MEASURING THE ALIGNMENT ACCURACY OF SURFACE MOUNT ASSEMBLY CIRCUIT BOARD MASKS

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Abstract

An automated system for measuring the alignment accuracy of an exposed photosensitive film resist circuit pattern on a metalized ceramic substrate is described. The system is robust and capable of handling low contrast images with high noise levels and varying degrees of degradation of the circuit pattern. The technique that we will present involves estimating, with the aid of a calibrated vision system, the actual coordinates of two predefined salient features of the circuit pattern, component pads, and calculating the horizontal, vertical, and rotational deviation of the expose mask. The vision algorithm that was implemented will be detailed and its development as an optimization problem, to satisfy the speed, accuracy, and hardware constraints of the system will be discussed. Measurements are accurate to the nearest 2.5 microns and the processing time of each ceramic substrate is not more than sixty seconds using an IBM AT microcomputer.

KEYWORDS – Alignment, registration, template matching, machine vision.

1. Introduction

In recent years, automated electronic assembly technology has been utilizing miniaturized surface mountable integrated circuit packages to produce assemblies that are more densely populated, reliable, and cost effective than traditional through-the-hole circuit board assemblies. The production of high quality assemblies is dependent upon the accuracy with which their basic elements: a substrate, conductive circuit patterns and electronic components, can be registered or aligned with one another. In part, the required accuracy is attained by adhering to rigorous quality control standards at each stage of the manufacturing process. The exacting tolerances imposed by these standards necessitates the implementation of sophisticated automated measurement and inspection procedures, for which image processing systems are fast becoming an invaluable and integral tool. We describe an approach for measuring the alignment accuracy of surface mount assembly circuit board masks.

The production of a surface mount assembly board's circuit pattern involves several stages. Layers of metal are sputtered onto the surface of the substrate and then coated with a film of photosensitive resist. Exposure is achieved by projecting a circuit mask onto the photosensitive film with ultra violet light. The film is developed, leaving a visible image of the circuit pattern on the metalized substrate. The registration of the circuit pattern is then measured. If it is not within specifications, adjustments are made to the position of the expose mask, the resist is removed, and the process is repeated. Otherwise, the substrate is etched, producing the conductive circuit pattern onto which the electronic components will be soldered.

An automated computer vision based measurement system provides a reliable and efficient means of examining the registration of circuit masks. Several advantages over performing the task manually includes increased throughput due to high speed location of pre-programmed inspection positions, improved location accuracy, more consistent measurements, and the possibility of implementing more diverse testing. These factors enable an automated system to yield a final product which can conform to more rigid specifications. In addition, statistical analyses of the data, which can be easily integrated into an automated system, can aid in process control by identifying trends and allowing problems to be diffused before they become serious.

This paper describes an automated system, that was developed as part of a feasibility study for IBM Canada Ltd., for measuring the alignment accuracy of an exposed photosensitive film resist circuit pattern on a metalized ceramic substrate of a surface mount assembly module. The design constraints of the automated system were as follows. Cost effective hardware had to be employed with the heart of the system being an IBM AT microcomputer. The system had to be robust, capable of handling low contrast images with high noise levels and varying degrees of degradation of the circuit pattern. Measurements had to be accurate to the nearest 2.5 microns. Deviations of the circuit pattern from its nominal position of up to ± 51 microns had to be measured. Finally, the total processing time could not exceed sixty seconds per part.

The technique that we will present involves estimating the actual coordinates of two predefined salient features of the circuit pattern, component pads, and calculating the horizontal, vertical, and rotational deviation of the expose mask. The vision algorithm that was implemented will be detailed and its development as an optimization problem, to satisfy the speed, accuracy, and hardware constraints of our system will be discussed.

