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A SMT Pin Soldering Defect Detection System based on Improved Connectivity Domain Algorithm

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Abstract

To address the issue of misjudgment in traditional connected domain marking algorithms during the dense assembly and welding of SMT components, a method combining connected domain marking with localized watershed algorithms has been proposed. After preprocessing the component images, including grayscale conversion and noise filtering, the connected domain marking algorithm's identified soldered areas are masked and processed. The soldered areas are then extracted, histogram equalization and distance transformation are performed, and the watershed algorithm is used to segment the misjudged soldering areas. An SMT solder defect detection test bench was developed on the LabVIEW platform, and a comparative experiment was conducted with traditional connected domain algorithms. The experimental results demonstrate that the optimized algorithm not only maintains the accuracy of traditional connected-component labeling but also significantly reduces the false-positive rate in densely soldered environments. Consequently, it exhibits stronger adaptability and robustness to interference, better fulfilling the requirements of real-world engineering applications. This method exhibits superior environmental adaptability and markedly higher interference resistance, rendering it well-suited to real-world engineering applications.

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Keywords

machine vision; image segmentation; solder spot detection; distance transformation; watershed algorithm

0 Introduction

With the rapid advancement of mechatronics technology, industrial instruments and equipment are increasingly moving towards intelligence, modularization, and miniaturization. Surface Mount Technology (SMT), known for its low cost, high assembly density, compact size, and excellent high-frequency performance, is widely used in the integration of mechatronic devices[1]. However, the widespread use of SMT has also led to numerous defects in the welding process of components within products, such as false soldering, lead connection issues, and lead misalignment. Among these, lead connection issues are the most severe defect in SMT components, causing unnecessary connections in the circuit and potentially damaging components, which can affect product output. Therefore, it is essential to detect lead connection defects in components during the production process[2].

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In machine vision, the connected domain algorithm is commonly used to identify defects in SMT component pins. The connected domain marking algorithm proposed by Susan et al. [3], which is based on the principles of 4-connected and 8-connected regions, performs well in defect detection for standard SMT component pin binarized images. Gao Hongbo et al. [4] introduced a new connected domain marking algorithm for binarized images, which reduces the number of comparisons during the marking process, thereby improving the efficiency and stability of connected domain identification. Dai Huadong et al. [5] developed a single-target detection algorithm based on connected domain marking, which simplifies the process, enhances real-time performance, and improves tracking capabilities.

As the density of SMT component assembly increases, traditional connected domain algorithms, when used to inspect the pins of tightly packed SMT components, may incorrectly identify two separate pins as being soldered together, significantly impacting the system's accuracy. Therefore, it is necessary to adapt this algorithm to improve the detection system's accuracy.

This paper is based on machine vision, and aims at the problem that the commonly used connected domain marking algorithm is prone to misjudgment in SMT lead connection identification. The connected domain marking algorithm is improved, and a SMT lead connection defect detection system is developed by using LabVIEW platform, and the test is carried out.

1 The principle of the connectivity domain marking algorithm to detect the defect of SMT pin connection

The preprocessing step of the connectivity domain algorithm to determine the soldering of SMT component pins is as follows: use an industrial camera to obtain the image of SMT patch board, convert the acquired image into a grayscale image, select an appropriate threshold to binarize the image, and finally remove the noise [6-7] in the binary image through the filtering process of the image.

A connected region typically refers to an area in an image where pixels have the same value and are adjacent. In any digital image, a pixel is considered the most basic unit. When identifying objects, a pixel can be scanned in four directions or eight adjacent directions. These two methods of identification are known as the 4-connected method and the 8-connected method [8], respectively. The principle is illustrated in Figure 1.

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(A) 4 connectivity (b) 8 connectivity (A) 4 connectivity (b) 8 connectivity

Figure 1 Schematic diagram of connected domain

In the binary image of SMT component pins, each pin can be identified as a connected domain, and each soldered area can also be identified as a connected domain. However, since soldered areas are generally larger than pins, the number of pixels in the soldered areas is significantly higher than that in the pin areas. Therefore, by setting a pixel count limit for connected domains, the areas within this range

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can be identified. The method for identifying pin defects in SMT components using the connected domain marking algorithm is detailed in Table 1.

condition	Identify the results
Xmin<X<Xmax	pin-level solder bridge region
Ymin<Y<Ymax	Normal pin area

Based on the connected-component principle described earlier, when a component pin is properly soldered, the pixel values in the corresponding image region are almost uniform. This region can be segmented and labeled, and its pixel count can be recorded. By repeating this procedure on a batch of correctly soldered parts, we obtain the typical pixel-count range for a normal joint: Xmin ≤ normal-pixels ≤ Xmax.

