

Optimization of Pick-and-Place Path for Vertical Rotary Pick-and-Place Machine

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Abstract. This paper investigates the feeder arrangement and component placement sequence optimization for a vertical rotary pick-and-place machine. First, the feeder positions are determined based on the distribution of components on the Printed Circuit Board (PCB). Then, a mathematical model is developed to minimize the placement time during the pick-and-place process. Experimental results demonstrate that the proposed approach effectively reduces the time consumption during the placement process and significantly improves the placement efficiency of the vertical rotary pick-and-place machine.

Keywords: Vertical Rotary Pick-and-Place Machine; Feeder Arrangement; Placement Sequence Optimization.

1. Introduction

Surface-Mount Technology (SMT) technology involves using a placement machine to mount components onto a PCB. Due to the complexity of the placement process, which involves a large number of components, the optimization of pick-and-place machine scheduling has received considerable attention and research. The vertical rotary pick-and-place machine, as shown in Figure 1, features a vertically rotating placement head that can be equipped with multiple nozzles, along with a feeder base, machine frame, placement mechanism, and an automatic nozzle change device (ANC). Each component produced by this machine is supplied by a tape feeder and placed into a feeder slot, with each feeder providing only one type of component.

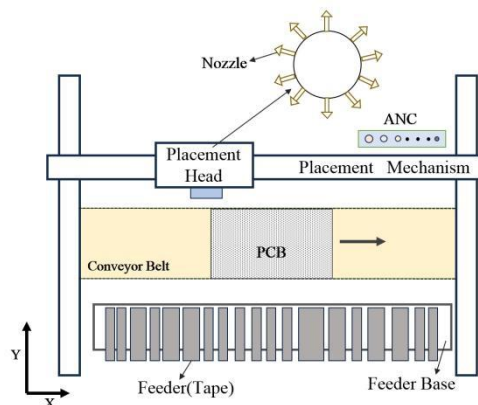


Fig. 1 Schematic Diagram of Vertical Rotary Pick-and-Place Machine

The PCB enters and exits the machine via a conveyor belt, where it is fixed during the placement process. The placement head can move along the X-axis, and the placement mechanism moves along the Y-axis. During placement, the placement mechanism and placement head move above the feeder base. After the placement head's nozzle picks up the corresponding component, it then moves to the PCB to place the component one by one. This process forms a "pick-and-place" cycle, which repeats until all required components are placed on the PCB.

Furthermore, there is a one-to-one or one-to-many relationship between the nozzles and components, meaning that one nozzle can correspond to one or more components. To ensure correct

placement, the nozzle must be switched during the process based on the corresponding relationship between the component and nozzle, allowing the nozzle to properly pick and place the component.

2. Problem Description and Model Formulation

2.1 Problem Assumptions

The pick-and-place process reveals that the primary factors influencing placement efficiency are as follows: (1) Nozzle Switching Time: Switching a nozzle requires a significant amount of time. Reducing the frequency of nozzle switches can effectively minimize placement time. (2) Movement Time of the Placement Mechanism and Head: The placement mechanism moves along the Y-axis, facilitating the movement between the PCB, feeder base, and the Automatic Nozzle Changer (ANC) to position components above the PCB. Simultaneously, the placement head moves along the X-axis, traveling between various feeders to pick up components and sequentially placing them on the PCB.

Due to the complexity of the problem, it is necessary to decompose it in order to reduce the model's complexity and improve solution efficiency. Therefore, we divide the problem into two parts. In the first part, the feeder allocation positions are determined. In the second part, the placement sequence of components within each pick-and-place cycle is decided.

The following assumptions are made: (1) A single machine is sufficient to complete the placement task. (2) Each type of component is supplied by only one feeder and picked up by a single nozzle. (3) The placement head operates at a constant speed vertical rotation and horizontal movement, the placement mechanism also moves at a constant speed. (4) The descent motion of the placement head is neglected.

2.2 Analysis of Nozzle Allocation Problem

The placement of components corresponding to a single nozzle should be continuous. Otherwise, two inefficiencies arise: either the nozzle corresponding to the unfinished component must be replaced and later reinstalled, or the nozzle fails to pick up or place any component during a pick-and-place cycle. Both scenarios result in wasted time. Furthermore, the placement sequence of components on the PCB is identical to their pickup sequence during a pick-and-place cycle. Ensuring a streamlined and uninterrupted sequence is critical for improving efficiency.

