VisionSpec-QC: Automated PCB Defect Detection Using Computer Vision

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1. Abstract

Printed Circuit Boards (PCBs) are a critical component in electronic devices, and defects in PCBs can lead to device failure, increased maintenance cost, and reduced product reliability. Traditional manual inspection methods are time-consuming, inconsistent, and unsuitable for high-volume manufacturing environments. This project, VisionSpec-QC, presents an automated and intelligent quality control system for PCB inspection using computer vision and deep learning techniques.

The proposed system utilizes transfer learning with the MobileNetV2 convolutional neural network to classify PCB images into PASS and DEFECT categories. To address real-world data imbalance, class weighting techniques are applied during training. Furthermore, Explainable Artificial Intelligence (XAI) is incorporated using Gradient-weighted Class Activation Mapping (Grad-CAM) to visually highlight the regions of the PCB that influence the model's decision, thereby improving transparency and trust in the system.

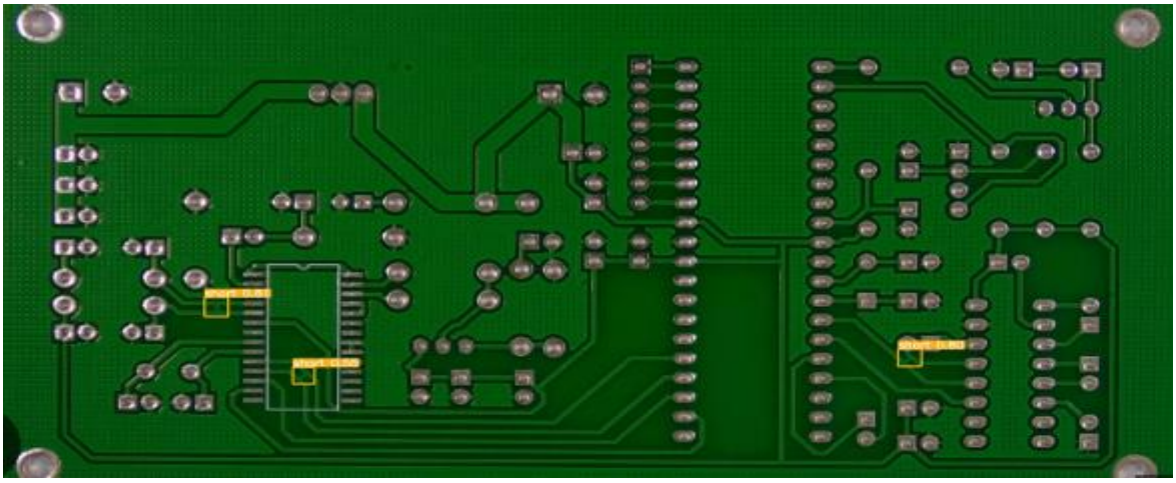
The trained model is deployed as an interactive web application using Streamlit, allowing users to upload PCB images and receive predictions along with visual explanations in real time. Experimental results demonstrate that the system effectively identifies defective PCBs and provides meaningful defect localization. VisionSpec-QC offers a scalable, reliable, and industry-relevant solution for automated PCB quality inspection in modern manufacturing systems.

2. Introduction

In modern electronic manufacturing industries, Printed Circuit Boards (PCBs) play a crucial role as the backbone of electronic devices. The quality of PCBs directly impacts the performance, reliability, and safety of electronic products. Traditional PCB inspection methods rely heavily on manual visual inspection, which is time-consuming, error-prone, and inefficient for large-scale production.

With advancements in Artificial Intelligence (AI) and Computer Vision, automated visual inspection systems have become a powerful alternative. These systems can analyze PCB images accurately, consistently, and at high speed. This project, **VisionSpec-QC**, aims to design and implement an intelligent PCB quality control system using deep learning techniques.

The system classifies PCB images into **PASS** or **DEFECT** categories and provides visual explanations using Explainable AI techniques, ensuring transparency and trustworthiness in industrial applications.



3. Problem Statement

Manual inspection of PCBs in manufacturing industries faces several challenges:

- Human fatigue leading to missed defects
- Inconsistent inspection results
- High labor cost
- Difficulty in detecting minute defects

Therefore, there is a need for an automated, accurate, and explainable inspection system that can identify defective PCBs and highlight defect regions effectively.

4. Objective

The main objectives of this project are:

1. To develop a computer vision model for PCB defect classification.
2. To use deep learning and transfer learning techniques for higher accuracy.
3. To handle imbalanced datasets effectively.
4. To implement Explainable AI using Grad-CAM.
5. To deploy the trained model as an interactive web application.

5. Dataset description

5.1 Dataset Source

The dataset consists of PCB images collected for industrial quality inspection. It includes both defective and non-defective boards.

5.2 Dataset Structure

The dataset is organized into two main classes:

- PASS: PCB images without defects
- DEFECT: PCB images containing manufacturing defects

5.3 Dataset Statistics

- DEFECT images: 6370
- PASS images: 2164

Since the dataset is imbalanced, class weights were applied during training to ensure fair learning.

6. Methodology

6.1 Data Preprocessing

- Images were resized to 224 × 224 pixels
- Pixel values were normalized between 0 and 1
- Dataset was split into training and validation sets

6.2 Model Architecture

This project uses **Transfer Learning** with **MobileNetV2**, a lightweight and efficient Convolutional Neural Network.

Key reasons for choosing MobileNetV2:

- Pretrained on ImageNet
- Fast training and inference
- Suitable for deployment on low-resource systems

The final layers were customized for binary classification.

