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The optimisation of the single surface mount device placement machine in printed circuit board assembly: a survey

Masri Ayob[a] and Graham Kendall[b]*

[a]*Department of Computer Science, Faculty of Information Science and Technology, University Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia;* [b]*ASAP Research Group, School of Computer Science, The University of Nottingham, Nottingham NG8 1BB, UK*

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This article surveys research on the single surface mount device (SMD) placement machine optimisation problem. We classify the optimisation problem into five sub-problems: feeder setup, component placement sequencing, nozzle optimisation, component retrieval plan and motion control; and analyse issues relevant to each of these. One of the aims of this article is to provide guidance to other researchers and gain a deeper understanding of the various optimisation issues that arise in this domain. This could lead to the design of improved heuristics, which are more appropriate to the real-world scheduling problem of the SMD placement machine.

Keywords: scheduling; heuristic; printed circuit board assembly; component placement sequencing; feeder setup

1. Introduction

Over the last 20 years, printed circuit board (PCB) production has evolved from a labour-intensive activity to a highly automated activity (Crama, Flippo, Klundert and Spieksma 1997). The introduction of surface mount technology (SMT) has almost replaced pin-through-hole technology in PCB assembly and has enabled the production of high density (allowing many components to be placed onto a PCB in a small area) PCB's (Jeevan, Parthiban, Seetharamu, Azid and Quadir 2002). However, pin-through-hole technology is still preferred for some applications which use high-voltage components, or for applications subject to environmental stresses such as vibration. To be more competitive in today's global marketplace, PCB assembly manufacturers are striving to respond to emerging trends including high quality, low-cost and just in-time delivery. Therefore, in order to enhance their competitiveness, many PCB assembly manufacturers are developing computer integrated manufacturing systems that are capable of producing an effective planning, scheduling and control procedure. Moreover, the demand of automating PCB assembly is increasing with the miniaturisation of component designs and the increasing density of components on the PCB (Moyer and Gupta 1996a and b).

Tirpak (2000) asserts that SMT assembly involves three operations: solder paste, component placement and solder reflow. Surface mount device (SMD) placement machines, which cost between $300,000 and $1,000,000, are often a bottleneck in the assembly line (Moyer and Gupta 1997; Tirpak, Nelson and Aswani 2000; Csaszar, Nelson, Rajbhandari and Tirpak 2000a). It would obviously be beneficial if more effective use could be made of this expensive resource.

Once a PCB has been loaded into the machine, a *fiducial marks* (two to four points, located near the corners of the PCB) operation identifies the position and orientation of the PCB (Magyar, Johnsson and Nevalainen 1999). Once the PCB is secured, the components are placed onto the PCB. The software which guides the placement operation is usually supplied by the machine vendor and is often not very efficient (Shih, Srihari and Adriance 1996). Indeed, Magyar et al. (1999) argued that until now, PCB machine vendors and software companies have not been capable of solving even a single machine optimisation problem efficiently. Once all available components have been placed (some may be missing due to component run outs) the PCB is unloaded from the machine before undergoing a soldering process to adhere components to the PCB (known as solder reflow) (Leu, Wong and Ji 1993).

Due to a lack of standardisation among SMD placement machines, the optimisation of the pick-and-place operations is largely influenced by the constraints of a given machine and the production environment under which the machine is installed (Leipälä and Nevalainen 1989; Shih et al. 1996; Duman and Or 2004).

*Corresponding author. Email: gxk@cs.nott.ac.uk

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When hundreds (possibly thousands) of electronic components of different shapes and sizes have to be placed at specific locations on a PCB, finding an optimal robot travelling route is a complex scheduling task (Su and Fu 1998). Many researchers have modelled the component pick-and-place sequencing problem as a travelling salesman problem (TSP). Therefore, like the TSP, this problem is also NP-Hard and the majority of practical instances are difficult to solve to optimality in a reasonable time (De Souza and Lijun 1995; Ellis, Vittes and Kobza 2001). Indeed, the general PCB assembly problem is at least as complex as the TSP, which is known to be NP-complete (Nelson and Wille 1995).