2.3 Arrangement of Component Feeder Positions

The position of component feeders directly affects the travel distance of the placement head. Therefore, the feeder positions should be determined based on the distribution of components on the PCB. Specifically, the closer a feeder is to its corresponding component placement point along the X-axis, the shorter the travel distance of the placement head. To address this, a weighted component feeder allocation method is proposed. Let J represent the set of placement points, $J = \{1, 2, 3, \dots, M\}$ and indexed by j , M represents the total number of placement points.

The vertical distance from the j -th placement point to the left edge of the PCB is d_j . Let $\alpha_{ij} = 1$ represent the j -th placement point requires the i -th type of component, and $\alpha_{ij} = 0$ otherwise, the average distance of the i -th type of component to the left edge of the PCB \bar{d}_i is calculated as:

$$\bar{d}_i = \frac{\sum_{j \in J} \alpha_{ij} d_j}{\sum_{j \in J} \alpha_{ij}} \quad (1)$$

where $\sum_{j \in J} \alpha_{ij}$ represents the total number of placement points for the i -th type of component. This formula ensures that the feeder position assignment takes into account the weighted distribution of placement points for each component type, minimizing the travel distance of the placement head.

Feeders are then assigned sequentially from the left side of the feeder base in ascending order of this average distance. In essence, components closer to the left side of the PCB will have their

feeders positioned closer to the left side of the PCB, minimizing the placement head's travel distance. Figure 2 shows a simple example of the feeder arrangement, where the triangular shape of the component is placed closer to the left side of the PCB, so the feeder for that component is placed on the far left.

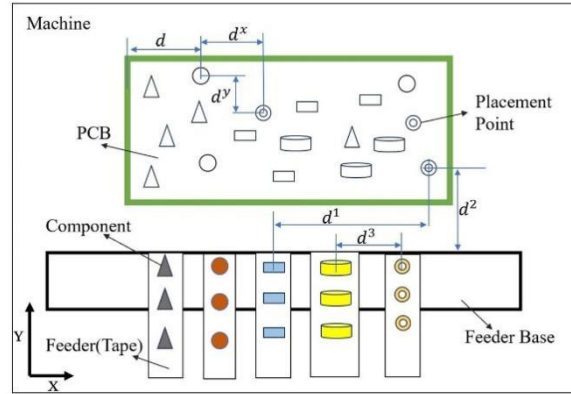


Fig. 2 Schematic Diagram of the Feeder Arrangement

2.4 Overall Placement Sequence of Components

We assume that components using the same nozzle must be placed consecutively to minimize nozzle switching times. The disassembly and alignment processes during nozzle switching account for the majority of the switching time. The placement sequence of components affects the time required for the placement head to travel from the PCB to the ANC. Therefore, this study omits the time required for travel from the PCB to the ANC, having minimized the number of nozzle switches to reduce the back-and-forth time at the ANC.

Let S represent the set of nozzles, indexed by s , the parameter $\beta_{is} = 1$ indicates that component i can be picked up using nozzle s , and $\beta_{is} = 0$ otherwise. $K = \{1, 2, 3, \dots, k^{end}\}$ represents the set of cycle, indexed by k , and k^{end} represents the last cycle. As shown in Figure 2, $d_{jj'}^x$ and $d_{jj'}^y$ represent the distance between placement points j and j' along the X-axis and Y-axis, respectively. d_j^2 represents the distance between the feeder base and placement points j along the Y-axis, $d_{jj'}^1$ represents the distance between the placement points j and the feeder corresponding to placement points j' along the X-axis. Let v_1 represent the horizontal movement speed of the placement head, t_0 represent the time required for vertical rotation of the placement head, v_2 represent the horizontal movement speed of the placement mechanism. R represents the number of nozzles on the placement head.

Let binary variable $x_{jk} = 1$ indicate placement point j is assigned to k -th pick-and-place cycle, and $x_{jk} = 0$, otherwise. Let binary variable $z_{jj'k} = 1$ indicate that placement points j and j' are placed consecutively in the k -th pick-and-place cycle, and $z_{jj'k} = 0$, otherwise. The binary variable $z_{ajk} = 1$ indicate that placement points j is first placed in the k -th pick-and-place cycle, and $z_{ajk} = 0$, otherwise. The binary variable $z_{jbk} = 1$ indicate that placement points j is last placed in the k -th pick-and-place cycle, and $z_{jbk} = 0$, otherwise. The continuous variable u_{jk} represents the order of placement points j in the k -th cycle.

