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PCB Defect Detection Methods: A Review of Existing Methods and Potential Enhancements

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Abstract

Printed Circuit Board (PCB) serves as the fundamental backbone of the modern electronics industry, providing essential support and connectivity for a wide range of electronic components within electronic devices. This research paper provides an overview of PCB defect detection techniques and different categories of defects. Various defects have been identified using current methods; however, certain defects persist undetected. This paper offers insight that can propel researchers towards innovations in this domain, coupled with a thorough exploration of potential enhancements. A total of twelve papers have been taken into account, and this survey examines the papers spanning from the years 2019 to 2023. The goal is to provide a comprehensive review of cutting-edge techniques, the models used, their accuracies, defects detected, and improvements, intending to advance the field of PCB defect detection. It also outlines potential avenues for further research, making it a valuable resource for researchers seeking to enhance this field in the future. The survey encompasses diverse detection techniques, which include algorithms based on the CNN, MobileNet, YOLO, SSD, and FPN models, etc. By comparing their accuracy, researchers can gain valuable insights into the effectiveness of each approach for different types of PCB defects. The paper also addresses the limitations of existing methods, identifying areas for improvement and future scope. In conclusion, this study is a valuable resource for researchers, engineers, and business professionals involved in the fields of electronics manufacturing and quality control. By consolidating a diverse range of techniques and insights, it paves the way for the development of more sophisticated, accurate, and cost-effective PCB defect detection techniques that guarantee the performance and dependability of electrical equipment in all industries.

Keywords: PCB, AIML, Deep learning

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1. Introduction

Finding PCB defects is a critical step in the electronics manufacturing process. PCBs are an essential component in various electronic devices, from small consumer electronics like smartphones to complex industrial systems. They serve as the platform to connect and support electronic components, ensuring proper functionality and interconnectivity. Any defects in PCBs can lead to malfunctioning or failure of the entire electronic system. Early detection and rectification of defects during the manufacturing process contribute to reducing costs, increasing product reliability, and meeting industry standards, ultimately benefiting both manufacturers and end-users. PCB are the backbone of electronic devices, enabling the efficient and reliable functioning of circuits. They are the foundation upon which electronic components are mounted and interconnected to create functional electronic circuits. Their role in providing mechanical support, electrical connections, signal routing, and heat dissipation is essential to the functionality and durability of electronic equipment. The customizability and cost effectiveness of PCBs also make them indispensable in the electronics industry. The purpose of conducting this survey is to discuss various types of PCB defects and their consequences. Additionally, we aim to explore current methods for detecting these defects, address the associated challenges, compare various models along with their accuracies, examine ongoing research directions, and outline potential future advancements in this field. Rest of the paper is organized as follows: section 2 contains types of defects, section 3 contains Methods for PCB defect detection, section 4 contains Literature review, section 5 contains research area, section 6 contains Future scope, while section 5 concludes the paper.

2. Types of defects

Table 1 indicates different types of defects and their information. Most of the defects are due to the soldering of electronic components on PCB.

3. Methods for PCB Defect Detection

PCB defects can occur during manufacturing and assembly processes, leading to potential malfunctions in electronic devices. Different techniques are employed to find these flaws, but the choice of technique depends on aspects such as the type of defect, the stage of manufacturing, the complexity of the PCB, and the available equipment and resources. Often, a combination of these methods is used to ensure comprehensive defect detection and quality assurance. Common methods for detecting PCB defects are discussed hereunder.

Visual Inspection

Manual Inspection: According to Caixia Wu et.al [1] trained technicians visually examine the PCB for soldering defects, misaligned components, and other visual

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abnormalities Visual inspection technology has become increasingly prevalent in industrial manufacturing, playing a pivotal role in enhancing production efficiency and intelligence. The Fig 1. shows manual inspection, to enhance the monitoring of sorting equipment, it's essential to conduct precise real-time monitoring of vital actuators and functional components during the sorting process. In conventional assembly line sorting, manual sorting is the primary approach. However, prolonged manual sorting by workers falls short of meeting the necessary standards, significantly impeding work efficiency and accuracy.

Table 1. Types of Defects

Sr. No	Type of defect	Information about that defect
1	Gaps In Solder Joints	Gaps often occur due to insufficient solder paste on the joint. Other causes include component misalignment, thermal shock, or vibration during soldering
2	Solder Balling	This issue is caused by the presence of impurities in the solder paste, such as oxides or contaminants. Solder balling can also be caused by too much heat during soldering.
3	Cold Solder Joints	This defect occurs when the solder joint is not heated to the proper temperature. Cold solder joints can also be caused by insufficient flux or too much heat during soldering
4	Solder Bridging	Bridging is a common soldering defect that occurs when two conductors are connected by a solder bridge. Often, this is caused by too much solder paste on the joint or component misalignment
5	Component Shift	This defect occurs when the component is not properly aligned before soldering. A component shift can also be caused by too much heat during soldering, which causes the component to move. While visual inspection can reveal this defect, automated inspection and testing are required to confirm it
6	Lifted Pads	Lifted pads occur when the solder mask or copper pad becomes detached from the PCB substrate. Other causes include thermal shock or vibration during soldering. This defect can also be caused by a faulty component. Automated optical inspection can be used to detect lifted pads.
7	Webbing And Splashes	Pollutants can sometimes cause webbing or splashes on the PCB. Webbing refers to thin solder connections between adjacent components or pads, while solder splashes involve excessive solder that has splattered onto unintended areas. These defects can be caused by poor solder paste quality, inadequate cleaning, or insufficient flux. The defects will affect the appearance of your printed circuit board and sometimes even cause short-circuit failures
8	Sunken Joints	Sunken joints occur when the solder does not adequately fill the space between the components and the PCB pads, leaving a depression or void in the solder joint. Sunken joints often happen during wave soldering when molten solder wicks up the lead before it can solidify.
9	Tombstoning	Due to a thermal imbalance, discrete components can sometimes stand up on one end during wave soldering. This is called tombstoning, and it can cause a short circuit or an open circuit
10	Shadowing	Shadowing also happens during waver soldering when surface-mount components do not make full contact with the solder. The result is an incomplete or poor connection, which can cause electrical problems, and functional testing is required to detect this defect.
11	Opens	An open solder joint occurs when there's an open connection between the lead and pad, or the point of connection with a PCB. This usually happens when the lead and the pad don't bond, or when the solder is only on the PCB but not on the component lead.
12	Excessive solder	When too much solder is used, large bubbles of solder can form at the joint. The joint itself could be functional, but the PCB could have hidden mistakes beneath the solder ball.
13	Missing solder	Solder paste not available (missing) on PCB pad
14	Solder short	Components short by solder paste
15	Less solder	Less amount of solder available on PAD
16	Missing component	Component not available
17	Tilt component	Occur due to nozzle wrong selection or nozzle blockage
18	Lift up (IC pin)	IC lead not soldered with PCB pad. occur due to using loose component
19	Upside down	Occur due to component flip over which has polarity
20	Wrong component	Occur due to wrong component selection
21	Scratches	The state in which there are scratches on PCB surface
22	PCB bend or warp	The case in which PCB has not been flat and has bends
23	Overheat blister	In the event of occurring ripples and overheat in the reflow oven and damaging in PCB component
24	Poor print alignment	Poor alignment is a PCB (Printed Circuit Board) defect that occurs when electronic components are not properly placed or aligned on the PCB during the assembly process. This defect can have various negative consequences, including electrical and mechanical issues, reduced product reliability, and increased production costs
25	Scooping	"Scooping" is a PCB (Printed Circuit Board) defect that typically occurs during the soldering or reflow soldering process. One common cause of scooping defects is related to the

