Augmented Reality and Artificial Intelligence Based Smart Circuit Trainer with PCB Fault Detection

Prepared by:

Abdur Rafay Mansab

Enrollment No. 01-133222-003

Aqeel Ahmed Khan

Enrollment No. 01-133222-010

Supervised By:

Dr. Junaid Imtiaz

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Department of Electrical Engineering

Bahria University H-11 Campus, Islamabad.

Certificate

We accept the work contained in this report as a confirmation to the required standard for the partial fulfillment of the degree of BS(EE).

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Head of Department

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Supervisor

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Internal Examiner

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External Examiner

Dedication

We dedicate this project to our beloved parents, whose endless support, prayers and love have been our strength through every step of this journey. Their sacrifices and encouragement have inspired us to strive for excellence. We also dedicate this work to our teachers and friends who stood by us with motivation, ideas and kindness throughout our academic years.

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Thank you all for your support and encouragement.

Abstract

Learning electronics and inspecting circuit boards can be challenging, especially when students struggle to visualize circuits or when labs lack affordable diagnostic tools. At the same time, professional PCB inspection systems are often expensive, making them impractical for education and lower level use. To address these challenges, this project introduces an AR and AI-Based Smart Circuit Trainer with PCB Fault Detection—a system designed to make circuit learning more interactive while also providing automated fault analysis for printed circuit boards. Using Augmented Reality students can view and build circuits in 3D and identify components and receive step-by-step guidance. The AI-powered fault detection feature analyzes PCB images and compares them with reference designs to detect issues such as broken tracks, soldering errors or missing components or lines on PCB board. The hardware setup progresses from a simple manual inspection model to a fully automated system for accurate and reliable scanning. By combining AR for learning and AI for smart inspection, this project offers an automatic and cost-effective solution that supports students, teachers and small-scale electronic development with real-time visualization and intelligent fault detection.

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Chapter 1

Introduction

The concept and objective of designing the AR and AI-based smart circuit trainer with PCB fault detection are discussed in this chapter. Real circuit connections are hard to understand by many students, and manual checking of PCB faults is confusing, slow, and costly using industrial tools. Learning, understanding, and troubleshooting in new technologies such as AR and AI will become much easier. The system integrates 3D visual guidance in circuit building with smart fault detection to make electronics more understandable, practical, easy, and accessible.

1.1 Background

Typically, electronics education suffers from a practical perspective because it's hard for students to visualize real connections of circuits and troubleshooting faults. With the increasing power of Augmented Reality (AR) and Artificial Intelligence (AI), one can now realize such interactive platforms that will not only instruct and build the circuit but also analyze and detect PCB faults in real time. The current research aims to connect the theory and practice through the implementation of AR, AI and latest Computer Vision technologies.

1.2 Problem Statement

The inspection of PCBs is a critical but difficult task.The challenges that current practices face are:

- Manual inspection is slow, inconsistent, and error-prone.
- AI or AOI machines are expensive and inaccessible for small-scale labs or educational use.

- Most simulation tools used in the educational process do not emulate real circuit inspection.

Traditional circuit labs have some challenges for beginner students such as difficulty understanding circuit diagrams, wrong wiring. There is a need for a hybrid tool that shows real-world visualizations of circuits while guiding students step by step. [1–3]

1.3 Objectives

The objectives of this project are as follows:

- Design an AR-based mobile and PC-compatible app to visualize electronic circuitry on breadboards and flat surfaces in real time.
- Bridge the gap between simulation and practical learning by enabling step-by-step 3D guided circuit building.
- Reduce wiring errors and enhance conceptual understanding through Interactive AR instructions and automatic circuit analysis.
- Integrate fault detection by comparing golden reference PCBs with Test boards for educational or prototyping purposes.
- Provide scalable solutions for schools, colleges, labs, and remote learning with a built-in component knowledge module.

1.4 Features

Here we discuss about the the Basic and Advanced features of my project.

1.4.1 Basic Features

1. **Circuit Building:** The software will help students identify physical components on an actual breadboard or circuit. Using Augmented Reality (AR), it will highlight names, functions and allow real-time Guided 3D visualization.

2. **Analysis:** The application will analyze the circuit to explain the type of connections series or parallel and the function of each component.

3. **Scan Circuits from Book:** Students can upload an image of the circuit and the software will be able to detect the parts and explain the function of each component to them.

4. **Knowledge:** The software will have 3D models of electrical components with information about their function, smart budget estimator an AI assistant for circuit building in the circuit.

1.4.2 Advanced Features

1. **Fault Detection:** It will be able to automatically detect potential defects such as missing traces and components, poor soldering and faulty components in printed circuit boards. It further utilizes artificial intelligence techniques to take this one step forward and offer possible solutions by redesigning circuits.

1.5 Methodology

Methodology for the suggested system can be divided into multiple stages, involving both hardware and software approaches. All these stages are aimed at creating an AI and AR based system for PCB faults detection and visualization..

1. **Data Collection:** Taking photos of faulty and golden standard boards as well as the circuit design of the board itself.

2. **Pre-processing:** This step involes the image enhancement and component extraction of the images captured.

3. **Component Recognition:** Object recognition via AI through deep learning algorithms such as YOLO, to identify various electronic components from resistors to capacitors and ICs.

4. **AR Module:** Designing an AR interface using Unity or ARCore technology that will produce a 3D model of a circuit onto a breadboard or any other flat surface to facilitate visualizations and enhance the learning process. []

5. **Fault Detection:** Using different AI detection methods for comparing a scanned PCB with a reference PCB image to identify faults such as missing tracks or improper soldering and many more.

6. **Testing & Validation:**Assess the efficiency and precision of the system by testing it on the PCB dataset provided by university labs and through the data available across the web browser.

1.6 Block Diagram

This is a brief description of the flow of the project.

1.6.1 Diagram

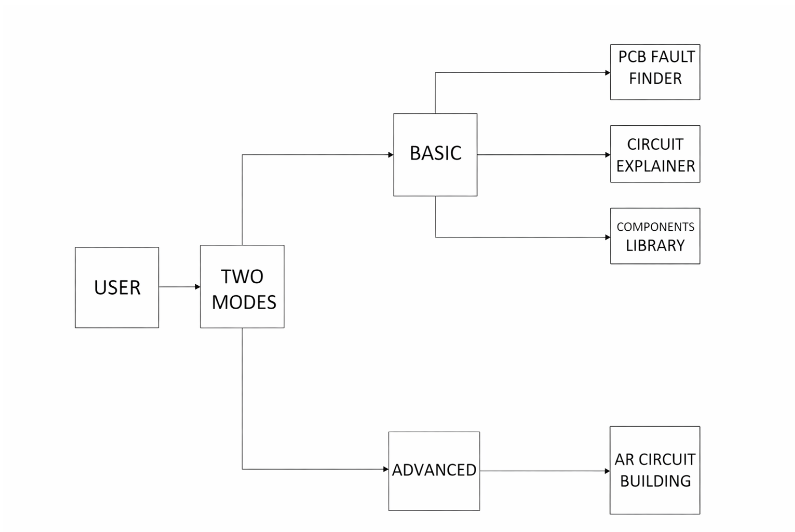

Figure 1.1: Block Diagram

1.6.2 Basic Mode

Under Basic Mode, the basic analysis is carried out alongside simple diagnostic methods for inexperienced users. The basic mode incorporates **PCB Fault Finder**. PCB Fault Finder is an image processing software that analyzes faults commonly encountered in printed circuit boards (PCBs). With the use of the software, any problem within the PCB such as faulty components, broken circuit paths, shorts and bad soldering can be easily detected.

Through this method, problems within the PCB image captured by the system are analyzed using computer vision technology and any anomalies highlighted.

Additionally, the Basic Mode includes:

- **Circuit Explainer** Offers a detailed explanation of how a circuit works, thus aiding in comprehending the current path, the role played by each component, and the entire operation of the circuit.
- **Components Library** Functions as a comprehensive database for electronic parts, their symbols, working process, specifications and real-life applications.

This mode aims at strengthening basic knowledge and incorporating practical fault-finding skills.

1.6.3 Advance Mode

The Advance Mode facilitates interactive learning via augmented reality systems. One of the features is **AR Circuit Building**, which allows the user to create and visualize electronic circuits using augmented reality technology.

Using the interactive 3D visualization method, the user will be able to:

- Create virtual electronic components
- Visualize how the circuit is connected
- Understand the spatial arrangement of signals
- Test and simulate the performance of the circuit in the immersive environment.

With this advanced mode, users get a chance to understand circuit creation not just in terms of 2D images but in an user-friendly AR environment.

1.6.4 Overall System Working

The technology combines aspects of artificial intelligence, computer vision, image processing and augmented reality to serve the purpose of being educative and also practical to use in real life.

- **Basic Mode** is mainly concerned with PCB fault detection, troubleshooting and learning from basics.
- **Advance Mode** involves designing circuits through immersive AR experience.

Together, the platform serves as a comprehensive tool for students, researchers and engineers in electronics by combining learning, simulation and intelligent fault detection within a single system.

1.7 Scope of the Project

This project's scope identifies the boundary conditions regarding what the system is to achieve, which technologies are integrated, and the intended deliverables. This project would integrate the use of Artificial Intelligence and Augmented Reality in developing an educational and inspection tool targeted for electronics students, laboratories, and small-scale industries.

1.7.1 Functional Scope

The scope of the project which focuses just on the functioning of project are discussed below.

AR-Based Circuit Learning Module (Advanced Mode)

This part of the system is designed to assist novices who have problems visualizing real-world circuit construction. The module visualizes circuits in

AR on a breadboard or any flat surface. It contains step-by-step guidance, automatic component identification, and a library explaining the purpose, ratings, and usage of electronic components. Additionally, users are able to scan the circuit diagram in textbooks into the system, which converts that into AR-based 3D guided layouts.

AI-Based PCB Fault Detection (Basic Mode)

Advanced mode for AI and Image Processing-based Automatic PCB inspection: Various image-processing operations such as enhancement, filtering out noise, and component extraction on captured images of PCBs are done. The AI model identifies faults such as missing components, broken traces, solder bridges, burnt regions, and misaligned parts. Further, the scanned PCB is compared with its golden reference to outline all discrepancies. Scanned defect locations are marked for easy output by the system.

1.7.2 Hardware Scope

The different hardware ideas for the project are mentioned below.

Wooden Inspection Box

The hardware consists of a 2ft × 2ft wood enclosure providing a controlled and accurate lighting environment. The box ensures uniform lighting and minimizes shadows for higher-quality image capture, which is very important for accurate detection.

Camera Mounts and Sliders

The design holds fixed or motorized camera mounts. Some new model versions also include motorized sliders that allow different angles and 360°

image capture. A PCB holding mount enables stable placement and optional rotation of the board.

1.7.3 Software Scope

The software scope of the project are discussed in following section.

AI Model and Image Processing

The system will integrate a deep learning-based detection model, namely YOLO. The pre-processing of images includes filtering, edge detection, contrast enhancements, and thresholding. The component identification and defect detection are done by the trained model.

AR Visualization Module

The AR interface, prepared on Unity , demonstrates the elements and schemes of works in 3D space. It lets the user get a view of real-time circuit assembly, explore component functionality, and understand wiring patterns interactively.

User Interface and Modes

The software combines the functionality of both Basic and Advanced modes. While the former is used for AR-based learning, the latter manages PCB inspection along with AI-powered fault detection. It supports image input, processing, and result display along with real-time rendering of AR.

1.8 Review Questions

The questions which arise among the minds of users are answered below.

1.8.1 Industrial Applications Not Clear

The industrial applications of the project include the prototyping of PCBs, small-lot manufacturing, and quality control. Although there are machines for large-scale production of PCBs, most of them are actually for fabrication and offer no fault detection in detail or inspection during prototyping.

The verification of new designs in industries is mainly done manually by engineers, sometimes with the support of expensive AOI machines. Manual methods are time-consuming and error-prone, while the AOI machines are expensive and not feasible for all small companies or labs.

The solution provided by our system lies in the fact that we offer an artificial intelligence-based tool for identifying faults, such as missing tracks, soldering problems or damaged components. This ensures a more effective and economical process of inspecting electronic products. []

Linked SDGs:

- **SDG:** Industry, Innovation and Infrastructure → by introducing innovative AI-powered verification tools in manufacturing.

1.8.2 Future Use In Industry

The industries would employ this since manual PCB inspection is very slow and relies heavily on expert engineers. An experienced professional would actually detect the faults visually, which again is subjective, error-prone, and not scaling well.

The current automated fabrication machines consider speed and efficiency of production, but fault detection or verification tasks are not within their design scope.

Our system provides an affordable and scalable solution for these gaps. Using AI and computer vision, the detection of faults in a PCB is done in a matter of seconds. This helps industries by:

- Reducing inspection time.
- Improving accuracy and reliability of defect detection.
- Lowering dependency on skilled manual inspectors.
- Reducing costs of rework and wasted materials.

Linked SDGs:

- **SDG:** Decent Work and Economic Growth → by increasing productivity and reducing reliance on repetitive manual inspection.
- **SDG:** Responsible Consumption and Production → by minimizing material waste due to faulty PCB production.

1.8.3 Career & Degree Relevance

This is a highly relevant project in the domain of Electrical Engineering, as it intersects several emerging technologies that are in demand around the world. By integrating the hardware part of this project, represented by the PCB design and circuit analysis, with advanced software technologies like AI, computer vision, and AR, the project establishes a multidisciplinary foundation valued in academia and industry. [4]

Key Areas of Relevance:

- **PCB Design & Analysis:** Focuses on how to understand circuit layouts, route traces and carry out fault analysis, important skills in the prototyping and testing of electronics.
- **Computer Vision & AI:** Computer vision, coupled with deep learning, is one of the cornerstones in Industry for carrying out sev-

eral applications: automated inspection, quality assurance, robotics, etc.

- **Augmented Reality (AR/VR/XR):** AR is gaining recognition in engineering education and technical training for enhancing visualization, reducing errors and improving learner engagement.

- **Embedded Systems & Hardware-Software Integration:** Camera and sensor integrations, micro-controllers and AI models show practical examples of integrating hardware-software systems, reinforcing embedded solutions competence.

Industrial & Academic Value:

- Electronics manufacturing and prototyping (for quality assurance and defect detection)

- AI and computer vision research (for automated inspection and intelligent systems)

- AR/VR platforms (for training, simulation, and visualization tools)

- Academic environments (where hybrid learning models demand hands-on, technology-driven solutions)

[5–7]

Chapter 2

Literature Review

This chapter presents all the ideas of a damaged PCB board and oversees and discusses them. The detection removing mechanism and reverse engineering about how to remove the defects is also discussed in detail in the chapter. Furthermore, integration of AR and AI in the fault detection of the PCBs and circuit training for educational purposes. AR will provide interactive visualization by overlaying information on components, step-by-step repair guidance and highlighting faults directly on the physical PCB, which will enhance hands-on learning while reducing errors. Artificial Intelligence uses computer vision techniques such as deep learning with algorithms like YOLO to detect various faults like missing components, broken tracks, short circuits and soldering defects. The AI module compares images of PCBs with reference designs, reconstructs schematics through reverse engineering, and provides suggestions for corrective actions.

2.1 PCB Board Damaged Ideas

The different ways in which a PCB board can be damaged are discussed here.

2.1.1 Copper Track Faults

- **Open Track:** A broken track on a PCB includes physical damage or disconnection to any copper trace, which hampers the flow of current. It may be because of excessive bending, mishandling, overheating or poor etching during fabrication. Even a minor break can disrupt the whole path of a signal and result in circuit failure or unexpected behavior. Such faults are easily visible by image inspection since they appear as discontinuities or gaps in the copper pattern.

- **Shorted Track:** Shorted tracks are a kind of fault that involves the unintentional connection between two or more conductive paths on the PCB, resulting in a short circuit. In most cases, this is caused by too much solder, copper debris or bridging within the manufacturing or soldering process. It could lead to severe results, causing abnormal current flow, overheating and burning of components. In AI-based fault detection, these shorts are normally identified as small metallic bridges or abnormally bright regions between two tracks in a captured image.

- **Over-Etched and Under-Etched Track:**Poor chemical etching in the manufacture of a PCB can result in over-etching-thin tracks- or under-etching-thick or merged tracks. Over-etching may result in easy breakage of tracks or higher resistance, while under-etching may cause bridging between adjacent paths, resulting in a short circuit. The find may reveal these minute manufacturing defects by comparing the image with the reference board to determine abnormalities in track width or continuities.

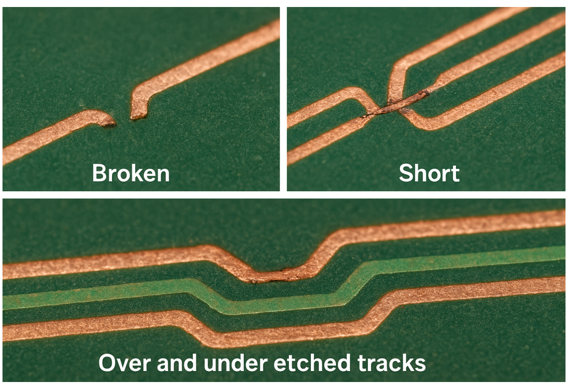

Figure 2.1: Basic Defects of PCB Board

2.1.2 Components Realted Problems

- **Missing and Misplaced Components:**A missing component fault arises when one or more components fail to be mounted on the board, leaving the solder pads empty. Most often, this occurs during manual soldering or in automated placement errors. Missing components completely disrupt the operation of the circuit, especially if some of the critical components like resistors, capacitors or ICs are missing. Employing computer vision, such faults can be detected by identifying unoccupied solder pads in areas where components should be located. Misplaced components occur when parts are soldered out of position or at wrong orientations. Polarized components, for instance, may be placed in reverse polarity, such as diodes or electrolytic capacitors, which could result in malfunction or further damage. Even slight positional errors in these complex PCBs lead to performance degradation. AI-based models can detect such faults by comparing component positions, shapes, and angles against reference layouts.

