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Autonomous Pest Detection and Pesticide Spraying Drone using Machine Learning

G. Kalpana Devi Ch. Gunasekhar G. Suresh A. S. Vijay Chandhan Kumar

UG Student Department of ECE R.V.R & J.C.C.E Chowdavaram India

UG Student Department of ECE R.V.R & J.C.C.E Chowdavaram India

UG Student Department of ECE R.V.R & J.C.C.E Chowdavaram India

UG Student Department of ECE R.V.R & J.C.C.E Chowdavaram India

ABSTRACT: This work presents an edge AI-enabled pest detection and pesticide spraying system for agricultural drones designed to address yield losses and chemical overuse in resource-constrained rural settings. The proposed framework employs the ESP32-S3 CAM module to capture real-time crop images and a binary classification model developed with Edge Impulse to perform on-device pest/no-pest inference without reliance on cloud connectivity. Upon detection the system autonomously triggers targeted pesticide spraying thereby minimizing chemical exposure and environmental impact.

The integration of machine learning with Unmanned Aerial vehicles (UAV) technology enables precise site-specific pesticide application supporting farmers with early pest identification and sustainable crop protection. Experimental evaluation demonstrates reliable performance achieving an overall classification accuracy of 98.7% and pest detection accuracy of 99%. By combining affordability scalability and low-latency operation the system contributes to advancing precision agriculture offering farmers a practical and eco-friendly solution to safeguard crops and enhance food security.

Keywords: ESP32-S3 CAM Edge Impulse Precision agriculture Binary Classification

I. INTRODUCTION

Agriculture remains central to global food security and economic stability yet crop losses due to pest infestations continue to pose a major challenge. Conventional pest control methods often rely on indiscriminate pesticide spraying which increases production costs degrades soil fertility and threatens human and environmental health. The demand for sustainable precise and technology-driven solutions has therefore become critical in modern farming practices.

Recent advances in unmanned aerial vehicles (UAVs) and machine learning have opened new possibilities for precision agriculture. UAVs equipped with intelligent sensing systems can monitor crop health detect pest infestations and enable site-specific pesticide application. While these approaches reduce chemical usage and environmental impact many existing systems depend heavily on cloud-based processing or high-performance hardware. Such requirements limit their applicability in rural and resource-constrained environments where connectivity and cost are significant barriers.

To address these limitations this work proposes an autonomous pest detection and pesticide spraying drone system that leverages edge AI capabilities of the ESP32-S3 CAM. By deploying a binary classification model directly on embedded hardware the system eliminates reliance on cloud infrastructure ensuring low-latency and cost-effective operation. The integration of pest detection with UAV spraying enables targeted pesticide application only in affected areas thereby improving efficiency reducing chemical exposure and supporting sustainable farming practices.

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II. LITERATURE REVIEW

Recent research highlights the growing role of UAVs IoT and machine learning in precision agriculture particularly for pest detection and targeted spraying. Several approaches have been explored each with distinct strengths and limitations:

Author & Year	Approach / System	Limitations
Omer Alaa Abd Al-Hadi & Davood Akbari Bengar 2024	Proposed UAV-based crop monitoring integrated with IoT and cloud servers for real-time analysis.	Dependence on stable internet or GSM connectivity reduces reliability in rural regions where network access is limited.
Avneet Kaur et al. IEEE 2022	Applied YOLO-based deep learning models for pest detection from aerial imagery	Requires high computational resources making it unsuitable for lightweight low-cost embedded platforms.
Ridha Guebsi Sonia Mami & Karem Chokmani MDPI 2023	Comprehensive review of UAV applications in precision agriculture including pest detection spraying and crop health monitoring	High deployment costs and regulatory restrictions hinder scalability for small-scale farmers.
Sheng Wen et al. IEEE Access 2019	Designed UAVs with variable spray systems controlled by artificial neural networks (ANN)	Complex architecture demands advanced hardware integration limiting ease of adoption.
Martinez Guanter et al. Sensors 2019	Developed a low-cost aerial spraying system tailored for orchards	System applicability restricted to specific crop types raising scalability concerns.

