Placing Surface Mount Components Using Coarse/Fine Positioning and Vision

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Abstract—**Fine pitch surface mount devices (SMD's) are becoming more frequently used in circuit board manufacturing. These components have many closely spaced leads that are soldered to pads on a printed circuit board (PCB). Better accuracy in aligning the device to the PCB pads is needed as the number of external device leads increase and the pitch between the leads becomes smaller. This paper describes an experimental system that can accurately align and place SMD's on a PCB, using a coarse/fine positioning component placement strategy and end point sensing to measure the alignment error. Coarse positioning is done with an IBM 7576 robot and fine positioning using a custom designed precision micropositioning device attached to the end of the IBM 7576 robot. The endpoint sensor is a single camera vision system that by image analysis determines the alignment error of the SMD to the board. System performance was evaluated by placing SMD's of 100 leads with 0.63-mm (25 mil) lead spacing on a board. An alignment error of less than 12 μm (0.5 mil) and 0.015° was obtained independent of feeder and board position error or robot repeatability. The average cycle time is less than 10 s.**

I. Introduction

Surface mount devices (SMD's) are high density integrated circuits used in the manufacturing of electronic circuit boards. Because of the reduction of dimensions and increased functionality of the integrated circuits, the packages tend to have larger numbers of more closely spaced external connection leads. Spacing or pitch for SMD leads is between 1.25 mm (50 mil) to 0.4 mm (16 mil). Typical fine pitch SMD's include a 100 lead device with 0.63-mm (25 mil) pitch and a 40 lead device with 0.5-mm (20 mil) patch.

During the manufacturing process, the SMD lead pattern is aligned with the pads on a printed circuit board (PCB). The SMD is placed on the board and attached by soldering the leads directly to the pads. Placement of fine pitch SMD's is done mainly with automation equipment. Equipment manufacturers have demonstrated systems that place 100 lead 0.63-mm (25 mil) and 40 lead 0.5-mm (20 mil) devices on a PCB with apparent acceptable lead to pad overlap [1], [5]. Current automation equipment may not be adequate to use in the future, for the following reasons.

1) As packages become larger with more leads of smaller pitch, the alignment task becomes more difficult and better accuracy is required of the placement task. Traditional methods that use fixturing and depend on machine repeatability may not be sufficient.
2) Because the IC's have increasing functionality, smaller numbers of the same package have to be assembled on each board. This creates the need for assembly methods that can place a mix of package types.

In addition to accurately positioning SMD's, the overall process time is an important consideration in determining the performance of the manufacturing operation. The elapsed time for the pick-and-place operation can be a significant part of the total throughput. Therefore, it is necessary to keep the placement cycle time at a minimum.

The key element of our system is a custom designed micropositioner [6] attached to the terminal link of the robot. Coarse/fine positioning is accomplished with the combined motions of the two systems. This can lead to an overall move speed and repeatability close to that of the micropositioner [7]. Coarse/fine positioning and endpoint sensing using vision facilitate the placement of SMD's on a PCB. This paper describes an experimental system to demonstrate this technique, using a 0.63-mm (25 mil) 100 lead quad-pack SMD. Part of the SMD and PCB pad pattern are shown in Fig. 1.[1] The features of the system are:

- use of a SCARA robot;
- micropositioner;
- use of a single camera;
- coarse/fine positioning;
- a single motion sequence to pick-and-place the SMD on the board.

The placement system hardware will be described, after which an overview will be given of the vision, calibration and alignment software. Finally the system performance will be addressed.

II. System Hardware

The experimental placement system consists of an IBM 7576 SCARA type robot, Fig. 2, with a special purpose end

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[1] A previous version of this system is described in [3].

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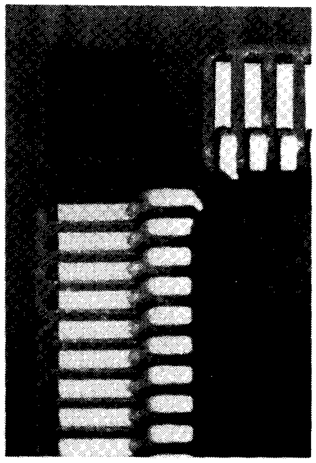

Fig. 1. A SMD aligned to a PCB. Photograph of one corner of a 0.63-mm (25 mil) 100 lead quad-pack SMD aligned to a PCB with the aid of fiducial marks next to the pad pattern. One of the two fiducials is shown.

