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State of the art on methods for automatic detection of defects on PCBs

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State of the art on methods for automatic detection of defects on PCBs

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***Abstract*—Visual inspection systems(VIS) are essential for ensuring the quality and the reliability of products in many fields including the electronic manufacturing industry. This article focuses particularly on reviewing the advancements of printed circuit boards (PCBs) visual inspection technology, emphasizing three key aspects: the contribution of the innovative imaging types, the capability of the advanced image processing techniques, and the recent need of integrating artificial intelligence (AI) models. The paper also explores industrial applications, mentioning the current challenges and future research directions.**

I. Introduction

Automated visual inspection (AVI) systems have revolutionized the quality control process in modern electronic manufacturing, particularly for printed circuit boards (PCBs). Traditional manual inspection methods are labor-intensive, time-consuming, and prone to human error, making them inefficient for ensuring the high standards required for electronic devices. AVI systems leverage advanced imaging technologies, such as high-resolution optical imaging, X-ray imaging, and thermal imaging, combined with sophisticated image processing techniques and machine learning algorithms to detect and classify defects on PCBs swiftly and accurately. By employing methods like edge detection , image segmentation and utilizing convolutional neural networks (CNNs) for feature extraction and classification, these systems can achieve remarkable precision and speed. The integration of real-time processing capabilities further enhances their effectiveness, making AVI systems indispensable for maintaining the reliability and longevity of electronic products in today's market.

II. PCB visual inspection system overview

A visual inspection system in PCB manufacturing is an automated system that uses cameras, lighting, and image processing software to examine product quality. It detects defects, ensures accurate component placement, and verifies solder joints, performing detailed inspections more efficiently than human inspectors manually examining can do . The main components of a visual inspection system are:

- The cameras are the crucial sensors that capture detailed images or other forms of data from the products being inspected. Different types of cameras are used based on the specific requirements of the inspection task, including high-resolution[1] infrared, 3D , and X-ray cameras. Each type of camera offers unique capabilities that make it suitable for detecting various kinds of defects and features.Next section presents an overview of the different types of cameras used as sensors in visual inspection systems.
- The image processing software represents the core intelligence behind visual inspection systems for PCBs, enabling the analysis and interpretation of the images captured during manufacturing. Utilizing complex algorithms and filters, the software meticulously examines these images, distinguishing between acceptable variations and actual defects. By leveraging image processing methods such as the edge detection , the image segmentation and the artificial intelligence models.

III. Advanced Imaging Techniques for PCB Inspection

Advanced imaging techniques have become indispensable in the visual inspection of PCBs, providing enhanced accuracy and efficiency in defect detection. Techniques such as high-resolution imaging[1], 3D imaging[2], Automated Optical Inspection (AOI) and infrared imaging[3]in addition to X-ray inspection[4] , enable the identification of various defects, from surface-level issues to hidden internal flaws as it is detailed below.

- High-Resolution Imaging offers detailed and precise capture of board surfaces to facilitate comprehensive defect detection. By employing cameras with high pixel density, these systems can discern minute flaws, such as micro-cracks and soldering defects, ensuring stringent quality control standards are met throughout the manufacturing process.
- Infrared imaging enables the detection of thermal anomalies such as overheating components or areas with excessive current flow, which may indicate potential failure points or design flaws. By identifying these issues early in the manufacturing process, infrared imaging helps prevent high cost defects and ensures the reliability of the final product[3].