		stencil used for applying solder paste. If the stencil is not properly aligned with the PCB or if it has defects, it can lead to inconsistent solder paste deposition.
26	Solder peaking	This defect involves the formation of raised or peaked solder joints on the PCB, often resembling small mountains or bumps.
27	Solder bleeding	This defect involves the unintended spreading or flowing of solder beyond the intended solder joints or pads, often leading to solder bridges or shorts between adjacent components or traces
28	Solder slump	This defect involves the unintended movement or shifting of molten solder away from its intended location, often leading to issues like insufficient solder joints, poor electrical connections, or even shorts.
29	Head in pillow	Solder on both the sides on the board itself and on component during reflow, and two solder areas move apart
30	Non wet open	Solder paste that was originally on the pad of the circuit board is sucked up on to the component side
31	Solder Flags/Spikes	Solder flags or spikes are due to inconsistent flux application. Poor control of separation from the solder wave would tend to be a random fault. The length of the pins is also excessive. Lead length should not exceed 1.5-2.0mm below the level of the board.
32	Cracked Join	The solder joint is on a single-sided board. The joint has failed due to expansion and contraction of the lead in the joint. shows a crack around the base of the fillet and has separated from the copper pad. This is most likely to be related to the basic solderability of the board. Lack of wetting between the solder and the pad surface caused this crack at the base of a fillet.
33	Flux Residues	Flux is a material used in soldering to facilitate the wetting and bonding of solder to the components and PCB. When used correctly, flux residues are typically minimal and do not cause problems. However, excessive or improperly managed flux residues can lead to various issues.

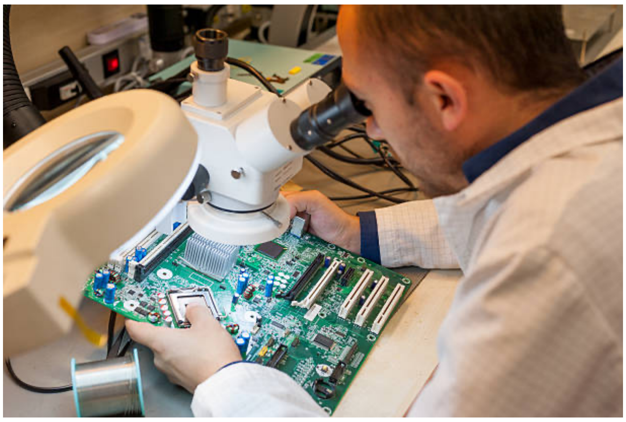


Fig. 1. Manual Inspection

Automated Optical Inspection (AOI): Quality monitoring is crucial in various industries to reduce product defects. As shown in Fig 2. Automatic Optical Inspection (AOI) is a commonly used method for this purpose, involving a wide array of subjects, including hardware, image acquisition, and decision-making algorithms. Many electronics manufacturers in Asia are integrating AOI systems to cut costs and avoid human errors. In this study, Abd Al Rahman M. Abu Ebayyeh [2] more than 300 articles were reviewed, highlighting the wide use of AOI in detecting defects in applications like semiconductor wafers, Flat Panel Displays (FPDs), Printed Circuit Boards (PCBs), and Light Emitting Diodes (LEDs). Hardware and software setups impact image quality and classification accuracy. Proper selection of image sensors and lenses is vital. Various inspection algorithms, involving preprocessing, feature extraction, and classification, are used. Learning-based algorithms, including machine learning and deep learning, offer advantages in defect detection accuracy but require substantial data and processing resources. While AOI has limitations in inspecting surface defects and fixed viewing angles, there are ongoing efforts to improve these systems. The technologies reviewed are being tested and implemented in an EU-funded project called IQONIC, focusing on optoelectronics defect inspection.

Fig. 2. AOI System

X-ray Inspection: Fig 3. shows Automated X-ray inspection which is a valuable tool for enhancing solder joint quality control in electronic manufacturing. C. Neubauer 4 et.al [3] states that this work introduces a hierarchical approach that combines 2- D and 3-D inspection methods for fast and precise testing. Most components are assessed using rapid 2-D inspection, while more accurate 3-D techniques, such as digital laminography, are used when components overlap. Neural network-based classifiers are employed for 2-D solder joint evaluation to identify defects. Various 2-D features and 3-D reconstruction techniques are explored. The current system's image processing speed allows for 100 percent inspection of boards, making it suitable for inline testing. Future efforts will focus on enhancing reconstruction and classification algorithms and developing new X-ray sensor concepts with high resolution and dynamic range. Additionally, X-ray inspection can be applied to tasks beyond solder joint assessment, such as identifying voids in heat conductive adhesives and inspecting connections based on conductive adhesive for applications like BGA. These tasks can be integrated into automated solder joint testing for specialized purposes.

