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Morphological Image Techniques for Predictive Maintenance Detection

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Abstract: The advancement of modern manufacturing industry increases the need for fast, accurate, and efficient defect detection, especially in PCB (Printed Circuit Board) production. Image morphology techniques offer an effective solution by utilizing basic operations such as erosion, dilation, opening, and closing to extract important features and eliminate noise. This study discusses the application of morphology techniques to detect defects in PCBs as part of a predictive maintenance strategy. The process includes image acquisition, pre-processing, segmentation, feature extraction, and defect classification using machine learning algorithms. The results show that the use of morphology techniques can improve the accuracy of defect detection and optimize product quality while reducing manual inspection costs. The main contribution of this research is the development of an efficient defect detection framework that integrates morphological operations with machine learning to enhance early failure prediction and support improved system reliability and operational efficiency in PCB manufacturing.

Keywords: Morphology, Image, Detection

INTRODUCTION

Progress and speed in production make manufacturing defects a serious problem for the modern manufacturing industry (Yang et al., 2020). If defects are not detected effectively, a company's ability to compete in the market will be compromised, and production costs will increase significantly (Mohammed et al., 2021). Therefore, it is necessary to use defect detection for early detection of defects and eliminating potential safety risks (Zhang et al., 2023). Defect detection by visual inspection is very important in the manufacturing and quality control industries (Diers & Pigorsch, 2023). Visual inspection is done manually in various industries. However, manual visual inspection is labor-intensive, expensive, and highly subjective.

The limitations of manual inspection encourage research into automated defect detection methods to improve efficiency, accuracy, and reliability. To improve efficiency and reliability, as well as reduce labor costs, automation of defect detection with machine vision systems is in great demand (Xie & Wu, 2020). one production is the manufacture of pcbs, which have many electronic components mounted on their surface. Due to the increasing complexity and density of printed circuit boards, automatic defect detection has become very important in the manufacturing process. The increasing complexity of pcbs requires reliable automated solutions to ensure product quality.

Implementation of automatic defect detection algorithms offers several advantages over traditional manual inspection. These benefits include, increasing efficiency and reducing human error, automation provides a faster and more consistent way to evaluate products, leading to increased yields and reduced waste. Defects can be detected early on the production line, enabling timely corrective action to prevent further defects and reduce costs. This system also reduces labor costs, as one operator can supervise multiple automated inspection systems, rather than multiple manual inspectors.

By analyzing the shape, size, and orientation of image features, morphological techniques can effectively highlight anomalies that may indicate potential maintenance problems. Morphological techniques involve the use of probing images with small shapes called structural elements, modifying the image based on local comparisons of the shape of the structural elements with the shape of the image. Basic operations such as erosion and dilation, as well as advanced combinations such as opening and closing, make it possible to extract relevant features and remove noise, thereby facilitating accurate defect detection.

Morphological methods can be used to detect defects in PCB macros, such as open circuits (Tibyani et al., 2021). Morphology can also be used to patch small defects. Morphology can be used to detect defects by extracting relevant features and removing noise. Morphology is a versatile tool for image analysis and processing, offering a variety of operations that can be tailored to specific flaw detection applications. As was done in previous research using the morphological method, the circle object detection speed reached an average value of 87.36% (Hatta & Mahmudi, 2019).

Research Gap

Although manual visual inspection remains widely used for defect detection in PCB manufacturing, it is labor-intensive, subjective, and prone to human error, limiting its scalability and consistency in modern high-speed production environments. Automated inspection systems have been introduced to address these challenges, but many existing methods either lack the flexibility to adapt to diverse defect types or struggle to balance accuracy and computational efficiency, especially when dealing with complex and high-density PCB layouts.

