Generative AI-Driven PCB Defect Detection and Classification System

Gayatri M. Phade, Sahil Papal, Saish Aher and Sanket Chaudhari
Department of Electronics and Telecommunication, Sandip Institute and Technology and Research Centre, Nashik, India

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Abstract: Traditionally, PCB testing is done manually. It has limitation like it is a time-consuming process, high cost, human error, low accuracy etc. This manual process leads to high processing time, increased product cost and quality. To overcome this limitations Generative AI enabled PCB testing System is proposed that will detect and classify the defects in PCB. The Generative AI Based PCB Tester (GABPT) system uses AI enabled image processing to make the process faster and more accurate. The GABPT classify defects like scratch, missing holes, Missing Path, Mouse-bite, Short-circuit, missing Conductor etc. The main objectives to reduce human error, speed up testing, and lower the testing costs.it will give an approach on machine-based methods like emphasizing image pre-processing, image acquisition and analysis. The system uses high-resolution cameras to capture the relative image of the PCB to be tested, an Arm Cortex A72 processes for analysing the captured images and LCD to monitor the tested result. It identifies and categorizes defects, providing immediate feedback to help users resolve issues efficiently. This paper improves the efficiency of PCB testing by using automation. This helps save time and money while making the process more accurate. As a result, we proposed a better--quality products and reduce human errors, which encourages innovation in the industry. By using resources more efficiently, we also support more sustainable manufacturing practices.

1 INTRODUCTION

The electronics industry is advancing rapidly, creating an increasing need for high-quality printed circuit boards (PCBs). As these boards grow more complex, effective testing methods become essential to ensure their reliability and performance. Traditional manual testing is often slow, susceptible to human error, and may overlook subtle defects. (Rao, Abhinav, et al. , 2024)

In this paper a fully automated ai based PCB tester system is proposed to meet these challenges. The purpose of the proposed system is to develop an automated system that uses generative ai and advanced image processing in order to enhance the speed and accuracy with which PCBs can be tested. Our system utilizes machine vision, automatically recognizing and classifying defects such PCB-scratches, misalignments, and shorts-automatically. It thereby not only makes quality control processes much more efficient but also less vulnerable to the risk of human error entailed by manual inspections.

Image preprocessing is an integral part of the proposed system. It deals with the enhancement of PCB images for quality purposes before analysis. Various operations on the PCB images were performed, which include noise reduction, contrast enhancement, and edge detection. For example, noise reduction is helpful in removing unwanted artifacts masking defects. Contrast enhancement brings the key features to prominence and edge detection outlines the boundary of components and defects thereby improving classification accuracy.

Crucial to PCB tester employs is the data collection method; it is a critical requirement for training the ai model. We compiled a diverse set of images of PCBs with different types of defects, ensuring that every probable issue of the defect is accounted for. This dataset was acquired from existing databases as well as the images captured during the actual manufacturing process itself. We have taken special care to cover very common as well as rare defects to make the model robust. This extensive dataset we have gathered, which encompasses common and rare defects, assists in the improvement of the precision of the model as it detects and classifies the defects. High resolution cameras coupled with advanced algorithms were used

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in our system to make it possible for it to accomplish the tasks we had in mind.

The TensorFlow library was the driving force of all machine learning activities we planned; this is because it allows the model to learn what we want from a huge collection of PCB images. That way, our ai could easily identify some defects and continually perfect its defect identifying capabilities. We utilized the OPENCV library for image processing tasks. The OPENCV will assist in bringing useful tools for image manipulation into our preprocessing efforts. Filtering and edge detection methods make the images of better quality before analysis by the ai. TensorFlow and OPENCV were added to enhance the capabilities of our system regarding instant feedback on defect detection. From the hardware perspective, our generative ai-based PCB tester is built around a raspberry pi 4b+ with the arm cortex a72 processer as the processing unit. It is small yet powerful and capable of processing real-time images, along with ai computation. This will enable us to form a harmonious whole by effectively integrating these components.

To download high-resolution images required to detect any faults, we have the camera module v2. In that camera, the resolution is so good; hence it will be possible for us to download the images of the printed circuit boards in which even small fault is detectable. For training our ai model with various faults, images in high definition are very crucial for the purpose. The user-friendly touch screen display comes with our generative ai-based PCB tester, which can be easily integrated with the raspberry- pi. The interface of this system is developed to be simple and practical so that users, the operators, can easily get things done in the system. One of the impressive features of this display is that it depicts its results in real time while inspection is underway.

