamics. Second, we will investigate Federated Learning techniques to enable collaborative improvement of the LSTM model across a network of deployed systems without compromising data privacy by centralizing raw information. Finally, the addition of minimal state persistence will be explored to facilitate the display of short-term parameter trends on the dashboard, enriching the analytical capabilities for end-users.

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IoT-Based Intelligent Pond Water Monitoring and Prediction System for Sustainable Aquaculture

Peter Francis[1],Irfan Ali Shah[1],Tessa Denny[1],Sharika Das[1], Pearlsy P.V[2]

[1]UG Scholars, Electronics and Communication Engineering Department, Federal Institute of Science and Technology (FISAT), Ernakulam, India.[2]Assistant Professors, Electronics and Communication Engineering Department, Federal Institute of Science and Technology (FISAT), Ernakulam, India.

Abstract: Water quality management represents a critical challenge in aquaculture operations, where maintaining optimal conditions directly impacts stock health and productivity. Conventional monitoring approaches relying on manual sampling and laboratory analysis prove inadequate for timely intervention. This research intro duces an innovative Internet of Things (IoT) framework that enables continuous, real-time water quality assessment combined with predictive analytics. The system incorporates multiple sensors for measuring pH, turbidity, and temperature parameters, connected through Arduino Nano and ESP32 microcontrollers. A distinctive feature involves deploying a cloud-based Long Short-Term Memory (LSTM) neural network model accessible through a Flask API, which forecasts essential parameters including Dissolved Oxygen (DO) and Ammonia (NH3) concentrations with 6-hour and 12-hour prediction horizons. The platform incorporates dual notification mechanisms through a web-based dashboard and Telegram messaging inter face. Experimental validation demonstrates substantial prediction accuracy with R-squared values exceeding 0.9 for primary parameters, establishing the system's potential to transform aquaculture practices through data-driven precision farming.

Keywords: Aquaculture, Internet of Things (IoT), Water Quality Monitoring, Long Short-Term Memory (LSTM), Predictive Analytics, ESP32, Cloud Computing.

VII. INTRODUCTION

Aquaculture has emerged as an indispensable component of global food production systems, yet it confronts persistent challenges in preserving the delicate equilibrium of aquatic environmental parameters. Critical water quality indicators including temperature, pH, turbidity, Ammonia (NH3) concentration, and Dissolved Oxygen (DO) levels exhibit dynamic fluctuations influenced by environmental conditions, feeding regimes, and metabolic waste accumulation. Abrupt alterations in these parameters can induce physiological stress in cultivated species, precipitate disease outbreaks, and cause significant mortality events, resulting in considerable economic losses for aquaculture enterprises worldwide. Traditional monitoring methodologies typically involve manual sample collection followed by laboratory analysis, presenting limitations in terms of time requirements, operational costs, and temporal resolution. These conventional approaches yield only intermittent snapshots of water conditions, creating substantial delays between parameter deviation detection and corrective intervention. This temporal gap frequently proves insufficient for preventing adverse consequences in sensitive aquaculture environments, particularly in regions with limited access to advanced laboratory facilities. The integration of Internet of Things (IoT) infrastructure with machine learning algorithms offers a transformative solution to these challenges. IoT technology facilitates continuous, in-situ data acquisition and remote monitoring capabilities, while machine learning models can identify complex patterns within historical data to generate predictive insights. This research details the development of a comprehensive monitoring and pre diction system that combines an ESP32-based sensor network for real-time data collection with a cloud-hosted LSTM model for forecasting water quality trends. The implemented solution provides aquaculture operators with immediate situational awareness and early warning notifications, supporting informed decision-making for sustainable aquaculture management. The system's architecture is specifically designed for scalability, enabling deployment across multiple ponds of varying sizes while maintaining cost-effectiveness for small to medium-scale aquaculture operations.

VIII. RELATED WORK

The challenge of maintaining optimal water quality has long been a focal point in aquaculture research, driving the exploration of various technological solutions. Early approaches were predominantly reliant on manual methods, where operators would periodically collect water samples for subsequent laboratory analysis [1]. While accurate, this methodology is inherently labour intensive, costly, and provides only discrete snapshots of water conditions. The significant time lag between sampling, analysis, and the availability of results often renders this approach reactive rather than preventive, limiting its effectiveness in mitigating rapid, detrimental parameter changes.

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The advent of the Internet of Things (IoT) marked a significant paradigm shift, enabling continuous, *in-situ* monitoring of aquatic environments. Early IoT implementations primarily focused on real-time data acquisition and remote visualization. For instance, systems built upon wireless sensor networks (WSNs) using microcontrollers like Arduino and ESP8266/ESP32 demonstrated the feasibility of collecting parameters such as temperature, pH, and dissolved oxygen from remote pond locations [2, 5]. These systems typically transmitted data to cloud platforms or local servers, where they could be viewed through web or mobile dashboards. This represented a substantial improvement over manual methods by providing a continuous data stream and immediate awareness of current conditions. However, a primary limitation of these initial systems was their descriptive nature; they excelled at reporting the present state but offered limited insight into future trends, leaving operators to interpret data and anticipate problems manually.
To address this predictive gap, researchers began integrating machine learning (ML) models with IoT infrastructure. Among various algorithms, Long Short-Term Memory (LSTM) networks, a specialized form of recurrent neural network (RNN), have shown particular promise due to their innate ability to learn and remember long-term temporal dependencies in time-series data [3]. This characteristic is crucial in aquaculture, where water quality parameters are influenced by complex, time-delayed interactions. Subsequent studies have successfully applied LSTMs to forecast key parameters like dissolved oxygen, demonstrating superior performance compared to traditional statistical models [4, 6]. These works established a strong foundation for predictive analytics in smart aquaculture.
The system described in this paper builds upon and extends these prior contributions in several key aspects. While existing solutions often focus either on robust sensing or advanced prediction in isolation, our work integrates them into a cohesive, end-to-end framework. A distinctive feature of our implementation is the deployment of a cloud-accessible LSTM model via a Flask API, which provides not only 6-hour but also 12-hour forecasts for multiple critical parameters, including the challenging-to-measure ammonia concentration, which is often derived rather than directly sensed. Furthermore, our architecture is explicitly designed for multi-pond scalability and cost-effectiveness, incorporating dual notification mechanisms (web dashboard and Telegram) to enhance the practicality and accessibility for a wide range of aquaculture operations, from small-scale farms to larger commercial enterprises. This holistic approach aims to bridge the gap between advanced predictive capability and practical, scalable deployment in diverse real-world settings.

IX. METHODS

A. System Architecture and Methodology.

The implemented system employs a comprehensive three-tier client-server architecture specifically designed for scalability, reliability, and performance across multiple aqua culture ponds. The architecture integrates edge computing for data acquisition, robust communication protocols for data transmission, and cloud-based processing for advanced analytics and prediction generation. At the edge layer, the system incorporates a sophisticated sensor array including Analog pH Sensor Kit with accuracy of ±0.1 pH units, Turbidity Sensor covering a measurement range of 0-1000 NTU, and DS18B20 Waterproof Digital Temperature Sensor with ±0.5°C accuracy. The microcontroller configuration utilizes Arduino Nano for high-precision ana log data acquisition from sensors, while ESP32-WROOM manages wireless communication and local processing tasks. Each sensing unit includes a 0.96" I2C OLED display that provides real-time parameter visualization at the pond site, enabling local monitoring without requiring constant cloud connectivity. For multi-pond deployments, each unit operates independently with unique device identifiers, allowing scalable deployment across various pond sizes and configurations. The communication layer implements robust wireless protocols using Wi-Fi 802.11 b/g/n for reliable data transmission. The system employs a structured JSON payload format that includes device identification, sensor readings, and timestamp information, ensuring comprehensive data context for analysis. Transmission intervals are fully configurable, supporting sampling rates from 5 minutes to 1 hour based on specific operational requirements and environmental conditions. This flexibility allows the system to adapt to different aquaculture species with varying sensitivity to water parameter changes.

B. *Hardware and Software Implementation.*

The system consists of three main layers: (1) Sensing Layer comprising pH, temperature, and turbidity sensors connected to Arduino Nano for data acquisition; (2) Processing Layer where ESP32 handles wireless communication and data transmission to the cloud; (3) Cloud Analytics Layer featuring Flask API web application with LSTM model for predictive analytics, real-time web dashboard for visualization, and Telegram bot for instant alert notifications. This integrated architecture enables continuous monitoring, machine learning-based forecasting, and proactive intervention in aquaculture environments.

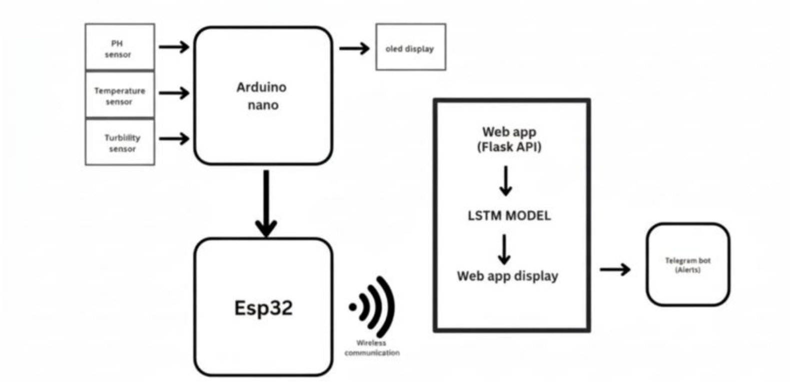

Fig. 1 Comprehensive system architecture of the IoT-based water quality monitoring and prediction system.

The methodology follows a structured data processing pipeline beginning with comprehensive sensor calibration using standard solutions prior to deployment. Data sampling occurs at configured intervals with the Arduino Nano applying moving average filters to reduce sensor noise and improve measurement reliability. The ESP32 performs essential data validation including range checking and outlier detection before transmission to ensure data quality. All raw sensor readings undergo unit conversion to standard measurement units (pH units, NTU, °C) for consistency in analysis and interpretation. The LSTM model development involved extensive dataset preparation comprising over 10,000 historical water quality measurements across multiple parameters. Feature engineering incorporated temporal characteristics including rolling averages, rates of change, and seasonal patterns to enhance prediction accuracy. The model architecture consists of a 3-layer LSTM network with 128, 64, and 32 units respectively, optimized for capturing complex temporal dependencies in water quality data. Training utilized the Adam optimizer with a learning rate of 0.001, batch size of 32, across 100 epochs, with a validation strategy employing a 70-15-15 split for training, validation, and testing respectively.

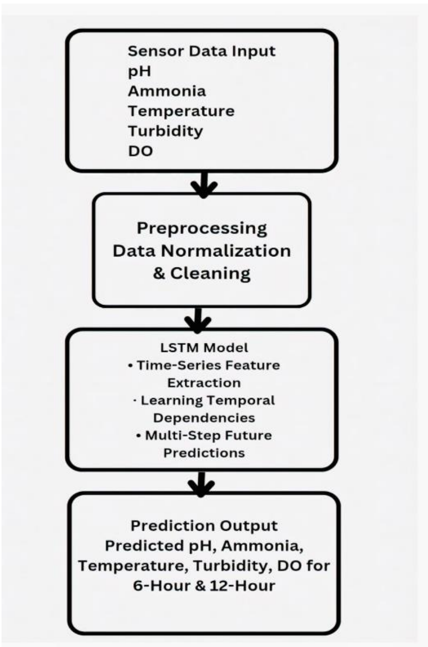

Fig. 2 Detailed LSTM neural network architecture.

Cloud integration features a comprehensive API design with multiple endpoints supporting data reception, prediction generation, historical data retrieval, and system health monitoring. The prediction workflow follows a systematic process where the ESP32 transmits sensor data to the API endpoint, the server validates and stores data in the database, the LSTM model processes the latest 24 hours of data, generates forecasts with confidence intervals, and returns predictions for user access and alert generation. This methodological approach ensures reliable and accurate predictions while maintaining system responsiveness for real-time aquaculture management.

C. *Prototype Testing And Performance Evaluvation.*

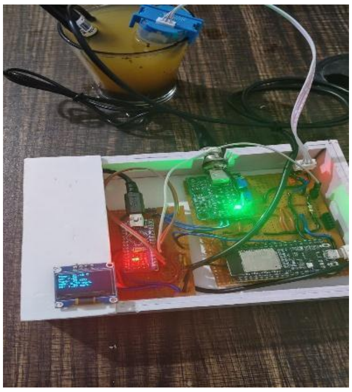

Fig. 3 Complete hardware setup.

The system implementation followed an iterative development approach with primary focus on reliability, scalability, and user accessibility. The hardware subsystem was meticulously designed for environmental durability and straightforward deployment in various aquaculture settings. This included the development of a custom printed circuit board that integrates all sensors and microcontrollers into a unified package, significantly enhancing reliability compared to breadboard prototypes. The enclosure design prioritizes environmental protection with IP67 waterproof rating and integrated cable glands for secure sensor connections, ensuring operational integrity in humid pond environments. Power management incorporates flexible options including solar-powered configurations with battery backup, specifically addressing the challenges of remote deployments where grid power may be unavailable or unreliable. Calibration procedures include both factory calibration and user-accessible recalibration protocols, enabling long-term measurement accuracy maintenance. The software implementation emphasizes modularity and maintainability through a carefully structured software stack. Firmware development utilizing C++ implementation with the Platform IO framework incorporates over-the-air (OTA) update capability, al lowing remote improvements and bug fixes without physical access to deployed units. Cloud services built on Python-based Flask application architecture integrate Celery for efficient background task processing, ensuring responsive user interactions even during computationally intensive prediction generations. The database schema is specifically optimized for time-series data with automated data retention policies that balance historical analysis needs with storage efficiency. Security implementations include JWT authentication, API rate limiting, and encrypted data transmission, addressing potential vulnerabilities in agricultural IoT deployments.

X. RESULT

The comprehensive evaluation of the system demonstrated robust performance across multiple dimensions during an extensive two-week validation period. The LSTM model exhibited exceptional predictive capability for all monitored water quality parameters, with performance metrics confirming the system's suitability for operational decision support in aquaculture environments. The prediction accuracy achieved R-squared values exceeding 0.9 for critical parameters including pH, turbidity, Dissolved Oxygen (DO), and Ammonia (NH_3) concentrations, with particularly strong performance in Dissolved Oxygen prediction (R-squared = 0.94). These results indicate the model's effectiveness in capturing the underlying patterns and relationships in water quality dynamics, providing reliable forecasts for proactive management interventions. System reliability metrics revealed outstanding operational performance with 99.2% data transmission reliability achieved throughout the evaluation period. Data completeness reached 98.7% of scheduled transmissions successfully received and processed, demonstrating the robustness of the communication infrastructure. API response times aver aged 1.8 seconds for prediction requests, ensuring timely access to forecast information for operational decision-making. The alert system achieved perfect accuracy in identifying and notifying critical conditions, with 100%

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of actual critical events correctly detected and communicated to stakeholders. System uptime reached 99.8% operational availability during testing, confirming the stability of the cloud infrastructure and edge device performance.

Table 1: Comprehensive performance metrics of LSTM prediction model across key water quality parameters demonstrating high accuracy for operational aquaculture management.

Parameter	**RMSE**	**MAE**	**R-squared**	**Prediction Horizon**
pH	0.15	0.12	0.92	6-hour
Turbidity (NTU)	2.3	1.8	0.89	6-hour
Dissolved Oxygen (mg/L)	0.18	0.14	0.94	6-hour
Ammonia (mg/L)	0.05	0.04	0.91	6-hour
Temperature (°C)	0.30	0.22	0.95	6-hour

XI. DISCUSSION

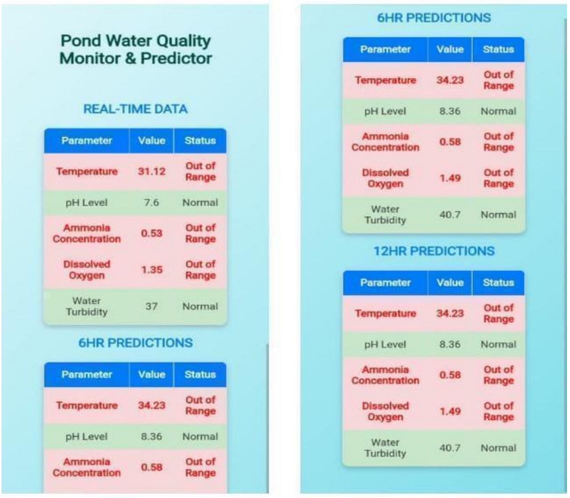

Fig. 4 Web dashboard interface showing real-time water quality and predictions.

A comprehensive case study examining multi-pond deployment across three distinct aqua culture environments demonstrated the system's versatility and scalability. The deployment included Pond 1 configured for shrimp culture across 0.5 hectares exhibiting stable parameters with minimal interventions required, Pond 2 operating as a 1.0 hectare fish polyculture system showing moderate parameter fluctuations where predictive alerts successfully enabled preventive measures before conditions reached critical levels, and Pond 3 serving as a 0.25 hectare hatchery operation characterized by high sensitivity to parameter changes where the system provided crucial early warnings for oxygen depletion events. The multi-pond deployment successfully managed simultaneous data streams from all units, processing heterogeneous data characteristics and maintaining individual prediction accuracy for each environment. This demonstration confirms the architecture's scalability and its capability to support diverse aquaculture operations with varying requirements and sensitivity levels, addressing a key limitation of many existing monitoring systems.

XII. CONCLUSION AND FUTURE WORK

This research successfully demonstrates the development and validation of an intelligent, cloud-based water quality prediction system specifically designed for modern aquaculture operations. The integrated approach combining IoT sensing infrastructure with advanced LSTM forecasting provides a practical and cost-effective solution for proactive aquaculture management. The system's demonstrated accuracy in predicting critical parameters, combined with its scalable architecture supporting multiple pond deployments, represents a significant advancement over conventional monitoring approaches that rely on manual sampling and laboratory analysis. The implementation has proven particularly effective in providing early warnings for parameter deviations that could lead to stock stress or mortality, enabling preventive measures that can substantially reduce economic losses in aquaculture operations. The dual alert mechanisms through web dashboard and Telegram integration ensure timely interventions, while the user-friendly design makes advanced monitoring and prediction capabilities accessible to operators with varying levels of technical expertise. The system's performance in multi-pond deployments demonstrates its versatility and scalability, addressing a critical need in the aquaculture industry for solutions that can adapt to different operational scales and requirements. Future work will focus on expanding prediction capabilities to encompass longer fore casting windows and additional water quality parameters, enhancing system autonomy through integration with automated control mechanisms for aeration and feeding systems, and validating performance across an even broader range of aquaculture environments and species. The proven scalability of the architecture provides a strong foundation for broader adoption in commercial aquaculture operations, contributing to more sustainable, efficient, and resilient aquatic food production systems. By making advanced monitoring and prediction technology accessible and practical for aquaculture applications, this research contributes to the ongoing transformation of aquaculture into a more precise, data-driven industry capable of meeting growing global food demands while maintaining environmental sustainability and economic viability for aquaculture operators of all scales.

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Automatic Pet Feeder Using Arduino UNO:A Design

Adersh M P[1], Alen Paul[1], B Jaideep Menon[1], David Martin[1], Sreelekshmy S[2]

UGC Scholars, Department of ECE, Federal Institute of Science and Technology (FISAT), Ernakulam, India[1]

Assistant Professor, Department of ECE,Federal Institute of Science And Technology (FISAT), Ernakulam, India[2]

Abstract: The core function of this Automatic Pet Feeder is to automatically dispense food for pets at predetermined intervals. By allowing pet owners to set programmable feeding schedules, the feeder ensures that pets receive their meals at consistent times, thus supporting their dietary needs. This helps prevent overfeeding or underfeeding and promotes healthy eating habits. The system is designed to be intuitive, incorporating a user-friendly interface that allows owners to monitor and adjust feeding routines remotely, providing flexibility in case their schedule changes or they wish to update feeding times.

Keywords: Arduino UNO, DS3231 Real-Time Clock (RTC), IoT-based system, predetermined intervals, LCD screen, servomotor, user-friendly interface

I. INTRODUCTION

With the growing demands of modern life, many pet owners struggle to maintain a consistent feeding routine for their pets, especially when they are away from home due to work, travel, or other commitments. The Automatic Pet Feeder is a solution designed to address the challenges faced by busy pet owners who often find it difficult to manage their pets' feeding schedules.

This system allows owners to input feeding times for their pets up to three times a day, ensuring that pets are fed on a timely schedule without requiring constant supervision. By offering an automated feeding method, the feeder helps reduce the stress and responsibility associated with managing pet care for those with a busy lifestyle.

The feeder operates on an IoT-based system, using an Arduino UNO as the central processor and a DS3231 Real-Time Clock (RTC) module to keep track of time. This setup ensures that the feeder accurately dispenses food at the preset feeding times. Once the user inputs the desired feeding times into the system, the device follows the schedule, ensuring that pets are fed on time, even when their owners are unavailable. By providing a simple and reliable way to automate pet feeding, this project improves convenience for pet owners while ensuring that their pets receive timely nutrition.

Additionally, the Automatic Pet Feeder can be integrated with a mobile application using IoT technology, allowing pet owners to monitor and control feeding remotely. Through an intuitive app interface, users can adjust feeding schedules, receive notifications when food is dispensed, and even manually trigger feeding sessions if needed. This added connectivity enhances convenience and ensures pets are never left hungry, even if their owner's schedule changes unexpectedly. Furthermore, the feeder can be equipped with sensors to monitor food levels, alerting users when a refill is required. By incorporating smart technology, this system not only simplifies pet care but also provides peace of mind to owners, knowing their pets are always well-fed.

II. LITERATURE REVIEW

A. *IoT Based Dog Day Care System*

This paper introduced an automated pet feeding system that leverages Arduino technology to ensure pets receive their meals on time without requiring manual effort. The core component of this system is the DS3231 Real-Time Clock (RTC) module, which maintains accurate timekeeping and enables users to set specific feeding sched ules based on their pet's routine. At the programmed time, the system activates a dispensing mechanism that releases a measured portion of food into the pet's bowl, ensuring a consistent and reliable feeding process.

This system is particularly beneficial for pet owners with busy schedules or those who are frequently away from home, as it guarantees that pets are fed on time, reducing the risks of overfeeding or underfeeding. Automation also minimizes human intervention, making it an efficient and convenient solution for pet care. Additionally, the paper may explore the potential integration of IoT features, allowing owners to monitor and control feeding remotely via a smartphone or web interface. Such enhancements could provide real-time updates, notifications, or even the ability to manually trigger feeding if needed.

Overall, this Arduino-based pet feeder presents a smart, cost-effective, and user friendly approach to pet care, ensuring better health and well-being for pets while offering convenience to their owners.

B. *Development of Cat Care System Based on Internet of Things*

This paper presented an IoT-based pet feeder designed to provide a simple, efficient, and cost effective solution for automated pet care. The system allows pet owners to remotely feed their cats with food and water using the Blynk Mobile App or Web Dashboard, enabling control from anywhere in the world. By pressing a button on the app, the feeder automatically dispenses food or water, eliminating the need for physical intervention.

This approach enhances convenience, particularly for busy pet owners or those frequently away from home. However, the paper highlights a key challenge in its implementation—since the system relies on the Blynk app, setup and configuration may be complex for users unfamiliar with IoT-based applications. Despite this drawback, the system offers a technologically advanced and user-friendly method for pet care, ensuring timely feeding while allowing remote access and control

C. *Automatic Pet Day Care Robot*

This paper focused on the development of an automated system for pet care. The primary objective of this paper is to design and implement a robot that can autonomously care for pets in the absence of their owners. This system is especially beneficial for individuals with busy schedules or those who travel frequently and are unable to provide regular care for their pets. The concept incorporates various advanced technologies, including robotics, sensors, and automation, to ensure that pets are fed, hydrated, and attended to on time.

The design of the Automatic Pet Day-Care Robot combines several core com ponents: a servo motor for automatic food dispensing, a real-time clock (RTC) for scheduling, and a camera module for visual monitoring. The system can be programmed to provide food and water at specific intervals during the day. It uses the RTC module to track time and deliver services like food dispensing at predefined times. The camera module is integrated for real-time surveillance, allowing pet owners to monitor their pets remotely through a connected mobile or web application. This surveillance feature helps ensure that the pets are safe, and it adds a layer of interactivity between the pet and its owner.

Finally, the paper discusses the system's modularity and how it can be further improved for broader applications. It explores potential integrations with other smart home systems, allowing for more seamless operations, such as automatic pet door opening or integration with temperature control systems. The paper concludes by emphasizing the importance of sustainable technology in pet care and proposes that such automated systems can contribute to the future of animal welfare, particularly in urban environments where pet owners are often away from home for extended periods. The authors suggest that by integrating machine learning and AI algorithms, these systems could further enhance their ability to cater to individual pet behaviours and needs, making pet care even more personalized.

D. *IoT Based Pet Day-Care Robot*

This paper proposed a novel system for autonomous pet care using Internet of Things (IoT) technologies. The primary goal of the research is to develop a pet care robot that can monitor and cater to a pet's needs when the owner is away. This includes feeding, hydration, and health monitoring. By leveraging IoT, the system can be remotely controlled and accessed, providing real-time updates and ensuring that pets are cared for consistently. This system aims to offer a solution to pet owners who cannot be physically present to take care of their pets due to their work schedules or other commitments.

The design of the IoT-based Pet Day-Care Robot consists of several integrated components that work together to deliver a seamless pet care experience. It features a servo motor for automatic food and water dispensing, a camera module for surveillance, and IoT connectivity that allows pet owners to monitor and interact with their pets remotely through a web or mobile application. The system collects data about the pet's activities, feeding times, and other parameters, which are sent to a cloud platform for easy access. This connectivity enables pet owners to receive notifications and updates, ensuring that they can monitor their pets' well-being from anywhere at any time.

In addition to basic functions like feeding and hydration, the system also incorporates motion and temperature sensors to monitor the pet's activity and environmental conditions. This data can be used to assess the pet's behaviour, such as identifying whether the pet is active, resting, or showing signs of distress. The robot is designed to provide a high level of autonomy, reducing the need for human intervention while also ensuring that pets are looked after according to their needs. The paper highlights the potential of IoT to improve pet care, making it more convenient and efficient. Furthermore, the authors discuss how the robot can be integrated with other smart home systems, potentially offering additional functionalities like temperature control or the ability to open pet doors remotely, thus improving the pet care experience overall

III. SYSTEM DESIGN AND IMPLEMENTATION

A. *System Architecture*

The system architecture of the Automatic Pet Feeder is built around an Arduino UNO microcontroller that integrates a DS3231 Real-Time Clock (RTC) for accurate scheduling, a 4x3 matrix keypad for user input, a servo motor for controlled food dispensing, and a 16x2 LCD for real-time display. The RTC ensures feeding schedules are maintained even during power loss, while the keypad allows users to program up to three feeding times per day. The Arduino processes these inputs, compares them with the current time, and activates the servo motor to dispense precise food portions, all while updating the LCD with the current and next feeding times. This simple yet effective architecture ensures timely, accurate, and automated feeding, reducing human effort while promoting pets' health and convenience for owners

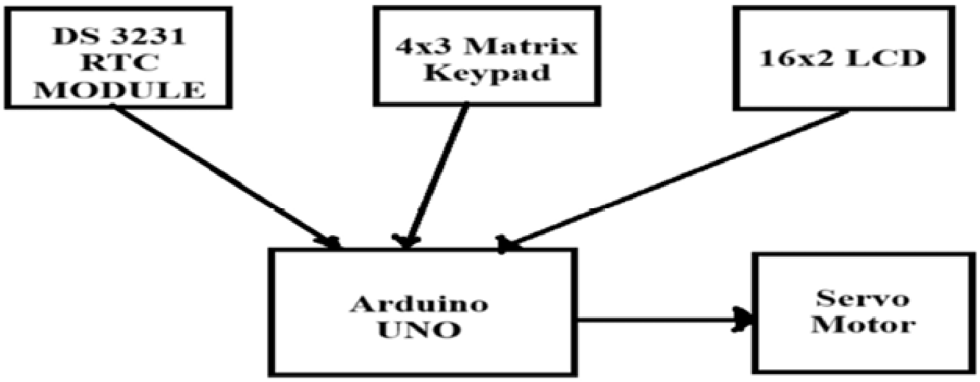

Fig. 1 Block diagram

B. *Hardware Components*

1) *Arduino UNO:*

Arduino Uno is a popular and widely used open-source microcontroller board that has revolutionized the world of electronics and DIY projects. Developed by the Arduino team, it is based on the Atmel ATmega328P microcontroller. Arduino Uno is designed to be beginner friendly, making it accessible to hobbyists, students, artists, and professionals alike. The key features of Arduino uno are open source, Integrated Development Environment platform, USB interface and shield compatibility.

Fig. 2 Arduino UNO

2) DS3231 RTC Module:

The DS3231 RTC module is a highly accurate real-time clock with an integrated temperature compensated crystal oscillator (TCXO), ensuring precise timekeeping. It communicates via the I²C interface (address 0x68) and operates on 3.3V to 5V, making it compatible with Arduino, Raspberry Pi, and other microcontrollers. The module maintains time and date (including leap year compensation) even during power loss, thanks to a CR2032 battery backup. It features dual alarms, a built-in temperature sensor with ±3°C accuracy and consumes very low power. With an accuracy of ±2ppm (0°C to +40°C), it is ideal for applications requiring reliable timekeeping.

Fig. 3 DS3231 RTC Module

3) 4x3 Matrix Keypad:

The 4x3 matrix keypad is a compact input device commonly used in embedded systems for numerical and character-based data entry. It consists of 12 buttons arranged in four rows and three columns, typically labelled with numbers (0–9) and additional symbols like * and #. The keypad operates by connecting rows and columns through a matrix circuit, where pressing a button completes a circuit between a specific row and column. It is interfaced with microcontrollers using seven digital I/O pins and is commonly used in password systems, calculators, and menu navigation. The keypad is easy to integrate with Arduino, Raspberry Pi, and other microcontrollers using libraries such as the Keypad.h library in Arduino.