Previous studies have demonstrated the potential of image morphology techniques in enhancing defect detection by enabling effective feature extraction and noise reduction. However, most research has focused on detecting relatively large or well-defined defects, with limited exploration of detecting small-scale or subtle defects that can significantly impact PCB performance. Additionally, while some studies have integrated morphological operations with basic classification methods, few have leveraged the combination of advanced morphological processing with machine learning algorithms to improve detection robustness and enable predictive maintenance strategies.

This research addresses these gaps by developing an automated defect detection framework that combines morphological image processing techniques with machine learning-based classification. The proposed approach aims to enhance the detection of both macro and micro defects in PCBs, improve prediction accuracy, and support efficient and reliable quality control within high-speed manufacturing environments.

RESEARCH METHOD

The methodology commonly employed in applying morphological techniques typically commences with **image acquisition**. This stage entails capturing images of the component or system under inspection. Depending on the specific application requirements, the acquired images may be in two-dimensional (2D) or three-dimensional (3D) formats.Preprocessing is performed on the acquired images to improve their quality and prepare them for further analysis. Preprocessing techniques include noise reduction, sharpening, and contrast adjustment. Image segmentation divides an image into several different regions or objects.

Feature extraction involves extracting relevant features from segmented images that reflect important characteristics of the component or system being inspected. these features can include texture, edge, corner, and shape information. Morphological operations are applied to an image to modify its shape and structure based on certain rules.

Common morphological operations include erosion, dilation, opening, and closure. Erosion shrinks objects, while dilation expands them. Opening removes small objects and smoothes contours, while closing fills small gaps and connects adjacent objects. The most optimal erosion technique is carried out several times using mse. (Riantama et al., 2019).

This erosion technique has been carried out twice, able to increase detail and remove small noise. By applying these operations strategically, certain characteristics of the image can be enhanced or suppressed, thereby facilitating defect detection. Defect classification and detection involves the use of extracted features and morphologically processed images to classify and detect defects.

Morphological operations can be combined to achieve certain effects, such as extracting edges or filling holes. Defect detection involves the analysis of extracted features and morphologically modified images to identify defects or anomalies.

Dilation techniques in defect detection in electronic PCBs can be applied to ensure that there are no bent or missing pins from installed components, because defective components cause the circuit to become incomplete and fail to function.

The opening technique can be used to remove noise and small artifacts from the image, making it easier to identify defective components, such as missing capacitors or resistors. and by applying appropriate algorithms, systems can accurately and reliably identify defects, enabling timely corrective action and improving product quality (Kumar & Harsha, 2024).

Closing techniques can be applied to fill small gaps or holes in PCB traces. Morphological operations can be used as a preprocessing step to improve image quality and simplify subsequent analysis. Morphological operations can be used to extract relevant features from images, such as edges and corners, which can be used to identify defects.

Techniques such as Optical Character Recognition can be used to analyze characters found in an image (Hamidah et al., 2022). Machine vision-based defect detection involves steps such as image acquisition, preprocessing, segmentation, feature extraction, and classification (Kumar & Harsha, 2024). Visual inspections using machine vision can help businesses automate inspections and improve product quality.

Visual inspection using computer vision can improve product quality and automate inspections. by combining machine vision and image processing techniques such as morphology, businesses can achieve greater accuracy and efficiency in their defect detection processes, thereby reducing costs and increasing customer satisfaction (Kumar & Harsha, 2024). The use of machine learning algorithms can build models to predict the occurrence and location of railway track breaks (Hakim, 2020). This can be done by analyzing system errors from interacting objects (Mangengre, 2019).

