Applied Research of Hierarchical Multi-objective Optimization Method in High Speed and High Precision Placement Machine

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Abstract: In practical engineering, placement optimization of multi-head in the high speed and high precision Surface Mount Technology (SMT) is a multi-objective optimization problem. It mainly includes the feeder distribution optimization, the component placement sequence optimization and the nozzle configuration optimization. Optimization problems are complicated and mutual coupling between them. In this paper, the hierarchical multi-objective optimization model is developed. In the hierarchical structure, the nozzle optimization is constructed as a 0-1 integer programming optimization model for the first master hierarchy. In the second hierarchical, component mounting sequence, feeder optimization and picking order are parallel optimized based on the first hierarchy optimization. The respective problems related algorithm strategies have been proposed. The engineering experiments show that this hierarchical multi-objective optimization method can significantly improve the overall performance of the multi-head placement machine with high speed and high precision.

1. Introduction

Multiple machine optimization problems are mainly surfacing mount distribution path optimization and the optimization goal is to make every SMT machine has the highest utilization [1-2]. SMT machine efficiently run is the typical assembly planning, optimization problem, which mainly includes three kinds of decision-making problems of completely different, depend on each other and different levels. The three main problems are discrete, high dimension, nonlinear optimization problem [3]. Most of the previous studies solve these problems by decoupling method [4-5]. The whole optimization effect is not ideal.

In recent years, there are all kinds of intelligent optimization algorithm to solve optimization problem of the multi-head gantry machine with high speed and high precision [6], e.g. hybrid leaping frog algorithm [7], genetic algorithm [8], ant colony algorithm [9], heuristic algorithm[10], particle swarm algorithm [11]. Established model and used intelligent algorithm in the above documents has a good optimization effect. However, the working efficiency of the machine is often optimized through the combination of the feeder optimization and the sequencing optimization, and nozzle optimization study considered to improve the efficiency of the SMT machine is relatively few, especially the research of the nozzle optimization is combined with them is even less.
In this study, the mounting process of multi-head gantry machine with high speed and high precision is presented. Hierarchical multi-objective optimization method is proposed. The 0-1 integer programming optimization model that nozzle matching degree and change number are as optimization goal is built in the least pick-and-place cycle premise. Picking, mounting and feeder layout is further optimized based on this optimization model.

2. Mount process of multi-head gantry machine with high speed and high precision

![Structure of multi-head gantry machine with high speed and high precision](image)

Figure 1 is the structure of multi-head gantry machine with high speed and high precision. In the mounting process, the main factors influencing the efficiency of placement are component assignment, sequence of component placements, nozzle change and heads loads. Therefore, minimizing the replacement times of nozzle, maximizing the heads, loads and arranging the location of the feeder reasonably and pick-and-place cycle of components can reduce the overall time of mount process and improve the efficiency. In this paper, the optimization goal includes: the minimum number of replacements of the nozzle, the minimum number of pick-and-place cycle, as well as the minimum whole appropriateness degree of each pair of nozzle with the components, the most optimal sequence of component placements, the least number of feedings and the shortest moving distance.

3. Hierarchical multi-objective optimization method.

To solve optimization problems of the multi-head gantry machine with high speed and high precision, the two-hierarchy multi-objective optimization method has been proposed. The first hierarchical optimization model is as the nozzle related optimization model in this paper. The optimization mode considers how to configure the nozzle and component assembly under the minimum number of times of pick-and-place cycle. The purpose is to make the nozzle exchange number and the whole appropriateness degree of each pair of nozzle with the component's minimum. Three optimization sub-problems is dealing with parallel at the same time in the second hierarchy. (1) Placement sequencing optimization of components. (2) Assignment optimization of feeders. (3) Sequencing optimization of components picking up.