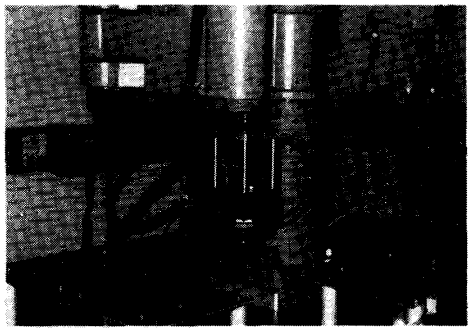

Fig. 2. The component placement system hardware. Photograph shows the IBM 7576 robot, the end effector, the component feeder tray and PCB locations.

effector, Fig. 3, attached to its terminal link. The end effector configuration and system controller will be described.

A. End Effector

The micropositioner is rigidly mounted to the terminal link of the robot and its movable platform provides the small X-Y-Θ motions needed to align the SMD to its pads on a PCB.

A two-section optical system, shown in Fig. 3, is mounted on the platform of the micropositioner. The upper section of the optical system consists of a Pulnix 510 × 492 pixel CCD camera with a 25-mm lens supported on a tube positioned through the hole in the micropositioner. The lower section consists of a vacuum chamber made from two polystyrene discs and a spacer. A detachable pickup tube protrudes from the bottom disc to pickup the SMD. The illuminator is a single ring fluorescent light source to give uniform light distribution. The camera views the component and the PCB pad pattern through the transparent vacuum chamber. The optical reduction is selected so that the image of the outline of the SMD and the pad pattern cover the major area of the CCD imager.[2]

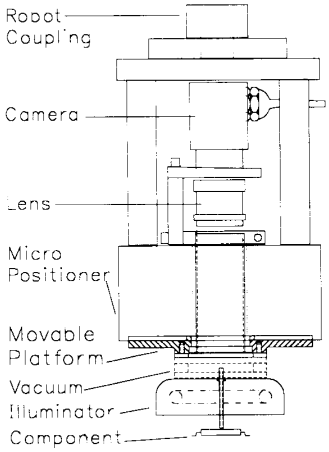

Fig. 3. The end effector. A single CCD camera, a vacuum pickup system, and illuminator are mounted on the programmable X-Y-Θ platform of a micropositioner.

The fact that the camera is mechanically linked to the movable platform of the micropositioner simplifies the fine positioning while aligning the component. It also makes it possible to calibrate the micropositioner to the vision system using the fiducial marks of a PCB pad pattern. This will be explained later.

B. Positioner Specifications

The IBM 7576 robot is a SCARA type robot with a maximum reach of 800 mm. The X-Y repeatability is ± 0.05 mm. The micropositioner uses direct drive to provide X-Y-Θ motion to a single air bearing supported movable platform. The platform is magnetically driven in orthogonal directions to provide the small X-Y motions of the coarse/fine positioning technique. Small Θ rotations are generated by simultaneous excitation of the two linear magnetic actuators. The micropositioner is programmable in 0.5-μm steps in the X-Y directions over a range of ± 1.0 mm and 0.0003-deg steps for the Θ rotation over a ± 1.75-deg range [6].

C. System Controller

The system controller consists of two IBM PC/AT's, a Matrox MVP-AT/NP vision system, and a micropositioner controller (Fig. 4). One PC/AT acts as a supervisor and controls the vision system. It also does motion computations and handles communication to the secondary PC/AT and micropositioner controller over two RS-232 communication links. The second PC/AT has autonomous control of the IBM 7576 robot through an AML/2[3]-based program and interprets and executes commands from the supervisor.

III. PLACEMENT SEQUENCE

SMD placement is a pick-and-place operation where an object is "picked" or retrieved from a feeder position and placed at an assembly position. In this experiment, a plastic waffle

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[2] This design is similar to a previously disclosed concept [2].

[3] AML/2 is an IBM manufacturing language, used as robot controller.

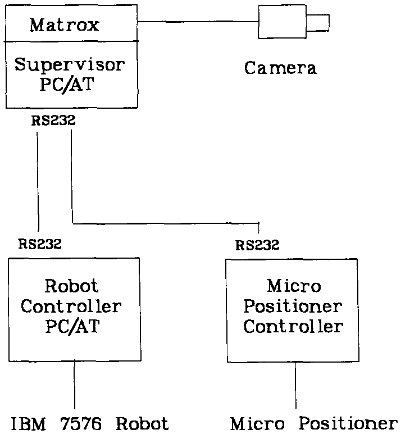

Fig. 4. System control components. System consists of two IBM PC/AT's, a Matrox vision system with Pulnix camera, an IBM 7576 robot and a micropositioner.

tray with SMD's becomes the feeder location. A PCB with pad patterns is placed against hard stops at the conveyor location.