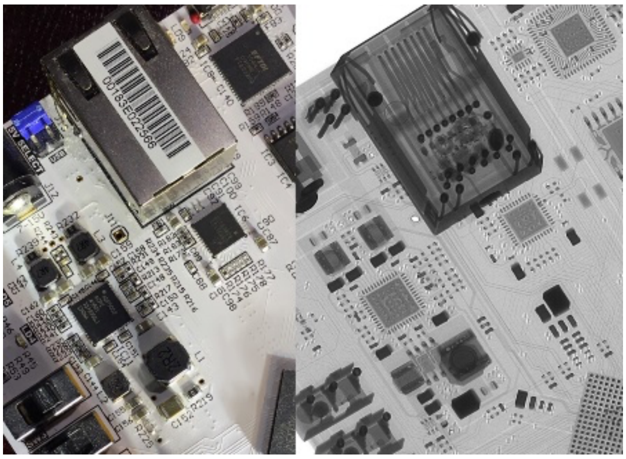


Fig. 3. X-ray Inspection

In-Circuit Testing: The above Fig 4. shows the image of In-circuit testing. The graph-based representation of a board design is a versatile tool for easily calculating false paths and impedances between specific nets. It can transform unreachable structures into reachable compound ones and break the graph into its biconnected components. These sub-graphs are used in the minimal guard set algorithm to identify all potential combinations of guarding vertices. This helps determine the maximum voltage that can be applied to a net using the original graph. Tests from a predefined library can be mapped to components in the Device Under Test (DUT). If a test matches a specific structure, the mapping can proceed. For cases not covered by the test library, a generic test method is developed, primarily performing impedance measurements, which effectively increases test coverage. Harm van Schaaijk et.al [4] stated the effectiveness of a proposed test can be optimized and guaranteed using PCOLA-SOQ properties. Tests that are dominated by other tests are automatically eliminated. The PCOLA-SOQ score serves as a well-defined metric for comparing and combining the effectiveness of different test equipment.

Fig. 4. In-Circuit Testing

Flying Probe Testing: In brief, existing PCB FPT testing falls short in achieving complete test coverage due to factors like restricted physical access and complex interconnections. This leads to components outside the FPT coverage area going unnoticed as we can see in Fig 5. Previous hybrid approaches attempted to solve this but faced challenges related to setup time, costs, and issues like image deformations affecting component registration and inconsistent lighting conditions. P. Radevet.al [17] in this paper introduces a novel concept, a hybrid FPT-AOI approach for PCB inspection. It leverages CAD-CAM files for acquiring component images and building a component database using FPT and AOI results. A new classification algorithm utilizing "eigen component" features to create component "models" was developed and tested. This system successfully handles severe image deformations, accurately classifying rotated components (up to 15 degrees in both directions) and components shifted up to 7 pixels in both horizontal and vertical directions. It performs well even under varying lighting conditions, occlusion, and Gaussian noise.

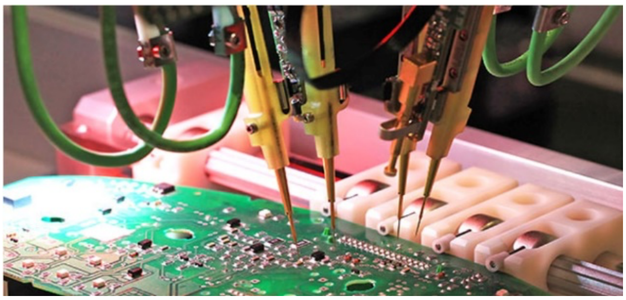


Fig. 5. Flying Probe Testing

Boundary Scan Testing (JTAG): The In-Circuit Tester (ICT) requires a significant number of physical test points on a PCB, leading to larger PCB sizes and high testing costs. There is a need for a cost-effective PCB testing technology that allows for smaller PCBs with simple design rules. The Fig 6. shows the solution of "Boundary Scan" which implements the IEEE1149.1 boundary scan test standard into ICs, significantly contributing to PCB miniaturization. H B Shashidhara et.al [5] in this paper focuses on applying JTAG boundary scan testing and developing a boundary scan test solution for the "Main Processor Unit" (MPU). The MPU comprises various components, including Altera's EP3C40 and EP3C25 FPGAs, Analog Devices' ADSP-BF548, and Marvel's 88E1111 PHY Boundary scan-compatible ICs. The experiments show that the boundary scan test solution for the MPU reduces test time from several hours to just 1 minute and 52 seconds compared to conventional testing. The paper also discusses the challenges of probing arising from device miniaturization and the drawbacks of ICT. Boundary scan technology has become the mainstream solution for addressing issues related to miniaturization, saving time in detecting structural or functional defects. It is accessible to both designers and test engineers.

Fig. 6. Boundary Scan Testing

Thermal Imaging: Developing a system for detecting faulty Integrated Circuits (ICs) is a significant challenge in the electronics industry. Excessive heat in ICs can lead to performance degradation and pose hazards to Printed Circuit Boards (PCBs). Thermal image processing shown in Fig 7. is non-contact, non-invasive method, proposed for IC fault detection. The paper focuses on identifying faulty ICs in PCBs using thermal imaging cameras and image processing techniques. Thermal images of a sequence detector circuit under various fault conditions are collected. Image matching is accomplished by comparing features in training and test images using the Speeded-Up Robust Features (SURF) algorithm. The system categorizes images into specific fault classes, offering enhanced accuracy and early fault prevention. Akshay A. Sarawade et.al [6] presents an efficient prototype method for identifying faulty ICs through thermal image processing of PCBs. The method achieves 100 percent accuracy in classifying test images with minimal computational time. By combining thermal cameras and the SURF algorithm, it can alert users to circuit faults. The approach can be automated using Internet of Things (IoT) technology.

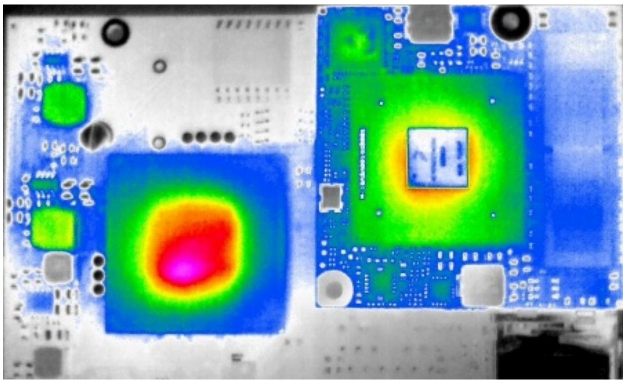


Fig. 7. Thermal Imaging

Ultrasonic Testing: Ye Zhu et.al [7] states that Ultrasonic waves are highly effective for detecting internal defects and have a broad range of applications. As shown in the Fig 8. the process of ultrasonic C-scan involves sending a short electrical pulse to generate an ultrasonic pulse from the transducer. Subsequently, the reflected signal from the test piece is received. The time it takes for the signal to return and its amplitude are then used to estimate the presence and size of defects. C-scan provides a two-dimensional projection of the test piece, where a transducer conducts a 2D scan on the surface of the test piece. This scan enables the acquisition of the 2D shape and distribution of defects within a specific depth range.

