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Scheduling and Feeder Arrangement for Simultaneous Pickup in PCB Assembly

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Abstract: In this paper, we propose a new method for reducing assembly time in printed circuit board (PCB) assembly by prioritizing efficient simultaneous pickup operation of placement machines. There are three major problems of the scheduling: (1) component feeder location (affects efficiency of pickup operation), (2) mounting sequencing (affects total distance of the mounting tour) , and (3) simultaneous pickup (affects efficiency of pickup operation). To solve these problems, this paper proposes the following approaches. We solve (1) and (3) in a heuristic way by using a random multi-start local search. We solve (2) greedily with putting the result of the feeder array to effective use. The effectiveness of the proposed method was shown through simulations.

Keywords: Optimization, Scheduling, Printed Circuit Board Assembly

1. INTRODUCTION

In this paper, we propose a new method for reducing assembly time in printed circuit board (PCB) assembly by prioritizing efficient simultaneous pickup operation of placement machines.

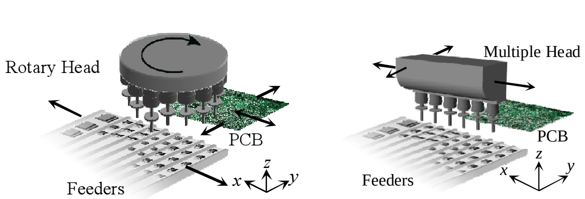
By recent advancement of the surface mount technology (SMT), PCBs have been able to contain smaller and more components. However, it also causes high complexity of the scheduling of component mounting. Despite using same placement machine, the efficiency of the schedule results in major different assembly time. Therefore, it is important to optimize the scheduling of component mounting in order to reduce the assembly time.

Although there are a variety of types of the placement machines, they can be roughly classified into two groups, a rotary type (also known as a revolver type) and a non-rotary type (see also [1] for more detailed grouping)(Fig. 1).

Every placement machine mainly consists of the following elements:

- A component feeder, which contains components,
- A feeder slot, where the feeder is set,
- A nozzle, which picks up the components and mounts them on a PCB,
- A head, which holds the nozzle.

The rotary placement machines have a rotary head



(a) Rotary type.

(b) Non-rotary type.

Fig. 1 An example of the two different types of the placement machines.

to pick up and mount the components simultaneously. While the head is fixed on the placement machine and rotates at the same position, the feeder array and the worktable move so that the head can pick up and mount the components only with its rotation. This type has the advantage of being able to pick up and place the components very speedily, and has been used from the early period on the SMT.

The production planning problems in PCB assembly are surveyed and classified into eight sub problems by [2]. Many of them are NP-hard and it takes high computational cost to solve them. For this reason, conventional works produced a variety of heuristic methods such as [3, 4].

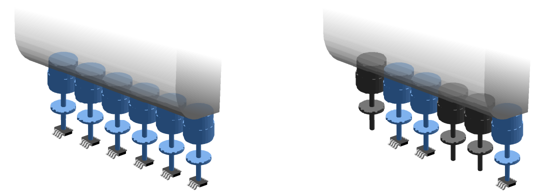
In this paper, we focus on the non-rotary type placement machines. This type is getting popular because of its space-saving and cheaper cost rather than rotary one. They have a multiple head can move freely along the X and Y axes.

For those machines, [5–10] proposed optimization methods. However, relatively few studies consider simultaneous pickup which is efficient technic for reducing assembly time. It shortens assembly time by reducing the number of picking up all the components.

An example of the simultaneous pickup is shown in Fig. 2. When the head approaches a certain position above the feeder, it can pick up not only one component, but also multiple components from the feeder array as many as the other nozzles located above a feeder. This means that the number of pickup times can be minimized to *the quantity of the components divided by the number of heads*.

Simultaneous pickup execution depends on some conditions, e.g., the positions of heads, the feeder array, and so on. Especially the feeder array is important for simultaneous pickup.

Therefore, we focus on the simultaneous pickup, and



(a) Picking up of six components simultaneously. (b) Picking up of three components simultaneously.

Fig. 2 An example of the simultaneous pickup.

propose a method that can optimize a suitable feeder array for simultaneous pickup in order to minimize the assembly time. Because this problem is NP-hard, we solve it in a heuristic way with a random multi-start local search (MLS) which is a simple and robust algorithm [11].