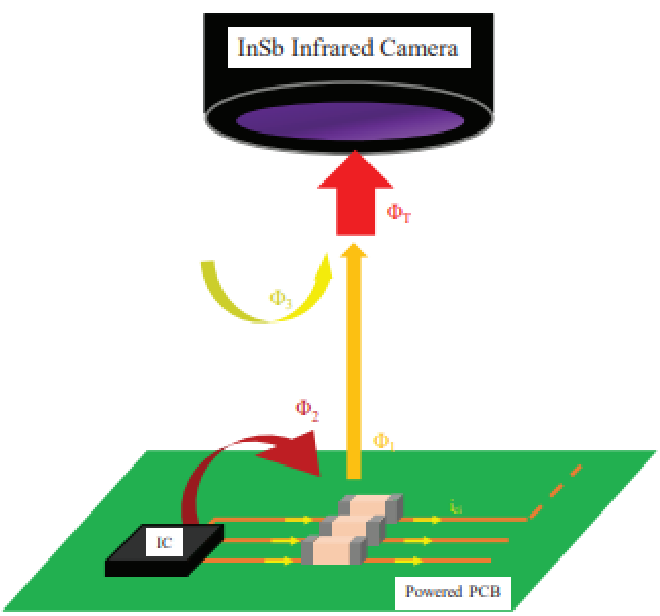

Fig. 1. Infrared Technology for Enhanced PCB Inspection

- 3D imaging enables precise measurement and verification of component placement, ensuring that components are correctly aligned and oriented according to design specifications. By comparing the captured 3D images to the expected positions of components, these systems can detect deviations and misalignments, facilitating corrective actions before assembly is completed. Furthermore it yields thorough inspection of solder joints, enabling the assessment of their height, volume, and uniformity. This capability is particularly valuable for detecting defects such as insufficient or excess solder, solder bridges, and non-wetting, which may compromise the electrical conductivity and reliability of connections. By accurately measuring the dimensions of solder joints in three dimensions, 3D imaging ensures the quality and the integrity of the soldering process[2].

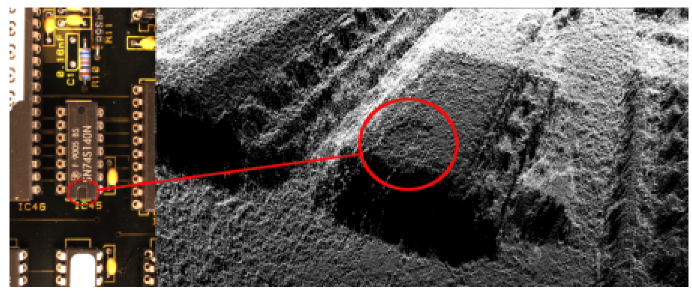

Fig. 2. 3D Modeling Techniques for PCB Visual Inspection Systems

- X-Ray imaging enables rigorous inspection of solder joints, particularly those hidden beneath surface-mounted components or within multilayer PCBs. The fig.3 shows how X-ray imaging is used in PCB visual inspection systems to check the alignment of holes in a multilayer PCB. The top view displays the placement of holes on the surface, while the side view shows their alignment through the layers. This helps ensure that the holes are properly aligned, which is important for electrical connections and the quality of the PCB. [4]

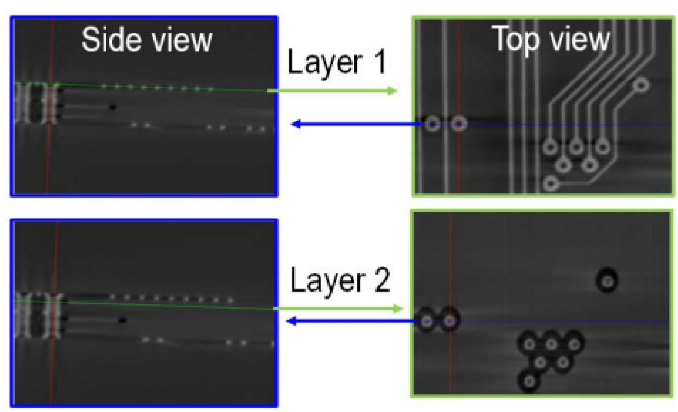

Fig. 3. X-Ray Technology in PCB Visual Inspection Systems

IV. Advanced image processing techniques

Advanced image processing techniques are methods used to analyze images of circuit boards to detect defects and ensure quality. These techniques include edge detection to identify component boundaries and pattern matching to find specific shapes. By processing images in these ways, the visual inspection system can accurately check for issues like misaligned parts, missing components, and soldering defects, ensuring reliable and high-quality PCBs.