Real time results during inspections, is one of the features of the display. The instant feedback of images after they are captured and analysed is what operators will see in case defects are detected. This real-time information allows them to quickly decide what action needs to be taken next—be it reworking a PCB or specific quality-related issues. Overall, the touchscreen display dramatically enhances the usability of our PCB tester. It simplifies the tasks facing the operators while managing the inspections, thereby enhancing quality production in the PCB manufacturing process. There will be improvements in the system itself, and future dataset growth will see newer types of defects that might evolve at the production stage. Improvement of our algorithms regarding accuracy levels and processing times is also something to which we are committed. We also foresee, in the future, adding new functionalities such as predictive maintenance features for manufacturers whereby they can predict problems before it happens.

In this paper, we detail the methodologies behind generative ai approach through describing the image preprocessing techniques and detection algorithms that we used. We also discuss some of the issues we have faced in development and how our system can be smoothly integrated into any manufacturing process. Our aim is to demonstrate that this advanced testing solution will significantly increase the efficiency of defect detection even in images of very low quality, thus promoting the production of more reliable electronic components.

2 RELATED WORK

In recent years, various methods have emerged for detecting faults in printed circuit boards (PCBs). Initially, the process relied on manual inspections using magnifying tools. Unfortunately, this method was often insufficient because small defects were difficult to spot. This challenge led the industry to explore image processing systems that utilize technology for more effective fault detection. These image processing systems work by capturing a photograph of the PCB being inspected and comparing it to a reference image of a perfect PCB. This comparison makes it easier to identify any discrepancies or faults that might be missed during manual inspections. A major advantage of this approach is its speed; it can quickly detect a variety of defects. (Rao, Abhinav, et al. , 2024), (Raj, and, Sajeena, 2018).

Recent studies have produced outstanding advances in PCB flaw identification by using different methods. A certain study looked at the use of artificial neural networks (ANN) and resistance analysis. Researchers were able to distinguish between crucial characteristics such as traces and contacts and probable flaws using thinning methods and clustering approaches. This method relates the trace current shifts to fault features, it boosting both visual and electrical investigations, which assists in properly spotting issues even tiny issues. (Lee, and, Kim, 2021), (Thomas, Sutar, et al. , 2017), (Cheng and Liu, 2022)

Research also involves a small scanning parts of PCB images to detect the PCB defects. This method is flood-filling, k-means clustering, and statistical analysis to focus on specific components. By analysing these smaller sections, it increases precision and efficiency across various types of PCBs. (Melnyk, and, Shpek, 2023), (Malin, et al. , 2022)

A comparative study looked at different imaging techniques—visible light, x-ray, and near-infrared (NIR)—for defect detection. While x-rays are effective for revealing internal flaws, they come with health risks due to radiation exposure. The research emphasizes NIR images as a safer and equally reliable option, it also suggesting it could effectively replace x-ray inspections. (Malin, et al. , 2022), (Yadav, Gupta, et al. , 2021), (Cheng and Liu, 2022)

A paper proposed on a machine learning system for to detect defects such as missing components and circuit breaks using the yolo (you only look once) algorithm. This approach allows for real-time identification and classification of defects by processing grayscale images and employing edge detection, enhancing visibility and speeding up inspections. (Yadav, Gupta, et al. , 2021), (Purva, Shubhangi, et al. , 2022).

Additionally, a different study utilized image processing techniques like median filtering to reduce noise and the Sobel operator for edge detection. By applying template matching to compare test images with a standard reference, this system improves both the accuracy and efficiency of defect detection. (Cai, Li, et al. , 2012)

An automated visual inspection system detailed in another study used a subtraction algorithm to compare inspected PCBs with a standard reference. This method assessed the impact of noise on detection accuracy and categorized various defects, such as missing holes and short circuits, thereby improving the reliability of inspections in industrial settings. (Raj and Sajeena, 2018)

Other research works show that convolutional neural networks (CNNs) are great at detecting defects in images of printed circuit board (PCB) as they can automatically learn key features for the classification task. To further improve effectiveness, researchers attempt various applications of data augmentation, such as rotating and flipping images, during training. They also adopt transfer learning, which is the fine-tuning of pre-trained models toward PCB inspection, especially when labelled data is in short supply. The other approach is that f anomaly detection, which identifies defects through comparisons made between images of PCBs and defect-free images. The methods include u-net and mask r-CNN, which allow for full inspection by automatically breaking down images into distinctive parts. (S. A., et al. , 2025), (Hu and Wang, 2020), (Cheng and Liu, 2022)

Finally, research on the image subtraction method approaches the studied identifying faults such over-etching and under-etching, use of segmentation and thresholding methods along with neural networks for efficient classification, which leads to faster and more accurate results. (Mishra, Das, et al. , 2020)

3 METHODOLOGY

The proposed method for the system involves the acquisition of two PCB images one is a reference image that has no defects and another is a test image of the same design that may contain defects then image pre-processing, thresholding, defect detection and identification is carried out. The resultant image is the defects present in the test PCB that can located.