- **Wrong Component Type and Value:** Sometimes, the components are correctly placed but with wrong ratings or values. For example, instead of a 1 kΩ resistor, a 10 kΩ might be placed, which will change the circuit behavior from what it should be. These types of issues are also not easy to visually detect and require advanced image recognition techniques, such as optical character recognition on component markings or metadata comparisons against the design file.

- **Lifted and Wrongly Soldered Components:**The most common cause of lifted components is insufficient solder, contamination or heat stress, which can prevent one or more of the component terminals from being effectively soldered to its pad. Such faults can cause intermittent and/or open connections, making the board behave unreliably. From an inspection viewpoint, these appear as either elevated or shadowed areas beneath the component leads. Machine vision techniques can detect these faults by analyzing height variation or shadow irregularities in the captured PCB image.

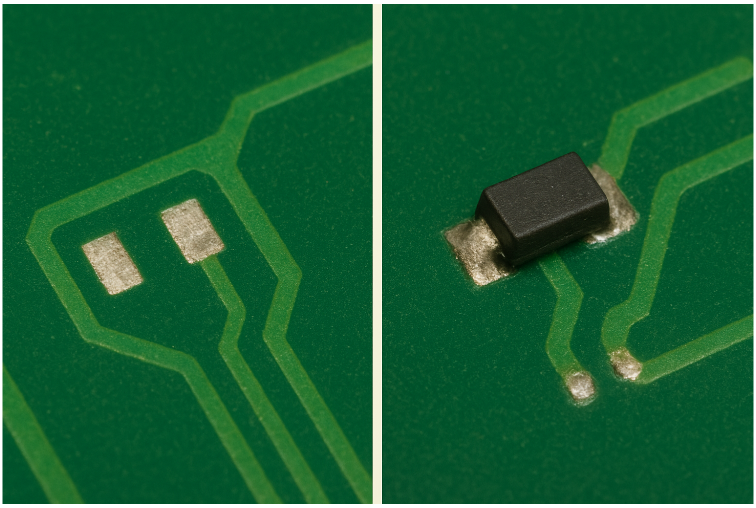

Figure 2.2: Missing And Wrongly Soldered Component

2.1.3 Soldering and Assemble Defects

- **Cold Solder Joint:**Cold solder joints are the result of insufficient heat in the process of soldering, which leads to dull, grainy or cracked solder surfaces. Sometimes, such joints may allow temporary connections that fail under stress or vibration. Since the visual texture of a cold solder joint differs from a proper shiny joint, AI vision systems can detect them through texture and brightness analysis.

- **Solder Bridging:** The solder bridge defect connects two or more adjacent pins due to excessive solder, which in turn creates a short circuit. It mainly occurs with fine-pitch ICs and on densely packed components. Solder bridges can easily be detected by image processing because they appear as abnormal connections between pins or conductive areas that are quite different from the reference design.

- **Excess or Incomplete Solder:**Another problem that may occur in a circuit board is soldering defects caused by improper amounts of soldering. Bridging occurs when there is excess soldering, whereas inadequate soldering causes poor and incomplete connections.

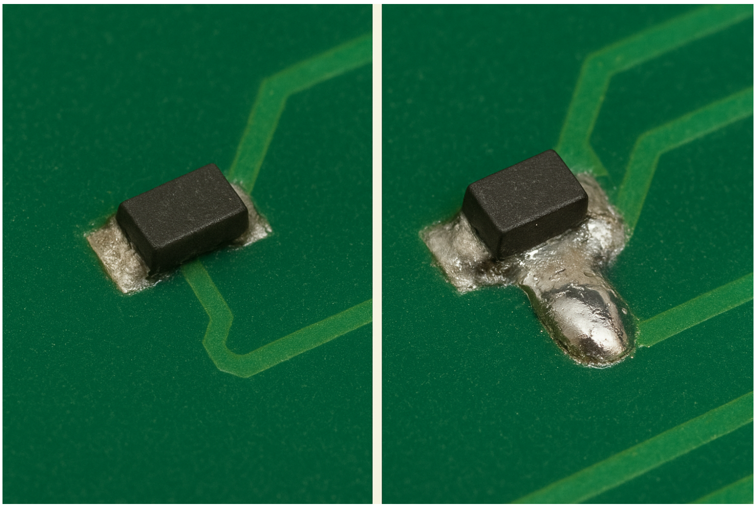

Figure 2.3: Cold Solder Joint And Excess Soldered Component

2.2 Detection Mechanism

The workflow in which image is acquired and then processed through different stages to get the required output are discussed here.

2.2.1 Image Detection Stage

- **Image Acquisition:** The process of detection begins with acquiring quality images of the PCB using cameras inside an inspection box. Images are captured from multiple angles, top, side and diagonal, under controlled lighting conditions. This ensures that every track, solder joint and component will be clearly visible for analysis, reducing the possibility of missing defects that may remain hidden.

- **Image Preprocessing:** These images go through a process of preprocessing, aimed at improving their quality after they have been captured. The process of preprocessing includes noise reduction using either the Gaussian or median filter, followed by the step of edge detection to detect the copper tracks and connections. Thus, methods of contrast enhancement are applied to improve the recognition of the important areas. These processes help to prepare the images, making it easier for the system to recognize certain features.

- **Fault Detection via AI:**After the preprocessing stage, the processed images are then fed to the AI-based computer vision techniques, such as YOLO. Such trained models can detect, classify and localize several components of the board. On the other hand, the image of the printed circuit board is compared with a golden reference image present in the database for any mismatches that may arise from missing components, broken/shortened circuits or problems in the soldering process. These faults are then marked for easy identification.

2.2.2 Reverse Engineering Stage

This section discusses the reverse engineering stage of our project:

- **Circuit Reconstruction:**The system will then proceed with the reconstruction of the circuit to come up with a schematic representation of the defective PCB. During the detection process, each of the identified components is matched into entries in a pre-defined library by using shape recognition and optical character recognition. The interconnections of different components are determined by tracing copper tracks in order to establish the electrical pathways of the circuit. After the extraction of the nets and components, the software reconstructs a logical circuit schematic. Such a schematic ensures an interpretable visualization of the physical board, which helps users understand which connections or components are responsible for malfunctioning.

- **Comparison with Reference Images:** The automatic comparison between the constructed schematic and the reference schematic will be done to identify problems with the circuit. This includes any missing or additional links, the wrong orientation of the components and value mismatches. These are indicated in a color overlay with different colors for correct links. It is an easy way for the user to understand the problem with his circuit and its effect on the performance of the circuit.

- **Fault Localization:**Once mismatches are identified, the system inspects how each detected defect impacts the overall functionality of the circuit. For instance, a broken track between a transistor base and resistor will interrupt signal amplification, whereas a misplaced capacitor can affect the frequency response of the circuit. Fault localization of this nature assists in determining the seriousness and type of each defect, hence it assists the system to prioritize which issues need to be attended to first in the repair process.

2.2.3 Fault Removal Mechanism

- **Suggestive Repair Actions:** Once the faults have been localized, the system provides intelligent repair suggestions, depending on the type of defect that it identifies using the system AI bot assistant. It would thus recommend for a broken track either re-soldering or the use of a jumper wire to restore connectivity. In the case of shorted tracks, it recommends cleaning the bridging area and removing excess solder. If a component is missing or placed in the wrong position, it indicates which one it should be according to its database and advises on its correct positioning or orientation. Similarly, cold solder joints are flagged with recommendations to reheat and reapply solder for a secure connection. All these recommendations come automatically from an AI pre-trained rule set, where specific fault types link to suitable corrective measures.

[8–10]

2.3 Augmented Reality (AR) and Artificial Intelligence (AI) in the Real World

AR and AI application in real life and our project is discussed here.

2.3.1 Augmented Reality (AR)

AR is a technology that helps project models in 3D, gestures and instructions texts to the real world with the use of cameras and displays The use of this technology in the project ensures the bridging of the gap between learning about circuitry theoretically and its visualization practically with the help of an interactive medium.

AR Circuit Trainer can allow the user to visualize their circuit construction on the actual surface such as a table or breadboard using a device camera. Components can be visualized and labeled as well as connected in real-time. As a result, a better understanding of the functionality of each component can be gained by the user. In the process of fault correction, visual guidance will be provided in such a way that faulty areas on the PCB are marked out in red and the user is guided step-by-step towards making the required changes. Thus, the inclusion of this technology will assist in achieving this in an effective manner.

As regards this, AR would help in gaining more knowledge, reduce errors during circuit construction and ensure that the user gains practical experience of the same without putting any physical component at risk.

2.3.2 Artificial Intelligence (AI)

AI can be defined as a technology that builds intelligent machines having the ability to learn, reason and make competitive decisions on their own. In this project, AI is applied as the main concept to enable automation in the process of fault detection and analysis of PCBs. Applying computer vision along with deep learning algorithms, the system analyzes images of the PCB to look for faults such as missing components, broken tracks, short circuits, and soldering defects.

It does so by processing captured PCB images through an AI module that extracts relevant visual features and compares them to reference or "golden" images of PCBs. The most precise models are built based on recognition and identification of objects known as YOLO object detectors that allow the system to draw insights from historical data and refine its detection performance through machine learning.

In other words, AI will transform the fault detection process from a manual and time-consuming process into one that is fast, automated, and intelligent in its inspection system. The intention is to minimize human error through enhanced accuracy and allow the system to adapt to new designs of PCBs over time. The AI component ensures that not only does it detect visible defects, but also predicts them for scalability and industrial suitability.

2.4 AR Usage and AI Algorithm & Structure Implementation

To implement the AR usage and AI algorithm in real world we are mentioning different strategies to fulfill it.

2.4.1 AR In Education

AR has redefined educational experiences by allowing students to visualize complex electronic circuits in three dimensions, directly overlaid on physical components or printed diagrams. It helps students bridge the gap from a theoretical understanding to practical implementation through immersive visualization. AR can provide step-by-step guidance, highlighting components, connections, and assembly procedures in real-time and reducing errors, thus reinforcing learning. Furthermore, it provides a safe environment to study, allowing students to interact with virtual circuits without risk of damaging real components. The motivation of learners is increased by the use of AR because of the interactivity involved in the process of learning. The fact that AR learning can be done on mobile and PC applications makes it possible for learners to conduct practical classes away from laboratory environments.

2.4.2 AR In Industry

AR has been applied in the industry for training engineers and technicians in the installation of printed circuit boards (PCB), fault detection and quality control activities. The technology facilitates interactive documentation where digital schematics, assembly directions and warnings are imposed onto hardware to minimize mistakes and enhance operational efficiency. AR helps in facilitating maintenance and troubleshooting operations by guiding the operator to the precise position of the component, wiring and faulty area to ensure there is no downtime. Moreover, AR provides the ability to collaborate remotely through which experts can help the operator in their tasks, a useful feature especially in the installation of complex electronics.

2.4.3 AI Algorithm Implementation

The AI will detect faults, recognize the components and recommend repair solutions for the PCB. First of all, the data collection involves images taken under different light and angle conditions of a reference and a faulty PCB to make sure that the model will be robust. The steps before being processes that includes noise reduction, contrast enhancement and edge detection, enhance the image to highlight the components and copper tracks. In the next step, deep learning-based object detection models such as YOLO recognize each resistor, capacitor, IC, diode and solder joints by their location, position and orientation. Then, this detected information about components and tracks is compared with a reference PCB to find open circuits, short circuits, missing parts and defects in soldering. Finally, reverse engineering reconstruction of the PCB schematic enables the system to locate discrepancies and create recommendations for repairs that include re-soldering, reconnecting or replacing components.

2.4.4 AI Structure Implementation

Modularity of the design of the AI system makes it possible to perform analysis efficiently and accurately. The whole process begins with an image acquisition unit under controlled lighting conditions, which captures images of PCBs. These images are then preprocessed to improve their quality and then sent through a component recognition unit where the deep learning algorithm recognizes the type, location and orientation of the components on the circuit board. In addition, there is a fault detection unit which compares the identified components with the reference board in order to detect any discrepancies. Lastly, there is a reverse engineering unit which creates a schematic diagram of the circuit board and detects any faults. [3, 11, 12]

2.5 AR and AI Usage in Project

The use of AR & AI in our project is mentioned here.

2.5.1 Artificial Intelligence (AI)

Technology that falls under Artificial Intelligence is key in this task because it will be used in automating the detection of faults in a printed circuit board (PCB). In doing this task, computer vision and deep learning technologies are going to be applied to the images of PCBs with the aim of identifying faults such as missing tracks, absence of components and short circuits amongst others. With technology like YOLO, the artificial intelligence module will be able to accurately detect and classify components. Each captured image will be compared to the reference PCB for any form of variation and difference. [7,13–15]

2.5.2 Augmented Reality (AR)

The use of AR technology is aimed at facilitating learning and error correction in the course of the project. The AR Circuit Trainer enables learners to visualize and assemble circuits using their mobile devices on various surfaces such as breadboards and tables. Components are highlighted and labeled and then connected dynamically by the software to facilitate users while assembling the circuit. The use of Augmented Reality during fault detection is through overlaying visualizations that facilitate users by highlighting the faulty parts on the PCB and how to connect the right parts in the right direction and positions. Hands-on practice of the learners will be made easier through AR without any risk of damaging components. [7,13,15,16]

2.6 Limitations of Existing Systems

- There are numerous drawbacks associated with existing techniques for PCB fault detection and electronic training programs. In most of the conventional techniques, the fault detection is done through visual inspection or using basic tools. These techniques are slow and can also result in human errors. The process is also unreliable since it depends on the expertise of the person conducting the test and may overlook minute faults such as micro-cracks, problems with soldering or shorts. Automated techniques which have been developed use very basic principles such as primitive image processing and pattern recognition and hence cannot identify complex and diverse types of defects in PCBs with different designs. The automated techniques also do not offer any form of user interaction where the user identifies what type of defect there is, its location, and how it can be corrected.

- Currently, the Augmented Reality-enabled training methods that can be employed are mostly inflexible in nature because they are meant to be used on specific circuits and do not have any provision for changes to suit different circuits or identify various faults simultaneously. Another drawback associated with most of the AI-enabled systems is their limited generalization ability because of which they largely depend on labeled datasets and fail in identifying fault conditions that are unknown. Other shortcomings are related to cost, hardware dependency, real-time implementation and lack of training support systems. This indicates the need for a holistic framework that integrates both AI and AR, which is what our FYP project seeks to achieve.

2.6.1 Educational Limitations

The current state of the practice shows that PCB training and fault detection tools available at schools and universities are too theoretical in nature. The majority of current education programs include teaching using pre-developed circuits with certain faults; therefore, there is no room for interaction with different problems. Moreover, not all possible causes of the faults may be known to learners since their current approach is too theoretical as well. Another critical disadvantage of current training approaches lies in their inability to provide learners with an adequate level of feedback, which leads to lower motivation and lack of engagement. Existing AR educational tools do not possess necessary adaptability either.

2.6.2 Industrial Limitations

As far as industries are concerned, there are challenges related to scalability, speed and accuracy when it comes to the current state-of-the-art PCB fault detection systems. The automated fault detection system uses static algorithms or preset fault patterns that find it difficult to detect faults that are unique and subtle in different PCB design structures. While humans can detect faults accurately through their ability in terms of detection process, they are slower and susceptible to mistakes. In addition, industries require fault detection in real time with zero downtime; something which traditional fault detection techniques find it hard to accomplish. Expensive, complex and inadequate integration make these systems less viable. Therefore, there is a necessity for using AI-integrated intelligent detection system and AR visualization technique.

Chapter 3

Requirement Specifications

This chapter presents the main specifications of the AR- and AI-based Smart Circuit Trainer with PCB Fault Detection. This chapter will start with related work, indicating the weaknesses and shortcomings of existing solutions, followed by the presentation of the proposed system for the enhancement of the learning and inspection process in electronics education and prototyping. The functional, hardware, and software requirements will be discussed in detail to develop the integrated solution comprising basic and advanced modes of operation, along with the necessary hardware configurations for an optimal user experience.

3.1 Existing System

This section provides a review of a number of existing systems related to the scope of the proposed AR and AI-Based Smart Circuit Trainer with PCB Fault Detection. These existing solution analyses are important in terms of finding their gaps, limitations, and requirements to be addressed by the proposed system. These reviewed systems generally consist of industrial automatic inspection tools, manual inspection processes, AR-based learning applications, AI-driven PCB defect detection models, and prototype inspection boxes. Each of these systems offers particular functionalities but also lacks important features critical for an educational, affordable, and multi-functional tool such as the one developed in this project. [17]

3.1.1 Automated Optical Inspection (AOI) Systems

Fully automatic optical inspection systems find extensive applications in the electronic manufacturing industry due to their high-speed, high-precision PCB inspection capabilities. The working of such systems depends on a number of high-resolution cameras, controlled lighting, and machine vision algorithms to spot issues such as soldering, missing parts, misalignment, open, and short circuits in the boards. AOI machines operate with conveyor-based scanning and rapid defect classification during production cycles. [18, 19]

Limitations: While AOI systems boast a very high accuracy, they are highly expensive and targeted at industrial-scale mass production rather than an educational or prototyping setup. They also have no interactive learning aspect, since their entire concentration is on automation and throughput. Other shortcomings include their large size, reliance on skilled operators, and no augmented visual explanations. These point out the necessity for a compact, low-cost system that is suitable for universities and small laboratories—requirements that the proposed system addresses.