2. Hardware Configuration

The inspection station is comprised of three subsystems: an image acquisition system, a mechanical positioning system, and a processing system (Figure 1). The image acquisition system digitizes and stores 512 by 480 pixel by 8 bit gray level images of the circuit pattern obtained through a 100X incident light microscope with fluorescent illumination. This magnification produced a pixel size of approximately 1.5 microns. The level of magnification was selected to attain the required level of measurement accuracy while ensuring that the area of the circuit pattern of interest will be entirely within the field of view. The fluorescent illumination produces a high contrast bright field image in which the substrate material is bright and the circuit patterns are dark. The mechanical system includes a substrate locating nest, with centering jaws for accurately positioning the substrate in the center of the nest, and stepper motor controlled horizontal and vertical positioning stages. At a magnification of 100X, it is only possible to view a small region of the part at a time. A motorized positioning system is therefore necessary for placing each region of interest within the field of view. The processing system is an IBM AT microcomputer which manages the sequence of events, executes the computer vision and measurement software, issues instructions to the mechanical and image acquisition systems, and provides the man-machine interface.

3. Registration Measurement

3.1 Pad Models

The position and orientation of the circuit pattern on the substrate can be determined by comparing the actual locations of at least two salient features of the circuit pattern to their nominal locations. The location and orientation of a single salient feature could also be determined but this approach requires a higher degree of measurement accuracy. There are numerous salient features the pad located to the left of the vertex that could be examined to evaluate the circuit pattern's registration. These include circuit traces or electrodes, component pads, product labels, and an assortment of various other *target* objects. Our approach was to examine the location of two symmetric features, namely component pads, since their positions can be determined with a computationally inexpensive template matching algorithm that is independent of the orientation of the circuit pattern.

The substrate is positioned under computer control at each of two predefined pad locations which are specified in a data base. The actual coordinates of the centers of the pads are estimated by the computer vision system. These estimates are then compared to the pads' nominal coordinates and the horizontal, vertical and angular deviations of the circuit pattern from its nominal position and orientation are computed.

The circuit patterns of a wide variety of different products could contain pads of many different sizes, shapes and orientations. A pad consists of a roughly circular region to which an electrode may or may not be connected; the pad center refers to the center of the circular region. The two pads that are used in determining the pattern's registration are selected in advance and therefore can be restricted to those belonging to a small class of pad types. Based on a study of the pad types that would be encountered in our application, it was determined that any particular pad could be modeled as one of four general types, depending on the characteristics of the electrode, and in one of eight different orientations, as described in Figure 2. For each different part number included in this study, the type, orientation, size, and nominal horizontal and vertical location of the center of each of the two pads were specified in a data base.

The actual pads do not strictly conform to the models; their shapes and orientations only roughly correspond. Typical variations from the models include different electrode widths, electrodes not centered on the pads, and square rather than round pads. To some extent, slight variations in pad size must also be tolerated. A typical image of an actual pad at a magnification of 100X is shown in Figure 3. The image contains the pad of interest and its electrode, portions of other pads and electrodes, and a noisy background caused by the rough metalized surface of the substrate. Notice the erosion at the electrode and pad boundaries.

3.2 Computer Vision Approach

An algorithm for estimating the actual coordinates of the pad centers must be able to accommodate the different pad models and orientations as well as both variations of the actual pads from the models and erosion of the pattern components. In addition, the algorithm must adhere to the stringent accuracy and speed requirements of the project specifications.

A number of algorithms have been developed which can be used for measuring the position of objects in digital pictures [1]. One example is thinning algorithms that reduce closed regions into thin lines or skeletons [2]. This approach is well suited for the identification of the pad's type and orientation but is computationally expensive and sensitive to noisy boundaries when an accurate estimate the pad's center is required. Mathematical morphology is a useful approach for identifying shapes but would also be computationally expensive [3]. Two relatively fast methods, examining horizontal and vertical projections and determining the center of mass were not found to be sufficiently accurate when applied to actual pads with eroded boundaries. Template matching is a classical approach to the problem of locating objects in digital images. However, exhaustive template matching is also computationally expensive. VanderBurg and Rosenfeld have shown that multistage template matching algorithms, based on a partial and a full template, can provide a cost efficient approach [4]. In addition, there are a several commercially available products based on dedicated bit-slice or parallel processing technology that address this problem but their high cost is prohibitive in our application [5].