A. Edge Detection techniques

A large PCB image is acquired . It is often dark and noisy due to various factors during acquisition. Therefore, preprocessing steps like median filtering (to remove noise) and homomorphic filtering (to correct image blurring) are crucial. The combination of gray redundancy removal and gray scale transformation enhances the image, improving brightness and clarity.

Edge information is detected using an adaptive iterative threshold selection algorithm, yielding continuous edges with clear boundaries and minimal noise, Fig.4 shows the application of an edge detection technique on a PCB, clearly highlighting the boundaries of each component[5].

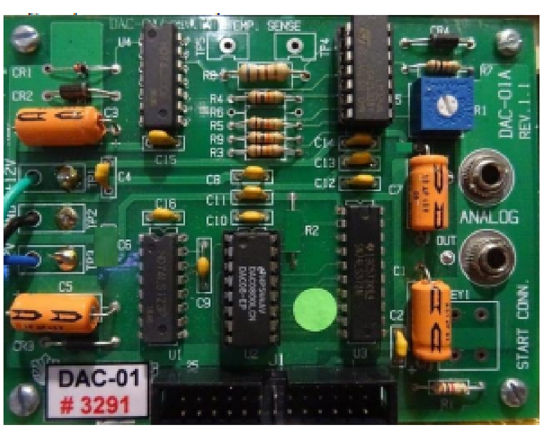

Fig. 4. High resolution PCB image

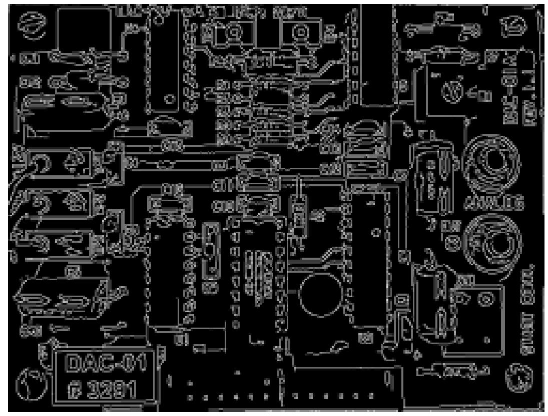

Fig. 5. Advanced Edge Detection of the PCB image

Sobel and Canny edge detection are fundamental techniques in image processing for identifying edges in digital images.

1) Sobel Edge Detection in PCB Visual Inspection: Sobel edge detection is a fundamental technique used in PCB VI to identify edges by calculating the gradient of the image intensity. This method utilizes convolutional kernels to detect gradients in both the x and y directions, which helps highlight areas of high spatial frequency that typically correspond to edges. In PCB inspection, Sobel edge detection is useful for identifying defects such as cracks or incomplete etching. Its simplicity makes it easy to implement, but it can struggle with noise, producing thicker and less smooth edges compared to more advanced methods like Canny[6].

2) Canny Edge Detection in PCB Visual Inspection: Canny edge detection is a more sophisticated technique employed in PCB VI for its superior accuracy in detecting fine edges and details, even in noisy environments. The Canny method involves several steps: noise reduction using a Gaussian filter, finding the intensity gradient, non-maximum suppression, and edge tracking by hysteresis. This comprehensive process results in thin, smooth, and continuous edges, making it effective for identifying subtle defects such as hairline fractures and micro-corrosions. While Canny is computationally more intensive than Sobel, its ability to produce precise and noise-resistant edge detection makes it the preferred choice for high-precision PCB inspections [6].

B. Image Segmentation techniques

Image segmentation is a technique used in image processing that involves dividing an image into distinct regions or segments to simplify and change the representation of an image, making it easier to analyze and detect specific features.

