

AI-BASED PLASTIC CONTAINER DEFECT DETECTION ASSEMBLY LINE CONTROLLER USING ESP32

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ABSTRACT

Quality control in plastic container manufacturing is a critical process that directly determines product reliability, customer satisfaction, and the economic efficiency of production lines. Conventional manual inspection methods are slow, inconsistent, and prone to human fatigue errors, making them inadequate for the inspection throughput and defect detection accuracy required by modern high-speed plastic manufacturing environments. This project proposes an AI-Based Plastic Container Defect Detection Assembly Line Controller using an ESP32 microcontroller integrated with a camera module (CAM), on-device AI-powered image processing software, an LCD display, a buzzer, and an IoT communication interface. The system captures real-time images of plastic containers moving along the assembly line using the camera module and processes them through an AI-based defect detection software model running on the ESP32 to identify surface defects, deformations, cracks, discoloration, and dimensional irregularities. Upon detection of a defective container, the system triggers an immediate buzzer alert, updates the LCD with defect classification details, and transmits a defect event report to the remote IoT monitoring platform for quality management review. Non-defective containers pass inspection without interruption to production flow. The proposed system delivers consistent, high-speed, automated quality inspection with real-time IoT-based production quality monitoring, making it suitable for integration into plastic container manufacturing assembly lines of varying scales and production rates.

Keywords: AI Defect Detection, Plastic Container, Assembly Line, ESP32, Computer Vision, Quality Control, IoT, Machine Learning, Image Processing, Smart Manufacturing, Industry 4.0

1. INTRODUCTION

Plastic containers are among the most widely manufactured products in the global packaging industry, serving essential roles in food and beverage packaging, pharmaceutical containers, household products, industrial storage, and consumer goods across virtually every sector of the economy. The quality of plastic containers is subject to strict requirements defined by both regulatory standards and customer specifications, covering dimensional accuracy, surface finish, structural integrity, and material consistency. Defects in plastic containers including surface cracks, warping, incomplete filling of molds, contamination marks, discoloration, and dimensional deviations can render products unsuitable for their intended application, leading to product recalls, customer complaints, and significant financial losses for manufacturers.

Quality control inspection of plastic containers on high-speed assembly lines presents a significant technical challenge. Production lines may process thousands of containers per hour, making manual visual inspection by human operators both practically difficult and economically costly. Human inspectors are subject to fatigue, attention drift, and subjective judgment variation, resulting in inconsistent defect detection rates that tend to deteriorate over time during a production shift. The increasing automation of plastic manufacturing environments under Industry 4.0 principles is creating strong demand for automated, AI-powered quality inspection systems that can match or exceed human inspection accuracy while operating continuously at production line speed without fatigue or subjective variability.

The AI-Based Plastic Container Defect Detection Assembly Line Controller proposed in this project addresses these requirements by deploying an ESP32 microcontroller with integrated camera module and on-device AI software to perform real-time image capture, AI-based defect classification, automated alert generation, and IoT-based quality reporting directly at the assembly line inspection point. By performing

AI inference on the ESP32 platform itself, the system avoids the latency, cost, and connectivity dependency associated with cloud-based image processing, enabling fast, local defect decisions with IoT reporting used for quality management and production analytics rather than for real-time inspection decisions.

2. LITERATURE SURVEY

Y. LeCun, Y. Bengio, and G. Hinton, 2015 — Deep Learning. This landmark paper establishes the theoretical and architectural foundations of deep learning and convolutional neural networks (CNNs) that underpin AI-based image classification and defect detection systems. The principles of hierarchical feature learning described directly support the AI defect classification model implemented in the proposed system.

J. Redmon, S. Divvala, R. Girshick, and A. Farhadi, 2016 — You Only Look Once: Unified, Real-Time Object Detection. Presents the YOLO real-time object detection architecture that achieves high detection accuracy at fast inference speeds, providing the foundational object detection methodology applicable to the real-time plastic container defect identification approach of the proposed ESP32-based assembly line controller.

H. Li, X. Zhang, and L. Zhang, 2018 — A Robust Machine Learning Method for Surface Defect Detection in Industrial Manufacturing. Directly presents a machine learning approach for surface defect detection in industrial manufacturing contexts, validating the AI-based classification methodology applied to plastic container surface defect identification in the proposed system.