The placement sequence is as follows. The SMD is picked up from the feeder and a vision image is acquired of the outline of the SMD. During the transport of the SMD to the PCB location, the SMD image is analyzed for bent or missing leads and the SMD position is determined in camera coordinates. The SMD is lowered to 0.50 mm over the approximate location of the PCB pad pattern, after which a new image is acquired of a pair of fiducials registered to the pattern (Fig. 1). The pattern location is determined in camera coordinates. If the misalignment of pads and SMD is larger than the range of the micropositioner, the robot is used to perform coarse positioning, after which the new pads location is measured. The micropositioner is now used to perform the fine alignment of the SMD to the pads. The fiducials can be measured again and the micropositioner repositioned, according to the needed alignment accuracy. Finally, the SMD is placed on the board.

IV. Vision Software

The vision software for the component placement system was implemented on top of a Matrox image processing system, which consists of two IBM/PC attachment cards and C interface software. The tasks of the component placement vision software are:

- measuring the centroid and orientation of the component and checking the number of leads and the lead pitches against component specifications;
- measuring the centroid and orientation of the pad pattern.

A. Measuring the Component

The analysis of a component image is shown in Fig. 5. The component centroid is obtained from the image as follows. First, the image is scanned from left, right, top, and bottom to calculate a window which contains the component. Once a window has been established, lead points are located by performing edge detection along four line scans parallel to the edges of the window, at a fixed distance within the window boundary.[4] Edge detection returns one point on each lead. The x and y values of the leads on each side of the component are averaged, thereby computing the average lead point on each side. Let l_v denote a line through the average top and bottom lead points, and let l_h denote a line through the average left and right lead points. The centroid of the component is computed by intersecting l_v with l_h. The orientation of the component is computed by averaging the orientation errors of l_v and l_h.

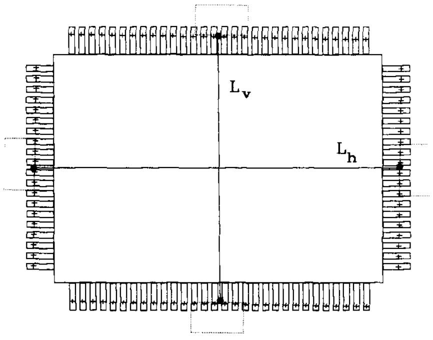

Fig. 5. SMD image with analyzing lines. This image is acquired as the SMD is retrieved from the tray before transporting it to the PCB.

After calculating the component centroid and orientation, the algorithm compares the number of leads and the lead pitches with component specifications, and returns an error if there are discrepancies. Coplanarity of leads is not checked in this implementation.

B. Measuring the Pads

The pads cannot be measured directly because the component leads obscure the view of the circuit board pattern. Instead, a measurement is made on the two fiducial marks to locate the centroid of the circuit board pattern, shown in Fig. 1. Since the fiducials were generated as part of the board pattern artwork, their location accuracy is consistent with the pattern accuracy.

First, the centroid of each fiducial is calculated separately, as described below. Then the centroid of the pad pattern is computed by averaging the fiducial centroids. The orientation of the pattern is calculated as the orientation of a line through the fiducial centroids, relative to the nominal orientation of the same line based on data from the fiducial specifications.

The analysis of a fiducial image is shown in Fig. 6. To calculate the centroid of a fiducial, four lines scan the fiducial at locations that are guaranteed to strike the fiducial despite the uncertainty that is present in its position. Two of the line scans are horizontal, and two are vertical. Using edge detection along the four scan lines, eight points are calculated from the boundary of the fiducial, two on each side. Let l_l denote a line through the two boundary points on the left side of the fiducial. Similarly, let l_r denote a line through the right boundary, l_t a line through the top boundary, and l_b a line

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[4] The edge detection algorithm uses gray level analysis to compute edges at subpixel resolution.

