Improving the Pickups of Components on a Gantry-Type Placement Machine

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***Abstract*— The advantages of using multi-head gantry machines in printed circuit board assembly are flexibility and efficiency combined with a relatively low acquisition price. However, the practical efficiency of this machine type depends on several difficult decisions that have to be made by a machine operator. In this paper two basic problems that have a significant effect on the use of a gantry machine are considered. The first problem deals with the pick-ups of the components using the nozzles in the placement arm and the second problem is about selecting suitable nozzles into the placement arm. The goal is to achieve a better understanding of the difficulty of these two problems and build up effective algorithms that can be used to solve problems in a restricted environment where the rest of the factors, such as the placement order of the components or the component to feeder slot assignment, are fixed.**

***Index terms:* Printed circuit boards, electronics assembly, multi-head placement machines, optimisation, production control**

I. Introduction

Multi-head gantry-type surface mounting placement machines are increasing their popularity because of their speed, flexibility and a relatively low acquisition price. In gantry-type machines the circuit board and the feeders that are located on one or both sides of the placement machine are kept in place, see Fig. 1. The placement arm can be programmed to move along two rails on the (x, y)-plane parallel to the table where the circuit board (PCB) is held. In order to increase the speed of manufacturing there are usually several placement heads for choosing and attaching appropriate nozzles in the placement arm. For an illustration of a placement arm see Fig. 2. The nozzles are interchangeable and there is a separate nozzle magazine adjacent to the machine. While the nozzle capacity of the placement head is typically rather small (say 3 to 10) the magazine is capable of storing more nozzles in order to make the placement of all component types possible. This design brings an element of flexibility to the operation of the machine. There can also be two arms in the machine configuration, in which case they can only pick up components from their own side of the holding table. Then the system has to make sure that collisions are avoided.

Even though the above outlined machine type seems to have a fairly simple structure, defining the most effective way of using it is extremely difficult. This is because there are many choices in methods that can be chosen such as choosing and tactics of using the nozzles, choosing the order of the component feeders and the order of placing the components. All these problems can be formulated into a single optimisation problem that one can attempt to solve using well-known and well-researched operational research methods. However, even most of the single subproblems are too complex to be solved optimally in practical situations and the defining of a relevant target function is a complex matter because the problems are typically multi-goal tasks where the goals contradict each other and are hard to measure. Furthermore, malfunctions and their randomised nature in a deterministically functioning machine can significantly weaken the accuracy of assumptions made using known models. To make matters even more complicated, reaching the globally best solution would demand solving all subproblems simultaneously which is impossible as already many of the subproblems are too complex to be solved optimally.

In this paper we will study the production control of gantry machines through the subproblems moving from simpler problems to more complex ones. The goal is to understand the natural complexity of each problem and for solving the more complex subproblems, introduce algorithms that are sufficiently fast to be used in practice and that find good, often even optimal solutions. Deviating from earlier research [1][4][3] the goal of this paper is not the overall optimisation of the production control, which is extensively handled in for example [2], but a better understanding of the separate subproblems. By this we hope to achieve a better overall view into the factors affecting the efficiency of manufacturing. In particular, we discuss the component pick-up problem in Section 2. The placement sequence is assumed to be fixed. The assignment of nozzles to the placement head is considered in Section 3. An efficient heuristic for the selection of the nozzles is given.

The present paper is a brief introduction into the challenging field of the optimal control of gantry-type placement machines. A preliminary version of this study has been presented in [6] (in Finnish). Full details and proofs are found in [5] and [7] (at the present moment in preparation).