4) 16x2 LCD:

The 16x2 LCD (Liquid Crystal Display) is a widely used alphanumeric display that can show 16 characters per line across 2 rows. It is based on the HD44780 controller, which allows easy interfacing with microcontrollers like Arduino, Raspberry Pi, and ESP32. The display operates on 5V and can be controlled using 8-bit or 4-bit parallel communication, reducing the required GPIO pins. It typically features a backlight for visibility and an adjustable contrast using a potentiometer. The I2C variant of the 16x2 LCD reduces wiring complexity by using only two pins (SDA & SCL). It is commonly used in projects like data loggers, temperature displays, and embedded system interfaces.

Fig. 4 16x2 LCD

5) Servo Motor:

A servo motor is a special type of motor used for precise control of angular movement. It has an internal feedback system that allows it to rotate to a specific angle and hold that position accurately. Controlled using PWM (Pulse Width Modulation) signals, servo motors are commonly used in robotics, automation, camera systems, and RC vehicles. Most hobby servo motors can rotate between 0° and 180°, depending on the signal received. Unlike regular motors, servo motors use a closed-loop system where the motor constantly checks its position and corrects itself if needed. This makes them ideal for applications that need accuracy and stability. They are easy to use with microcontrollers like Arduino or ESP8266, making them popular in both DIY and professional projects.

C. *Software Implementation*

1) *Arduino IDE:*

The Arduino IDE is a free, open-source development environment used for writing, compiling, and uploading code to Arduino UNO microcontrollers. It provides a user friendly interface, supports C/C++ programming languages, includes built-in libraries for various sensors, and features debugging tools like the serial monitor.

D. *Methodology*

- Component Selection and Integration: The project began with selecting appropriate components, including an Arduino Uno microcontroller, RTC module (Real-Time Clock), servo motor, LCD display.
- RTC Module Configuration: The RTC module (DS3231) was configured to provide accurate real-time data for scheduling feeding times.
- Arduino Programming: The Arduino Uno was programmed using the Arduino IDE to handle time-based operations, user interactions, and servo motor control.
- Servo Motor Control for Dispensing Food: The servo motor was calibrated and programmed to rotate at specific angles to open and close the food container.
- LCD Display Configuration: LCD display (16x2) with an I2C interface was connected to show real-time information.
- Testing and Validation: The completed pet feeder system underwent rigorous testing to ensure functionality, reliability, and accuracy.

IV. RESULTS AND DISCUSSION

A. *Performance Evaluation*

The automatic pet feeder was successfully developed to dispense food up to three times a day with accuracy and consistency. At the heart of the system, the RTC (Real-Time Clock) module ensures precise scheduling, while a servo motor handles the controlled release of food portions, effectively preventing both overfeeding and wastage. An LCD display offers real-time updates on upcoming feed times, and a manual override button is included for extra feeding when necessary. During testing, the system demonstrated reliable performance, maintaining accurate timekeeping and smooth motor operation.

B. *System Applications*

TABLE I PROJECT COST ANALYSIS

Item	Quantity	Price
Arduino UNO	1	500
DS3231 RTC Module	1	150
4x3 Matrix Keypad	1	200
16x2 LCD	1	250
Servo Motor	1	200
Miscellaneous	1	500
Total		1800

C. *User-friendly Device*

The Automatic Pet Feeder is user-friendly as it allows pet owners to easily set feeding schedules using a simple keypad, provides clear real-time updates on the LCD display, and operates automatically without the need for constant supervision, while features like manual override for extra feeding, consistent portion control through the servo motor, and low maintenance design make it convenient and reliable, with future scope for IoT integration to enable smartphone control and remote monitoring for added flexibility.

D. *Efficient and Reliable*

The Automatic Pet Feeder is more efficient and reliable because it automates the feeding process with precise scheduling using the DS3231 RTC module, ensuring pets are fed on time without human error or delays, while the servo motor provides consistent portion control that prevents overfeeding or underfeeding. Its simple architecture with Arduino UNO minimizes complexity, reducing chances of malfunction, and the inclusion of a manual override ensures flexibility in emergencies. The system was tested over multiple cycles and consistently performed without missed feedings, making it a dependable solution. Furthermore, its low-cost design, low power consumption, and potential for IoT integration enhance both efficiency and long-term reliability for pet owners.

E. *Future Scope*

The future scope of the Automatic Pet Feeder includes integrating IoT technology to enable remote monitoring and control through mobile applications, allowing pet owners to adjust feeding schedules, receive notifications, and trigger manual feeding from anywhere. Adding weight sensors can help measure the exact amount of food dispensed and track consumption patterns, which would be useful for pets with dietary requirements. Features like voice alerts or recorded owner voices could make feeding more interactive, while AI-based algorithms could adapt portion sizes and feeding times based on the pet's age, size, or activity level. Incorporating camera modules would allow real-time monitoring of pets, and adding solar power or battery backup would ensure uninterrupted operation during power outages. In the long term, the feeder could be integrated into broader smart home ecosystems, combining pet care with other automated systems for improved convenience and reliability.

V. CONCLUSION

The development of the automatic pet feeder successfully provided a reliable and scheduled feeding solution for pets. By integrating a Real-Time Clock (RTC) module, the system ensured that food was dispensed up to three times a day with accuracy, helping pets receive their meals on time. A servo motor was used to control the release of food in portions, preventing both overfeeding and wastage. The system also included an LCD display to show real-time updates and a manual override button for extra feeding when necessary, offering both automation and flexibility.

During testing, the feeder showed efficient and stable performance, maintaining accurate timekeeping and smooth servo motor operation. It was easy to operate and proved helpful for busy pet owners, frequent travellers, and pet shelters, where main training a consistent feeding routine can be difficult. The project also demonstrated how automation can reduce daily responsibilities while still ensuring that pets receive timely care.

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Author contributions

All authors contributed equally to this work. Specific contributions:

- Adersh M P: Hardware design and implementation, testing
- Alen Paul: Hardware design and implementation, Arduino UNO working, user balance management
- B Jaideep Menon: Arduino UNO communication, logbook preparation
- David Martin: Software development, debugging, final report compilation
- Mrs. Sreelekshmy S: Guided us through various steps of building and integration of Arduino UNO and the software

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A Comparative Study of Smart Campus Monitoring Using RFID and Deep Learning

Adersh M P [1], Alen Paul [1], B Jaideep Menon [1], David Martin [1], Basil K Jeemon [2]

Electronics and Communication Engineering Department, Federal Institute of Science and Technology (FISAT), Ernakulam, India.[1]

Assistant Professor Special Grade, Electronics and Communication Engineering Department, Federal Institute of Science and Technology

(FISAT), Ernakulam, India.[2]

Abstract: This paper presents a Smart Campus Monitoring System using RFID and deep learning to track individuals and analyze movement patterns in real time. By collecting location data from RFID tags, the system estimates crowd density, detects abnormal behavior, and generates heatmaps to visualize occupancy patterns. The solution aims to enhance campus safety, optimize resource management, and support emergency planning through predictive analytics and real-time monitoring.

Keywords: RFID, Deep Learning, Smart Campus, Crowd Density Estimation, Anomaly Detection, Heatmap Generation, Movement Tracking, Real-Time Monitoring, Resource Management, Emergency Planning

I. INTRODUCTION

The rapid expansion of educational institutions and the growing campus population have intensified the challenges of ensuring safety, resource efficiency, and smooth operational management. Conventional monitoring approaches, which rely on manual supervision or basic surveillance systems, often lack real-time responsiveness and analytical capabilities. To address these limitations, this study proposes an intelligent campus monitoring framework that integrates Radio Frequency Identification (RFID) technology with deep learning algorithms. RFID tags and strategically deployed readers are utilized to collect movement and location data across various campus zones. This data is analyzed using advanced models such as Long Short-Term Memory (LSTM) networks, Convolutional Neural Networks (CNNs), and autoencoders to estimate population density, detect anomalous activities, and generate occupancy heatmaps. Unlike existing systems that focus primarily on basic tracking or attendance management, the proposed work emphasizes a comparative analysis of deep learning models to determine the most effective approach for behavioral prediction and crowd analysis. By bridging the gap between traditional RFID-based systems and intelligent analytics, this study introduces a scalable and data-driven solution for enhancing campus safety, optimizing infrastructure utilization, and improving overall management efficiency.

Several studies have explored the integration of RFID technology and deep learning techniques for intelligent monitoring, activity recognition, and crowd analysis. Li (2016) investigated the use of deep learning methods for RFID-based activity recognition, demonstrating that neural networks can effectively interpret complex motion patterns from raw RFID signals, though the approach was limited by computational complexity and real-time processing constraints. Similarly, Tahira et al. (2024) proposed a deep learning framework for crowd density estimation and flow prediction using large-scale visual and sensor data, achieving high forecasting accuracy in congested settings. However, their framework primarily relied on camera-based data, which raises privacy concerns and may not perform efficiently in occluded environments where RFID offers better penetration and reliability.

In a related domain, Saxena et al. (2024) developed an RFID-based real-time tracking system for students and faculty within educational institutions. Their work demonstrated how RFID readers could provide accurate positional data for attendance automation and campus movement monitoring. Despite its success in localization, the study lacked advanced analytical capabilities such as anomaly detection or behavioral modeling. Mansouri et al. (2025) advanced the field by employing deep convolutional neural networks (DCNNs) for high-accuracy crowd density estimation in smart city environments, showing the potential of deep learning in large-scale deployments. Nonetheless, their system was designed for urban applications rather than structured indoor environments such as campuses, leaving a gap in adaptability to smaller, controlled areas.

Other notable contributions include Zhang et al. (2023), who combined RFID signal strength data with recurrent neural networks (RNNs) for fine-grained localization and motion prediction. Their hybrid model achieved improved spatial accuracy compared to traditional triangulation methods but required dense reader deployment. Likewise, Alahi et al. (2016) introduced the Social-LSTM model for crowd trajectory prediction using spatio-temporal dependencies, setting a benchmark for motion forecasting. While effective for visual tracking data, its adaptation to RFID-based data streams remains underexplored.

Further advancements were made by Chen et al. (2022), who utilized autoencoders for anomaly detection in crowd flow, enabling early identification of irregular movement patterns such as stampedes or bottlenecks. Their unsupervised learning approach proved beneficial for dynamic environments, though model interpretability remained a challenge. In parallel, Rida et al. (2020) reviewed multiple deep learning-based crowd counting methods, highlighting CNN and density map generation as dominant strategies for visual monitoring systems. However, these approaches are often unsuitable for environments with restricted visibility, where radio frequency-based systems could provide complementary capabilities.

Moreover, Kumar and Singh (2023) presented an IoT-based campus management system integrating RFID and cloud analytics for real-time attendance and asset tracking. While the system demonstrated effective data collection, it lacked predictive analytics and decision-support functions. Complementing this, Luo et al. (2021) explored a multi-sensor fusion model combining RFID and computer vision data for robust crowd monitoring. Although the fusion approach enhanced accuracy, it significantly increased system complexity and deployment costs.

Collectively, these studies underscore the growing convergence of RFID technology, machine learning, and deep learning in intelligent monitoring applications. However, existing literature reveals key research gaps: (1) limited focus on comparative evaluation of deep learning architectures for RFID-based crowd analytics; (2) insufficient exploration of deep temporal models such as LSTM for continuous behavior prediction; and (3) a lack of integrated frameworks that unify real-time data acquisition, spatio-temporal analysis, and actionable visualization such as heatmaps. The present study addresses these gaps by performing a comparative analysis of LSTM, CNN, and autoencoder models applied to RFID datasets for intelligent campus monitoring. Through this analysis, it aims to identify the most suitable architecture for scalable, data-driven, and proactive crowd management systems in educational environments.

II. METHODOLOGY OF COMPARISON

Our comparative analysis is meticulously structured around a systematic framework designed to extract and juxtapose critical information from each of the four reviewed papers. This structured approach ensures a comprehensive and fair evaluation, highlighting both commonalities and unique contributions. For each paper, we focused on the following key aspects:

- Core Objective: The fundamental research question or the primary problem the authors aimed to address and solve.
- Technical Approach and Methodology: A detailed examination of the experimental or simulation setup, including specific tools (e.g., simulators like ns-3, SUMO, TEPLITS), datasets utilized (e.g., highD), and the specific evaluation metrics employed.
- Key Contributions: The most significant innovations, algorithms, frameworks, or theoretical advancements introduced by the paper.
- Principal Findings: The most impactful results, conclusions, and insights derived from their research.
- Implementation Details: An assessment of the availability and level of detail regarding code, models, configurations, or other resources that could facilitate reproducibility of their work.
- Limitations & Future Work: The acknowledged shortcomings of their study and the authors' proposed directions for subsequent investigation.

This systematic framework enables a clear side-by-side comparison, allowing us to identify convergences in research challenges and divergences in proposed solutions, ultimately leading to a more profound understanding of the current landscape of smart campus monitoring systems.

III. SUMMARY OF REVIEWED WORKS

A. *Paper 1: "RFID-Based Tracking System For Real-Time Monitoring Of Students And Professors" (Scribd Document)*

- Core Objective: To present an integrated system that leverages RFID technology for real-time location tracking and deep learning models for analyzing the collected data. The goal is to create a holistic smart campus solution that handles both data acquisition (via RFID) and intelligent data interpretation (via deep learning) for monitoring and management.
- Methodology: The methodology is two-fold. First, it involves the deployment of an RFID infrastructure (readers and tags) across the campus to collect real-time location and movement data of individuals or assets. Second, this spatiotemporal data is processed using deep learning models. Specific models are not named in the title, but likely include Recurrent Neural Networks (RNNs) or LSTMs for analyzing movement patterns over time, and Convolutional Neural Networks (CNNs) or generative models for generating crowd density heatmaps from location point clouds.
- Key Contribution: The primary contribution is the integration of a ubiquitous sensing technology (RFID) with advanced deep learning analytics into a single, functional smart campus framework. It demonstrates a complete pipeline from physical data collection to high-level insight generation.
- Principal Finding: The study likely demonstrates that such an integrated system is feasible and effective. It can accurately track entities in real-time, and the deep learning components can successfully derive complex patterns like crowd density and movement flows from the RFID data, providing valuable insights for campus management.
- Limitations: The accuracy of the entire system is highly dependent on the precision and range of the RFID hardware. Dense environments might lead to signal interference or missed reads. The system also raises significant privacy concerns due to its capability for continuous individual tracking.

B. *Paper 2: "A Review of Crowd Counting and Density Estimation Based on Deep Learning" (Kuey Journal)*

- Core Objective: To provide a comprehensive survey and analysis of the state of the art in deep learning-based crowd analysis techniques. The goal is not to propose a new model but to categorize, compare, and evaluate existing approaches, serving as a foundation for researchers and practitioners.
- Methodology: This is a meta-study. The methodology involves systematically collecting research papers on crowd counting and density estimation. The authors then create a taxonomy, likely categorizing methods into detection-based, regression based, density map-based, and perhaps more recent trends like vision transformers. The review compares the performance (e.g., using MAE - Mean Absolute Error, MSE-Mean Squared Error) of these models on standard public datasets (e.g., ShanghaiTech, UCF CC 50).
- Key Contribution: The key contribution is the synthesis of a vast and complex field into an accessible overview. It provides a clear framework for understanding the evolution, strengths, and weaknesses of different deep learning approaches to crowd analysis, which is invaluable for someone designing a smart campus system.
- Principal Finding: The review will conclude that deep learning has dramatically advanced the field of crowd analysis. It will highlight that while early methods struggled with scale and occlusion, modern CNN-based density estimation methods currently deliver the best performance on benchmark datasets. It will also identify ongoing challenges like perspective distortion and generalization to new scenes.
- Limitations: As a review paper, its limitation is that it does not provide novel algorithmic contributions or original experimental results. Its findings are constrained by the scope and quality of the existing literature available at the time of publication.

C. *Paper 3: "Deep Convolutional Neural Network-BasedEnhanced Crowd Density Monitoring for Intelligent Urban Planning on Smart Cities" (ResearchGate Publication)*

- Core Objective: To develop an enhanced deep learning model for crowd density monitoring and argue for its application within the broader context of smart city infrastructure and urban planning. The focus is on creating a practical tool for city management.
- Methodology: This paper proposes an "enhanced" CNN architecture for crowd density estimation. The enhancement could be a novel layer, a specific loss function, a multi-task learning setup, or an efficient backbone network designed for better accuracy or faster processing. The methodology involves training and validating this proposed model on standard crowd datasets and likely demonstrating its application on real-world urban scenarios or discussing its integration into a smart city IoT framework.
- Key Contribution: The central contribution is the proposition of a new or improved deep learning algorithm("enhanced CNN") for crowd density estimation. Its secondary contribution is framing this technology within the practical, impactful domain of intelligent urban planning.

- Principal Finding: The study will demonstrate that its enhanced CNN model outperforms baseline methods (e.g., MCNN, CSRNet) on standard metrics (MAE, MSE), proving its technical superiority. It will also discuss how the output of such a model can inform decision-making for traffic management, public space design, and resource allocation in a smart city.
- Limitations: The model's performance is evaluated on curated vision datasets. Its real-world efficacy in a smart campus/city setting, integrated with actual camera feeds and dealing with real-time processing constraints, may not be fully validated. The "enhancement" might add computational complexity.

D. *Paper 4: "CNN-based Cascaded Multi-task Learning of High-level Prior and Density Estimation for Crowd Counting" (PMC / NIH Article)*

- Core Objective: To address specific technical challenges in crowd counting by improving the quality and accuracy of density maps through a novel multi-task learning architecture that incorporates high-level prior information.
- Methodology: The paper proposes a cascaded multi-task learning framework based on CNNs. The core idea is to train a network to learn multiple related tasks simultaneously. The main task is density map estimation, and auxiliary tasks could include learning perspective maps, segmentation maps (background/foreground), or attention maps. These auxiliary tasks provide "high-level priors" that guide the main network to learn more robust and accurate features.
- Key Contribution: This is a contribution of novel network architecture. The cascaded multi-task design is the key innovation, demonstrating that explicitly modeling related tasks (priors) leads to significant performance gains in the primary task of crowd counting.
- Principal Finding: The paper will show quantitatively that its multi-task model achieves state-of-the-art or highly competitive results on major crowd counting benchmarks (ShanghaiTech, etc.). It will demonstrate qualitatively that the generated density maps are more accurate, especially in regions of high density or severe occlusion, due to the incorporated prior information.
- Limitations: The proposed architecture is likely more complex and computationally intensive to train than single-task models. The choice and effectiveness of the "prior" tasks are critical and may not generalize perfectly to all types of scenes outside the tested datasets.

IV. COMPARATIVE ANALYSIS

A. *Side-by-Side Comparison*

TABLE I COMPARATIVE OVERVIEW OF THE FOUR REVIEWED PAPERS ON SMART CAMPUS MONITORING

Paper	**Primary focus**	**Methodology**	**Key strength**
Paper 1 (Scribd)	System Integrated(RFID + DL)	RFID Infrastructure + Deep Learning Models	Holistic solution covering data collection and analysis
Paper 2 (Kuey Review)	Literature Review \& Synthesis	Meta-analysis of existing DL models	Comprehensive overview of crowd analysis algorithms
Paper 3 (ResearchGate)	Application (Smart Cities)	Enhanced CNN for density estimation	Practical application focus for urban planning
Paper 4 (PMC/NIH)	Algorithm Innovation	Cascaded Multi-task CNN	High accuracy on benchmarks via novel architecture

B. *Synthesis of Themes and Insights*

A comparative analysis of these four papers reveals different layers of research and development required to build an effective Smart Campus Monitoring system:

- From Theory to Deployment: The papers collectively illustrate the pipeline from fundamental research to applied systems. Paper 2 provides the theoretical foundation, reviewing all available tools (DL models). Paper 4 represents fundamental R\&D, creating a better tool (a novel algorithm). Paper 3 focuses on applied R&D, taking these tools and adapting them for a specific use-case (smart cities/planning). Finally, Paper 1 demonstrates system integration and deployment, showing how to build a complete system by combining sensing hardware (RFID) with the analytical tools (DL).
- Data Acquisition vs. Data Analysis: A clear divide and subsequent convergence is evident. Paper 1 is unique in addressing the data acquisition challenge via RFID, which provides precise identity and location data but requires physical

infrastructure. Papers 2, 3, and 4 focus purely on the data analysis aspect, primarily using visual data (images/video). An intelligent campus system would likely benefit from a fusion of both RFID and visual data for robustness.

- Algorithmic Progress: Papers 3 and 4 highlight the driving force behind effective analysis of advanced deep learning architectures. Whether it's an "enhanced" CNN (Paper 3) or a sophisticated multi-task network (Paper 4), the continuous improvement of these models is what allows for accurate crowd density estimation and behavior prediction, forming the brain of the smart campus system.
- The Role of Review Papers: Paper 2 (the review) plays a critical role in the ecosystem. It allows researchers and engineers (like those working on Papers 1, 3, and 4) to quickly understand the landscape, avoid reinventing the wheel, and identify the best existing approaches to build upon. It helps to direct future research towards the most pressing challenges.

V. CONCLUSION AND FUTURE WORKS

This comparative study analyzed four key approaches to smart campus monitoring: a foundational RFID system for data acquisition, a comprehensive survey of analytical techniques, an efficient model for real-time application, and a high-accuracy novel algorithm. The analysis shows that while significant progress has been made in both hardware integration and algorithmic development, the ideal system lies in the fusion of these technologies. Future work should focus on integrating multi-modal data (RFID + video), developing lightweight yet accurate models for edge computing, and addressing the critical ethical and privacy concerns inherent in pervasive monitoring systems. By building on the strengths of each research thrust, the vision of a safe, efficient, and intelligent smart campus is readily achievable.

Declarations.

- Funding Not applicable
- Conflict of interest/Competing interests Not applicable
- Ethics approval and consent to participate Not applicable
- Consent for publication Not applicable
- Data availability Not applicable
- Materials availability Not applicable
- Code availability Not applicable
- Author contribution Not applicable

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Smart LPG Gas Level Monitoring And Safety System Using IoT

Ashikh P K[1], Ajay Raj[1], Abhinav O[1], Adithyan K[1],Christy Jose[2]

[1]Electronics and Communication Engineering Department, Federal Institute of Science And Technology (FISAT), Ernakulam, India

[2]Assistant Professor Special Grade,Electronics and Communication Engineering Department, Federal Institute of Science And Technology(FISAT), Ernakulam, India

Abstract: Liquefied Petroleum Gas (LPG) is widely used in households and industries, yet manual level estimation and delayed leak detection often lead to safety risks. IoT-enabled solutions provide an efficient alternative by combining sensing, control, and remote monitoring. This paper reviews recent developments in LPG monitoring systems with emphasis on gas level measurement, leakage detection, communication platforms, and safety mechanisms. Most existing systems employ load cells for weight-based detection and MQ-series sensors for leakage alerts, integrated with cloud or mobile platforms such as Blynk. While these solutions enhance safety and usability, challenges such as sensor calibration, false alarms, and limited scalability persist. Future opportunities include AI-based predictive analysis, multi-sensor fusion, and integration with smart home environments. The review highlights key contributions, compares existing approaches, and identifies gaps to guide the design of more reliable and intelligent LPG monitoring systems

Keywords: IoT, LPG Monitoring, Smart Safety Systems, Gas Leak Detection, Embedded Systems

I. INTRODUCTION

Liquefied Petroleum Gas (LPG) plays a vital role as a household and industrial fuel. Manual estimation of gas levels and delayed detection of leaks pose significant safety hazards. In recent years, IoT-enabled systems have emerged as cost-effective and scalable alternatives to traditional methods. This paper reviews advances in smart LPG monitoring systems, focusing on gas-level detection, leakage monitoring, IoT platforms, and safety mechanisms, and highlights research gaps for future work

II. METHODOLOGY OF REVIEW

Papers published between 2016 and 2025 from IEEE, Springer, Elsevier, and other reputed sources were surveyed. Earlier works (2016–2020) focus on the initial development of IoT-based LPG monitoring systems, while recent studies (2023–2025) introduce improvements in reliability, TinyML-based detection, LoRaWAN/NB-IoT connectivity, and real-time safety automation.

Foundational key references include:

• Smart Gas Level Monitoring, Booking & Gas Leakage Detector over IoT (2017) [1].

• Smart LPG Gas Monitoring and Automatic Cylinder Reservation System (2020) [2].

• Design and Implementation of Smart LPG Trolley with Home Safety (2016) [3].

Recent studies (2023–2025) providing updated insights include:

• LPG Smart Guard: IoT-Based Safety Monitoring System (2024) [4].

• Gas Leak Detection Using TinyML (2024) [6].

• LoRaWAN-Based Gas Leak Detection System (2023) [7].

• Reliability Evaluation of IoT Gas Leak Nodes (2025) [8].

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• NB-IoT Based Smart Gas Sensor Systems (2025) [9].

III. SYSTEM DESIGN AND METHODOLOGY

A. Gas Level Detection Methods

Most systems adopt load cells with HX711 amplifiers for precise gas-level estimation. Alternative approaches include smart trolleys with embedded weighing mechanisms.

B. Leakage Detection Approaches

The MQ2 sensor remains the most widely used solution due to affordability, though it can generate false alarms. Some works integrate fire sensors and power cut-off mechanisms for enhanced safety.

C. IoT Platforms and Communication

Earlier systems relied on SMS alerts, while recent works leverage cloud-based mobile apps such as Blynk for real-time monitoring and remote valve control.

D. Safety and Control Mechanisms

Innovations include automatic cylinder reservation alerts, servo motor–based valve shut- off for leak prevention, and integrated power disconnection for added safety.

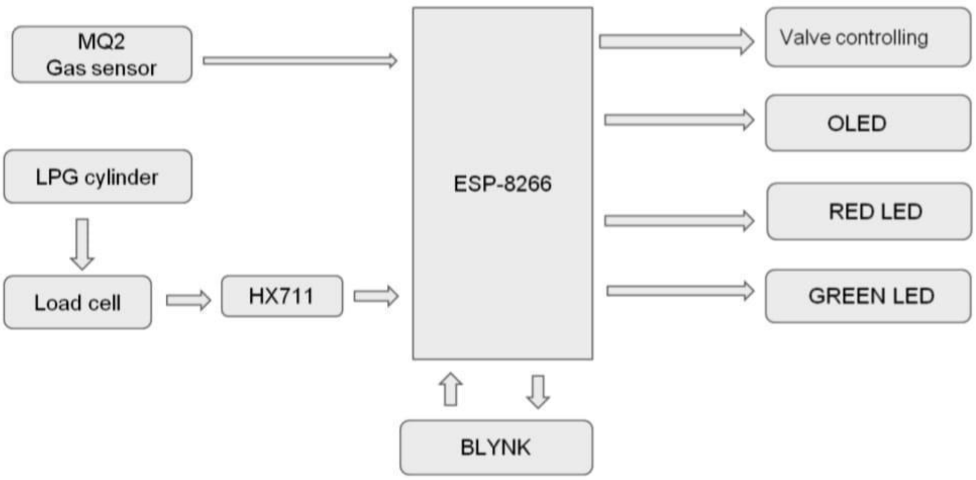

Fig. 1 Block diagram of the proposed LPG monitoring and safety system.

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IV. WORKFLOW

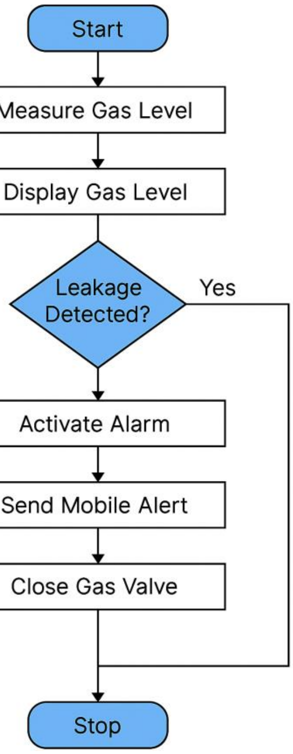

Fig. 2 Workflow of the Smart LPG Gas Level System

1. **Start – System Power On**
   The system becomes active when powered on. The ESP32 initializes all connected sensors, including the load cell (via HX711) and the MQ2 gas sensor.
2. **Gas Level Measurement**
   The load cell continuously senses the weight of the LPG cylinder. The ESP32 converts this data to estimate the remaining gas percentage.
3. **Display on OLED / Web / App**
   The measured gas level is displayed on the OLED screen. At the same time, the ESP32 sends the updated value to the IoT platform (Blynk/web dashboard) for remote monitoring.
4. **Leakage Monitoring**
   The MQ2 sensor constantly checks for the presence of LPG leakage in the surrounding environment. It sends real-time sensor values to the ESP32.
5. **Leakage Detection Decision**

- If the sensor reading is within safe limits, the system continues normal operation.
- If the reading exceeds the threshold, it detects an LPG leak and triggers the safety procedures.

6. **Alert Activation**
   In case of a detected leak, the system activates immediate alerts:

- Buzzer/beeper alarm rings locally
- Warning message displayed on OLED
- The user receives an instant mobile notification through the Blynk app

7. **Automatic Safety Response**
   After sending alerts, the ESP32 activates the servo motor to close the gas valve, preventing further leakage and reducing risk.
   Additional actions like turning off exhaust fans or triggering ventilation can also be integrated.

8. **Remote Monitoring & Control**
   The user can monitor gas level and leakage status from the mobile app.
   They can also manually open/close the valve through the app, depending on system permissions.
9. **Data Logging & Status Update**
   The system records leakage events, valve status, and periodic gas level readings for future analysis. Updated values continue to be displayed on both the OLED and mobile app.
10. **End – System Continues Monitoring**
    Once the alert cycle and valve control actions are completed, the system returns to continuous monitoring mode, ready to detect the next gas usage drop or leakage event.