When solder bridging occurs, the merged region can likewise be labeled and its pixel count computed. Since a bridge is caused by the accidental joining of two or more pins, its area is usually at least twice that of a single normal joint; hence bridge-pixels ≥ 2×Xmax. Consequently, for any given production lot we can establish ,normal-joint range: Xmin, Xmax ,bridge range: Ymin, Ymax and the two ranges never overlap: Ymin > Xmax.Xmin, Xmax, Ymin, Ymax are boundary symbols that define the range of the pixel analysis region, rather than fixed threshold values.

Table 1 Connectivity domain identification criteria

2. Improvement of connectivity domain marking algorithm

The connected domain marking algorithm first converts the image to grayscale, then selects an appropriate threshold to binarize the

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image to separate the background from the target. It then identifies particles in the image using the 4-connected or 8-connected principle. After comparing the pixel counts, particles with a certain number of pixels are marked as connected regions.

Although the 4-connected or 8-connected principle is better for particle recognition in binarized images, when SMT components are assembled intensively, the binary images of adjacent component pins are relatively close, and the connectivity domain marking algorithm may mark them as connected, resulting in misjudgment, which has a very adverse effect on the accuracy of the system.

To address the aforementioned issues, following the original connected domain marking algorithm process, after the soldered areas are marked, a local watershed and a second connected domain marking are performed on the marked regions. The primary function of the local watershed is to segment the soldered areas. Since the watershed algorithm excels at handling weak edges [8], it can effectively segment the boundary between the background and the pins in the misjudged areas. The second connected domain marking aims to re-evaluate the particles after the watershed segmentation to correct the misjudgments.

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2.1 Principle of algorithm improvement

In order to obtain a more satisfactory particle segmentation effect, the following operations need to be carried out on the image before the local watershed segmentation of the connected tin region is performed:

1) Masking (Mask) Processing: Masking processing is a prerequisite for the watershed algorithm, which can isolate and segment the regions of interest in an image for further processing. The process begins with masking the connected regions, followed by applying the watershed algorithm to these regions. This approach not only reduces the system's memory usage but also makes the results before and after segmentation more clearly visible [9].

2) Histogram Equalization Since the watershed algorithm is very sensitive to noise, excessive segmentation may occur after the watershed algorithm is applied to the tin-lead region [10]. In order to reduce the influence of noise and improve the contrast of the image, histogram equalization can be applied to the tin-lead region.

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3) Distance Transformation Distance transformation is used to calculate the distance of a point in an image to the nearest point on a target, such as an edge. The distance field is a set of points with different pixel values (i.e., a grayscale image) derived from the distance transformation formula, where each point's grayscale value represents its distance [11] to the reference point or the edge of the region. Once the distance field of the connected regions is obtained, the connected regions can be separated from the background by thresholding the distances and other operations based on the proximity of the pixels to the particle boundary. This system uses Euclidean distance, and the calculation formula is as follows [12]:

$$d=\sqrt{(x_2-x_1)^2+(y_2-y_1)^2}$$

4) localized watershed Algorithm Segmentation The implementation of the watershed algorithm can be illustrated through the flooding process. Assuming water is evenly distributed across the basin, the lowest point (the farthest from the boundary) will be flooded first, followed by the gradual filling of the basin. When the water level reaches a certain height, it will overflow, and the watershed can be delineated at the point of overflow. The process of marking particles with the watershed is similar to this. The watershed segmentation method offers high real-time performance[13]. It first calculates the distance field of binary particles, then marks each particle based on this distance field, and delineates the watershed between particles[14]. Misjudged connected particles are also segmented using this method.