This paper consists of six sections as detailed below. In Section 2, the placement machine is explained, and the scheduling model of our target is described. In Section 3, the problem is described and Section 4 discusses the method of optimization of the placement machine. Section 5 shows the computational experiments and results, and Section 6 describes conclusions and future works.

2. PLACEMENT MACHINE

Here, we describe more details of the placement machine currently we use in this paper (Fig. 3).

One type of the components is lined up on a tape and wound on a reel. The reel is stored in the feeder so that the components can be served one by one to the nozzle. The feeder has several sizes depending on the tape width. It is installed in a feeder slot, and usually occupies one slot. However, wide feeders occupy more than one feeder slot. Therefore, it is necessary to install the feeders appropriately into the slots without feeder overlapping. The feeder slots are obtained at front feeder bank.

After installation of the feeder, the assembly of the PCB starts. The multiple head that is mounted on X-Y beams has several nozzles. The nozzle can pick up and mount the components. The assembly is simply described in the following steps:

1. The head moves to a certain position above the feeder array.
2. The head picks up the components simultaneously as many as possible and iterates from 1) until each nozzle has a component.
3. The head moves to the PCB and places the components one by one on a certain location depending on the component type mounted. After all mounting of the components which are picked up in step 2), the head iterates from 1) until all the components are mounted on the PCB.

To solve the problem, we set the following assumptions:

- The nozzle can pick up any type of components, so that the nozzle changing is unnecessary. Although, we explained that it is necessary to change nozzles appropriately in Section 2. We simplify this problem with this assumption.
- The head can move everywhere without any regard for mechanical restrictions of the movable X-Y beams.
- The components have lower height, so the nozzle does not hit the mounted components on the PCB during the assembling.

The following notations are used in this paper (Fig. 4):

$p_{\max}$: the total number of the placement points,
t : the type of the components $(t = 1, \ldots, t_{\max})$,
j_t : the number of the components of type t $(j_t = 1, \ldots, j_{\max_t})$,

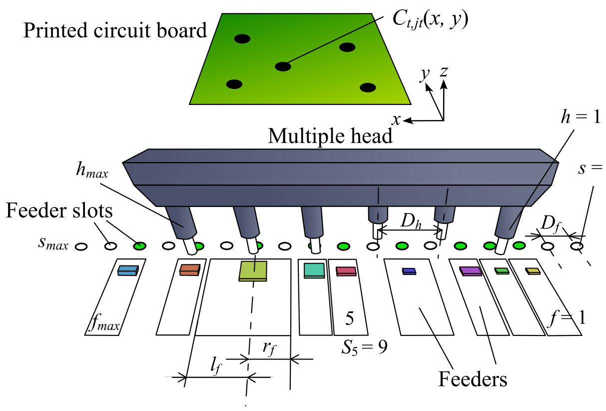


Fig. 4 The structure of our model with the notations $(h_{\max} = 6, f_{\max} = 9, s_{\max} = 18, D_h/D_f = 2)$.

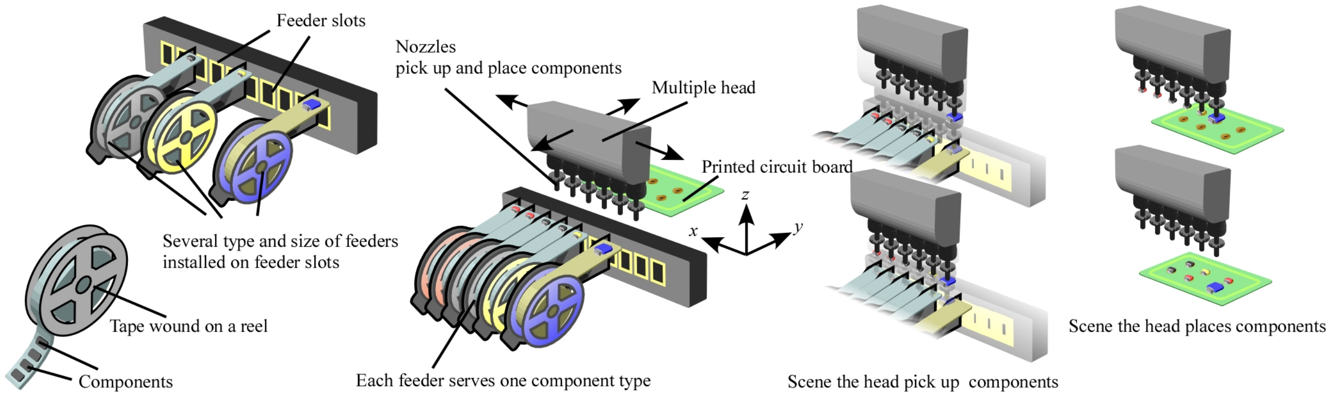


Fig. 3 The structure of the placement machine.