II. Component pick-up problem

The component pick-up problem is about minimizing the number of component pick-up phases. In this simple problem it is assumed that the placement order of the components is fixed, each component can be placed using only a certain type of nozzle and the assignment of nozzles to the placement arm

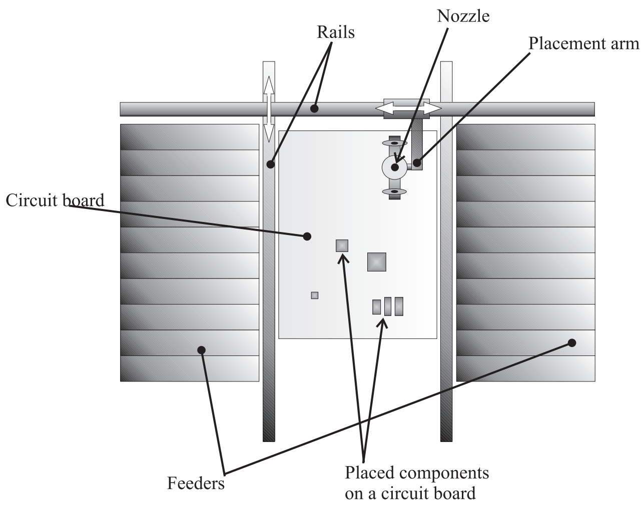

Fig. 1. The structure of a gantry-type machine equipped with one placement arm as seen from above.

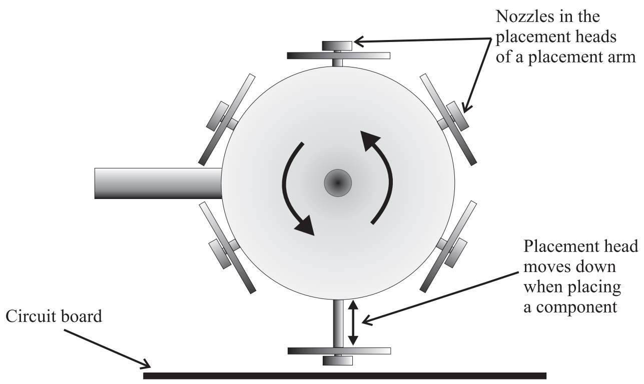

Fig. 2. A side view of the placement arm of Figure 1. The arm has 6 placement heads in which nozzles are attached.

is fixed. The first assumption is actually a simplifying assumption. In practice there are commonly primary and secondary nozzles for some or all components in use but we omit this possibility here to facilitate the understanding of the main idea. It is also postulated that the nozzle capacity of the placement arm is greater than (or equal to) the number of different nozzles required to place all the components on the circuit board so that nozzle changes are not needed. The arm can therefore contain duplicates of some frequently needed nozzles. (A common practice here is to avoid unnecessary nozzle changes by dividing the whole placement task to parts which use the same set of nozzles and to optimize the operations of each of these parts separately.) In the component pick-up problem the goal is to find such a pick-up order of components that the total number of component pick-up phases is the smallest possible. The pick-up phase is an operation where at least one of the nozzles picks up a component from the feeder. Note that the order in which the components are picked up from the feeder to the placement arm is not necessarily exactly the same as the fixed placement order of the components. However, in a single pick-up phase the placement arm has to pick up a certain set of components so that the fixed placement order can still be satisfied. Therefore, the order in which the components are picked up in every isolated pick-up phase is not essential. On a high abstraction level the component placing machine operates in the cycle of four phases: 1) picking up components from the feeder with the placement arm (*pick-up phase*), 2) moving the placement arm above the circuit board (*dislocation to the circuit board*), 3) placing the components on the circuit board (*placement phase*), and 4) moving the placement arm back to the feeder (*dislocation to the feeder*). Thus, in the component pick-up problem the abstraction level is rather high since it is assumed that nothing other than the number of pick-ups has relevance in the overall efficiency of the placing machine, see Fig. 3. It is especially assumed that there are no additional conditions between the pick-up order, the order of the feeder slots and the nozzles in the placement arm. In some machine types the orders of these three parts have to be equal (from left to right) and then this condition has to be taken into account.

An obvious greedy algorithm (`Greedy` from [5]) for the component pick-up problem picks up in each pick-up phase as many consecutive components in a fixed placing order that can be held at a time by the nozzles in the arm. The pick-up phase ends when the next component determined by the fixed placing order cannot be picked up anymore because of the lack of a free suitable nozzle. `Greedy` returns the minimum number of pick-up phases for any job.