It is evident that no single technique would be satisfactory. A multistage algorithm was therefore developed to attain both the *high speed* and *measurement accuracy* demanded by the project specifications. Early stages of the algorithm derive a coarse approximation of the pad center while maximizing speed. The later stages, which are computationally more expensive, improve convergence with a small number of iterations. The problem becomes one of optimization, determining which techniques should be employed and the extent of their usage. A multistage algorithm is also desirable in that, through its dependence on a variety of successive procedures, it can be more robust than a single stage technique.

3.3 Image Segmentation

The first step of our algorithm is isolation of the pad region. The substrate is mounted in a locating fixture on the motorized stages directly under the microscope and moved under the control of the computer to the position corresponding to the nominal coordinates of the center of the first pad. An image is acquired and a working window which would normally contain the pad under investigation is defined. The purpose of the window is to impose a bound on the size of the image and therefore reduce the processing time. The size of this window is dictated by the ± 50 micron worst case specification within which the pad's center should be located for automatic operation. The microscope's magnification was chosen so that the window would fit within the field of view and contain a sufficient number of pixels to attain the required measurement accuracy without excessive processing.

The image window contains the pad of interest and its electrode, portions of other pads and electrodes, and a noisy background caused by the roughness of the metalized surface of the substrate. The substrate region of the image is primarily made up of pixels of high gray level intensities, while the pad and electrode areas are characterized by lower intensities. The histogram of this type of image is bimodal and it is possible, by intensity thresholding, to construct a binary image that partially differentiates between the circuit pattern regions and the background, as shown in Figure 4. In this procedure, each pixel is classified into one of two groups, foreground or background, depending on whether its intensity exceeds a chosen threshold level. An optimal threshold level is derived from a statistical analysis of variance procedure which maximizes the ratio of the total variation of pixel intensities between the two groups, foreground and background, to the total variation within the two groups [6].

Following thresholding the foreground of the image is composed of numerous closed regions, one of which represents the pad of interest and its electrode. The region describing the pad is isolated from the other foreground regions using component labeling [7]. This technique assigns a unique label to each closed region by sequentially scanning the image, examining each pixel and its connected neighbors, to determine if the pixel in question is part of the background, is connected to a foreground component that has already been labeled, or identifies a new component. A replica of the original image is constructed, with the background and each distinct foreground region described by different intensity levels. A single component is then isolated by assimilating all other foreground components into the background, as shown in Figure 5.

The problem now becomes one of determining which components should be considered as possible representations of the pad. Although the pad is probably not centered at the nominal location, its deviation from this point is sufficiently small that it will usually be one of the largest foreground components described within the window. Initially it is assumed that the largest component represents the pad of interest. Other criteria such as component size, shape, and orientation are evaluated by the subsequent image processing stages to determine if this assumption is correct. In the event that it is determined that the component selected does not describe the pad of interest, the second largest component is then examined. The process is repeated an additional time if necessary before an error message is generated and manual mode is invoked.

3.4 Search Algorithm

Once the pad has been isolated, its center is determined by applying several successive procedures which ensure proper convergence by refining the previously derived estimates. Initial estimates of the coordinates of the pad center are determined from horizontal and vertical projection curves. A projection is the signature that results when the pixel intensities of a binary image are summed along an axis. This data is used, along with the *a priori* knowledge of the pad's size, shape, and orientation, to identify critical points on the projections and estimate the coordinates of the pad's center. The relative position of the critical points can also be used to estimate if the proper foreground component is being examined. For example, for a pad of *type 1* with *orientation 1*, the horizontal projection, traced in Figure 6, resembles a parabola shaped curve, with the center of of the curve. The primary advantage of using projections is high speed and noise immunity relative to other pixel based methods such as exhaustive template matching.

Once an approximation of the pad center has been determined from the projection curves, refinements to the estimates are achieved using a two stage heuristic template matching routine. The first stage of the matching routine uses an elliptic disk template while the second stage employs a concentric elliptic ring template, as shown in Figure 7. Elliptic templates are necessary to compensate for the pixel aspect ratio of our image acquisition system, that is, the discrepancy between the horizontal and vertical dimensions of each pixel. An acquired digital image of a circular object is represented by an elliptic region in the acquisition system's memory; when the digital image is displayed on a monitor, the elliptic region appears circular (as is apparent in the figures in this paper). Thus the pixel aspect ratio is transparent to the user. However, this factor must be considered when measuring distances within a digital image.