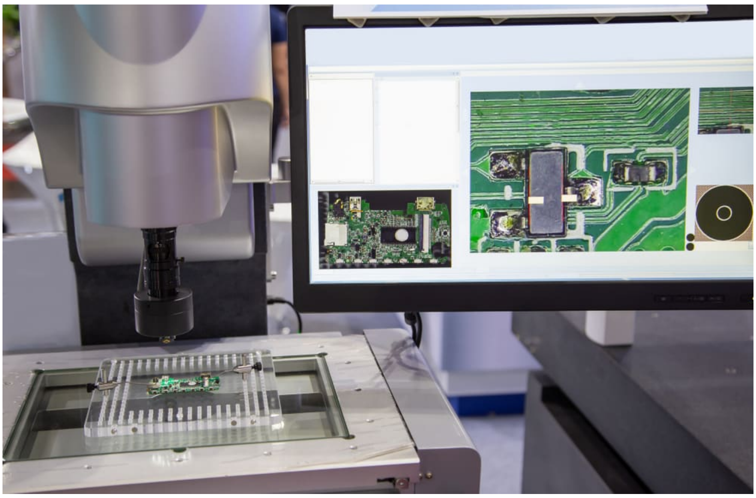

Figure 3.1: Automated Optical Inspection

3.1.2 Manual Visual Inspection (MVI)

In small laboratories, R&D facilities, and academic institutions, it is still common to perform MVI. An engineer or technician visually inspects the PCB, usually with the aid of magnifying lamps or microscopes. The effectiveness of MVI depends directly on human expertise, experience, and concentration. Although MVI is flexible and low in cost, the process is not only slow but also error-prone and inconsistent from inspector to inspector.

Limitations: Human error and personal judgment are the usual culprits behind overlooking such faults, but there exists no proper way to document these or provide instructions to students. Moreover, MVI does not aid in learning on its own and needs to be supplemented with proper training sessions. These gaps highlight the requirement for developing an automated, AI-based inspection tool without any bias introduced by humans. The development of such a system would enhance student comprehension by means of visualization techniques.

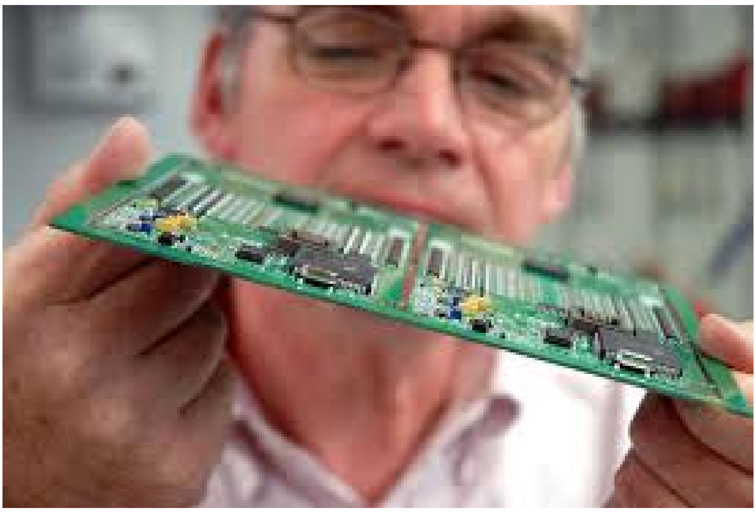

Figure 3.2: Manual Visual Inspection

3.1.3 AR-Based Circuit Learning Applications

The following modern applications allow students to study basic electrical connections, identify components, and visualize simplified circuits by offering them Augmented Reality-based virtual circuit building environments. Examples include CircuitsAR, Phet AR Circuits, Merge Cube educational apps, and several mobile AR simulators. These applications contribute positively toward introductory electronics education, improving engagement, understanding, and interactivity.

Limitations: Despite their advantages, these platforms cannot go beyond virtual circuit constructions and theoretical learning. They do not connect to real PCBs, cannot detect faults, and do not apply machine learning or computer vision. Their instructional value is limited to simple circuits and therefore cannot substitute university-level labs, where using physical hardware and the actual inspection of faults is necessary. This is where the gap exists, which requires the hybrid AR system that will visualize but also interact with real boards and offer fault detection, exactly what this project has achieved.

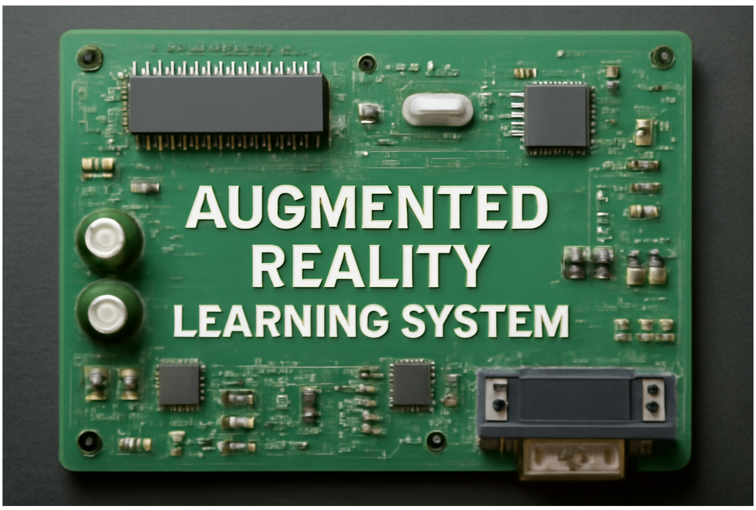

Figure 3.3: AR-Based Circuit Learning System

3.1.4 Prototype Inspection Boxes and DIY Vision Systems

Examples of some cheap prototypes of such devices that are available in markets involve basic inspection boxes with fixed or manually adjustable cameras for taking photos of the printed circuits in certain lighting conditions to help with the detection of defects. Even though prototypes like that can be helpful to obtain consistent imaging results, they require manual inspection and do not perform any AI-based image analysis.

Limitations: The limitations associated with the prototypes under discussion are low accuracy, inability to identify complex or subtle defects, the lack of automation and most importantly, the lack of implementation of any modern approaches such as augmented reality. Prototypes mentioned above can serve only as basic scanners and cannot perform any type of image analysis or offer additional educational opportunities in the process of testing.

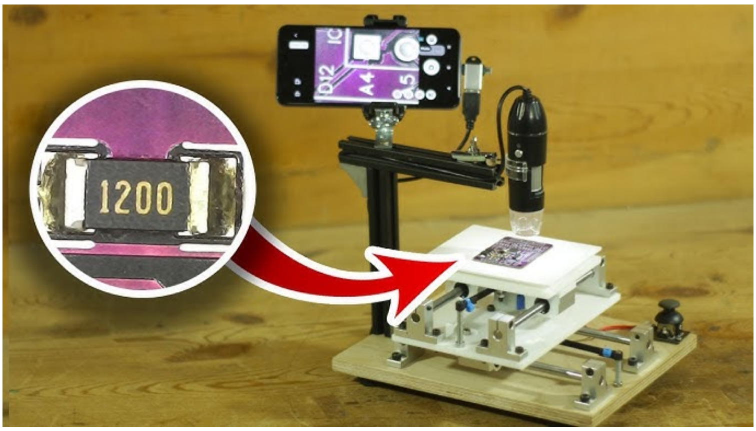

Figure 3.4: DIY Vision Systems

Table 3.1: Comparison of Existing Systems

Feature	AOI Machine	Manual Inspection	AR Learning System	DIY Inspection Box
Operation Type	Fully Automated	Manual	AR-Assisted Learning	Semi-Automated
Camera & Lighting	Industrial cameras + lighting	Human eye	Mobile camera	Fixed camera + LEDs
Fault Detection	High accuracy	Limited	None	Basic
Automation Level	Very High	None	Medium	Low–Medium
Accuracy	Excellent	Low–Medium	Medium	Medium
Cost	Very High	Very Low	Medium	Low
Limitations	Expensive	Conducive to error	No PCB fault detection	Limited accuracy

3.2 Proposed System

The prospoosed system will be a such a platform that will be designed to become an intelligent and hybrid solution which will facilitate enhanced electronics training and detection of problems on printed circuit boards with the help of technologies such as AR and AI altogether. In other words, the system will allow people to understand how their circuit is built with the help of AR and find defects on PCBs using AI technologies. This combination of solutions allows the development of a system that can be applied both by amateurs and professionals for PCB inspection purposes.

The system supports two major modes:

- **Basic Mode:**AI-based PCB Fault Detection and Component Detection.

- **Advanced Mode:**AR-based circuit visualization and learning.

This system addresses the challenge of understanding circuit layouts, detecting wiring mistakes, and finding defects in PCB prototypes by providing dual functionality. [10, 12, 15, 20]

3.2.1 AR-based Circuit Learning Module (Advanced Mode)

The AR module is designed to enhance conceptual understandings of physical circuits by projecting virtual components and connections onto real-world surfaces. It overlays 3D circuit components when users point the camera at a breadboard or sheet, highlight nodes and guide them through a step-by-step process in the construction of the circuit.

This mode is intended for those who struggle to interpret a circuit diagram and translate it into actual connections. AR-based guidance reduces common wiring errors, makes it easier to learn and reinforces the relationship between theory and practice. Users can also upload circuit diagrams from books or online and get an AR representation generated by the system for clearer visualization.

3.2.2 AI-Based PCB Fault & Component Detection Module (Basic Mode)

Fault and component identification in the PCBs, processed through computer vision and machine learning algorithms, is done by the AI module. Here, a user captures an image of their PCB, which then undergoes preprocessing techniques such as image amplification and edge detection.

The proposed system identifies components, traces, solder joints and pads with the use of trained models (CNN or YOLO). Further, it compares the scanned PCB with a stored golden reference for deviation detection. Missing paths, bridged solder joints, reversed components, burned areas and missing elements are highlighted automatically.

Time spent on inspections would be reduced and the analysis conducted would be objective, giving an added advantage especially during prototyping when manual inspections are time-consuming and error-prone. [21, 22]

3.2.3 Integrated Hardware Prototype

An example of an inspection tool is a customized inspection box that utilizes an illumination unit consisting of a light box, usually made of either glass or acrylic, containing LED lights to eliminate shadows and reflections from interfering with the images captured. In addition, optimized angle cameras provide high-quality images of the PCB and the basic design incorporates sliders for different scanning angles. The use of such an enclosure will enable consistency and uniformity in the inspection process.

3.2.4 User Workflow

Workflow for the system varies depending on whether the user chooses to use the system in Basic Mode or Advanced Mode.

When using the system in Advanced Mode, the camera captures the breadboard or the workspace that is flat, and the AR engine overlays the virtual components in the breadboard. With step-by-step instructions on assembly, the user creates the circuitry as explanations, component information, and connection rules are shown in real-time.

However, in Basic Mode, the user uploads the picture of the PCB. The system will pre-process the uploaded picture and detect the components, comparing them to the reference PCB. Faults are highlighted, and suggestions on how to correct them are provided.

3.2.5 Benefits of the Proposed System

Advantages of proposed system comes with a number of benefits over existing manual or automated approaches such as:

- Cost-efficient as opposed to pricey commercial AOI devices.
- AR improves learning by means of visual interactivity, which minimizes wiring errors.
- AI guarantees quick, reliable and consistent PCB fault detection.
- Incorporates two capabilities in one: teaching and checking.
- Applicable to multiple target audiences: from students and trainers to researchers and electronics engineers industry.
- Enables distance learning, prototyping and laboratory studies.

Thus, AR combined with AI presents an advanced and novel tool that may help advance electronics engineering to an entirely new level of learning and assessment. Conclusion The offered solution presents an effective strategy to overcome current limitations related to electronics learning and PCB inspections. Combining AR visualization with AI fault identification creates a complete platform designed to increase knowledge and detection skills of its users. Such a system will be especially useful for new learners and experienced specialists alike.

3.3 Different System Model

Here we introduce the other models that can be used to make my proposed system work into a reality:

3.3.1 Model 1

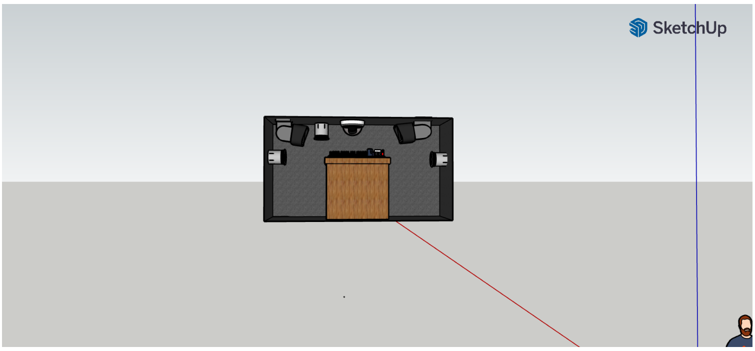

Figure 3.5: Glass Box Inspection System (Front View)

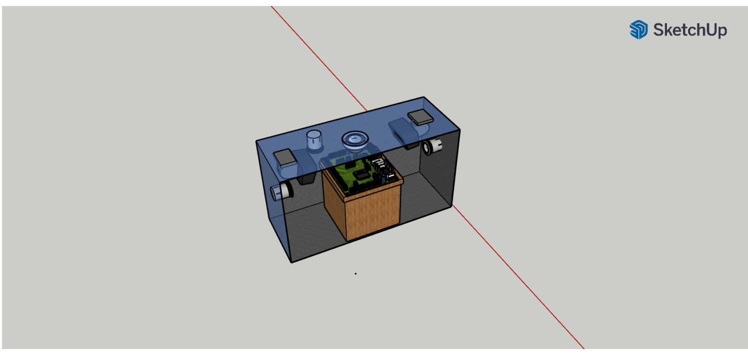

Figure 3.6: Glass Box Inspection System (Side View)

Working Principle:

- This is the most basic level of design for the inspection box.
- The process takes place primarily by way of fixed cameras installed around the PCB.

- The board stays still as images are taken from various angles.
- Lighting and positions are adjusted manually prior to the inspection process.

Functionality:

- Proof of concept to take pictures of PCB.
- Can be used for manual or static test.
- Useful to determine whether the image quality and lightings are sufficient for finding defects.

Limitations:

- Automatic motion is not available.
- The system cannot provide 360 degree coverage.
- Repeatability and accuracy are poor due to manual positioning of the camera.

3.3.2 Model 2

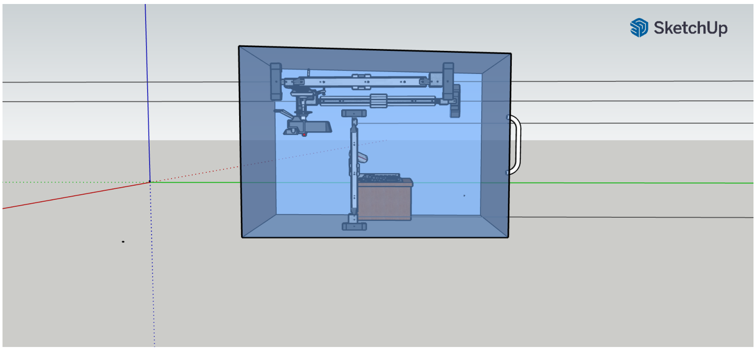

Figure 3.7: Semi-Automated Inspection System (Front View)

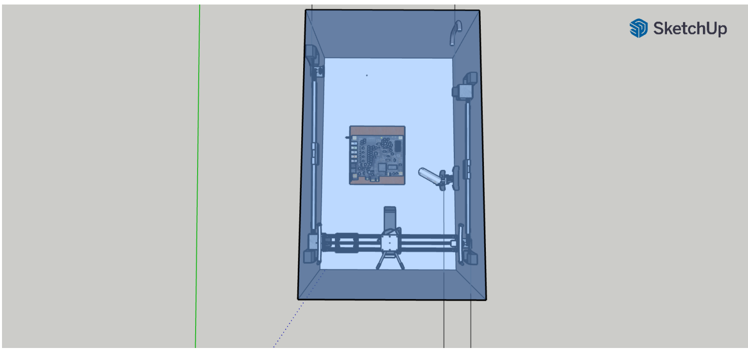

Figure 3.8: Semi-Automated Inspection System (Top View)

Working Principle:

- Motorized sliders and adjustable camera mounts introduced.
- Cameras can slide on both X and Y axis giving a 360-degree coverage around the circuit board.
- Circuit board can also be rotated for acquiring multiple angles views.
- Controlled by a microcontroller/computer to minimize human errors.

Functionality:

- Allows scanning to be done automatically from different perspectives.
- Enables capturing the top and lateral images of the PCB.
- Makes possible synchronization of image capture and movement using software.

Limitations:

- This system still requires someone to operate it.
- The operator needs to set camera for better calibration and images to get accurate results.

3.3.3 Model 3

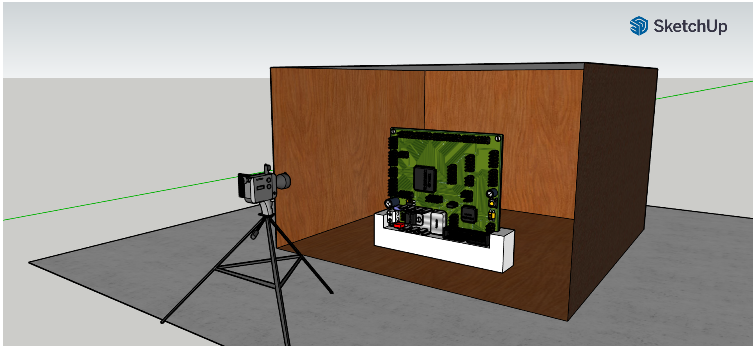

Figure 3.9: Fully Automated Smart Inspection System (Front View)

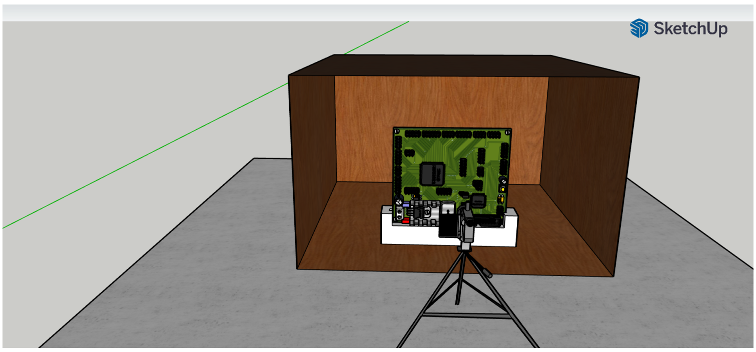

Figure 3.10: Fully Automated Smart Inspection System (Side View)

Working Principle:

- The last model forms a perfect smart inspection station.
- The camera operates on automatic operation using a pre-programmed model.
- The images are also processed automatically using image processing tools that identify any defects such as wrong alignment and solder bridging.