First, based on connected-component labeling, the bridging region is tagged (its pixel count is larger than that of a single pin). Using the resulting label, a mask is created to isolate the suspected bridge area. The extracted patch is then histogram-equalized, which both suppresses noise and increases contrast. Finally, a distance transform is performed on the equalized image, turning the region into distinct distance fields so that the subsequent localized watershed algorithm can more easily deliver the final segmentation.

After the localized watershed algorithm has segmented the falsely detected brittle-tin regions, the resulting mask is reintegrated into the original image by morphological operations, thereby replacing the misclassified areas and producing the final segmentation. Finally, the

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second connected domain marking algorithm is applied to the final segmented image to determine whether there are any tin-ductile defects in the image. The location of the tin-ductile zones and the segmentation results from the localized watershed algorithm need to be obtained through further experiments.

2.2 Metric Definitions

For the defect class, precision is the proportion of samples predicted as defective that are actually defective.

$$\text{Precision}=\frac{TP}{TP+FP}$$

For the defect class, recall is the proportion of actually defective samples that are correctly predicted as defective.

$$\text{Recall}=\frac{TP}{TP+FN} \quad (3)$$

The F1 score is the harmonic mean of precision and recall, providing a single overall measure.

$$\text{F1 Score}=2\times\frac{\text{Precision}\times\text{Recall}}{\text{Precision}+\text{Recall}} \quad (4)$$

True Positive (TP) is the Number of samples correctly predicted as defective.False Positive (FP)is theNumber of samples incorrectly predicted as defective (actually normal).False Negative (FN)is the Number of samples incorrectly predicted as normal (actually defective).

3. Hardware design of detection system

The primary function of the hardware in the detection system is to collect and transmit images. The image acquisition module requires industrial cameras, image acquisition cards, light sources, and a host computer. To ensure high-quality and stable image acquisition, the overall hardware system uses the MV-EM series industrial cameras and lenses. The image acquisition card receives images from the camera and transmits them to the host computer. The schematic diagram of the hardware system is shown in Figure 2.

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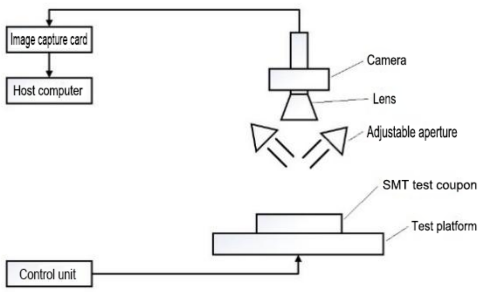

Figure 2 Schematic diagram of hardware system

4. Detection system software design

After using the hardware part to collect the image of SMT component pins, a SMT component pin soldering defect detection system can be designed based on LabVIEW development environment.

4.1 Overall process design of software

The system software primarily consists of an image acquisition and storage module, an image processing module, and a result evaluation module. The image processing module includes an improved algorithm process: the first connected domain marking algorithm, the local watershed algorithm for the connected regions, and the second connected domain marking algorithm. The specific program flowchart is shown in Figure 3.

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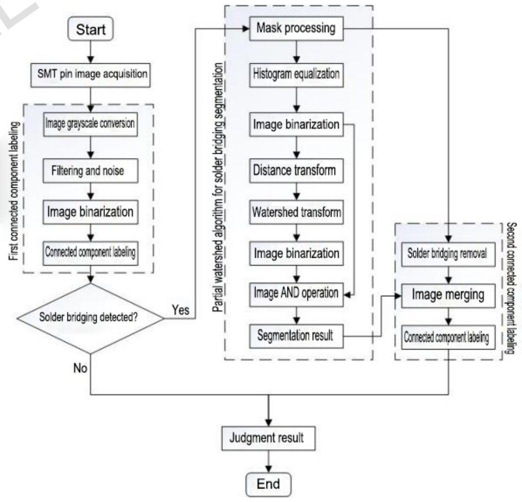

Figure 3 Measurement system software flow chart

4.2 Image segmentation program for part of the watershed in the Lianxi region

After the first connectivity domain marking of the SMT component pins to obtain the soldered areas, it is impossible to determine if there are any misjudgments in these areas. Therefore, a localized watershed algorithm image segmentation is required for the soldered areas. Before the segmentation process, the image must

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undergo the following steps: mask processing, separate segmentation of the soldered areas, histogram equalization to reduce noise and enhance contrast, image binarization to segment the background and soldered areas, and distance transformation to isolate the soldered areas. After completing these steps, the processed image undergoes a watershed transformation. The binary image after the watershed transformation is then compared with the optimized binary image through an AND operation, which separates all particles. The program is illustrated in Figure 4.