3.1 Nozzle optimization

The known information of components on the PCB are as input parameters shown in Table 1. The related variable parameters will be solved for the nozzle configuration, optimization problem in the first hierarchy as shown in Table 2. In the entire pick-and-place cycle, the total number of nozzle exchange and matching degree have defined the optimal goal. The following head-nozzle optimization model(I) is established.
\[
\min \ a \sum_{k=1}^{K} \sum_{h=1}^{H} \left| X_{khq} - X_{(k+1)hq} \right| + b \sum_{k=1}^{K} \sum_{h=1}^{H} X_{kht} Z_{kht} \tag{1}
\]

Subject to:
\[
\sum_{k=1}^{K} \sum_{h=1}^{H} Z_{kht} = N_t, \ \forall t
\]
\[
\sum_{q=1}^{Q} X_{khq} = 1, \ \forall k, h \tag{2}
\]
\[
\sum_{t=1}^{T} Z_{kht} \leq 1, \ \forall k, h \tag{3}
\]
\[
X_{khq} = X_{K+1hq}, \ \forall h, q \tag{4}
\]
\[
\mu_k = \sum_{k=1}^{K} \sum_{h=1}^{H} \sum_{t=1}^{T} (X_{khq} - X_{k+1hq}), c_k = \sum_{h=1}^{H} \sum_{t=1}^{T} Z_{kht} \cdot m_{kt} = \sum_{h=1}^{H} Z_{kht} \tag{5}
\]

In the above model formulation (I), a and b are given weight parameters. Constraint (1) guarantees that the sum of the mounting components on the PCB in a k cycle. Constraint (2) ensures that a component type is assigned to a head. Constraint (3) guarantees a component must be handled by only one nozzle. Function (4) introduces t for the convenience of last pick-and-place cycle. Function (5) is for the assignment operation in practice. Its main purpose is to convenient optimization solving in the next hierarchy.

In the nozzle optimization model (I) based on the minimum pick-and-place cycle number, loop variables \( K = \left\lceil \frac{N}{T} \right\rceil \) can be directly get. \([\cdot]\) is said to round up. So \( X_{khq} \) and \( Z_{kht} \) are to solve the variables in the nozzle optimization model (I). They are considered as 0–1 manner. There are \((K \times H \times T + K \times H \times T)\) variables. Constraint (4) and constraint (5) are assignment operation. The total constraints are no more than \((K \times H \times Q + K \times H \times T)\). Obviously, when the head count \( H > 2 \), the total number of variables is greater than the number of constraints. So the above optimization problem always has a solution. The 0-1 integer optimization problem can be directly solved quickly by some mature linear programming algorithm, such as enumeration algorithm or branch and bound algorithm, etc.

| Parameters signs | Parameters description | Parameters signs |
|------------------|------------------------|-----------------|
| \( H \) \( (h) \) | \( H \) is the number of heads, \( h \in \{1,2,\ldots,H\} \) is an index of heads | \( T \) \( (t) \) |
| \( Q \) \( (q) \) | \( Q \) is the number of nozzle types \( q \in \{1,2,\ldots,Q\} \) is indexed | \( N_t \) |
| \( S(s) \) | \( S \) is the number of feeder bank, \( s \in \{0,1,\ldots,S-1\} \) is indexed | \( N \) |
| \( \lambda_{tq} \) | The matching degree when nozzle \( q \) handles components of type \( t \) | \( u_i \) |

\( \lambda_{tq} \) is location coordinates on PCB for components of type \( i \) \( (i = 1,2,\ldots,N) \).
Table 2: Variables in the nozzle optimization model

| Variables signs | Variables description | Variables signs | Variables description |
|-----------------|-----------------------|-----------------|-----------------------|
| \( X_{khq} \)   | 0-1 variable: if component type k is handled by nozzle q on head h, it is 1; otherwise, it is 0 | \( Z_{kht} \)   | 0-1 variable: if component type t is handled by cycle k on head h, it is 1; otherwise, it is 0 |
| \( c_k \)       | The total number of components in the k cycle | \( m_{kt} \)   | The total number of components of type t in the k cycle |
| \( \mu_k \)     | The total number of nozzle exchanges in k cycle | \( K(k) \)     | K is the total number of cycles, \( k \in \{1, 2, ..., K\} \) is cycle index |