Threshold segmentation with transition areas :

In PCB image analysis, threshold segmentation with transition areas is crucial when grey levels of objects are close to each other. To enhance contrast, the top-hat transformation, which highlights bright regions (grey peaks) by subtracting the morphologically opened image from the original, is used alongside the bottom-hat transformation, which highlights dark regions (grey valleys) by subtracting the original image from the morphologically closed image. The enhanced image is obtained by adding the original image to the top-hat transformation. This enhanced image is then compared to the bottom-hat transformation to maximize contrast. The maximum contrast image is subjected to thresholding to create a binary image that clearly distinguishes regions of interest, such as solder joints, from the background. Finally, morphological opening and closing are applied to the binary image to refine the segmentation, removing noise and preserving essential features. This method effectively retains the original characteristics of the soldered dots, enhancing the accuracy and convenience of subsequent morphological inspections.

The Fig.5 depicts various stages of processing for a PCB image to enhance and extract important features. Starting with (a) the original image, which shows the raw, unprocessed details of the PCB including traces, pads, and any noise or defects. The next image (b) illustrates the result of a top-hat transform, a morphological operation that enhances small, bright features on a dark background, highlighting elements like solder pads and fine traces. Image (c) represents the low cap shear transform, a likely specialized filtering or morphological operation designed to emphasize specific characteristics, such as reducing noise or enhancing contrast in certain regions. The transformation shown in (d) maximizes the image contrast, making features and defects more distinguishable, possibly through techniques like histogram equalization or contrast stretching. Image (e) displays the result of a close operation, which fills small holes and gaps in the bright areas, merging close features and filling imperfections through dilation followed by erosion. Finally, (f) shows the outcome of an open operation, which removes small objects from the dark areas, eliminating noise and artifacts by performing erosion followed by dilation. Each transformation serves to preprocess and enhance the PCB image for more effective feature extraction and defect detection.[7]

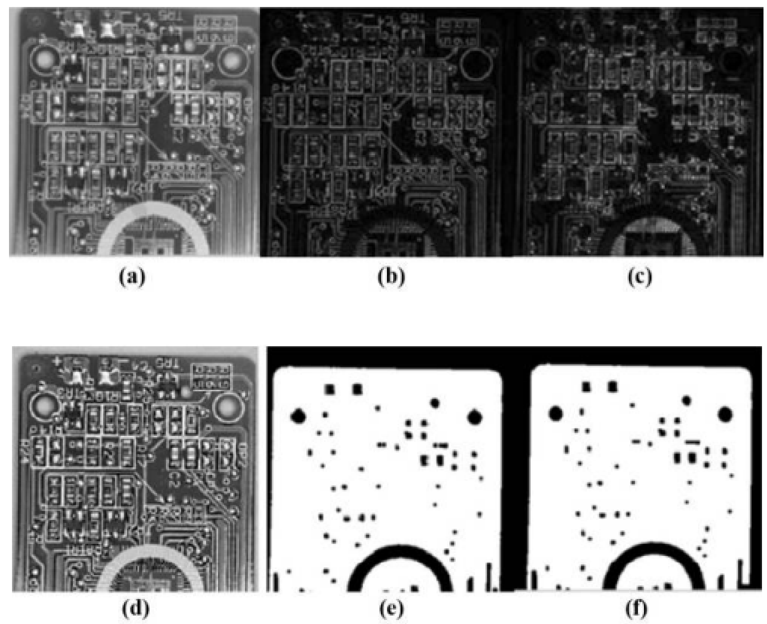

Fig. 6. (a) the original image (b) top hat transform (c) low cap shear transform (d) the image with maximum contrast (e) the close operation (f) the open operation

V. Artificial Intelligence in Visual Inspection Systems for Printed Circuit Boards

AI in VIS for PCBs employs advanced algorithms to autonomously analyze images, effectively detecting and categorizing defects with precision, thus enhancing manufacturing quality and efficiency. In this section, we are going to discuss the applications of AI in defect detection on PCBs and component recognition.