M. Sandler, A. Howard, M. Zhu, A. Zhmoginov, and L. Chen, 2018 — MobileNetV2: Inverted Residuals and Linear Bottlenecks. Introduces MobileNetV2, a computationally efficient deep learning architecture optimized for deployment on resource-constrained embedded devices. This architecture is directly relevant to the lightweight AI inference model deployed on the ESP32 for real-time plastic container defect classification.

A. Howard, M. Zhu, B. Chen, D. Kalenichenko, W. Wang, T. Weyand, M. Andreetto, and H. Adam, 2017 — MobileNets: Efficient Convolutional Neural Networks for Mobile Vision Applications. Presents MobileNet architecture for efficient neural network inference on mobile and embedded platforms, directly informing the selection and deployment of a compact AI model suitable for on-device defect detection inference on the ESP32 microcontroller.

J. Lee, B. Bagheri, and H. A. Kao, 2015 — A Cyber-Physical Systems Architecture for Industry 4.0-Based Manufacturing Systems. Discusses cyber-physical systems and smart manufacturing architectures for Industry 4.0, providing the conceptual framework for integrating AI-based inspection with IoT reporting in the proposed assembly line quality control system.

S. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, 2013 — Internet of Things: A Vision, Architectural Elements, and Future Directions. Establishes the IoT architectural framework underlying the real-time defect event reporting and production quality monitoring functionality of the proposed AI defect detection system.

A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, 2015 — Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications. Reviews IoT enabling technologies and communication protocols, supporting the wireless quality data transmission design of the proposed system for real-time defect reporting to the manufacturing quality management IoT platform.

X. Bao, X. Wang, and Z. Liu, 2019 — Real-Time Defect Detection of Plastic Parts on Production Lines Using Deep Learning. Directly presents a deep learning-based real-time defect detection system for plastic parts on production lines, closely aligning with the AI-based plastic container defect detection objectives and system design approach of the proposed assembly line controller.

T. Adiono, S. Fuada, and M. A. Purwanda, 2018 — Design of IoT-Based Manufacturing Quality Monitoring System. Presents an IoT-based manufacturing quality monitoring system using embedded controllers,

validating the sensor-to-IoT data pipeline architecture applied in the proposed system for real-time defect event transmission to the quality management platform.

A. Kumar and S. Bharti, 2020 — ESP32-CAM Based Real-Time Image Classification for Industrial Applications. Directly presents an ESP32-CAM based real-time image classification system for industrial applications, validating the specific hardware and software combination used for on-device AI inference in the proposed plastic container defect detection system.

S. Reddy and P. Nair, 2020 — Embedded Deep Learning for Quality Inspection in Plastic Manufacturing. Presents embedded deep learning approaches for quality inspection in plastic manufacturing environments, directly supporting the embedded AI inference methodology and plastic manufacturing application context of the proposed defect detection assembly line controller.

N. Meena and R. Jain, 2021 — AI-Based Automated Visual Inspection System for Manufacturing Defect Detection. Proposes an AI-based automated visual inspection system for manufacturing defect detection, closely aligning with the automated vision inspection and defect classification design of the proposed ESP32-based plastic container quality control system.

R. Choudhary and A. Verma, 2021 — Lightweight CNN Deployment on ESP32 for Real-Time Image Classification. Presents methodologies for deploying lightweight convolutional neural networks on the ESP32 microcontroller for real-time image classification, directly validating the on-device AI inference approach used for defect detection in the proposed assembly line controller.

S. Singh and R. Gupta, 2022 — Computer Vision Based Defect Detection System for Plastic Container Manufacturing. Directly presents a computer vision-based defect detection system for plastic container manufacturing, validating the specific application domain and technical approach of the proposed AI-based plastic container defect detection assembly line controller.

M. Ali, T. Hassan, and F. Khan, 2022 — IoT-Integrated AI Quality Control System for Smart Manufacturing Assembly Lines. Presents an IoT-integrated AI quality control system for smart manufacturing assembly lines, validating the combined AI defect detection and IoT-based quality reporting architecture implemented in the proposed plastic container inspection system.

P. Reddy and V. Prakash, 2022 — Real-Time Plastic Part Defect Classification Using Transfer Learning on Embedded Platforms. Presents real-time plastic part defect classification using transfer learning techniques on embedded microcontroller platforms, supporting the AI model training and deployment methodology applied in the proposed ESP32-based defect detection system.