- Ambient lighting incorporated into the system ensures that there is even illumination.

Functionality:

- Fully automated inspection and analysis process.
- Real-time detection using AI classification.
- Capable of data logging and comparison with golden PCB images for precise defect identification.

Limitations:

- More complex to build and program.
- Requires calibration and software integration testing.

3.3.4 Comaprison Of Models

Table 3.2: Comparison of Three Models

Feature	Model 1	Model 2	Model 3
Operation Type	Manual	Semi-Automated	Fully Automated
Camera Movement	Fixed	Motorized Sliders	Program-Controlled
PCB Handling	Stationary	Rotatable / Adjustable	Automatically Rotated or Mapped
Lighting Control	Manual	Integrated	Auto-adjusted
Data Processing	Manual Image Analysis	Partial Computer Assistance	Fully AI-Based Image Processing
Accuracy & Repeatability	Low	Medium	High
System Complexity	Simple Prototype	Intermediate	Advanced Intelligent System

Chapter 4

System Design

This chapter describes the complete system design of the AR and AI-Based Smart Circuit Trainer with PCB Fault and Component Detection. The chapter discusses the system architecture, hardware components, software process, design of the artificial intelligence model and the augmented reality module. This chapter emphasizes the interaction of various components of the system to provide an integrated solution for circuit learning and PCB fault detection.

4.1 System Overview

The proposed system is designed as a hybrid platform that combines Augmented Reality (AR) for interactive circuit learning and Artificial Intelligence (AI) for automatic PCB fault detection. The system will work in two modes: Advanced Mode for AR-based circuit learning and Basic Mode for AI-assisted PCB Fault and Component analysis. Both modes will share common hardware resources but differ in software processing and interaction.

4.1.1 Architecture Summary

The overall system architecture consists of four main layers, each responsible for a specific function within the proposed system:

- **User Interface Layer**

  This layer allows the user-system interaction through an application on either a mobile phone or a PC. This layer helps the users in selecting the mode of operation, capturing images, showing circuits by AR and showing the results of the fault detection of PCBs.

- **Image Acquisition Layer**

  This layer consists of the camera module and the controlled lighting environment that is used to take high-quality images of the PCB. Uniform lighting ensures proper image preprocessing and the accuracy of defect detection.

- **Processing Layer**
  The processing layer is responsible for handling both AR and AI functionalities. It includes:
  - AI-based image preprocessing and PCB fault detection using the YOLO deep learning model, Python, Google Colab, VS Code, Unity 3D models, Roboflow and Stream Lit.
  - AR-based visualization and rendering of 3D circuit components for interactive learning.
- **Data and Reference Layer**
  This layer stores datasets, trained AI models, electronic component libraries and golden reference PCB images. These resources are used for comparison, fault identification, and system learning.

4.1.2 System Workflow

The workflow of the system begins with the user selecting either **Basic Mode** or **Advanced Mode**:

- **Basic Mode (AI-Based Fault and Component Detection)**
  In Basic Mode, the system is centered on the automated inspection of the PCB using Artificial Intelligence. The inspection of the PCB is done by capturing the image of the PCB using the inspection box configuration in a controlled lighting environment. The captured image is then preprocessed to remove noise and is then fed to the AI-based detection algorithm. The algorithm is responsible for

component recognition and the detection of defects like missing components, broken tracks, soldering defects and short circuits.

- **Advanced Mode (AR-Based Circuit Learning and Visualization)**
  With the Advanced Mode, the system uses the Augmented Reality engine to help the user learn circuits. The camera scans the environment, and the system projects interactive 3D circuit models, component names and step-by-step assembly instructions onto real-world surfaces. The Advanced Mode improves conceptual understanding by using interactive visualization to display electronic circuits.

Figure 4.1: System Workflow

4.1.3 Functional Modules

The system require following major steps resulting in it's accurate functionality:

- **Image Acquisition Module**

  This module makes use of a camera installed within an inspection box in order to capture high-resolution images of the PCB.

- **Image Preprocessing Module**

  The preprocess module improves the captured images by removing any kind of noise present within the images and enhancing the contrast.

- **AI-Based Fault Component Detection Module**

  In this module, deep learning object detection is applied in order to detect the electronic components on the PCB as well as identify different types of faults like missing components, broken tracks, solder bridges and misalignments.

- **AR Circuit Visualization Module**

  The module is employed in the development of AR-based circuit components and links. The module provides help in the visualization of circuit arrangements, component placement and cabling.

- **Reference PCB Comparison Module**

  This module facilitates comparison between the image of the inspected PCB and the reference PCB to locate faults in component placement, connectivity and layout.

- **Results Visualization and Reporting Module**

  This module allows users to interpret detected faults and results visually with the help of highlighted regions, bounding boxes and feedback.

Each module works individually but is also coordinated with the system process as a whole to give us the best possible output and results.

4.2 Hardware Design

The hardware configuration provides reliable image acquisition, balaced lighting and consistent inspection conditions that are needed for proper fault detection using artificial intelligence technology.

4.2.1 Inspection Box

The inspection box is a box made from wood, which helps shield the influence of any exterior lighting while inspecting the PCB. The inspection box forms an environment where images are taken by eliminating the influence of shadow, glare and light.

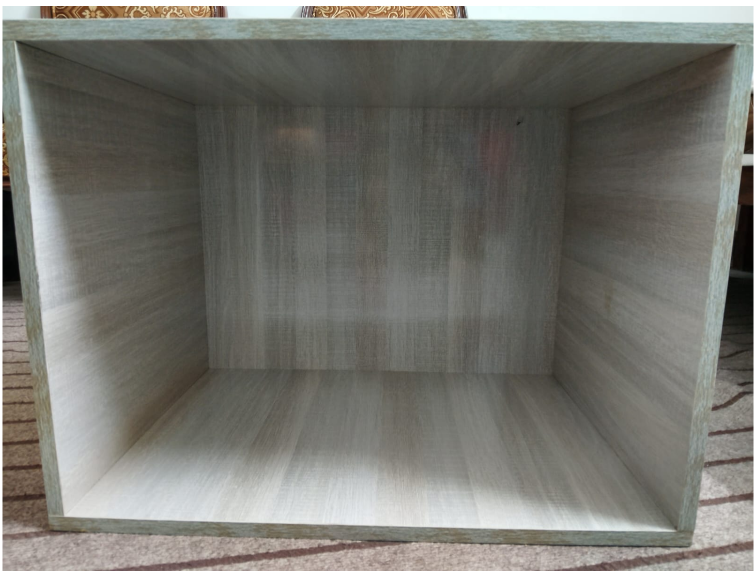

Figure 4.2: Front View Of Inspection Box

Figure 4.3: Side View Of Inspection Box

4.2.2 Ambient Lighting System

The ambient lighting system consists of equally spaced LEDs used as light sources within the inspection box. The use of LEDs guarantees an even illumination of the PCB and eliminates reflections. Even illumination plays a critical role in pre-processing and fault detection using artificial intelligence (AI).

4.2.3 Camera Placement and Specifications

The camera is mounted on a fixed tripod stand within the inspection box to generate multi-angle images of the PCB. Mounting of the camera externally provides convenience and freedom to align the camera without having to attach it to the inspection box. The optional adjustment or positioning of the tripod stand allows the camera to take images at various angles.

Figure 4.4: Camera

Figure 4.5: Tripod Stand

4.3 Software Design

The system software design incorporates artificial intelligence, augmented reality and interaction in an integrated way. The system software design has a modular approach in order to provide for scalability, maintainability and effective interaction between the components of the software system.

4.3.1 System Software Flow

System software flow begins with acquisition of the images for inspection of the PCB. After that, the acquired images go through preprocessing. The analysis is then carried out depending on the selection of the mode by the user that he wither wants to detect fault, get budget estimate of circuit, get a datasheet lookup of IC”s or design a circuit in AR.

4.3.2 User Interface Design

The User interface design is user-friendly and seamless, allowing for easy interactions within the system. There are different choices provided to the user for the selection of the mode, capturing images, and live visualization of the process. The faults in the printed circuit board and the AR circuit overlay faults are shown visually and described to the user.

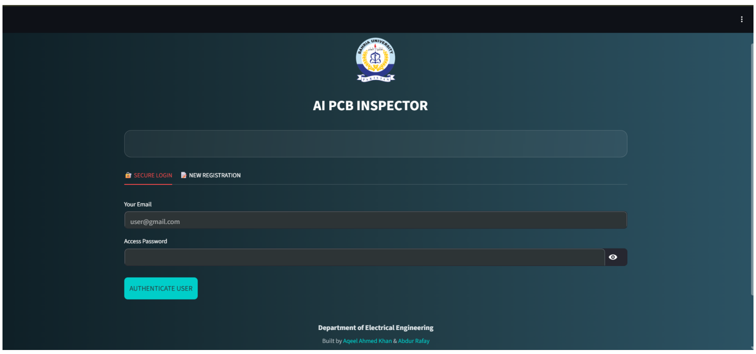

Figure 4.6: GUI User Login Page

4.3.3 Basic Mode (AI-Based Component & Fault Detection)

The Basic Mode performs Automated PCB Inspection using Artificial Intelligence. Image processing operations such as noise reduction and image enhancement are employed to enhance the accuracy of the process. The YOLO Deep Learning Algorithm is deployed for detecting electronic components, as well as tracking and soldering joints. Results are later compared against the reference.

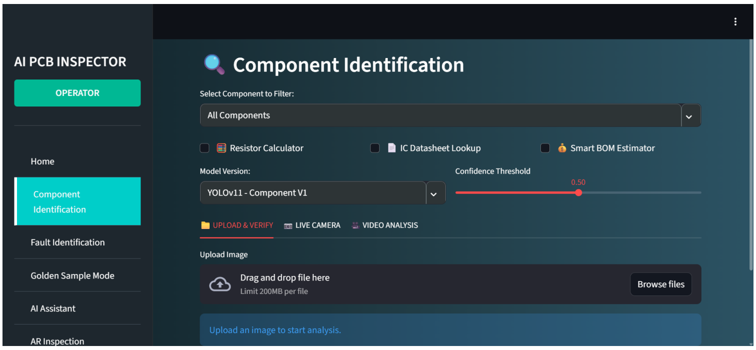

Figure 4.7: Component Detection Menu

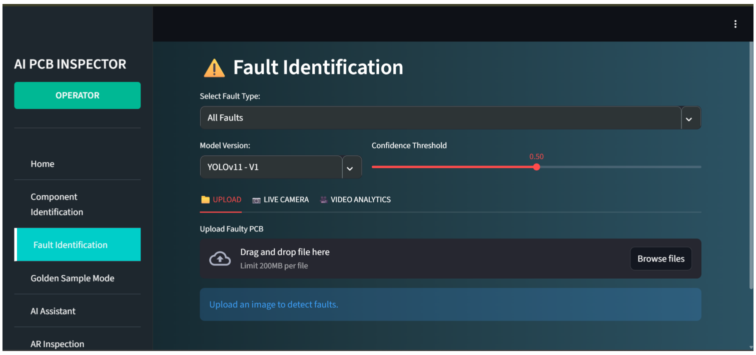

Figure 4.8: Fault Detection Menu

4.3.4 Advanced Mode (AR Learning Interface)

In Advanced Mode, the Augmented Reality interface for learning is employed by the system to enable the user to understand electronic circuits. Through the AR tool, a virtual 3D interface of the circuits and the various parts involved in making the circuits together with the process of assembling them will be made available to the user. Real-time visualization and interaction help improve the user's conceptual understanding of component positioning, connections and circuit functionality.

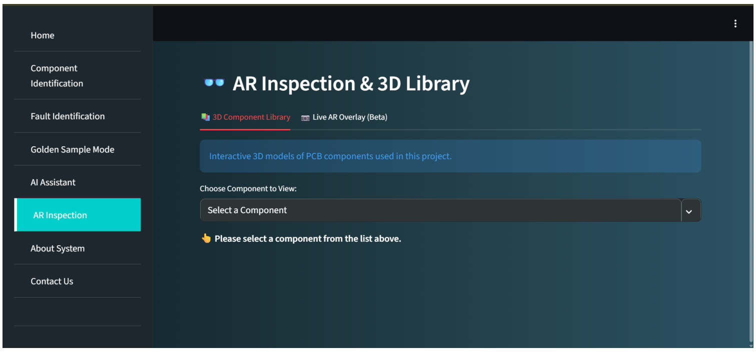

Figure 4.9: Augmented Reality Menu

4.4 Image Acquisition System

The image obtaining system is tasked with acquiring high-quality images of the PCBs that are amenable to analysis by AI. A good camera system coupled with the right imaging environment is used for this purpose.

4.4.1 Camera Calibration

Calibration of the camera ensures that there is no distortion of the image taken through the lens. Since the camera is fixed on a tripod stand placed above the inspection box, calibration of the camera also helps in proper alignment of the camera, PCB surface, and reference plane.

4.4.2 Multi-Angle Capture Strategy

For improved accuracy of detection, the system allows for a multi-angle image capturing approach. Through the adjustment of the position or orientation of the tripod-mounted camera, images can be taken from various angles without having to alter the structure of the inspection box. The multi-angle images are useful in the detection of defects such as lifted parts, solder bridges and broken tracks, which may not be observable from a single top view perspective.

4.5 AI Model Design and Software Tools (Fault & Component Detection Engine)

The AI model is the core of the automated PCB fault and component detection system. The fault and component detection system is built using a variety of software tools such as Python, YOLOv11, Google Colab, Visual Studio Code (VS Code), Roboflow, Streamlit and Unity 3D. The software tools are used for different purposes in the data preparation, development, and visualization stages.

4.5.1 Dataset Preparation

The dataset is comprised of images of both defect-free (golden), defective PCBs and labelled components taken under controlled lighting conditions. The images are taken with faults such as missing components, broken tracks, misaligned components and soldering defects.

The annotation and preprocessing of the dataset are done using Roboflow, which allows for easy annotation of electronic components and defective regions. The annotated dataset is then structured and exported in a YOLOv11-compatible format.

4.5.2 Model Architecture (YOLOv11)

The system uses the YOLOv11 (You Only Look Once) object detection model because of its high detection accuracy and real-time capabilities. YOLOv11 can detect PCB images in one pass, which allows for the detection and classification of electronic components and PCB faults. [23–25]

4.5.3 Model Implementation Environment

The AI model is developed using Python as the main programming language. The training of the model is done in the Google Colab environment to take advantage of the GPU acceleration and speed up the training process. Visual Studio Code (VS Code) is used for development.

4.5.4 Unity 3D Integration

Unity 3D is employed for developing the Augmented Reality learning interface of the system. It takes care of 3D graphics, interaction and the real-time overlay of virtual circuit components on physical surfaces.

4.5.5 Roboflow for Dataset Annotation

Roboflow is used for dataset labeling, preprocessing, and augmentation. It facilitates accurate annotation of PCB components and fault regions and ensures compatibility with the YOLOv11 training pipeline.

4.5.6 Streamlit for Result Visualization

Streamlit is employed to develop an interactive web interface for visualizing the results of PCB fault detection. It enables users to upload images of the PCB and display the results of the detection, including bounding boxes, labels and marked regions of faults. [16]

4.5.7 Training and Validation Strategy

These datasets will be split up into a training set, a validation set and a test set. The efficiency of our models is measured based on several parameters, including accuracy, precision, recall and loss value.

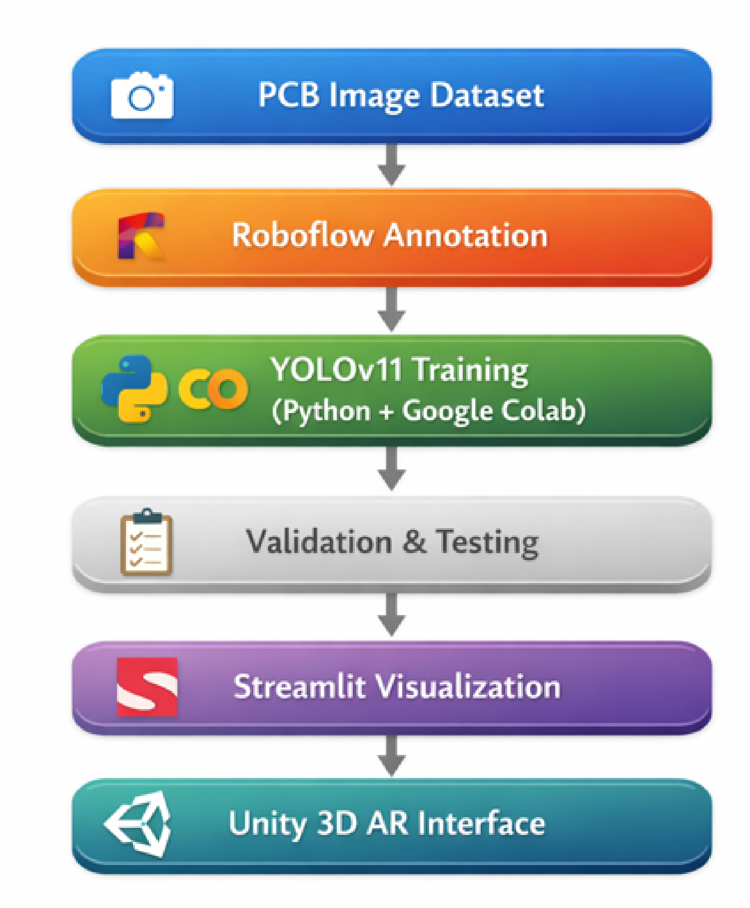

Figure 4.10: Software Tools Workflow

Chapter 5

System Implementation

This chapter presents the implementation of the AR and AI-Based Smart Circuit Trainer with PCB Fault Detection. It will discuss the process of transforming the designed system architecture into a practical prototype by incorporating hardware components, artificial intelligence techniques and augmented reality tools. It is noteworthy to mention that the implementation process is the main focus of this chapter.

5.1 AI-Based PCB Component Detection

In this section, we will be discussing the implementation of the AI-driven PCB component detection system. This component detection module is among the different models presented in the system. The primary function of this component detection model is to automatically detect and locate the electronic components present on the PCB.