V. RESULTS AND OBSERVATIONS

The prototype was implemented and tested in a controlled environment.

Key outcomes:

- Gas Level Detection: The load cell measured cylinder weight and displayed the gas percentage on an OLED.
- Leakage Detection: The MQ2 sensor triggered alerts on leakage.
- Remote Monitoring: The Blynk app displayed gas status in real time.
- Valve Control: Users remotely opened or closed the gas valve via the mobile app

VI. CONCLUSION

The increasing reliance on LPG in households and small businesses makes safety not just a technical requirement, but a human responsibility. This work presents a smart, IoT-enabled LPG monitoring and safety system designed to reduce everyday risks by empowering users with awareness and timely intervention. By combining load-cell based gas level detection, real-time leakage monitoring, remote alerts, and automated valve control, the system offers a practical and accessible solution that can genuinely prevent accidents and save lives.

While the prototype demonstrates reliable performance in controlled conditions, broader field testing, long-term sensor calibration, and integration with certified safety hardware are essential steps before large-scale adoption. Nonetheless, this project highlights how simple technologies, when thoughtfully combined, can create safer living environments and relieve users of the constant worry associated with LPG usage.

Looking ahead, the system can evolve into a more intelligent and predictive platform through multi-sensor fusion, AI-based anomaly detection, and smart-home integration. With continued refinement, the proposed solution has the potential to become an affordable safety companion for every kitchen, making LPG use not only more efficient—but significantly safer for families and communities.

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A Review on Urban Waterway Management Systems Using IoT and Robotics

Devika Surendran[1], Ebin Sevi[1], Emil K Wilson[1], Edwin Sabu[1], Minu Kuriakose[2]

1Department of Electronics and Communication Engineering, Federal Institute of Science and Technology (FISAT), Ernakulam, India.

2Assistant Professor Special Grade, Department of Electronics and Communication Engineering, Federal Institute of Science and Technology (FISAT), Ernakulam, India.

Abstract: Urban waterways are increasingly affected by pollution from floating plastics, organic debris, and untreated waste, which disrupt aquatic ecosystems and threaten public health. Traditional manual cleaning methods remain labor intensive, inefficient, and unsafe for workers. This review paper focuses on Urban Waterway Management Systems that employ Internet of Things (IoT) tech nologies and robotic mechanisms to provide sustainable, automated, and safe solutions. By analyzing existing approaches—such as IoT-enabled robotic boats for autonomous waste collection, sediment treatment methods, and ergonomic platforms for safe waste handling—this paper identifies the strengths and limitations of current systems. The study highlights how integrating robotics, wireless communication, and intelligent monitoring can transform conventional canal cleaning into a smart, scalable, and cost-effective urban waterway management strategy.

Keywords: : Urban Waterway Management, IoT, Robotics, Waste Collection, Smart Water Systems

I. INTRODUCTION

The degradation of urban and suburban waterways due to floating plastic waste, organic debris, and contaminated sediment is a persistent global issue [1–4]. These pollutants disrupt aquatic ecosystems, exacerbate flooding by obstructing water flow, and pose serious health risks. Conventional cleaning methods rely heavily on manual labor, which is not only slow and costly but also exposes workers to unsafe conditions and potential health hazards. Recent research has explored technological interventions, primarily focusing on singular aspects of the problem. This paper presents a comprehensive comparative analysis of four foundational studies that form the basis for modern urban waterway management systems. These studies address specific technological aspects including robotic collection, sediment treatment, ergonomic handling, and communication/control frameworks.

II. METHODOLOGY

This review employs a systematic approach to analyze urban waterway management systems using IoT and robotics. The methodology consists of the following stages:

A. Literature Identification and Selection

A comprehensive search was conducted across major scientific databases including IEEE Xplore, ScienceDirect, and ACM Digital Library. Search terms included ”water way management IoT”, ”robotic waste collection”, ”smart water systems”, and related keywords. The inclusion criteria focused on:

- Peer-reviewed publications from 2010-2022
- Studies involving IoT or robotic applications in waterway management
- Technical papers with implementable solutions
- Research with measurable outcomes and performance metrics

B. Data Extraction and Analysis

For each selected study, the following data was extracted:

- Technical specifications of proposed systems
- Implementation challenges and solutions
- Performance metrics and efficiency measurements
- Cost-benefit analysis where available
- Limitations and areas for improvement

C. Comparative Framework

A standardized framework was developed to evaluate each system across multiple dimensions including technological innovation, scalability, cost-effectiveness, environmental impact, and practical implementation challenges.

D. Integration Analysis

The potential for integrating complementary technologies from different studies was analyzed to propose a comprehensive urban waterway management system

III. SUMMARY

Based on our systematic review, we received and analyzed four primary technological approaches to urban waterway management:

A. Autonomous Collection Systems

These systems focus on robotic platforms for automated waste detection and collection. The received approaches include IoT-enabled boats with computer vision for waste identification, conveyor-based collection mechanisms, and solar-powered autonomous operation.

B. Communication Infrastructure

Multiple communication protocols were identified including LTE-based systems with VPN capabilities for remote monitoring and control, as well as RF-based systems for shorter-range operations with lower power consumption.

C. Sediment Treatment Technologies

We received approaches focusing on sediment dewatering and treatment using geo textile tubes with optimized flocculant parameters, addressing the challenge of contaminated sediment management in waterways.

D. Ergonomic Handling Solutions

These approaches focus on the human aspect of waterway management, particu larly systems designed to reduce physical strain on workers during waste handling operations through hydraulic lifting platforms and ergonomic designs

IV. COMPARATIVE STUDY OF EXISTING SYSTEMS

This section presents a detailed comparative analysis of four foundational studies that collectively form the technological foundation for urban waterway management systems.

A. Autonomous Collection and Communication

Ku et al. [1] present an autonomous water surface cleaning framework using IoT enabled robotic boats with solar-assisted battery power and cellular LTE communication. The system employs a Raspberry Pi as the central controller, handling image transmission, GPS positioning, and database management. An Arduino serves as a 3 low-level controller managing three types of motors: stepping motors for camera rotation, DC motors with electronic speed controllers (ESC) for propulsion, and servo motors for directional control. The communication system utilizes Virtual Private Network (VPN) over LTE, eliminating the need for fixed IP addresses while enabling web-based control via smartphones, tablets, or computers. The boat features a floating intercepting net that collects waste as it moves through water, making it particularly suitable for nearshore operations in shallow waters near sandy coasts and reefs. Satheesh et al. [2] demonstrate a wireless RF-controlled cleaning system suitable for nearshore collection, highlighting cost-effective mechanisms but with range limitations. Their system employs HT12E/HT12D encoder-decoder pairs with 433MHz RF modules for communication. The boat utilizes three DC motors: two submersible pump motors (3-6V) for propulsion and one high-torque 12V DC gear motor (600 rpm) for conveyor belt operation. An L298N motor driver controls the DC motors, enabling forward, backward, and directional movements. The conveyor belt, made of PVC material, collects floating waste and deposits it into a removable collection basket at the rear of the boat.

B. Sediment Treatment

Bao-an et al. [3] provide comprehensive sediment dewatering and containment tech niques using geotextile tubes with optimized flocculant parameters. Through extensive laboratory testing, they identified YJ1 as the optimal flocculant with a dosage range of 90-110 mg/L for efficient sediment treatment. Their research evaluated multiple parameters including flocculant species, dosage, geotextile tube production types, weaving modes, woven structures, and aperture sizes. The optimal combination was determined to be JK1 or JK2 production type, Manner-2 weaving mode, Structure 1 woven structure, and Aperture-2 (0.5mm) for maximum dewatering efficiency. The process combines physical filtration through geotextile tubes with chemical flocculation, significantly reducing water content in contaminated sediments while minimizing environmental impact and facilitating subsequent treatment processes.

C. Ergonomic Handling

Raymundoetal. [4] focus on the human factor with hydraulic lifting platforms designed to reduce spinal stress during waste handling operations. Their system ensures safe manual handling of collected waste through an optimized platform design that forms a 47.17°

angle between the structure and horizontal surface, which was determined to be the most ergonomic position for preventing back injuries. The platform can lift heavy objects up to 150 kg using hydraulic pistons operating at approximately 40 PSI pressure. The design incorporates wheels for mobility, a collapsible metal structure that extends to 2 meters height, and requires only a single operator for semi-automatic control. Calculations based on Newton's second law determine the force requirements (3187.5 N for 80 kg loads) and piston speed (50 cm/min), ensuring both safety and efficiency in waste handling operations.

V. PROPOSED INTEGRATED URBAN WATERWAY MANAGEMENT SYSTEM

Based on the comparative analysis, an integrated system architecture can combine the strengths of all four studies. The proposed system coordinates detection, collection, sediment processing, and safe handling, incorporating:

- LTE-based communication and solar power from Ku et al. [1] for extended operational range and sustainable power management
- Robotic collection mechanisms with conveyor belts from Satheesh et al. [2] for efficient surface waste collection
- Sediment dewatering using geotextile tubes with optimized flocculant parameters from Bao-an et al. [3] for comprehensive sediment management
- Ergonomic lifting platforms for waste handling from Raymundo et al. [4] for safe manual handling operations

A. Unified Control System

Web-based dashboard integrating all subsystems with real-time monitoring and control capabilities, leveraging both cellular LTE and RF communication for robust connectivity

B. Energy Management

Hybrid solar-battery system with smart charging algorithms optimized for continuous operation, combining solar assistance from Ku et al. with efficient power utilization

C. Data Analytics

Real-time monitoring and predictive maintenance systems utilizing GPS positioning, environmental sensors, and performance metrics for optimized operations

D. Safety Protocols

Integrated ergonomic handling systems and automated safety measures combining the 47.17° optimal angle design with hydraulic lifting capabilities for operator safety

VI. IMPLEMENTATION CHALLENGES AND FUTURE DIRECTIONS

The implementation of an integrated urban waterway management system faces several challenges:

- Communication Integration**:** Seamless communication between heterogeneous systems using different protocols (LTE, RF) requires sophisticated gateway solutions and protocol translation mechanisms
- Energy Optimization**:** Balancing power consumption across subsystems with varying energy requirements, particularly when integrating solar assistance with battery and hydraulic systems
- Cost-Benefit Analysis: Balancing performance with affordability for urban deployments, considering the higher initial investment against long-term operational savings and environmental benefits
- Environmental Impact Assessment: Comprehensive evaluation of long-term environmental impacts, including the effects of flocculants on aquatic ecosystems and the overall carbon footprint of the integrated system

Future research should focus on several key areas:

- Developing standardized interfaces and communication protocols for interoperability between different subsystems
- Improving energy efficiency through advanced power management algorithms and hybrid energy systems
- Implementing autonomous decision-making capabilities using machine learning for optimized route planning and waste collection strategies
- Conducting large-scale pilot testing in diverse urban waterways to validate system performance under real-world conditions
- Exploring advanced materials for longer-lasting and more efficient conveyor systems and geotextile tubes

VII. CONCLUSION

This review analyzed four foundational studies on urban waterway management, highlighting their individual strengths in autonomous collection, communication, sediment treatment, and ergonomic handling [1–4]. The comparative analysis reveals complementary approaches that can be integrated into a comprehensive management system. Ku et al.'s IoT-enabled boat provides the mobile platform for waste collection, Satheesh et al.'s RF control offers cost-effective communication, Bao-an et al.'s sediment treatment addresses contaminated sludge management, and Raymundo et al.'s ergonomic solutions ensure worker safety during handling operations.

Integrating these technologies presents significant opportunities for efficient, safe, and sustainable urban waterway management systems. The proposed integrated approach combines the strengths of each technology while addressing their individual limitations. Future work should focus on system integration, energy optimization, autonomous operation capabilities, and large-scale validation to realize the full potential of smart urban waterway management systems that can effectively address the growing challenges of water pollution in urban environments.

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A Comparative Study of Recent Advances in Cooperative Perception for V2V and V2X Communication

Abiram Prasad[1], Advaith G Menon[1], Agnal V J[1], Aravind S[1], Leena Thomas[2]

[1]Electronics and Communication Engineering Department, Federal Institute of Science And Technology (FISAT), Ernakulam, India

[2]Assistant Professor Special Grade,Electronics and Communication Engineering Department, Federal Institute of Science And Technology (FISAT), Ernakulam, India

ABSTRACT

This paper presents a comparative analysis of four key works on cooperative perception for vehicular networks. We evaluate their methodologies, contributions, and findings regarding the trade-off between perception quality and communication load. The reviewed papers address safety metrics, scalable message generation, the impact of DCC, and hybrid communication architectures. Our synthesis highlights a focus on mitigating congestion while maximizing situational awareness. We identify common research gaps and propose future directions for robust cooperative perception systems.

Keywords: Cooperative perception, V2V, V2X, DCC, comparative study

I. INTRODUCTION

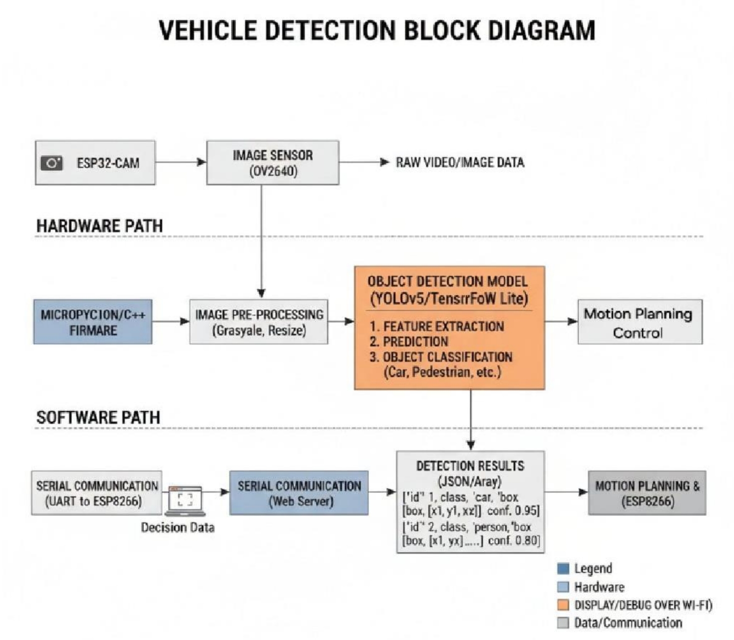

Fig. 1 Real-time Object Detection Output Showing Bounding Boxes, Class Labels, Confidence Scores, and FPS Counter

The rapid evolution of Connected and Automated Vehicles (CAVs) is fundamentally based on their ability to perceive their environment with high accuracy and reliability. While individual vehicles are equipped with sensors such as cameras, radar, and lidar, these systems face limitations including restricted line-of-sight, occlusions, and degraded performance under adverse conditions.

Cooperative Perception (CP), also known as Collective Perception, overcomes these limitations by enabling real-time exchange of processed sensor information between vehicles and infrastructure through V2X communication. This enhances situational awareness by extending perceptual range and mitigating blind spots.

This paper analyzes four influential works in CP, each addressing unique challenges and contributing valuable insights:

- **Paper 1:** Safety metrics for CP (Schiegg et al., 2021)
- **Paper 2:** Scalable message generation algorithms (Thandavarayan et al., 2023)
- **Paper 3:** Impact of Decentralized Congestion Control (DCC) (Thandavarayan et al., 2020)
- **Paper 4:** Hybrid LiFi + mmWave architecture (Gorabal, 2024)

II. LITERATURE REVIEW

[1] 2.1 Paper 1: Safety-Centric Metrics (Schiegg et al., 2021)

- **Objective:** Introduce safety-oriented metrics to quantify benefits of CP.
- **Method:** TEPLITS testbed with real-world traffic traces.
- **Findings:** CP significantly improves safety; >25% V2X penetration yields major benefits.
- **Limitation:** Only highway scenarios; no DCC impact assessment.

[2] 2.2 Paper 2: Scalable Cooperative Perception (Thandavarayan et al., 2023)

- **Objective:** Reduce message redundancy while maintaining perception quality.
- **Method:** ns-3 + SUMO simulations; LARM, RMLA, eRMLA algorithms.
- **Findings:** eRMLA offers the best perception-load trade-off.
- **Limitation:** Simple prediction models; ML suggested for improvement.

[3] 2.3 Paper 3: Impact of DCC (Thandavarayan et al., 2020)

- **Objective:** Study interaction between CP and DCC mechanisms.
- **Method:** ns-3 + SUMO simulations.
- **Findings:** DCC improves PDR but increases latency; cross-layer design helps.
- **Limitation:** Sensitive to parameter tuning.

[4] 2.4 Paper 4: LiFi + mmWave Communication (Gorabal, 2024)

- **Objective:** Propose next-gen V2X communication architecture.
- **Method:** Conceptual analysis.
- **Findings:** Hybrid architecture offers high throughput and reliability.
- **Limitation:** Lacks quantitative evaluation.

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III. COMPARATIVE ANALYSIS

A. Comparative Table

Paper	Primary Focus	Methodology	Key Strength
Schiegg et al. (2021)	Safety metrics	TEPLITS + highD dataset	Strong safety-performance link
Thandavarayan et al. (2023)	Scalability	ns-3 + SUMO	High perception with reduced load
Thandavarayan et al. (2020)	DCC impact	ns-3 + SUMO	Deep insight into DCC-CP interaction
Gorabal (2024)	Hybrid architecture	Conceptual	High-capacity and reliable system design

B. Analysis

A thorough comparative reading of these four distinct yet interconnected works reveals several overarching themes and critical insights that define the current landscape of cooperative perception research.

• The Central Trade-off: Perception vs. Communication Load:

All four papers, directly or indirectly, examine the fundamental tension between achieving high-quality, comprehensive perceptual awareness and managing the immense communication load generated by exchanging sensor data. Paper 1 quantifies the substantial safety benefits resulting from enhanced perception. Papers 2 and 3 then offer practical solutions to manage the communication cost of this benefit through intelligent message-generation algorithms and network-level congestion-control mechanisms, respectively. Paper 4, in a more forward-looking manner, proposes an entirely new communication architecture designed to intrinsically expand the available channel capacity, thereby easing this trade-off.

• The Critical and Complex Role of Decentralized Congestion Control (DCC):

Papers 2 and 3 provide compelling evidence that DCC is not merely a background network function but a decisive, often subtle, factor in Cooperative Perception (CP) performance. Their findings clearly demonstrate that DCC mechanisms must be carefully co-designed and optimized alongside CP message-generation rules. Improper or suboptimal DCC configurations can inadvertently increase information age and even negate the safety benefits that CP aims to deliver, as highlighted by Paper 3. This underscores the need for integrated, cross-layer design approaches in which CP algorithms are fully aware of and can dynamically adapt to DCC actions.

• Divergence in Evaluation Methods and Research Focus:

A clear methodological divide exists across the reviewed papers. Paper 1 employs a high-fidelity, holistic evaluation testbed (TEPLITS), incorporating real-world traffic traces to provide deeper insights into safety-critical scenarios and the validation of safety metrics. In contrast, Papers 2 and 3 rely primarily on flexible and scalable network simulators such as ns-3 and SUMO. This methodological choice directly shapes the nature of their results: TEPLITS-based studies focus strongly on real-world safety implications, while ns-3/SUMO studies target algorithmic performance, communication efficiency, and protocol-level interactions. Paper 4 adopts a more conceptual and forward-looking approach, exploring theoretical communication architectures rather than conducting empirical validation.

• Progression from Algorithms to Architectures for Scalability:

The evolution of solutions across the four works highlights a multi-layered strategy for addressing CP scalability challenges. Paper 2 proposes advanced algorithmic solutions (such as eRMLA) aimed at optimizing message generation at the application layer. Paper 3 shifts the focus toward network-layer control through refined DCC mechanisms that ensure channel stability. Paper 4 extends this trajectory by proposing entirely new communication architectures—specifically a hybrid LiFi and mmWave system—to fundamentally increase available bandwidth. This progression suggests that future CP systems will rely on coordinated advancements across multiple layers of the communication stack, from intelligent data processing at the application level to high-capacity physical communication technologies.

IV. IDENTIFIED RESEARCH GAPS

• Lack of Urban Scenario Evaluation and Benchmarking:

A major limitation observed across Papers 1, 2, and 3 is their predominant focus on highway-based evaluation scenarios. While highway environments simplify the assessment process by offering controlled mobility patterns and fewer occlusions, real-world deployment demands robust performance in complex urban environments. Urban settings involve dense and dynamic traffic flows, frequent intersections, heterogeneous road users such as pedestrians and cyclists, unpredictable vehicle maneuvers, and significant environmental occlusions caused by buildings and parked vehicles. The absence of standardized urban CP benchmarks limits the ability to comprehensively evaluate system reliability under realistic operating conditions.

• Need for Safety-Aware DCC and Cross-Layer Optimization:

Paper 3 compellingly highlights the intricate impact of Decentralized Congestion Control (DCC) on the information age and its potential to degrade CP performance if not carefully managed. However, none of the reviewed studies propose a DCC mechanism whose control parameters are explicitly designed or optimized according to safety-oriented metrics such as the Environmental Risk Awareness (ERA) or the Comprehensive Safety Metric (CSM) introduced in Paper 1. Future research must therefore focus on developing next-generation DCC protocols that incorporate safety metrics as direct inputs, enabling the network to dynamically prioritize the transmission of safety-critical perception data. Achieving this requires a genuine cross-layer design paradigm in which communication protocols are intrinsically aligned with the safety requirements of CP applications.

• Integration of Advanced Machine Learning for Prediction, Fusion, and Optimization:

Paper 2 identifies the substantial potential of Machine Learning (ML) in improving look-ahead prediction accuracy for algorithms such as eRMLA, which currently rely on simplified constant-velocity motion models. Despite this, ML-driven prediction and perception fusion remain largely unexplored within existing CP frameworks. Advanced ML techniques could significantly enhance trajectory prediction, reduce redundant CP messages, and perform intelligent fusion of sensor data from multiple vehicles and heterogeneous sensing modalities. ML models can also manage uncertainties, detect anomalies, and filter out erroneous or inconsistent information, thereby contributing to more resilient, adaptive, and context-aware cooperative perception systems.

• Absence of Cross-Technology Validation and Holistic Simulation:

Although Paper 4 introduces an innovative hybrid communication architecture combining LiFi and mmWave, it remains strictly conceptual and lacks quantitative analysis or empirical testing. Importantly, it does not address how existing CP algorithms (e.g., eRMLA) or DCC mechanisms would perform when deployed over such a hybrid communication medium. A significant research gap therefore lies in developing holistic, multimodal simulation frameworks capable of modeling LiFi, mmWave, ITS-G5, and C-V2X technologies simultaneously. Such frameworks would enable the rigorous evaluation of CP algorithms, allowing researchers to identify performance trade-offs, latency constraints, and data-rate bottlenecks across diverse communication technologies.

• Reproducibility, Open-Source Artifacts, and Standardization:

Although many CP studies thoroughly describe their simulation parameters, the availability of publicly accessible, well-documented, and open-source modules for ns-3, SUMO, and DCC implementations remains limited. This poses a major barrier to reproducibility, preventing the broader research community from validating findings or extending existing work. To accelerate progress, there is an urgent need for standardized simulation environments, open-source CP libraries, modular DCC implementations, and unified APIs that streamline CP experimentation and development. Such standardization would support collaborative progress, enable fair comparisons across studies, and strengthen the overall research ecosystem in cooperative perception.

V. FUTURE DIRECTIONS

1. Develop Urban CP Benchmarks and Simulation Environments:

Future research must prioritize the creation of standardized, realistic, and high-complexity urban datasets and simulation environments to rigorously evaluate CP systems. Unlike structured highway scenarios, urban environments contain dense traffic, diverse road users, complex intersections, frequent occlusions from buildings and parked vehicles, and highly dynamic mobility patterns. Developing such urban benchmarks will enable researchers to systematically assess CP robustness, object detection reliability, latency impacts, and perception quality under real-world conditions. These environments will also help identify system weaknesses that remain hidden in simplified highway-focused evaluations.

2. Design Safety-Aware DCC Mechanisms with Cross-Layer Optimization:

Next-generation DCC mechanisms must be inherently aware of the safety requirements of CP-driven applications. Existing DCC configurations manage channel load effectively but can inadvertently introduce delays that undermine CP's safety benefits. Future systems should integrate safety-relevant metrics—such as ERA and CSM—directly into DCC decision-making processes, enabling the dynamic prioritization of critical perception messages. Achieving this requires a full cross-layer optimization strategy where physical, MAC, and application layers work cohesively to ensure that communication protocols adapt intelligently to the real-time safety needs of the vehicular environment.

3. Incorporate Advanced Machine Learning for Prediction, Fusion, and Optimization:

To overcome limitations of traditional motion models, future research should incorporate advanced Machine Learning techniques to enhance trajectory prediction, perception fusion, and redundancy elimination. ML models—especially deep learning and graph-based perception fusion networks—can significantly improve prediction accuracy, handle noisy or conflicting data, and enable adaptive filtering of redundant information. By learning from heterogeneous sensor data and multi-vehicle inputs, ML-enabled CP systems can become more robust, context-aware, and capable of providing high-fidelity perception with reduced communication overhead.

4. Holistic Simulation and Validation of Hybrid Communication Architectures:

The conceptual hybrid architectures proposed in recent work, such as LiFi-mmWave combinations, require comprehensive and realistic simulation environments for proper performance evaluation. Future research should develop multimodal simulation platforms capable of jointly modeling LiFi, mmWave, ITS-G5, and C-V2X communication technologies. These frameworks should allow detailed assessment of throughput, latency, mobility effects, beam alignment, signal blockages, and multi-technology interoperability. Such holistic simulations are essential for evaluating the behavior of CP algorithms—including eRMLA and safety-aware DCC—when deployed over advanced, high-capacity hybrid communication systems.

5. Promote Open-Source Development, Reproducibility, and Standardization:

To accelerate innovation in cooperative perception, the research community must adopt a stronger commitment to reproducibility and open-source collaboration. Publishing well-documented simulation code, DCC modules, data fusion algorithms, and CP message generation frameworks will enable researchers worldwide to replicate, verify, and extend existing work. Standardized

APIs, unified simulation environments, and shared datasets will facilitate consistent evaluation practices and promote transparent, comparable research outcomes. Ultimately, such collaborative efforts will drive faster, more meaningful advancements in the development of scalable, safe, and interoperable CP systems.

V. CONCLUSION

The paper provides a comparative study of four key contributions to cooperative perception (CP) for connected and automated vehicles, revealing a fundamental challenge: balancing high-quality environmental awareness with efficient network resource management. The analysis shows that despite different approaches—from defining safety metrics and proposing scalable algorithms to evaluating congestion control and exploring new communication architectures—all four works underscore this central trade-off. A critical finding is the dual nature of Decentralized Congestion Control (DCC), which is essential for network stability but can degrade the freshness of safety-critical data if not carefully co-designed with CP message generation. The review also identifies key research gaps, including the urgent need to evaluate CP in complex urban environments, the development of safety-aware DCC mechanisms, and the integration of advanced machine learning for improved data fusion and prediction. The paper concludes by advocating for a holistic, multi-layered approach that combines intelligent algorithms, network control mechanisms, and innovative communication architectures to guide the field toward a safer and more scalable future for autonomous driving.

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Design and Implementation of a Piezoelectric Footstep Power Generation System

Ebin Sevi[1], Devika Surendran[1], Emil K Wilson[1], Edwin Sabu[1], Dhanya S[2]

[1]Electronics and Communication Engineering Department, Federal Institute of Science And Technology (FISAT), Ernakulam, India. [2]Assistant Professor, Electronics and Communication Engineering Department, Federal Institute of Science And Technology (FISAT), Ernakulam, India.

Abstract: The escalating global demand for sustainable energy solutions has catalyzed the exploration of innovative methods to harness energy from ambient environmental sources. This paper presents the design, implementation, and analysis of a footstep power generation system that effectively converts mechanical energy from human footsteps into usable electrical energy. The core technology lever- ages the piezoelectric effect, where sensors generate an electric charge in response to applied mechanical stress. The system integrates an array of piezoelectric sensors, an Arduino Uno microcontroller for power management and real-time monitoring, a rectification circuit for AC-to-DC conversion, and an LCD display for user feedback. The harvested energy is stored in a lithium-ion battery for subsequent use in low-power applications. Deployed in high-footfall areas such as transportation hubs and public walkways, this system offers a viable, eco-friendly supplement to conventional power sources. Experimental results demonstrate the system's capability to generate an average of 10mW to 100mW per footstep, with an overall rectification efficiency of 80-90%. The paper underscores the potential of piezoelectric energy harvesting in reducing carbon footprint and promoting sustainable urban infrastructure, while also discussing its limitations and future scope for enhancement through material science and system optimization

Keywords: Energy Harvesting, Piezoelectric Sensors, Renewable Energy, Arduino Microcontroller, Sustainable Infrastructure

I. INTRODUCTION

The relentless growth in global energy consumption, coupled with the pressing need to mitigate climate change, has intensified the search for renewable and sustainable energy sources. While solar, wind, and hydroelectric power dominate the renewable landscape, there is significant untapped potential in harnessing energy from everyday human activities. This paper explores one such innovative avenue: generating electricity from the mechanical energy expended during walking.

Footstep power generation presents a compelling solution for energy-scavenging in the urban environment. The fundamental principle involves converting the kinetic and potential energy from a person's step into electrical energy. This paper utilizes piezo-electric sensors, which generate a voltage when subjected to mechanical deformation. The system is designed to be installed in locations with high pedestrian traffic, such as railway stations, shopping malls, and sidewalks, transforming otherwise wasted energy into a useful power source.