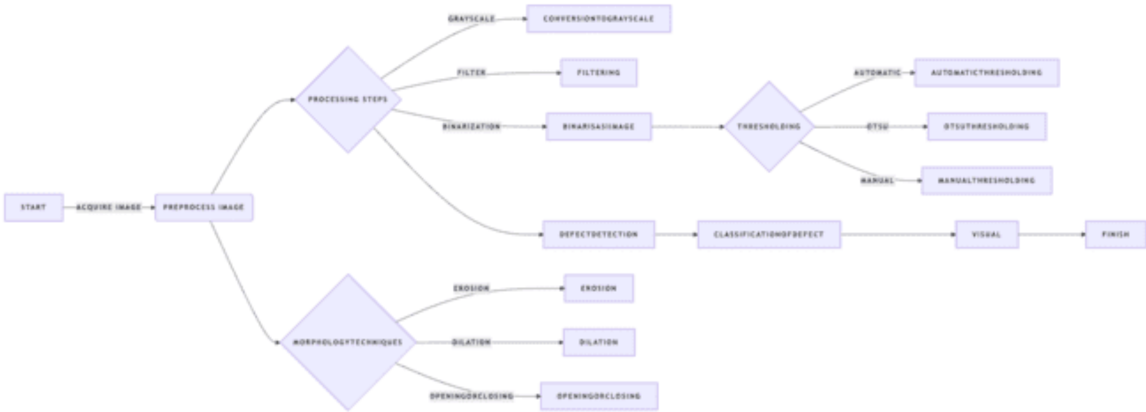

Figure 1. Method for Morfology Technic

RESULT AND DISCUSSION

Many algorithms are available for computer-assisted digital image processing (Fuady et al., 2020). Image processing algorithms and methods provide tools for tasks such as image enhancement and feature extraction (Adhinata et al., 2020). techniques such as segmentation, feature extraction, and classification are used in machine vision based defect detection. Morphological operations can be tailored to specific flaw detection applications, with different combinations achieving specific effects, such as extracting edges or filling holes.

Improving image quality is very important in digital image processing, and can be achieved through various methods. Preprocessing may involve techniques such as color correction to ensure accurate representation of colors in the image. Preprocessing is very important to improve image quality and prepare it for further analysis and segmentation (Adhinata et al., 2020). Image segmentation is an important step in image analysis, which allows separating different regions or objects in an image. Methods such as wavelet transform can be used for feature extraction, converting images into numerical representations for further analysis (Febrianti, 2017).

This technique can be used to reduce the impact of lighting variations and increase the accuracy of object detection (Rahmannuri, 2019). machine vision-based inspection systems utilize steps such as optical illumination, image acquisition, image processing, and image analysis to detect defects (Kumar & Harsha, 2024). the system can be used for a variety of inspection tasks, including surface defect identification, dimensional measurement, and component presence verification.

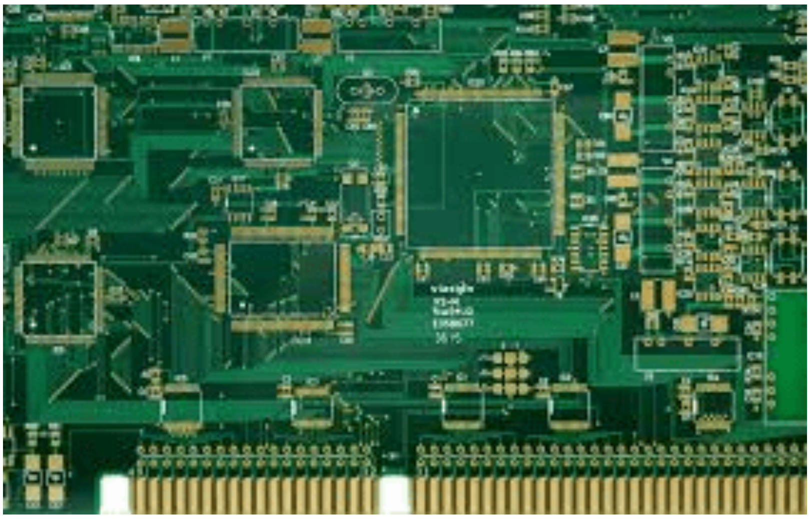

Figure 2. PCB image

(Source: https://www.viasion.com/blog/pcb-layers-traces-and-pads-explained/)

The Figure 1 show a PCB component that can be seen in size and has different dimensions for each component, such as resistors, capacitors, diodes, transistors, ICs and others. With a small size, installation errors, non-installation or lack of components can occur, so detection using appropriate image processing techniques is required.