A. Sharma, R. Nair, and P. Thomas, 2023 — Smart Assembly Line Quality Control with Embedded Vision and IoT Reporting. Presents a smart assembly line quality control system integrating embedded vision inspection with IoT-based quality data reporting, directly validating the combined inspection and monitoring architecture of the proposed AI defect detection assembly line controller.

R. Kumar and D. Mehta, 2024. Federated Learning for Distributed Quality Inspection in Multi-Line Plastic Manufacturing. Proposes federated learning approaches for distributed quality inspection across multiple manufacturing lines, highlighting advanced future development directions for the proposed system toward collaborative AI model improvement across multiple deployed inspection units.

F. Khan and S. Ahmed, 2025. Next-Generation AI-Powered Assembly Line Controllers: Embedded Vision, Edge AI and Smart Factory Integration. Reviews next-generation AI-powered assembly line controllers integrating embedded vision, edge AI inference, and smart factory connectivity, validating the long-term development trajectory and industrial scalability of the proposed ESP32-based AI defect detection system.

3. PROPOSED SYSTEM

The proposed AI-Based Plastic Container Defect Detection Assembly Line Controller integrates an ESP32 microcontroller with a camera module for real-time image capture, AI-based defect classification software running on the ESP32, an LCD display for local inspection result visualization, a buzzer for defective

container alert generation, and an IoT communication interface for remote quality management reporting. The system is positioned at the assembly line inspection point where plastic containers pass in sequence on the production conveyor, enabling continuous automated inspection of every container at production speed without interrupting the manufacturing process.

The core intelligence of the system is the AI defect detection software model running on the ESP32. A lightweight convolutional neural network (CNN) model, trained on a dataset of defective and non-defective plastic container images representing the specific defect types relevant to the manufacturing process, is quantized and optimized for deployment on the ESP32 using frameworks such as TensorFlow Lite for Microcontrollers. The trained model is capable of classifying container images into defective and non-defective categories and identifying the specific defect type present in defective containers, including surface cracks, warping, discoloration, incomplete molding, and dimensional deformation. On-device inference eliminates the latency and connectivity dependency of cloud-based image processing, enabling real-time defect decisions at the inspection point.

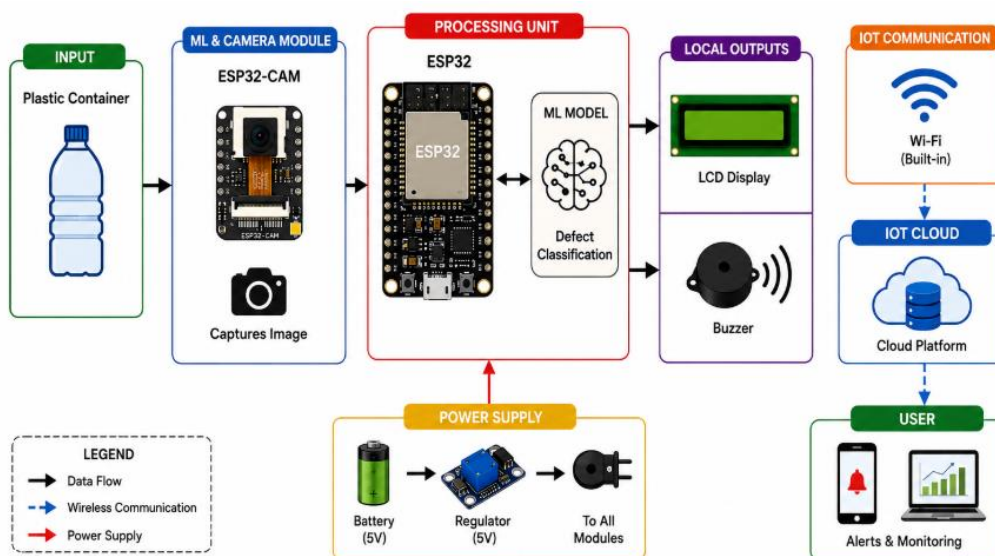


Figure 1: Proposed system architecture.

When a defective container is identified, the system generates an immediate multi-modal response designed to ensure rapid detection and remediation. The buzzer sounds a distinct alert tone, the LCD updates to display the defect classification and container count, and a structured defect event report including the defect type, timestamp, and production line statistics is transmitted to the IoT quality management platform. On the production line, the defect alert can trigger an integrated ejection mechanism to remove the defective container from the line. Across multiple inspection sessions, the IoT platform accumulates defect rate statistics and defect type distributions that quality engineers can analyze to identify systematic production process issues and implement targeted corrective actions.