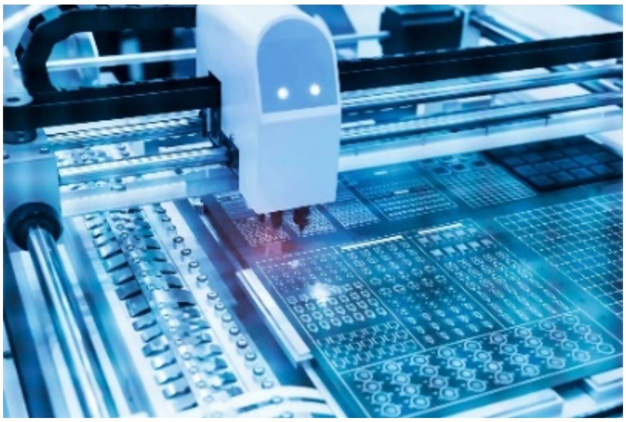


Fig. 8. Ultrasonic Testing

Automated Functional Testing: Bujanca Ana-Maria et.al[8] The author stated the technology is in a constant state of evolution, and the automotive industry is swiftly adapting to emerging trends. Subsequently, functional testing is conducted to assess a module's performance based on specified requirements, without delving into the module's internal structure. An automated testing tool has the capability to replicate pre-recorded and predefined actions, compare the outcomes against the anticipated behavior, and communicate the results, either success or failure, to a test engineer. Once automated tests are developed, they can be effortlessly repeated and expanded to execute tasks that would be unfeasible through manual testing methods.

Artificial Intelligence and Machine Learning: Wei Chen et.al [9] in this research introduces a novel hybrid network model for detecting PCB defects, departing from the commonly used target detection network model. It addresses issues with the current clustering algorithm to improve anchor box generation for the PCB defect dataset. The study employs an attention mechanism network to extract image features and enhances the interaction between the image feature extraction network and the feature detection network by incorporating an attention mechanism module. In summary, the network model developed in this study achieves the highest detection accuracy on public PCB datasets, surpassing current mainstream techniques, and is well-suited for industrial applications.

5. Literature Survey

There are various methods already available by which we can detect the defects in PCB. These existing methods are employed to ensure the quality and reliability of PCB. In our study, we reviewed several papers and have compiled the findings in this survey paper and Table 2 shows the comparison of different models. The paper offers an overview of the existing techniques and explores potential enhancements that can be implemented in this domain.

Guangzai-Ran et al. [10] presents an algorithm based on the SSD framework for defect detection and recognition on PCBs. The algorithm utilises multi-scale feature maps to customise boundary boxes of different scales and uses (3*3) convolution kernels for classification and boundary box prediction. Non-maximum suppression (NMS) is applied to optimise the detection results. Comparative experiments are conducted to demonstrate the algorithm's superiority. The results show a correct recognition rate of up to 94.69 for PCB defect types. However, the algorithm's performance in identifying and classifying small defects on PCBs is not yet optimal. Future work 8 will focus on improving the algorithm's ability to detect small PCB targets while maintaining quality in detecting multiple defects. This research emphasises the need for techniques or modifications that can handle the challenges of accurately localising and classifying smaller defects on PCBs.

Jianfeng-Zheng et al. [11] stated a method for detecting defects in PCBs using an improved fully convolutional neural network. The four typical defects that the study focuses on include spurs, mouse bites, short circuits, and open circuits. The process comprises improving training data as well as picture pre-treatment to highlight features, defect area extraction using image registration and difference operations, and defect area extraction. On the test set, the suggested method outperforms conventional

ResNet-50 and Vgg-16 pre-trained fully convolutional neural networks, with a high classification accuracy of 92.86. However, it is limited to the detection of only the four most common defects in PCBs. Future research could be directed towards identifying and detecting rare defects in PCBs. This may involve collecting a more extensive dataset that includes a broader range of defects, even if they occur infrequently in production.

To address the issue of low accuracy and efficiency in PCB defect identification utilizing reference methods, a Transformer-YOLO network detection model is developed [12]. To create anchor boxes appropriate for the PCB defect dataset, the model uses an improved clustering technique. Additionally, the suggested method improves detection accuracy by 23.9 when used in place of a conventional convolutional neural network for feature extraction. The suggested approach increases detection speed by 15.51 over the SSD network. Final results show that the model has a high detection accuracy of 97.04. The study demonstrates the effective use of deep learning methods in the area of PCB defect detection.

Author Wenkai-Huang et al. [13], It introduces the neighborhood correlation enhancement network (NCE-Net), a ground-breaking strategy that successfully makes use of defect and relationship information from the immediate environment to determine defects' authenticity. For more rapid and effective categorization of fictitious faults in industrial applications, NCE-Net additionally adds a short squeezing residual block (SRB) in addition to relevance residual blocks (RRBs) for establishing correlations between defects and their surroundings. The PCB-2-DET dataset is used to train the proposed lightweight high-precision detection approach, NCE-Net, which employs SRB and RRB modules for more accurate PCB defect identification. NCE-Net's attained accuracy is 92.59. Further improvements to the NCE-Net model's performance and speed could be made in future work, and the PCB defect classification dataset (PCB-2-DET) could be expanded to cover a wider variety of PCB flaws and more realistic real-world scenarios.

Utilizing polarization and infrared imaging sensors, this research [14] offers a novel multi-sensor picture fusion method for finding PCB defects. To gather a dataset of seven different types of faults under varying lighting circumstances, the authors construct a multi-source picture capture system. They suggest a Multisensor Lightweight Detection Network (MLDN) to find flaws that traditional optical inspection methods have trouble finding. This network combines polarization information with infrared and visible brightness intensities. The experimental results show an impressive accuracy of 96.2. This study contributes to advancing the field of defect detection and quality control in PCB manufacturing. Future research directions for the presented multisensor image fusion approach for PCB defect detection can include expanding the dataset to encompass a wider variety of defects and lighting conditions and optimization of the sensor configuration for better performance.