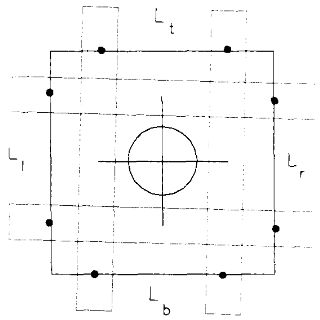

Fig. 6. Fiducial with analyzing lines. The image of this fiducial is acquired and analyzed when the end effector is over the PCB pad pattern.

through the bottom boundary. The centroid of the fiducial is then computed by intersecting the bisector of l_l and l_r with the bisector of l_t and l_b.

V. Calibration Techniques

The integrated vision/micropositioner system eliminates several calibration steps of the more conventional multicamera systems. However, it remains necessary to calibrate the robot and micropositioner to the one vision system. Only approximate calibration is necessary, because of the use of repeated positioning. The end effector is constructed so that the focal line of the camera is parallel to the vertical robot axis. The measurement of leads and fiducials is assumed to take place in the same plane. The remaining calibrations are:

- calibrating the pixel size to the step size of the micropositioner;
- calibrating the angular and translation offset of the robot and the micropositioner to the vision coordinate system.

A. Calibrating Pixel Size to Positioner Step Size

The spacing between two fiducials of a pad pattern is accurately defined by its specifications. By measuring this spacing in vision coordinates, a transformation between pixels and micrometers is found. To calibrate the positioner step size, the micropositioner is moved over a certain distance, while a fiducial is measured before and after the move. The measured pixel distance is converted to micrometers. The scale of the positioner step size is found by dividing the measured distance by the moved distance.

B. Calibrating Positioner to Vision Coordinate System

Because of the hardware configuration, the calibrations are exactly the same for both the robot and the micropositioner. The angular and translation offset calibration is defined as:

- angular offset (off_Θ): angle between the x-axis of the vision system and the x-axis of the micropositioner (robot);
- translation offset ($\mathrm{off}_{X,Y}$): x and y distance between the vision center and the micropositioner (robot) center.

C. Angular Offset

A point that can be located in vision coordinates (f_1) is measured again (f_2), after the positioner is moved in its positive x direction. The angular offset (off_Θ) is the angle between the positive vision x-axis and the line through f_1 and f_2.

D. Translation Offset

A point that can be located in vision coordinates (f_1) is measured again (f_2), after the positioner is rotated over α degrees. The translation offset ($\mathrm{off}_{X,Y}$) is defined by two constraints. First, $\mathrm{off}_{X,Y}$ is a point on the perpendicular bisector of f_1 and f_2. Second, the angle between the line through $\mathrm{off}_{X,Y}$ and f_1 and the line through $\mathrm{off}_{X,Y}$ and f_2 equals α. This gives two points on the bisector. The direction of rotation of the positioner gives $\mathrm{off}_{X,Y}$.

VI. Component Alignment

The alignment takes place using a single camera. Because the component is fixed to the end effector after pick-up, its position has to be measured only once. The measurement of the pads location and movement of the positioner can be executed repeatedly until the desired accuracy has been achieved.

For component alignment, the positioner move must be computed from the component location ($\mathrm{comp}_{X,Y,\Theta}$) and pads location ($\mathrm{pads}_{X,Y,\Theta}$), using the calibrated positioner offset ($\mathrm{off}_{X,Y}$ and off_Θ). The motion computation is done in two steps. First the positioner rotation is computed, being $\mathrm{pads}_\Theta - \mathrm{comp}_\Theta$. The virtual point ($\mathrm{rot}_{X,Y,\Theta}$) that represents the location of the component if it were only rotated, is used for finding the positioner translation. $\mathrm{rot}_{X,Y,\Theta}$ is computed by translating $\mathrm{comp}_{X,Y,\Theta}$ over $-\mathrm{off}_{X,Y}$, rotating it over $\mathrm{pads}_\Theta - \mathrm{comp}_\Theta$ and translating it over $\mathrm{off}_{X,Y}$. The positioner translation is computed by translating $\mathrm{rot}_{X,Y,\Theta}$ over the translation error ($\mathrm{pads}_{X,Y} - \mathrm{comp}_{X,Y}$) and transforming this error to positioner coordinates, using off_Θ.

VII. System Performance

After the system was implemented, cycle time and accuracies were measured. The next two subsections give the results.

A. Cycle Time

The average pick-and-place cycle time was found to be under 10 s. The times are given in Table I. *Pick-and-place times* gives the times for one pick-and-place sequence, if only one fine alignment is performed. Because *vision SMD* is done while the robot moves to the PCB, this time is not included in the *move to PCB* time. The accumulated time is given in *total. Alignment times* gives the times necessary for coarse and fine alignment. When coarse alignment is done before the fine alignment or when two fine alignments are done, the cycle time increases as shown under *cycle times*.