A. PCB defect detection algorithm based on CDI-YOLO

Integrating AI for defect detection in PCBs provides superior accuracy and efficiency compared to traditional methods.

YOLO (You Only Look Once) is a real-time object detection system that employs a single neural network to analyze entire images, predicting bounding boxes and probabilities for objects simultaneously, renowned for its speed and accuracy in object detection.

YOLOv7-tiny enhances defect detection on PCBs by integrating the Coordinated Attention (CA) module. This module improves the identification of small and subtle defects through processes like Coordinate Information Embedding for detailed feature mapping and Coordinate Attention Generation using convolution to highlight critical features. Additionally, YOLOv7-tiny employs Depthwise Separable Convolutions (DSConv) for efficient feature extraction and reduces computational complexity. The use of Inner-Complete Intersection over Union (Inner-CIoU) as the loss function further accelerates and enhances the accuracy of defect localization [8].

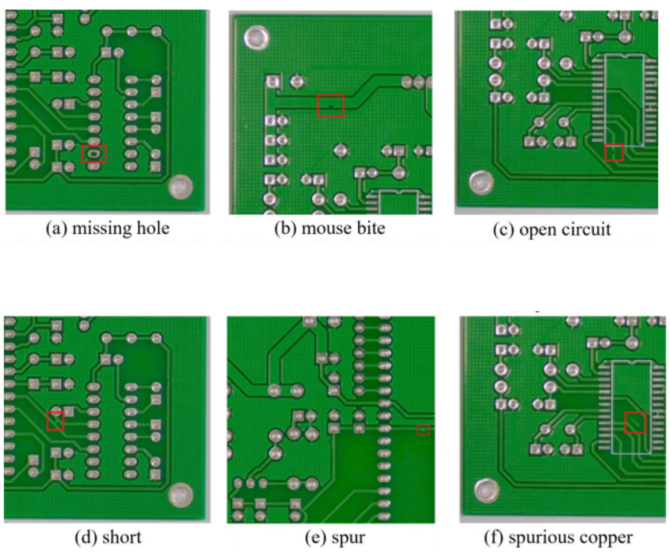

Fig. 7. AI-Powered Defect Detection in PCB Inspection.

In Fig.6 we can find a the following deffects A missing hole disrupts proper component mounting or connection. An open circuit creates a break in the electrical path, impeding signal or power flow. Mose bites result from mishandling or cutting, damaging copper traces. Spurs are extraneous protrusions or sharp edges on the PCB surface. Spurious copper refers to unwanted or excess copper traces. Shorts occur when unintended connections bridge two points, leading to electrical malfunction.

B. component detection

The detection of electronic components using AI models in general involves leveraging advanced computer vision techniques to identify and classify components on a PCB. These AI models, which can include not only YOLOv3 but also other architectures like SSD (Single Shot Multibox Detector) or Faster R-CNN (Region-based Convolutional Neural Network), are trained on extensive datasets containing images of PCBs with labeled electronic components. During training, the AI model learns to recognize the visual features and patterns associated with different types of components such as resistors, capacitors, integrated circuits, and connectors. This learning process enables the model to accurately detect and classify components in real-time images [9]