III. METHODOLOGY OF PROPOSED SURVEY

Problem Statement

Pest infestation remains one of the most persistent challenges in agriculture leading to significant yield losses and forcing farmers to rely on indiscriminate pesticide spraying. Conventional spraying methods lack precision resulting in excessive chemical usage environmental pollution and health hazards. Although UAVs and machine learning have shown promise in precision agriculture most existing systems depend on cloud connectivity or high-end computational hardware restricting their use in rural and resource-constrained environments. A low-cost edge AI-based drone system is therefore required to autonomously detect pests in real time and spray pesticides only in affected areas thereby improving efficiency reducing chemical exposure and supporting sustainable farming practices.

Objectives

1. Accurate Pest Detection: Develop a binary classification model capable of distinguishing pest-infested crops from healthy plants using real-time images.
2. Targeted Pesticide Spraying: Integrate pest detection with UAV spraying mechanisms to apply pesticides only in affected regions minimizing chemical usage.
3. Edge AI Deployment: Implement machine learning inference directly on embedded hardware (ESP32-S3 CAM) eliminating cloud dependency and ensuring low-latency operation.
4. Cost-Effective and Scalable Solution: Design a system that is affordable energy-efficient and adaptable for small and medium-scale farms particularly in rural settings.

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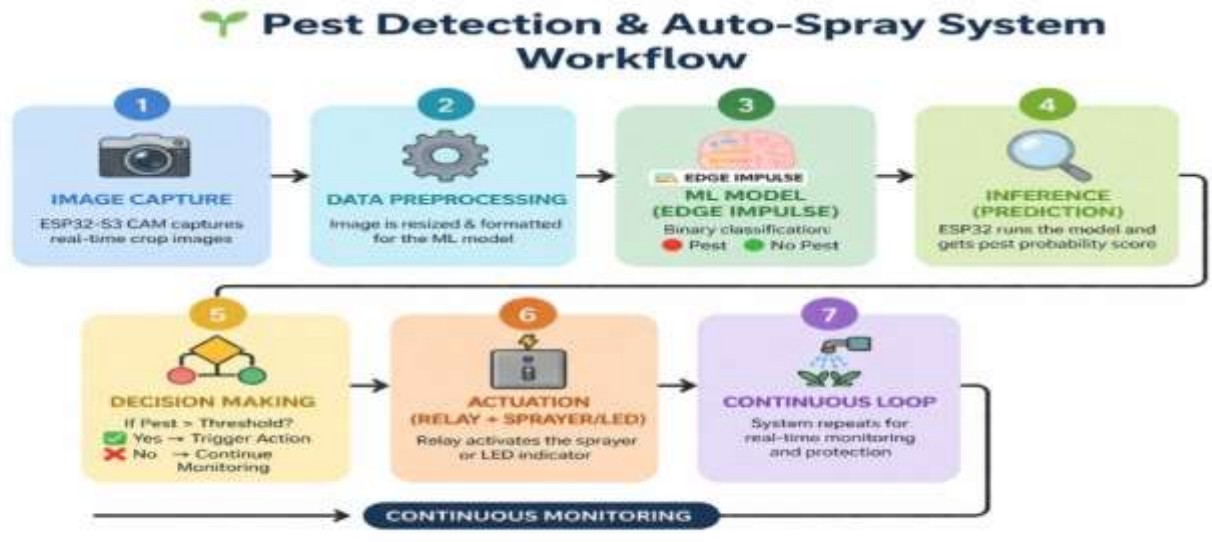

Fig1: Workflow

Workflow

The proposed methodology follows a structured workflow (Fig. 1):

- Data Collection & Preprocessing: Crop images containing pests and non-pest samples are collected and labeled into two classes.
- Model Development: Features are extracted using Edge Impulse DSP blocks followed by training a binary classification model.
- Model Optimization: The trained model is optimized for embedded deployment and exported as a C/C++ library.
- On-Device Inference: The ESP32-S3 CAM executes real-time pest/no-pest classification without cloud dependency.
- Spraying Mechanism Integration: Upon pest detection the relay module activates the spraying system (or LED simulation) ensuring targeted pesticide application.
- System Validation: Accuracy metrics and confusion matrices are used to evaluate model performance followed by hardware integration tests for UAV operation.