The total time for component pick-up T_1 includes the time spent by the placement head picking up components from the feeders. It is given by:

$$T_1 = \sum_{k \in K} \sum_{i \in I} \sum_{i' \in I} \sum_{j \in J} \sum_{j' \in J} \max \{t_0, d_{ii'}^3 / v_1\} \alpha_{ij} \alpha_{i'j'} \cdot z_{jj'k} \quad (2)$$

The total placement time T_2 refers to the time spent placing components onto the PCB, including the movement time between consecutive placement points. It is expressed as:

$$T_2 = \sum_{k \in K} \sum_{j \in J} \sum_{j' \in J} \max \{d_{jj'}^x/v_1, d_{jj'}^y/v_2\} \cdot z_{jj'k} \quad (3)$$

Let $t'_{jj'}$ represent the longest time between placement point j and feeder corresponding to placement point j' , where $t'_{jj'} = \max \{d_j^1/v_1, d_{jj'}^2/v_2\}$. The time taken to move from the feeder base to placement points is expressed as:

$$T_3 = \sum_{k \in K} \sum_{j \in J} \sum_{j' \in J} t'_{jj'} \cdot z_{j'bk} z_{aj'k} \quad (4)$$

The time taken to move from above the PCB to the feeder base is expressed as:

$$T_4 = \sum_{k \in K \setminus \{k^{end}\}} \sum_j \sum_j t'_{jj'} \cdot z_{j'bk} z_{aj'(k+1)} + \sum_j \sum_j t'_{jj'} \cdot z_{j'bk^{end}} z_{aj'1} \quad (5)$$

The objective is to minimize the total time spent by the placement head and placement mechanism during the entire placement process, the objective function T is to minimize the total time:

$$\min T = T_1 + T_2 + T_3 + T_4 \quad (6)$$

The constraints are as follows:

(1) Each placement point has only one predecessor or successor placement point.

$$\sum_{j \in J \cup \{a\}} \sum_{k \in K} z_{jj'k} = 1, \forall j' \in J, j \neq j' \quad (7)$$

$$\sum_{j \in J \cup \{b\}} \sum_{k \in K} z_{j'jk} = 1, \forall j' \in J, j \neq j' \quad (8)$$

(2) In each cycle, point a is followed by only one point, and point b is preceded by only one point.

$$\sum_{j \in V} z_{ajk} = 1, \forall a, k \in K \quad (9)$$

$$\sum_{j \in V} z_{j'bk} = 1, \forall b, k \in K \quad (10)$$

(3) Introduce constraints to ensure the correct sequence for each placement point.

$$u_{jk} \leq Mx_{jk}, \forall j \in J, k \in K \quad (11)$$

$$u_{jk} + 1 - u_{j'k} \leq M(1 - z_{jj'k}), \forall j \in J \cup \{a\}, j' \in J \cup \{b\}, k \in K \quad (12)$$

(4) A placement point can only have preceding or subsequent placement points within that cycle if it has been assigned to that cycle.

$$z_{j'jk} \leq x_{jk}, \forall j' \in J \cup \{a\}, j \in J, k \in K \quad (13)$$

$$z_{jj'k} \leq x_{jk}, \forall j' \in J \cup \{b\}, j \in J, k \in K \quad (14)$$

(5) Each placement point can only be assigned to one pick-and-place cycle.

$$\sum_{k \in K} x_{jk} = 1, \forall j \in J \quad (15)$$

(6) Each cycle must have no more than the number of nozzles available for the placement head.

$$\sum_{j \in J} x_{jk} \leq R, \forall k \in K \quad (16)$$

(7) Each nozzle used in a cycle can pick a maximum of one component type at a time.

$$\sum_{i \in I} \sum_{j \in J} \alpha_{ij} \beta_{is} x_{jk} \leq 1, \forall s \in S, k \in K \quad (17)$$

(8) A nozzle can only be replaced when all component types assigned to it have been placed.

$$\sum_{k \in K} kx_{jk} - \sum_{k \in K} kx_{j'k} \leq \sum_i \sum_j \alpha_{ij} \beta_{is} - 1, \forall j, j' \in J | \alpha_{ij} \beta_{is} = 1, i \in I, s \in S \quad (18)$$

In solving the model, we incrementally increase k^{end} starting from 1 and solve the model at each step. The minimum number of cycles is determined when the model first becomes feasible, and the solution obtained at that point is considered the shortest placement path.

3. Numerical Study

3.1 Instances

This case involves 13 types of components, with each component having between 1 and 6 mounting points, totaling 34 placement points. The distribution of these mounting points is shown in Figure 3. Each cycle can accommodate a maximum of 11 components. The optimization model is solved by Gurobi 10.0.3. and executed on a Linux server with Intel(R) Xeon(R) Gold 6242R CPU @ 3.10GHz and 251GB RAM in Python.

