# SOLVING THE FEEDER ASSIGNMENT ON A REVOLVER-HEAD GANTRY MACHINE

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Abstract: Revolver-head gantry machines are nowadays very popular because of their flexibility, accuracy and high enough placement speed. In the optimization of this machine type the selection of nozzles into the placement head, the order of the component reels in feeder slots, and the pick-up and placement sequences have to be considered.
In this article, it is assumed that the selection of nozzles and the pick-up and placement sequences are fixed and the feeder assigment is to be solved. The problem statement is formed by analysing the operation properties of a real placement machine. Contrarily to previous literature dealing with this problem, in this work each component can be picked up only by a certain type of nozzle. Finally, four algorithms for solving the problem are proposed and tested. In the experimental tests with realistic data the algorithms performed equally.

## 1 INTRODUCTION

Electronic devices having at least one *printed circuit board (PCB)* inside have become more common in the last 20 years. The PCBs are used not only in the consumer electronics but also for example in cars and as parts of other bigger products. It is typical that a great number of PCBs of the same type are produced in batches and their manufacturing is done in assembly lines which normally comprise of multiple placement machines.

Research on optimisation problems of placement machines dates to late 80's (Ball and Magazine, 1988; Leipälä and Nevalainen, 1989) and it has continued actively through years to these days. There are currently several different types of placement machines in use. They all have their own technical properties and are suitable for different types of assembly tasks, see e.g. (Ayob and Kendall, 2008) for thorough review of different machines, their features and occurring problems in every machine context.

There is a lot of literature that concerns the optimisation of the operations of different types of machines except for *revolver-head gantry machines*. However, this machine type is very popular in industry at the moment. In particular, this deals with the feeder assignment and pick-up-and-place scheduling problems of this machine type. One can find two main trends in the literature on the subject. While there are methods using an evolutionary approach and solving the feeder assignment and plamecent sequence at the same time (Ho and Ji, 2004; Kulak et al., 2007), the others approach these two problems using hierarchic methods, see (Grunow et al., 2004; Lee et al., 1999; Sun et al., 2004; Ho et al., 2007).

In this article, controlling of revolver-head gantry machines is discussed. These machines are known with several names: *multi-spindle gantry placement machines*, *a revolver-head gantry machines*, *a revolver-head machines* and *collect-and-place machines*. See (Ayob and Kendall, 2008) for an illustration of the parts of this machine type. Note, that the placement head of the collect-and-place-machine can also be organised in different way so that the place-

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ment head is a linear array of spindles.

In the revolver-head gantry machine the PCB to be manufactured is kept on the table at a fixed location. The placement head of the machine moves in the $(x, y)$-plane on the PCB and the feeder unit. The placement head is also called revolver-head or even an arm. It picks up the neccessary components from the feeder unit that is located on the side (or sides) of the machine and then mounts them on the PCB.

The placement head is moved by three step motors which run independently. The first one moves the whole gantry on its rails (in $x$-direction). The second motor moves the revolver-head on the gantry (in $y$-direction) and the third motor is used to rotate the revolver-head.

The revolver-head is equipped with multiple spindles, typically 6-12. Each spindle can hold a nozzle which can grab a component. There are many different types of component nozzles. Each component type requires a compatible nozzle. The shape of a component defines what type of nozzle should be used for grabbing it. It is also possible that a certain nozzle type is compatible with several different component types.

The feeder unit is divided into a set of feeder slots of fixed width (typically 8 mm). The slots are loaded with component tapes in which the components are stored one after the other. There are only components of the same type in each tape. Usually, the dimensions of the components are notably smaller than 8x8 mm and they fit a 8 mm tape. However, there are also wider components which are supplied in wider tapes, for example 16 mm. These tapes occupy more than one feeder slots but their use is similar to that of narrow tapes.

At a high abstraction level, revolver-head gantry machines operate in cycles of four phases:

1. *pick-up*-phase
2. *travel onto the PCB* -phase
3. *placement*-phase
4. *travel onto the feeder* -phase

While there are slight differences in the operation principles of different machines, we consider a case, where the design of the machine includes the following details: In the first phase, the revolver-head moves on the feeder unit and collects one component after the other from the right feeder slots keeping the component tapes. Between two pick-up events the revolver-head has to rotate at least one step to get an empty nozzle operable. It is also possible that the revolver-head has to move in the $x$-direction (which is parallel to the length of the feeder unit) onto a correct feeder slot. The revolver can rotate while it is moving to the next pick-up location. In the pick-up-phase, we suppose that the revolver never rotates more than 360° and it can leave one or more nozzles empty by skipping them during the pick-ups.

