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An adaptive clustering-based genetic algorithm for the dual-gantry pick-and-place machine optimization

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ABSTRACT

This research proposes an adaptive clustering-based genetic algorithm (ACGA) to optimize the pick-and-place operation of a dual-gantry component placement machine, which has two independent gantries that alternately place components onto a printed circuit board (PCB). The proposed optimization problem consists of several highly interrelated sub-problems, such as component allocation, nozzle and feeder setups, pick-and-place sequences, etc. In the proposed ACGA, the nozzle and component allocation decisions are made before the evolutionary search of a genetic algorithm to improve the algorithm efficiency. First, the nozzle allocation problem is modeled as a nonlinear integer programming problem and solved by a search-based heuristic that minimizes the total number of the dual-gantry cycles. Then, an adaptive clustering approach is developed to allocate components to each gantry cycle by evaluating the gantry traveling distances over the PCB and the component feeders. Numerical experiments compare the proposed ACGA to another clustering-based genetic algorithm LCO and a heuristic algorithm mPhase in the literature using 30 industrial PCB samples. The experiment results show that the proposed ACGA algorithm reduces the total gantry moving distance by 5.71% and 4.07% on average compared to the LCO and mPhase algorithms, respectively.

1. Introduction

Surface mount technology (SMT) has been widely used in the past two decades to produce printed circuit boards (PCBs). A typical SMT assembly line involves screen printing, component placement and solder reflow operations, as shown in Fig. 1. An electronic device that mounts or places electronic components directly onto the surface of PCBs is called an SMT placement machine. Analyses of SMT assembly lines have shown that SMT placement machines are often a bottleneck whether arranged in parallel or sequentially [1–3]. The focus of this research is the optimization of a dual-gantry pick-and-place machine, which is a category of SMT placement machines, to increase the throughput of an SMT line.

There are many types of SMT placement machines, such as turret-type (also called chip shooter), multi-station, dual-delivery (or dual-gantry), etc. [3]. The technological characteristics of SMT placement machines influence the nature of the problem and its model formulation with constraints [4]. Therefore, it is necessary to state the machine characteristics. A dual-gantry pick-and-place machine has two stations with symmetrical layouts. Each station has one gantry, one fixed camera, one PCB conveyor and one feeder bank. The conveyor belt delivers PCBs in x-direction to a specific position where the electronic components will be placed. The gantry moves between its corresponding feeder bank and the placement area in x-y directions. On each gantry, multiple vacuum nozzles are installed on a revolver head. The nozzles are used to grasp components for the pick-and-place operations. A certain type of nozzle can grasp a subset of components. In each cycle, the revolver head moves to the feeder bank to pick up components one by one from feeder slots, goes through the fixed camera to check quality, and finally places components onto the fixed PCB in the same sequence as the pick-up. Each gantry can take nozzles and components from only its own station but can place components on the PCB at the other station. The unique and important feature of a dual-gantry machine is that each pick-and-place operation alternates between two stations [3]. To be specific, while one gantry is picking up components from feeder slots, the other gantry is placing components on the PCB. Several assumptions are made to define clearly the dual-gantry alternate assembly operations in this research: (1) to avoid gantry collision, one gantry must wait at its corresponding fixed camera while the other gantry is placing components; (2) there are no nozzle change operations during the middle of the placement process, because nozzle change operations are time consuming [5]; (3) two gantries work alternately to mount components onto the PCB at the front station; (4) for each PCB, the front gantry starts placement first.

In most research, the objective of SMT placement machine optimization is to minimize total cycle time [6–9]. However, the calculation of cycle time depends on machine specifications, such as the speed and acceleration of

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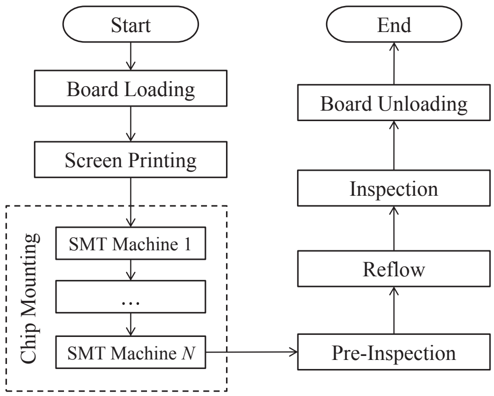

Fig. 1. A typical SMT production process flow chart.

the gantry movement in x, y, and z directions, the rotational speed of heads, etc. To make the results more generic and comparable, distance is selected as a measurement in this research as in [10–12]. Therefore, the objective function in this paper is to reduce the total gantry moving distance, which is similar to the assembly cycle time if the gantry moving speed is a constant. It is noted that because the two gantries could work in synchronization, the total gantry moving distance is not the sum of all moving distances. If two gantries are moving simultaneously, only one gantry's distance is counted. The details of the objective function are presented in Section 3.2. Given the gantry moving speed and pick-and-place time information, such as the table provided in [7], it is possible to translate the gantry moving distance into the cycle time. Six highly interrelated operational decisions should be made to perform assembly operations:

1. The **nozzle setup** decision determines the number and type of nozzles to be installed on the front and the rear gantry heads;
2. The **component allocation** decision determines the components that are placed by each gantry;
3. The **gantry cycle formation** decision determines the components to be picked and placed in a cycle;
4. The **feeder setup** decision determines how the feeders of different component types are arranged on the feeder slots of the feeder bank;
5. The **pick-and-place (PNP) sequencing** decision determines the order in which the components are picked and placed within each cycle;
6. The **gantry scheduling** decision determines the sequence of gantry cycles.