The types of defects on PCBs vary greatly, ranging from defects on the PCB surface or on installed components. With image processing techniques, such errors can be detected and preventive action can be taken, so that PCB malfunctions do not occur.

In addition to component defects, other common problems in PCB manufacturing are incorrect component placement, inadequate solder joints, short circuits, or open pathways. These errors can be reduced by using appropriate algorithms.

Algorithm Explanation

To address defects such as incorrect component placement, inadequate solder joints, short circuits, and open pathways in PCB manufacturing, a combination of **image processing algorithms** and **machine learning techniques** is typically employed. The process generally involves several key stages:

1. **Pre-processing algorithms**: These include filtering (such as Gaussian or median filtering) to reduce noise and improve the clarity of critical features in the image.
2. **Segmentation algorithms**: Techniques like thresholding, edge detection (e.g., Canny or Sobel operators), or advanced methods like watershed segmentation are used to separate components and solder joints from the background for easier analysis.
3. **Morphological operations**: As in your main method, algorithms such as erosion, dilation, opening, and closing help refine the segmented regions, highlight structural defects, and remove irrelevant noise.
4. **Feature extraction algorithms**: Shape, size, and texture features are extracted using algorithms like Hough Transform for line and circle detection, or SIFT/SURF for identifying keypoints and descriptors.
5. **Classification algorithms**: Machine learning classifiers (e.g., Support Vector Machine, Decision Trees, Random Forest, or Deep Learning models like Convolutional Neural Networks) are trained to recognize patterns and classify whether a component is correctly placed, a solder joint is adequate, or if a short/open circuit is present.
6. **Defect localization and decision algorithms**: After classification, algorithms such as contour analysis or connected component labeling help in localizing the exact position of the defect on the PCB, enabling precise corrective action.

The use of machine vision and image processing techniques allows businesses to achieve greater accuracy and efficiency in their defect detection processes leading to reduced costs and increased customer satisfaction (Kumar & Harsha, 2024). Morphological operations are also used to remove small imperfections and smooth edges in binary images.

Mechanical Defects

PCBs are thin and fragile components that are susceptible to mechanical damage during the fabrication process. Impacts, scratches, bends, dents, and other sources can cause physical damage. PCBs come into contact with many surfaces, fixtures, and handling equipment during the manufacturing process.

Figure 3.Mechanical Defect

Source: https://morepcb.com/common-pcb-manufacturing-defects/

Soldering Defects

The soldering process is an important stage in PCB assembly. Solder is carefully applied to the PCB to electrically and mechanically attach the components to the proper pads on the board.

Soldering defects can cause performance and reliability problems. Solder shortage, solder overload, cold soldering, raised pads, dry solder joints, and solder bridges are examples of soldering problems.

Figure 4. Soldering Defect

Source : https://morepcb.com/common-pcb-manufacturing-defects/

Figure 3 show solder defects that can cause performance and reliability problems on the PCB. These defects can include lack of solder, excess solder, cold soldering, raised pads, dry solder joints, and solder bridges.

As was done in previous research in detecting PCB defects using morphological techniques (Qin & Isa, 2023). Printed Circuit Board is one of the most important units in the electronics industry. It plays a key role in electronic devices, mechanically holding and connecting various electronic parts together (Qin & Isa, 2023). Due to the complexity of the design and high density of circuits, manufacturing errors often occur during the production process (Realyvásquez-Vargas et al., 2018).

Therefore, PCB defect detection is very important in the field of industrial inspection. Traditional PCB detection methods, such as contact detection, tend to damage the PCB surface and have a high false detection rate (Zhang et al., 2021). To achieve this goal, digital image processing is increasingly being used.