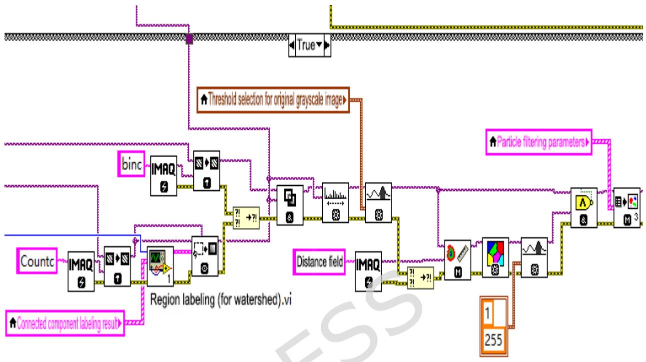

Figure 4 Image segmentation program of part of the watershed in the tin-connected area

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4.3 Image second connectivity domain marking program

After separating the misjudged 'solder bridging' areas from the background, the watershed algorithm's sensitivity to edges results in the segmented image containing not only the separated pins but also numerous small particles. Therefore, it is necessary to filter out these irrelevant particles from the segmented result, outputting an image that contains only the key particles. In subsequent processing, the image's addition and subtraction operations are used to replace the 'solder bridging' areas in the first connected domain marking result with the local watershed algorithm's segmented image, outputting the final image. The second connected domain marking algorithm is then used to determine the' solder bridging 'status of the final image. Specifically, if the number of' solder bridging 'areas is 0, the result is determined as no' solder bridging '; if the number of' solder bridging 'areas is greater than 1 but less than or equal to 3, the result is determined as mild' solder bridging '; if the number of' solder bridging 'areas exceeds 3, the result is determined as severe' solder bridging'. The program is illustrated in Figure 5.

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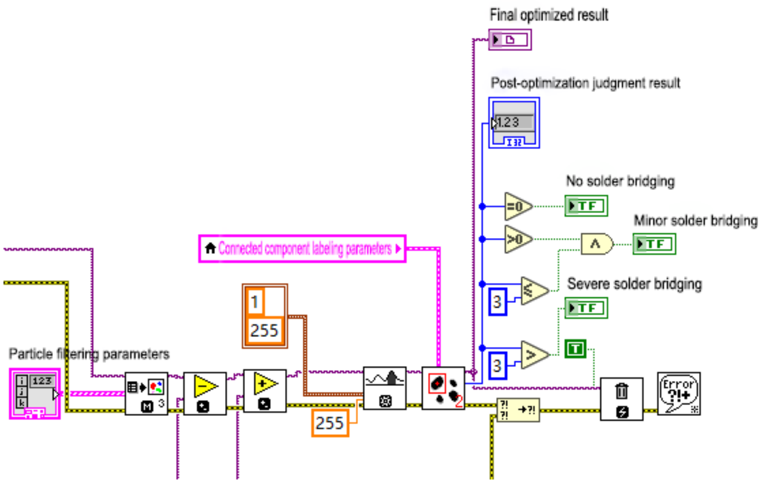

Figure 5. Image second connectivity domain marking program

5 System testing

To validate the applicability and accuracy of the developed SMT pin bridging detection system, an experimental setup was built with off-the-shelf hardware and used to test real SMT devices. The dataset employed in this work is the PCB-AoI solder-joint surface-defect set released by KubeEdge-Ianvs in 2022, augmented with images captured from our own test board, the Machine-Vision Experimental Board V1.0. The measurement results indicate that the normal lead search pixel range is 50×50 to 150×150 pixels,and the lead connection area pixel range is 20×20 to 30×30 pixels. To demonstrate the effects of the algorithm optimization, multiple control groups were established for testing, including different test groups with normal lead spacing and closer lead spacing, and then the optimized algorithm was used for evaluation. Figure 6 shows sample images from the dataset; Figure 7 shows the data processing process and results of one of these groups.