It can be shown [5] that the algorithm `Greedy` minimizes the number of pick-up phases. Despite of the fact that the argument looks obvious the solution found by the algorithm is not the only existing optimal solution. In Fig. 3, for example, we have multiple optimal solutions with arm a_1 because in the second last pick-up phase we can pass the last component of type 2 and take it along in the last phase and we will still gain 4 pick-ups which is optimal. The same applies to arm a_2.

III. Nozzle Selection

Another obvious problem related to the policy of using nozzles is the *optimal nozzle selection problem (ONS)*. As with the previous problem it is assumed that the placing order of components and the mapping from the set of components to the set of nozzles are given. It is also postulated, as before, that the nozzle capacity of the arm is greater than the number of different nozzles required to place all the components on the circuit board. Therefore we can make the placing operation more effective by selecting into the arm some extra copies of the nozzles that are already chosen in the arm. The goal is to find such a multiset of nozzles into the placing arm that minimizes the number of pick-ups. In this case the solution of the pick-up problem for a given nozzle multiset can be determined as in Section 2. In Fig. 3, for example, the multiset of nozzles is the best possible in placing arms a_1 and a_2 but it is not optimal in arm a_3 since it yields 5 pick-ups total whereas the optimal would be 4. It turns out that ONS can be solved (at least theoretically) in polynomial time by searching through all possible nozzle combinations that fit in the placing arm. There is a polynomial amount of these kinds of nozzle

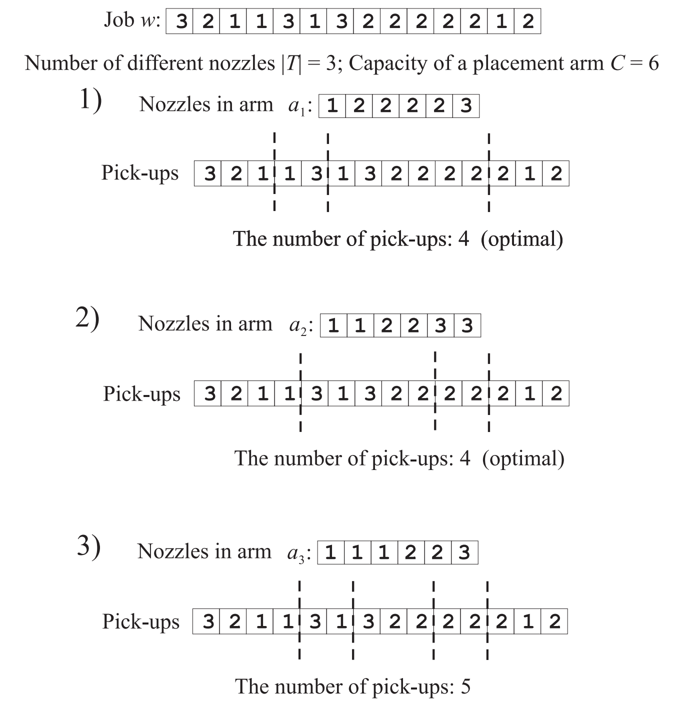

Fig. 3. The pick-ups done by three different arms for a fixed job w. Vector w determines the type of each component to be placed and vector a_i specifies the number of copies of the nozzle types in the arm. In this case arms a_1 and a_2 yield a minimal amount of component pick-up phases but arm a_3 is non-optimal in this respect.

combinations regarding the arm capacity but the degree of the polynomial is very high. In fact, the polynomial is of the form $(C-1)\cdots(C-|T|+1)\ /\ (|T|-1)!$ where C is the arm capacity and T is the set of all nozzle types. Because of the high degree of the polynomial finding out the solution with enumeration will quickly become difficult when the arm capacity and the number of different nozzle types (which is the dominating factor in the polynomial) increase.