3.2 Sequencing optimization of placement

Sequencing optimization of placement site is defined \( U = \{u_1, u_2, ..., u_N\} \), that \( u_i \) is location coordinates on PCB for the ith sequence components in the set \( U \). \( \vec{r} \) is the coordinates of the feeder bank in the most left. Based the \( c_k \) and \( m_{kt} \) obtained in the first hierarchy, the optimization model for each pick-and-place cycle is defined as Eq.(II).

\[
D = \min \left( \sum_{n=1}^{N} d(u_n, u_{n+1}) + \sum_{k=1}^{K} \left( u \sum_{i=1}^{c_k} - \vec{r} \right) - w \sum_{k=1}^{K} d \left( u \sum_{i=1}^{c_k} + \sum_{i=1}^{k} c_i, u_1 + \sum_{i=1}^{k} c_i \right) \right) \tag{II}
\]

In the Eq.(II), \( \sum_{n=1}^{N} d(u_n, u_{n+1}) \) is the relative distance between all components on PCB. \( \sum_{k=1}^{K} d \left( u \sum_{i=1}^{c_k} + \sum_{i=1}^{k} c_i, \vec{r} \right) \) is distance between the last component location and the most left location of the feeder bank on the distance in the left in each pick-and-place cycle. \( \sum_{k=1}^{K} d \left( u \sum_{i=1}^{c_k} + \sum_{i=1}^{k} c_i, u_1 + \sum_{i=1}^{k} c_i \right) \) is the relative position of the last mounting component in the post pick-and-place cycle and the first mounting component in the next pick-and-place cycle for the two adjacent pick-and-place cycle. \( \omega \) is adjust parameter \((0 \leq \omega \leq 2)\). The parameter adjusts the distance optimization objective function of adjacent pick-and-place cycle links. The smallest value of \( \omega \) the less is concerned with it by the model. When \( \omega = 2 \), the overall mounting distance is minimized as much as possible.

In view of the solution of the optimization model (II), the leapfrog algorithm combined with an improved nearest neighbour method is used in this paper. Shuffled frog leaping algorithm (SFLA) is a new heuristic evolutionary algorithm. (SFLA) has efficient computing performance and good global search ability.

Because the initial population in leapfrog algorithm is randomly generated, which increase the randomness and influence performance of the algorithm. An improved nearest neighbour algorithm is used to construct the initial populations to narrow the search space.

3.3 Feeder layout optimization and Feeding sequence optimization

Unilateral feed bank layout is considered in this paper. In subsequent process, feeding is done as far as possible at the same time to reduce the total number of feedings. Voting and grading are used to construct feeder layout according to the upper information. After completion of the feeder layout, the maximize the feeding times at the same time is as the goal. Use the upper information and a heuristic greedy algorithm to optimize the feeding sequence.

4. Engineering experiments

In order to verify the effectiveness and practicability of the hierarchical multi-objective optimization method, the actual engineering experiment has been carried on in this paper. The experiment platform

4
isan SMT machine developed by the institute of Advanced Manufacturing Technology of Changzhou in China. This SMT machine has 80 feeders. There are 40 feeders on each side. The distance between the feeder banks is 21.5 mm. There are 8 heads. The distance between adjacent heads is 21.5 mm. The optimal solution is obtained by the 2010 Ra MATLAB of American Math Works company. Then the related variable information is imported in the second hierarchy. Off-line optimization software of the related optimization algorithm is written for the second hierarchy in VS platform.

The related data, information about PCB in the experiment is shown in Table 3. The number 2 PCB is for example. The matching value situation for the components and the nozzle tip is roughly divided such as Table 4. The smaller $\lambda_{tq}$ is, the more matching of components is. The minimum value is 1. The value that can't match is 1000. This can avoid the model using a nozzle that can't match when the solution is obtained to optimize the changing times.