Because the problem is complex, it is unrealistic to solve it exactly using optimization theory [13]. Thus, a genetic algorithm integrated with an adaptive clustering (AC) approach is developed. In this adaptive clustering-based genetic algorithm (ACGA), the component allocation and gantry cycle formation decisions are made by the AC approach, while the other four decisions are solved simultaneously by the genetic algorithm. A numerical experiment is done based on 30 PCB samples from industry to test the proposed method. The experiment results show that the proposed ACGA method yields better solutions than the other clustering-based genetic algorithms and heuristics in literature.

The rest of this paper is outlined as follows. A literature review about the problem, and its solving methods are addressed in Section 2. Section 3 explains the proposed ACGA in detail. Section 4 discusses the experiment results and analysis. Finally, a summary of this paper is provided in Section 5.

2. Literature review

There is an abundance of research on improving the efficiency of SMT machines. To solve an SMT machine operational optimization problem, a series of operational decisions must be made [4]. Thus, many optimization sub-problems have arisen, such as clustering, allocation, assignment and sequencing. No matter what category of an SMT machine is studied, the general SMT machine operational optimization problem is at least as complex as a traveling salesman problem (TSP), which is known as NP-complete [13]. Therefore, it is unrealistic to solve it exactly using optimization theory. Most articles design meta-heuristic algorithms, such as genetic algorithms (GAs) [7,14], simulated annealing (SA) [2,15], and shuffled frog leaping algorithm [16]. Some others solve these sub-problems in a hierarchical structure [17–19].

Electronic components generally have different sizes or types. A certain type of nozzle can pick up a subset of the component types. That is, a nozzle type corresponds to a set of component types, which is referred to as the component-nozzle compatibility [20]. In the context of SMT machine optimization, a nozzle decision involves searching for an effective nozzle assignment and sequencing to ultimately improve the machine throughput [5]. In the problem hierarchy, the nozzle assignment solution acts as a constraint for pick-and-place sequencing. Research on component specific nozzles has been increasing. There are some articles that address nozzle assignment in the context of single-gantry SMT machine optimization [5,20,6].

A dual-gantry multi-head SMT machine is a specific category of SMT placement machines. Dual-gantry operation differs from the simple single-gantry-single-board mode because each pick-and-place operation alternates between two sides [3]. A dual-gantry operation considers more challenging operational decision problems: component allocation (i.e., to balance the workloads of two gantries to maximize the synchronic operations), and gantry scheduling (i.e., to schedule the movement of two gantries to avoid gantry collision) [14]. This research focuses on the optimization of a dual-gantry multi-head pick-and-place machine. A similar machine structure has been studied in [2,7], using SA and GA, respectively. However, to simplify the problem, the component allocation decision is not included in [2]. It is assumed that both feeder banks have the same feeder arrangements, which is not practical. As for the solution, an adaptive simulated annealing method is proposed along with some heuristics such as cheapest insertion, nearest neighbor, and constraint satisfaction swapping. Kulak et al. tackle the problem of determining feeder assignment and placement sequence for both single-gantry and dual-gantry SMT machines by developing GAs [7]. A clustering algorithm called density search construction method (DSCM) [21] is integrated into the GAs for generating groups of placement operations to reduce searching space. Two different component allocation heuristics for feeder duplication and no duplication scenarios are proposed. However, it is assumed that there are universal nozzles. Other works on dual-gantry multi-head machines are [14,18]. Unfortunately, the problem and the associated model formulations are different because of different characteristics of machines.

GA-based approaches have been widely applied in SMT machine optimization. In the conventional GA approach for single-gantry machines, feeder assignment and all placement sequences are represented by a single chromosome and solved together, as in [22,9]. Because more operational decision problems arise in dual-gantry machine optimization, a hybrid GA is usually presented. For instance, a GA is developed for solving the component allocation and feeder assignment problems in combination with a greedy heuristic for workload balancing and pick sequencing [14]. A clustering algorithm and a heuristic component allocation strategy are hybridized into the conventional GA [7]. In addition, GA approaches can solve a specific sub-problem in the context of SMT machine optimization, such as a feeder assignment sub-problem [1], and a placement sequence sub-problem [10]. However, it has been noted that the performance of GA declines significantly when the number of placement operations increases because the efficiency of the GA operators deteriorates in a broader search space.

3. Adaptive clustering based genetic algorithm for dual-gantry optimization

This research focuses on a single SMT machine dual-gantry optimization problem. Two gantries, from the front and rear stations