The algorithm described above will find the best solution for the ONS but it requires a long execution time and therefore it is useful to build a well working heuristics for the ONS. One way of building up the heuristic algorithm is to base the operation of the algorithm on the usage frequencies of the nozzles. Since the number of components to be placed is usually greater than the capacity of the placing arm we have to select the nozzles into the arm one by one in a heuristic manner. At the beginning we select one nozzle of each type needed. Then we select nozzles into the rest of the nozzle positions one at a time. Each time we take a nozzle of the type which has currently the greatest relative workload (*usage frequency / number of nozzles of a certain type*). We name this principle the *uniform allocation policy*. However, we can also use a *geometric allocation policy* in which the usage frequency is divided by 2 instead of the number of nozzles of a certain type in every inclusion step. Using the geometric allocation policy for arm generation one can achieve solutions where often-used nozzles occur relatively less frequently than in the solutions which have been generated using the uniform allocation heuristic.

The third heuristic for the ONS analyzes the reason for the termination of pick-up phases. The component pick-ups of the job are passed through using the greedy algorithm we discussed in chapter 2. In each greedy pick-up we also write down which nozzle would let us pick up one more component when the lack of a free nozzle ends the pick-up phase. Based on this statistics we give out the next free nozzle position for the nozzle that got most votes and after that we continue this kind of counting until all the C nozzle positions have been filled up.

In the performed tests the frequency-based techniques turned out to be superior. Good results can be reached by using a method that applies the geometric allocation policy which gets close to the optimal results found by brute force algorithms (at least in cases where it is still possible in terms of complexity). Frequency-based techniques can be further improved by local search in the neighbourhood of the initial solution. This is done by removing one copy of a nozzle from the arm at a time and replacing it with a new copy of another nozzle. The added nozzle is the one that causes the number of pick-ups to decrease the most. This process can then be repeated until there is no more improvement. It is guaranteed that the new resulting arm has at least as good performance as the initial solution.

In Fig. 4 there are results from tests of 70 different jobs with the length of 400 component placements. The jobs have been generated using a Markov-model in which the probability of the next nozzle type depends on the type of the previous one. By this model it is possible to generate jobs that have a better resemblance to real life situations than jobs created by using simply a random generator. The Markov-model (see Fig. 5) has six states. States 1, 4 and 2 tend to shape a cycle because they have greater probability to follow each other. State 5 represents a steady state and all states follow states 3 and 6 with the same probability. For clarity the all existing transitions are not drawn into the picture but are given in the abbreviated form. The jobs are generated by selecting a random initial state and proceeding probabilistically to new states until a job of the desired length is drawn. The state numbers indicate the nozzle types of a job. It can be seen from Fig. 4 that it is beneficial to perform local search (imp_ geo) to improve an initial solution given by the geometric allocation policy. This action finds usually an optimal or nearly optimal nozzle assignment.

IV. Conclusion

The algorithms for the ONS problem have been tested on different distributions of the use of nozzles. However, research in this field is still preliminary; even though the results are good, they have been reached by applying the algorithms in simulations. It will be interesting to find out whether for instance an optimal nozzle collection can be directly defined on the basis of the order of the use of nozzles defined by the placing order of the components. Still, this type of analysis seems rather complicated. Another on-going research concerns