After at least one component has been picked up the placement head moves onto the PCB area. This is called travel onto the PCB -phase. During this movement, the revolver rotates so that the component which was picked up first in the pick-up-phase can be placed immediately after the head has reached the placement location.

In the placement-phase, the collected components are placed onto the PCB in their correct locations in the same order as they were picked up. The rotation limit of 360° concerns this phase, also. Finally, the empty revolver-head is moved back onto the feeder unit and rotated so that the suitable nozzle for the next component to be picked up is operable again.

If for example 180 components have to be placed on a single PCB the gantry machine with revolver spindle count of 12 makes at least 15 tours described above. However, this requires that all the nozzles are loaded in every single tour. In practice, it is usually impossible to get full loads because of component-nozzle incompatibilities. If the next nozzle in the revolver is not compatible with the next component that should be picked up, the revolver is rotated more than one step forward.

There are placement machines that can change nozzles automatically during the manufacturing process but in many cases the change-process takes too much time and it is therefore avoided. On the otherhand, in some placement machines the nozzle changes can be done only manually and the placement process has to be stopped for doing that.

A setup operation (i.e. change of component tape reels, conveyor belt adjustment etc.) of the placement machine must be performed before the machine can manufacture any new PCB types. At least the following decicions have then to be made:

1. assign the component types into the slots of the feeder unit,
2. define the set of component nozzles and their order in the revolver-head, and
3. define the sequence and tours in which components are picked up and placed.

It has been commonly assumed in previous literature that each nozzle can grab any type of component exist, so there has not been a need to solve the nozzle selection for the revolver-head. However, the situation is often more complicated in practice. The consideration of the nozzle-component compatibility is one of the aspects which tends to make the design of the machine control more difficult. If it is assumed (as it is often done) that every nozzle can pick up any type of component in a single machine then we also have to assume that there are (even for narrow component types) multiple machines in the production line and components are divided among them so that universal nozzle compatibility is achieved in every machine. Algorithms for deciding the nozzle selection of the revolver are proposed in (Pyöttiälä et al., 2006).

The goal of this article is to find such a feeder setup that minimizes *the assembly cycle time (ACT)* of the single multi-spindle gantry machine. We suppose that sequence of component placements and the assignment of nozzles for the head are fixed. We thus consider a subproblem of the total machine control problem. It is assumed that a significant number of PCBs of the same type are manufactured. This set of PCBs is called a *batch*. Here, *ACT* is the time required to manufacture a single PCB in the batch. Clearly, minimizing *ACT* minimizes also the time requirement of the whole batch.

We formulate the *Optimal Feeder Assignment problem (OFA)* in Section 2. The formulation is then used in four heuristics to solve the problem in Section 3. In this formulation we omit the possibility of duplicate compoment tapes in the feeder unit and the delays caused by camera inspections. Further, we suppose that the nozzle-to-arm assignment is fixed for the whole PCB job and revolver rotations can be done in parallel with the head movements. Results of the heuristics are compared with a lower bound in Section 4.

# 2 PROBLEM STATEMENT

## 2.1 Notation and Terminology

The discussion of the previous section leads to the following notation which can be used to describe the determination of *ACT*.

- the set of component types $CT = \{ct_1, \ldots, ct_m\}$
- the recipe of a PCB *i.e.* the set of components and their locations $C = \{c_1, \ldots, c_n\}$, where $c_i = (t, (x_i, y_i))$ such that $t \in CT$ and $(x_i, y_i) \in \mathbb{R}^2$
- the set of nozzle types $NT = \{nt_1, \ldots, nt_l\}$
- for convenience, the location of a component on the PCB is also given by function $cl : C \mapsto \mathbb{R}^2$
- the type of component is given by function $ct : C \mapsto CT$
- the location of the component of a certain type in the feeder is given by function $fl : CT \mapsto \mathbb{R}^2$
- the nozzle requirement of a certain component type is given by function $nt : CT \mapsto NT$
- the nozzle sequence of the revolver-head *i.e.* an *arm* is $\alpha = (n_1, \ldots, n_k)$, where $n_i \in NT$
- distance (Chebychev) between two locations is given by function $d : \mathbb{R}^2 \times \mathbb{R}^2 \mapsto \mathbb{R}$ so that $d((x_1, y_1), (x_2, y_2)) = max(|x_1 - x_2|, |y_1 - y_2|)$
- time required by the revolver-head to *travel* a certain distance is given by function $tt : \mathbb{R} \mapsto \mathbb{R}$
- function $re : C \times \alpha \mapsto \mathbb{N}$ gives the number of rotation steps required to rotate the revolver-head so that the next suitable empty nozzle can pick up a certain component
- function $rf : C \times \alpha \mapsto \mathbb{N}$ gives the number of rotation steps required to rotate the revolver-head so that the next nozzle that holds a component can place it
- time required by the revolver-head to *rotate* certain steps forward is given by function $rt : \mathbb{N} \mapsto \mathbb{R}$
- *pt* is a constant time that a single pick-up or placement takes