### Table 3: PCB experimental data

| Group number | PCB index | 1 | 2 | 3 | 4 | 5 | 6 |
|--------------|-----------|---|---|---|---|---|---|
| PCB index   | 1         | 2 | 3 | 4 | 5 | 6 |
| The total number of components | 24 | 57 | 54 | 34 | 52 | 49 |
| Component type number | 4 | 8 | 6 | 9 | 12 | 14 |
| Nozzle type number | 1 | 4 | 4 | 6 | 9 | 10 |

### Table 4: $\lambda_{tq}$ for PCB index is 2

| Component (t) | Nozzle (q) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------------|------------|---|---|---|---|---|---|---|---|
| 1             | 1          | 1 | 3 | 1000 | 1 | 1000 | 3 | 1 | 1000 |
| 2             | 3          | 1 | 1000 | 1000 | 1 | 1 | 3 | 1000 |
| 3             | 5          | 1000 | 1 | 3 | 1000 | 1000 | 5 | 3 |
| 4             | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1 |

Experiment model algorithm parameters are set: the 0-1 integer programming model (I) of the first hierarchy, parameter $a=6$ and $b=1$. The MATLAB optimization toolbox is used to solve. In the sequencing optimal model (I) of the first hierarchy, $\omega = 1.5$, parameters in SFLA are: In the first group experiment, frog group size $P=240$, the number of sub-group $xm=15$, every sub-groups size $xn=16$, iteration number of sub-group $LS=25$. The update location for the frogs allowed size range $\Delta U_{min} = -5$ and $\Delta U_{max} = 5$. The total group iteration $SF=1000$. Termination condition is that the global best solution without obvious improvement after the global ideas consecutive exchange within 10 times. In the second group, $P=360$, $xm=20$, $xn=18$, $LS=35$, $\Delta U_{min} = -8$ and $\Delta U_{max} = 8$, $SF=1000$. The total group iteration $SF=1000$. Termination condition is that the global best solution without obvious improvement after the global ideas consecutive exchange within 15 times.

### 5. Results and discussion

### Table 5: The optimization results

| Group | PCB index | Some main indicators of optimal solution | The second hierarchy |
|-------|-----------|-----------------------------------------|---------------------|
|       |           | The first hierarchy                      | The second hierarchy |
|       |           | Cycles K                                 | Nozzle Exchange number | Match value | Total Moving distance /mm | Maximum feeding times | Minimum feeding times |
|       |           | Variable number                         | Constrain number     | Time        |                          |                      |                      |
| 1     | 1         | 120                                     | 52                   | 8.12        | 0                        | 40                   | 4021.4               | 2                     | 12.67                 |
|       | 2         | 768                                     | 136                  | 68.28       | 0                        | 72                   | 13430.7              | 2                     | 41.97                 |
|       | 3         | 560                                     | 118                  | 43.76       | 0                        | 65                   | 11678.2              | 3                     | 43.92                 |
| 2     | 4         | 600                                     | 89                   | 58.13       | 0                        | 54                   | 6843.6               | 3                     | 21.62                 |
|       | 5         | 1064                                    | 124                  | 163.8       | 1                        | 54                   | 11964.3              | 3                     | 43.92                 |
|       | 6         | 1344                                    | 126                  | 234.5       | 2                        | 51                   | 12076.4              | 4                     | 45.75                 |
The results are shown in table. Table 5 shows some main indicators of optimal solutions. It can be found that when the type of nozzle for PCB requirement quantity is less (nozzle types is less than heads), the nozzle is not changed in first hierarchy. The overall matching is optimized as much as possible. When nozzle types are more than heads, the optimization model is emphasized on how to reduce nozzle change times as much as possible. At the same time, the overall matching value is considered. Obviously the matching value size is less than 1000 and there is not nozzle and components are not matched.

6. Conclusion
Mounting performance optimization of SMT machine with high speed and high precision is studied in this paper. Hierarchical multi-objective optimization method is proposed. Engineering experiments show that the above scheme can better improve the efficiency of multi-head gantry machine with high speed and high precision. Especially hierarchical multi-objective optimization method which dominated by nozzle optimization model has obviously performance optimization for the requirements are relatively high in the PCB mounting process.

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