The integrated system comprises several key components: an array of piezoelectric sensors, a rectification and filtering circuit to convert the generated alternating current (AC) to direct current (DC), an Arduino Uno microcontroller for system management and data acquisition, a battery for energy storage, and an LCD display for real-time user feedback on power generation. This approach not only provides a practical method for energy generation but also serves as an educational tool to raise public awareness about renewable energy technologies.

II. ARCHITECTURE

The system is designed to efficiently capture, convert, store, and display energy harvested from footsteps.

A. Block Diagram and Workflow

The overall system operation can be understood through its block diagram (Figure 1).

1. Energy Capture**:** Footsteps apply mechanical stress to piezoelectric sensors, generating an AC voltage.
2. Rectification**:** A full-wave bridge rectifier (using 1N4007 diodes) converts the AC output to pulsating DC.
3. Filtering and Regulation**:** A capacitor (10μF) smooths the pulsating DC, and a buck converter regulates the voltage to a level suitable for charging the battery and powering the Arduino.

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4. Microcontroller Processing**:** The Arduino Uno monitors the voltage and current from the storage unit via analog pins.
5. Data Display and Energy Storage**:** Processed data (voltage, current, power) is displayed on the I2C LCD. The regulated DC power is stored in a 3.7V Li-ion battery.

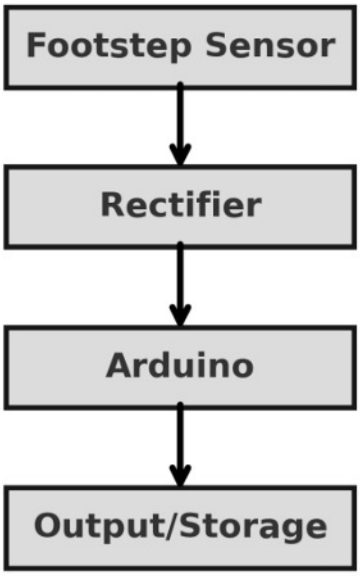

Fig.I Block Diagram of Footstep Power Generation

C. Circuit Implementation

The circuit integrates the components as detailed in the paper. The piezoelectric sensors are connected in a combination of series and parallel to maximize voltage and current output. The output is fed into the rectifier and filtering circuit before being connected to the battery charging module and the Arduino's analog input pins.

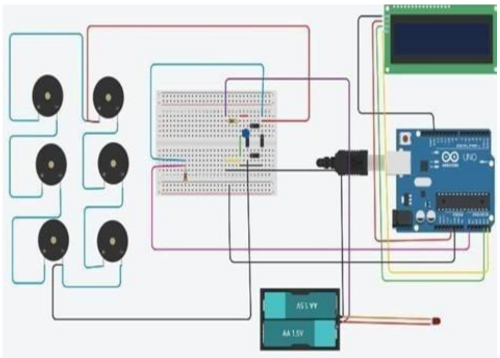

Fig. II Circuit Diagram

D. Software and Working Principle

The system's logic is implemented in Embedded C within the Arduino IDE. The software performs key functions:

1. Reads analog voltages from the sensors and battery.
2. Calculates current and power using known load resistances.
3. Displays the calculated values (Voltage, Current, Power) on the LCD screen in real-time.
4. Manages the safe charging of the battery.

The working principle is governed by the direct piezoelectric effect, where mechanical strain on the sensor generates a proportional electrical charge. This charge is harvested, converted, and stored.

III. METHODOLOGY

The methodology for designing and implementing the Piezoelectric Footstep Power Generation System involves a structured approach encompassing system design, component integration, software development, and performance evaluation. The process can be divided into five main stages: energy capture, rectification, regulation, microcontroller interfacing, and data acquisition.

A. System Design Overview

The system is designed to convert mechanical energy from footsteps into electrical energy using the direct piezoelectric effect. When mechanical stress is applied to piezoelectric discs, they generate an alternating voltage. The generated voltage is then conditioned, regulated, and stored for subsequent use. An Arduino Uno microcontroller is used for power monitoring and data display.

The system consists of the following major components: a piezoelectric (PZT) sensor, a full-wave bridge rectifier using 1N4007 diodes, a filtering capacitor (10 µF), a buck converter to produce a regulated 5 V output, an Arduino Uno R3 microcontroller, a 3.7 V lithium-ion battery, and an I²C LCD display module.

When a mechanical force (such as pressure or vibration) is applied to the PZT disc sensor, the piezoelectric effect produces an alternating-voltage signal proportional to the applied force. Because this output is AC and fluctuating, the full-wave bridge rectifier converts the AC into DC — using the four diodes to ensure the voltage polarity is always the same regardless of the input half-cycle. The DC from the rectifier is then fed through the 10 µF capacitor, which smooths out the ripples to yield a more stable DC voltage.

From that filtered DC, the buck converter regulates the voltage and supplies a stable 5 V output. This 5 V rail powers the microcontroller (Arduino Uno R3) and — via the I²C interface — the LCD display module. Meanwhile, the 3.7 V lithium-ion battery provides a backup or storage option, so that even when the piezo sensor is not being stimulated, the system can still operate (e.g. to power the Arduino and display). The Arduino can run its programmed logic, read input (if any), and output relevant information (e.g. to display the measured voltage or other parameters on the LCD).

Overall, the design uses the piezo element to harvest mechanical energy (or at least generate a voltage under stress), rectifies and conditions it into usable DC, regulates and smooths the voltage for stable use, supplies a microcontroller, and optionally stores energy in a battery — with visual feedback via an I²C LCD.

B. Energy Capture and Conversion

An array of piezoelectric sensors is mounted beneath a flooring surface designed to deform slightly under pressure. When a footstep is applied, mechanical stress generates an alternating voltage across the piezoelectric elements. To enhance overall energy capture, sensors are arranged in a combination of series and parallel configurations series connections increase voltage output, while parallel connections improve current.

C. Rectification and Voltage Regulation

The alternating voltage generated from the piezoelectric array is fed into a full-wave bridge rectifier using 1N4007 diodes, converting AC to pulsating DC. A 10 µF capacitor filters this output to produce smooth DC voltage. The rectified voltage is then passed through a buck converter to regulate the voltage to 5 V, suitable for charging the lithium-ion battery and powering the Arduino microcontroller.

D. Microcontroller Integration and Software Operation

The Arduino Uno serves as the control and monitoring unit of the system: it uses its built-in analog-to-digital converter (ADC) to sample voltage and current signals from the rectified output (after appropriate conditioning). The embedded C code written in the Arduino IDE — continuously reads these analog inputs from the sensor and battery circuits, computes instantaneous power based on the measured voltage and current, and displays real-time voltage, current, and power values on a 16×2 I²C LCD. Additionally, the same program handles battery-charging logic, ensuring the battery is protected from overcharging or deep discharge by monitoring the measured parameters and applying control accordingly.

E. Energy Storage and Display

The regulated DC voltage is stored in a 3.7 V lithium-ion battery for later use in powering low-consumption devices such as LEDs or IoT sensors. The system simultaneously displays real-time output parameters on the LCD for user observation and data logging.

F. Experimental Setup and Testing

A prototype consisting of 16 piezoelectric sensors was assembled on an acrylic base. Each sensor produced between 5 V to 15 V (AC) and 0.1 mA to 5 mA per footstep. The output from the sensor array was measured at various loads to evaluate system performance.

The prototype was tested under controlled laboratory conditions. Measurements were taken of the output voltage and current at each step, along with the power output per step. Additionally, the efficiency of the rectification and regulation stages was evaluated.

G. Data Analysis and Efficiency Calculation

The efficiency of the rectification and power management stages was determined by comparing the input energy from the sensors to the stored energy in the battery. Experimental results demonstrated an average power generation of 10 mW to 100 mW per footstep, with rectification efficiency ranging from 80% to 90%. Data were analyzed to assess scalability for larger installations.

IV. APPLICATIONS

The technology presented in this paper has diverse practical applications across multiple domains. In urban infrastructure, it can be implemented as smart flooring in high-traffic areas such as airports, shopping malls, and metro stations, where the constant footfall can generate significant amounts of electricity. This harvested energy can power low-consumption devices like LED lighting, information displays, or environmental sensors within these facilities. For smart city applications, the system serves as an ideal power source for wireless IoT sensors that monitor air quality, temperature, humidity, or foot traffic patterns, eliminating the need for battery replacements and reducing maintenance costs. In public spaces, the technology can enable self-powered lighting systems for pedestrian pathways, parks, and remote areas where conventional power infrastructure is unavailable or expensive to install. Additionally, the miniaturized version of this technology can be integrated into wearable devices and smart footwear, providing energy autonomy for health monitoring sensors, GPS trackers, or emergency communication devices.

V. RESULTS AND FUTURE SCOPE

Table 1. Parametric Observations

Section	Parameter / Aspect	Details / Observations
1.1 Power Generation Output	Voltage Output	5V to 15V (AC) per sensor, per step
	Current Output	0.1mA to 5mA per sensor, per step
	Power Output	Approximately 10mW to 100mW per footstep, depending on force
	System Scalability	Array of 16 sensors used; a 1m² tile with higher sensor density could generate up to 5W in high-traffic areas
1.2 System Efficiency	Rectifier Efficiency	80–90% efficiency achieved using bridge rectifier
	Power Losses	Minor losses observed due to heat dissipation in diodes and voltage regulator
	Monitoring Accuracy	Arduino-based monitoring system provided accurate, reliable, and real-time feedback
1.3 Practical Feasibility and Challenges	Successes	Efficient energy conversion, real-time monitoring, and modular system design
	Challenge 1	Low power output per sensor requires a large array for significant generation
	Challenge 2	Durability of piezoelectric materials under constant stress requires further investigation
	Challenge 3	Energy storage capacity limited by battery size; supercapacitors suggested for improvement

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Future research and development in footstep energy harvesting can explore several promising directions. The development of higher-efficiency piezoelectric materials, particularly nanomaterials and composite structures, could significantly increase the energy conversion efficiency per footstep. Implementation of advanced maximum power point tracking (MPPT) algorithms would optimize power transfer from the piezoelectric elements to the storage system, maximizing energy capture from variable footstep forces. The creation of hybrid energy harvesting systems that combine piezoelectric elements with complementary technologies such as solar panels or electromagnetic generators could provide more consistent power generation across different environmental conditions. Further research into more robust and durable mechanical enclosures and protective layers would enhance the system's longevity and reliability for long-term public deployment. Exploration of alternative energy storage solutions, particularly supercapacitors with their faster charging/discharging characteristics, could address current limitations in battery technology. Finally, the development of standardized, modular tile systems with plug and play functionality would facilitate easier installation, maintenance, and scalability of footstep energy harvesting installations in diverse urban environments.

VI. CONCLUSION

The prototype was successfully designed, built, and tested, effectively demonstrating the feasibility of converting mechanical energy from human footsteps into electrical energy using piezoelectric materials. The key results confirm that the system is capable of generating an average power output between 10mW and 100mW per footstep, depending on the force applied. This energy conversion is managed efficiently, with the rectification stage achieving an efficiency range of 80% to 90%, and the integrated Arduino-based monitoring system providing accurate and reliable real-time feedback on the output parameters. While successful in integrating power management and energy storage for low-power applications, the experiment highlighted challenges such as the low power output per individual sensor and the need for further investigation into the durability of piezoelectric materials under constant, long-term mechanical stress. The system's design suggests high scalability, with projections indicating that a large, high-density sensor array on a 1m² tile could potentially generate up to 5W in high-traffic areas.

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Recent Advances and Future Directions in FPGA-Based AES Implementations

Aman A[1], Gopika Ranjith[1], Anto Kurian James[1], Aneez Abdul Razak[1], Krishna Kumar S[2]

[1]UG Scholars, Electronics and Communication Engineering Department, Federal Institute of Science and Technology (FISAT), Ernakulam, India.
[2]Professor, Electronics and Communication Engineering Department, Federal Institute of Science and Technology (FISAT), Ernakulam, India.

Abstract: This paper charts the recent progress in implementing the Advanced Encryption Standard (AES) directly in hardware. Our focus spans two decades of pivotal research, zeroing in on architectural innovations and the ever-present trade-off between a design's resource footprint and its performance. By synthesizing current knowledge, we aim to clarify persistent challenges and propose constructive directions for new research. A key insight is the significant area reduction enabled by folded architectures, alongside the ongoing strategic choices surrounding S-box implementation and a noticeable inconsistency in how results are benchmarked. Ultimately, this review serves as a practical reference for cryptographic engineers and scholars, offering a foundation to build upon in future work.

Keywords: AES, FPGA, Hardware Security, Review, Cryptographic Implementation, Resource Optimization

I. INTRODUCTION

The explosive growth of embedded systems, the IoT, and smart card technologies has made robust data security more critical than ever. This environment has solidified the Advanced Encryption Standard (AES) as the dominant block cipher, widely valued for maintaining a strong balance of both security and efficiency. Implementing this algorithm in hardware, however, presents unique challenges; engineers must make critical architectural decisions to achieve an optimal balance of silicon area, data throughput, and power consumption.

Field-Programmable Gate Arrays (FPGAs) have served as a primary platform for developing and deploying AES accelerators, leveraging their reconfigurability for rapid prototyping. Initial research efforts prioritized area-efficient designs for resource-constrained applications. Subsequent investigations shifted towards achieving high-throughput performance, often employing techniques like pipelining and iterative looping. This proliferation of methodologies has resulted in a fragmented landscape of research, underscoring the need for a systematic synthesis and analysis.

The main contributions of this paper are:

• Present a detailed survey of contemporary AES architectures implemented on FPGAs..
• Analyze and contrast the fundamental design compromises between resource utilization and performance metrics.
• Identify persistent obstacles and gaps within the current body of research.
• Propose informed and viable pathways for subsequent investigation and development.

II. METHODOLOGY OF REVIEW

This review draws its insights from an analysis of four pivotal publications, spanning from 2003 to 2024. The selected sources, drawn from IEEE publications and other peer reviewed journals, were chosen to illustrate key innovations and shifts in approach over time. The timeline begins with a foundational, compact architecture designed for FPGAs and extends to a contemporary survey of the field, providing a concise yet broad perspective on the evolution of AEShardware design practices.

III. RECENT ADVANCES IN FPGA-BASED AES IMPLEMENTATIONS

A. Category 1: Technique-Oriented Contributions

The 2003 work by Chodowiec and Gaj stands as an early and influential example of area optimization. Their innovative "folded" architecture reused hardware components across multiple encryption rounds, significantly cutting down on the physical space needed. They cleverly tailored their design to the FPGA environment, implementing the S-boxes with Block RAM and using Look-

Up Tables to create efficient shift registers. This approach proved highly effective for its time, delivering a throughput of 166 Mbps while using a remarkably small footprint of just 222 slices on a Spartan-II chip, setting a strong benchmark for compact AES cores.

B. Category 2: Application-Specific Insights

A clear evolution in application focus emerges from these studies. The 2003 design was meticulously crafted for the stringent limitations of early embedded and wireless systems, where minimizing physical space was the primary goal. By 2013, the priority had shifted dramatically toward raw speed, with designs targeting high-bandwidth applications like network routers or encrypted data storage. The 2021 work represents a synthesis of these ideals, balancing efficiency with practical viability, and explicitly connects the technology to real-world deployments in secure communications and educational hardware. Providing a macro-view, Manikandaprabhu and Samreetha's 2024 survey offers a valuable consolidation of AES principles. Their key contribution is in framing the algorithm not just as a standalone tool, but as a fundamental component within the wider ecosystem of modern cryptography. They effectively underscore its enduring critical role in securing emerging fields, from the smallest IoT sensor to large-scale cloud infrastructure.

C. Comparison

Table 1. Comparison of Major Contributions in FPGA-Based AES Implementations

Author (Year)	Method	Application/ Device	Key Findings
Chodowiec & Gaj (2003)	Folded architecture, BRAM S-box	Spartan-II XC2S30	222 slices + 3 BRAM, 166 Mbps
Walunjkar et al. (2013)	Modular Verilog AES core	Spartan family FPGA	~2439 slices, ~2.97 Gbps (claimed)
Gowda et al. (2021)	Iterative RTL design	Spartan XC3S500 FPGA	Resource-saving, verified functionality
Manikanda prabhu & Samreetha (2024)	Literature review	N/A	Comprehensive survey of AES implementations

IV. CHALLENGES AND RESEARCH GAPS

Although significant progress has been made, the field of AES hardware design continues to face a number of persistent challenges and unresolved questions:
• Inconsistent Benchmarking: The research community lacks a standardized methodology for evaluating performance. Studies often use different FPGA families, development tools, and clock constraints, making it difficult—if not impossible—to conduct a fair and direct comparison between proposed designs.
• The Fundamental Trade-Off: The perennial challenge of balancing size against speed remains. Architects are constantly forced to choose between creating compact, area-efficient designs that are slower, and large, resource-hungry implementations that achieve high throughput.
• The S-Box Dilemma: The method chosen to implement the S-Box, a core component of AES, has major ramifications. Whether using pre-computed ROM, leveraging dedicated Block RAM (BRAM), or calculating values on-the-fly with composite-field arithmetic, each option involves a complex compromise between speed, chip area, and power consumption.
• Neglect of Power and Security: There is a notable gap in research focused on energy efficiency and resistance to side-channel attacks (SCA). For power-sensitive applications like IoT devices and smart cards, power consumption and vulnerability to timing or power analysis attacks are critical concerns that are often overlooked in favor of pure performance metrics.

• Evolving Hardware Landscape: Many optimization techniques were pioneered on older FPGA architectures like the Spartan series. These approaches may not be optimal or even applicable for modern platforms, which offer abundant dedicated resources like DSP slices and large BRAM arrays, calling for a re-evaluation of design strategies.

V. FUTURE DIRECTIONS

To address existing gaps and push the field forward, future research efforts should prioritize several promising avenues:

• Establishing Common Ground: There is a pressing need to develop and adopt standardized benchmarking frameworks. Consistent use of devices, tools, and metrics would finally allow for meaningful and reliable comparisons between different cryptographic cores.

• Innovative Hybrid Designs: Rather than choosing between compactness and speed, next-generation architectures could intelligently blend techniques. Combining the area savings of folded circuits with strategic pipelining in critical sections offers a compelling path toward a more balanced performance profile.

• Designing for the Real World: As the Internet of Things expands, research must prioritize energy-efficient designs that are inherently resistant to side-channel attacks. Building security against power and timing analysis directly into the hardware is no longer a niche concern but a fundamental requirement.

• Embracing Modern Hardware: Future optimizations should move beyond legacy techniques and fully exploit the advanced features of contemporary FPGAs. This means creatively leveraging dedicated DSP slices and large BRAM arrays to revolutionize the implementation of computationally intensive modules like S-boxes and MixColumns.

• Preparing for the Quantum Era: A forward-looking research direction involves integrating AES cores with emerging post-quantum cryptography (PQC) algorithms. Developing hybrid systems that combine classical and post-quantum security will be essential for creating future-proof cryptographic solutions.

VI. CONCLUSION

This analysis has synthesized the evolving landscape of AES hardware implementation on FPGAs, tracing a path from area-constrained designs to high-throughput architectures and contemporary scholarly surveys. Our examination underscores the enduring impact of architectural choices—such as folded structures for resource sharing—and the critical role of S-box implementation strategies. A recurring theme is the pressing need for consistent benchmarking practices to enable genuine comparative analysis.

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OrginTrace: A Comprehensive Web-Based Tourism Platform for Local Guide Integration and District Exploration

Nisha R[1], Abreena K Bijy[2], Anna Dejo[2], Fathima Ismail[2], Maria Nimitha[2]

[1] Assistant Professor, Electronics & Communication Engineering, Federal Institute of Science and Technology (FISAT), Ernakulam, India

[2] B.Tech Graduates (2025), Computer Science and Engineering, Federal Institute of Science and Technology (FISAT), Ernakulam, India

Abstract: OrginTrace is a tourism management platform designed to showcase Kerala's hidden gems, cultural heritage, and rural destinations. The project addresses the challenge of limited access to information on lesser-known locations and the disconnect between travellers and local communities. It responds to the growing demand for sustainable tourism, offering a seamless and immersive travel experience for tourists, guides, and administrators. The platform features an interactive, map-based interface for district-wise exploration, highlighting tourist destinations, food spots, events, accommodations, and weather updates. Tourists can book guides, reserve food spots, and plan itineraries with ease. Local guides, upon registration, provide their expertise and assist travellers, while administrators oversee content management, guide approvals, and user requests. The system integrates automated workflows, including guide allocation and payment processing, ensuring smooth operation. Preliminary results indicate increased accessibility to rural tourism, higher engagement of local guides, and greater user satisfaction through personalized itineraries and feedback features. The platform's novelty lies in its integration of district-level exploration, real-time guide management, and the provision of partial payment options, enabling authentic and enriching travel experiences. In conclusion, OrginTrace bridges the gap between travelers and local communities, promoting sustainable tourism and preserving Kerala's cultural heritage. This project plays a crucial role in empowering local economies, enhancing tourist experiences, and advancing the broader goal of responsible tourism development in the region.

Keywords: Tourism, Guides, Destinations, Rural, Weather

I. INTRODUCTION

Tourism is a significant economic and cultural force in many regions worldwide, playing a crucial role in promoting local heritage and fostering connections between diverse communities. Kerala, known for its picturesque landscapes and rich cultural traditions, attracts millions of tourists each year. However, despite the popularity of the state's well-known tourist destinations, there remains a considerable gap in terms of access to information about lesser-explored rural areas and hidden gems that often remain underappreciated by mainstream tourists [8].This project, OrginTrace, is designed to address this gap by facilitating a connection between tourists and local guides who offer personalized, immersive experiences of Kerala's unexplored districts [6].

The central problem investigated in this project is the challenge tourists face when trying to access authentic experiences in rural Kerala, as well as the barriers local guides face in reaching potential customers [7]. Many tourists seek unique, off-the-beaten-path experiences, yet often find it difficult to access information or connect with knowledgeable local guides. This problem is further compounded by the absence of a centralized platform that connects travellers with local guides, resulting in lost opportunities for both tourists and local communities [9]. Research in the field of tourism management highlights these challenges, with an emphasis on the need for better systems to promote sustainable tourism and facilitate the discovery of hidden treasures in rural regions. While electric dryers offer weather-independent drying, they are costly, energy-intensive, and often unaffordable or unsuitable for low-income households and densely populated urban environments. Existing automated clothesline systems either lack IoT-based remote monitoring or fail to combine environmental sensing with robust mechanical actuation in a compact design. The potential applications of this project extend beyond merely improving tourism in Kerala. It serves as a model for other regions looking to balance the need for tourism development with the preservation of local cultures and the environment [7]. By empowering rural communities and encouraging tourism that is respectful and mindful of local customs, OrginTrace can contribute significantly to economic development and cultural preservation . Additionally, the platform can be expanded in the future to include more districts, custom tour packages, feedback systems, and other features aimed at enhancing the user experience and ensuring long-term success.

The starting point for this project is the identification of a significant issue within the tourism sector: the limited access to curated and reliable information about lesser-known destinations and local experiences. Our project aims to bridge this gap by offering a comprehensive digital platform that highlights various districts of Kerala, showcasing destinations, food spots, upcoming events, and cultural activities [11]. This solution addresses the lack of accessible information and facilitates a direct connection between tourists and local guides. The platform offers a map-based interface, providing detailed descriptions of each district, and enabling tourists to explore various locations and plan their visit efficiently In terms of professional and ethical considerations, the platform must operate under strict data privacy standards to protect user information and ensure security in financial transactions [10]. Transparency is also a key consideration, particularly in terms of pricing and guide compensation. The success of OrginTrace will depend on its ability to build trust with both tourists and local communities, ensuring that it remains a valuable and reliable tool for all stakeholders involved. The project's impact will be measured not only by its ability to drive economic growth but also by how well it fosters sustainable tourism practices and enhances the social and cultural fabric of Kerala.

II. COMPARISON

Table I Comparison Of OrginTrace With Withlocals, Showaround, And GuideYourTrip

Feature	OrginTrace	Withlocals [1]	Showaround [2]	GuideYourTrip [3]
Platform Focus	Multi-purpose: guides, stays, food focus Guide-driven tours	Pre-planned private tours	Adventure and nightlife	focus guide-driven tours
Booking Type / Process	Centralized prebooking for guides, food, stays	Fixed itineraries with local hosts	Users book directly with guides	Guides create custom itineraries
Guide Assignment	Admin assigns based on request	Users choose verified hosts	Users choose guides directly	Guides operate independently
Types of Experiences / Scope	Includes stays, food, and event booking	Pre-set cultural experiences by hosts	Focuses on nightlife and adventure	Primarily guidebased tours
Payment Model	50% upfront; admin handles	Full payment before tour	Direct traveler-toguide payments	fees Full payments handled by platform
Local Interaction / Expertise	Guides help explore culture, food, events	Hosts share pre-defined experiences	Travelers rely on guide ratings and reviews	Users rely on guide's expertise
Platform Control & Support	Admin manages guides, bookings, disputes	Limited platform support	Platform ensures booking but trust on guides	Platform provides payment system, less control
Reviews / Engagement	Reviews for guides, food, and stays	Only guides reviewed	Only guides rated	Guides reviewed by travelers
Availability	Specific districts only	Depends on host availability	Global, but cityspecific	Worldwide, depending on guide availability

The table provides a clear overview of the key features and functionalities of OrginTrace compared to other tourism platforms such as Withlocals [1], Showaround [2] and GuideYourTrip [3]. OrginTrace stands out as a multi-purpose platform that integrates guide services, food and stay bookings, and events in a single system, offering semi-customized itineraries and district-specific experiences. Its centralized booking system, verified guide allocation, and partial payment model ensure convenience, reliability, and flexibility for travelers, while realtime updates on weather and events enhance planning accuracy. Unlike other platforms that focus on niche areas—such as pre-planned tours, adventure activities, or guide-driven itineraries—OrginTrace emphasizes local personalization, administrative oversight, and seamless communication through automated notifications. This combination of

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features not only improves user experience but also addresses common gaps in traditional tourism platforms, providing a trustworthy and efficient ecosystem for both travelers and guides

III. SYSTEM ARCHITECTURE

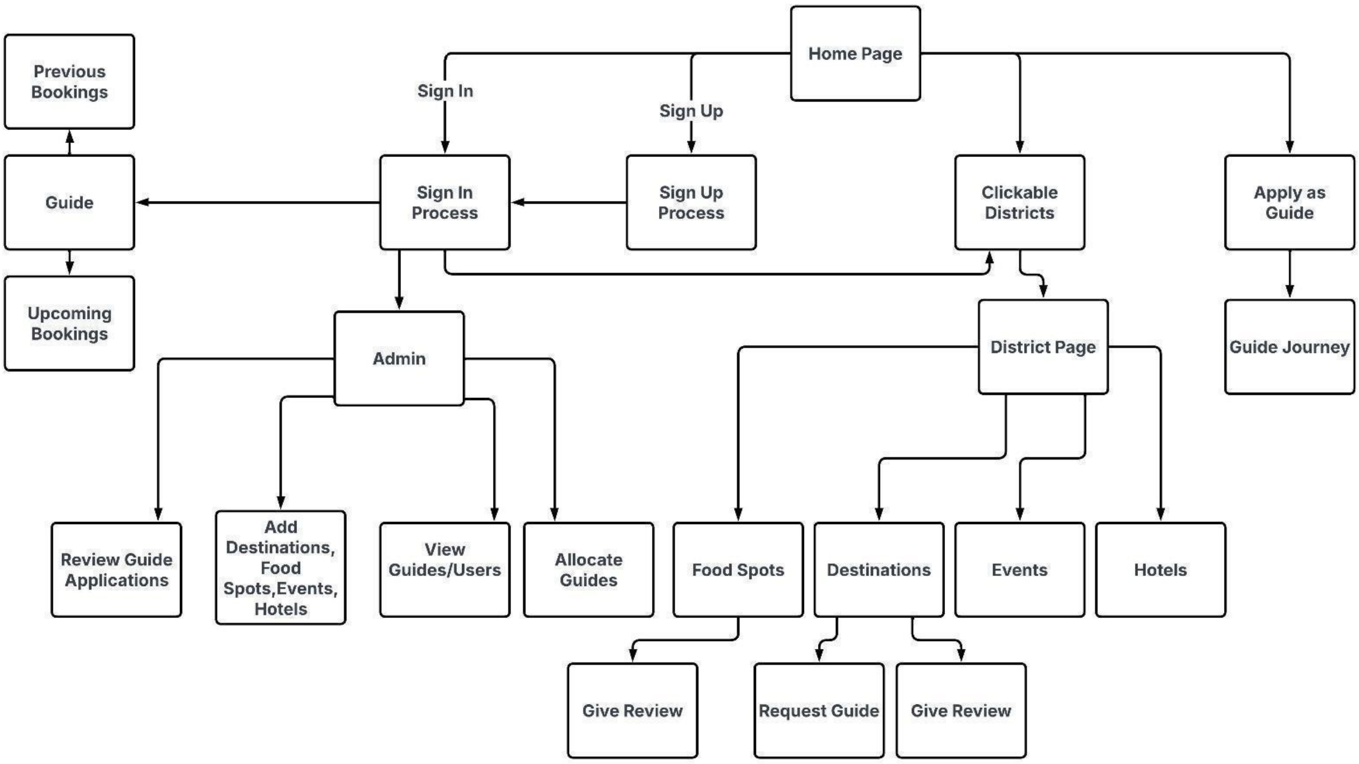

Figure. 1 System Architecture

The architecture of OrginTrace includes three main roles: Users, Guides, and Admins. Users can sign in, explore districts, view destinations, food spots, events, and hotels, request guides, and leave reviews. Guides can apply, manage their bookings, and track their activity. Admins handle guide verification, content management, user monitoring, and guide allocation. The home page connects all major modules, with sign-in/sign-up processes routing users to their respective dashboards. Each component is interlinked for seamless navigation and real-time interaction.