A permutation of PCB recipe $C$ is called a *job* and it determines an order in which the components can be placed on the PCB. Each component of set $C$ occurs exactly once in a permutation. Often, we use symbol $W$ for a job and it can be partitioned into $p$ separate subjobs such that $W = W_1 \cdot W_2 \cdots W_p$. (The partitioning is discussed for example in (Knuutila et al., 2007).)

**Definition 1.1** Given arm $\alpha$ of size $k$ and any partition of job $W_i = (c_1^i, c_2^i, \ldots, c_s^i)$, where $s \leq k$. We say that $\alpha$ *can pick up* $W_i$ if and only if $W_i$ is a *subsequence* of $\alpha$.

**Definition 1.2** Given arm $\alpha$ and job $W = W_1 \cdot W_2 \cdots W_p$. We say that $\alpha$ *can execute* $W$ if and only if $\alpha$ can pick up each $W_i$.

## 2.2 Assembly Cycle Time

Suppose that job $W$ of length $n$, arm $\alpha$ of size $k$ and functions as above in section 2.1 are given. Further, let us assume that $\alpha$ can execute $W$ in $p$ separate pick-up and placement tours and the revolver-head (arm) is initially located at the park position $(x_{pp}, y_{pp})$. The assembly cycle time can then be defined as follows

$$ACT(W, \alpha) = cost_1 + \sum_{i=2}^{p-1} \left( cost_i \right) + cost_p,$$

where $cost_1$ is the time consumed in travelling from park position to the location of the feeder slot of the first component type, $cost_i$ is the time that passes in the $i$th tour of the process and $cost_p$ is the time of the last tour and travel time from last placement location to the park position. We denote by

$$cost_1 = tt(d((x_{pp}, y_{pp}), fl(ct(c_1^1)))),$$

$$cost_i = pt + \sum_{j=1}^{|W_i|-1} (cost_{i,j}^{pickup}) + cost_i^{travel\_PCB} + pt + \sum_{j=1}^{|W_i|-1} (cost_{i,j}^{place}) + cost_i^{travel\_feeder},$$

and

$$cost_p = pt + \sum_{j=1}^{|W_p|-1} (cost_{p,j}^{pickup}) + cost_p^{travel\_PCB} + pt + \sum_{j=1}^{|W_p|-1} (cost_{p,j}^{place}) + tt(d(cl(c_{|W_p|}^p), (x_{pp}, y_{pp}))),$$

furthermore,

$$cost_{i,j}^{pickup} = max\left(tt\left(d\left(fl(ct(c_j^i)), fl(ct(c_{j+1}^i))\right)\right), rt\left(re(c_{j+1}^i, \alpha)\right)\right) + pt,$$

$$cost_i^{travel\_PCB} = tt(d(fl(ct(c_{|W_i|}^i)), cl(c_1^i)),$$

$$cost_{i,j}^{place} = max\left(tt\left(d\left(cl(c_j^i), cl(c_{j+1}^i)\right)\right), rt\left(rf(c_{j+1}^i, \alpha)\right)\right) + pt,$$

and

$$cost_i^{travel\_feeder} = tt(d(cl(c_{|W_i|}^i), fl(ct(c_1^{i+1})).$$

Note, that revolver-head rotations and $(x,y)$-travels are simultaneous operations and one has therefore considered which one of these takes longer time (c.f. formulae for $cost_{i,j}^{pickup}$ and $cost_{i,j}^{place}$).

We still summarize the assumptions relating the operation principle of the placement machine.

- Placement head may rotate at most 360° in a single pick-up phase. This concerns also the placement phase.
- The nozzle setup of arm $\alpha$ has at least one nozzle of each type that the executing of job $W$ requires.
- There can be multiple nozzles of the same type in the arm.
- Note, that in our model the number of nozzle types required by $W$ is $\geq 1$ instead of being $= 1$. (This makes a difference from earlier literature on revolver-head gantry machines.)

Now, the main problem of this work can be stated as

**Optimal Feeder Assignment Problem (OFA).** Given recipe $C$, job $W$ and its partition $W = W_1 \cdot W_2 \cdots W_p$, arm $\alpha$ of size $k$ and functions as above (except $fl$). Assign component types to feeder slots so that $ACT(W, \alpha)$ is minimized.