$C_{t,j_t}(x,y)$: the j_t-th placement coordinate in the components of type t,
f : the number of the feeder ($f = 1, \ldots, f_{\max}$),
s : the number of the feeder slot ($s = 1, \ldots, s_{\max}$),
S_f : the feeder slot number of the feeder f,
T_f : the component type of the feeder f,
Q_f : the component quantity of the feeder f,
r_f : the right half of the width of the feeder f,
l_f : the left half of the width of the feeder f,
D_h : the head pitch,
D_f : the feeder pitch,
h : the number of the head ($h = 1, \ldots, h_{\max}$).

3. DESCRIPTION OF PROBLEMS

Many different types of placement machines have common problems which are described by [2]. According to [2], our model is classified into "*single machine, single board type problems*." This problem has mainly three problems related to our model, "*feeder location* (feeder array)", "*placement sequencing* (mounting sequencing)", and "*component retrieval*." Above all, our placement machine model has one more issue that is capable of reducing the assembly time, simultaneous pickup.

The feeder array requires installing the variety of feeders appropriately. The placement sequencing requires deciding the tour on the PCB so that the head can move effectively. The assembly time varies according to the adequacy of the feeder array and placement sequence. The component retrieval becomes a problem in the case that several component feeders of the same type have been assigned to the feeder bank, and it is necessary to decide from which feeder the head should retrieve the component.

4. OPTIMIZATION OF SCHEDULING

To solve the problem of the feeder array, we focus on the contribution of the simultaneous pickup to the assembly time. We aim to optimize the feeder array in order to obtain a maximum quantity of the simultaneous pickup. As this problem is highly NP-hard, we approach it in a heuristics way using random multi-start local search (MLS).

Before deciding the tour, we make pickup patterns capable of the simultaneous pickup regardless of the same type of feeders installed in the feeder bank. As we get pickup patterns first, there is no need to solve the component retrieval which is to decide from which feeder the head should pick up the component in the case that several component feeders of the same type have been assigned to the feeder bank. Considering component distributing to each component feeder of the same type is important. To solve this, we assume that components are distributed equally to the feeders of the same type.

To solve the placement sequence, we choose the shortest way greedily on the basis of the combinations of the pickup patterns.

4.1 Multi-start Local Search

The MLS is one of the meta heuristics method that is an effective approximate for combinatorial optimization problems.

In the local search (LS), an initial solution x is generated at first. Next, a better solution x' adjacent to x is searched changing x slightly. If x' is obtained, adopt x' as x and iterate searching x' until no more better x' can be obtained. The MLS is the method that generates the initial solutions a lot, and it outputs the best solution among the converged solutions.

4.2 Feeder Array

Step 1: Initialization. We define a condition of a feeder array installed to feeder slots as the initial solution. The initial solution is generated as follows:

1. Choose $f_{\max}$ number of feeder slots in a random manner.
2. Initialize all the feeder slots as 0.
3. Allot $f(f = 1, \ldots, f_{\max})$ to each feeder slot chosen by 1), in a random manner.

Step 2: Neighborhood Search. We propose a simple swapping method that swaps two feeder slots chosen in a random manner.

Step 3: Evaluation. In order to obtain an ideal feeder array, it is important to evaluate the solution properly by treating the structure of the problem. Therefore, we designed three evaluation functions, i.e. "feasibility", "head efficiency", and "simultaneous pickup availability." Those evaluation functions output values of V_1, V_2, and V_3 respectively. In order to evaluate the solution, we use the following value V,

$$V = \alpha V_1 + \beta V_2 + \gamma V_3, \tag{1}$$

where α, β, and γ are weighting factors for the evaluation functions. The search is processed by our MLS in a direction of minimizing V.