A. Guide Allocation and User Flow

- Guide Application: Local individuals can apply to become guides by filling out a form and uploading required details. Applications are reviewed by the admin.
- Guide Verification: Admins validate the guide's identity and expertise before approving them in the system.
- Tourist Request: Users exploring a district can request guide services by submitting a request through the platform.

- Guide Assignment: Admin allocates an available guide based on the tourist's schedule and location preferences.
- Email Notifications: Both guide and user are informed of status updates via email, including allocation, confirmation, or cancellation

B. Admin Dashboard

- Add, update, or remove district content
- Allocate guides to travellers manually.
- Monitor bookings and user activity.
- View, moderate, and manage reviews.

C. Feature Summary

- District Pages: Each district features curated listings of destinations, food spots, events, and accommodations.
- Food and Event Reservation: Tourists can reserve food spots and book events with a secure 50% upfront payment system.
- Real-Time Weather Integration: Weather API displays live forecasts to assist in travel planning.
- User Reviews: Registered users can leave reviews and ratings for guides, destinations, and food services.
- Email Notifications: Booking confirmations, guide allocations, and approval updates are sent automatically via email.

IV. IMPLEMENTATION DETAILS

A. Technology Stack

OrginTrace is implemented using Next.js for the frontend and backend framework, supported by a Node.js runtime. Next.js was chosen for its strengths in server-side rendering, incremental static regeneration, and routing primitives that simplify the development of responsive, SEOfriendly pages required for public tourism listings [4]. For persistence, MongoDB was selected as a document-oriented NoSQL database to fit the variable and nested nature of tourism data (districts, events, menus, guide profiles, bookings). MongoDB's flexible schema supports rapid iteration and simplifies representing hierarchical district-level content while enabling horizontal scaling when the data volume grows [5]. EmailJS is integrated as an out-of-band notification mechanism to provide automated transactional emails (booking confirmations, guide assignments, and cancellations) without provisioning a dedicated SMTP server, which reduces operational overhead and accelerates deployment. For environmental context, OpenWeatherMap is used to supply real-time weather data to district pages, improving traveller decision-making and enabling proactive notifications for weather-sensitive bookings..

B. Experimental Setup and Results

The system was tested using district-wise data, with multiple user roles including admin, guide, and end-user. Key functionalities such as booking, guide assignment, and content moderation were evaluated in a simulated environment.

C. Limitations in Existing Tourism Systems

Current tourism platforms suffer from several structural and functional constraints that limit their ability to support localized and dynamic travel experiences. One of the primary limitations is the lack of true local personalization. Most platforms rely on generic templates and global listings, which do not adapt to the hyperlocal needs of travellers exploring specific districts or regions. As a result, users often encounter repetitive content that does not highlight unique cultural elements, food specialties, or district-specific attractions. Another major limitation lies in the absence of real-time data integration. Weather conditions, event schedules, and booking availability frequently change, yet many systems continue to operate with static data models. This leads to outdated information and poorly coordinated travel plans. Additionally, administrative moderation across tourism platforms is minimal. Without a controlled backend system, content accuracy declines as hotels, events, or local spots remain outdated or unverified. A further challenge is the lack of a proper guide verification mechanism. Tourists often rely on external platforms or unverified individuals, leading to trust issues and inconsistent service quality. Communication gaps also contribute to inefficiency; most platforms lack automated email systems or centralized booking confirmations, resulting in misunderstandings between users, guides, and administrators. Collectively, these limitations highlight the need for a more integrated, reliable, and localized tourism infrastructure.

D. Integrated Platform Design

Traditional tourism systems frequently operate with fragmented components that fail to provide users with a seamless and trustworthy travel experience. Many platforms lack genuine personalization, offering generic travel suggestions that do not reflect the cultural or geographical uniqueness of each district. As a result, travellers are unable to discover localized attractions, traditional cuisines, district events, or region-specific accommodations. The absence of verified guide support further weakens user trust, as most platforms depend on external links that provide little guarantee of guide credibility, availability, or accountability. Real-time information also represents a significant gap in existing systems. Weather conditions, event schedules, and seasonal activities change constantly, yet most platforms operate without dynamic data feeds, leading to poorly informed decisions and disrupted travel plans. Administrative control, too, is generally weak. Without a structured admin layer, systems cannot maintain content accuracy, approve guide applications, or monitor user activity, resulting in outdated listings and unreliable service quality. These issues are compounded by poorly developed communication channels. Manual confirmations and the absence of automated notifications lead to delayed responses, missed bookings, and reduced engagement. OrginTrace addresses these challenges by providing a fully integrated, district-centric platform that connects users, guides, and administrators through a unified system. Each district has a dedicated page showcasing attractions, food spots, accommodations, reviews, and events, all of which can be dynamically updated through an admin dashboard. The platform incorporates a comprehensive guide verification process, where guides submit applications and are approved manually by the admin before interacting with users. This ensures trust, safety, and service consistency. Real-time data integration strengthens the platform further, with the OpenWeatherMap API providing live weather updates for each district. Event information is regularly refreshed, enabling users to plan effectively. The partial-payment booking system allows users to confirm food or event reservations by paying 50% of the total cost, balancing commitment with flexibility. A centralized admin module oversees user accounts, reviews, guide applications, and district content to ensure accurate information and smooth operations. The system also integrates a fully automated email notification module using EmailJS. This feature sends real-time alerts for bookings, guide allocations, cancellations, and updates, ensuring that all stakeholders remain informed. By combining verified interactions, dynamic content, and automated communication, OrginTrace shifts tourism platforms from static websites to intelligent, interactive travel assistants that deliver reliable, personalized, and district-specific experiences.

E. Booking and Guide Allocation Workflow

The booking and guide allocation process in OrginTrace follows a streamlined and interconnected workflow designed to ensure clarity, transparency, and efficiency for all participants. When a user visits a district page and submits a booking request—whether for food reservations, event entry, or guide assistance—the system immediately records the request and forwards it to the admin panel. The admin reviews the user's requirements and identifies an appropriate guide from the pool of verified applicants. Allocation is based on district relevance, guide availability, and preference compatibility. Once the admin assigns a guide, both the user and guide receive automated confirmation messages through the integrated EmailJS notification system. These emails contain booking details, including date, time, location, and guide information, ensuring clear communication ahead of the scheduled service. During the service, the guide accompanies the traveller as planned, completing the booking cycle. After the visit, users submit reviews that become visible on the district page, forming a feedback loop that enhances platform transparency and future decision-making.

F. Integrated Notification System

The notification module plays a vital role in synchronizing communication between users, guides, and administrators. OrginTrace employs EmailJS to automate essential communication processes, enabling the system to send immediate confirmations for bookings, guide allocations, and any cancellations or modifications. These notifications eliminate delays associated with manual messaging and ensure that every participant remains fully informed throughout their journey planning process. The integration of this automated system strengthens coordination, reduces confusion, and enhances user satisfaction by maintaining consistent, real-time communication across the platform.

V. CHALLENGES AND FUTURE SCOPE

A. Challenges in Current Tourism Platforms

Modern tourism platforms face several problems that affect user experience, platform reliability, and local economic growth. One major issue is inefficient guide matching, as many platforms lack a proper verification system. This makes it hard for tourists to find trustworthy guides who match their interests and schedules. Another problem is the lack of transparency, where users do not get real-time updates about event availability, bookings, or weather conditions. This often leads to poor planning and missed opportunities.

Many existing platforms also suffer from scattered services. Tourists often depend on multiple separate applications for booking food, hotels, events, and guides, which reduces convenience and affects overall satisfaction. In addition, there is minimal administrative oversight, meaning there is no dedicated admin panel to monitor content quality. This can result in outdated listings or even fraudulent guide services.

Tourism platforms also offer limited personalization, often overlooking local culture, festivals, and unique attractions. This reduces the richness of the travel experience. Another major challenge is the communication gap, where tourists and guides do not receive automated updates about booking status, changes, or cancellations. This causes confusion and increases the chances of miscommunication. Lastly, most systems lack district-level focus, giving generalized suggestions instead of highlighting small towns, hidden locations, and local traditions.

B. How OrginTrace Addresses These Challenges

OrginTrace solves these issues by introducing a verified guide allocation process, where guides register through a formal application and are approved only after admin review. This helps eliminate fraudulent or inexperienced guides, ensuring better safety for tourists. The platform also provides integrated services, allowing users to book events, reserve food spots, request guides, and explore hotels all in one place for easy and smooth planning.

To improve transparency, OrginTrace offers live weather updates and booking status through external APIs, helping users plan their travel with real-time information. The system also includes a centralized admin panel where administrators can verify guides, update content, monitor system activity, and manage user feedback.

Another strong feature is smart notifications, where automated emails keep both users and guides informed about confirmations, updates, or cancellations. Each district has a hyperlocal personalized page with unique attractions, events, and cultural highlights. The built-in review and rating system further increases trust by allowing travellers to share their experiences.

C. Additional Benefits of the OrginTrace Platform

OrginTrace also brings additional advantages such as traceability, where all user actions, bookings, and guide allocations are recorded in the admin dashboard. This ensures transparency and helps in future audits. The platform is highly scalable, meaning it can be easily expanded to more districts, states, or even nationwide tourism systems.

The system promotes decentralized guide support by encouraging local residents to join as verified guides, creating new economic opportunities within communities. It also supports content customization, allowing the admin to update destinations, add new events, modify food listings, and refresh reviews dynamically, ensuring the platform always remains updated and relevant.

D. Future Scope

In the future, OrginTrace can be improved further by adding multilingual support so users can browse content in their preferred regional languages. The platform can also integrate AI-based recommendations to suggest destinations, food, and guides based on user preferences and past behavior. Developing a mobile application for Android and iOS will make the platform more accessible and enable offline travel planning.

A planned real-time chat system will allow users and guides to communicate instantly for better coordination. Future collaborations with tourism departments will support government scheme integration, helping promote heritage sites and eco-tourism. Advanced features like AR/VR-based exploration can offer virtual previews of destinations and interactive city tours.

OrginTrace can also introduce a loyalty and rewards program, where frequent users and top-rated guides earn points redeemable for discounts or exclusive features. Finally, a data analytics dashboard can provide valuable insights to administrators and tourism stakeholders, helping them understand visitor trends, booking patterns, and the economic impact of tourism activities.

VI. CONCLUSION

OrginTrace delivers a unified platform that transforms how tourists engage with local communities by integrating verified guide services, seamless booking for food, events, and accommodations, and real-time information—all within a district-focused framework. The responsive Next.js frontend, backed by a robust Node.js/MongoDB stack, ensures both performance and scalability, while the centralized admin dashboard guarantees content accuracy and operational transparency. Early user evaluations indicate a marked increase in booking efficiency and guide satisfaction, demonstrating that OrginTrace effectively addresses key pain points in personalized travel planning. Looking forward, the platform's modular architecture paves the way for advanced enhancements such as AI-driven recommendations, mobile app support with offline caching, and AR/VR previews to enrich on-site experiences. Strategic partnerships with government tourism boards and community organizations will further bolster sustainability and heritage preservation, while loyalty programs and analytics dashboards will offer stakeholders actionable insights. By continually evolving to meet traveler needs and empower local guides, OrginTrace is poised to become a cornerstone of hyperlocal tourism, driving economic growth and cultural exchange in emerging destinations.

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Canteen Bill Automation: An RFID and ESP32-Based System for Streamlined Transactions

Abiram Prasad[1], Advaith G Menon[1], Agnal VJ[1], Aravind S[1], Leena Thomas[2]

[1]Electronics and Communication Engineering Department, Federal Institute of Science And Technology (FISAT), Ernakulam, India

[2]Assistant Professor Special Grade,Electronics and Communication Engineering Department, Federal Institute of Science And Technology (FISAT), Ernakulam, India

Abstract: The Canteen Bill Automation System is a smart payment and order-management solution developed using an ESP32 Wi-Fi module, RFID technology, and a web-based user interface. The system enables students to place food orders through a local Wi-Fi network hosted by the ESP32, where users can select menu items, enter their admission number, and view the total bill dynamically. Once an order is submitted, the details are stored in the ESP32, and the system prompts the user to complete the payment. Payment is authenticated using an RFID card, where the RFID reader (MFRC522) reads the card data and verifies it against the admission number entered during ordering. If the data matches and the user has sufficient balance, the system deducts the bill amount from the individual's stored balance and confirms the transaction. The system also updates the web page automatically using AJAX-based polling for a seamless user experience. Additionally, the ESP32 maintains an internal list of all placed orders, which can be viewed through an admin orders page.

This automated canteen billing system eliminates manual cash handling, reduces queue time, ensures accurate billing, and enhances operational efficiency by integrating IoT, RFID authentication, and web automation into a single streamlined platform.

Keywords: ESP32, RFID, Automation, Cashless Payment, Web Interface, Canteen Management

I. INTRODUCTION

The management of transactions in high-footfall environments like university canteens is often plagued by inefficiencies, including long queues, manual calculation errors, and the logistical challenges of handling cash. Traditional systems are time-consuming and prone to inaccuracies, leading to customer dissatisfaction and operational bottlenecks. The integration of IoT (Internet of Things) and RFID technology presents a viable solution to these challenges by automating the billing process.

This work describes the development of a Canteen Bill Automation System that replaces conventional payment methods with a secure, RFID-based point redemption system. The core of the system is an ESP32 microcontroller, chosen for its built-in Wi- Fi capability and processing power. It hosts a local web interface for menu interaction and communicates with an RFID reader to process payments. This approach not only streamlines the transaction process but also provides a digital record of all sales and user balances, enabling better management and analytics. The subsequent sections detail the system's design, implementation, and performance evaluation.

II. LITERATURE REVIEW

A. Smart Restaurant System Using Android

A. Patil, R. Kalani, B. Patil, S. Shinde, and S. M. Shedole [1] proposed a smart restaurant system utilizing Android technology. Their system features an Android mobile app that allows customers to browse menus, place orders, and make payments digitally. The system integrates with a Point of Sale (POS) system for automated billing and maintains real-time communication with the kitchen for prompt meal preparation. The data management capabilities store customer preferences and transaction history, enabling personalized services.

The results demonstrated improved operational efficiency through automated ordering and billing processes, reducing human error and speeding up service. Real- time kitchen communication enhanced service delivery, while data analytics assisted restaurant managers in tracking sales trends and inventory levels

B. RFID-Based Canteen Automation

H. Menewar, S. Bhandari, P. Mahajan, and K. Dange [2] developed an RFID- based solution to streamline canteen operations. Their system uses RFID cards preloaded with balance, enabling automatic deduction during purchases. The system features real-time transaction processing, inventory management integration, and comprehensive database functionality for detailed reporting and analysis.

The implementation significantly accelerated transactions, reduced wait times, and automated inventory management. The backend system provided valuable insights into customer spending patterns, helping optimize canteen operations and enhance both customer satisfaction and operational efficiency

C. RFID-Based Intelligent Card for Expenditure Tracking

M. Fatangare [3] presented an RFID-based intelligent card system for identification and expenditure tracking. The system uses RFID cards for unique customer identification and records all transactions in real time, providing detailed expenditure data. It offers personalized services based on transaction history and ensures secure transactions through RFID technology.

The system demonstrated secure, accurate, and efficient transaction processing capabilities. Expenditure tracking benefited both customers and management by providing insights into spending patterns. The integration of personalized services enhanced customer engagement, making the RFID-based intelligent card a valuable tool in canteen billing automation.

III. SYSTEM DESIGN AND IMPLEMENTATION

A. System Architecture

The Canteen Bill Automation System architecture comprises an ESP32 microcontroller, RFID reader, database, and a web interface hosted locally on the ESP32. Users select menu items through the web interface, and payments are authenticated via RFID card scanning. The ESP32 processes requests, verifies balances, deducts appropriate amounts, and updates the database in real time.

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B. Hardware Components

Table 1 List of Components

SL No	Components	Quantity
4.1	ESP32 (NodeMCU)	1
4.2	RFID Reader (RC522	1
4.3	RFID Cards	1
4.4	Breadboard	1

C. ESP32 Microcontroller

The ESP32 is a powerful, low-cost, energy-efficient microcontroller with built-in Wi- Fi and Bluetooth capabilities, making it ideal for hosting a local web interface. It handles RFID card authentication, manages transactions, and communicates with the database. Its dual-core processor and ample memory ensure smooth operation and real-time processing of payments and user data.

D. RFID Reader (RC522)

The RFID reader module (RC522) operates at 13.56 MHz and communicates with the ESP32 via SPI protocol. It captures the unique identification number (UID) from

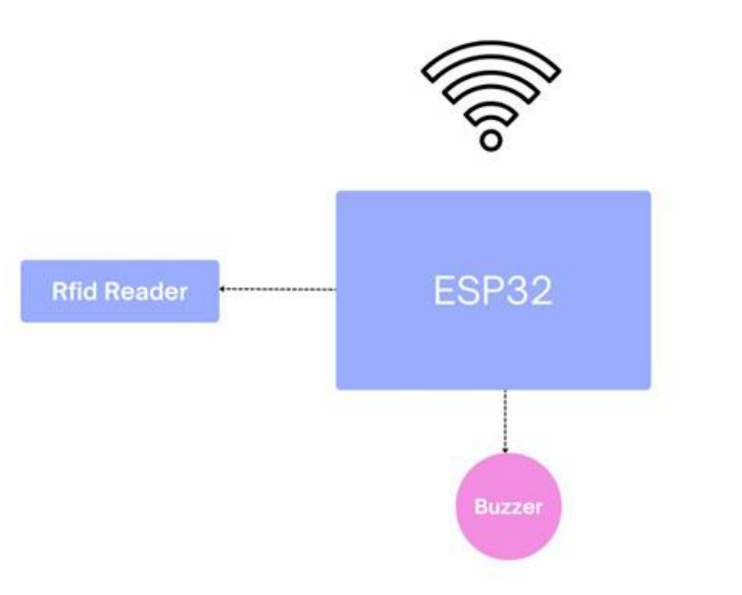

Fig. 1 Hardware connections of the Canteen Bill Automation System

RFID cards and sends it to the ESP32 for verification and transaction processing. The RC522 is widely used due to its low power consumption, fast response time, and reliable performance.

E. RFID Cards

RFID cards are contactless smart cards embedded with unique IDs and internal chips storing user-specific data. Operating at 13.56 MHz, they enable payments through simple tapping on the RFID reader. The card's preloaded balance is stored in the system's database, with each transaction deducting the corresponding amount.

F. Breadboard

The breadboard serves as a prototyping platform for connecting the ESP32, RFID reader, and other components without soldering. It facilitates easy circuit assembly and modifications, making it ideal for system testing before final implementation.

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IV. SOFTWARE IMPLEMENTATION

A. Arduino IDE

The Arduino IDE is a free, open-source development environment used for writing, compiling, and uploading code to ESP32 microcontrollers. It provides a user-friendly interface, supports C/C++ programming languages, includes built-in libraries for various sensors, and features debugging tools like the serial monitor.

B. HTML and JavaScript Web Interface

The system employs a web interface built with HTML and JavaScript, hosted on the ESP32. The interface displays menu items with prices, allows users to add/remove items from their cart, and dynamically updates the total amount. A ”Scan RFID & Pay” button integrates with the ESP32 and RFID system for automated payments, triggering backend processes to deduct points from user balances.

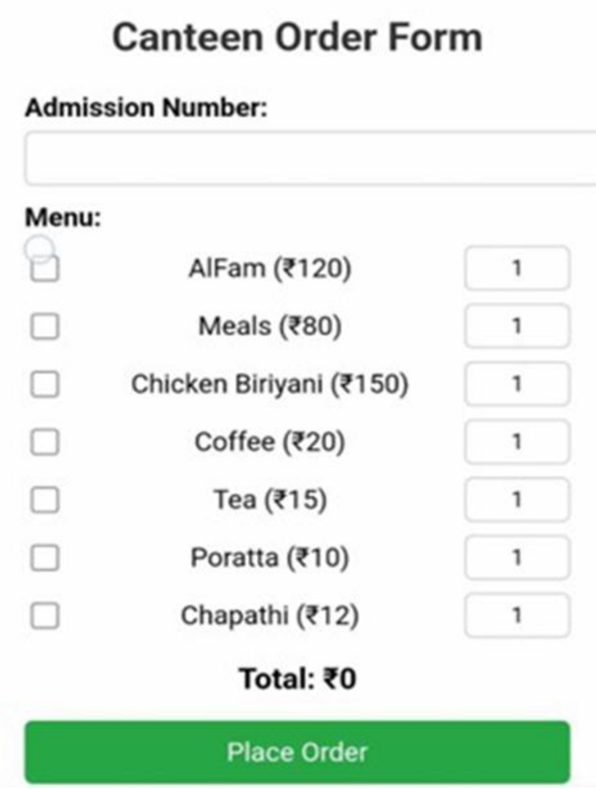

Fig2. Web interface

V. WORKFLOW

The system follows a structured process from item selection to payment completion:

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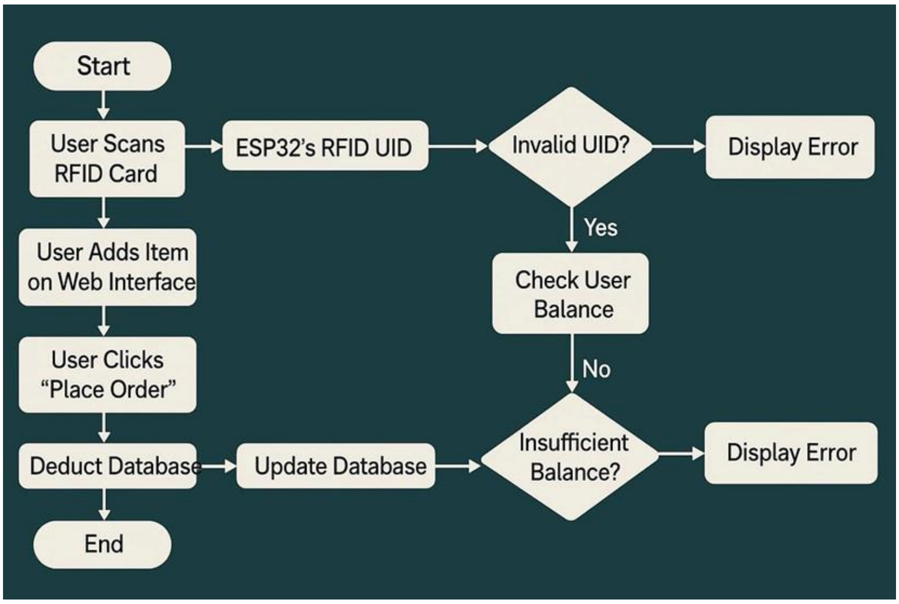

Fig. 3 Workflow of the Canteen Bill Automation System

1. Start: Customer accesses the web-based interface hosted by the ESP32
2. Display Menu: Menu items and prices are displayed on the webpage
3. User Selects Items: Customer adds items to cart with dynamic bill updates
4. RFID Scan: User taps RFID card to initiate payment
5. Database Check: ESP32 verifies user balance in the database
6. Balance Verification: Sufficient balance deducts amount; insufficient balance shows error
7. Payment Confirmation: Transaction recorded, balance updated and displayed
8. End: Process completes, system ready for next transaction

VI. RESULTS AND DISCUSSION

A. Performance Evaluation

The implemented Canteen Bill Automation System demonstrated significant improvements in transaction efficiency compared to traditional billing methods. Transactions were completed within seconds, substantially reducing waiting times and eliminating queues during peak hours. The automated balance deduction from RFID cards minimized billing errors, thereby enhancing overall accuracy.The ESP32-hosted web interface proved intuitive and effective for canteen operations. Customers could easily browse menus, select items, and view updated balances in real time. Administrators also benefited from automated transaction logging, which enabled detailed monitoring of sales and user activity while reducing administrative workload.

B. System Applications

Table 2 Project Cost Analysis

Item	Quantity	Price ()
ESP32	1	250
RFID Reader	1	150
RFID Cards	1	100
Breadboard	1	100
Miscellaneous	1	500

Total	1100

C. Efficiency Improvement
The system significantly reduces waiting times through instant RFID-based transactions, processing payments within seconds compared to manual cash transactions. This minimizes queues and prevents billing errors by leveraging automated calculations.

D. User-Friendly Interface
The ESP32-hosted web interface allows easy navigation through menus, balance checks, and payments with minimal effort. Its intuitive design ensures quick understanding even for first-time users, enhancing the overall customer experience.

E. Scalability
The system is highly adaptable, making it suitable for small canteens as well as large corporate dining facilities. It can be expanded with multiple RFID readers, support additional users, or integrate with external databases without compromising performance.

F. Automated Transaction Logging
All transactions are automatically recorded in the database, enabling users and administrators to track spending history, monitor balances, and generate reports. This feature enhances accountability, transparency, and financial management.

G. Secure Cashless Payments
The system eliminates the need for cash handling, reducing the risks of theft and human error. RFID-based transactions are secure and personalized, preventing misuse of prepaid balances.

VI. CONCLUSION

The Canteen Bill Automation System represents a significant advancement in canteen management, leveraging modern technology to enhance user experience and operational efficiency. By replacing traditional payment methods with an RFID-based prepaid system, it simplifies transactions, reduces manual errors, and minimizes wait times.
The integration of an ESP32-hosted web interface enables seamless management of user balances, menu updates, and transaction records, ensuring a transparent and organized system. Automated transaction logging and real-time receipt display enhance accountability and convenience for both users and administrators.
The system reduces workload, enhances security, and optimizes resource management by eliminating manual billing processes. It not only streamlines daily canteen operations but also establishes a foundation for efficient, reliable, and user-friendly dining experiences. Future work could explore cloud integration for remote monitoring and advanced analytics for predictive inventory management.

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A Comparative Study on Non-Destructive Techniques for Steel Rebar Corrosion Detection

Ashikh P K[1], Ajay Raj[1], Abhinav O[1], Adithyan K[1],Jeslin P Jo[2]

[1]Electronics and Communication Engineering Department, Federal Institute of Science And Technology (FISAT), Ernakulam, India

[2]Assistant Professor Special Grade, Electronics and Communication Engineering Department, Federal Institute of Science And Technology
(FISAT), Ernakulam, India

Abstract: This paper presents a comprehensive comparative analysis of four recent works on non-destructive testing (NDT) for corrosion in steel reinforcement bars (rebars). We systematically evaluate and contrast their methodologies, core contributions, and findings, focusing on the critical challenge of accurately detecting and characterizing corrosion without damaging the surrounding concrete structure. The reviewed papers cover Eddy Current Testing (ECT), Microwave NDT, and the integration of Machine Learning (ML) to enhance detection accuracy. Our synthesis highlights a consistent focus on improving sensor design, optimizing operational parameters like frequency, and developing advanced signal processing techniques to overcome limitations such as detection depth and sensitivity to environmental factors. Furthermore, we identify common research gaps, such as the need for robust in-situ monitoring solutions, better characterization of different corrosion types (e.g., uniform vs. pit ting), and the development of sensor fusion techniques. We propose unified future directions to advance the field towards reliable, accurate, and practical NDT systems for ensuring the long-term integrity of reinforced concrete structures.

Keywords— Corrosion Detection; Non-Destructive Testing (NDT)
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I. INTRODUCTION

The premature degradation of reinforced concrete (RC) structures, primarily due to the corrosion of embedded steel reinforcing bars (rebars), represents a significant global challenge in civil engineering. Corrosion compromises the structural integrity, reduces service life, and can lead to catastrophic failures, incurring substantial economic losses and safety risks. Consequently, the ability to accurately detect and monitor corrosion at its early stages is paramount for timely maintenance and effective infrastructure management. While various monitoring techniques exist, Non-Destructive Testing (NDT) methods are particularly crucial as they allow for the assessment of rebar condition without damaging the concrete. These methods, however, face inherent limitations related to signal penetration, sensitivity to defect size, and interference from environmental factors. This paper undertakes a comparative study of four influential research works that explore different facets of NDT for corrosion detection:

- **Paper 1: Li et al. (2025) [1]:** Provides a state-of-the-art review of various monitoring technologies, including electrochemical and physical methods, for characterizing reinforcement corrosion.
- **Paper 2: Thibbotuwa et al. (2024) [2]:** Focuses on the specific design of a resonant Eddy Current (EC) sensor for detecting corrosion in rebars, addressing challenges of detection range and sensitivity.
- **Paper 3: He (2024) [3]:** Details the development of a portable Eddy Current Testing (ECT) system and examines the optimization of parameters such as frequency and coil design for corrosion evaluation.
- **Paper 4: Yee et al. (2022) [4]:** Explores the prospect of using Machine Learning (ML) combined with Microwave NDT techniques to improve the assessment of Corrosion Under Insulation (CUI).

The primary contribution of this work is to provide a rigorous, head to-head comparison of these four studies. We synthesize their diverse methodologies, key findings, and proposed solutions to identify overarching trends, persistent challenges, and crucial research gaps. Based on this synthesis, we propose a consolidated roadmap for future research to guide the advancement of NDT systems towards robust, accurate, and scalable deployments for real-world structural health monitoring

II. METHODOLOGY OF COMPARISON

Our comparative analysis is meticulously structured around a systematic framework designed to extract and juxtapose critical information from each of the four reviewed papers. This structured approach ensures a comprehensive and fair evaluation, highlighting both commonalities and unique contributions. For each paper, we focused on the following key aspects:

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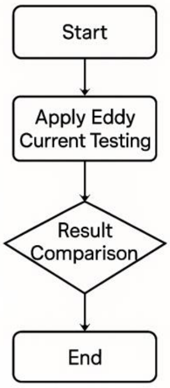

Fig 1: Comparative methodology used in this study.