The horizontal and vertical radii of the disk and ring templates are determined based on the nominal size of the pad and compensate for the pixel aspect ratio of the acquisition system. The application of the template at a given pixel determines the number of pixels which are within the radius of the disk from that pixel and are members of the image foreground component. Application of the template at the pad center would yield a high degree of matching.

A optimization search path is employed to obtain the position yielding the best match while attempting to minimize the number of applications of the template. The template is first applied at the pixel coordinates that were provided by the projection routine. The degree of matching at this pixel is compared to that at eight of its neighboring pixels, whose locations are on a grid of size three and are given by:

$$\{(x+3i, y+3j) \mid i,j \in \{-1,0,1\},\ |i|+|j| \neq 0\}$$

where (x,y) denotes the location of the given pixel. The pixel which yields the best match is tagged as the new estimate of the center and eight of its neighboring pixels are examined. The search continues until either a better match cannot be found or the degree of match exceeds a threshold value of 80% of the pad's area. Termination of the search once a satisfactory matching threshold has been attained is necessary to avoid the possibility of the search path digressing off the pad and into its electrode, as could occur in cases where the width of the electrode is close to the diameter of the pad.

The decision to examine pixels on a grid of size three was again based on the accuracy and speed constraints of the project specifications. As will be discussed below, the single disk template matching routine cannot be depended upon to provide an estimate of the pad center that is reliable regardless of the pad type and orientation and the degree of pad erosion. The objective of the application of the disk template is therefore twofold: to obtain an estimate of the pad center that is sufficiently accurate for the application of the ring template to be productive and to obtain that estimate quickly. Clearly, a heuristic search path is necessary to satisfy the second objective. The size of the grid used by the search algorithm affects both the speed of the search and the accuracy of the estimate. By shrinking the size of the grid, a more accurate estimate may be obtained but the time to complete the search increases; expanding the size of the grid improves speed but results in a poorer estimate. A grid of size three was found to be suitable with respect to both objectives, accuracy and speed.

The second template matching routine represents the final stage of the algorithm. The template consists of two concentric elliptic rings; the outer radii of the inner ring and the inner radii of the outer ring are both set to the pad's nominal radii. The inner ring is matched to the pad while the outer ring is matched to the background. The ring template is first applied to the pixel at which the disk template matching routine terminated. The same search strategy is employed for this template, with the exception that for increased accuracy, the pixel's eight-connected neighbors are examined. The pixel which produces the highest match is considered the new pad center and the search is repeated until a better match cannot be found.

The advantages of the disk and ring template matching routines were found to be complementary, resulting in an overall performance which exceeds that or either routine alone. The combination of the two templates was shown to be robust against different pad types and orientation, variations of actual pads from the pad models, and erosion or other malformations of the pad edges.

The application of the disk template prior to the ring template is essential to ensure that the ring template search algorithm will be productive. This results from the inability of the ring search algorithm to correctly locate the center of the pad if it is not applied sufficiently close to the pad center. Consider, for example, the application of the ring template near the edge of the pad. If the template is then positioned closer to the pad's center, any increased match of the inner ring to the pad will be negated by a corresponding decrease in the match of the outer ring to the background, rendering the search algorithm unproductive. Depending on the pad type, orientation and the degree of erosion, the seed provided by the projection routine may not be sufficiently close to the pad's center to apply the ring template matching routine directly. By first applying the disk template matching algorithm, the estimate of pad center from the projection routine is refined into one which is sufficiently near the pad's center to ensure effective ring template matching.