IV. IMPLEMENTATION OF THE SYSTEM

Requirements for Software and Hardware

Software Requirements:

Edge Impulse: The machine learning model for pest detection was… that is ,a dataset with images of crops which contains pests and does not contains pests are gathered and subsequently uploaded to Edge Impulse.

Labelling the data into two classes pest and no pest.

Image preprocessing and feature extraction are performed using built-in DSP blocks after the labeling. These features are then used to train a classification model. To validate the performance of the trained model calculating accuracy metrics and a confusion matrix.

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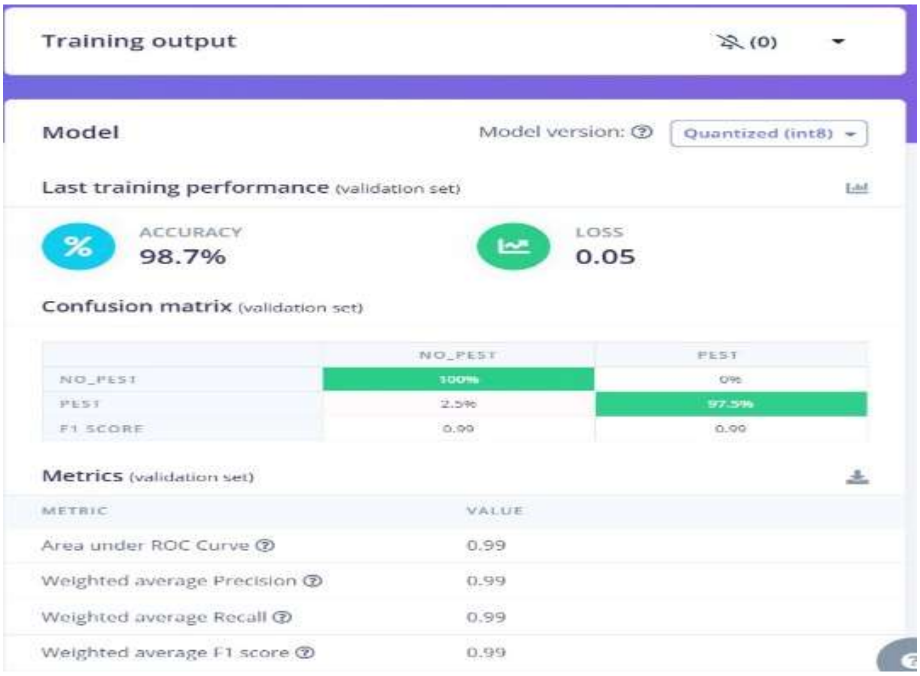