# 3 SOLVING OFA

In this section four different strategies to solve the OFA problem are proposed. The first strategy evaluates simply a set of random feeder assignments. In the second strategy, the neighborhood of the components on the PCB is analysed and the feeder assignment rests on that analysis. This method has been proposed before in (Grunow et al., 2004). The last two strategies are based on the frequencies of the different component types in a PCB recipe. The four methods are described in more detail in the following subsections.

## 3.1 Random Sample Feeder Assignment

The random strategy (random) to decide the feeder assignment is straightforward: a constant number (in our case 10000) of suitable random feeder assignments are formed and their $ACT$s are calculated. The feeder assignment with the lowest $ACT$ is the result of the search process.

## 3.2 MST-based Feeder Assignment

Grunow et al. (Grunow et al., 2004) used a minimum spanning tree (MST) for the analysis of the neighbourhood of components on the PCB. Here, the same idea is applied in algorithm mst.

At the beginning, a fully connected graph of all component placement points on the PCB is formed and the MST of this graph is solved. In the next phase the number of the neighbours in the MST is calculated for each component type. Then the different component types are put in a priority queue using the number of the neighbours as a priority index. Finally, the component type with the highest priority index gets the feeder slot which is at the center of the feeder unit. The component type with the second highest index is then put on the left side of the first one and the third goes to the right side of the first. This dealing process is iterated until all component types in the queue have been assigned to some feeder slot.

### 3.3 Frequency-based Feeder Assignment

In this method (freq), the frequencies of the component types of the PCB recipe are calculated and used as priority indices. The feeder slots are then occupied in the same way as in 3.2.

### 3.4 Frequency-based Balanced Feeder Assignment

Frequency based feeder assignment of subsection 3.3 may lead into a very unbalanced configuration if there are big differences in the number of every second component type. For example, the left half of the feeder unit may feed a significant amount of the components. This can be avoided if the next component type in the priority queue is always assigned on the side which has less components to feed at the moment. This heuristic (freq_bal) implements the balancing property which leads to a more balanced outcome in terms of feeded components. However, the other parts of this method follow the heuristic of subsection 3.3 closely.

## 4 EXPERIMENTAL TESTS

In this section, the results of a set of numerical test with the four heuristics of section 3 are discussed. There are 43 different PCB recipes based on genuine products but they differ from originals slightly. All of them are parts of the actual PCBs because the original PCBs were assembled in a production line of four different placement machines and this article concerns the production control of a single machine. The modifications of the PCBs were done by deleting random periods from the original recipies so that the requirements of different nozzles and the number of feeder slots needed met the limits of a single gantry machine.

The characteristics of the test PCB-recipe set are shown in Table 1. The technical properties of the placement machine are presented in Table 2 and they mainly follow those used in (Kulak et al., 2007).

Table 1: Dimensions and number of components and component types in the tests with 43 PCBs.

| | |
|---|---|
| min number of comp. on PCB | 34 |
| max number of comp. on PCB | 199 |
| smallest board size (mm) | 125.5 x 127.8 |
| largest board size (mm) | 400 x 255.2 |
| min number of comp. types on PCB | 1 |
| max number of comp. types on PCB | 40 |

During the tests, the nozzle selection of the revolver-head and the placement sequence were fixed. The feeder assignment was then solved using the heuristics and *ACT* was calculated for each of the solutions. *A theoretic lower bound* (described below) was also calculated using the written software.

The average values of *ACT*s of the 43 test cases are shown for the heuristics in Table 3. The table also shows an average *ACT* for the theoretic lower bound (theoretic) in which the *ACT* has been calculated for the case where all components are picked up from the center of the feeder unit and placed onto a placement point which is closest to the center slot of the feeder. The *ACT*s for all 43 test cases are presented graphically in Figure 1. The figure shows that there is no statistically significant difference (tested in Excel, t-test) in the efficiency of the different heuristics.

However, the *ACT*s calculated from the results of heuristics were clearly longer than the theoretic lower bound yielded which was naturally expected.

Because the test results of the different methods are equal it can be asked if the optimization of the placement process of the revolver-head gantry machines should be focused more on the placement sequencing and on selecting a suitable combination of nozzles into the revolver-head than on the feeder assignment.

Heuristics proposed in this article give a feasible enough solution for the feeder assignment problem and the placement sequence can be solved for a feeder assignment which has been determined by OFA. (Of course, it is also possible to solve these problems at the same time, for example using genetic approach, see (Kulak et al., 2007).) Even the trivial sampling method (in section 3.1) that randomly generates different solutions produced as good results as the more advanced heuristics. This encourages to think that because the rotation of the revolver takes time anyway between two pick-ups, the order of the component types in the feeder is not so critical when it comes to *ACT*.