The disk template matching routine alone can also be ineffective in accurately determining the pad center for a number of pad types and orientations. Consider a *type 3* pad where the width of the electrode is the same as the diameter of the pad, as shown in Figure 8. The disk template cannot distinguish the difference between a perfect match over the pad and a match of equal value when the template is positioned partly over the pad and partly over the electrode, or entirely over the electrode. As the ring template is displaced from the center of the pad in the direction of the electrode, the degree of match of the inner ring to the pad/electrode region may remain approximately constant, but the outer ring will increasing cover portions of the pad, resulting in a decreased total match. Thus the ring template matching algorithm will not tend to progress into the electrode region regardless of the pad characteristics. Estimation of the pad center by template matching of both pad and background pixels near the edge is found to be robust against both slightly eroded pad sections and wide electrodes. In fact, the concentric ring template also serves to smooth the rough eroded periphery of the pad and therefore provides better convergence.

Following the successful estimation of the pad center, the substrate is translated by the motorized linear stages to the nominal position of the center of the second pad and the computer vision algorithms are repeated. The horizontal, vertical, and rotational pattern position adjustments are then computed based on the nominal and estimated actual coordinates of the two pad centers.

4. Calibration and Alignment

Before the system can be used to obtain measurements, both the image acquisition and the mechanical positioning systems must be calibrated. This requires that the horizontal, vertical, and rotational transformations between the vision, mechanical, and world coordinate systems be established. Calibration is achieved by determining a set of parameters that can be used to calculate the actual displacement in microns from measured distance quantities of mechanical steps and image pixels.

To simplify the transformation from vision and mechanical coordinates to world coordinates, alignment of the coordinate axes is imposed. This eliminates the need for a rotational transformation and simplifies the computation process. Under this constraint, actual displacement in world coordinates may be expressed as

$$x_w = a_o + a_c \cdot x_c + a_s \cdot x_s$$

and

$$y_w = b_o + b_c \cdot y_c + b_s \cdot y_s$$

where

x_w, y_w denotes a measure of distance in world coordinates (microns).

x_c, y_c denotes a measure of distance in vision coordinates (pixels).

x_s, y_s represents the mechanical coordinates at which image was obtained (steps).

a_o, b_o measures the offset of camera and world coordinates at $x_s = y_s = 0$ (microns).

a_c, b_c denotes the equivalent displacements of one pixel in the x and y directions (microns/pixel).

a_s, b_s denotes the equivalent displacements of one step in the x and y directions (microns/step).

The world coordinate axes are defined to be parallel to the edges of the substrate. By aligning the substrate's locating fixture and hence the edges of the substrate with the mechanical stage axes, the world coordinate and mechanical axes are made to coincide.

The alignment of the vision axes with the mechanical and world axes requires that the offset of the camera and world coordinates at zero mechanical displacement be first established. Both the measurement of the offset and then the alignment of the axes are accomplished through the use of a calibration master. The dimensions of the master correspond to the nominal dimensions of the ceramic substrate. The master contains five accurately positioned circular holes that are in the form of a cross, with one hole at each end of the cross and one at its center. The master is mounted in the substrate locating jig on the positioning stage in such a way that the origin of the center hole corresponds with the origin of the stage's coordinate system. Images of the master are acquired and the offset of the hole's center from the center of the camera's field of view is measured using a disk template matching algorithm.

By centering the calibration master on the stage and then mechanically translating it in both the horizontal and the vertical directions to the four other holes, the angular deviations of the vision and mechanical axes can be observed. The camera is manually rotated until a satisfactory alignment of the vision and mechanical axes is achieved.

The equivalence of distance in world (microns) and mechanical coordinates (steps) can be verified using the calibration master. The position of the holes in the calibration master is well known and the number of steps of the positioning system per unit distance is provided by the manufacturer. The number of steps per unit distance can be verified by determining the number of steps required to motor from the center hole to each of the other holes.

The equivalence of distance in world coordinates (microns) and vision coordinates (pixels) is measured in the horizontal and vertical directions using stage micrometers. A stage micrometer is a glass slide that has parallel lines accurately etched at specified intervals in either the vertical or horizontal direction. An image of the micrometer scale is acquired and the average number of pixels between the etched lines is calculated.