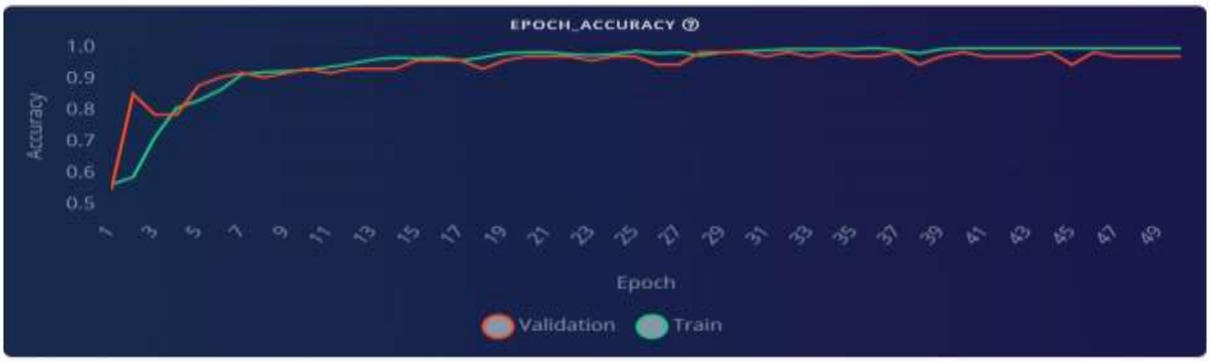

Fig2: Model Accuracy

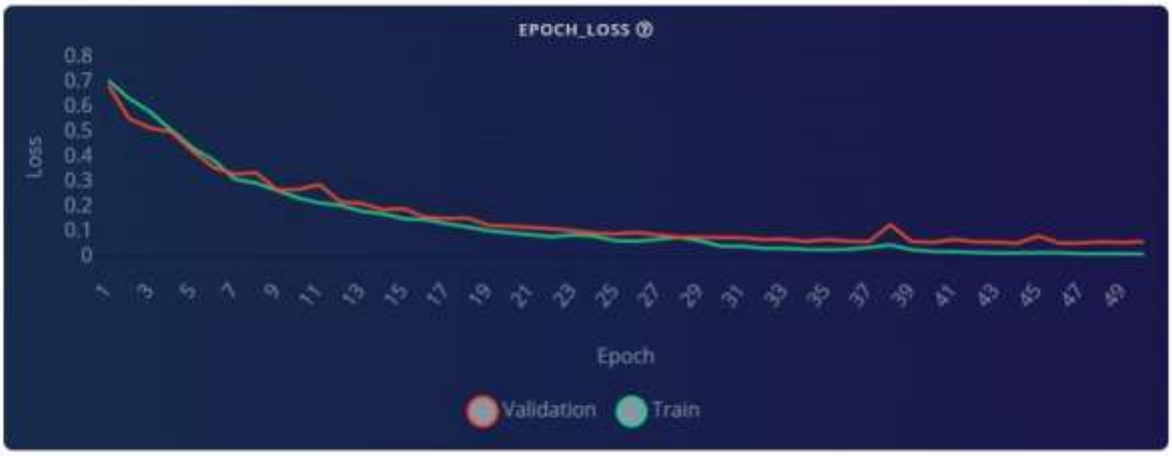

Fig3: loss

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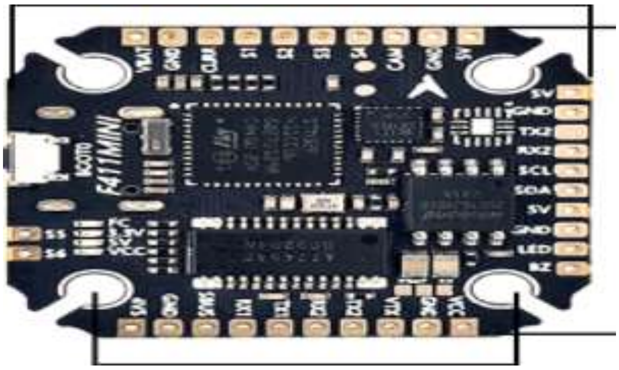
When the model is satisfactory accurate it is however optimized for embedded systems and exported as a C/C++ library. We will see real-time image classification in ESP32-CAM firmware without having to connect to the cloud as this exported model is embedded in it.

The trained model achieved an overall classification accuracy of about 98.7% with a high detection accuracy of roughly 99% for the pest class ensuring dependable real-time performance.

Hardware Requirements

ESP32-S3 CAM: Captures real time crop images and runs the machine learning model locally for pest detection.It enables edge AI inference without cloud dependency ensuring low latency operation.

Radio Transmitter: Sends Control signals from the operator to the drone.
Radio receiver: Receives signals and passes them to flight Controller.
Flight Controller: The central unit that processes input and manages drone stability navigation and spraying actions.



Relay Module: Acts as a switch controlled by the ESP32 to turn external devices on or off. In this project it triggers the sprayer or LED when pests are detected.