Table 2. Comparison Of Models

Sr No	Year of Publication	Problem statement	Model	Result	Advantages	Disadvantages	Improvement
1	2020	PCB defect detection and recognition algorithm based on deep convolutional neural network framework SSD	SSD (DL)	94.69	Compared with traditional target decision method, the defect recognition accuracy rate is greatly improved	The algorithm performance in identifying and classifying small defects on PCBs is not optimal	Ensuring the quality of multi target defect detection, focus on improving the ability to detect small PCB targets
2	2022	PCB defect detection method based on an improved fully convolutional neural network to detect four types of defects: spurs, mouse bites, short circuits and open circuits.	CNN and FCN based on MobileNet-V2 , ResNet-50 and Vgg-16, YOLO v3	92.86.	YOLO v3 has higher stability an accuracy of defect detection compared to ResNet-50 and Vgg-16, CNN and FCN	It is limited to only four common defects in PCBs	Collecting more extensive dataset that includes a broader range of defects
3	2023	In order to solve the problem of low accuracy and efficiency in PCB defect detection using Transformer-YOLO model	Transformer-YOLO	97.04	Achieves optimum detection accuracy on PCB public datasets and is better than the present techniques,	The main drawback of the method is the need for accurate alignment in space, otherwise the false detection rate is high.	The hybrid network model for PCB defect detection can continue to evolve and maintain its accuracy and efficiency in real-world applications.
4	2023	The neighborhood correlation enhancement network (NCE-Net), which effectively uses defect and surrounding relationship information to accurately distinguish defect authenticity.	NCE-Net method. SRB, LEL and RRB module.	92.59	NCE-Net gives better accuracy than SOTA	Defect identification cost is huge.	can contribute to the design of more effective defect capture modules and improve integration methods,

5	2021	Develop a system that combines data from multiple sensors to automatically identify defects in PCB.	MLDN (ML)	96.2	Improved detection compared to traditional optical inspection methods.	Sensor Costs, Generalization Challenges	More dataset with different variety of defects and lighting conditions
6	2023	Develop a probabilistic classification method using multiscale convolution for detecting defects in bare PCB	CNN	95.50%	High accuracy, advanced techniques for handling uncertainty and imbalance	Loss function and multiscale convolution can make model complex	Optimise the model for real time application
7	2022	Develop a PCB surface defect detection method using feature enhancement and multi-scale fusion for few-shot learning scenarios.	FPFM	69.52	Detects small-scale defects	Increase computational demands	Optimise the model's architecture and hyperparameters to enhance its performance.
8	2019	Detects defects on electronic surfaces using Fourier image reconstruction with templates.	Fourier Image Reconstruction	99.45	Not require extensive training data, which can be beneficial when data is limited.	Sensitive to noise	Noise Reduction
9	2022	Develop a Method for Finding Hard-to-See Defects in PCBs	FPN (DL)	96.2	Enhanced Accuracy and Visualization for small targets	Powerful processors and memory & expensive and time-consuming	Speeding up processing for real-time use
10	2022	Simplified YOLOX with Coordinate Attention for PCB Defect Detection	YOLOX (DL)	99.13	High Detection Speed of 47.6 FPS with Occupying Memory Space of 3.79M	More complex and difficult to troubleshoot	Reduce complexity and make easy to troubleshoot
11	2021	PCB Defect Detection Using Deep Learning Methods	FPN & SSD (DL)	SSD : 98.9 (PCB) 89.7 (Deep PCB) FPN : 96.4 (PCB) 92.7 (Deep PCB)	Two different models are trained and tested on two different dataset and provides high accuracy	Complexity increases as two models are trained also requires more time & storage	Reduce complexity and make faster and take less storage

The study [14] describes a technique dubbed "Multiscale Convolution-Based Probabilistic Classification for Detecting Bare PCB Defects." The strategy comprises creating a brand-new window-based loss function to deal with uncertainty and inter-class imbalance. With the aid of large-scale extraction features, it processes faults with intra-class variance using a multiscale convolution network. In order to make the final classification, the approach obtains classification probabilities and combines them into a multiscale probability matrix. The proposed methodology demonstrates superior performance compared to baselines in detecting bare PCB defects. Experimental results on practical bare PCB and HRIPCB datasets reveal accuracies of 98.6 and 95.5, respectively. Additionally, the approach offers improved detection performance, model complexity, and visual interpretability. Future work could be optimizing the model for real-time application on PCB inspection machines to ensure efficient defect detection during manufacturing processes.

The feature improvement module and the multi-scale fusion module are the two key modules that the authors of this work [15] have introduced. In order to highlight crucial regions of received feature maps and reduce extraneous data, the feature improvement module makes use of an upgraded version of the Convolutional Block Attention Module (CBAM). The objective is to improve the way that features are represented in the data. A multi-scale feature fusion approach is suggested to deal with the problem of finding minor PCB flaws. With this method, feature maps at various scales are extracted from the PCB data and combined to provide a high-quality feature map with data from several scales. The model can achieve improved detection precision for tiny object faults because to the integrated feature map. Future work could focus on optimizing the model's architecture and hyperparameters to enhance its performance even further.

Specifically for electronic surfaces, the work [16] introduces a global Fourier image reconstruction method for locating and identifying minute flaws in nonperiodic pattern images. The technique involves comparing the inspection image's Fourier spectra to the template image's whole Fourier spectrum. It recognizes and keeps the frequency components connected to the local spatial anomalies while discarding the common patterns that signify the uniform surface. The method reconstructs the test image while highlighting the local anomalies using the inverse Fourier transform. The suggested method can identify minute flaws in a variety of nonperiodic patterns typically encountered in the electrical industry that are as small as 1-pixel wide and is translation and illumination invariant. The global Fourier image reconstruction method presented in the paper offers a robust and effective approach for defect detection in electronic surfaces. It leverages the power of Fourier analysis to identify and localize small defects within complex and nonperiodical patterns. Researchers can explore refining the Fourier-based algorithm to improve its accuracy and efficiency. Fine-tuning parameters, exploring different Fourier transform variants, and incorporating advanced signal processing techniques may lead to better defect detection performance. An innovative technique for PCB flaw detection is presented in this study [17] and is based on an extended Feature Pyramid Network (FPN) model. The method uses the ResNet-101 backbone in part to precisely discover and pinpoint tiny flaws. The technique improves detection performance by combining low-level geometric information with high-level semantic information in a feature layer. Utilizing the focus loss function during training helps minimize overfitting. Additionally, to improve the original dataset, data augmentation methods such image cropping and rotation are used. The outcomes show improved performance, outperforming state-of-the-art techniques and obtaining a mean average precision (mAP) of 96.2 on a public PCB dataset. Dataset expansion, transfer learning, architecture tweaking, ensemble approaches, real-time implementation, and fault classification are some potential areas for advancement and investigation. By addressing these aspects, researchers can enhance the model's accuracy, efficiency, and applicability in diverse scenarios, ultimately advancing quality control in the electronics manufacturing industry.