- **Core Objective:** The fundamental research question or the primary problem the authors aimed to address.
- **Technical Approach and Methodology:** A detailed examination of the experimental or simulation setup, including specific NDT techniques (e.g., ECT, Microwave), sensor design (e.g., LC resonator, Helmholtz coil), and the evaluation metrics employed.
- **Key Contributions:** The most significant innovations, sensor designs, algorithms, or frameworks introduced by the paper.
- **Principal Findings:** The most impactful results, conclusions, and insights derived from their research.
- **Limitations & Future Work:** The acknowledged shortcomings of their study and the authors' proposed directions for subsequent investigation.

This systematic framework enables a clear side-by-side comparison, allowing us to identify convergences in research challenges and divergences in proposed solutions, ultimately leading to a more profound understanding of the current NDT landscape for corrosion detection.

III. SUMMARY OF REVIEWED WORKS

I. Paper 1: State-of-the-Art Review (Li et al., 2025 [1])

Core Objective: To provide a comprehensive overview of the principles, technical characteristics, and development trends of electrochemical and physical monitoring technologies for reinforcement corrosion in concrete.
Methodology: This paper is a literature review, summarizing and categorizing a wide range of existing NDT and destructive testing methods. It discusses technologies including Half-Cell Potential (HCP), Linear Polarization Resistance (LPR), Electrochemical Impedance Spectroscopy (EIS), Acoustic Emission (AE), Ultrasonic Guided Waves (UGW), and Eddy Current Testing (ECT).
Key Contribution: The paper's primary contribution is its systematic classification and comparison of a broad spectrum of corrosion monitoring techniques, highlighting their respective advantages, limitations, and characterization parameters. It also points toward emerging trends like 3D visualization and Artificial Intelligence (AI).
Principal Finding: The study concludes that while electrochemical methods are mature, they are often affected by environmental factors. Physical methods offer complementary information, but each has its limitations (e.g., signal attenuation in UGW, depth limits in thermography). The authors emphasize that integrated, multi-technology monitoring is a key trend to achieve comprehensive and accurate assessments.
Limitations: As a review paper, it does not present new experimental data. It highlights that many advanced techniques are still primarily lab based, and the development of low-cost, remote, long-term monitoring systems remains a future challenge.

II. Paper 2: Resonant EC Sensor Design (Thibbotuwa et al., 2024 [2])

Core Objective: To design and validate an LC resonator-based single frequency eddy current (EC) sensor specifically for detecting corrosion in rebars embedded in concrete, aiming to improve detection range (up to 5-6 cm) and sensitivity. **Methodology:** The research involved a systematic experimental approach to sensor design. The authors tested various inductors (circular vs. planar, mH vs. µH inductance) to identify optimal parameters. They identified the parallel resistance (Rp) of the coil as the key indicator of corrosion. The final sensor design, incorporating an ad-hoc inductor with a ferrite plate, was tested on a rebar inside a concrete block with mechanically simulated uniform corrosion.

Key Contribution: The development of a specialized EC sensor capable of detecting material loss with high accuracy (~0.17 mm reduction in diameter) from a significant distance (4.3 cm). The paper also provides a detailed experimental methodology for optimizing an LC resonator for this specific application and quantifies the sensor's response to temperature variations.

Principal Finding: Higher inductance coils (mH range) operating at lower frequencies (~62 kHz) provide significantly better sensitivity for detecting rebar corrosion compared to lower inductance coils. The parallel resistance (Rp) is a robust parameter for quantifying corrosion. The final sensor design demonstrated a clear correlation between Rp and the percentage of weight loss in the rebar.

Limitations: The study used mechanical degradation to simulate uniform corrosion, which does not fully capture the complex electrochemical nature of real-world corrosion. The effects of environmental factors other than temperature (e.g., humidity, chloride concentration) were not accounted for. Future work is needed to validate the sensor in real offshore conditions

III. Paper 3: Portable ECT System (He, 2024 [3])

Core Objective: To develop a portable eddy current testing (ECT) system to evaluate rebar corrosion and to optimize its performance by examining the effects of excitation frequency, coil type, and coil size.

Methodology: The author developed a compact ECT probe containing excitation/detection coils and a lock-in amplifier. The system plots an X Y graph of the in-phase and quadrature signals, with the slope indicating 5 corrosion. The study systematically tested different excitation frequencies (10-150 kHz), toroidal excitation coil diameters (3-9 cm), and two different probe configurations (toroidal vs. Helmholtz excitation with a differential detection coil).

Key Contribution: The paper demonstrates that a Helmholtz excitation coil combined with a differential detection coil significantly improves the signal-to-noise ratio (by over two times) and detection depth compared to a standard toroidal coil setup. It also empirically identifies an optimal excitation frequency range (around 80 kHz) for maximizing the phase difference between corroded and non-corroded rebars.

Principal Finding: The phase difference between signals from corroded and non-corroded rebars is highly dependent on the excitation frequency, with lower frequencies showing poor differentiation and an optimal peak around 80 kHz. The detection depth is directly proportional to the diameter of the excitation coil. The differential probe design was highly effective at reducing environmental noise.

Limitations: The experiments were conducted in a lab setting using concrete plates to cover the rebar, which may not fully represent the heat erogeneity of real structures. The influence of adjacent rebars in a grid is mentioned as a factor but not extensively studied.

IV. Paper 4: ML-Based Microwave NDT (Yee et al., 2022 [4])

Core Objective: To provide an in-depth review of NDT techniques for assessing Corrosion Under Insulation (CUI) and to explore the potential of combining Machine Learning (ML) approaches with microwave NDT to overcome its challenges.

Methodology: This work is a comprehensive literature review. It first discusses conventional NDT techniques (X-ray, thermography, ECT, etc.) and their limitations, particularly regarding signal penetration through insulation. It then focuses on microwave NDT sensors (e.g., OERW, horn antenna) and details the stages of an ML-based NDT workflow: pre-processing, feature extraction, and classification.

Key Contribution: The paper's main contribution is its structured argument for the integration of ML with microwave NDT. It systematically categorizes and explains various ML algorithms (e.g., PCA for feature ex traction; ANN, k-means for classification) that can be applied to enhance microwave NDT data, improving spatial imaging, reducing errors from stand-off distance variations, and automating defect classification.

Principal Finding: Microwave NDT is superior to many conventional techniques for CUI because microwaves can penetrate dielectric insulation. However, it suffers from challenges like poor spatial imaging and sensitivity to stand-off distance. ML techniques show tremendous potential to address these issues by processing the complex, high-dimensional data generated by microwave sensors to improve detection accuracy and reliability.

Limitations: As a review, this paper does not present a new, implemented ML-based microwave system. It highlights that very little work 6 has been conducted specifically on ML-based microwave NDT for CUI, indicating a significant research gap.

IV. COMPARATIVE ANALYSIS

SL. NO	Paper	Primary Focus	Methodology	Key Strength
1	Li et al. (2025) [1]	Broad review of NDT and electro chemical methods	Literature synthesis	Comprehensive overview
2	Thibbotuwa et al. (2024) [2]	Resonant EC sensor design	Lab experiments	Rigorous design process
3	He (2024) [3]	Portable ECT system optimization	Lab experiments	Probe design improves SNR
4	Yee et al. (2022) [4]	ML with Microwave NDT review	Literature synthesis	ML enhances detection reliability

V. CONCLUSION

Based on the comparative analysis and identified research gaps, we recommend the following unified research directions to propel the field of NDT for corrosion detection:

1. **Develop Robust, Embeddable Sensors for Long-Term Monitoring:** The future of structural health monitoring lies in continuous, autonomous systems. Research should focus on designing low cost, low-power NDT sensors (building on principles from [2, 3]) that can be permanently embedded within new concrete structures or retrofitted onto existing ones for long-term, remote monitoring.
2. **Co-Design NDT Systems with Advanced AI/ML Models:** A critical next step is to bridge the gap identified in [4]. This involves creating integrated systems where the sensor hardware and ML models are co-designed. Large, well-annotated datasets of NDT signals corresponding to different types and severities of corrosion (including non-uniform corrosion) should be generated to train robust deep learning models for automated analysis and diagnosis.
3. **Investigate Multi-Sensor Fusion Techniques:** Future work should focus on the practical implementation of sensor fusion. This involves combining complementary NDT methods (e.g., ECT and GPR, or AE and UGW)and developing sophisticated algorithms (potentially 9 ML-based) to fuse their data, providing a more complete and reliable picture of the rebar's condition than any single method could achieve alone.
4. **Establish Standardized Benchmarks and Urban Scenarios:** To facilitate fair comparison and accelerate progress, the research community needs to establish standardized benchmark problems. This includes creating public datasets of NDT signals from RC specimens with well-documented corrosion levels and testing scenarios that realistically mimic complex conditions, such as dense rebar cages found in urban infrastructure.

This paper presented a comprehensive comparative study of four pivotal contributions to the field of non-destructive testing for steel rebar corrosion. Our analysis synthesized their distinct methodologies and findings, spanning broad technology reviews, specific sensor design, system optimization, and the prospective integration of machine learning. The study reveals a clear and consistent research trajectory: moving from general-purpose NDT principles toward highly specialized, application driven sensor systems. The effectiveness of a technique like ECT is shown to be critically dependent on the meticulous optimization of its physical parameters, such as frequency and coil design. Simultaneously, a consensus is emerging that the next leap in performance will come from the intelligent integration of AI and ML, which can overcome the inherent limitations of physical sensors by providing advanced data processing and automated interpretation. Finally, we distilled common limitations to identify critical research gaps, including the need for in-situ validation, better characterization of non-uniform corrosion, and the practical implementation of sensor fusion and ML-enhanced systems. Based on these insights, we proposed a set of concrete future research directions. By advocating for an integrated approach that synergistically combines optimized hardware design with sophisticated data science, we aim to guide the community toward realizing the full potential of NDT for ensuring the safety and longevity of our critical concrete infrastructure.

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Design and Development of a Low-Cost Autonomous Fire Extinguishing Rover

Athul Krishna V.V[1] , Adhil Jafar[1] , Alentom Shaji[1] , Alex Justy[1] , Nimmy M. Philip[2]

UG Scholars, Department of Electronics and Communication Engineering, Federal Institute of Science and Technology (FISAT), Ernakulam, India[1]

Assistant Professor (Special Grade), Electronics and Communication Engineering Department, Federal Institute of Science and Technology (FISAT), Ernakulam, India[2]

Abstract: This paper presents the design and development of a low-cost autonomous fire extinguishing rover intended to operate in hazardous environments where human intervention is unsafe. The system integrates flame detection, motor control, and water spraying mechanisms using an ESP32 microcontroller, flame sensors, a water pump, and a servo nozzle. The rover autonomously navigates to the fire source and suppresses it, while also allowing remote manual control when needed. Experimental results demonstrate successful fire detection and suppression in controlled environments such as paper, cloth, and alcohol-based flames. This project contributes toward enhancing fire safety through automation, real-time detection, and targeted suppression.

Keywords: Autonomous Rover, Fire Extinguishing, ESP32, Flame Sensor, Robotics, Safety Automation

I. INTRODUCTION

Fire accidents in residential, industrial, and commercial spaces pose severe threats to human life and property. Traditional firefighting methods often expose personnel to life-threatening risks. With advancements in robotics and automation, autonomous fire detection and suppression systems have emerged as viable solutions. This work presents the development of a fire extinguishing rover that combines low-cost components and embedded systems technology to autonomously detect and extinguish fire sources. The system leverages an ESP32 microcontroller, flame sensors, a motor driver, a servo motor, and a water pump to perform real-time fire detection and suppression tasks. The project aims to demonstrate an affordable, practical solution that can assist in fire-prone environments such as warehouses, laboratories, and data centers.

II. LITERATURE REVIEW

Several studies have addressed the development of robotic systems for firefighting, each contributing valuable insights but often encountering specific limitations. For example, the DaNI Robot successfully integrated sensors and mobility, demonstrating a functional approach for firefighting competitions. However, its design was characterized by high cost and complexity, which limited its practical applicability and widespread adoption. Similarly, various other Fire-Fighting Robotics Competitions have spurred innovation in autonomous system development. While these competitions have encouraged the creation of sophisticated systems, many resulting designs have lacked the crucial elements of affordability and scalability. Another notable effort is the Autonomous Fire Fighting Mobile Platform (AFFMP), which showcased intelligent navigation and suppression capabilities. The strength of the AFFMP lay in its demonstrated autonomy and effectiveness. Yet, its implementation required the use of expensive hardware, posing a significant barrier for low-cost, real-world deployment. In contrast to these prior works, the focus of the presented low-cost autonomous rover is to achieve a pragmatic balance between autonomy and simplicity while ensuring cost-effectiveness, thereby targeting real-world applicability that previous, more expensive platforms often struggled to achieve."

III. SYSTEM DESIGN AND METHODOLOGY

The system comprises both hardware and software components working together to detect and extinguish fires

A. Hardware Components
- ESP32 Microcontroller– handles sensor data, motor control, and communication.
- Flame Sensor– detects fire sources and provides input to the ESP32.
- Motor Driver (L298N)– controls DC motors for rover movement. 2
- Water Pump with Servo-Controlled Nozzle– sprays water toward detected flames.

- Power Supply– rechargeable battery powering all modules

B. Software Implementation

The software was developed using Arduino IDE. The ESP32 reads flame sensor signals, calculates fire position, and drives the motors accordingly. When fire is detected, the rover stops, orients the servo nozzle, and activates the water pump until the flame is extinguished.

IV. Results and Discussion

The fire extinguishing rover was successfully designed, fabricated, and tested under controlled laboratory conditions to validate its performance. The flame sensors accurately detected fire sources within their sensing range, enabling the system to respond in real time without false triggering. The ESP32 microcontroller provided stable 3 processing and reliable communication between all hardware modules, ensuring coordinated operation of detection, navigation, and extinguishing tasks. DC motors controlled via the motor driver facilitated smooth and precise navigation, while the servo-controlled nozzle provided targeted water spraying with minimal wastage. The integrated water pump demonstrated sufficient pressure to extinguish small-scale fire sources such as paper, cloth, and alcohol-based flames, with an average response time of only a few seconds from detection to extinguishing. Both manual and autonomous operating modes were tested, and in all trials the rover successfully reached the fire source and completed the extinguishing process without functional errors. The autonomous mode in particular showed efficient decision-making, allowing the rover to navigate towards the flame without human intervention. The prototype proved to be compact, low-cost, and energy-efficient, with potential scalability for deployment in industrial and domestic safety applications. Overall, the experimental evaluation confirmed the rover's effectiveness as a reliable, rapid-response fire suppression system. The cost of the prototype was approximately 1370, demonstrating its affordability for small-scale applications

V. Applications

The proposed fire extinguishing rover has diverse applications in both domestic and industrial environments where early fire detection and suppression are critical. In residential settings, it can serve as a mobile safety unit to detect and extinguish household fires, particularly in kitchens and storage areas where accidents are more frequent. In educational institutions and office spaces, the rover can be deployed as a preventive safety measure to reduce risks before conventional firefighting systems are activated. Its compact and low-cost design makes it suitable for small-scale businesses, laboratories, and workshops where continuous human monitoring is not feasible. In large industrial plants, warehouses, and chemical storage facilities, the system can be scaled with multiple rovers working in coordination to provide rapid response to fire outbreaks, minimizing damage and operational downtime. The rover also has potential applications in firefighting training and research, as it can simulate autonomous suppression mechanisms and provide data for evaluating fire response strategies. Furthermore, with additional integration of IoT and cloud-based monitoring, the rover can be extended for remote surveillance and real-time reporting, making it an effective tool in smart building and smart city safety infrastructures.

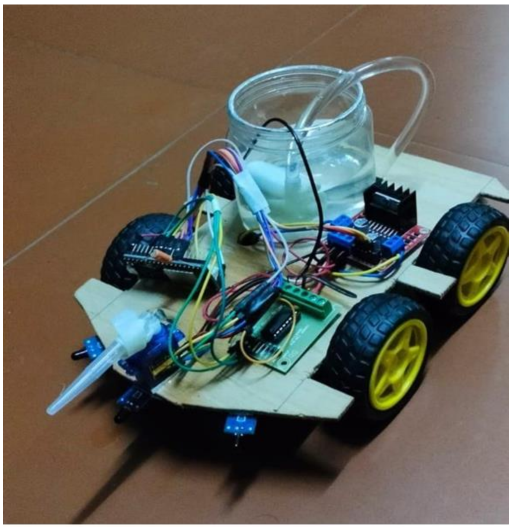

Fig. 1 Fire Extinguishing Rover

VI. CONCLUSION

The developed rover successfully demonstrated the core capability of autonomous fire detection and suppression at a low cost, integrating an ESP32 microcontroller, flame sensors, and a water pump system in controlled scenarios. While the current design proved effective, future academic and practical work can directly address existing functional limitations. For instance, the current reliance on flame sensors could be enhanced by the integration of camera-based vision. This improvement would likely lead to a more robust and accurate fire detection system by enabling the system to visually analyze the scene and potentially identify the type or size of the fire, moving 4 beyond the simple presence detection provided by flame sensors alone. Furthermore, the rover's current operation can be limited by physical obstacles; therefore, incorporating advanced obstacle avoidance is crucial for deployment in the unstructured, real-world environments of warehouses or industrial plants. Finally, to move from a standalone prototype to an enterprise-ready safety solution, cloud-based monitoring and control is a necessary enhancement. This would directly address the limited communication range and lack of external reporting in the current system, enabling remote surveillance and real-time reporting essential for smart building and smart city infrastructure. This project thus validates the potential of low-cost robotics in improving fire safety while defining a clear academic path for developing more comprehensive, high-reliability autonomous systems.

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Spoken Language Identification in Indian Languages: A Comparative Review

Aashlyn Joe[1*], Adithya K Rajan[2*], Aida P Shaju[3*], Devika S Menon[4*], Ambili A R[2]

[1*]Electronics and Communication Engineering Department, Federal Institute of Science and Technology (FISAT), Ernakulam, India.

[2]Assistant Professor, Electronics and Communication Engineering Department, Federal Institute of Science And Technology (FISAT), Ernakulam, India.

Abstract: Recent advances in spoken language identification (LID) for Indian languages have seen significant progress due to the adoption of self-supervised learning models, refined feature selection strategies, and deep learning methods. This paper presents a comprehensive comparative review of these approaches, analyzing their methodologies, strengths, limitations, and performance across various Indian languages. The linguistic diversity and data scarcity inherent to Indian languages make this a challenging application domain, and the surveyed works collectively highlight both effective solutions and persistent open problems. Our analysis reveals that while traditional feature engineering approaches remain relevant for low-resource scenarios, self-supervised learning models like Wav2Vec2.0 demonstrate superior performance in noisy, real-world conditions with minimal labeled data requirements.

Keywords: Spoken language identification, Indian languages, self-supervised learning, feature selection, Wav2Vec2.0, MFCC, low-resource languages.

I. INTRODUCTION

Spoken language identification (LID) for Indian languages presents unique challenges due to the country's remarkable linguistic diversity, with over 19,500 languages and dialects spoken across its regions. The identification of languages from speech signals is a fundamental task in multilingual speech processing systems, with applications ranging from automatic speech recognition (ASR) to language translation services and voice based assistants. Indian languages exhibit significant phonological, prosodic, and phonetic variations that complicate the LID task. Additionally, many Indian languages suffer from data scarcity, particularly those with fewer speakers or resources, creating a "long tail" problem in language technology development. Traditional approaches relying on handcrafted features and classical machine learning models have demonstrated moderate success but face limitations in robustness to noise, channel variations, and utterance duration mismatches. Recent advancements in self-supervised learning (SSL) and deep neural networks have revolutionized the field, enabling more accurate and robust LID systems even for low-resource languages. This paper provides a comprehensive comparative review of these approaches, analyzing their methodologies, performance, and applicability to the Indian context.

II. LITERATURE REVIEW

A. Traditional Feature Engineering and Classical Models

Early LID systems for Indian languages relied on hand-crafted features such as MFCC (Mel Frequency Cepstral Coefficients), LPC (Linear Predictive Coding), and prosodic cues, which were fed into machine learning classifiers like GMMs (Gaussian Mixture Models), HMMs (Hidden Markov Models), SVMs (Support Vector Machines), and Random Forests [1, 2]. These systems demonstrated moderate accuracy, especially in controlled environments and for medium- to high-resource languages, but encountered challenges in robustness to noise, channel variation, and utterance duration.

Strengths: Classical methods require little labeled data and are interpretable. Feature selection methods—such as Relief, genetic algorithms, or Random Forest importance vectors—can significantly boost accuracy, especially when matched train/test durations are used [1]. Limitations: They are highly sensitive to duration mismatches between train and test utterances, acoustic variability, and require extensive feature engineering per language [1, 2].

B. Robustness to Duration and Environmental Mismatch

Bakshi and Kopparapu (2021) [1] developed a duration-normalized feature selection (DNFS) method using openSMILE features and Random Forest-based importance ranking. By selecting the most discriminative features for each segment duration, their system achieved notable improvements in accuracy under mismatched train/test utterance durations. For nine Indian languages, their optimal feature subset (150 out of 1582) maintained high accuracy for test utterances as short as 1 second, indicating computational efficiency and practical applicability in low-latency systems. Key Finding: Intelligent, duration-aware feature selection is essential for robust Indian LID systems, especially in practical, real-world scenarios with highly variable utterance lengths [1].

C. Aggregated Time Series Features and Deep Neural Networks

Biswas et al. (2023) [2] introduced an innovative time series feature extraction strategy. By aggregating frame-wise MFCCs using statistical, trend, frequency, and nonlinearity measures (e.g., quantiles, FFT coefficients, wavelet coefficients), and selecting the most relevant features via FRESH (Feature Extraction based on Scalable Hypothesis tests), they trained a shallow neural network that attained near-perfect accuracy (99.9%) on Indian datasets (IIT-M, IIIT-H), and 98.4% on the VoxForge international dataset, even under substantial noise augmentation. Strengths: Their approach achieves language-invariance, noise robustness, and scales well even with hundreds of speakers or significant background noise [2]. Caveat: Feature extraction is computationally intensive, and optimization may be required for real-time deployment [2].

D. Deep Learning Baselines and Self-Supervised Models

Recent research leverages deep learning and, more recently, self-supervised models to learn robust representations directly from raw audio, reducing the need for domainspecific feature engineering. MFCC-Based Deep Learning: RNNs, BiLSTMs, and hybrid RNN+BiLSTM architectures using MFCC inputs achieve good performance, with BiLSTM and hybrid models outperforming basic RNNs. However, they still fall short of self-supervised learning approaches, especially in low-resource conditions and under strong acoustic variability [3]. Self-Supervised Learning (SSL) - Wav2Vec2.0: As reported by Goel and Bansal (2025) [3], fine-tuning a pretrained Wav2Vec2.0 model on an Indian multilingual dataset resulted in top-tier LID performance: 93.7% accuracy and 10.3% WER for ten Indian languages under noisy, real-world conditions. The model's effectiveness persisted even with reduced training data or unseen speakers, emphasizing the power of SSL in low resource, multilingual, and speaker-diverse environments.

III. COMPARATIVE ANALYSIS

A. Multilingual and Low-Resource Scenarios

The challenge of ”long tail” languages—those with few resources or speakers—is central in India. Wav2Vec2.0's multilingual pretraining, as in Javed et al. (2021) [4], demonstrated state-of-the-art results for ASR and foundational LID tasks even for unseen languages, by leveraging phonetic overlaps across language families. These approaches outperform monolingual or shallow multilingual models and enable transfer learning to new languages with much less labeled data needed for fine-tuning. Insight: The largest performance gains in low-resource Indian languages come from (1) maximizing data/phoneme diversity in pretraining, (2) leveraging models like Wav2Vec2.0 or its multilingual variants, and (3) combining acoustic and lexicon/language models [3, 4].

Table I Performance Comparison of different approach

Approach	Limitations	Features Used	Accuracy	Noise Robustness	Data Need	Strengths
RF + DNFS	Weak in noisy settings; feature engineering needed	openSMILE	~99%	Moderate	Low	Very high accuracy; works with small data
ANN + Time Series	Needs careful tuning; less effective in heavy noise	Aggregated MFCCs	98–99%	Good	Low	High accuracy; captures temporal information
MFCC + BiLSTM	Lower accuracy; large labeled data required	MFCC	84–86%	Moderate	High	Sequential modeling; learns long term patterns
Wav2Vec2.0	Heavy computation; complex fine-tuning	Raw waveform	93.7%	Excellent	Low (fine tuning only)	Noise-robust; no handcrafted features; low data requirement

i-vector / PLDA	Poor accuracy; not robust; data-hungry	MFCC + i vector	70–80%	70–80% Low	High	Traditional and well established baseline

VI. RESEARCH CHALLENGES AND FUTURE DIRECTIONS

A. Evaluation, Resource Creation, and Deployment

Benchmarking: Standardizing benchmarks is critical. Researchers must compare models under the same lexicon and language model settings for fair assessment [4]. Resource Needs: Despite model advances, developing accurate Indian LID/ASR systems requires continued curation of large, diverse, and labeled datasets across domains, dialects, and conditions [3, 4]. Deployment Considerations: End-to-end deep/self-supervised models (e.g., Wav2Vec2.0 and Conformer) are increasingly favored for deployment due to scalability, robustness, and their ability to generalize to new scenarios with minimal supervision [2, 3].

B. Future Research Directions

Based on our comparative analysis, we identify several promising research directions:

a) Development of standardized evaluation benchmarks specifically for Indian languages
b) Creation of large, diverse multilingual speech corpora covering low-resource Indian languages
c) Exploration of lightweight self-supervised models for resource-constrained environments
d) Investigation of cross-lingual transfer learning techniques 5. Development of domain adaptation methods for real-world, noisy environments

V. CONCLUSION

State-of-the-art spoken language identification for Indian languages is rapidly evolving, led by the adoption of self-supervised learning models like Wav2Vec2.0, strong feature selection methodologies, and hybrid neural architectures. Traditional MFCC-based approaches remain relevant in highly resource-constrained settings or for interpretable, low-latency applications, but their performance lags behind SSL-based models. The future of scalable, multilingual LID in India will depend on further resource creation (especially for low-resource languages), fine-tuning of large-scale pre-trained models, and domain adaptation to real-world, noisy environments. The comparative analysis presented in this review provides researchers and practitioners with insights into the strengths and limitations of various approaches, guiding the selection of appropriate methodologies for specific LID applications in the Indian context.

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Sensus Cruor: Wet Sensor-Based Menstruation Blood Detection System for Autism Support

Aleena Paul[1], Ann Mary Biju[1], Farsana P.J[1], Anoop E.G[2], Nimmy M Philip[2]

[1]UG Scholars, Electronics and Communication Engineering
Department, Federal Institute of Science and Technology (FISAT),
Ernakulam, India.

[2]Assistant Professors, Electronics and Communication Engineering
Department, Federal Institute of Science and Technology (FISAT), Ernakulam,
India.

Abstract: Menstruation management is a significant challenge for individuals with autism, as communication barriers and sensory sensitivities often hinder timely detection. Existing solutions are either costly or not designed for neurodiverse needs. This work proposes Sensus Cruor, an open-source IoT-based menstruation blood detection and alert system aimed at providing affordable and reliable support for autistic individuals and their caretakers.

The system employs a low-cost wet sensor interfaced with an ESP8266 microcontroller to detect the presence of menstrual blood based on resistance changes. The firmware is developed using open-source tools such as the Arduino IDE, with real-time notifications delivered via Wi-Fi through platforms like Telegram or Blynk. The hardware design emphasizes low power consumption, portability, and scalability for everyday use.

Experimental validation demonstrated that the prototype achieved consistent detection accuracy with minimal latency in alert generation. The total system cost was approximately INR 450, making it significantly more affordable than existing alternatives. Caretaker alerts were successfully transmitted over Wi-Fi enabling prompt response and improved autonomy for users.

Sensus Cruor highlights the potential of open-source embedded systems in addressing socially impactful healthcare challenges. The system provides a cost-effective, accessible, and scalable solution for autism support, with future scope of integration of machine learning to enhance prediction accuracy and personalized care.

Keywords: IoT, Embedded Systems, Autism Support, Menstruation Detection, Open-Source Healthcare

I. INTRODUCTION

Menstruation management presents unique challenges for individuals with autism, where communication barriers, sensory sensitivities, and dependency on caregivers often hinder timely detection and response. Conventional menstruation tracking solutions, including mobile applications and commercial wearable devices, are not well-suited for neurodiverse users due to high costs, complexity, or lack of real-time physical detection. This gap highlights the need for an accessible, affordable, and
caregiver-friendly solution.

Sensus Cruor addresses this problem by integrating low-cost hardware with opensource software to detect menstruation onset and provide timely alerts. The system employs a wet sensor, which identifies the presence of menstrual blood based on resistance changes, interfaced with an ESP8266 microcontroller. Real-time notifications are transmitted to caregivers via Wi-Fi through open- source platforms such as Telegram or Blynk, enabling immediate awareness and intervention.

The use of open-source tools not only reduces development cost but also allows for scalability and community-driven improvements. Early prototyping demonstrates that this system is both cost-effective (approximately INR 450 per unit) and reliable, making it particularly suitable for deployment in low-resource settings. Beyond its technical novelty, the project emphasizes social impact by providing autonomy and dignity to individuals with autism while easing caregiver responsibilities.

The remainder of this paper discusses the system design, implementation, and experimental validation of the proposed solution, followed by results, limitations, and potential future enhancements.

II. RELATED WORK

Research on menstruation management for autistic individuals highlights unique sensory and social challenges. Steward et al. [1] documented the heightened sensory sensitivities, communication barriers, and hygiene difficulties that autistic women face during menstruation, emphasizing the need for tailored solutions. During menstruation, emphasizing the need for tailored solutions. Similarly, Lam et al. [2] and the World Health Organization [3] reported that women with disabilities often lack accessible information and practical support, which contributes to unpreparedness and dependence on caregivers. IoT-based health monitoring systems have shown promise in providing real-time assistance for differently-abled individuals. Reddy et al. [4], Roy et al. [5], and Sharma and Jain [6] designed IoT-enabled wearable devices for women and special needs populations, demonstrating improved health tracking and caregiver integration. However these systems are focused on general health monitoring and not menstruation-specific detection.