Moyer and Gupta (1996b) argued that the PCB assembly problem is easy to describe, but due to the computational complexity of the sub-problems involved, in practical terms, it is hard to solve to optimality using mathematical programming approaches. Nelson and Wille (1995) stated that an exact solution using optimisation theory is unrealistic. For example, the component pick-and-place sequencing problem is a quadratic integer program that is difficult to solve using exact methods for even unrealistically small problems (Liggett 1981). The complexity of the problem is due to the interrelated sub-problems where the quality of the component pick-and-place sequence is dependent upon the feeder setup and component retrieval sequence, and vice versa (Bard, Clayton and Feo 1994). Indeed, the concurrent movement of many machine parts (such as turret rotation, feeder carrier and PCB table) requires a full examination of all feasible combinations of feeder setups and component retrieval sequences in order to determine the best feeder setup and component retrieval sequence for each feasible solution of the component pick-and-place sequence. Moreover, the component pick-and-place sequencing problem is also tightly intertwined with the nozzle optimisation problem where seeking a good component pick-and-place sequence, without considering nozzle optimisation, might lead to unnecessary (possibly many) nozzle changes, which is very inefficient. In addition, there are many other issues that should be considered in optimising these sub-problems such as the grouping of components in a sub-tour (i.e. what components should be picked-and-placed together in each route if there is more than one pipette/nozzle per head); the speed differences among PCB table, feeder carrier and head movement; component transportation time; simultaneous pickup; etc.

De Souza and Lijun (1995) stated that exact methods are unsuitable for this problem and, as a consequence we have to consider heuristic and meta-heuristic approaches so that we can find good quality solutions in reasonable times. As an alternative, Moyer and Gupta (1996a) recommended simplifying the problem. For example, Ball and Magazine (1988), Gavish and Seidmann (1988), Leipälä and Nevalainen (1989), Chiu, Yih and Chang (1991), Ahmadi (1993), Van Laarhoven and Zijm (1993), Bard et al. (1994), Crama et al. (1996, 1997), and others have split the problems into a series of sub-problems in order to reduce the size of the search space.

Ayob and Kendall (2002a, 2008), carried out a survey of machine classifications and addressed optimisation issues based on the characteristics and operational methods of the SMD placement machines. The work related the machine characteristics and operational methods with the heuristics that have been applied. To complement these surveys, this article surveys a single machine optimisation problem that highlights optimisation issues in each sub-problem. The optimisation problems are classified into five sub-problems, revealing some of the issues from each category, these being feeder setup, component placement sequencing, nozzle optimisation, component retrieval plan and motion control sub-problems. We aim to provide other researchers with a better understanding of the various optimisation issues in this field, and subsequently enable them to design and utilise heuristics, which are more appropriate to the real-world scheduling problem.

2. The SMD placement machine

The first pick-and-place SMD machines were introduced in the 1980s. These machines had only one placement head (Bentzen 2000). Many other types of machines are now available including sequential pick-and-place, rotary disk turret, concurrent pick-and-place, dual-delivery, multi-station, multi-head, etc. (Grotzinger 1992; Khoo and Loh 2000; Gastel 2002; Ayob and Kendall 2008). As different SMD machines exhibit different characteristics, Wang, Nelson and Tripak (1999), Burke, Cowling and Keuthen (2001) and Ayob and Kendall (2008) argued that the PCB scheduling process is heavily influenced by the particular SMD machine being used.

Typically, each placement machine is fitted with feeder carrier(s) (or feeder magazine), PCB table(s), head(s), nozzle(s) (tool or gripper), pipette(s), tool magazine(s) (or tool bank), camera and trash bin. Figures 1 and 2 show one type of SMD placement machine (the picture was taken at the DIMA (DIMA SMT Systems, NL, B.V., Beukelsdijk, 5753 PA Deurne. (url: http://www.dimasmt.nl/)) factory, Holland). Depending on the machine specification, the feeder carrier, PCB table and head can either be fixed or moveable.

