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Hierarchical planning for a surface mounting machine placement*

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Abstract: For a surface mounting machine (SMM) in printed circuit board (PCB) assembly line, there are four problems, e.g. CAD data conversion, nozzle selection, feeder assignment and placement sequence determination. A hierarchical planning for them to maximize the throughput rate of an SMM is presented here. To minimize set-up time, a CAD data conversion system was first applied that could automatically generate the data for machine placement from CAD design data files. Then an effective nozzle selection approach was implemented to minimize the time of nozzle changing. And then, to minimize picking time, an algorithm for feeder assignment was used to make picking multiple components simultaneously as much as possible. Finally, in order to shorten pick-and-place time, a heuristic algorithm was used to determine optimal component placement sequence according to the decided feeder positions. Experiments were conducted on a four head SMM. The experimental results were used to analyse the assembly line performance.

Key words: Printed circuit board, Surface mounting machine, Hierarchical planning, Feeder assignment, Placement sequence

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INTRODUCTION

Surface mounted technology (SMT) has been adopted widely in printed circuit board (PCB) assembly. Among various stages of a PCB assembly, component placement is considered critical, so the efficiency of surface mounting machine (SMM) is critical to the efficiency of the whole assembly line. SMM's set-up time and operation time must be minimized to improve productivity. For single SMM, problems are as follows:

1. CAD data conversion: converting CAD data to data needed by assembly.
2. Nozzles selection: selecting nozzles for components.
3. Feeder assignment: finding the location on the feeder rack for feeders containing components.
4. Placement sequence determination: determining component placement sequence.

Design data output by CAD system of PCB is not equivalent to manufacturing data needed by SMM. At the same time, there are many different CAD systems such as PROTEL, ORCAD and so on. Commonly, different CAD system outputs have different format and content design data files. So in order to minimize the set-up time, one good way is to transform these design data automatically to manufacturing data.

Problems 3 and 4 are combinatorial optimization problems, which are well known to be NP-hard (Laarhoven and Zijm, 1993). A few literature discuss these problems about single head SMM. Ball and Magazine (1988) were the first to discuss the placement sequence problem and modeled it as a

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traveling salesman problem (TSP). Leipala and Nevalainen (1989) formulated Problem 3 as a quadratic assignment problem and Problem 4 as a 3-dimensional asymmetric TSP. Yu *et al.*(1997) presented heuristic algorithms to solve these two problems respectively. In addition, there were some researches on SMM with multiple heads. Lee *et al.* (1997; 1998) and Hong *et al.*(1995) proposed some approaches for an SMM with three heads. Burke *et al.*(1999; 2000) proposed a new model to consider both problems together and solve them together for a multi-head placement machine.

In this paper, we consider these problems for SMM with multiple heads and present a hierarchal planning for them. The paper is structured as follows. Section 2 introduces SMM and its placement planning procedure. Section 3 presents the CAD conversion system. Section 4 focuses on Problems 2, 3 and 4. Section 5 discusses the experimental results. The last section covers the conclusion drawn from this research and further research.

MACHINE AND HIERARCHICAL PLACEMENT PLANNING DESCRIPTION

The SMM considered in this paper is illustrated in Fig.1. The machine consists mainly of three parts: worktable, feeder racks and placement heads. The PCB is firstly moved onto the worktable of the machine by a conveyer belt, where it remains fixed at a predefined location during the placement process. Two feeder racks are located on both sides of the PCB conveyor. Each rack has a number of slots for feeders. The number of slots that the feeder occupies depends on its size. Components are supplied to the machine by feeders. Each feeder contains only one type of component. Tape feeder contains small components such as resistors and capacitors. Tray feeder contains large components such as QFP (Quad Flat Pack) and BGA (Ball Grid Array). Multiple heads are installed on the arm and move together with the arm. Each head uses a variety of nozzles for vacuum picking up or placing components. Nozzles of different diameters are used depending on the size of components. The heads pick up components from feeders and place them on the board. We call one time of this picking up and placing components as one pick-and-place cycle. Since the distance between adjacent heads is equal to a whole number of the distance between two adjacent slots, multiple components can be picked up simultaneously in some pickup operations.

Fig.2 shows the hierarchical placement planning procedure and function. The CAD data conversion system first extracts manufacturing data from the PCB design data. Then the converted data are put into a database providing manufacturing data for SMM. This greatly shortens the set-up time. Finally the PCB operation assembly data on nozzle selection, feeder assignment optimization and placement sequence optimization are obtained. The goal of these three optimizations is to minimize operation time.