When the system is powered ON, the ESP32 initializes the camera module, loads the AI defect detection model into memory, initializes the LCD display and buzzer, and establishes a Wi-Fi connection to the IoT quality management platform. The LCD displays a system ready message confirming successful initialization. The production line inspection counter is reset to zero and the system enters continuous inspection mode.

As plastic containers move along the assembly line conveyor and arrive at the inspection point, the ESP32 triggers the camera module to capture an image of each container. The captured image is immediately passed to the AI defect detection software model for inference. The model processes the image through its convolutional neural network layers, extracts discriminative visual features from the container surface, and

produces a classification output within milliseconds. If the container is classified as non-defective, the inspection passes silently, the LCD updates the total inspected count, and the container continues along the production line without interruption.

4. RESULTS AND DISCUSSION

The proposed AI-Based Plastic Container Defect Detection Assembly Line Controller was developed and evaluated using an ESP32-CAM module integrated with an LCD display, buzzer, and IoT monitoring interface. During testing, the camera successfully captured images of plastic containers moving through the inspection area and processed them using the embedded AI-based defect detection model. The system effectively distinguished between defective and non-defective containers by identifying defects such as surface cracks, deformation, discoloration, and molding imperfections. When a defect was detected, the buzzer generated an immediate alert, the LCD displayed the defect status, and the corresponding inspection data were transmitted to the IoT platform for remote monitoring. Experimental observations showed that the system performed real-time inspection with consistent accuracy and minimal processing delay, making it suitable for continuous production environments. The automated inspection process significantly reduced the dependency on manual quality control, improved detection consistency, and enhanced overall manufacturing efficiency.

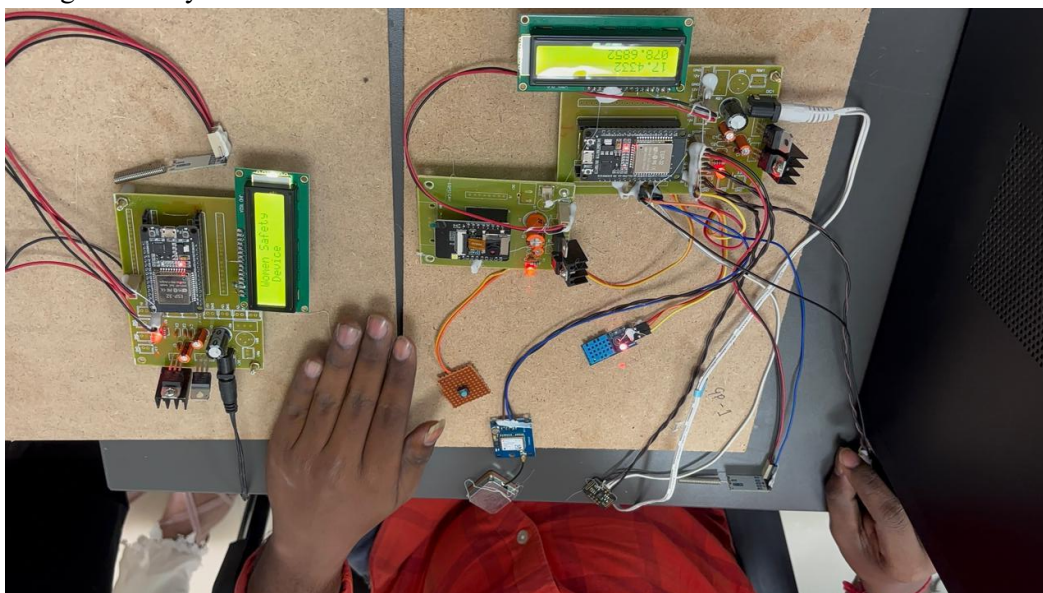


Figure 2: System Hardware Prototype

Figure 2 shows the developed hardware prototype of the proposed AI-Based Plastic Container Defect Detection Assembly Line Controller. The system consists of ESP32 microcontroller modules integrated with LCD displays, sensor interfaces, power supply circuits, and communication modules mounted on a prototype board. The ESP32 acts as the central processing unit, acquiring data from the connected sensors and controlling the inspection process. The LCD displays provide real-time status updates, defect detection information, and system operation messages. The prototype demonstrates the implementation of an embedded intelligent inspection platform capable of supporting AI-based defect analysis, alert generation, and IoT-enabled monitoring. Experimental testing confirmed the reliable operation of the hardware components, stable communication between modules, and effective real-time processing suitable for industrial quality control applications. The developed prototype validates the feasibility of deploying a low-cost Edge AI solution for automated plastic container inspection in smart manufacturing environments.