Table 2: Technical properties of the placement machine in simulations.

| | |
|---|---|
| velocity in x- and y-axis | 800 mm/s |
| step rotate time | 0.05 s |
| single component placement time | 0.04 s |
| single component pick-up time | 0.04 s |
| feeder slot sizes | 8.0, 12.0, 16.0 mm |
| number of spindles | 12 |
| feeder slot capacity | 40 |

Table 3: Average of *ACT*s for four heuristics and the value of the theoretic lower bound.

| | |
|---|---|
| theoretic | 34.85 |
| random | 41.29 |
| mst | 41.46 |
| freq | 41.50 |
| freq_bal | 41.43 |

# 5 CONCLUSIONS

In this article, the control of a revolver-head gantry machine was discussed and its properties were described. A mathematical model for the assembly cycle time was given for the machine type and the optimal feeder assignment problem (OFA) was formulated.

Four heuristics were proposed for solving OFA of the revolver-head gantry machine. The heuristics were tested and the test results were compared to each other and a the theoretic lower bound. The heuristics performed equally when tests were done with realistic PCB assembly data. Since the different methods yield different solutions to OFA and it still does not have a significant affect on *ACT*, the other problems in the placement machine control context may be more important objects for optimization. For example, selecting a good nozzle combination into the revolver-head and pick-up- and place-sequencing seems to be such a problem.

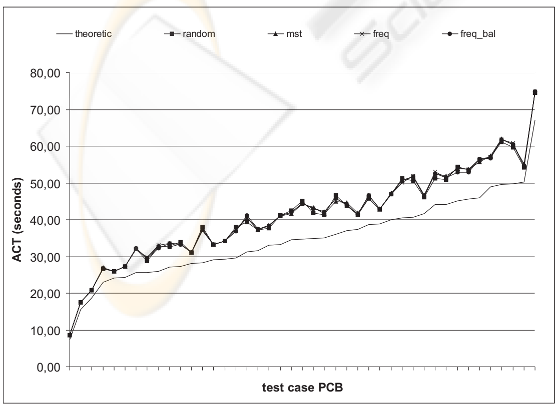


Figure 1: Assembly cycle times of heuristics and theoretic lower bound for all 43 test PCB-recipies.

# REFERENCES

Ayob, M. and Kendall, G. (2008). A survey of surface mount device placement machine optimisation: Machine classification. In *European Journal of the Operational Research, vol. 186, pp. 893-914*.

Ball, M. and Magazine, M. (1988). Sequencing of insertions in printed circuit board assembly. In *Operations Research 36(2), pp. 192-201*.

Grunow, M., Günther, H.-O., Schleusener, M., and Yilmaz, I. (2004). Operations planning for collect-and-place machines in pcb assembly. In *Computers & Industrial Engineering, Vol. 47, pp.409-429*.

Ho, W. and Ji, P. (2004). A hybrid genetic algorithm for component sequencing and feeder arrangement. In *Journal of Intelligent Manufacturing, 15, pp. 307-315*.

Ho, W., Ji, P., and Wu, Y. (2007). A heuristic approach for component scheduling on a high-speed pcb assembly machine. In *Production Planning & Control, Vol. 18, No. 8, pp. 655-665*.

Knuutila, T., Pyöttiälä, S., and Nevalainen, O. (2007). Minimizing the arm movements of a multi-head gantry machine. In *Proceedings of 4th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2007)*.

Kulak, O., Yilmaz, I., and Günther, H.-O. (2007). Pcb assembly scheduling for collect-and-place machines using genetic algorithms. In *International Journal of Production Research, Vol. 45, pp. 3949-3969 No. 17*.

Lee, S., Lee, H., and Park, T. (1999). A hierarchical method to improve the productivity of a multi-head surface mounting machine. In *Proc. of the IEEE International conference on Robotics and Automation*.

Leipälä, T. and Nevalainen, O. (1989). Optimization of the movements of a component placement machine. In *European Journal of Operational Research, 38, pp. 167-177*.

Pyöttiälä, S., Knuutila, T., and Nevalainen, O. (2006). The selection of nozzles for minimizing the number of pick-ups on a multi-head placement machine. In *GTCM2006 Conference, Groningen, The Netherlands*.

Sun, D.-S., Lee, T.-E., and Kim, K.-H. (2004). Component allocation and feeder arrangement for a dual-gantry multi-head surface mounting placement tool. In *International Journal of Production Economics 95 pp. 245-264*.