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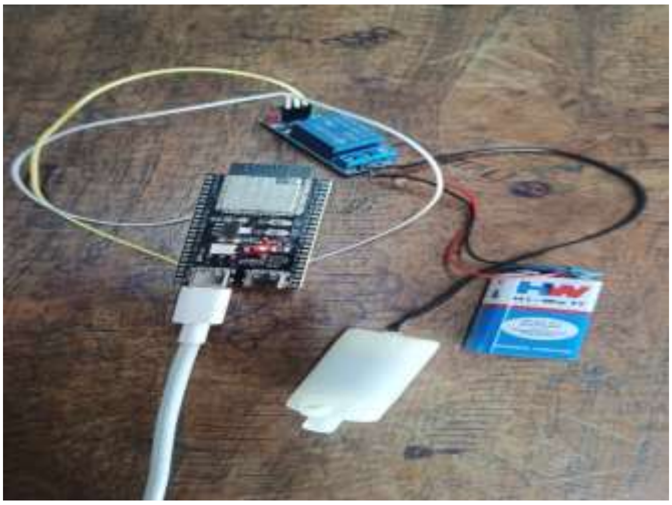
Water Pump: Pumps pesticide solution through the spraying mechanism when activated. It ensures targeted pesticide application only in affected crop areas.

Battery: Provides portable power supply to the ESP32 relay and pump. It enables autonomous drone operation without reliance on external power sources.
Electronic Speed Controllers: Regulate the speed of each motor based on flight controller commands.

Motors and Propellers: Provide lift and directional movement; typically four motors (three clockwise one counter-clockwise).
Power Distribution Board: Distributes battery power to ESCs and other components.

Hardware setup



V. RESULT

The trained pest detection model was successfully integrated into the ESP32S3/Arduino environment using the pestdetectioninferencing.h library. Input features were allocated statically to optimize memory usage on the microcontroller. The system initialized correctly as indicated by the serial output: “ML Model Started”.

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Fig4: Model output when pest is detected

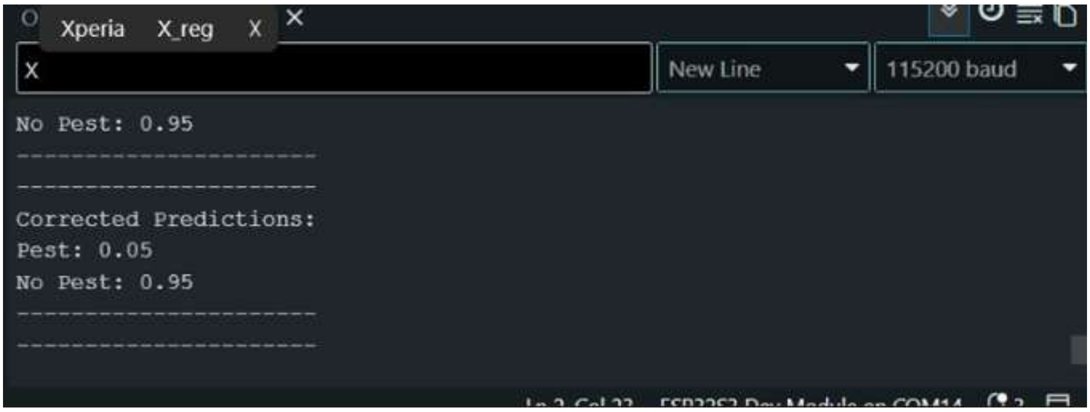

Fig5: Model output when pest is not detected

Results Analysis:

Test Sample	Pest Probability	No Pest Probability
Sample_data4(No pest)	0.05	0.95
Sample_data5(pest)	0.77	0.23
Real Larva Image	0.99	0.01

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VI. CONCLUSION

This study demonstrates the successful design and deployment of an autonomous pest detection and pesticide spraying drone system that integrates machine learning with UAV technology for precision agriculture. By embedding a binary classification model directly onto the ESP32-S3 CAM the system achieves real-time pest identification without reliance on cloud infrastructure ensuring low-latency and cost-effective operation.

The integration of pest detection with UAV spraying enables site-specific pesticide application which significantly reduces chemical usage minimizes environmental impact and supports sustainable farming practices. Experimental results confirm reliable classification accuracy and effective hardware integration with pest detection rates exceeding 98%.

Compared to existing cloud-dependent or high-computation approaches the proposed system offers a scalable affordable and eco-friendly solution tailored for small and medium-scale farms particularly in rural settings. Future work will focus on enhancing detection robustness across diverse pest species optimizing drone deployment strategies and validating performance in large-scale field trials.

Overall this research contributes to the advancement of smart agriculture by providing farmers with a practical edge-AI tool to safeguard crops improve productivity and strengthen food security.

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