Step 3–a: Feasibility. The feeder array generated in a random manner may have a case that it is not feasible to install them on the feeder slots because of a feeder overlapping (refer to Fig. 5 for an example). We actually allow the infeasible feeder array for diversity of the earlier solutions. As a final feeder array has to be feasible, we evaluate the feasibility by Eq. (2) setting α weighty

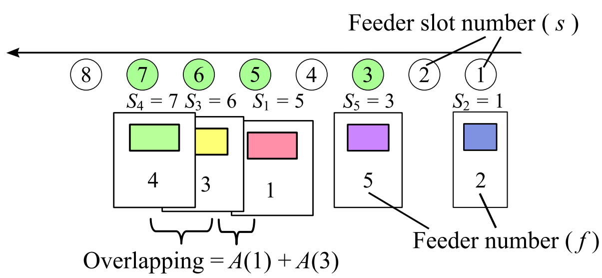


Fig. 5 An example of the overlapping.

rather than β and γ,

$$V_1 = \sum_{f=1}^{f_{\max}} A(f), \tag{2}$$

where $A(f)$ is a quantity of the overlap of a feeder f.

Step 3–b: Head Efficiency. When the head picks up components, it should move effectively to go to and from the PCB without any loss of time. To solve this problem, it needs to gather feeders together near the mounting point on the PCB. Since generating initial solution and neighborhood search tend to have feeders installed discretely on the feeder slots, this function also operates in order not to have scattered feeders. We evaluate the head efficiency by Eq. (3),

$$V_2 = \sum_{f=1}^{f_{\max}} Q_f \left| S_{G_{t_f}} - S_f \right|, \tag{3}$$

where $S_{G_{t_f}}$ is the nearest feeder slot from G_{T_f} which is the arithmetic average of T_f type of components, and G_{T_f} is calculated as follows:

$$G_{T_f} = \sum_{n=1}^{j_{\max T_f}} C_{T_f,n}(x, y). \tag{4}$$

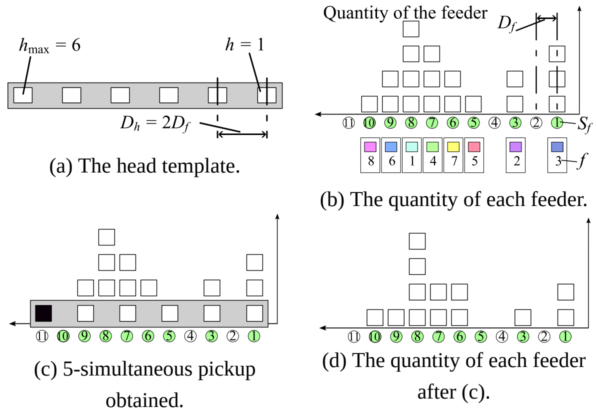
Step 3–c: Simultaneous Pickup Availability. The simultaneous pickup has $h_{\max}$ types which are subject to components number that the multiple head picks up simultaneously. We describe simultaneous pickup which picks up $h_{\max}$ components as "$h_{\max}$-simultaneous pickup."

In order to minimize the pickup times, it is desirable to have the $h_{\max}$-simultaneous pickups as many as possible. In case of having the other simultaneous pickups less than the $h_{\max}$-simultaneous pickup, it is also important to have larger simultaneous pickups than smaller ones.

We propose the head template referring to Fig. 6 to calculate the number of each simultaneous pickup available from the feeder array. The head template is created by D_h/D_f, where D_h is the head pitch and D_f is the feeder pitch. The head template (Fig. 6(a)) shows the case of $D_h/D_f = 2$, and Fig. 6(b) shows component quantity of each feeder by a symbol "□". When the template lies on as Fig. 6(c), 5-simultaneous pickup can be detected(Fig. 6(d)).

The number of each simultaneous pickup is calculated as follows:

1. Choose a feeder slot that has the symbol □ from right side. If there is no feeder slot which has symbol □, stop.
2. Set the head template so that head number "$h = 1$" is located in the feeder slot chosen by 1).
3. Calculate the number of execution of simultaneous pickup.
4. Iterate 3) until the all symbol □ of the feeder slot is taken up.



(a) The head template. (b) The quantity of each feeder. (c) 5-simultaneous pickup obtained. (d) The quantity of each feeder after (c).

Fig. 6 An example of calculating the number of the simultaneous pickups ($h_{\max} = 6, f_{\max} = 8, s_{\max} = 11, D_h/Df = 2$).