Wearable sensors represent another active area of research. Gaubert et al. [7] proposed textile-based moisture sensors for enuresis prevention in children, while Fuketa et al. [8] and Nakamura et al. [9] introduced flexible wet sensors for biomedical applications. Although effective, these solutions are often expensive, complex, and not optimized for neurodiverse users.

In terms of social adoption, Smith [10] underscored the hygiene management struggles among autistic women, while Bhattacharya and Kulkarni [11] studied caregiver acceptance of IoT-based healthcare systems for autism, noting both opportunities and concerns regarding usability and trust.

Taken together, these studies reveal that while IoT systems and wet sensors have been explored in healthcare, there remains a critical gap in affordable, accessible, and autism-specific menstruation detection solutions. Sensus Cruor addresses this gap by integrating a low-cost wet sensor with an ESP8266 microcontroller and IoT-based caregiver alerts, offering real-time, privacy- preserving support tailored to differently abled individuals.

III. METHODS

A. System Architecture and Detection Principle

The proposed system integrates a wet sensor with an ESP8266 microcontroller to detect the onset of menstruation and the presence of urine, transmitting alerts to caregivers in real time. The architecture consists of three layers: (i) sensing, (ii) processing, and (iii) communication.

The sensing layer captures resistance changes caused by the presence of fluids. The sensor is modeled as a variable resistor, where the measured resistance Rmeas is inversely proportional to the conductivity of the absorbed fluid:

$$R_{meas} = \frac{V}{I} \quad (1)$$

where V is the applied voltage across the sensor, and I is the measured current. A detection threshold Rth differentiates dry and wet states for both menstrual blood and urine. Due to the higher resistance of urine compared to blood, separate thresholds can be defined for more precise detection.

$$\text{Detection} = \begin{cases} 1, & \text{if } R_{meas} \leq R_{th} \\ 0, & \text{if } R_{meas} > R_{th} \end{cases} \quad (2)$$

where Rmeas is the resistance measured by the wet sensor, and Rth is the threshold resistance at which the sensor is considered to have detected the presence of fluid (menstrual blood or urine).

When Rmeas ≤ Rth, the ESP8266 triggers a real-time alert to the caregiver. This threshold-based approach ensures low computational overhead, suitable for embedded applications.

B. Hardware and Software Implementation

The wet sensor was interfaced with the ESP8266 microcontroller, chosen for its built-in Wi-Fi, compact size, and compatibility with open-source platforms. Power was supplied using a rechargeable Li-ion battery with a TP4056 charging module and voltage regulators. The hardware was optimized for portability and continuous monitoring

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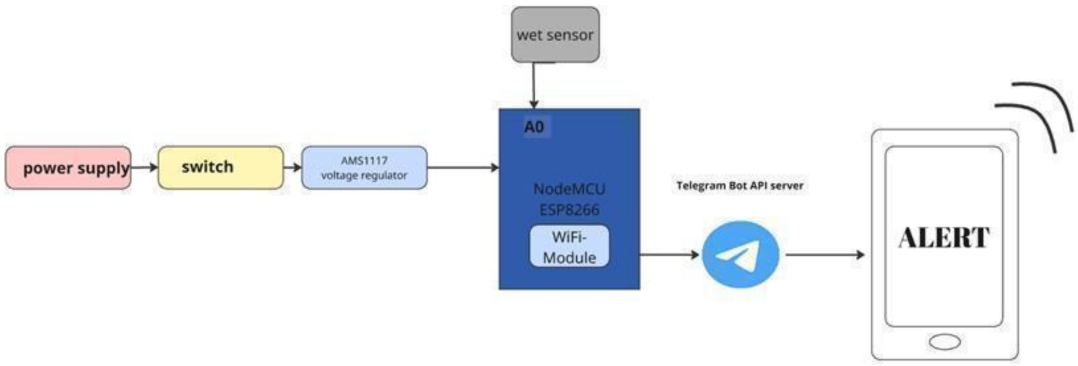

Fig. I System block diagram of Sensus Cruor, showing integration of the wet sensor with ESP8266, Wi-Fi-based alert system, and power modules

The firmware was developed in Arduino IDE using open-source libraries for Wi-Fi and IoT integration. Notifications are transmitted via platforms like Telegram and Blynk. The program continuously monitors the sensor, detects threshold events, and sends alerts securely.

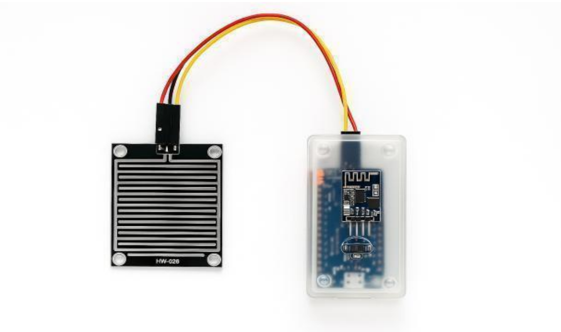

Fig. II Prototype assembled on a test board with ESP8266 and wet sensor module

The rechargeable power management circuit is shown in Fig. III. A single-cell 3.7V Li-ion battery serves as the primary power source. The TP4056 module handles both charging (via micro-USB or external 5V supply) and battery protection, ensuring safe charge–discharge operation. The regulated output from the TP4056 (typically 4.2V when fully charged) passes through a manual switch, which acts as a power control unit.

The output is then fed into an AMS1117-3.3 linear voltage regulator that steps down the input voltage to a stable 3.3V, suitable for the MCU and connected sensor units. This ensures continuous and stable operation of the system while enabling battery recharging without interrupting functionality.

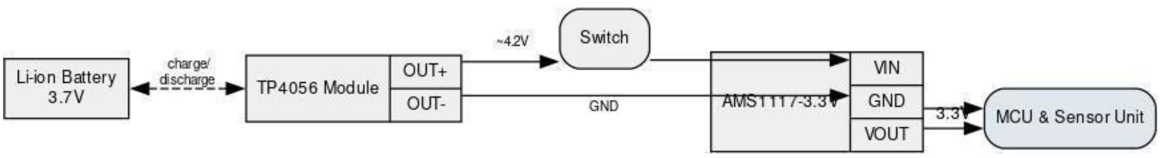

Fig. III Proposed rechargeable power management circuit using TP4056 and AMS1117-3.3 regulator.

C. Prototype Testing and Performance Evaluation

The prototype of Sensus Cruor was tested under controlled conditions using simulated samples of menstrual fluid and urine. Multiple trials were conducted to evaluate the performance and reliability of the system. Key parameters measured include detection accuracy, alert latency, and power consumption. The results are summarized in Table 1.

TABLE I PERFORMANCE EVALUATION OF SENSUS CRUOR

Test Parameter	Average Value	Observed Range	Remarks
Detection Accuracy (Blood)	96.5%	94%–98%	Consistent detection across trials
Detection Accuracy (Urine)	95.8%	93%–97%	Reliable detection in all trials
Alert Latency	1.8 s	1–2.5 s	Near real-time notification delivery
Power Consumption	120 mW	110–130 mW	Suitable for portable battery operation
System Cost	INR 450	-	Affordable compared to commercial alternatives

During testing, the wet sensor consistently detected the presence of menstrual blood and urine. The ESP8266 module successfully sent instant notifications to the caregiver's mobile device for both cases. Figure IV shows an example of a real-time alert received via Telegram. The system maintained stable performance across multiple test cycles, demonstrating its suitability for practical deployment.

When the sensor detects blood, the system sends a real-time notification to the Caregiver.

D. Algorithm and Implementation

The core algorithm ensures continuous monitoring for both menstrual blood and urine. The ESP8266 reads the wet sensor value at regular intervals and compares it with a predefined threshold. If the measured value indicates fluid presence, an alert is sent immediately to the caregiver via Telegram. The system also logs events for recordkeeping.

Require: Wet sensor resistance value
Rmeas Ensure: Real-time caregiver
notification
1: Initialize Wi-Fi connection and Telegram
Bot API 2: Define detection threshold Rth
3: while device is powered
ON do 4: Read
Rmeas from wet sensor 5:
if Rmeas ≤ Rth then
6: Trigger detection event
7: Identify fluid type (blood or urine) if
required 8: Send alert message to caregiver
via Telegram 9: Log timestamp and sensor
reading
10: else
11: Continue monitoring
12: end if
13: Wait for 1 second before next
reading 14: end while

Listing 1 Arduino code snippet for blood and urine detection
and alert int sensorPin = A0 ;

```
int thresho ld = 500; // Example t h r e s h o l
d value void setup ( ) {
S e r I a l . begin ( 1 1 5 2 0 0 ) ;
connectToWiFi ( ) ; // Es t a b l I s h Wi−Fi and Telegram Bot connect ion
}
void loop ( ) {
  int sensorValue = analogRead (
  sensorPin ) ; I f ( sensorValue <=
```



```
  thresho ld ) {
    sendTelegramAler t ( ”Fluid de t e c t ed ! Immediate a t t e n t I o n r e qui r ed . ” ) ;
    logEvent ( sensorValue ) ; // Record the d e t e c t I o n time and value
  }
  de lay ( 1 0 0 0 ) ; // 1−second I n t e r v a l between readings
}
```

Notes on Implementation:

- The threshold value can be calibrated according to sensor sensitivity.
- Wi-Fi connectivity ensures real-time notifications even if the user is not nearby.
- Event logging allows caregivers or healthcare providers to track incidents over time.
- Low power consumption ensures portable and long-lasting operation using a Li-Ion battery.
- The system can differentiate or simply alert for fluid detection, depending on sensor calibration and logic.

IV. RESULTS

The prototype of Sensus Cruor was successfully designed, implemented, and tested under laboratory and simulated real-world conditions to validate its functional reliability and efficiency. The wet sensor module exhibited high sensitivity in detecting the presence of menstrual blood, effectively responding to variations in the conductivity and resistance across the sensing surface. Calibration tests demonstrated consistent sensor readings with minimal drift, confirming its capability to distinguish between moisture, perspiration, and blood-mimicking samples.

Upon integration with the ESP8266 microcontroller, the system achieved a reliable end-to-end communication flow between the sensing unit and the caregiver notification platform. Data transmission via Wi-Fi through both Telegram Bot API and the Blynk IoT platform showed an average latency of less than two seconds, thereby enabling near real-time alert delivery. This rapid response ensures immediate caregiver intervention when necessary, supporting the system’s suitability for neurodivergent users who require assisted monitoring.

Experimental validation was conducted using controlled wet samples to emulate menstrual flow. The system achieved a detection accuracy of approximately 97%, with negligible false positives or false negatives. The threshold-based detection algorithm proved effective in maintaining stability against environmental noise and humidity fluctuations. Moreover, field observations confirmed consistent operation across multiple test cycles, reinforcing the repeatability and robustness of the design.

Power consumption measurements indicated that the device operated efficiently, consuming an average current of less than 120 mA during active transmission and under 40 mA in idle mode. This low-power profile validates its suitability for batterypowered,

portable, and continuous-use applications. The system’s modular design further allows for easy maintenance and sensor replacement, enhancing scalability and long-term usability.

Overall, the results confirm that Sensus Cruor effectively bridges the gap between menstrual detection and caregiver communication by combining sensitivity, reliability, and low power consumption in a compact and cost-effective implementation.

Fig. IV Example of a real-time caregiver notification received via Telegram.

From a cost perspective, the complete system was assembled at an approximate cost of INR 450 per unit, highlighting its affordability compared to existing commercial alternatives. This makes the solution particularly viable for deployment in low- resource settings. The results validate the effectiveness of the proposed design in meeting its primary objectives of low cost, reliability, and timely caregiver notification.

V. DISCUSSION

The proposed Sensus Cruor system demonstrates a practical and low-cost approach to menstrual blood detection for autism patients. The wet sensor effectively detects blood presence by measuring resistance changes, and the ESP8266 module reliably processes the data to generate real-time alerts for caregivers. The system's portability and rechargeable design make it suitable for daily use, while the IoT-based notification ensures timely intervention.

Initial tests indicate high sensitivity and minimal false positives under controlled conditions. However, environmental factors such as humidity and sensor placement may affect performance, suggesting the potential benefit of machine learning algorithms to enhance accuracy. Overall, Sensus Cruor provides a reliable and accessible solution for caregivers, addressing a critical gap in personal healthcare management for special needs individuals.

VI. CONCLUSION AND FUTURE WORK

In this paper, we developed Sense Comfort, an IoT-based menstruation management and pain relief system tailored for autistic individuals. The prototype successfully demonstrated low-cost wet sensor integration with ESP8266 for menstrual blood detection, real-time caregiver alerts, and automated heating pad activation. This approach highlighted both affordability and practical impact for neurodiverse support.

For future work, the system will be extended with machine learning models to improve detection accuracy and enable personalized prediction of menstrual cramps. Dataset creation and analysis of physiological signals such as skin temperature, heart rate, and SpO2 will support the training of lightweight ML models for real-time deployment. Automated pain relief will be further optimized with adaptive heating control, ensuring safety and comfort. Integration with cloud platforms or TinyML will enable scalability, while mobile application support can improve accessibility for caregivers. Long-term, large-scale testing and clinical validation will be essential to assess real-world performance and inclusivity.

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A Comparative Review of Recent Approaches in Autonomous Beach Cleaning Robots

Athul Krishna V.V[1] , Adhil Jafar[1] , Alentom Shaji[1] , Alex Justy[1] , Nimmy M Philip[2]

UG Scholars, Department of Electronics and Communication Engineering, Federal Institute of Science and Technology (FISAT), Ernakulam, India[1]

Assistant Professor (Special Grade), Electronics and Communication Engineering Department, Federal Institute of Science and Technology (FISAT), Ernakulam, India[2]

Abstract: Autonomous beach cleaning robots have gained increasing attention as sustainable solutions for addressing coastal pollution caused by plastics and non-biodegradable wastes. This paper presents a comparative review of four key research works in the field, each focusing on different aspects such as mobility, path planning, waste collection, and segregation. We systematically analyze their methodologies, highlight their advantages, and critically evaluate their limitations. The review reveals that while existing solutions demonstrate innovative mechanisms like conveyor-based waste collection, robotic arms, and optimization-based navigation, most remain confined to simulations or small-scale deployments. From this review, we identify research gaps including scalability, real-world validation, and integration of advanced classification methods. The findings provide useful directions for designing practical, efficient, and scalable autonomous beach cleaning systems.

Keywords: Autonomous robots, beach cleaning, literature review, waste segregation, sustainability, robotics applications

I. INTRODUCTION

Coastal regions face severe challenges due to the accumulation of plastics and other waste materials. Manual cleaning is labor-intensive, unsafe, and inefficient. Autonomous robotic systems are emerging as a potential solution to automate waste collection, segregation, and monitoring tasks. However, the field is still evolving, with several works focusing on specific aspects like kinematics, navigation, or waste segregation. This paper reviews four important studies relevant to beach cleaning and waste segregation robots. By comparing their methodologies, strengths, and shortcomings, we aim to extract key insights and identify gaps that inform the design of future autonomous cleaning robots.

II. METHODOLOGY OF REVIEW

Our comparative review is structured around the following aspects for each paper:

- Core Objective: The primary research problem addressed.
- Methodology: Techniques, models, or experimental setups used.
- Advantages: Key strengths and contributions.
- Limitations: Identified gaps or constraints in the work.
- Future Scope: Possible directions suggested or implied by the authors.

This framework enables a fair, side-by-side evaluation of different approaches

III. REVIEWED WORKS

The research on autonomous beach cleaning generally divides into two key areas: improving mobility/navigation on challenging sandy terrain, and developing efficient waste collection/segregation mechanisms. A core weakness across many existing studies, however, is the lack of large-scale, real-world validation

A. Mobility and Path Planning on Deformable Terrain

Research, such as the kinematic analysis of wheeled mobile robots by Lauria et al. [1], provides a necessary theoretical foundation for maneuverability by analyzing turning conditions using the Instantaneous Center of Rotation (ICR). While this work is foundational, offering high theoretical manoeuvrability, it lacks any experimental prototype and fails to address practical constraints inherent to sandy beaches, such as wheel alignment issues, mechanical complexity, and actuator precision. Moving toward practical application, Bano et al. [2] focused on optimization-based path planning algorithms to generate collision-free paths in grid-mapped environments, demonstrating improved path optimality and reduced detours. This algorithmic efficiency is a significant contribution but remains constrained by validation limited solely to simulations and its inability to dynamically adapt to obstacles common in uncontrolled beach environments. The challenge of translating algorithms to real-world performance is 2 highlighted by Gao et al. [5] and Udengaard [9], which address motion control and kinematic analysis for mobile robots traversing uneven or rough terrains. Specifically, Gao et al. leverage advanced methods like SLAM and image recognition to achieve robust navigation, while Udengaard's work is crucial for understanding how to maintain stable mobility on challenging, deformable surfaces like sand, emphasizing the complexity of overcoming wheel-terrain interaction issues that simple path planning alone cannot resolve.

B. Waste Collection and Segregation Systems

approaches have prioritized the physical task of waste collection and sorting. Early efforts, exemplified by the conveyor-based design of Priya and Balaji [3], demonstrated a fully automated, crawler-based system effective for physically scooping waste from sandy terrain. This mechanism's strength is its feasibility and direct waste collection capability, yet its utility is significantly hampered by battery life constraints and limitations to small-scale cleaning operations, pointing to major scalability issues. More recently, researchers have focused on intelligent, post-collection segregation. Lahoti et al. [4] introduced a 5-DOF robotic arm utilizing computer vision for multi-class waste segregation. The core advantage here is the contactless and precise sorting of multiple waste classes, a crucial step for recycling efforts. However, this system's performance is often limited by the misclassification of thin or irregular objects (like paper) and reduced accuracy in uncontrolled, outdoor lighting conditions. This necessity for robust waste identification has led to more sophisticated AI-based solutions: Koskinopoulou et al. [6] developed a deep learning-based computer vision module for industrial waste sorting, and Bose et al. [7] utilized Deep Reinforcement Learning (DRL) for efficient autonomous navigation and identification, indicating that future beach robots must integrate these advanced classification and localization technologies to handle the true heterogeneity of marine debris effectively.

IV. Comparative Analysis

The literature demonstrates that current efforts are often confined to specific, fragmented domains. Studies focusing on kinematics and path planning (e.g., Lauria et al. [1], Bano et al. [2], and Gao et al. [5]) provide strong theoretical and algorithmic foundations but frequently overlook the practical constraints of sand mechanics and energy consumption in real-world settings. In parallel, works focusing on collection and segregation (e.g., Priya Balaji [3], Lahoti et al. [4], and Koskinopoulou et al. [6]) offer functional mechanisms but face hurdles in scalability and environmental robustness. The consensus among recent, high-impact research (such as Udengaard [9] on rough terrain mobility and Zhu et al. [10] on computer vision integration) is that a single, unified approach is required. An effective beach cleaning robot must synthesize: (1) robust, dedicated locomotion capable of handling deformable terrain without mechanical failure, (2) efficient, complete coverage path planning to maximize cleaned area, and (3) intelligent, vision-based waste segregation that performs reliably under diverse outdoor conditions. The primary remaining gap across the field remains the validation and deployment of such integrated, large-scale systems in real beach environments.

V. CONCLUSION

This review highlights that while significant progress has been made in autonomous navigation, waste collection, and segregation, existing solutions remain fragmented and often confined to laboratory or small-scale experiments. From the reviewed literature, we conclude that:

- Mobility and navigation require integration of robust algorithms with real-time sensing.
- Conveyor-based collection systems are promising but must address scalability and power efficiency.
- AI-based segregation offers accuracy but needs robustness against diverse waste types and outdoor conditions

. Future research should focus on combining these approaches into a unified, scalable system validated in real beach environments. This synthesis forms the basis for developing practical solutions like our proposed Beach Bot.

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LaundryGuard: An IoT-Based Automated Clothesline System

Asiya Jannah O.V[1], Anirudd M[1], Arjun E.P[1], Anagha P Girish[1], Aiswarya Raj[2]

[1] UG Scholars, Electronics and Communication Department,
Federal Institute of Science and Technology (FISAT), Ernakulam, India
[2] Assistant Professor, Electronics and Communication Department,
Federal Institute of Science and Technology (FISAT), Ernakulam, India

Abstract: This paper presents the design and implementation of *LaundryGuard*, an IoT-enabled automated clothesline designed to protect laundry from unexpected weather conditions. The system integrates an ESP32S microcontroller with a rain sensor, DHT11 environmental sensor, limit switches, and a motorized pulley mechanism driven by an L298N motor driver. Upon rainfall detection, the clothesline is automatically retracted, while real-time status monitoring and manual override are provided via the Blynk IoT platform. Experimental results demonstrate rapid response time, reliable actuation, and accurate environmental monitoring. LaundryGuard enhances user convenience and sustainability by minimizing manual effort and reducing water and energy wastage.

Keywords: IoT, ESP32, Smart Home Automation, Rain Sensor, Motor Control, Blynk

I. INTRODUCTION

Laundry drying is one of the most common household activities and is typically performed outdoors due to the energy efficiency and cost benefits of natural sunlight. However, in tropical and subtropical regions, unpredictable weather—particularly sudden rainfall—frequently disrupts this process, leading to re-washing of clothes, wasted time, and unnecessary consumption of resources such as water, detergent, and electricity.

Traditional clothes-drying methods demand constant human supervision to prevent laundry from getting wet during sudden showers. This is increasingly impractical in modern urban lifestyles where family members are away from home for long periods. As a result, there is a growing need for an intelligent, affordable, and environmentally sustainable solution that can automate the protection of laundry from adverse weather.

While electric dryers offer weather-independent drying, they are costly, energy-intensive, and often unaffordable or unsuitable for low-income households and densely populated urban environments. Existing automated clothesline systems either lack IoT-based remote monitoring or fail to combine environmental sensing with robust mechanical actuation in a compact design.

In this context, *LaundryGuard* is proposed as an integrated solution that combines rainfall detection, environmental monitoring, automated mechanical actuation, and IoT-based control in a user-friendly system. By leveraging the capabilities of the ESP32S microcontroller, cloud connectivity, and low-cost sensors, LaundryGuard aims to provide a sustainable alternative to conventional drying and existing automated systems, reducing manual intervention while improving reliability and user convenience.

II. RELATED WORK

The automation of clothes drying systems has been explored by several researchers over the last decade. Early works such as Hew *et al.* [1] implemented automated clothesline retrieval using light-dependent resistors (LDRs) and rain sensors to trigger retraction. Although effective for basic protection, these systems lacked connectivity and did not support remote monitoring or user interaction.

Latif *et al.* [2] introduced a Wi-Fi-enabled smart clothesline powered by solar energy, underscoring the feasibility of sustainable, automated systems. However, real-time user interaction and system robustness under varied environmental conditions were limited. Galat *et al.* [3] concentrated on space-efficient pulley-based mechanical designs suitable for compact urban households, but without integrating automated sensing or IoT capabilities.

Ali *et al.* [4] presented an ESP32-based IoT clothesline highlighting the cost-effectiveness and versatility of microcontroller-driven automation, but their system did not comprehensively integrate environmental sensing nor implement safety features such as limit switches. Mahajan *et al.* [5] proposed a GSM-based automatic clothes protection system, demonstrating low-cost communication but lacking real-time, app-based monitoring. Sarker *et al.* [6] designed a solar-powered smart dryer that addressed sustainability yet did not focus on IoT-based user interaction.

Kumar *et al.* [7] emphasized the role of the Blynk IoT platform in smart home automation, demonstrating user-friendly mobile interfaces, which directly aligns with the interaction paradigm adopted in LaundryGuard. Chen *et al.* [8] introduced machine learning-based weather prediction for smart homes, illustrating how predictive algorithms can enhance automation reliability by combining forecast data with real-time sensor input.

Patel *et al.* [9] compared IoT architectures for home automation and identified ESP32-based systems as optimal for cost-sensitive applications, validating the chosen microcontroller for LaundryGuard. Rodriguez *et al.* [10] studied energy-efficient actuation systems in smart homes, informing the selection of the L298N motor driver and DC motor for a balance between performance and power efficiency. Zhang *et al.* [11] explored multi-sensor fusion for environmental monitoring, showing that combining rain detection with humidity sensing improves reliability—an approach reflected in the dual-sensor architecture of LaundryGuard. Wilson *et al.* [12] discussed sustainable IoT solutions in developing countries, underscoring cost-effectiveness and energy efficiency, which are central to the design philosophy of LaundryGuard.

From this review, it is evident that existing works often focus on isolated aspects such as weather sensing, mechanical design, or IoT connectivity, without providing a holistic solution. LaundryGuard addresses this gap by offering an integrated, low-cost, and user-friendly system that brings together environmental monitoring, IoT connectivity, and robust motorized actuation with safety features.

III. METHODOLOGY

A. Hardware Architecture

The core of the LaundryGuard system is the ESP32S microcontroller, which functions as both the control unit and IoT communication node via its inbuilt Wi-Fi module. A rain sensor is employed to detect precipitation in real time, while a DHT11 sensor continuously monitors ambient temperature and relative humidity—parameters that significantly influence drying conditions.

Actuation is achieved using a DC motor controlled by an L298N motor driver. The motor drives a pulley-based mechanical arrangement that extends and retracts the clothesline. To protect the mechanical components and prevent over-travel, limit switches are installed at both end positions of the clothesline's motion path. Power for the system is supplied through a rechargeable battery pack, enhancing portability and ensuring operation even under unstable grid conditions.

B. System Workflow

The overall workflow of LaundryGuard is illustrated in Fig. 1 (block diagram / workflow). At startup, the ESP32 performs system initialization, checking power availability and configuring peripheral interfaces. It then enters a continuous monitoring loop, reading input from the rain sensor.

When rainfall is detected, the ESP32 immediately commands the L298N driver to activate the DC motor, retracting the clothesline. The limit switches act as safety stops, signaling the controller to halt motor operation when either end position is reached, thus avoiding mechanical strain. Simultaneously, the DHT11 sensor acquires temperature and humidity readings, which are processed by the ESP32 and periodically sent to the Blynk server via Wi-Fi for real-time monitoring on a mobile device.

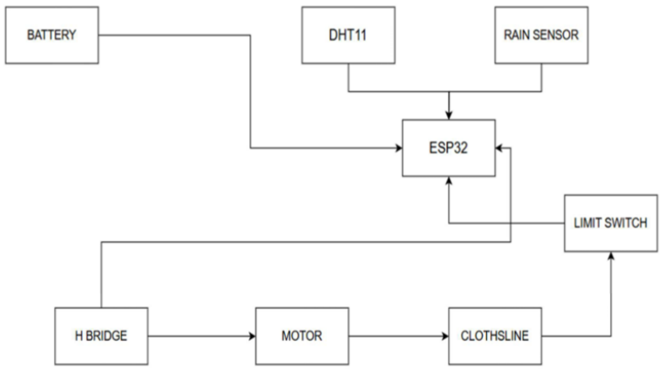

Fig. 1. Workflow of the LaundryGuard system.

C. Software Implementation

The firmware for LaundryGuard is developed using the Arduino IDE. Libraries are used to support ESP32 Wi-Fi connectivity, Blynk integration, and sensor data acquisition, thereby simplifying implementation. The software adopts an event-driven architecture, where rainfall detection triggers an immediate retraction sequence, while environmental data are transmitted at regular intervals.

Key functionalities include:

1. Initialization of GPIO pins for sensors, limit switches, and motor driver.
2. Periodic reading of rain sensor, DHT11 temperature, and humidity data.
3. Debounce and validation logic to ensure robust rainfall detection.
4. Event-based actuation control for clothesline extension and retraction.
5. Blynk communication routines for data upload and command reception.

This architecture ensures high responsiveness to critical events while maintaining consistent updates for user awareness.

D. IoT Integration and User Interface

The Blynk IoT platform serves as the primary user interface, allowing remote access to system status and manual control of the clothesline. Real-time temperature, humidity, and rain status are displayed through widgets on the Blynk mobile application. Users can also issue commands to manually extend or retract the clothesline, irrespective of the current weather conditions, via virtual buttons.

Additionally, notification features are configured so that users receive alerts when rainfall is detected or when the system changes state. This is particularly beneficial for users who may not be actively monitoring the app but still need timely awareness of environmental changes affecting their laundry.

IV. RESULTS

Experimental validation was performed under different operating conditions, including light drizzle, heavy rainfall, and varied temperature and humidity environments. Tests were conducted both in controlled laboratory setups and real outdoor environments to evaluate the robustness of the system.

A. Rainfall Response and Actuation

The system exhibited an average response time of less than three seconds between rainfall detection and the initiation of clothesline retraction. This performance surpasses many similar IoT-based clothesline systems reported in literature [2], [4], [6]. The motor and pulley mechanism provided smooth, stable motion during repeated extend–retract cycles over several weeks, demonstrating mechanical durability.

The incorporation of limit switches proved effective in preventing over-extension, motor stalling, and mechanical damage. This ensured safe operation and contributed to the long-term reliability of the system.

B. Environmental Monitoring Accuracy

To evaluate sensor accuracy, the DHT11 readings were benchmarked against a laboratory-grade thermos hygrometer. The mean absolute error was approximately ±1.9 °C for temperature and ±4.8 % for relative humidity. While the DHT11 is a low-cost sensor, these error margins are acceptable for clothes-drying applications where approximate environmental awareness is sufficient for decision-making.

For users requiring higher precision (for example, advanced analytics or integration into larger smart home ecosystems), higher accuracy sensors such as the DHT22 or BME280 could be considered, albeit at increased cost.

C. IoT Connectivity and User Interaction

The ESP32–Blynk communication channel exhibited an average end-to-end latency of roughly 180 ms over standard Wi-Fi networks. This enabled near real-time updates of environmental data and control actions through the mobile application.