In the alignment times, a delay is included. This is necessary to settle the motion of the robot. The delay could be omitted with a much faster vision and communication system, using closed-loop control [7].

B. Accuracy

Traditionally, the lead/pad overlap is used as the measure of placement accuracy. In industry, margins of 50% are often considered acceptable. However, designing a placement machine to this margin would result in a low reliability [4].

TABLE I
CYCLE TIMES, IN SECONDS

PICK-AND-PLACE TIMES (sec)

pick-up SMD	0.08
move to PCB	0.78
vision SMD	1.23
delay	1.12
fine align	2.1
place SMD	0.62
move to tray	1.87 +
total	7.8

ALIGNMENT TIMES (sec)

	coarse	fine
vision pads	1.03	1.03
computing	0.15	0.15
move	0.52	0.10
delay	1.30 +	0.80 +
total	3.0	2.1

CYCLE TIMES (sec)

coarse alignments	0	0	1	1
fine alignments	1	2	1	2
total	7.8	9.9	10.8	12.9

TABLE II
ACCURACIES OF THE SYSTEM, 3σ'S IN MICROMETERS AND DEGREES

	x(μm)	y(μm)	θ(deg.)
MECHANICAL NOISE			
robot	5	4	0.009
micro positioner	0.9	0.9	0.001
VISION MEASUREMENT			
inaccuracy smd center	1.9	1.2	0.009
inaccuracy pads center	2.3	2.1	0.017
FIXTURE			
maximum feeder and board error	900.0	900.0	2.0

TABLE III
ALIGNMENT ERROR AND COMPUTED OVERLAP FOR VARIOUS MOTIONS, 3σ'S IN MICROMETERS AND DEGREES

ALIGNMENT ERROR	x(μm)	y(μm)	θ(deg.)	computed overlap
coarse	145	90	0.1	92 %
first fine	24	30	0.086	97 %
second fine	8	6	0.012	99 %

measured worst case overlap 95 %

Allowing 95% as a margin, the maximum displacement error of a 100 lead 0.63-mm (25 mil) SMD is 60.0 μm of translation and 0.1 deg of rotation, assuming nominal component and pad dimensions.

Table II gives the measured accuracies of the system. The values given are 3-σ values, computed over a set of values for which occasional outlying values are not included. (Less than 1% of all measurements were rejected.) If normal distribution is assumed, the deviation from the mean is less than 3σ for 99% of all possible values. The x direction is defined along the longer side of the SMD.

The position accuracy of the robot is very dependent on its location in the work space. The values given here apply when the robot is positioned over one specific PCB pad pattern. It should also be noted that these values are only valid after the robot has settled completely.

Alignment accuracy is given in Table III. The computed overlap is calculated from the maximum misalignment and nominal part and board dimensions. The measured overlap is the overlap obtained from photographs of 20 placements (two fine alignments), taken at 50× magnification. The measured accuracy is slightly less than the predicted accuracy because of uncalibrated camera fixturing errors and the slippage in the final component release. The measured overlap also takes bent leads and board errors into account.

VIII. CONCLUSION

A system was developed that consistently placed fine pitch surface mount components accurately on electronic circuit boards with lead to board pattern overlap to better than 95%. The result was achieved by attaching a precise high resolution micropositioner (fine motions) to a general purpose robot (coarse motions) to enhances its placement accuracy. An industrial machine vision system was integrated with a micropositioner to measure the error between the component at the end of the robot pickup device and the PCB target. Placing components with the technique of coarse/fine positioning with endpoint sensing does not require the use of accurate equipment or the need to accurately position the component feeder trays or PCB's. These features offer several advantages over typical component placement systems using coarse positioners and multicamera vision systems. The feature of a single camera vision system provides other advantages.

1) Extra placement steps required with the multicamera systems have been eliminated as the vision processing is done simultaneously with the move of the component from the feeder tray to the circuit board.
2) The number of precise calibrations have been reduced as a result of extra step elimination.
3) Average component placement cycle times of less than 10 s have been achieved.

Improved cycle times as well as improved accuracy would be achieved with a faster vision and communications system. Faster vision processing could allow real-time closed-loop control in aligning the component with its circuit board pattern. Research is under way to investigate the feasibility of closed-loop control [7], [8].

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