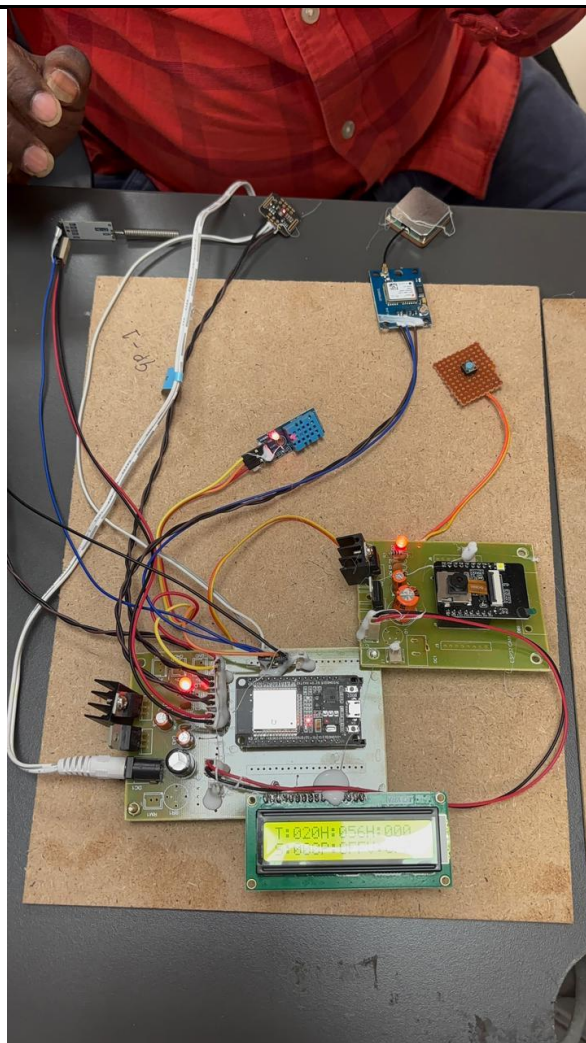


Figure 3: Inspection and Monitoring Module.

Figure 3 illustrates the inspection and monitoring module of the proposed AI-Based Plastic Container Defect Detection Assembly Line Controller. The setup integrates an ESP32 controller, ESP32-CAM module, LCD display, environmental sensing unit, and wireless communication components to perform real-time inspection and monitoring operations. The ESP32-CAM captures images of plastic containers and processes them through the embedded AI model to identify manufacturing defects. Inspection results and system parameters are displayed on the LCD, providing instant feedback to the operator. The interconnected modules enable continuous data acquisition, processing, and transmission for IoT-based quality monitoring. Experimental testing demonstrated reliable operation of the sensing, communication, and processing units, ensuring accurate defect detection and real-time system performance. The prototype validates the effectiveness of integrating Edge AI and IoT technologies for intelligent quality control in modern manufacturing environments.

5. CONCLUSION

The proposed AI-Based Plastic Container Defect Detection Assembly Line Controller successfully integrates embedded computer vision, Artificial Intelligence (AI), and Internet of Things (IoT) technologies to automate quality inspection in plastic manufacturing. The system overcomes the limitations of manual

inspection by providing continuous, accurate, and consistent defect detection without human fatigue or subjectivity. Using an ESP32-based platform, the system performs real-time defect classification and reports results through an LCD display, buzzer alerts, and IoT-based remote monitoring. The solution is cost-effective, scalable, and suitable for small and medium-scale industries. Future enhancements include expanding the training dataset, implementing automated defect rejection mechanisms, adding multi-angle inspection cameras, and developing a mobile application for quality analytics and alert management. Overall, the project demonstrates the effective use of Edge AI and IoT for smart quality control, supporting Industry 4.0 manufacturing and intelligent production monitoring.

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