5.1.1 Overview of PCB Component Detection

The objective of the component detection system for the PCB component is to recognize various components that exist on a PCB to ensure proper placement and to support intelligent inspection. The detection of components on a PCB automatically can be used to validate the assembly and can be considered a basic component for other complex analysis and learning-based applications.

The system uses images of the PCB and detects individual components by categorizing them according to a predefined category using an AI-based model.

5.1.2 Dataset Preparation for Component Detection

The dataset for component detection includes images of PCBs taken in a well-controlled environment with respect to lighting and positioning. The images contain a variety of electronic components mounted on different types of PCB layouts.

The components in the images are annotated using bounding boxes and labels through a dataset annotation tool. Data preprocessing techniques such as image resizing and data augmentation are employed to enhance the model's validity.

5.1.3 Component Classes Considered

The component detection system is trained to identify commonly used electronic components found on printed circuit boards. These include both passive and active components, as well as embedded boards.

The typical component classes considered in this work include:

- Resistors
- Capacitors
- Inductors
- Diodes
- Transistors
- Integrated Circuits (ICs)
- Voltage Regulators
- Relays
- Connectors

- Light Emitting Diodes (LEDs)
- Embedded boards (e.g., microcontroller platforms)

This wide range of component classes enables comprehensive PCB inspection and analysis.

5.1.4 Model Training and Implementation

The implementation of the component detection model is done with the YOLOv11 object detection architecture. The model is trained with the labeled images of the PCB and optimized to recognize more than one component at a time from a single image.

The training of the model is done with a GPU-accelerated version of Python, which enables the efficient training of features of the components, including their shape, size, orientation, and location. Once the training is done, the model is integrated into the system.

5.1.5 Component Detection Workflow

The process of detecting the components is done through the following steps:

1. PCB image capture using the inspection system
2. Pre-processing of images to highlight the features better
3. Inference through Artificial Intelligence by running the model trained on the dataset
4. Classification of the detected components
5. Visual representation of the detected components using bounding boxes and labels

The above process helps identify several components within one inspection process.

5.1.6 Integration with Fault Detection System

The detection component model is integrated with the PCB fault detection system, thus creating an effective platform to conduct the inspection process. The information from the components is quite helpful in diagnosing any problem in that it helps verify the presence and the state of the components.

Through this incorporation, the inspection process becomes much easier because the system can be able to identify the problem and pinpoint it.

5.1.7 Role of Component Detection in the Overall System

The PCB component detection module is crucial in the system architecture since it enables:

- Confirmation that components have been placed correctly
- Automated component fault detection
- Intelligent component inspection of the PCB
- Data collection for future use in AR learning systems

The component detection system automates the component inspection process and greatly reduces time and effort involved.

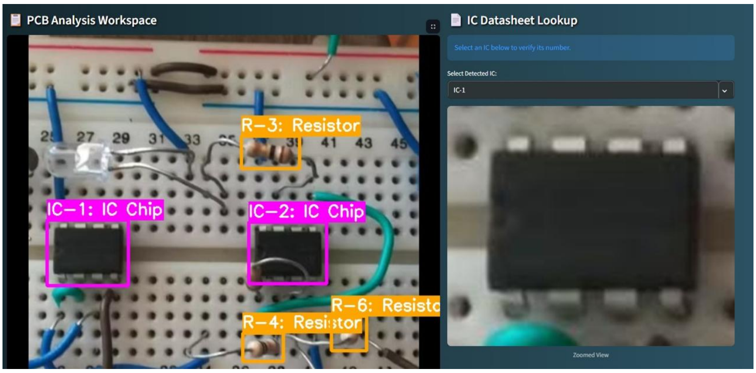

Figure 5.1: Component Detection

5.1.8 Additional IC Datasheet & Budget Estimator

In the component detection step, the GUI offers an option to view the data sheet of the detected ICs, where the data sheet is opened in a new tab, offering details such as the pin configuration and electrical characteristics of the device. Moreover, the Smart Budget Estimator estimates the total price of all the detected components on the circuit board, creates a bill of materials (BOM) summary in PKR and lets users make adjustments manually, thus offering an easy solution for budget management.

5.1.9 F1 Score vs Confidence Curve

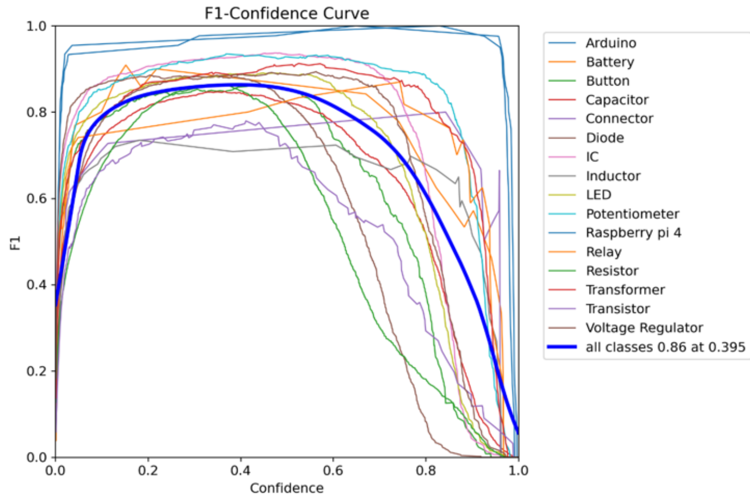

Figure 5.2: F1 Score vs Confidence Curve

F1–Confidence graph shows the variation in the F1 score with respect to the value of confidence threshold for different classes of PCB components. The bold line plotted in the figure represents the overall performance of the trained model across all the classes of components.

As can be seen from the graph, all of the classes exhibit high F1 score values at moderately higher confidence threshold values. In terms of overall model performance, the highest F1 score is around 0.86 at a confidence threshold value of 0.395. At low confidence threshold values, the recall value is high but the precision value is low because of the presence of many false detections. As the confidence threshold value increases, precision increases, but the value of recall falls. This leads to the decrease in the value of F1 score.

It is generally seen with models used in object detection applications that they behave in this manner. From the above graph, it is clear that the trained component detection model has the ability to successfully detect PCB components at different confidence levels.

5.1.10 Precision-Recall (PR) Curve

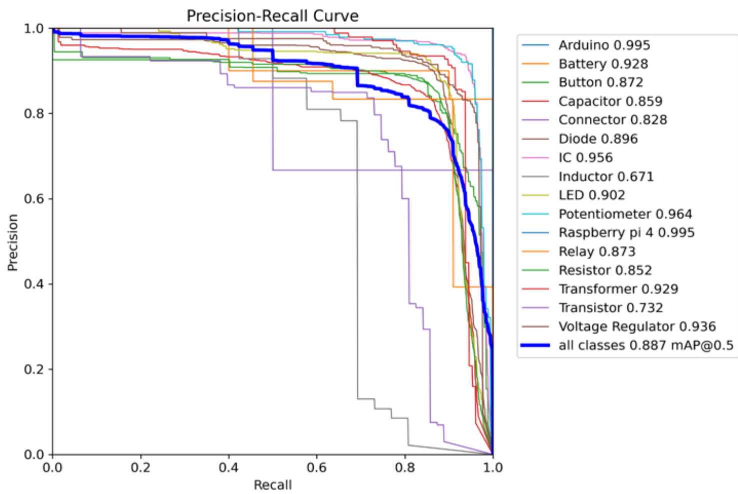

Figure 5.3: Precision–Recall Curve

This graph illustrates the relationship between precision and recall for various component classes on PCB at various thresholds. The thick black line illustrates the average performance of the whole model.

The graph includes the PR curves for particular classes of PCB components like resistors, capacitors, ICs, connectors, LEDs and embedded boards. Precision is defined as the number of correct detections among all detected objects, while recall denotes the number of correct detections among all objects.

The model's precision and recall rates illustrate the mAP@0.5 of 0.887, which demonstrates an excellent rate of precision in detecting different components. Some component types, including Arduino, Raspberry Pi 4, ICs and potentiometers provide extremely accurate precision with high recall values, which means that their precision is practically perfect.

However, some components, such as inductors and transistors demonstrate quite low precision with a high rate of recall, which may be due to the similarity with other components and their absence of distinguishing features.

To summarize, the presented Precision-Recall analysis confirms that our component detection model performs well with various electronic components.

5.1.11 Confusion Matrix

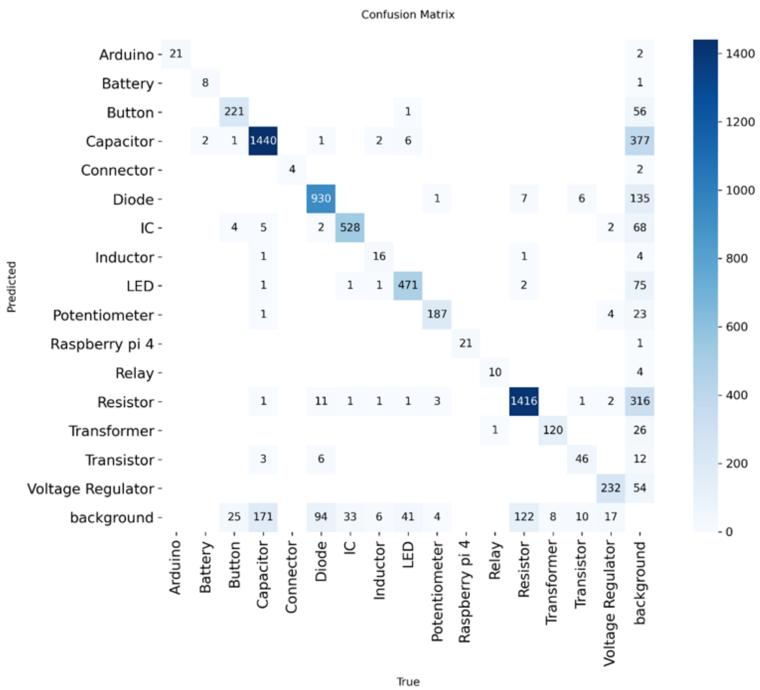

Figure 5.4: Confusion Matrix

The confusion matrix presented above indicates the performance of the AI-based PCB component detection system. The rows represent the classes while the columns represent the true class of the components. The confusion matrix presented above is for the PCB component detection system. It demonstrates the relationship between the predicted and true classes of the components. The components that have been classified well by the system are found along the main diagonal of the matrix.

The high numbers that can be observed along the main diagonal of the matrix indicate the good classification of some components such as capacitors, resistors, diodes, ICs, LEDs and some embedded boards including Raspberry Pi 4.

There are some misclassifications that can be identified among components that look similar to one another, such as inductors, transformers and transistors. In addition, some components have been misclassified as background, and this can be explained by the fact that some components may be occluded or may be very small and lack sufficient contrast to the PCB surface.

From the confusion matrix, it is clear that the diagonal is dominant, and this confirms the reliability of the proposed component detection model to work well with a variety of electronic components. [26, 27]

5.2 AI-Based PCB Fault Detection

This section describes the implementation of the AI-based PCB fault detection system. The fault detection module is designed to automatically identify common PCB manufacturing and assembly defects.

5.2.1 Overview of PCB Fault Detection

The PCB fault detection system is intended to detect faults that often occur during PCB manufacturing, soldering, and assembly processes. The system analyzes the PCB images taken during the detection process and uses an AI-based object detection model to pinpoint the faulty regions of the PCB. This automated detection of faults replaces the manual inspection of PCBs.

The fault detection system is integrated with the Basic Mode of operation under controlled image acquisition conditions.

5.2.2 Solder Bridge Detection

Solder bridges happen when there is an excessive solder that makes undesired electrical links between two pads or tracks that are next to each other. The AI system developed is designed to automatically identify the solder bridge areas by learning from visual features such as abnormal solder links and irregular metallic overlaps.

When the system recognizes the solder bridges, it marks the solder bridge areas using bounding boxes, enabling the user to easily locate the solder bridges. This is an important fault detection mechanism because solder bridges may result in short circuits and failure of the system.

5.2.3 Solder Ball Detection

Solder balls are unwanted solder balls that are usually formed during faulty soldering operations and are usually unwanted and unwanted solder balls that are usually formed around the solder joint during faulty soldering operations.

The detection system uses AI technology to locate solder balls by identifying circular shapes formed during the soldering process, and the solder ball regions are marked and labeled accordingly.

5.2.4 Damaged Board Detection

Damaged board detection concentrates on detecting physical damage on the PCB substrate, which may include cracks, burns and broken copper tracks.

The AI model identifies damaged areas on the board by detecting irregular textures, discoloration, and discontinuity in PCB textures. Early detection of damaged boards can be used to prevent faulty hardware and reduce the possibility of system failure.

5.2.5 Damaged Component Detection

Damaged components involve electronic components that are broken or damaged physically or have been burnt or poorly soldered. This type of damage can impact the functionality of the components considerably.

Components that the AI-based system detects as damaged include components that have abnormal shapes or surface discoloration or lack certain features. These components are localized and marked for easy identification of the damaged components that need to be changed.

5.2.6 Missing Component Detection

Missing components detection detects areas on the PCB where required components are not present. This type of fault is common due to assembly or manufacturing process faults.

This detection is done by learning the pattern of the presence of components and marking the areas that are empty or not completely filled for mounting the components.

5.2.7 Dataset Variation and Model Update

In order to enhance the accuracy of the detection, the fault detection model is trained with datasets obtained from different sources. The training of the model is done in two ways. The model is initially trained with a mixed dataset followed by retraining with a dataset obtained under controlled conditions. The variation of the dataset enables the model to adapt more effectively to real inspection conditions.

5.2.8 Fault Detection Workflow

The pipeline for the developed algorithm comprises the following steps:

- Placing the PCB board in the inspection box
- Capturing the image with a camera attached to a tripod
- Image processing for feature enhancement
- Fault detection via inference from YOLOv11
- Labeling of detected faults
- Visualization of results through the user interface

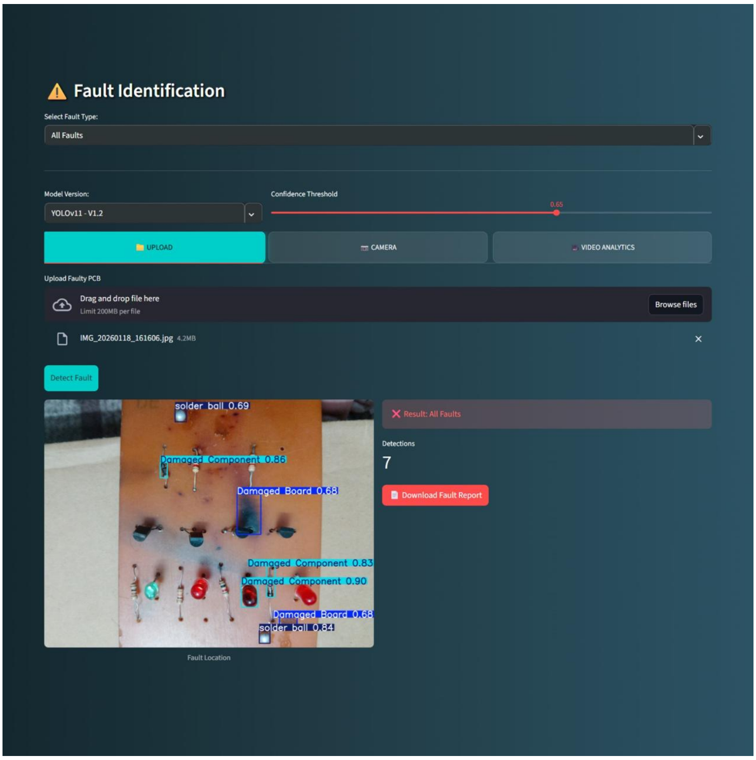

Figure 5.5: Fault Detection

5.2.9 F1 Score vs Confidence Curve

This workflow enables real-time fault detection and provides clear visual feedback to the user.

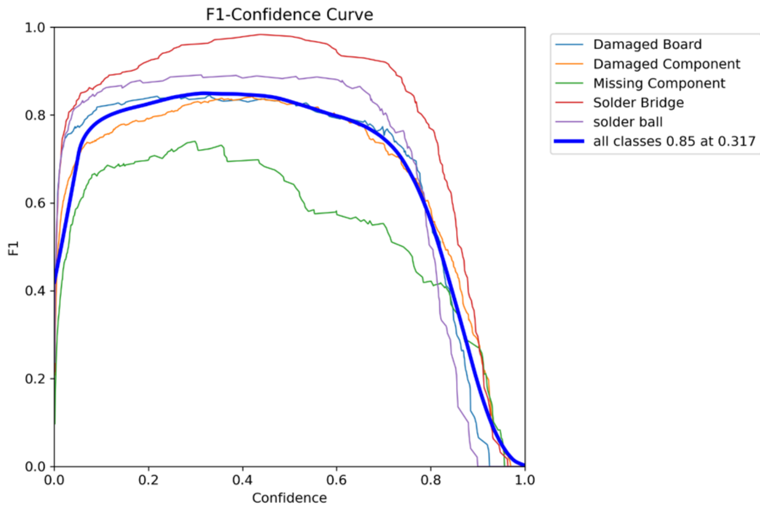

Figure 5.6: F1 Score vs Confidence Curve

The F1 Score vs Confidence curve demonstrates the connection between the model confidence threshold value and the F1 scores for various PCB faults detection. F1 score is the harmonic mean of Precision and Recall measures and it is the balanced metric to evaluate the model detection performance.

Every F1 Score vs. Confidence curve corresponds to the specific faults class that includes damaged board, damaged component, missing component, solder bridge and solder ball faults. The thick line corresponds to the performance of the model for all faults. The point on the F1 Score vs. Confidence plot that corresponds to the maximum F1 score for all faults classes defines the optimal confidence threshold for the model. From the results obtained, the maximum F1 score equals 0.85 and it is achieved for a confidence threshold of 0.317. This is the threshold at which the model will be used in inference since it provides good detection performance and avoids false positive and false negative rates. According to the plot, the detection performance for solder bridge and solder ball faults is better than that for missing component faults.