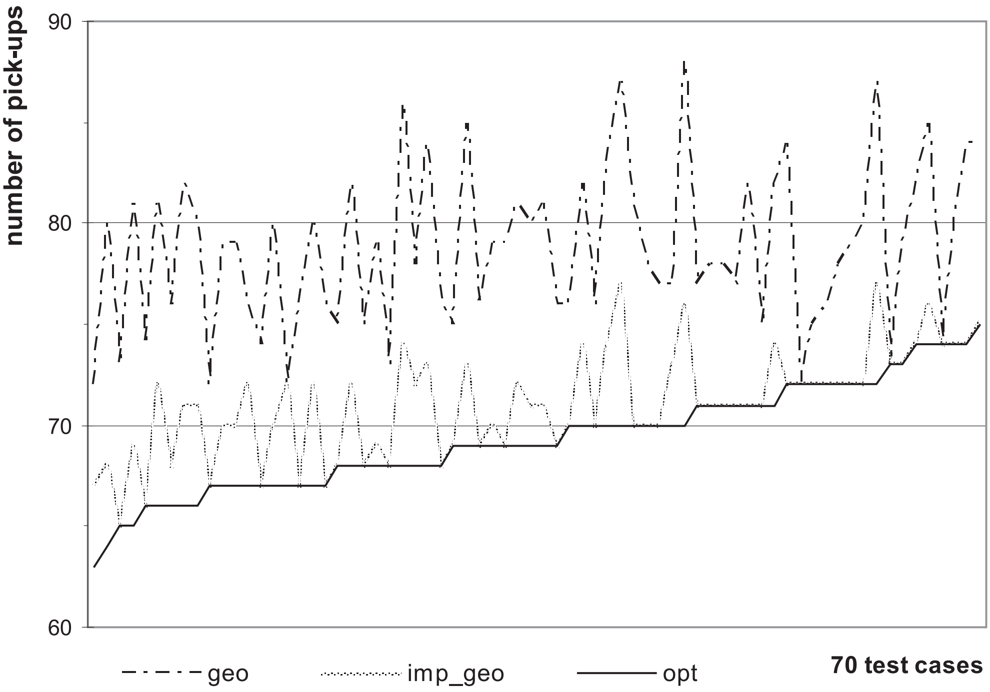

Fig. 4. The performance of the geometric allocation policy (geo) and its improved version (imp_geo) as compared to the optimal solution (opt) for the ONS problem. $|T| = 6$, $C = 12$ and there are 70 different test jobs with the length of 400 component placements each. The test cases have been arranged according to their increasing number of pick-ups.

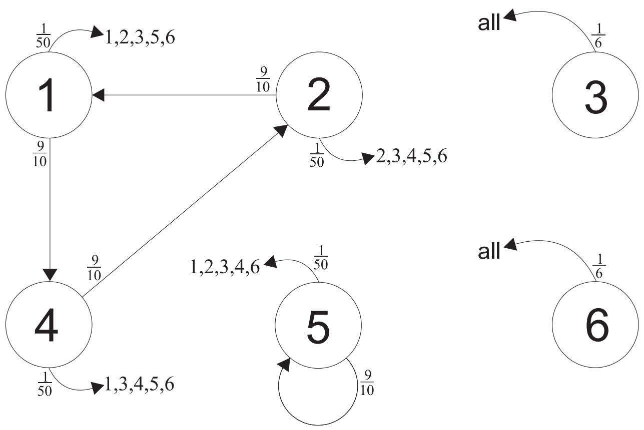

Fig. 5. The six state Markov-model used to generate the test data.

the analysis of the movement of the placement arm during the pick-up of components. Then the feeder setup and the nozzle collection of the placement arm have to be taken into consideration. The matter is further complicated by the fact that the problem must be solved separately for each possible nozzle combination.

It was assumed that no nozzle changes are necessary during the whole placement process. As noted above this is a good assumption when the fixed placement sequence has been planned such that it gives a natural way to partition the whole sequence to no-change parts. A question still remains how to do this partitioning: A new arm setting is needed because some particular nozzle type appears in the placement sequence. It is then possible that the tail of the previous no-change part could be placed with a smaller number of pick-ups by using the arm setting the following no-change part of the placement sequence. While the effect of this choice seems to be small, one should keep in mind that avoiding a number of details of "minor importance" may finally give a solution of second class. A third question deals with the component type to nozzle type mapping which was assumed to be of many-to-one class. The more general many-to-many class was possible to include in the ONS algorithms given here but then one should have some means to put costs to the use of secondary nozzles. A difficulty here is that while the number of pick-up phases is finally attributed to time the use of a secondary nozzle may be indirectly connected to the quality of the end product.

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