CAD DATA CONVERSION SYSTEM

The assembly data needed to operate SMM are data on placement positions, components, feeders, nozzles and PCB. Placement position data include

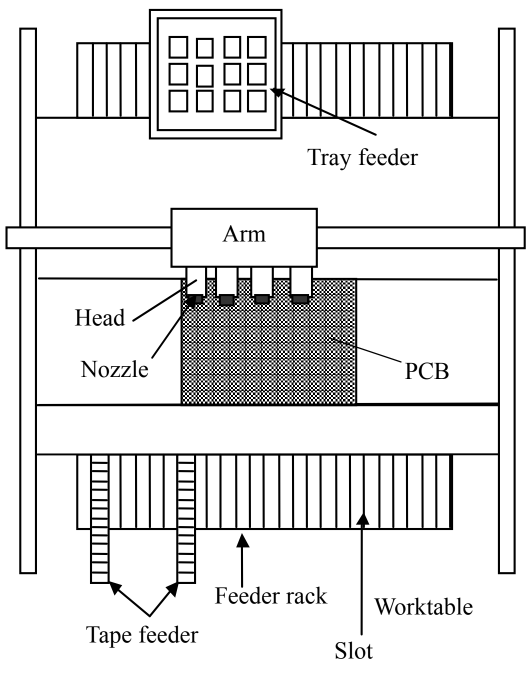

Fig.1 Structure of surface mounting machine

the component name, coordinates, rotation angles of the placing positions, etc. Component data include type and size of the components, etc. Feeder data include feeder types, component type provided by each feeder, feeder location on feeder racks, etc. Nozzle data include component types for the nozzle, position on the nozzle station, etc. PCB data include PCB size, etc. These data (except feeder data and nozzle data) can be obtained from the CAD design data. Design data output by CAD system of PCB has redundant information, such as PROTEL outputs data including pad and reference coordination.

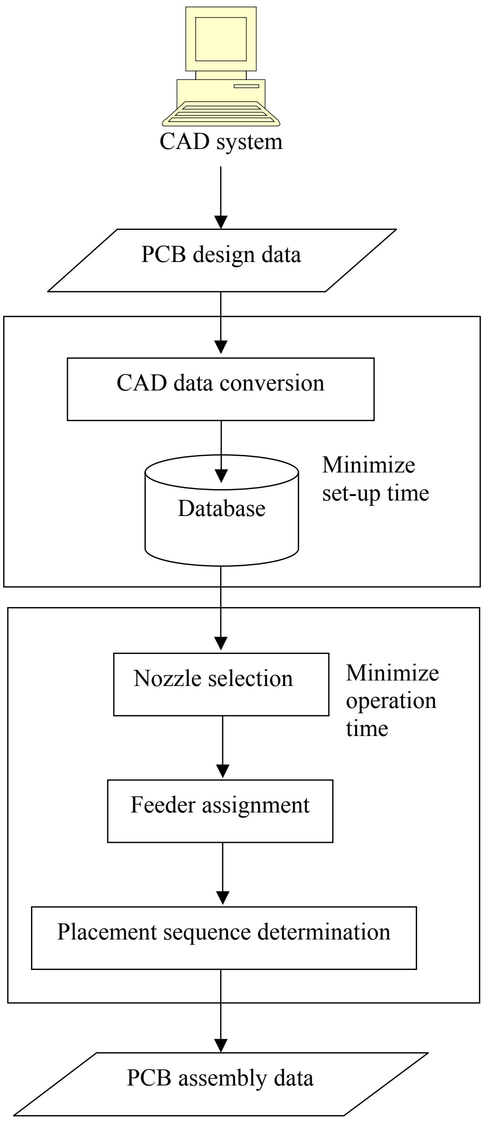

Fig.2 Hierarchical planning and function procedure for SMM placement

To automatically generate the assembly data needed for the machine, a data conversion system is needed to make the CAD design data directly available to the machine.

Fig.3 is the CAD data conversion flowchart. There are many different format design data files from different CAD system of PCB. The conversion system can flexibly extract the basic placing data from them. The basic placement data include design name, component name, coordinates, and rotation angles of the placement positions. In addition, PCB size and component data such as number of component types, component number and size of every type can be obtained too. After reading the CAD design data file, user defines the file format of the output data. Then these data are transformed into ACCESS or text data file to be saved in a database. After the data conversion, the SMM can get the basic operation data directly from the database. This greatly shortens the set-up time.