3.1 Image Acquisition

Figure 1 shows that image acquisition is the acquisition of images of real-world objects through devices such as cameras or scanners. The process, in our case, would be acquiring high-resolution images of PCBs that would later on be sent for image processing and analysis. To ensure the success of this operation, we acquire images using high-resolution cameras or scanners. We also created a controlled lighting environment that has less shadows and reflections so the images are clear. Again, a stable camera platform is essential for the camera to have stable image quality. We take the sufficient number of pictures of the different PCBs so as to prepare the robust dataset for analysis.

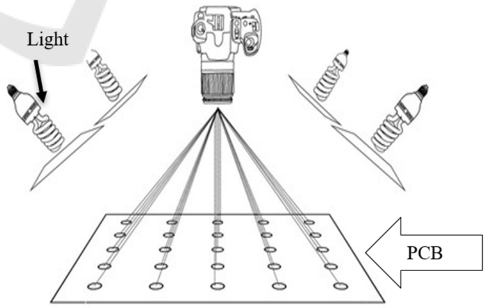

Figure 1: Image acquisition

3.2 Image Preprocessing

Image preprocessing is simply the set of techniques applied to improve the quality of raw images into clearer ones ready for analysis.

In proposed system, this improvement of PCBs images comes right before our search for defects. This is important because the quality of these images may determine exactly how accurate our results will be. Often, such raw images arrive with various noise-like shadows or multiple illuminations that might mask some important details. Applying noise reduction and contrast enhancement, they can be made clearer and therefore much more useful for our analysis. Equation 1 is used for image preprocessing.

$$(f*g)(x,y) = \sum = -k\sum = -kf(x-I,y-j).g(I,j) \qquad (1)$$

f (x, y) is the input image.

g (i, j) is the convolution kernel.

i, j are the indices of the kernel.

the result is the filtered image at position (x, y).

In image preprocessing to remove the noise from the image, the following formulae, given by equation 2, is used

$$g(x,y) = \frac{1}{n*n}\sum = -k\sum = -kf(x+I,y+j)$$

After the preprocessing, the image is converted into grey scale using equation 3.

Greyscale = 0.29*red+0.58*green+0.11*blue---3)

3.3 Image Segmentation

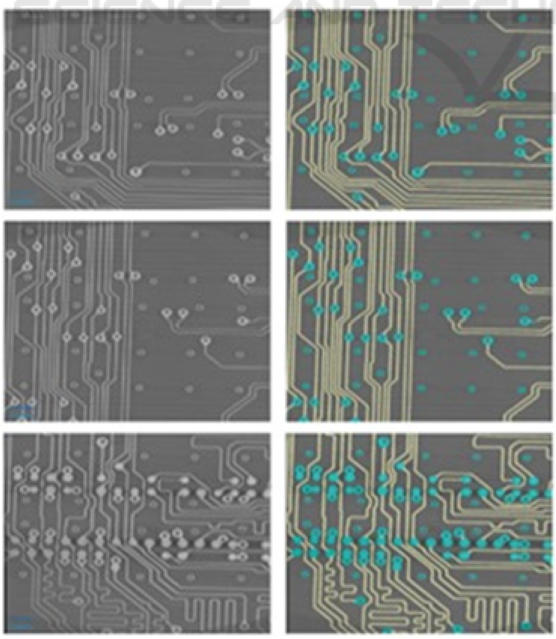

Figure 2: Image segmentation

Figure 2 shows two parts the segmentation of an image where the specific regions can be captured for discussion. To deal with the defect-detection system in printed circuit boards, this aspect is mainly required to separate components and capture traces, pads, and holes. Thus, we could more accurately capture defects.