5.2.10 Precision–Recall (PR) Curve

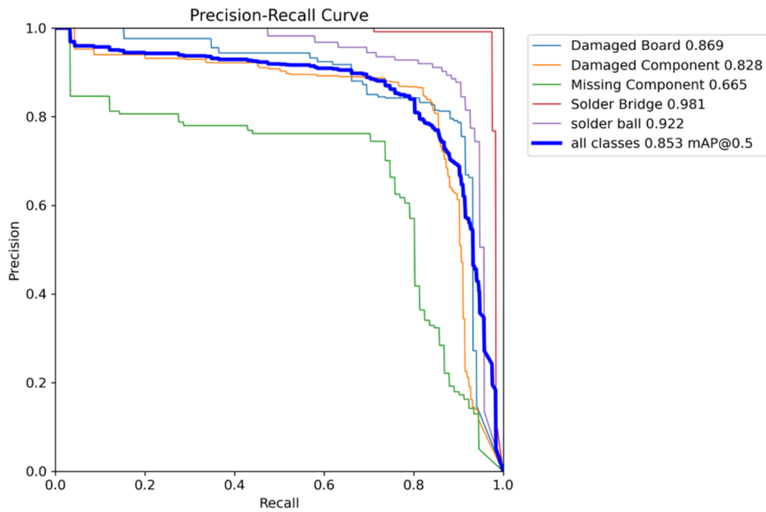

Figure 5.7: Precision–Recall Curve

The Precision-Recall (PR) curve will be used to present the tradeoff of the precision and recall of the PCB fault detection model depending on the different classes of faults.

Precision is the fraction of true positive cases among the total positive predictions while recall is the fraction of true positive cases among the total number of real positive cases.

Each PR curve depicts a specific class of faults within a circuit board, which include; damaged board, damaged components, missing components, solder bridge and solder ball. The area underneath each curve gives the average precision for each fault type. In general, mean Average Precision (mAP) will be applied when the Intersection over Union (IoU) threshold is set at 0.5.

From the analysis, solder bridge detection and solder ball detection give high Average Precision values. Missing component detection has lower values of precision and recall because there are limited visual features. With the mAP@0.5 equaling approximately 0.853, it means that the proposed AI-based model for detecting faults on a circuit board is highly efficient.

5.2.11 Confusion Matrix

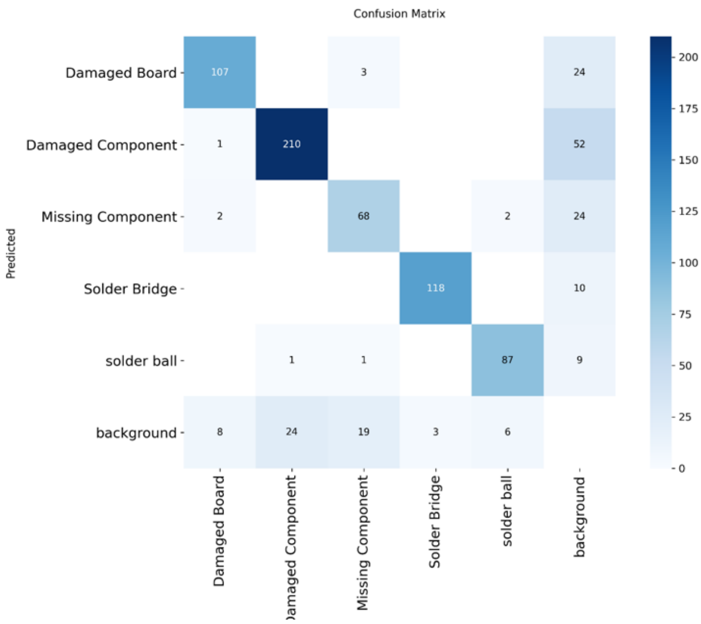

Figure 5.8: Confusion Matrix

From the above confusion matrix, it can be seen that there are many numbers of correct classifications on the main scores of the confusion matrix, which means that the AI-based model has performed extremely well in terms of accuracy in detecting the various types of faults.

Among the different faulty components, the AI-based model has achieved a very high level of correct classification for the damaged components and solder bridges. This is due to the presence of visually distinctive patterns for these faulty components. For the missing components, the AI-based model has achieved a relatively low level of correct classification, and some of the faulty boards have been misclassified as the background. This is due to the absence of visually distinctive patterns for the missing components.

Some misclassifications exist for the different fault classes and the background class. This is due to the slight visual differences between faulty regions and the normal PCB regions. In spite of the challenges associated with the experiment, the confusion matrix proves the efficiency of the proposed system in dealing with different fault types while maintaining a low rate of critical misclassification.

Generally, the confusion matrix proves the robustness of the AI-based fault detection system and suggests areas for potential improvement. [14, 17]

5.3 AR Component Integration for Circuit Visualization

5.3.1 Overview of AR Component Integration for Circuit Visualization

The Augmented Reality (AR) module in the Smart Circuit Trainer provides an interactive interface for visualizing electronic components and circuits in three dimensions, bridging the gap between theoretical knowledge and practical assembly. Using AR, it is possible to virtually place various components such as resistors, capacitors, integrated circuits, LEDs and batteries on workspaces like breadboards and flat surfaces. The tool will enable users to visualize their positions, orientations and connectivity in real time.

It should be noted that the AR solution will be fully integrated into the AI solution of component identification and fault diagnosis. This way, correct placements, missing components and detected faults will be highlighted to the user in real time. Furthermore, AR supports manipulations with components in three dimensions, including rotation, panning and zooming, which allows users to understand what role each particular component plays within a circuit. For the mobile version of the tool. The live AR mode will provide live manipulation using the camera on a mobile phone.

In summary, AR will enable us to integrate visualizing component manipulation, AI-based diagnostics, and live augmentation of components onto real-world environments.

5.3.2 User Interaction with AR Models

Interaction plays a crucial role in the AR module in ensuring that the learner gets both immersed and educated about electrical circuitry. The main interactive elements of the module include:

- **Component Manipulation:** The user will be able to select, drag, rotate and position the components in the AR interface through either touch controls or mouse clicks.
- **Zooming and Panning:** Zooming allows for closer inspection of component connections, while panning enables the user to have an overview of the entire circuit layout.
- **Hints and Visual Options:** The user receives hints and visual

options to guide them in placing components properly and in comprehending the function of the circuit.

- **Feedback Interaction for Fault Detection:** If a fault is detected, the user will receive feedback when he clicks on the designated area, which will display a possible correction to be made or a step-by-step procedure on how to fix the fault in a 3D demonstration.
- **Simulation and Testing:** The user will be able to simulate the assembled circuit to observe its behavior with regards to current flow, voltage drop and signals.

The use of these interactive features in an AR module not only facilitates in the learning of circuit assembly but also ensures that students get involved in the troubleshooting and repairing process.

5.3.3 AR Component Library Overview

Components are available in the AR Component Library inside the Smart Circuit Trainer in an interactive 3D format, enabling the user to interact, rotate and virtually assemble the components in the circuit. Every component is visualized realistically for proper understanding regarding the assembly of the component in a circuit. Some of the components present in the library are:

- **Resistor (Standard):** Represents a standard resistor with a option to set resistance value. This AR component enables users to visualize and orient themselves with the color code of the resistor and how it looks in a circuit assembly.
- **LED (Red):** Represents a red LED used to show current direction. Users can understand the polarization and how LEDs work.

- **Lithium Battery:** Represents a lithium battery with a voltage of 9 volts. It visualizes how the battery is oriented and placed inside a circuit assembly.
- **Complete Circuit Board:** Assembly of an entire circuit using several different components. This particular model is useful for viewing a functional printed circuit board and getting a good idea about the connections of components.
- **Integrated Circuit (IC):** The conventional IC structure with clearly visible pins. AR can be used to help visualize the IC structure, its orientation, and correct placement into a circuit.
- **Transistor (Low Poly):** Represents a generic transistor, either an NPN or PNP type. The terminals (collector, base, emitter) are shown and their correct position within a circuit can be visualized using AR.
- **All Components Combined Model:** An integrated model that includes all separate components from the library. It enables easy placement and assembly of several components at once in a virtual assembly.

Figure 5.9: AR Component Library

[3, 5, 11, 28]

Chapter 6

System Testing and Evaluation

This chapter covers the process of testing, deployment and performance evaluation of the suggested AI and AR-based intelligent circuit trainer with PCB fault detection capability. Upon successful development of both basic and advanced system modules, rigorous tests were performed to ensure that all functionalities are working as intended and that both modules are accurate and reliable. The performance of the AI-based module for detecting faults and identifying components within the PCB was assessed based on the accuracy of the YOLOv11 model after training. Meanwhile, the Web AR module's performance was validated based on its ability to visualize circuits in real-time and provide an interactive learning experience.

6.1 Supervisor Control Panel

Supervisor Control Panel is one of the essential option in the Smart Circuit Trainer GUI that is responsible for providing supervision and monitoring services regarding both system and user operations. This control panel is meant for the supervisor who will use it to effectively manage users and oversee the operations of the AI-assisted PCB inspection system.

6.1.1 Overview of Supervisor Functions

The Supervisor Control Panel enables supervisor who have been granted supervisor rights to be able to:

- Monitor the number of total system users.
- Look at the total stats of the system which include the total number of scans performed, faults detected and accuracy rate of the model.
- Check recent activities and scanning history within the system.

- Adjust user privileges to promote/demote them from operator/supervisor level.
- Delete or disable user account if necessary.

Such a centralized interface guarantees that supervisors have total control over the process, improving efficiency and responding promptly to any problems that arise. [4, 16, 19]

6.1.2 System Statistics

The Supervisor Control Panel displays statistics about the operation of the system in real-time. The following statistics are displayed on the panel:

- **Number of Scans:** It shows the total number of PCBs scanned each day.
- **Fault Detection:** The total number of faults detected by the system in comparison with the average rate of fault detection per day.
- **Accuracy Model:** This statistic is related to the accuracy level of the component/fault detection system using the AI model, usually the YOLOv11 metrics.
- **Health Check:** Whether the system is healthy or not (CPU status).

Such statistics give managers the ability to instantly evaluate the system's performance as well as the efficiency of the artificial intelligence models. [7, 22]

6.1.3 Component Detection Overview

The Control Panel shows the visualization of the AI component identification with the help of bar graphs and charts. The supervisors will be able to see how many components of each type have been identified by the machine learning algorithm, including resistors, LED lights, capacitors, ICs, connectors and transistors.

6.1.4 User Management

Proper management of users plays a vital role in ensuring system integrity. The Supervisor Control Panel comprises:

- **Role Assignment:** Supervisors have the ability to promote an operator to a supervisor or demote a supervisor to an operator.
- **User Deletion:** Users can be deleted from the system to avoid any unauthorized access.
- **User's Activity Tracking:** Users activities, including scanning and inspecting components that are logged into the system are tracked at every step for accountability against any foul actions.

These options give the supervisor complete authority in handling the workflow processes as well as security issues.

6.1.5 Recent Activity and Notifications

The dashboard comprises an update in real time regarding system operation, reflecting recent scanning, component recognition and any faults that may have occurred. Supervisors will be able to review such updates to recognize any recurring problems or abnormalities in PCB manufacturing operations. System performance, detection of faults and user activities generate alerts for effective system management.

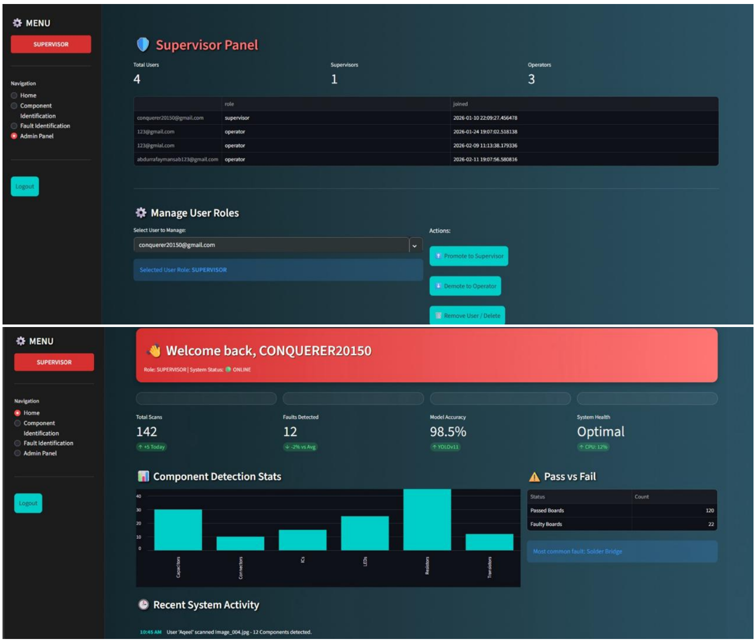

Figure 6.1: Supervisor Control Panel showing system statistics, component detection charts, and user management options

6.2 GUI AI-Based Component Detection Testing

The Smart Circuit Trainer's GUI highlights the application of AI technology for recognizing, identifying, and analyzing components on a printed circuit board (PCB). It combines visual recognition with interactive tools to help users learn, validate and debug circuits.

6.2.1 Resistor Detection and Color Code Identification

Resistors present on the printed circuit board can be identified by the AI module. These are highlighted in bounding boxes and can be selected from the GUI interface to see the estimated value of the resistor. Also, users can change the color bands of the resistor for verifying their values.

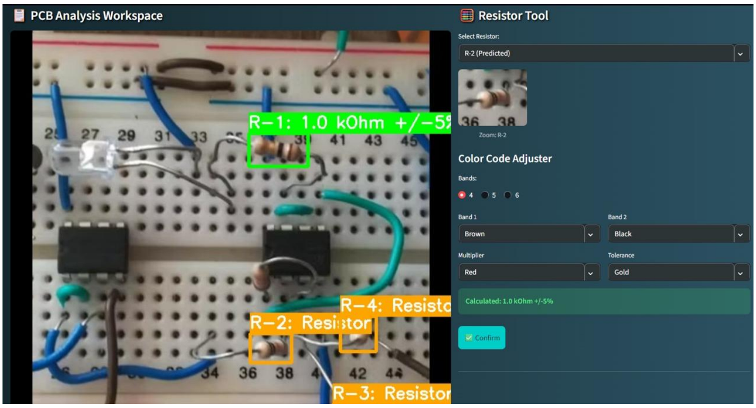

Figure 6.2: AI-based detection of resistors

6.2.2 IC Detection

Apart from detecting the presence of resistors on the circuit board, the AI system is able to detect other components, such as the IC chips. The user may zoom into the particular IC chip and identify its type by entering the specific name of the IC (e.g. LM741) and access its data sheet through the interface.

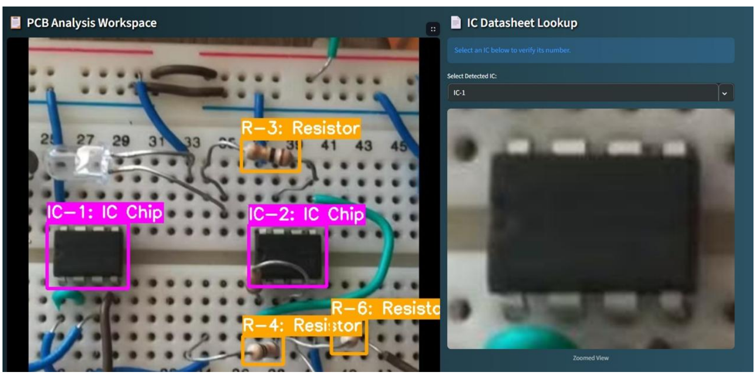

Figure 6.3: Detection of IC chips in the PCB workspace

6.2.3 Combined Component Visualization

The GUI is also capable of simultaneous identification of multiple types of electronic components. In the consolidated view, both resistors and IC chips are identified at once, thus giving a complete layout of the circuit board. The consolidated view serves as an effective method of validating placements and also aids in interactive learning as all identified components are shown together in one workspace. The above-discussed AI-based

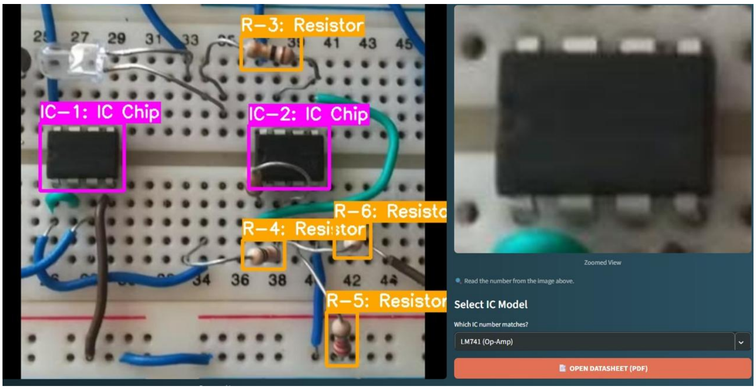

Figure 6.4: Combined detection of resistors and IC chips

identification process can be effectively implemented via the GUI.

6.3 GUI AI-Based Fault Detection Testing

The GUI for the AI-based fault detection testing is provided to detect faults from PCBs with the help of the AI model (YOLOv11). The graphical user interface helps to upload images of the PCB, set confidence level, and display detected faults.

6.3.1 Upload and Configuration

Choosing the kind of fault detection and uploading the image of the faulty PCB to set up AI parameters is the initial stage in the GUI process.

Users can do the following:

- Upload images of faulty PCBs through drag-and-drop or file browsing.