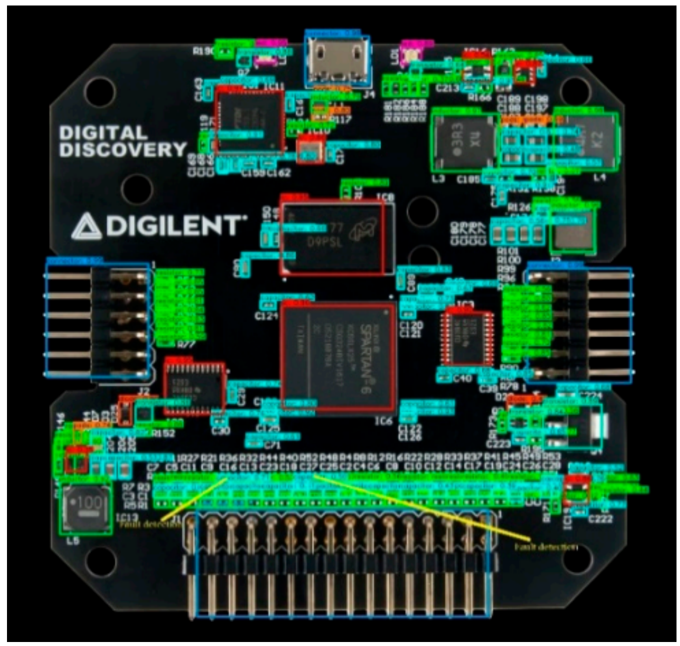

Fig. 8. Advanced AI Techniques for Component Identification in PCBs

VI. VIS Solutions for PCB Companies

Koh Young,and Omron are key players in the visual inspection market, specializing in advanced technologies for quality control in electronics manufacturing. Koh Young excels in 3D measurement and inspection, employing AI and machine learning for precise PCB examination. Mirtec offers automated optical inspection and SPI systems, renowned for reliability and high throughput. Omron provides vision inspection solutions with advanced image processing for defect detection and part verification across various industries. Together, these companies contribute significantly to improving product quality and operational efficiency in manufacturing processes.

A. Koh Young

Koh Young's Zenith AOI Series offers a cutting-edge solution to the evolving challenges in electronics manufacturing. Here's a breakdown of their Ultimate Solution for Inspection Challenges:
Incomparable True 3D Inspection Performance: The Zenith AOI Series stands out by providing True 3D inspection, addressing issues caused by highly specular packages and shadows from adjacent parts. It adheres to IPC-610 standards for electronic assembly acceptability, ensuring clear and precise measurements to identify multiple defects with exceptional accuracy and repeatability.
Total IPC-610 Compliance Solution: By importing PCB Gerber Data, Koh Young's 3D AOI system measures all component and solder joint aspects according to IPC-A-610 standards. This eliminates the need for a golden board and manual program set-up, with library thresholds defined as IPC-A-610 parameters, offering flexibility across different quality classes.
Full 3D Coverage with Powerful Side-View Camera: The Zenith 2, Koh Young's flagship AOI model, integrates advanced vision algorithms and "3D side-view cameras" to enhance inspection coverage. This includes improved defect identification for various components like leadless chips, connectors, and QFNs, advancing quality control capabilities.
AI-powered Auto-Programming (KAP): Koh Young's proprietary AI technology, combined with industry-leading 3D profilometry, enables true automatic programming. The Koh Young Auto-Programming (KAP) software reduces production preparation time and costs by streamlining the programming process [10].

B. Omron

advanced inspection technology featuring the latest camera technology, phase shift MPS, and MDMC illumination, each contributing to enhanced quality control and manufacturing processes. The OMRON in-house camera captures high-definition images with low noise and strong contrast, achieving inspection speeds about 150% faster than conventional methods. With CoaXPress 2.0, this system enables high-speed transmission of large data volumes, available in 12M and 25M pixel resolutions. Phase shift MPS, equipped with a proprietary design projector, automatically controls multiple fringe patterns and light intensity for optimal inspection, minimizing secondary reflections and enhancing accuracy with detailed pattern generation. MDMC illumination combines directional lighting with white lighting, utilizing multidirectional RGB lights to capture accurate shape information of complex geometries and improve component printing detection. These technologies significantly reduce noise, minimize shadow effects from large parts, and ensure visibility at critical points like connector solder joints, enabling stable inspection of microscopic parts. Integrating AI models generated from numerous images, this system further enhances detection and reading accuracy, ensuring higher precision in quality control. A QR code is provided for more detailed sample images and additional information [11].