6.3 System Architecture

The overall architecture of the VisionSpec-QC system consists of the following stages:

1. Image Input
2. Preprocessing
3. Feature Extraction using CNN
4. Classification Layer
5. Explainability using Grad-CAM
6. Web-based Deployment

7. Model Training

7.1 Training Configuration

- Optimizer: Adam
- Loss Function: Binary Cross-Entropy
- Epochs: 5
- Batch Size: 32
- Class weights applied to handle imbalance

7.2 Training Results

The model achieved good training accuracy, indicating effective feature learning. Although validation accuracy was lower due to dataset complexity, Grad-CAM visualization confirmed meaningful feature focus.

8. Explainable AI using Grad-CAM

Grad-CAM was used to explain the model's predictions by highlighting image regions that contributed most to the classification decision.

Benefits of Grad-CAM:

- Improves transparency and trust in AI
- Helps engineers verify model reasoning
- Identifies defect-prone regions

Heatmaps generated using Grad-CAM clearly indicate PCB areas such as solder joints and circuit paths.

9. Web Application Deployment

A **Streamlit-based web application** was developed to make the system user-friendly.

Application Features:

- Upload PCB image
- Predict PASS or DEFECT
- Display Grad-CAM visualization

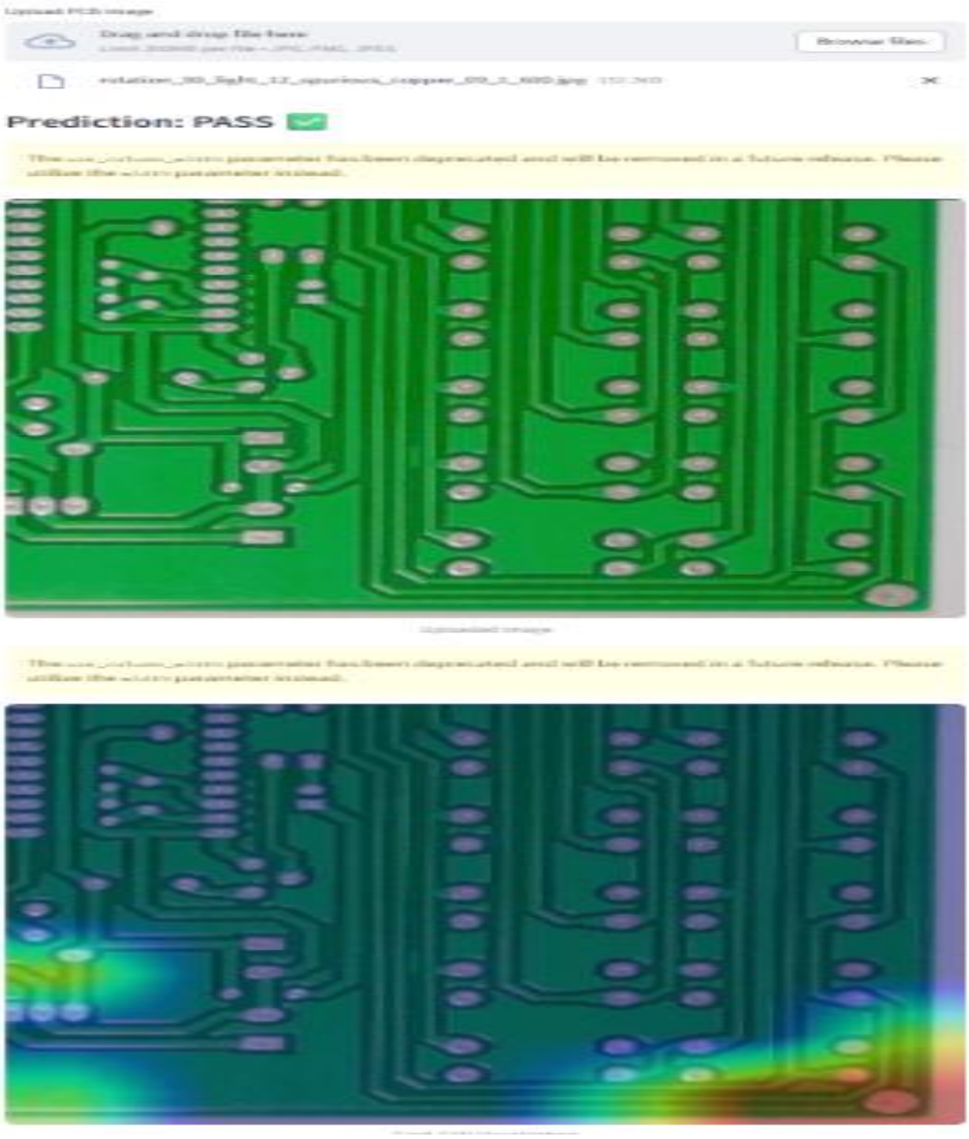
This allows real-time inspection and easy interaction without technical expertise.

10. Tools and Technologies Used

- Programming Language: Python
- Deep Learning Framework: TensorFlow / Keras
- Computer Vision: OpenCV
- Model Architecture: MobileNetV2
- Explainability: Grad-CAM
- Web Framework: Streamlit

11. Results and Discussion

The developed system successfully classifies PCB images and highlights important visual regions influencing decisions. The results demonstrate the effectiveness of deep learning and explainable AI in industrial quality control applications.



12. Applications

- PCB Manufacturing Quality Control
- Electronics Industry Automation
- Smart Factories
- AI-assisted Inspection Systems

13. Limitations

- Limited dataset diversity
- Validation accuracy affected by class imbalance
- Requires high-quality images for best results

14. Conclusion

This project demonstrates a complete end-to-end AI-based PCB quality inspection system. By combining deep learning, explainable AI, and web deployment, the system offers a practical and scalable solution for manufacturing environments.

15. Future Scope

- Improve dataset balance and diversity
- Add multi-class defect classification
- Integrate real-time camera inspection
- Deploy on cloud or edge devices