We will use the following notations:

$|S|$: Cardinality of a set S;

x^*: Minimum of x;

a: Number of slots on the feeder racks;

b: Number of feeders;

h: Number of heads;

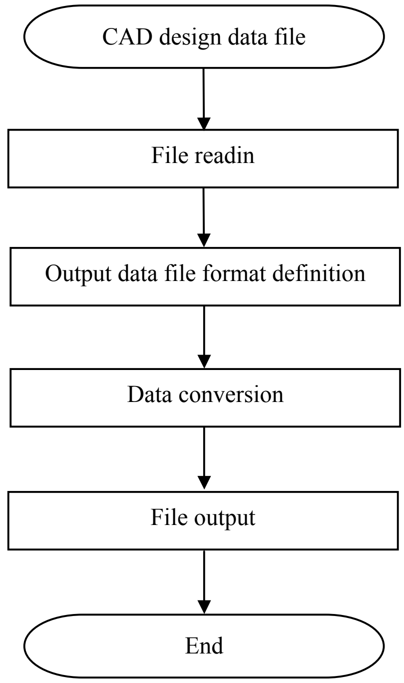

Fig.3 Flowchart of CAD data conversion

l: Number of nozzles chosen to place components;

m: Number of component types;

n: Number of components;

k: Total number of pick-and-place cycles. $n/h\le k\le n$;

c: Set of component types $\{c_1, c_2, \ldots, c_m\}$;

F: Set of feeders $\{f_1, f_2, \ldots, f_b\}$;

P: Set of all components $\{p_1, p_2, \ldots, p_n\}$;

S: Set of slots on the feeder racks $\{s_1, s_2, \ldots, s_a\}$;

Z: Set of chosen nozzles $\{z_1, z_2, \ldots, z_l\}$;

f_{ij}: The feeder that provides No. j component of the No. i picking cycle;

z^c: The nozzle chosen to pick up and place a c type component, $c\in C$;

s_{ij}: First slot occupied by f_{ij};

$\{p_{i1}, p_{i2}, \ldots, p_{ig_i}\}$: Set of components in the No. i pick-and-place cycle;

$\{s_{i1}, s_{i2}, \ldots, s_{ig_i}\}$: Set of first slots of feeders' location providing components in the No. i pick-and-place cycle;

$t_1\{s_{i1}, s_{i2}, \ldots, s_{ig_i}\}$: The total traveling time that heads pick up $p_{i1}, p_{i2}, \ldots, p_{ig_i}$ from feeders locating on the slots $s_{i1}, s_{i2}, \ldots, s_{ig_i}$;

$t\{p_{i1}, p_{i2}, \ldots, p_{ig_i}\}$: The total traveling time that heads place $p_{i1}, p_{i2}, \ldots, p_{ig_i}$ on the PCB;

D_{ij}: The traveling time that the heads move from the last placing position of the No. i pick-and-place cycle to the first picking position of the No. j pick-and-place cycle, $i\neq j$;

λ_{sf}: Binary decision variable equal to 1 if feeder $f\in F$ is in slot $s\in S$, 0 otherwise;

$C(\lambda_{sf})$: Set of component type provided by feeder $f\in F$ in slot $s\in S$ if $\lambda_{sf}=1$, Φ otherwise;

$S(\lambda_{sf})$: Set of slots occupied by feeder $f\in F$ in slot $s\in S$ if $\lambda_{sf}=1$, Φ otherwise.

OPERATION OPTIMIZATION

Nozzle selection

After the transformed data file is obtained, nozzles used to place the components must be selected. There are many types of nozzles equipped on the machine. Each type of nozzle can pick certain types of component. Some components can be picked up by more than one type of nozzle. But only one type of nozzle is used to pick up and place components of the same type here. The nozzle change is an extremely time-consuming operation; therefore the total number of chosen nozzles must be minimized. That is:

$$\mathrm{Min}|Z| \tag{1}$$

$$\text{Subject to } \left|Z \cap Z^c\right| = 1,\ \forall c \in C \tag{2}$$

Constraint (2) requires that there must be one and only one type of chosen nozzle used for one type of component.