In an industrial environment most of the calibration procedures need to only be performed when the equipment has been disturbed. Provided that the camera remains constrained and the magnification is not changed, no further alignment adjustments are required. The one exception may be the mechanical positioning system. Because this system may be prone to errors in counting steps, it is necessary to verify the offset between the origins of the vision and mechanical coordinate systems on occasion and recalibrate if necessary.

5. Conclusion

In this paper an example illustrating the application of computer vision techniques to the automated measurement of the alignment accuracy of an exposed photosensitive film resist circuit pattern on a ceramic substrate has been presented. The algorithms presented achieved an optimal combination of speed, accuracy, efficiency, reliability, and cost effectiveness with the hardware configuration adopted. A measurement accuracy of 2.5 microns and an execution speed of no more than sixty seconds per part were achieved on a large number of blind tests.

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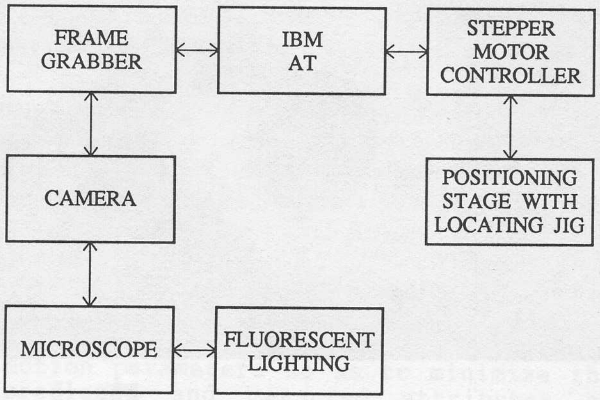

Figure 1: Hardware configuration of the system.

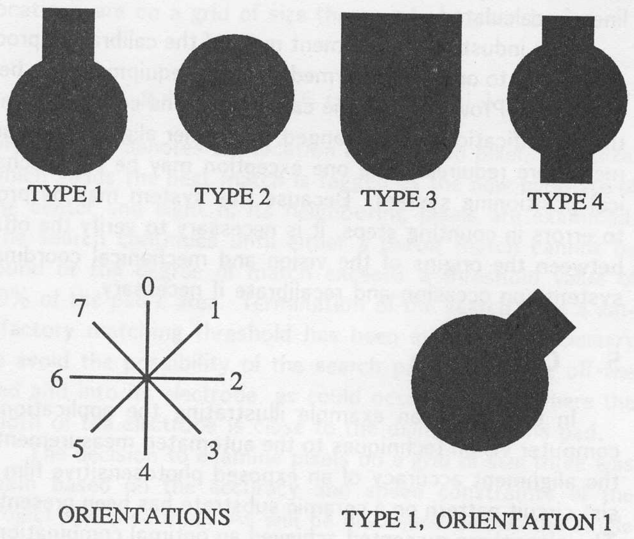

Figure 2: Pad types and orientations.

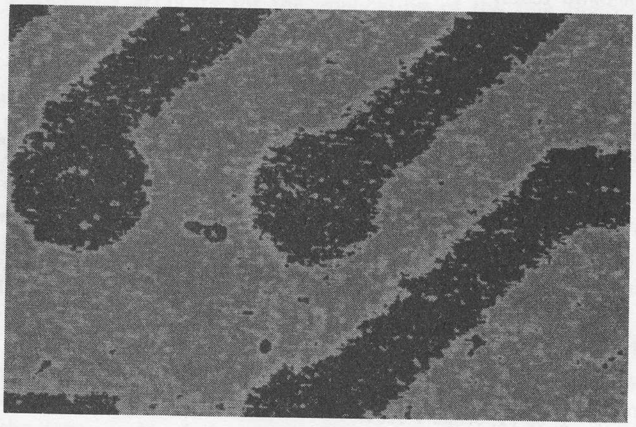

Figure 3: Raw image at a magnification of 100X.