The paper [18], introduces YOLOX-MC-CA, a lightweight deep-learning-based network for PCB surface defect detection. The proposed model combines the YOLOX architecture with a modified CSPDarknet backbone and integrates the coordinate attention (CA) mechanism to enhance small defect recognition. The modified CSPDarknet backbone reduces parameters while maintaining strong feature extraction capabilities. Experimental results show that YOLOX-MC-CA outperforms state-of-the-art (SOTA) networks for PCB defect detection, achieving a remarkable 99.13 mAP (mean average precision) and a high detection speed of 47.6 FPS (frames per second), all while occupying only 3.79M memory space. Furthermore, the model's efficient memory usage makes it an attractive solution for real-world applications in the electronics manufacturing industry.

In [19], It focuses on PCB defect detection using deep learning methods. Two classic target detection algorithms, FPN (Feature Pyramid Network) and SSD (Single Shot Multibox Detector), are applied to the task. Experimental results demonstrate that both methods achieve excellent performance on two different datasets. FPN's inverted pyramid structure makes it more suitable for small target detection, leading to better results overall. In conclusion, the study explores the application of deep learning methods for PCB defect detection, employing FPN and SSD algorithms. The results show that both methods perform well on the respective datasets. The researchers can explore and develop more advanced deep learning architectures tailored specifically for 11 PCB defect detection.

Table 3. Abbreviations

Abbreviation	Definition
SSD	Single Shot Detector
NMS	Non-maximum suppression
ResNet	Residual Network
Vgg-16	Visual Geometry Group with 16 layers
YOLO	You-Only-Look-Once
NCE-Net	neighborhood correlation enhancement network
RRBs	relevance residual blocks
SRB	squeeze residual block
MLDN	Multisensor Lightweight Detection Network
CBAM	Convolutional Block Attention Module
FPN	Feature Pyramid Network
mAPs	mean average precision
YOLOX-MC-CA	YOLOX with a modified CSPDarknet and coordinate attention
SOTA	state-of-the-art
AOI	Automated optical inspection

Table 3 presents a comprehensive list of abbreviations for key terminologies utilized throughout the survey paper.

This research [20], aimed to develop an automated optical inspection system using machine vision to detect micro-size defects in PCB assemblies. The system utilized LabVIEW programming with the OpenCV Library, connecting a Raspberry Pi board to a USB microscope camera. The focus was on monitoring copper leakage along the edges of the PCB assembly. The primary outcome was the creation of a prototype system capable of real-time monitoring and inspection of micro-size defects in printed circuit boards. Future research will concentrate on improving the system for industrial applications, aiming for real-time and accurate detection in the actual manufacturing process of micro parts and products. The focus will be on enhancing the AOI application to enable thorough examinations in IC inspections during production, thereby making it suitable for large-scale industrial use.

5. Research Areas

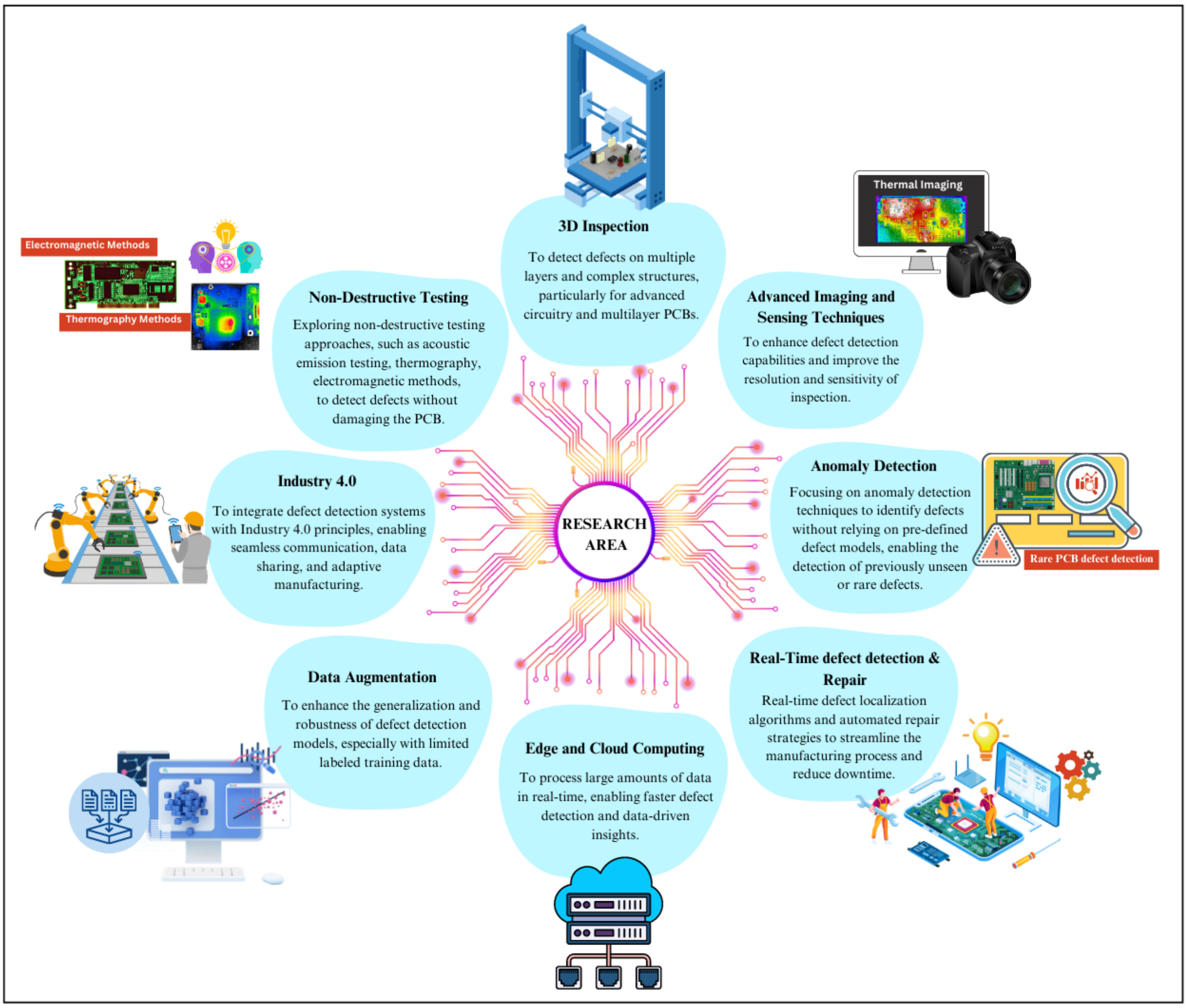
The methods for detecting PCB defects as of today are shown in Fig. 9. It is impossible to overestimate the significance of PCB defect detection techniques because they are essential to assuring the effectiveness, dependability, and quality of electronic equipment. There are several methods used for detecting defects in PCBs, each with its own advantages and limitations. Researchers can focus on the following aspects to advance the field and meet the demands of the electronics manufacturing industry. As shown in the figure, some key research areas in this field include Advanced Imaging and Sensing Techniques, AI and ML, Multimodal Fusion, 3D Inspection, Edge and Cloud Computing, AOI Improvements, Data Augmentation, and Industry 4.0 Integration.