5. Iterate from a) with transforming "right side" into "left side."

We evaluate the simultaneous pickup availability by (5),

$$V_3 = \sum_{n=1}^{h_{\max}} (h_{\max} - n)A(n), \tag{5}$$

where:

$$A(n) = \begin{cases} (p_{\max} - C_n) & \text{if } n = h_{\max} \\ C_n & \text{otherwise,} \end{cases} \tag{6}$$

C_n is the number of n-simultaneous pickups calculated in the above method 1–5.

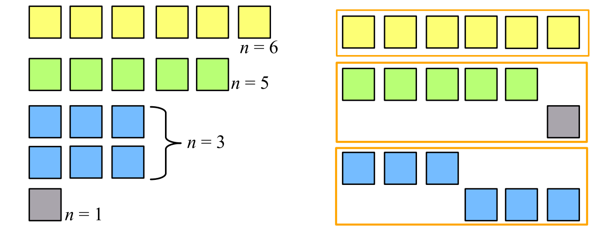
Step 4: Updating. This step compares the evaluated value of the swapped solution with the evaluated value of the former solution. If the swapped solution is better than the other, the MLS iterates from Step 2 with updating the solution by the swapped one. Otherwise it iterates from Step 2 until the neighborhood is all searched. In this case, it saves the converged solution and iterates from Step 1 with generating initial solution until it iterates as many as the specified iteration count. The MLS ends with outputting the best solutions from the converged solutions.

4.3 Pickup Combination

In order to obtain the set of n-simultaneous pickup patterns (Fig. 7 (a)) from the optimized feeder array, we reapply the method used in the "simultaneous pickup availability."

Except the patterns of the $h_{\max}$-simultaneous pickup, the other patterns of simultaneous pickup have to be combined into a group of $h_{\max}$ components (Fig. 7(b)).

Since this combination is also NP-hard, we combine them using our combination list referring to Table 1. Rank 1 means to make a group of 6-simultaneous pickup. Rank 2 means to make a combination of 5-simultaneous pickup and single pickup, which takes 2 times of a pickup action. In the pickup combination, we make the combinations of each rank from the optimized feeder array as



(a) n-simultaneous pickup patterns obtained through the MLS.

(b) Combined pickup patterns with (a).

Fig. 7 An example of pickup patterns before combination and after combination ($h_{\max} = 6$).

Table 1 The combination list ($h_{\max} = 6$).

Rank	Number of pickup times 1	2	3	4	5	6
1	6					
2	5	1				
3	4	2				
4	3	3				
5	4	1	1			
6	3	2	1			
7	2	2	2			
8	3	1	1	1		
9	2	2	1	1		
10	2	1	1	1	1	
11	1	1	1	1	1	1

many as possible, prioritizing a higher rank over a lower one. In order to prioritize a higher rank of the list, we divide some simultaneous pickup patterns into fewer multiple patterns.

The list is made in priority to the following three criteria,

1. The combination which has the $h_{\max}$ components in all,
2. The combination which enables us to pick up $h_{\max}$ components with fewer pickup times,
3. The combination which contains larger number of simultaneous pickups as many as possible.

4.4 Pickup and Placement Mounting

Finally, we solve the mounting sequencing by using the combined pickup patterns.

We calculate $\overline{G}_n$ which is the arithmetic average of the n-th combined pickup patterns.

Figure 8 shows an overview of the method, and detailed steps are shown as follows:

1. Input the initial location of the head C_{init}.
2. Search the nearest $\overline{G}_n$ to C_{init}, and choose n-th combination pickup pattern.
3. Choose components which are used by n-th combination pickup pattern from the one near the $\overline{G}_n$.
4. Make the shortest tour among the placement points.
5. Return to 1) redefining the C_{init} as the last location of the placement point until all placements are done.

5. SIMULATION

In our experiments, we used the parameters as follows:

- 90 placement points ($p_{\max} = 90$),
- 26 feeders ($f_{\max} = 26$),

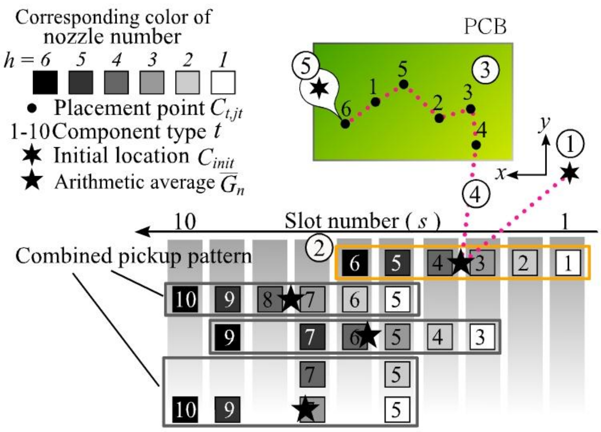


Fig. 8 The overview of the pickup and placement sequencing.