In our GABPT system, we use techniques like thresholding to separate based on the brightness of areas and edge detection to draw focus on the boundaries of the components. This allows zooming in on areas that are most likely to have defects. Thresholding distinguishes copper traces from board surface, edges detect important borders, breaking down an image into its component parts increases the accuracy of defect detection, so that every part of the PCB is dealt with in respect of any short circuits or misalignments as well as missing components

3.4 Proposed System

The figure 3 shows the block diagram of proposed system. Arm cortex-a72 is one of the most powerful processors ever produced with armv8-a architecture, which carries a 64-bit instruction set with wide performance in computer operations. It has a quad core structure that makes it very efficient in its real-time tasks like inspecting images of PCB for defects. Energy efficiency is guaranteed since the battery life is not drained while handling demanding jobs that makes it ideal for portable devices.

One of the main features of cortex-a72 is the support for machine learning, so quite apt for generative ai in PCB testing which quickly and accurately detects and classifies defects. Integrated graphics improve the visualization of layouts across PCBs. Furthermore, its architecture supports flexibility through multiple adaptation manners: prototyping or production. Overall, cortex-a72 accelerates PCB quality assessment speed and accuracy in a line so that it is more efficient for the manufacturing process and for products altogether.

We rely on a camera to capture images of printed circuit boards (PCBs). The 11.9 mega pixel camera is cost effective that delivers the high-quality images while seamlessly integrating with tools, and for image analysis purposes too. This method significantly enhances our ability to inspect PCB layouts accurately. To keep the raspberry pi 4b running smoothly, it needs a 5v dc power supply. The power supply provides 5v dc supply through ac to dc conversion. To make GABPT system even more user-friendly, we've added a 7-inch touchscreen display.

This allows for easy interaction, making it simple to input data, navigate menus, and receive visual

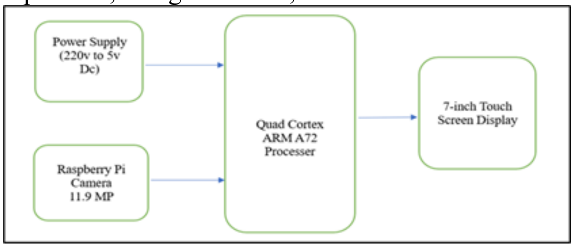

Figure 3: Block diagram of GABPT

feedback. It's perfect for any projects that require real-time responses or interactive controls, providing a more engaging experience for your users.

The figure 4 shows the flowchart of PCB tester which illustrates the overall objective of the PCB defect detection system is to make the inspection of printed circuit boards more efficient. It starts with expert inspectors who closely scrutinize the boards for any defects. These inspectors take high-quality images that act as the basis for further analysis. Once these images are collected, then comes the enhancement process. This enhancement process would involve the following: adjustment of brightness and contrast, noise removal, and segmentation of PCBs from their backgrounds. This stage also extracts critical characteristics indicative of flaws.

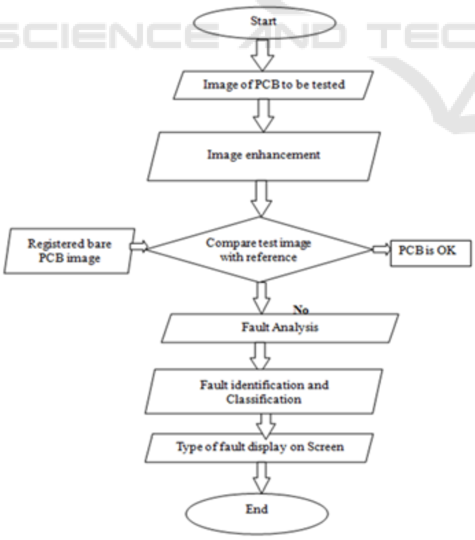

Figure 4: Flow chart of PCB tester

After processing images, this is then sent for validation check where data collected here needs to be verified to be complete and accurate. In case some errors are produced, the team returns to collect more data that will correct such errors. The validated data is then found in a centralized database for easy access and analysis. More advanced tools, such as OPENCV, are used to further analyse the images. Such tools may aid in the image segmentation process and examine each part of the PCB closely to look for defects. This approach makes it sufficiently extensive to enable machine learning integration into the project.

It employs one of the primary ingredients, which are frameworks such as TensorFlow and keras to develop and then train its CNN. Once trained on them, these models become rather effective in defect detection based upon the features that have been extracted from images. They can spot defects accurately in new PCB images. The analysis of the results obtained with these models will draw out patterns and trends that can bring about root causes of defects and a good amount of insight in regard to improved manufacturing.

For easy information access, a user-friendly dashboard is developed. The interface allows users to interact easily with the outcome of inspection results and produce a customized report about the object under test. In a general view, the structured workflow improves image processing and defect detection and provides critical insight into optimizing manufacturing practices.