1. Advanced Imaging and Sensing Techniques: The advancement of image sensors and the potential uses of advanced imaging and sensing technologies offer the promise of enhancing our quality of life. The progression of imaging technology continues to evoke human emotions through the capture of beautiful images. Sensing technology has also emerged to enhance our society by providing valuable data extracted from various scenes.

Yusuke Oike et.al[21] in this paper stated that the market for mobile imaging is being driven by technologies like pixel scaling and stacked device integration. Furthermore, significant progress has been made in practical applications of sensing technologies, including depth sensing, event-based vision sensing, and invisible light sensing. With the evolution of stack integration, the integration of edge AI into image sensors is expected to introduce new possibilities and increase scalability and flexibility in process technology. Image sensor technologies are expanding their sensing capabilities with the goal of creating a safer and more comfortable world that benefits people worldwide in their daily lives.

2. 3D Inspection: As per Zhifang Fu et.al [22] the Printed Circuit Boards (PCBs) serve as the fundamental platform for numerous electronic components in electronic devices. The quality of PCBs directly influences the performance of electronic devices, making it essential to perform defect detection during PCB assembly. Traditional methods for detecting defects are both inefficient and costly, making them unsuitable for meeting the demands of large-scale PCB inspection at this stage. Three-dimensional reconstruction, offering the advantages of being non-contact and swift, is gradually finding application in PCB defect detection. However, the conventional point cloud generation approach struggles to accurately identify defects closely linked to components, leading to potential instances of missed detection. To address this issue, the Iterative Closest Point (ICP) point cloud alignment optimization method proves effective. Initially, the point cloud is aligned in pairs, with the third piece aligned based on the successful alignment of the first two pieces, and so on. This sequential alignment process helps ensure that the 3D morphological characteristics of the point cloud are preserved while efficiently eliminating redundant data points. Duplicate points are removed, and non-overlapping sections are superimposed to enhance and optimize the point cloud model.

3. Anomaly Detection: Anomaly detection serves a valuable purpose by identifying unexpected patterns, commonly referred to as outliers. Sonali B. Wankhede et.al[23] states this technique is crucial for pinpointing unusual patterns in network traffic, which could potentially indicate a system breach, or in health monitoring, akin to detecting a malignant tumor within an MRI scan. Machine learning algorithms are applied to assess historical attacks and formulate suitable defense strategies. These algorithms scrutinize the navigation paths of a specific source or website, verifying the security standards of web application services. They can also identify, and flag malicious websites directed towards specific destination paths.



3D Inspection
To detect defects on multiple layers and complex structures, particularly for advanced circuitry and multilayer PCBs.

Non-Destructive Testing
Exploring non-destructive testing approaches, such as acoustic emission testing, thermography, electromagnetic methods, to detect defects without damaging the PCB.

Advanced Imaging and Sensing Techniques
To enhance defect detection capabilities and improve the resolution and sensitivity of inspection.

Industry 4.0
To integrate defect detection systems with Industry 4.0 principles, enabling seamless communication, data sharing, and adaptive manufacturing.

Anomaly Detection
Focusing on anomaly detection techniques to identify defects without relying on pre-defined defect models, enabling the detection of previously unseen or rare defects.

Data Augmentation
To enhance the generalization and robustness of defect detection models, especially with limited labeled training data.

Real-Time defect detection & Repair
Real-time defect localization algorithms and automated repair strategies to streamline the manufacturing process and reduce downtime.

Edge and Cloud Computing
To process large amounts of data in real-time, enabling faster defect detection and data-driven insights.

Fig. 9. State-of-the-art techniques for finding PCB defects

4. Edge and Cloud Computing: Around 2005, Cloud Computing gained significant popularity. This concept of storing, processing, and managing data in the cloud has brought about a substantial transformation in the way we work and live. Notably, platforms like Facebook, Twitter, WhatsApp, Google Apps, and others have become integral parts of our daily lives. The Internet of Things (IoT) emerged in 1999 with the idea of making various objects intelligent enough to collect and process data, enabling them to function autonomously without human intervention. However, cloud computing, despite its efficiency, may face limitations in handling the vast amount of data generated by IoT. To address this limitation, the concept of edge computing has emerged. Saksham Mittal et.al[24] described Edge computing as the practice of processing data at the network's edge. In simpler terms, it involves processing data as much as possible at the network's edge since data is often generated in large quantities at the edge, and then sending the processed data to the cloud.