- 60 feeder slots ($s_{\max} = 60$),
- The head pitch is 30 mm ($D_h = 30$) and the feeder pitch is 15 mm ($D_f = 15$).

In the MLS method, we used 500 times of the generating initial solutions as end condition. We decided the weighting factor of $\alpha = 1.5 \times 10^2$, $\beta = 5 \times 10^{-4}$, and $\gamma = 7.5 \times 10^{-1}$ by trial and error.

Figure 9 shows the availability of n-simultaneous pickup using the best results of each iteration of the initial solution, and each result is the average of five times of the MLS with changing the random number sequence we used. In the beginning of the iterations, the 6-simultaneous pickups are relatively rare rather than the other ones. It means that the initial solutions which had scattered feeders caused a difficulty of larger simultaneous pickups. As the iterations progressed, our method found better solutions for the 6-simultaneous pickups, and finally it output the best solution which had the 6-simultaneous pickups accounted for 35 % of total pickups.

The experimental results in Table 2 shows five different assembly times calculated using assembly data sets (AD) we generated as follows:

AD1: Data by our proposed method,

AD2: Data by changing simultaneous pickup into single pickup with AD1,

AD3: Data by our proposed method with setting $\beta =$

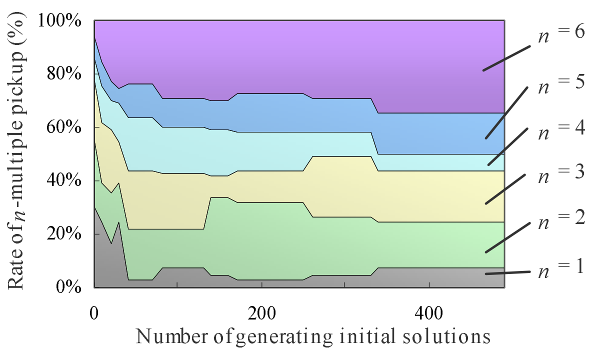


Fig. 9 Rate of n-simultaneous pickup.

Table 2 Assembly time of AD1–AD4

Assembly data	Assembly Time (unit time)		Improvement (%)	Computation time (sec)
	After one generation of initial solution	After 500 generation of initial solution		
1	551.9	168.0	69.6	83.8
2	738.0	255.0	65.5	79.8
3	675.7	180.0	73.4	92.1
4	703.5	191.4	72.8	85.7

5×10^{-3} in order to give the feeder efficiency a priority,

AD4: Data by our proposed method with setting $\gamma = 7.5$ in order to give the simultaneous pickup a priority.

We ran the experiment using a personal computer with Intel® Core™ 2 Quad 2.4 GHz and 2 GB RAM. Each assembly time was calculated by our placement machine simulator, and Table 2 uses internal unit time of our simulator. The improvement means the improvement rate between assembly time after one generation of initial solution and assembly time after 500 generation of initial solution.

The improvement shows that with the MLS of 500 generation of initial solution, we improve the assembly time by 65.5% to 73.4% over the one generation of initial solution (such as Local Search). The longest assembly time recorded by AD2. This indicates that the simultaneous pickup widely affects the assembly time. AD3 and AD4 indicate that the importance of balance of three evaluation values. As to the computation time, we think these results are acceptably short because the assembly data is basically prepared before a production starts (we do not target online calibration).

These results show the effectiveness of the proposed method.

6. CONCLUSION

In this paper, we propose a new method for reducing assembly time in PCB assembly by prioritizing efficient pickup operation of placement machines, simultaneous pickup.

The experimental results show that our method reduces the assembly time by maximizing the number of simultaneous pickups equal to the number of heads.

As a future work, we should improve the algorithm so that we can take nozzle changing, components height, and so on into consideration. Also we will consider using other major optimization method such as GA.

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