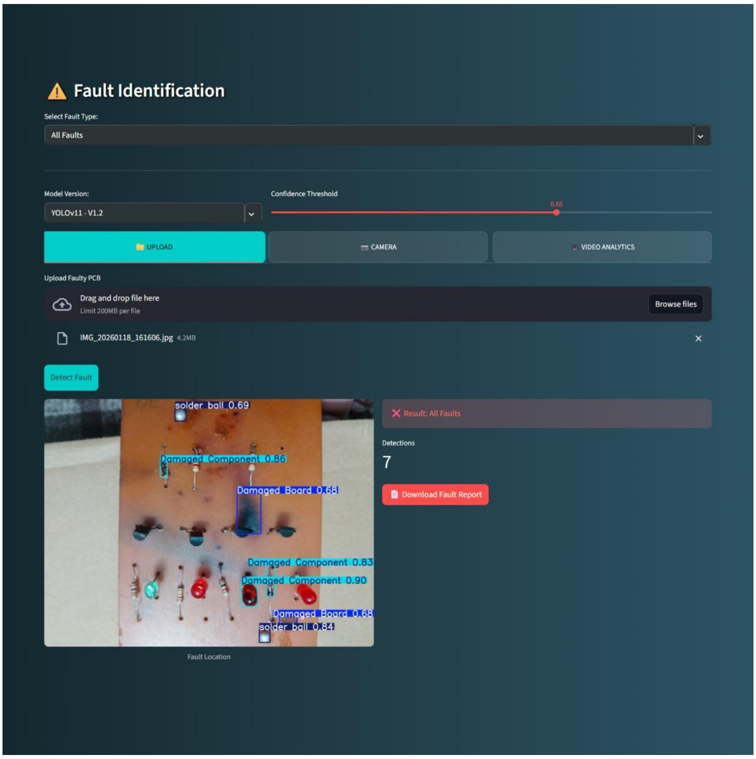

Figure 6.5: Fault Detection GUI

6.3.2 Fault Detection Results

Once the image is uploaded, the AI analyzes the circuit board and displays the faults that are identified on the same image. The faults are tagged by type (Damaged Components, Solder Bridges) and their probability. The GUI offers:

- Faults visualization with a box in real-time.
- The number of faults identified.
- Fault report download.

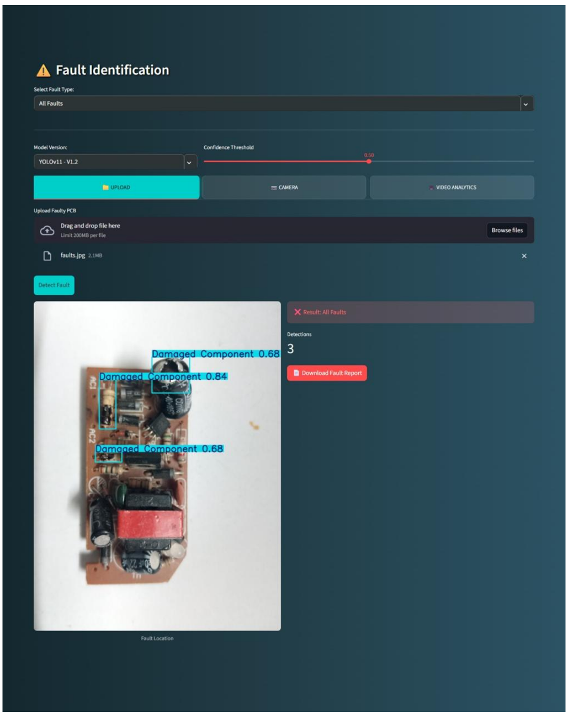

Figure 6.6: Detected damaged components

6.3.3 Solder Bridge Detection

There is an option of specific detection of defects like bridging and cold joints in soldering. Such defects are indicated in the info box form with each component along with their level of confidence, which means how certain the AI is about the defect.

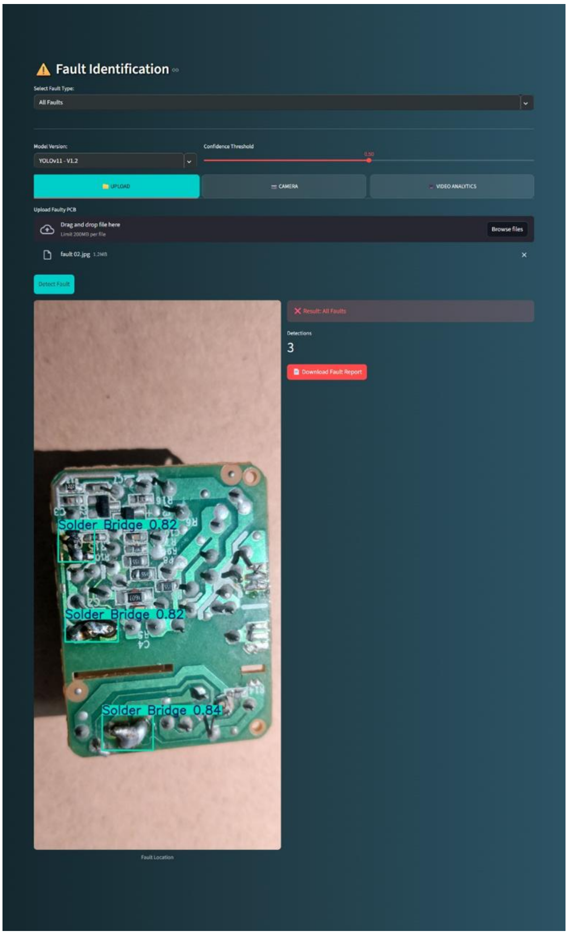

Figure 6.7: Detected solder bridge faults

6.3.4 Observations and Analysis

- The graphical user interface is capable of detecting various kinds of defects within a single picture.
- The confidence levels make it easier for users to separate the more likely defects from false negatives.
- Reports of the detected faults can be downloaded for analysis or educational purposes.
- It makes inspection of PCBs easier and faster, reducing chances of human error.

6.4 GUI Augmented Reality Testing

6.4.1 Overview of AR Integration in the System

The AR module allows the creation of an interactive interface in which the electronic circuit can be visualized and created. It works together with the hardware component where the real surface can be captured using the camera. This would then be used to overlay the 3D components within the physical environment.

Key Aspects of AR Integration

- **Real-time Visualization of Components:** Resistors, capacitors, ICs, transistors and other components can be visualized in 3D within the real PCB/breadboard, which will help users identify their location and orientation.
- **Guidance for Assembly:** Instructions regarding the correct wiring

and assembly of components can be provided by displaying them on the screen in the workspace.

- **Platform Availability:** This augmented reality interface can be used on a PC or mobile phone, thus increasing the accessibility of the system.

The above features will ensure that there is a perfect blend of theory and practice in the field of electronics circuit assembly. [24, 26]

6.4.2 Step-by-Step AR Process for Circuit Building

This AR-based module for the visualization of circuits helps in providing an interactive and practical learning process for the creation of electronic circuits. The steps involved in this process include the following:

1. Access AR Menu

The first step involves opening the AR inspection menu in the system interface. This menu provides options to access the 3D component library or launch the live AR overlay.

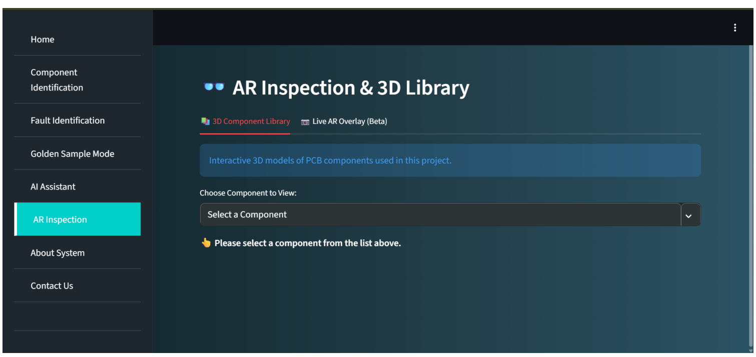

Figure 6.8: Access AR Menu

2. Select a Component

From the 3D Component Library, the user selects the desired electronic component, such as a resistor, LED, battery or IC. The library allows users to view individual components or a complete set of components for AR placement.

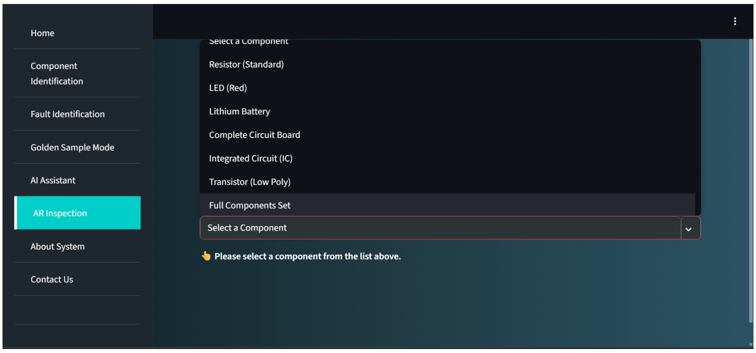

Figure 6.9: Component Selection

3. Visualize Component in AR

Once a component is selected, it appears in the AR workspace on the computer screen. The user can manipulate the component in 3D space by:

- Rotating
- Panning
- Zooming

to inspect it from different angles.

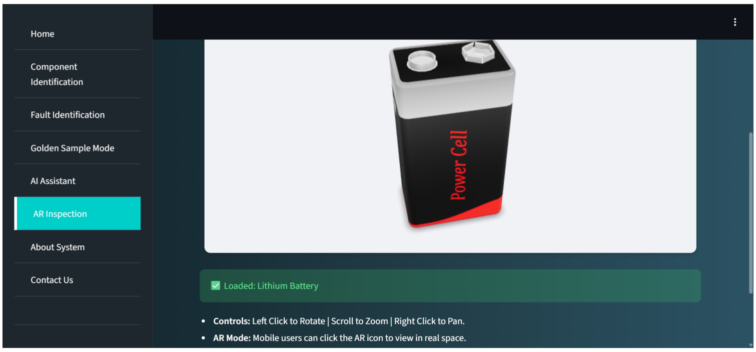

Figure 6.10: Component Visualization

4. Mobile AR Interaction

If the user accesses the system on a mobile device, they can open the selected component in live AR mode using the mobile camera. This allows the component to be virtually placed anywhere in the physical environment. Users can:

- Move the component freely across the surface
- Rotate and zoom to view details from different perspectives
- Position the component accurately in a real-world setup

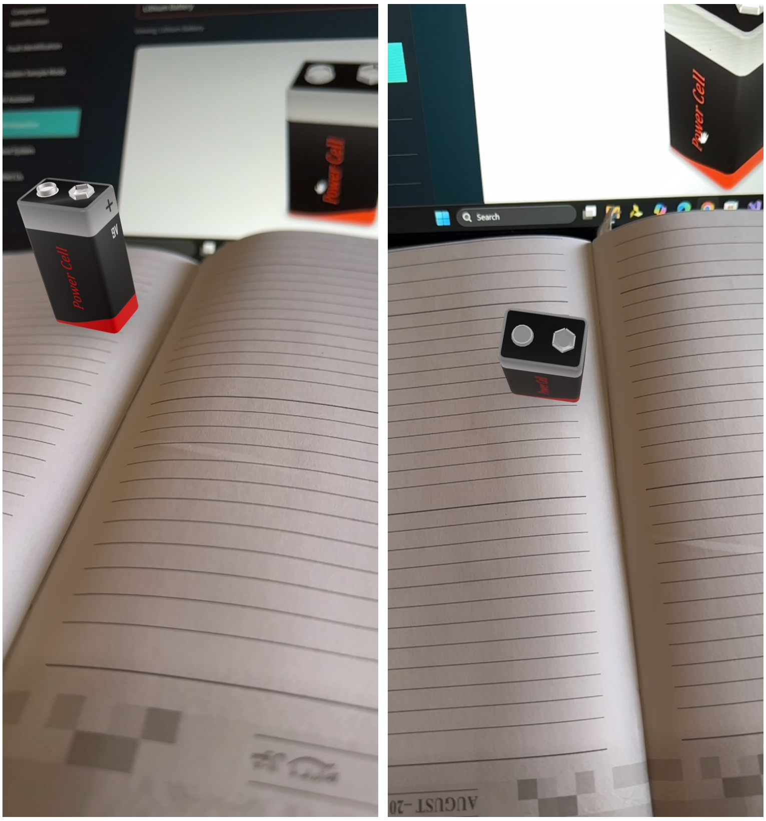

Figure 6.11: Mobile Interaction

5. Capture & Save Placement

After arranging the component in the desired location, users can capture an image from their mobile device. This snapshot records the placement for reference, learning documentation or demonstration purposes. This workflow ensures a seamless integration between digital AR models and real-world interaction, enhancing conceptual understanding, improving spatial reasoning and allowing students to safely experiment with circuit components in an interactive environment.

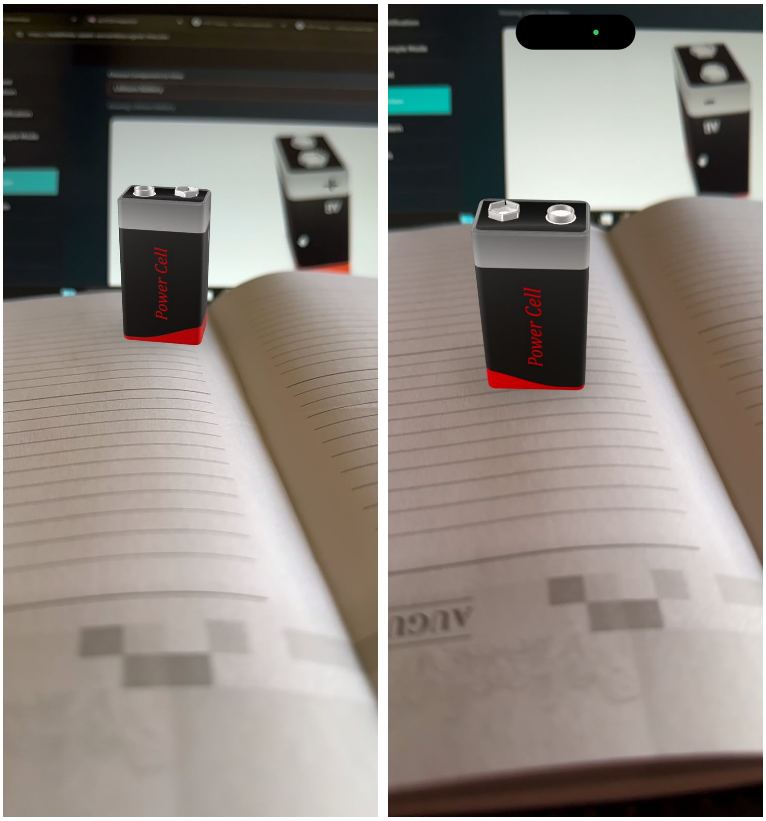

Figure 6.12: Mobile Image Capture

6.5 Additional GUI Specifications

The Smart Circuit Trainer GUI offers a wide range of advanced features to enhance component and fault detection, provide detailed component information and assist with cost estimation and reporting. The GUI specifications include email alerts, component detection, fault detection, resistor value finder, smart BOM, datasheet lookup, video analysis, AI Assistant, inspection report and cloud-ready deployment.

- **Email Alert:** Sends an email notification on user login or new registration.

- **Component ID:** Detects over 16 types of components including resistors, ICs and capacitors.
- **Fault Detection:** Identifies solder bridges, missing components, damaged components and more.
- **Resistor Value Finder:** Detects resistors in the image and provides an option to calculate their value manually.
- **Smart BOM:** Auto-calculates the Bill of Materials and estimated cost in PKR, allowing manual editing.
- **Datasheet Lookup:** Provides instant PDF retrieval for ICs and detailed component information.
- **Video Analysis:** Performs frame-by-frame inspection for video input.
- **AI Assistant:** Integrated AI chatbot (LLaMA 3.2) to assist users with queries related to components and faults.
- **Inspection Report:** Generates a PDF report of component and fault detection.
- **Core AI:** YOLOv11 (Ultralytics) for component and fault detection.
- **Email SMTP:** For automated login alerts.
- **Backend:** Python with OpenCV for image processing.
- **Frontend:** Streamlit framework for interactive GUI.
- **Reporting:** PDF for automated PDF IC report generation.
- **Deployment:** Cloud-enabled architecture to allow for easy accessibility.

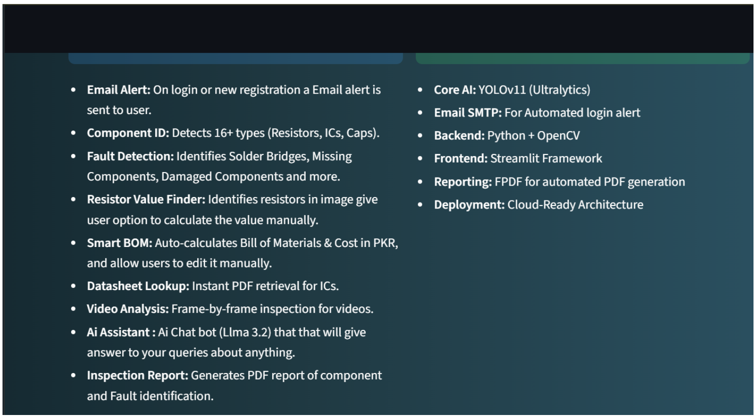

Figure 6.13: Additional Specifications

6.5.1 AI Assistant

The AI Assistant can be defined as a chat bot, which will aid users in understanding the detections of components and help in analyzing the detected faults along with offering guidance to troubleshoot them.