By using data from experts entered into the system, expert systems are very important because they do not experience aging or memory loss, in contrast to human experts who over time can experience memory decline (Amriana et al., 2020). Manual visual inspection is time-consuming, tedious, and inconsistent. (Judge, 2020).

Condition monitoring and predictive maintenance are effective strategies for improving the reliability and efficiency of engineering systems. Predictive maintenance, in particular, uses condition monitoring techniques to detect potential failures before they occur, enabling proactive maintenance actions that minimize downtime and costs (Nugraha & Sari, 2019). Maintenance is an important aspect that must be carried out by every company, because maintenance can affect the ongoing production process, sometimes the machine stops due to a disruption caused by the machine experiencing damage to one of the components, this usually happens because the machine is lacking or is not maintained, therefore the company must carry out good maintenance to avoid failure of the machine, which also results in decreased productivity (Suryanto, 2020).

Discussion

Image morphology techniques offer a powerful set of tools for processing digital images based on shape. In this study, morphological operations such as erosion, dilation, opening, and closing were applied to enhance important features and remove noise from

PCB images. This approach proved effective for texture analysis, image segmentation, and feature detection, supporting accurate identification of defects.

The developed method successfully analyzed images of PCB drill holes to assess whether the boards met industrial production standards, confirming the critical role of precise hole placement for component mounting and electrical interconnections. The morphological operations facilitated clear boundary detection and accurate measurement of hole dimensions, improving defect classification performance.

Additionally, the integration of automatic and semi-automatic image correction methods, adapted from textile product identification techniques, was customized in this research to optimize PCB defect detection, especially for detecting spliced connections and micro-defects.

The study also demonstrated how morphological techniques can contribute to maintenance prediction. By analyzing the morphological features of the detected defects, the system enabled early identification of damage patterns and wear, allowing for predictive maintenance scheduling. This capability helped prioritize necessary repairs, reducing downtime and enhancing production efficiency. The proposed framework validated the effectiveness of combining morphological image processing with predictive maintenance strategies in a PCB manufacturing context.

Key Findings

The application of morphological image processing techniques in this study successfully improved the detection and classification of PCB defects, including small-scale anomalies such as micro-cracks and misaligned drill holes. The proposed framework enhanced image segmentation accuracy and enabled precise feature extraction, leading to a significant reduction in false positives and improved defect recognition rates. Furthermore, by integrating defect feature analysis with predictive maintenance strategies, the system demonstrated the capability to prioritize maintenance actions and reduce production downtime.

Novelty Statement

This research presents a novel framework that integrates morphological image processing with machine learning-based classification to enhance PCB defect detection and predictive maintenance. Unlike previous studies that focused primarily on detecting large or obvious defects, this study emphasizes accurate detection of small-scale and complex anomalies, including micro-cracks and subtle misalignments. The developed system not only improves defect detection accuracy but also enables early prediction of maintenance needs, offering a cost-effective and scalable solution for modern PCB manufacturing environments.

CONCLUSION

This study demonstrated that the application of image morphology techniques significantly improves defect detection accuracy in PCB manufacturing. By extracting relevant features through morphological operations and integrating them with classification algorithms, the developed system successfully identified both major and minor defects, including micro-cracks and misalignments. The experimental results confirmed the framework's ability to support predictive maintenance by enabling early detection of potential failures, which can enhance system reliability, minimize downtime, and optimize maintenance schedules. Furthermore, the implementation of this approach in the production environment showed measurable improvements in inspection speed and reduced reliance on manual inspection processes. These findings validate the effectiveness of morphological image processing combined with automated classification in advancing quality control and predictive maintenance strategies in PCB manufacturing.

The proposed framework not only advances the current state of automated PCB defect detection but also establishes a scalable foundation for integrating predictive maintenance into modern manufacturing processes. Future research will focus on refining the system's adaptability to a wider range of defect types and extending its application to other industrial inspection domains.

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