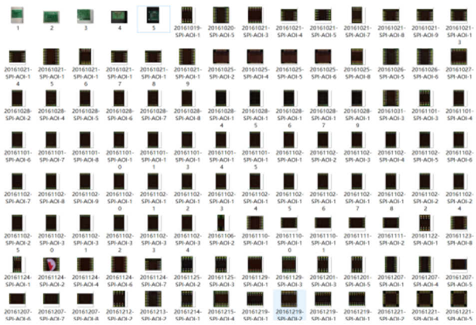

Figure 6 Dataset images

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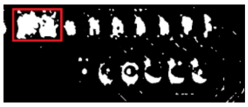


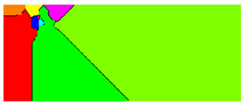
(a)Classical Connected-Component Labeling Result

Note:White regions indicate candidate solder bridges

(b)The image after histogram equalization

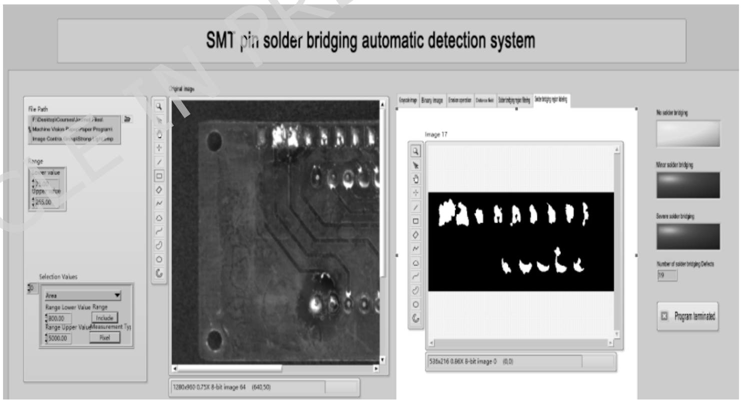
(c)Distance Transform of the Solder-Bridge Region

Note:Darker colors denote greater distances to the nearest background pixel, revealing a pronounced “ridge” line for subsequent watershed segmentation.



(d) Watershed Transform

Note:The watershed segmentation result is overlaid on the original image, with distinct colors representing separate regions



(e) SMT pin defect detection system interface

Figure 7 Defect detection process of part test group

From the results of the system tests, it is evident that some pin spacings being too close can lead to misjudgment by the connected domain marking algorithm. The optimized algorithm extracts the misjudgment areas through mask processing, followed by histogram equalization, distance transformation, and watershed algorithm segmentation. This process segments the misjudgment areas along the boundary between the background and the pins, thereby correcting the misjudgments.

After running the system program on all test sets, the bridging-detection results were obtained. Focusing specifically on solder-bridge defects, the outcomes are as follows:

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Table 2 Specific analysis results of solder-bridge defects

number of test images	Precision	Recall	F1-score
300	0.93	0.97	0.95

The analysis of the test results from different groups in the table shows that the system can accurately identify the areas and number of soldered pins. It also effectively separates the background of misjudged soldered areas from the pins. The system not only maintains the discrimination level of traditional connectivity domain algorithms but also reduces the misjudgment rate in environments with densely packed components, thereby enhancing its applicability, precision, and resistance to interference. This makes it better suited to meet the demands of practical engineering projects.

6 Conclusion

This paper presents a SMT component pin soldering detection system designed using the LabVIEW platform, which is based on an improved Connected Domain (CD) algorithm. The system uses the initial CD algorithm to identify soldered areas, the local watershed algorithm to correct misjudgments, and a second CD marking for final determination. This method is applied to detect SMT component pin diagrams under dense welding conditions, thereby optimizing the detection of pin soldering defects.

After practical testing, the optimized detection system, compared to its pre-optimization version, has a wider range of applicable environmental conditions and more accurate judgment results. This method effectively addresses the issue of misjudgment that often occurs in the dense assembly welding of components using traditional connected domain algorithms. It offers better applicability and interference resistance, providing valuable reference and academic significance for practical engineering.

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[reference documentation]

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Author Contributions

Wei Xiong: Writing – original draft, Investigation, Funding acqui-ition. Na Xiao: Methodology, Inves-tigation, Data curation. Ruili

Wang:Writing – review & editing, Funding acquisition, Conceptualization.

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