4 TYPES OF DEFECTS UNDER TESTING

In a defective PCBs, there are some different types of defects which can be classified into the following categories

Fig 5 shows the PCB with pin-hole defect, it means drilling is missing at the point focused in image.

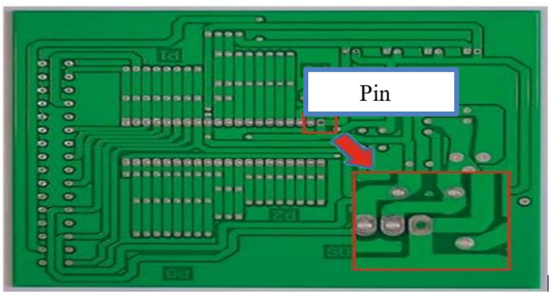

Figure 5: pin hole

An open circuit defect is illustrated in fig 6 which will highlight the breakage in the conductive path thereby circuit will not get closed and electricity will not flow through the circuit.

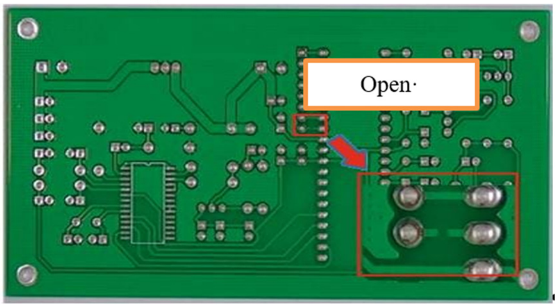

Figure 6: open circuit

Fig 7 shows the short circuit defect is due to the unintended connection between two separate conductive paths. Excessive current will flow the copper track and the track get may damage.

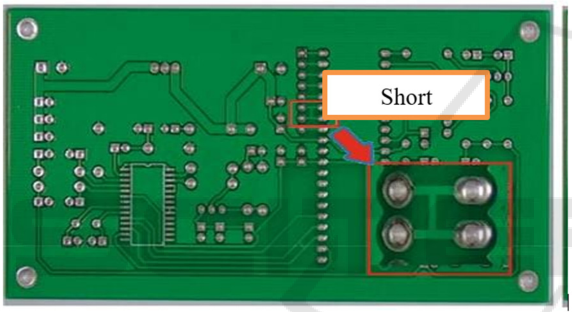

Figure 7: short circuit defect

Fig 8 shows the spur defect, in this an extra protruding conductor that shouldn't be there which can result in short circuit if in contact with other PCB elements.

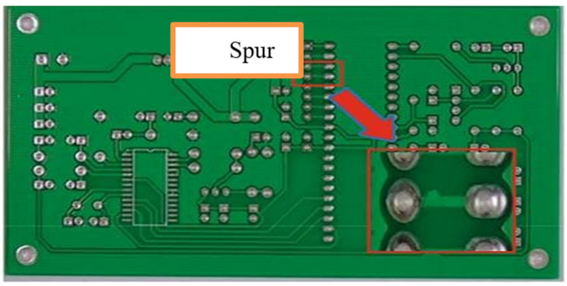

Figure 8: spur defect

An excessive copper defect is illustrated in fig 9 in this an unwanted copper left on the PCB after etching, it causes heating and damage to the circuit.

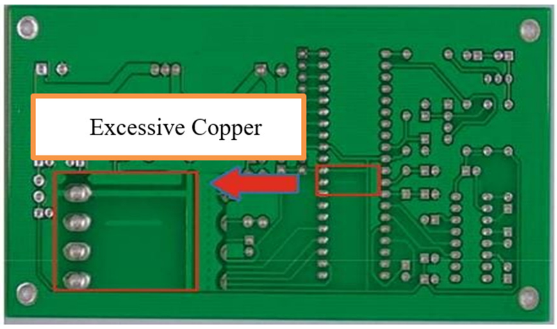

Figure 9: excessive copper defect

Fig 10 shows the mouse bite defects in this a small chunk of material missing from the edge of the PCB, resembling a "bite." mouse bite are capable of causing the performance of the PCB.