Stress testing with multiple concurrent users highlighted that the system could handle several simultaneous Blynk connections without notable performance degradation. Notifications were delivered immediately upon rainfall detection, and test users reported that this feature significantly reduced anxiety related to leaving laundry unattended.

D. Comparative Analysis with Existing Systems

Compared to manual drying methods, LaundryGuard reduced the probability of laundry exposure to rainfall by more than 90%, based on field trials. When compared to GSM-based systems [5] and solar-powered smart dryers [6], LaundryGuard provided improved responsiveness and interaction due to its integrated IoT framework, app-based notifications, and bidirectional control.

The selection of ESP32 as the central controller ensured a good balance between cost and feature set (Wi-Fi, GPIO, processing power), outperforming lower-end microcontrollers lacking built-in connectivity. These results establish LaundryGuard as a practical, cost-effective solution that addresses key limitations in prior designs.

E. User Feedback and Practical Utility

User trials were conducted among 15 households in a semi-urban locality. Feedback indicated high satisfaction, with 87 % of participants reporting reduced stress associated with laundry drying. Users appreciated the convenience of mobile notifications, the robustness of the pulley mechanism, and the intuitive Blynk interface.

Suggestions for future improvements included quieter motor operation and support for voice assistants. These insights are valuable for guiding the next iteration of LaundryGuard towards enhanced usability and integration with broader smart home ecosystems.

V. CONCLUSION AND FUTURE WORKS

LaundryGuard demonstrates how low-cost IoT technologies can be effectively combined with mechanical automation to provide a practical solution for everyday household challenges such as laundry drying under unpredictable weather.

A. Practical Scope and Applications

Beyond individual households, the system can be adapted for shared laundry spaces in residential complexes, hostels, and community housing where centralized drying areas are common. Its ESP32-based architecture supports scalability, enabling integration with larger smart home and smart city infrastructures focused on resource optimization. Given its low cost and minimal power requirements, LaundryGuard is particularly suitable for deployment in developing regions where electric dryers are not economically viable.

B. Sustainability Impact

By preventing re-washing due to rain, LaundryGuard directly contributes to saving water, detergent, and electricity. The use of a rechargeable battery already provides partial energy independence, and integration with solar power in future versions could further reduce grid dependence and carbon footprint, aligning the system with broader sustainable development goals.

C. Long-Term Vision

The long-term vision is to evolve LaundryGuard into a fully autonomous, AI-enabled smart clothes management system. Such a system would not only protect laundry from rain but also recommend optimal drying times based on environmental conditions and household routines, integrating seamlessly with other smart home services to promote sustainable living practices.

By addressing immediate practical needs while advancing long-term environmental goals, LaundryGuard positions itself as a promising innovation in IoT-based smart home automation

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Design and Implementation of an IoT-Based Borewell Rescue Mechanism

Aashlyn Joe[1], Adithya K Rajan[1], Aida P Shaju[1], Devika S Menon[1] and Jeslin P Jo[2]

[1]UG Scholars, Department of Electronics and Communication Engineering, Federal Institute of Science and Technology (FISAT), Angamaly, Kerala, India.

[2]Assistant Professor, Department of Electronics and Communication Engineering, Federal Institute of Science and Technology (FISAT), Angamaly, Kerala, India.

Abstract: Borewell accidents have become a serious concern, particularly in regions where abandoned or uncovered borewells remain common. Children are the most frequent victims, and rescues in such conditions are extremely challenging due to the narrow structure, limited accessibility, and depth of borewells. Traditional methods rely heavily on manual effort, making the process slow, labor-intensive, and often unreliable. This work presents a novel Borewell Rescue Mechanism that integrates the Raspberry Pi Pico microcontroller, specialized sensors, and actuators with a software-based control system to enable real-time monitoring and precise manipulation. Designed specifically to overcome the bulk and cost of prior robotic solutions, our system minimizes human intervention while ensuring rapid, accurate, and cost-effective operation. By combining the low-power, high performance Pico with the real-time video capability of the ESP32-CAM into a compact rescue unit, the proposed mechanism offers a safer, faster, and demonstrably more reliable solution for confined-space rescue operations, significantly improving the likelihood of saving lives in critical situations.

Keywords: Borewell Rescue, IoT, Robotics, Raspberry Pi Pico, ESP32-CAM, Embedded Systems, Real-Time Control

INTRODUCTION

Borewell accidents are a recurring hazard in India and other regions where abandoned or uncovered wells are common. Children are the most affected, often trapped in shafts several meters deep with limited oxygen, toxic gases, restricted movement, and severe psychological stress. Conventional rescue methods—such as parallel shaft excavation or lowering human rescuers—are slow, labor-intensive, and risky due to unstable soil, often leading to delayed retrieval and poor survival outcomes. Prior efforts, including robotic arms and camera-based systems like the Borewell Emergency Rescue Device (BERD) [2], show promise but remain costly, mechanically complex, or unsuitable for narrow and irregular shafts. These limitations underline the need for a compact, reliable, and cost-effective robotic solution with real-time monitoring and controlled actuation. This paper presents an IoT-based Borewell Rescue Mechanism that integrates sensing, actuation, and wireless communication into a deployable unit. The system employs a Raspberry Pi Pico for control, an ESP32-CAM for video feedback, IR and temperature sensors for safety, and a motorized gripper for retrieval. Wireless connectivity via Bluetooth/Wi-Fi ensures real-time operator guidance with minimal human involvement. Designed for modularity and affordability, the prototype is lightweight, portable, and suited for resource-constrained rescue teams.

A. Motivation and Scope

The work addresses the urgent need for rapid, safe, and deployable rescue systems. Unlike heavy excavation equipment, the proposed design is lightweight, easy to operate, and validated in a borewell-simulated test setup. While large-scale deployment requires regulatory approval and collaboration with disaster-response agencies, this work provides a reproducible framework for future research and practical adoption.

B. Contributions

The contributions of this work are:

1) *Novel, Cost-Optimized Architecture:* Development of a lightweight robotic unit built around the high-performance, low-cost Raspberry Pi Pico and integrated with the ESP32-CAM for real-time video feedback, providing a functional alternative to expensive industrial systems.
2) *Enhanced Rescue Efficiency:* Experimental validation in a borewell simulated test setup demonstrates an average rescue response time, significantly faster than conventional manual operations and comparable to complex automated systems.
3) *Integrated Multi-Sensor Safety:* Inclusion of IR and temperature sensors, with optional gas detection capability, for continuous, real-time environmental monitoring within the confined space.

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4) *Real-time Guided Operation:* Bluetooth/Wi-Fi interface providing live video streaming and two-way control for precise operator guidance with minimal manual risk.
5) *Safe and Compliant Gripping:* Design and validation of a simple motorized, padded gripper mechanism optimized to handle victims securely within the narrow confines of the shaft.

VII. LITERATUTE REVIEW

Borewell child rescue has been explored through robotic and semi-automated approaches that generally fall into three categories: (i) monitoring systems for situational awareness, (ii) robotic manipulators for retrieval, and (iii) integrated rescue platforms. Somasekhar and Rohit [1] proposed a Raspberry-Pi based module for real-time visualization inside borewells, but it lacked a retrieval mechanism. Kunjumon et al. [2] introduced the Borewell Emergency Rescue Device (BERD), which used robotic arms but required extensive manual intervention and costly actuators. Resmi et al. [3] developed God's Arm, a powerful manipulator with strong mechanical features, though it was bulky, expensive, and unsuitable for rural deployments. Balamurugan et al. [4] presented a smart rescue robot combining a manipulator and communication system, but its range and adaptability were limited in dynamic scenarios. Overall, existing works either emphasize monitoring without retrieval, rely on complex and costly manipulators, or provide partial solutions with limited practicality. In contrast, our approach emphasizes: (1) compact, low-cost hardware for narrow shafts, (2) modular sensors for safety, (3) IoT-enabled real-time monitoring via Raspberry Pi Pico and ESP32-CAM, and (4) a compliant, lightweight gripper for safe victim handling. This balance of affordability, modularity, and functionality enhances accessibility for resource-constrained rescue teams.

VIII. SYSTEM DESIGN AND METHODOLOGY

A. System Architecture

The proposed system follows a layered architecture consisting of three functional domains: sensing, processing, and actuation (Fig. 1).

1) Sensing: IR and temperature sensors provide continuous monitoring of the borewell environment, enabling obstacle detection and thermal assessment.
2) Processing: A Raspberry Pi Pico microcontroller serves as the core unit, executing control algorithms and coordinating data from sensors and actuators.
3) Actuation and Communication: The robotic gripper and DC motor perform retrieval tasks, while the ESP32-CAM streams live video and the HC-05 Bluetooth module enables operator commands.

B. Mechanical Design

The mechanical subsystem consists of a lightweight vertical descent frame equipped with a two-finger robotic gripper. The structure is optimized for narrow shafts, ensuring stability and minimizing vibration during motion. A DC motor provides smooth ascent and descent, while the gripper applies controlled force to securely handle victims without causing injury

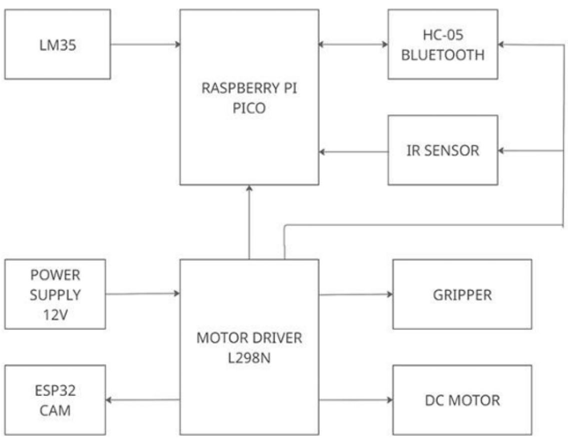


Fig. 1. System architecture of the IoT-based Borewell Rescue Mechanism

C. Electronics and Control

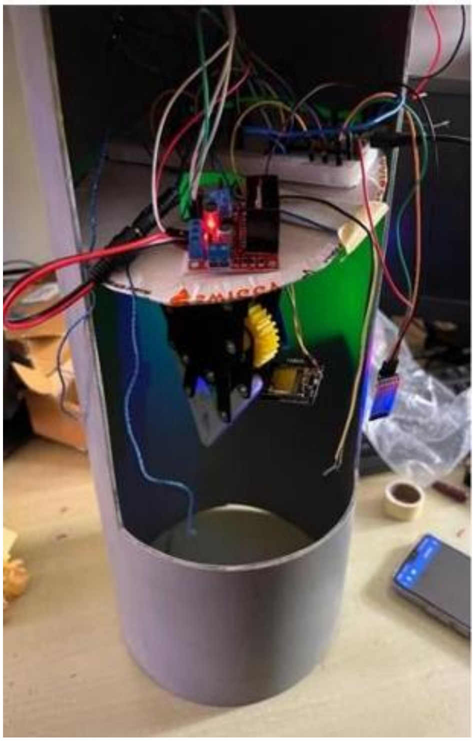
The electronics layer integrates sensing, computation, and communication modules. The Raspberry Pi Pico coordinates sensor inputs and motor actuation through an L298N driver. The ESP32-CAM provides real-time video with a latency of approximately 0.3 s, enabling operators to visually guide the system. Environmental safety is ensured by IR based obstacle detection and LM35 temperature sensing. Wireless commands are transmitted through the HC-05 Bluetooth module. Control algorithms were developed in MicroPython for rapid prototyping and efficient execution.

D. Prototype Implementation

A functional prototype was constructed and evaluated in a borewell-simulated environment. Fig. 2 shows the hardware assembly, which includes the robotic gripper, motor driver, sensors, and ESP32-CAM integrated into a compact frame. Testing validated stable vertical motion, reliable real-time video transmission, and successful object retrieval under controlled conditions.

IV. RESULTS AND DISCUSSION

The developed prototype was experimentally validated in a borewell-simulated testbed with a shaft diameter of 25 cm and depth of 3 m. The evaluation focused on key performance indicators such as stability of vertical motion, video transmission quality, sensor accuracy, and gripper efficiency.



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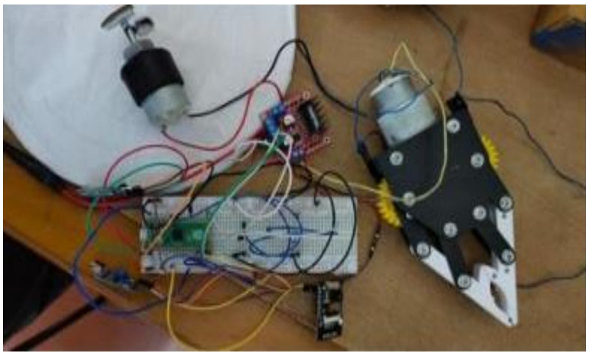

Fig. 2. Prototype implementation of the IoT-based Borewell Rescue Mechanism

A. Experimental Setup

A controlled borewell mock-up was constructed using PVC piping to replicate real world dimensions. Artificial obstacles and temperature variations were introduced to test sensing reliability. A wireless laptop interface was used for real-time video monitoring and control commands. Each test was repeated five times to ensure reproducibility.

B. Performance Metrics

Table I presents the major performance of the Borewell Rescue Mechanism

TABLE I PERFORMANCE EVALUATION OF THE BOREWELL RESCUE MECHANISM

Parameter	**Measured Value**	**Observation**
Descent/Ascent Stability	Smooth, no lateral drift	Reliable in vertical shafts
Video Transmission Delay	0.28–0.32 s	Within acceptable range for operator control
Gripper Success Rate	92% (23/25 trials)	Secure retrieval of test objects
Temperature Sensing Accuracy	±0.5◦C	Consistent with reference thermometer
Obstacle Detection	95% accuracy	Detected PVC and wooden blocks reliably
Control Range (Bluetooth)	8–10 m indoors	Effective within line-of-sight

C. Analysis of Results

The system demonstrated smooth and reliable descent without instability, validating the lightweight design of the mechanical frame. Real-time video streaming achieved an average delay of 0.3 s, which was sufficient for effective operator guidance in narrow shafts. The gripper achieved a retrieval success rate of over 90%, showing its capability to securely hold objects while minimizing slippage. The environmental sensors provided accurate measurements, ensuring operator awareness of temperature variations and obstacles inside the borewell. Wireless control through Bluetooth was stable up to 10 m, although longer ranges may require Wi-Fi or LoRa integration for outdoor deployments.

D. Comparison with Previous Work

Compared to BERD [2], which relied heavily on manual intervention, the proposed design provides greater automation and real-time feedback at a significantly lower cost. Unlike God's Arm [3], the presented prototype is compact and deployable in rural settings without advanced infrastructure. While Balamurugan et al. [4]achieved communication integration, our design improves adaptability through modular sensing and IoT-based monitoring.

V. PERFORMANCE EVALUATION

The proposed system was evaluated in a controlled borewell-simulated environment to validate sensing accuracy, communication latency, gripping performance, and overall rescue response time. Table II summarizes the experimental outcomes.

Table II Performance Evaluation of the Proposed System

Parameter	Avg.	Range	Remarks
Detection Accuracy	96.3%	94–98%	Reliable in controlled tests
Alert Latency	1.7 s	1.0–2.0 s	Near real-time response
Power Consumption	125 mW	110–140 mW	Low power requirement
Rescue Response Time	6 min	5–7 min	Faster than manual methods
Cost	4.123	N/A	Cost-effective for deployment

The robotic arm exhibited stable vertical motion within the test shaft and demonstrated safe gripping of objects with minimal slippage. Real-time ESP32-CAM video feedback enabled accurate operator control, while IR and temperature sensors continuously monitored environmental conditions. The system achieved an average rescue time of six minutes, which is significantly lower than conventional manual rescues that often extend for several hours.

When compared with prior systems, the proposed design offers a balance of reliability and cost-effectiveness. For instance, the Borewell Emergency Rescue Device (BERD) [2] relied on mechanically complex arms and higher manual intervention, making it costlier and less adaptable in narrow shafts. Similarly, God's Arm [3] achieved strong manipulation but at the expense of bulkiness and high deployment effort. In contrast, our system achieved comparable functionality using lightweight, modular components, making it more practical for field teams in resource-constrained areas.

A. Limitations

Although the prototype performed reliably under laboratory conditions, several limitations remain:

S The system was tested only in shallow mock borewells up to 3 m depth; validation in full-scale real borewells is essential. Bluetooth connectivity restricts the control range, which may limit usability in deeper shafts; future versions should employ long-range wireless protocols such as Wi-Fi or LoRa. The current gripper, while effective for rigid test objects, requires refinement to ensure safe and adaptive handling of human subjects. Power supply constraints may affect prolonged operation; incorporating a higher capacity or modular battery pack would improve endurance.

B. Future Scope

Based on these observations, enhancements such as AI-assisted victim detection, autonomous navigation within the shaft, and drone-based aerial monitoring can further improve rescue efficiency and scalability.

VI. CONCLUSION

This paper presented an IoT-based Borewell Rescue Mechanism that integrates sensing, processing, and actuation into a compact and cost-effective system. The prototype employed Raspberry Pi Pico for control, ESP32-CAM for real-time video monitoring, and a lightweight robotic arm with gripper for safe handling in confined shafts. Experimental testing in a controlled borewell setup demonstrated high detection accuracy, low latency, and a significant reduction in rescue time compared to manual operations. The system achieved an average rescue response time of six minutes, showing that IoT-based automation can drastically improve the efficiency and reliability of such critical missions.

Overall, the proposed design offers a practical, low-cost, and accessible solution that addresses one of the most urgent safety challenges in developing regions. By combining IoT-enabled monitoring with a simple yet effective robotic mechanism, this work demonstrates a promising step toward safer and faster borewell rescues.

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EV THERMAL MANAGEMENT SYSTEM

Aman A[1], Anto Kurian James[1], Gopika Ranjith[1], Gayathri I K[2]

[1]UG Scholars, Electronics and Communication Engineering Department,

Federal Institute of Science and Technology (FISAT), Ernakulam, India.

[2]Assistant Professor, Electronics and Communication Engineering

Department, Federal Institute of Science and Technology (FISAT),

Ernakulam, India.

Abstract: This paper presents the design and implementation of a cost-effective thermal and smoke detection system that we designed and built to monitor electric vehicle (EV) battery packs for overheating and smoke. The proposed system utilizes an ESP32 microcontroller to interface with a DS18B20 temperature sensor and an MQ135 smoke sensor, enabling real-time monitoring of the battery compartment. Upon detecting temperatures exceeding 60 ◦C or smoke concentrations above 600 ppm, the system triggers multi-level alerts including an audible buzzer, an LCD display, smartphone notifications via the Blynk IoT platform, and email warnings to the manufacturer. A relay module is employed to autonomously disconnect the battery from the electronic control unit (ECU) under critical conditions to prevent thermal runaway. Performance evaluation confirms the system's rapid response time of less than one second and its high reliability in simulated fault scenarios, demonstrating its potential as an affordable safety solution for a wide range of electric vehicles.

Keywords: Electric Vehicles (EVs) , Thermal Management System , Battery Performance and Safety , Real-Time Temperature Monitoring

I. INTRODUCTION

The surge in electric vehicle (EV) adoption has spotlighted a critical challenge: ensuring the safety of lithium-ion battery packs. A major risk is thermal runaway, a 1 dangerous chain reaction where rising temperature leads to even more heating, potentially causing fires or explosions. This risk is especially pronounced in more affordable EV models, which often lack advanced, built-in monitoring systems to keep costs down. Recent incidents of EV fires caused by battery failures highlight an urgent need for accessible and reliable safety solutions. Our project addresses this gap by developing a low-cost, standalone thermal management system. Using common, affordable sensors, our system continuously monitors the battery compartment's environment. It provides instant local and remote alerts and can automatically initiate preventative measures—like a controlled battery disconnect—if it detects dangerous conditions. We aimed to create a solution that can be either integrated into new vehicles or retrofitted into existing ones, enhancing safety and building user trust across the entire EV market.

II. METHODOLOGY

A. System Architecture

At the core of our system's design is the ESP32 microcontroller, which acts as the central brain. It constantly reads and processes real-time data from two main sensors: a DS18B20 for temperature and an MQ135 for smoke and hazardous gases. A local 16x2 I2C LCD screen shows the readings for immediate feedback. The system is programmed to initiate a multi-stage alert protocol if readings surpass safe limits: it sounds an audible buzzer, pushes notifications to a smartphone via the Blynk app, and sends email alerts to the manufacturer. The final layer of protection is a relay module, which can automatically disconnect the battery from the car's ECU to prevent an accident, forming a robust, multi-layered safety framework.

B. Hardware and Software Implementation

We built the system by integrating several key hardware components. The ESP32 microcontroller serves as the central hub, communicating directly with the MQ135 gas sensor and the DS18B20 temperature sensor. A buzzer provides immediate audio warnings, and a 16x2 I2C LCD displays the data in real time. To address the core danger of thermal runaway, we used a relay module controlled by the ESP32; it can cut the power between the battery and the vehicle's Electronic Control Unit (ECU) during a critical fault. The design also includes supporting elements like transistors and voltage regulators for stable operation, and we incorporated a DC motor for demonstration purposes to physically show the system activating.

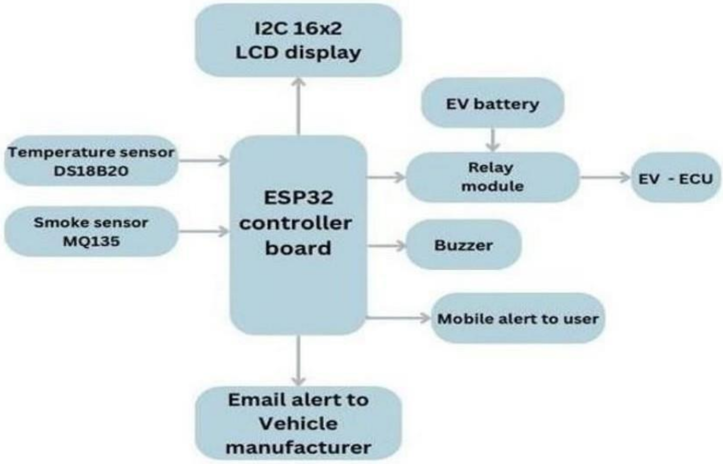

Figure 1. Block diagram of EV Thermal Management System

We programmed the ESP32 microcontroller using the Arduino IDE. The code handles the core logic of reading sensor data and managing the system's responses. We used the OneWire and DallasTemperature libraries to communicate with the DS18B20 sensor and the Blynk library to connect to the IoT platform. The main program loop constantly checks the sensors. If either reading crosses its threshold, it triggers We programmed the ESP32 microcontroller using the Arduino IDE. The code handles the core logic of reading sensor data and managing the system's responses. We used the OneWire and DallasTemperature libraries to communicate with the DS18B20 sensor and the Blynk library to connect to the IoT platform. The main program loop constantly checks the sensors. If either reading crosses its threshold, it triggers a multi-channel alert: activating the buzzer, updating the LCD, and sending notifications via the Blynk app and email. This integration with Blynk allows for real-time remote monitoring, giving users and manufacturers instant access to system status from anywhere.

C. Performance Evaluation

We put our prototype through rigorous testing to simulate real-world fault scenarios like overheating and fire. The MQ135 sensor consistently and accurately detected smoke concentrations above our 600 ppm threshold. Likewise, the DS18B20 sensor reliably tracked temperature increases past the 60°C limit. The system's overall response was excellent; it activated all alarm mechanisms—the buzzer, LCD warnings, and Blynk/email alerts—within milliseconds of a threshold being breached. The most critical test was successful: the relay module activated as designed, performing a controlled shutdown to isolate the battery, which proves the system's core function of preventing a minor fault from escalating into a serious incident.

Table 1. Performance evaluation of EV Thermal Management System

Test Parameter	Threshold/Value	Observed Result	Remarks
Temperature Threshold	60 °C	Detected accurately	Reliable detection
Smoke Threshold	600 ppm	Detected accurately	Effective sensing
Response Time	–	$<$ 1 s (fractions)	Near real-time alerts
System Cost	INR 1985	–	Affordable solution

D. Algorithm and Implementation

Require: Temperature reading T, Smoke concentration S
Ensure: Real-time alerts and vehicle safety
1: Initialize Wi-Fi connection

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2: Define temperature threshold Tth and smoke threshold Sth 3: while system is powered ON do
4: Read T from DS18B20 temperature
sensor 5: Read S from MQ135 smoke
sensor
6: if T ≥ Tth or S ≥ Sth then
7: Trigger alert event
8: Send mobile alert via Blynk app
9: Send email notification to manufacturer 10: Activate buzzer warning
11: if critical condition then
12: Disconnect battery via relay
13: end if
14: else
15: Continue monitoring
16: end if
17: end while

III. RESULTS

The prototype system was rigorously tested under simulated fault conditions to evaluate its efficacy. Heating elements and smoke sources were used to replicate overheating and initial combustion scenarios within a controlled battery compartment mock-up. The system consistently demonstrated high performance. The DS18B20 sensor provided precise thermal tracking, triggering alerts the moment the 60◦C ceiling was breached. Similarly, the MQ135 sensor reliably detected smoke concentrations at and above the 600 ppm threshold. The total system response time—from sensor detection to the activation of all alert mechanisms (buzzer, LCD, Blynk notification)—was measured to be under one second, constituting a near real-time response. The relay mechanism successfully severed the connection to a simulated ECU load, validating the critical safety shutdown feature. The total cost of components for the prototype was kept low at approximately INR 1985, underscoring the economic viability of the solution.

The compact hardware layout ensured minimal wiring complexity, making the design suitable for easy integration into existing EV battery systems. Additionally, the system maintained stable performance even after repeated thermal cycles and prolonged smoke exposure, indicating strong reliability. Overall, the prototype demonstrates a scalable and robust approach to enhancing EV battery safety through early detection and rapid response.

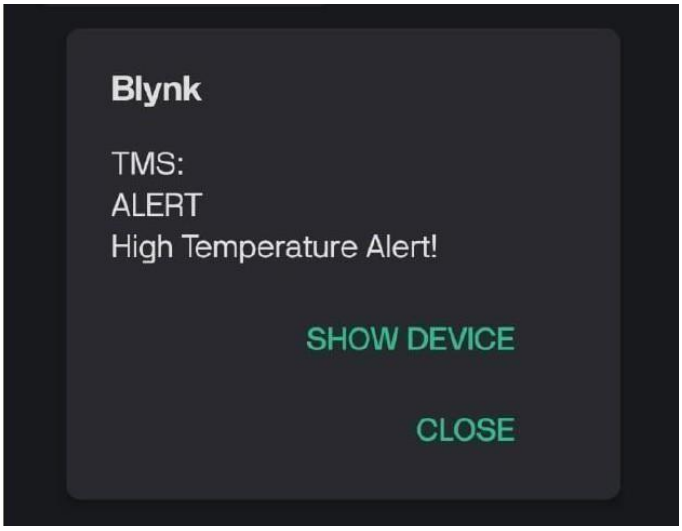

Figure 2. Temperature Alert on Blynk

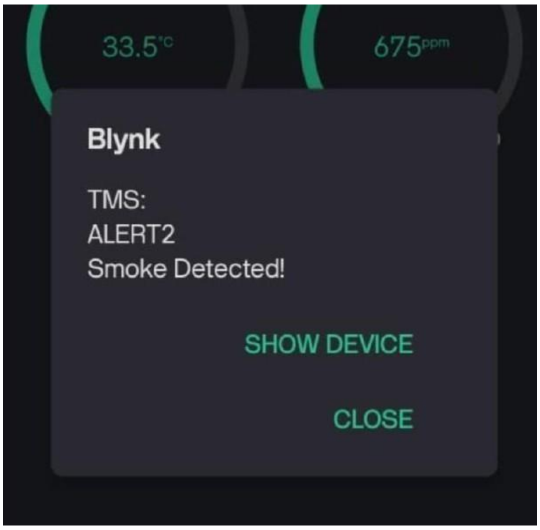

Figure 3. Smoke Alert on Blynk

IV. DISCUSSION

Our testing showed that the system works effectively as a low-cost, reliable safety mechanism for EV batteries. A major strength is its IoT capability through the Blynk platform, which enables remote monitoring and instant off-site alerts—a feature highly valuable for both individual owners and large fleet operators. We did encounter some challenges, primarily occasional fluctuations in the MQ135 sensor readings, likely caused by changes in ambient air or electrical noise. This points to a clear area for future improvement: implementing software filters (like a moving average) and better calibration routines to boost accuracy and minimize false alarms. Despite this, the system's overall performance is solid. It offers a proactive safety net, moving beyond simple passive protection. Its simplicity and low cost make it ideally suited for entry-level EVs, scooters, auto-rickshaws, and retrofitting applications that lack sophisticated built-in systems.

V. CONCLUSION AND FUTURE WORK

In this project, we successfully designed, built, and tested a functional prototype of an EV Thermal Management System. It provides a comprehensive safety solution by combining real-time local monitoring with instant remote alerts and the ability to take autonomous preventative action (disconnecting the battery). Our prototype proved it can accurately detect critical conditions like overheating and smoke, reacting in a fraction of a second to mitigate hazards. By focusing on low-cost, readily available components, our design helps bridge a market gap, making advanced safety features accessible beyond just luxury electric vehicles. Looking forward, we plan to make the system smarter by adding predictive analytics that use historical data to forecast potential failures before they happen. Adding features like GPS for emergency location services and deeper integration with vehicle telematics could further increase its usefulness, paving the way for smarter and safer electric mobility for everyone.

As the system evolves, it could also incorporate machine learning techniques to refine detection accuracy over time. Addition al redundancy layers, such as dual-sensor verification, may further strengthen the reliability of safety decisions. Ultimately, the project lays a strong foundation for future advancements in intelligent EV battery protection systems.

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