The following is nozzle selecting procedure:

Step 1: Get each set of component types which can be picked up by each type of nozzle.

Step 2: Select out the nozzle that can pick up the most types of components.

Step 3: If the selected nozzle can pick up all the types of components, then stop; otherwise repeat to pick out the nozzle that can pick up the most types of components in the remaining nozzles until the selected nozzles can pick up all the types of components.

Feeder assignment

During each cycle, the components are picked up from feeders. The goal of feeder assignment optimization is to obtain the minimum total traveling time of picking up all the components. The object function and its constraints are as follows:

$$\mathrm{Min}\sum_{i=1}^{k}\sum_{s_{i1}=1}^{a}\sum_{s_{i2}=1}^{a}\cdots\sum_{s_{ig_i}=1}^{a}\left\{t^*(s_{i1},s_{i2},\ldots,s_{ig_i})\prod_{j=1}^{g_i}\lambda_{s_{ij}f_{ij}}\right\} \tag{3}$$

Subject to

$$\sum_{s=1}^{a}\lambda_{sf}=1,\ \forall f\in F \tag{4}$$

$$\sum_{f=1}^{b}\lambda_{sf}\le 1,\ \forall s\in S \tag{5}$$

$$\sum_{f=1}^{b} \left| C(\lambda_{sf}) \right| = m \tag{6}$$

$$\sum_{f=1}^{b} \left| S(\lambda_{sf}) \right| \le a \tag{7}$$

$$S(\lambda_{sf}) \cap S(\lambda_{s'f'}) = \Phi,\ f \ne f'$$
$$\forall s, s' \in S,\ \forall f, f' \in F \tag{8}$$

$$\left| C(\lambda_{sf}) \right| = 1 \tag{9}$$

$$C(\lambda_{sf}) \cap C(\lambda_{s'f'}) = \Phi,\ f \ne f'$$
$$\forall s, s' \in F,\ \forall f, f' \in F \tag{10}$$

Eq.(4) requires that the number of one feeder's first slot is only one, e.g. it's position is fixed. Eq.(5) ensures each slot is occupied by at most one feeder. Eq.(6) means the assigned feeders provide all the components. Eq.(7) requires that the slots on the feeder racks can provide enough slots for the feeders. Eq.(8) requires that different feeders occupy different slots. Eqs.(9) and (10) require that one feeder contains only one type of component, and that at the same time, different feeders provide different types of components. Feeders' position and placement sequence affect the overall efficiency. Since the arm has several heads, it can pick up at least one component during one pick-and-place cycle. To maximize the possibility of picking up multiple components simultaneously for determining the placement sequence later, those feeders, from which components could be picked up simultaneously are grouped together and assigned to be adjacent on the feeder bank. It is depicted as follows:

Step 1: Sort the component types in the descending order of the number of components for each type of nozzle.

Step 2: Get the list of component types for each head.

Step 3: Group feeders: While the list of component types for any head is not vacant, pick out the first component type from the head. Group feeders of these selected component types together. Delete these selected component types from each list.

Step 4: Assign slot positions to the feeders in the group. The following is the approach:

(1) Calculate the center of feeder assigning.

(2) Calculate the total number of slots needed for the feeder group. Assign the nearest vacant slots to the center of the feeders in the group. Adjust feeder positions in the group so that the feeder with more components of the same nozzle is nearer to the center.

Step 5: Repeat Steps 3, 4 until the list of component types for each head is vacant.

Placement sequence determination

With the fixed feeder position, the placement sequence is finally determined. The objective mathematical function and its constraints are as follows:

$$\text{Min} \sum_{i=1}^{k} t_2^*(p_{i1}, p_{i2}, \ldots, p_{ig_i}) + \sum_{\substack{i,j=1 \\ i \ne j}}^{k} D_{ij} x_{ij} \tag{11}$$