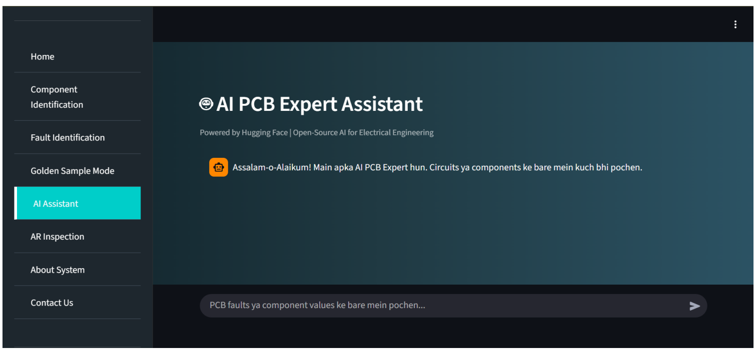

Figure 6.14: AI Assistant

6.5.2 Datasheet Lookup

In the process of detecting the components, when the IC has been detected, there is the option for opening its datasheet in a new tab. This allows for the viewing of information regarding the IC's pin arrangement, electric behavior and manufacture details. [?, 2, 22, 25, 29]

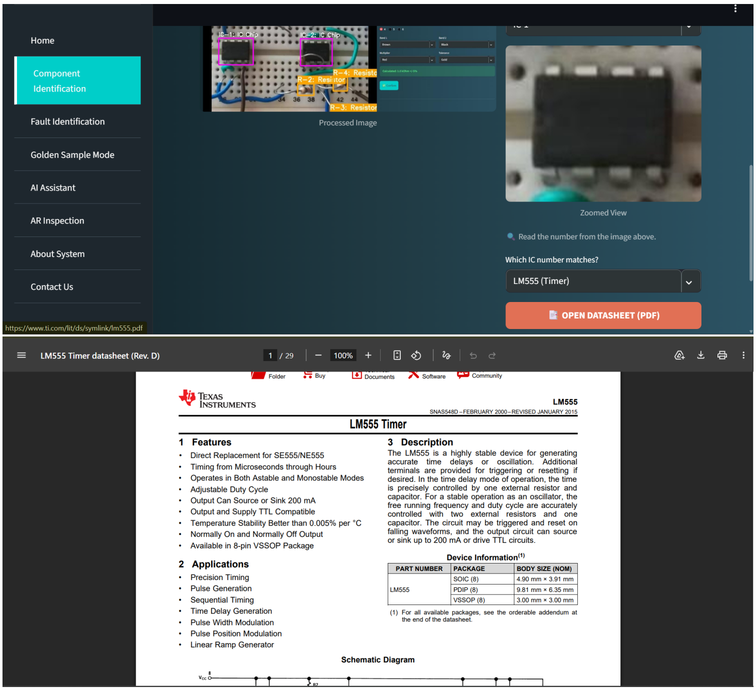

Figure 6.15: IC Datasheet

6.5.3 Smart Budget Estimator

The Smart Budget Estimator works by calculating the total estimated cost of all components identified on the PCB. The Smart Budget Estimator will provide a report in the local currency (PKR) of the bill of materials (BOM) summary and can be adjusted manually.

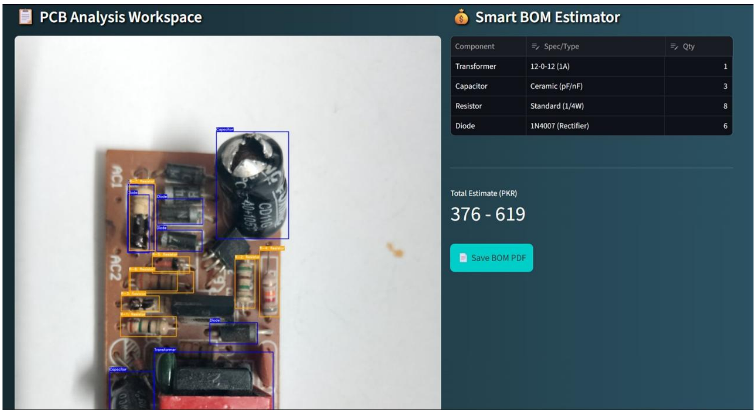

Figure 6.16: Smart Budget Estimator

6.6 Hardware-Software Integration Testing

6.6.1 Real-Time Performance Metrics

To conduct a real-time performance test on the proposed system, a comparison test was made between the AI-based fault detection module and the AI-based component detection module. This is essential to determine the real-time performance of the proposed system in terms of PCB inspection.

The fault detection module is defined as the early version of the AI-based module in detecting faults in the PCB, while the component detection module is the improved process of detecting electronic components.

Table 6.1: Real-Time Performance Comparison

Performance Metric	**Fault Detection**	**Component Detection**
Average Inference Time per Image (ms)	85 ms	62 ms
Frames Per Second (FPS)	11.7 FPS	16.1 FPS
End-to-End Detection Latency (ms)	120 ms	88 ms
Model Load Time (s)	4.6 s	3.2 s
Detection Stability	Moderate	High
Real-Time Usability	Acceptable	Improved

Based on the Table above, it can be observed that the component detection module offers better real-time performance compared to the fault detection module. The average inference time per image is decreased, thus increasing the frame rate.

The increased frame rate reduces the overall system latency. The improved real-time performance can be attributed to the optimized model configuration, preprocessing, and feature handling of the components. The evaluation of the real-time performance of the component detection module and the fault detection module revealed that the component detection module offers better real-time performance.

6.6.2 AI-Based Component Detection Model Accuracy & Precision

Accuracy

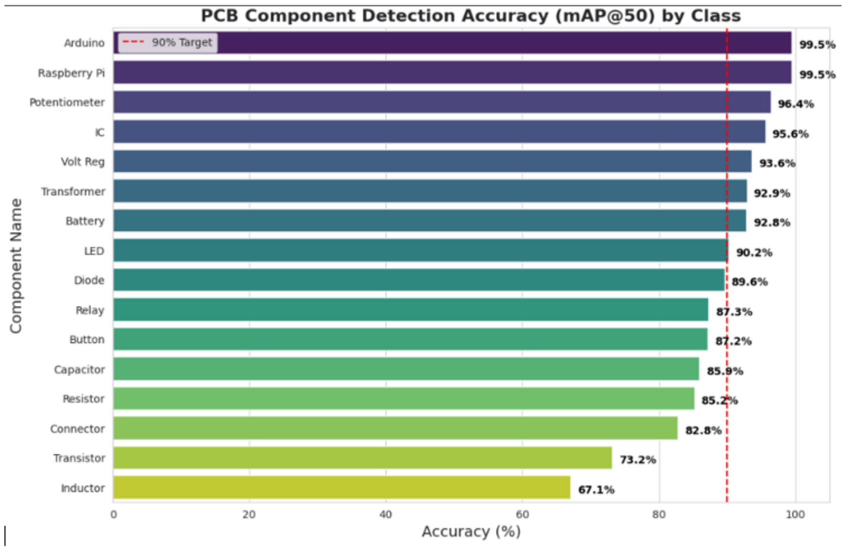

Figure 6.17: PCB Component Detection Accuracy by Class

The above figure shows the accuracy of the detection of the various classes with the help of the PCB component detection model. The accuracy of the detection model was evaluated using Mean Average Precision at IoU threshold of 0.5 (mAP@50).

The analysis indicates that there are many classes of components that possess extremely high accuracy in terms of their detection capability. Embedded boards, for instance, Arduino and Raspberry Pi, display almost flawless accuracy levels, with a level of 99.5%.

Other components include potentiometer, ICs, voltage regulators, transformers, batteries and LEDs, which demonstrate an accuracy of greater than 90%.

The red dashed line indicates the desired accuracy level of 90%. For components like relays, buttons, capacitors, resistors and connectors, there is an average accuracy level ranging from 82% to 88%. This is an acceptable range, considering the visual similarities of these components and their compact sizes.

Components like transistors and inductors also display low accuracy, with accuracy levels of 73.2% and 67.1%, respectively. These components are more difficult to detect, owing to their subtle visual features, their orientation, and their similarities to other passive components.

From the accuracy level, it is clear that the proposed AI-based system for detecting components on a PCB is robust and efficient for detecting a wide range of components.

Precision

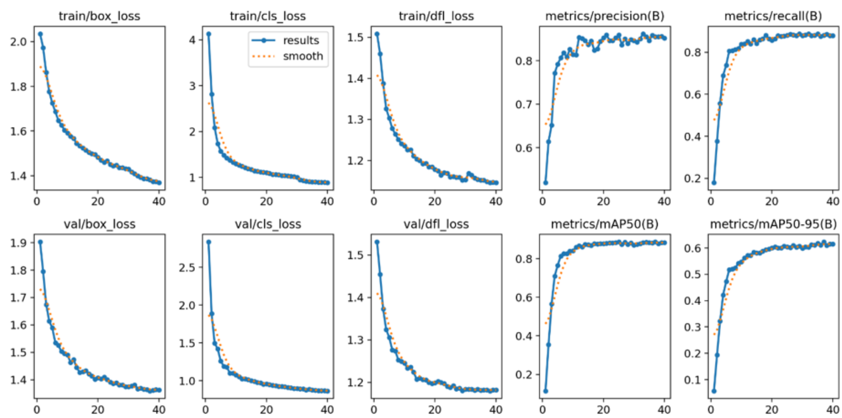

Figure 6.18: Training and Validation Losses and Performance Metrics

The above figure shows how the performance of the model used to detect components of the PCB changes during various epochs of training. The figure shows how loss functions and performance metrics are used to check how well the model is learning and how well it is able to generalize. [15] All loss functions employed in the process of training, namely, box loss, classification loss and distributional focal loss (DFL), tend to decrease as the number of epochs increases. This tendency is also observed in the case of validation loss functions. Therefore, the fact that no overfitting occurs can be concluded. Additionally, the precision and recall rates also increase sharply during the first stage of the training process but gradually stabilize. Thus, the rapid increase means that the model becomes trained to detect components of the PCB, while producing less number of false positives.

Furthermore, it should be noted that the values of the Average Precision metrics (mAP@50 and mAP@50–95) tend to constantly increase and converge at high values with increasing epoch numbers. The obtained results prove the high quality of the developed model from the point of view of its excellent detection ability for various IoUs.

In summary, the smooth convergence of the graphs of training and validation in terms of loss and metrics proves the high level of training and good quality of the proposed component detection model.

Table 6.2: Performance Status Summary

Component Class	Precision (P)	Recall (R)	mAP@50 (%)	Performance Status
Arduino	96.2%	100%	99.5%	Perfect
Raspberry Pi 4	94.7%	100%	99.5%	Perfect
Potentiometer	91.6%	95.0%	96.4%	Excellent
IC	91.5%	94.3%	95.6%	Excellent
Voltage Regulator	86.3%	91.1%	93.6%	Excellent
Transformer	86.3%	91.4%	92.9%	Excellent
Battery	89.6%	86.1%	92.8%	Excellent
LED	90.4%	87.2%	90.2%	Excellent
Diode	91.1%	85.0%	89.6%	Very Good
Relay	70.9%	90.9%	87.3%	Good
Button	86.3%	85.3%	87.2%	Good
Capacitor	84.8%	84.2%	85.9%	Good (Hard Class)
Resistor	88.0%	82.6%	85.2%	Good (Hard Class)
Connector	60.8%	100%	82.8%	Okay
Transistor	81.3%	73.0%	73.2%	Weak
Inductor	77.5%	65.4%	67.1%	Needs Improvement
Overall	**85.4%**	**88.2%**	**88.7%**	**Passed**

6.6.3 AI-Based Fault Detection Model Accuracy & Precisions

Accuracy

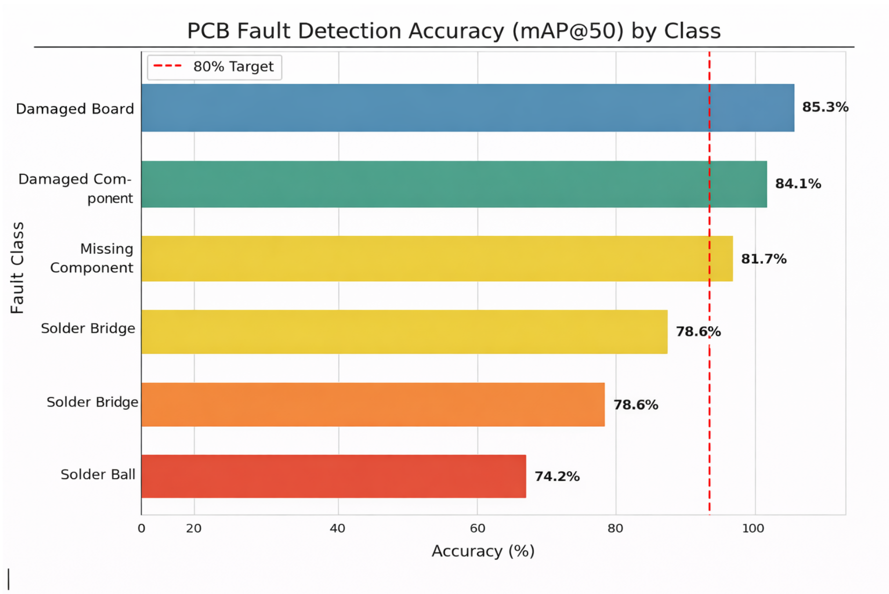

Figure 6.19: PCB Fault Detection Accuracy by Class

The above figure shows the class-wise accuracy of AI-based PCB fault detection model. The accuracy of the AI-based model is calculated using mAP@50. The horizontal bars represent the accuracy of detection of different classes of PCB faults, which include damaged board, damaged component, missing component, solder bridge, and solder ball.

The above results indicate that the accuracy of detection of damaged board and damaged component is higher than other classes of PCB faults. The mAP@50 value of damaged board and damaged component is higher than 84%, indicating that the AI-based model is more accurate for detection of damaged board and damaged component. The prominent visual characteristics of damaged board and damaged component make it easier to detect such types of faults.

The accuracy of detection of missing component is higher than the specified threshold value of 80%, indicating that the AI-based model is more accurate for detection of missing components on the PCB. The level of accuracy in detecting solder bridges and solder balls is somewhat low, which means that it is harder to detect solder bridges and solder balls on the PCB.

The dashed line with red color represents the accuracy target of 80%. This is the benchmark for determining how efficient the system is in performing its task. All the classes of faults have reached or almost reached this target, which proves that the fault detection model works effectively for the PCB inspection.The accuracy of the system has proved its effectiveness with room for improvement.

Precision

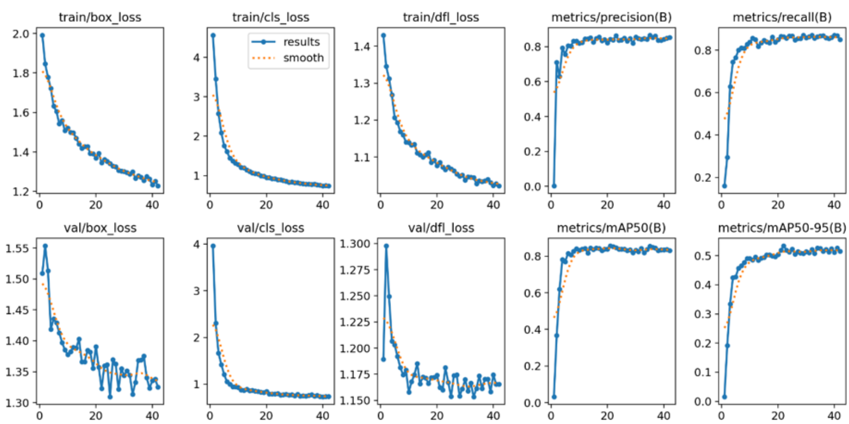

Figure 6.20: Training and Validation Performance Metrics

The above figure depicts the training and validation performances of the AI-based model used for detecting PCB faults. The above figure depicts major loss functions and performance metrics, which help in showing how the AI model works during its training. As evident from the training loss functions shown above as bounding box, classification and distribution focal losses, it is evident that the training process of the AI model is efficient since there are progressive reductions in the loss functions, indicating effective learning. In the same way, it is evident from the losses shown for the validation part that the model does not suffer from overfitting and has generalization skills.

It can be seen that from the precision recall graphs depicted above, improvements in the performance of the model are fast at the early epochs but gradually level off. This indicates that the AI model learns the faults effectively.

From the analysis above, it is evident that the designed AI fault detection model converges, generalizes well and is reliable.

Table 6.3: Comparison of Fault Detection Performance Using Mixed Data and Own Dataset

Class	**Old Result (Mixed Data)**	**New Result (Own Data)**
Overall mAP	81.5%	85.3%
Solder Bridge	98.2%	98.1%
Solder Ball	90.3%	92.2%
Damaged Board	81.2%	86.9%
Damaged Component	73.0%	82.8%
Missing Component	65.1%	66.5%

Chapter 7

Conclusion

This thesis covered the design, development and implementation of a Smart Circuit Trainer with PCB Fault Detection using artificial intelligence (AI) and augmented reality (AR). The main purpose of this thesis was to devise an intelligent, cost-efficient and interactive system that can automate PCB component detection and identification of faulty components and improve the learning process by means of visualization via AR technology.

The research started with analyzing limitations of the traditional approaches of teaching and inspecting printed circuit boards (PCBs). Based on the findings, certain engineering requirements and objectives were established. Consequently, a dual-mode system combining both the basic mode of PCB component detection and fault detection and the advanced Web AR-based mode of visualizing electronic circuits was developed.

The fundamental approach involves applying computer vision and deep learning methods for efficient analysis of PCB. A custom-designed YOLOv11 model was used for detecting electronic elements as well as identifying typical PCB issues, including missing components, misplacement and defective contacts. Data preparation and training of the model were done using Roboflow on Python in a cloud environment. Thus, real-time detection was provided with high accuracy and speed, eliminating the need for manual inspection. In addition, the advanced module incorporates Web AR functionality to ensure immersive learning. By means of visualizing circuits, users will be able to examine components, understand their interconnections and get detailed instructions right on the top of a printed board. This ensures better learning ability and reduces the theory-practice gap.

Thorough testing and validation procedures were applied to each subsystem of the system. The detection model showed sufficient reliability while Web AR provided good results regarding enhanced engagement and comprehension of information by users. Communication of the detection unit, processing and visualization module passed successfully during the integration testing stage.

The whole system implementation helps to make some contributions to the domain of smart education and intelligent inspection systems. The system is aligned with modern technological trends based on the principle of industry with application of technologies like automation, machine learning and augmented reality. Moreover, the proposed system provides affordable solutions that are useful for educational institutions and small companies for PCB inspection and learning.

In conclusion, it is important to mention that the proposed system meets all set criteria and objectives, since the system implements machine learning models to detect faults and applies augmented reality technology to develop interactive learning content. However, there is still room for improvement, which includes such tasks as improving the accuracy of the machine learning model by enlarging the dataset, implementing the system on embedded devices and developing more augmented reality use cases for multi-layer PCB inspection and collaboration.

Overall, the completed research is the foundation for new-generation smart inspection and education systems.

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