5. Non-Destructive Testing (NDT) Methods:
Infrared (IR) thermography: In industries across various sectors, Infrared (IR) Thermography has emerged as a dependable method for thermal assessment. Soumitra K. Ghosh et.al[25] indicates that IR cameras produce thermal profiles of objects, effectively identifying any unusual heat patterns with precision. Utilizing image processing techniques, subsequent modifications are possible. Multiple manufacturers offer camera systems, each with distinct advantages and drawbacks in their products. Determining the superior system is complex and not straightforward due to varied merits. Additionally, for users predominantly from non-photonics industries, the technical terminology further complicates the selection criteria. This paper aims to elucidate the specifications of an IR Imaging System.

X-ray inspection: The X-ray inspection system is a well-established and efficient non-destructive testing (NDT) method primarily employed to identify internal flaws within specimens. Kongjing Li et.al[26] explained in this process, an X-ray source emits X-radiation to penetrate the specimen and create an X-ray image. The X-radiation is received by a detector in areas where internal flaws such as voids or cracks are present, as these flaws do not absorb X-radiation. Conversely, flawless areas result in lower radiation intensity detected because some of the energy is absorbed by the materials. One notable advantage of X-ray testing lies in its high testing efficiency and the ability to provide real-time images. This real-time capability is particularly valuable in production lines, as it eliminates the need for any additional preparations for the devices under test (DUTs).

6. Data Augmentation and Preprocessing: While machine learning (ML) techniques have gained traction in the development of autonomous optical networks, there has been a notable lack of emphasis on the importance of data quality, a critical factor affecting ML performance. When it comes to using ML for failure management in optical networks, a challenge arises from the fact that certain failures may occur more frequently than others, leading to highly imbalanced datasets when training ML models. Lareb Zar Khan et.al[27] mentioned to address this issue, a data augmentation technique based on variational autoencoders can be employed in the data preprocessing stage to enhance data quality. This technique generates synthetic data using the variational autoencoder, which can then be used to mitigate the imbalance in an experimental dataset used to train neural networks (NNs) for failure management in optical networks.

7. Real-Time Defect Localization and Repair: Given the widespread use of software applications in our daily lives, ensuring the accuracy of their functions is a top priority for software developers. Author J. S. Collofello and L. Cousins et.al[28] involves two key activities in the debugging process: fault localization (identifying where faults are located) and repair (designing and implementing code fixes). Conventional fault localization methods, such as analyzing program logs, introducing breakpoints, 15 or using assertions in the program, are straightforward and commonly employed by software developers. On the other hand, Spectrum-Based Fault Localization (SBFL) techniques operate by identifying the program portion whose behavior is most closely related to error detection. In other words, SBFL techniques take the source code and a test suite as inputs and then generate a ranked list of code statements for review. This approach is effective and lightweight in nature.

8. Industry 4.0 Integration: from the point of view of author Alfredo Alan Flores Saldivar et.al [29] the field of design and manufacturing is currently undergoing a transformative shift, with a focus on innovation, cost reduction, improved responsiveness to customer needs, optimal solutions, intelligent systems, and the exploration of on-demand production methods. In the contemporary landscape, driven by advancements in digitalization and the internet, the realization of "smart manufacturing" and "smart factories" is becoming a tangible reality. This involves the integration of the physical manufacturing processes with their virtual counterparts in cyberspace through cloud service providers (CSP) and the Internet of Things (IoT). This integration is further extended to the Internet of Systems (IoS). In this new paradigm, businesses are establishing global networks that encompass their machinery, warehouse systems, and production facilities, forming a cyber-physical system. Within this system, there are "smart machines," storage systems, and production facilities that have the capability to autonomously exchange information, initiate actions, and independently control one another By focusing on these potential areas of improvement, researchers can elevate the accuracy, efficiency, and applicability of PCB defect detection methods, ultimately enhancing quality control and reliability in the electronics manufacturing industry.

6. Future Scope

Fig.10 shows future scope, researchers can focus on the following aspects to advance the field and meet the demands of the electronics manufacturing industry.
Dataset Expansion and Transfer Learning: Expanding and diversifying the training datasets can improve the model's generalization and robustness. In order to use pre-trained models on big datasets and improve them for PCB defect detection tasks, transfer learning techniques can be investigated.
Fine-Tuning Architectures and Ensemble Methods: Fine-tuning existing deep learning architectures and exploring ensemble methods can lead to improved accuracy and reliability in detecting defects, particularly small and subtle ones.

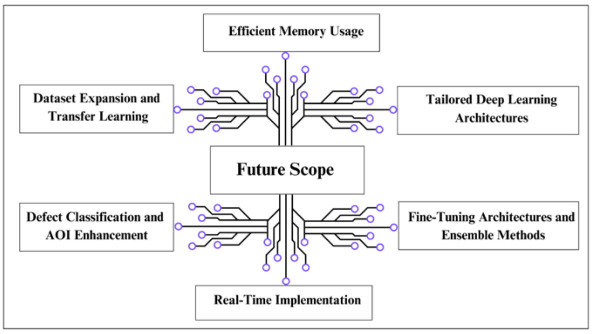


Fig. 10. Future Scope

Real-Time Implementation: Emphasizing real-time implementation is crucial to enable prompt defect detection during the actual manufacturing process. Developing efficient algorithms and hardware solutions will ensure the model's applicability in industrial settings.

Defect Classification and AOI Enhancement: Enhancing defect classification capabilities will enable the system to accurately categorize various defect types, streamlining the quality control process. Further, advancing automated optical inspection techniques will allow comprehensive and efficient IC inspections during large-scale production.

Efficient Memory Usage: Optimizing memory usage will make the model more suitable for real-world applications, where resource constraints may exist in the electronics manufacturing industry.

Tailored Deep Learning Architectures: Researchers can focus on developing specialized deep learning architectures specifically designed for PCB defect detection, considering the unique characteristics and challenges of this domain.

7. Conclusion

During this study, numerous papers were examined, revealing a variety of methods for detecting defects in PCBs. However, it was evident that further improvements are necessary to deploy the introduced model effectively in real-time analysis. The limited defect detection capabilities and a lack of sufficient training datasets present notable challenges. Within the scope of this research, it became evident that small defect detection methods require additional enhancements to attain higher accuracy. Moreover, the field of PCBA (Printed Circuit Board Assembly) defect detection demands attention to achieve enhanced accuracy and speed in the detection process.

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