Subject to

$$\{p_{i1}, p_{i2}, \ldots, p_{ig_i}\} \cap \{p_{j1}, p_{j2}, \ldots, p_{jg_j}\} = \Phi$$
$$i, j = 1, 2, \ldots, k,\ i \ne j \tag{12}$$

$$\bigcup_{i=1}^{k} \{p_{i1}, p_{i2}, \ldots, p_{ig_i}\} = \{p_1, p_2, \ldots, p_n\} \tag{13}$$

$$1 \le g_i \le h \tag{14}$$

$$\sum_{j=1}^{k} x_{ij} = 1,\ i = 1, 2, \ldots, k \tag{15}$$

$$\sum_{i=1}^{k} x_{ij} = 1,\ j = 1, 2, \ldots, k \tag{16}$$

$$\sum_{i=1}^{k} \sum_{j=1}^{k} x_{ij} = k - 1 \tag{17}$$

$$x_{ij} \in \{0,1\},\ i, j = 1, 2, \cdots, k,\ i \ne j \tag{18}$$

Eq.(12) is necessary to avoid a component being placed more than once. Eq.(13) ensures that all components are properly placed. Eq.(14) ensures that there is no vacant and overload operation of each pick-and-place cycle. Eqs.(15)−(18) are requirements for deciding the sequence of the pick-and-place cycles, e.g. components of each pick-and-place cycle must be picked up and placed once and only once. The following steps are used to determine the placement sequence:

Step 1: Sort order of components that each head can pick and place according to the feeder positions.

Step 2: Determine components to be placed in each pick-and-place cycle.

Step 3: Determine picking and placing sequence of each pick-and-place cycle.

Step 4: Determine pick-and-place cycles' sequence.

H stands for the set of components of each pick-and-place cycle, P_i stands for the set of all components that head i can pick, i=1, 2, …, h. The following is the description of method to implement Step 2:

Step 1: j=1

Step 2: set i=1, H_j={}, choose a component P_{new} from P_i, and add P_{new} into H_j

Step 3: if P_i is not empty, then

{

$i = i + 1$,

if existing components in P_i, which are contained by feeders different from all the feeders containing all the components of H_j, choose a component p^1_{temp} from these components, on condition that the distance between the position of P_{new} and the position of p^1_{temp} in PCB is shortest, P_{new}= p^1_{temp}, add p^1_{temp} to H_j,

else choose a component p^2_{temp} from P_i that is different from all the components of H_j and the distance between the position of P_{new} and the position of p^2_{temp} in PCB is shortest, P_{new}= p^2_{temp}, add p^2_{temp} to H_j

}

Step 4: repeat Step 3 until i=h

Step 5: delete the same components from P_1, P_2, …, P_h as components in H_j

Step 6: j=j+1, if P_1, P_2, …, P_h are empty then stop; else go to Step 2.

The problem of determining the sequence of pick-and-place cycles is modeled as a traveling salesman problem. Here the nearest neighbor heuristic algorithm is applied to resolve it.

EXPERIMENT RESULTS

After nozzle selection, feeders' position and placement sequence determine the overall efficiency. In order to validate that the operation optimization approaches, the product efficiency obtained by using the approaches introduced here was compared with the efficiency obtained by using optimized feeder assignment and un-optimized placement sequence. Experiments were carried out on a four head SMM. The distance between two adjacent heads was 17 mm and the distance between two adjacent slots was 8.5 mm. There were 80 slots in front and rear side of the feeder bank respectively.

Table 1 shows the experiment results. l means the number of nozzles. n represents the number of components. m refers to the number of component types. t_u stands for the total assembly time for using optimized feeder assignment and un-optimized placement sequence. t_o stands for the total assembly time by using the approaches introduced here. The measure unit of the total assembly time was second. The results showed that these algorithms could result in up to 45.94% improvement of efficiency when the result obtained by using optimized feeder assignment is compared with that obtained by using the un-optimized generated sequence.

CONCLUSION

This paper focuses on a hierarchal planning for the problems related to SMM placement. In order to

Table 1 Experiment results

l	n	m	t_u	t_o	Reduction (%)
1	41	5	22.88	17.90	21.77
1	88	8	58.97	38.49	34.73
2	116	11	77.10	41.68	45.94
2	151	14	92.33	56.54	38.76
3	189	15	104.56	74.59	28.66
3	230	21	151.40	91.63	39.48
4	264	24	172.00	105.10	38.89
4	372	29	207.38	158.39	23.62

minimize the set-up time a CAD data conversion system is adopted. In order to minimize operation time, optimization approaches for nozzle selection, feeder assignment and placement sequence determination are used. Experiments were done to verify the efficiency of these approaches. The results showed that these algorithms are effective in resolving the problems in the placement process of PCB assembly; and can result in up to 45.94% improvement of efficiency when they are used with the optimized feeder assignment as compared with their use with un-optimized generated sequence.

In further research, we will consider how to assign components of a PCB to several SMMs in a PCB assembly line.

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