3.2 Study Result

As shown in Figure 3, the feeders for each component are arranged in increasing order based on their average distance to the left side of the PCB. The figure illustrates the sequence of component pick-up and placement during the first cycle, with the pick-up and placement orders being the same. Since a mounting point associated with a nozzle can only be used once per cycle, only one point is placed in the fifth cycle.

It is evident that each cycle maximizes the number of points covered to minimize the number of placement cycles. Mounting points that are closer together are more likely to be grouped into the same cycle and placed in sequence. Additionally, mounting points closer to the feeding base are more likely to be included in a single cycle, while those farther from the feeding base are also more likely to be grouped together. This arrangement reflects practical considerations, as it helps reduce the placement machine's movement distance during the process.

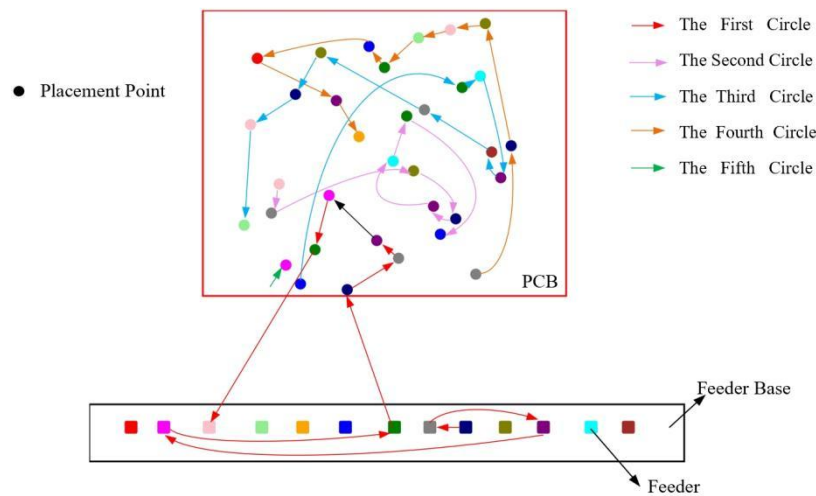


Fig. 3 Feeder Arrangement and Component Placement Sequence

4. Literature References

The optimization of pick-and-place operations in surface-mount technology machines involves multiple interrelated subproblems, making it an NP-hard problem. As the problem scale increases, the difficulty of solving it becomes significantly higher [1]. Therefore, decomposing the entire problem into smaller subproblems and adopting an iterative optimization approach can reduce the solution time. Additionally, using heuristic algorithms, such as genetic algorithms, can help lower the difficulty of solving the problem [2, 3]. Moreover, Zhang et al. aggregate multiple objective function values into the similarity of intuitionistic fuzzy sets and use the optimal foraging algorithm to solve a multi-objective model [4].

The research on Feeder Assignment and Component Sequencing for Vertical Rotary Pick-and-Place Machines is extensive [5,6], where effective reductions in placement time have been achieved through problem decomposition and the use of heuristic algorithms. Additionally,

optimization studies on the placement sequence for other types of pick-and-place machines are similar in approach. Li et al. propose a clustering-based heuristic to optimize nozzle and feeder assignments in a single spin-head gantry-type collect-and-place machine. They assign feeders based on the distance from each component type to the camera and iteratively solve the nozzle assignment, feeder assignment, and pick-and-place sequence subproblems [7]. He Tian et al. developed a genetic algorithm combined with an adaptive clustering approach to solve the entire optimization problem, which includes six interrelated combinatorial subproblems of the dual-gantry revolver-head pick-and-place machine [8]. Li et al. introduced the Cell Division Genetic Algorithm, which reduces the problem dimension to determine the component type handled by each head per pick-and-place cycle [9].

5. Summary

This study investigates the feeder arrangement and component pick-and-placement sequence for vertical rotary pick-and-place machines, aiming to minimize the time spent in the placement process. Specifically, the proposed method organizes the feeders for each component based on its distribution on the PCB, calculating the distance from each mounting point to one side of the PCB, and then arranges the feeders in increasing order of these distances. Furthermore, under the assumption that the feeder arrangement is fixed, each pick-and-placement cycle is modeled as a Traveling Salesman Problem (TSP), with the goal of minimizing the placement time. A mathematical model is developed and experimentally validated. The results demonstrate that the proposed approach significantly improves the placement efficiency of this type of pick-and-place machine. However, the study simplifies the overall placement process, so future research should focus on a more detailed analysis of the machine's entire placement process. Given that the TSP is NP-hard, obtaining the optimal solution becomes increasingly challenging as the problem size grows. Therefore, combining exact and heuristic algorithms may enable faster acquisition of the optimal solution.

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