C. Koh Young vs Omron systems

Koh Young's Zenith AOI Series offers advanced solutions for the evolving challenges in electronics manufacturing. It stands out with its True 3D inspection performance, addressing issues caused by highly specular packages and shadows from adjacent parts. Adhering to IPC-610 standards ensures clear and precise measurements, identifying multiple defects with exceptional accuracy and repeatability. Moreover, it eliminates the need for a golden board and manual program set-up, providing flexibility across different quality classes. The integration of powerful side-view cameras and advanced vision algorithms enhances inspection coverage, especially for leadless chips, connectors, and QFNs. Additionally, Koh Young's proprietary AI technology streamlines the programming process with the Auto-Programming (KAP) software, reducing production preparation time and costs.

Omron's visual inspection system incorporates advanced technology to ensure high-quality control and manufacturing processes. Its latest camera technology captures high-definition images with low noise and strong contrast, contributing to enhanced inspection accuracy. The Phase Shift MPS automatically controls multiple fringe patterns and light intensity, minimizing secondary reflections and enhancing accuracy. MDMC illumination combines directional lighting with white lighting, capturing accurate shape information of complex geometries and improving component printing detection. Moreover, Omron integrates AI models generated from numerous images to enhance detection and reading accuracy, ensuring higher precision in quality control.

Comparatively, Koh Young's Zenith AOI Series excels in True 3D inspection performance, IPC compliance, and flexibility in program set-up. It addresses the specific challenges of electronic assembly inspection with advanced features such as AI-powered auto-programming. On the other hand, Omron's visual inspection system offers comprehensive solutions for quality control across various industries, leveraging advanced camera technology, phase shift MPS, MDMC illumination, and AI integration to enhance speed, efficiency, and precision in inspection tasks. The choice between the two systems depends on specific requirements, such as the nature of the inspection task, industry standards, and the need for advanced AI capabilities.

VII. Current Challenges and Future Research Directions of Visual Inspection Systems for PCBs

With the rapid advancement of technology, visual inspection systems for printed circuit boards (PCBs) face numerous challenges and present opportunities for future research.

Current Challenges

- Achieving high accuracy in detecting small and intricate defects is a significant challenge. Current systems need to improve imaging and analysis techniques to increase accuracy and reliability.
- Visual inspection systems require high processing speeds to inspect a large number of boards efficiently. Enhancing algorithms and utilizing parallel processing are necessary to address this challenge.
- The increasing complexity of PCB designs, with multiple layers and components, poses a challenge for accurate and efficient inspection.

Future Research Directions

- **Integration of Artificial Intelligence and Machine Learning:** Incorporating AI and ML technologies can enhance defect detection capabilities and optimize inspection processes.
- **Development of Autonomous Inspection Systems:** Creating autonomous systems using advanced robotics can enable efficient and accurate inspection of PCBs, particularly in high-volume production environments [12].
- **Utilization of the Internet of Things (IoT):** IoT integration can facilitate continuous monitoring and real-time data analysis, improving overall system performance and enabling predictive maintenance capabilities [13].
- **Enhacement of Imaging techniques :** Research into advanced imaging techniques, such as hyperspectral imaging and 3D imaging, can provide more detailed and accurate inspection capabilities.

VIII. Conclusion

In conclusion , we can say that optical inspection systems for printed circuit boards have witnessed remarkable development thanks to the progress in imaging, image processing, and artificial intelligence technologies.

Systems such as those offered by leading companies like Koh Young and Omron stand out for their ability to provide innovative inspection techniques, enhancing inspection accuracy and reducing human errors. Advanced imaging technologies enable the capture of high-resolution images of printed circuits, while image processing techniques contribute to the analysis of these images with high precision. On the other hand, artificial intelligence works to improve prediction accuracy and defect detection thanks to machine learning and neural network techniques .

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