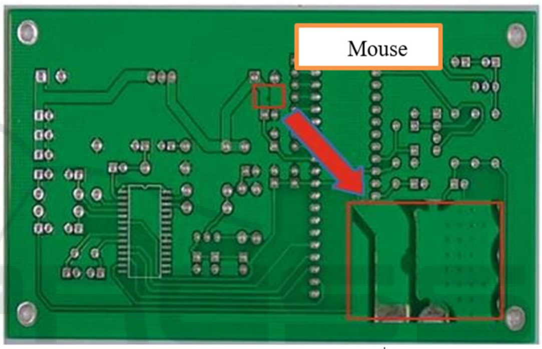

Figure 10: mouse bite defect

5 RESULT ANALYSIS

For testing purposes, single sided PCB images is taken for consideration and data set generated and tested under the proposed system. Following are the identified defects (Verma and Kumar, 2021).

5.1 PCB Without Defects:

Figure 11 shows the sample PCB to be tested. The system successfully captured high-resolution images of defect-free PCBs using image acquisition methods. Pre-processing of the images improves the quality of images and achieves a remarkable 99% accuracy in the identification of boards without defects, indicating that the system is highly reliable in validating integrity of the PCBs before production.

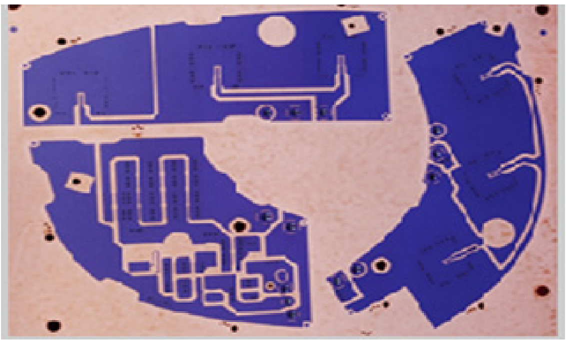

Figure 11: PCB Without Defect

5.2 Detection of Defect PCB:

In fig 12 we improved the image preprocessing techniques to improve the quality of images captured and thus image clarity. The system was able to detect defects, such as scratches and misalignment with an average detection accuracy of 95%. This means quick responses and thereby less production time is lost due to delays.

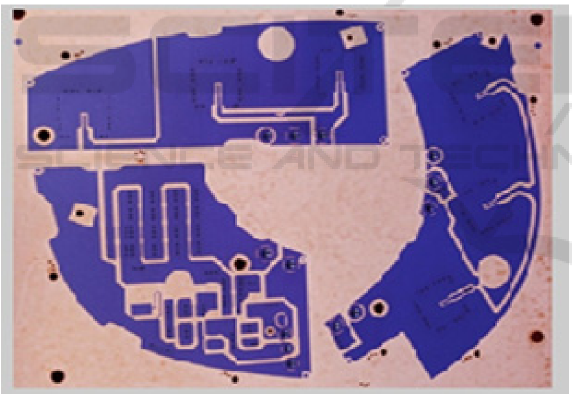

Figure 12: Defected PCB under test (Verma and Kumar, 2021)

5.3 Detection And Identification of Defect PCB:

In fig 13 for pinhole detection our proposed system carried out specific image analysis in the pre-processing stage, and so made it more sensitive. We have classified 90% accuracy for the pinhole defects. It allows the manufacturers to take immediate measures towards small critical flaws, ensuring high quality PCB production.

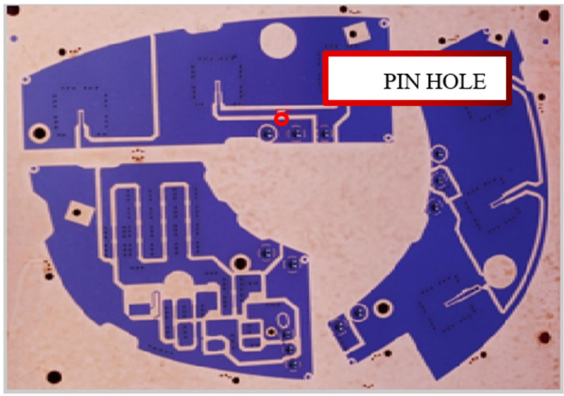

Figure 13: Pin hole defect detection

6 CONCLUSIONS

In summary, our proposed system proves to be impressive in successfully identifying the defects identified in AI based PCB inspection. Our system is effective in catching 99% of defect-free boards with almost the guarantee of a reliable preproduction validation process. By refining techniques in image preprocessing, we attained perfect defect detection accuracy for defects such as scratches and misalignments that minimize downtime in production. Such analysis helps a manufacturer quickly identify the critical issues in pinholes, with an accuracy of around 90%. All such improvements create enough assistance to a market leader in maintaining quality PCB productions along with frictionless manufacturing processes.

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