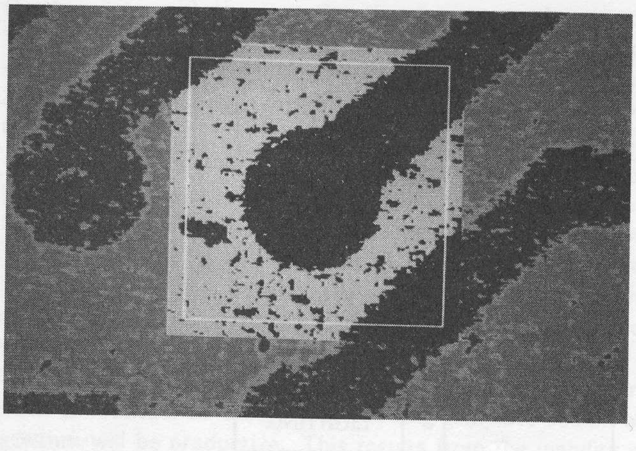

Figure 4: Thresholded image within working window.

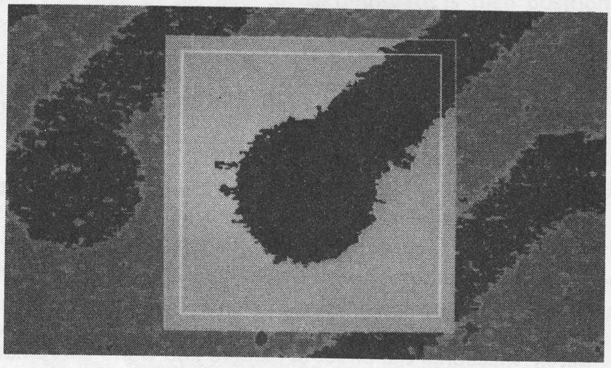

Figure 5: An isolated single component following component labeling.

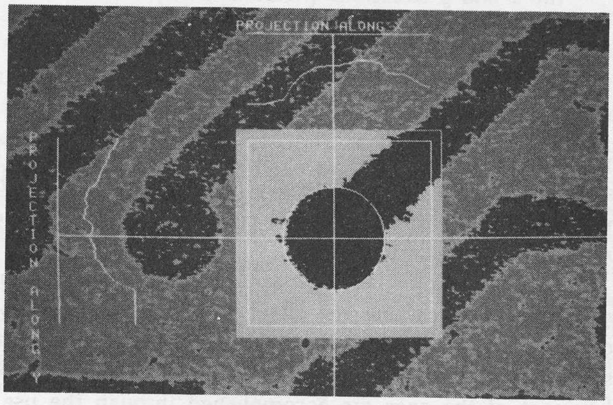

Figure 6: Horizontal and vertical projections of a pad of *type 1* and *orientation 1*.

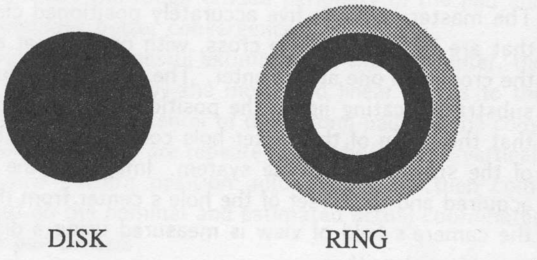

Figure 7: Disk and ring templates. Intensities of the disk and inner ring are equal to that of pad; intensity of the outer ring is equal to the background intensity.

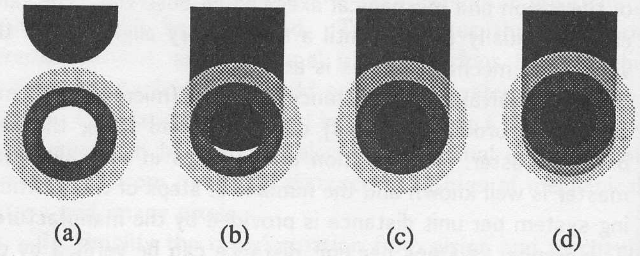

Figure 8: Ring template matching on type 3, orientation 0 pad: (a) pad and ring template; (b) initial match; template progresses upward to increase the match of the inner ring to the pad without decreasing the match of the outer ring to the background; (c) optimal match; (d) beyond optimal match, outer ring increasingly covers portions of the pad.