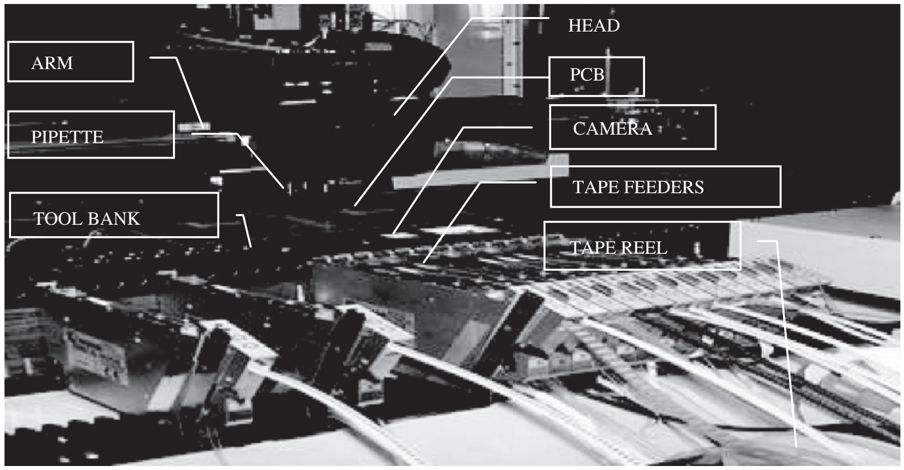

Figure 1. An example of an SMD placement machine (Dima HP-110).

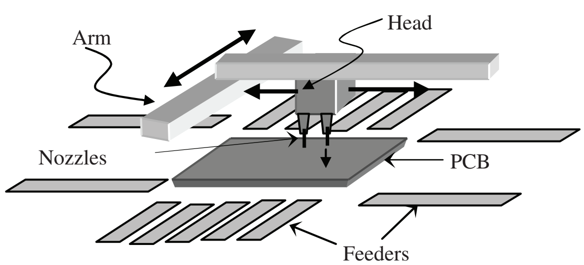

Figure 2. A multi-head SMD placement machine.

The feeder carrier is mounted on one, two, three or four sides of the machine and holds several feeder banks. The feeder bank has several feeder slots where the component feeders are located. The component feeders provide the machine with a continuous supply of components. The component feeders are arranged according to a predetermined arrangement. Figure 3 shows some of the available component feeders (pictured at the DIMA factory), which has various types of component packaging: tape, sticks and trays (or waffle). Tape reel feeders feed components that are packed in embossed, paper or surf tape. Depending on the component size, typical tape widths are 8, 12, 16, 24, 44, 56 and 72 mm (Bentzen 2000). Several slots may be occupied by one tape reel feeder (Sun, Lee and Kim 2005). If the components are supplied in sticks or tubes, then stick feeders are used to feed the components. Bentzen (2000) recommended avoiding using components with stick feeders for mass production, due to the delicate handling they require. The tape reel and stick feeders are arranged on the feeder slots of the feeder banks/carriers. Larger components, which are supplied in trays, are fed using tray feeders. Some machines allow a single tray to be placed into the machine feeding area whilst others use an automatic tray-handling unit. The use of a tray feeder further increases the optimisation problem that need to be addressed. A platform (that holds the trays component feeders) changeover takes about 10 s (for the HP-110 machine, for example). Therefore, optimising the tray feeder operation, if they are necessary, becomes a critical stage of the optimisation process.

The placement arm, that is equipped with head(s), is responsible for transporting components from feeders to PCB points. Located at the end of each head is a pipette(s), which hold a nozzle(s). The pipette(s) and nozzle(s) are used to grasp the components for the pick-and-place operations and moves in the Z direction (up–down). Each head may have more than one pipette and each machine may have more than one head. There are various types of placement heads, such as a rotating turret head, or a positioning arm head (Wang et al. 1999; Ayob and Kendall 2002a, 2008).

Each component packaging type can be associated with more than one nozzle type and vice-versa. The problem is more complicated as one component type can have more than one type of packaging. This means that each PCB point on the board can receive only one component type, but those components may have different packaging. The component packaging can be recognised and aligned without a vision camera (i.e. using mechanical alignment on the fly), using a small vision camera and/or a large vision camera, depending on the component packaging specification. When a defective component is detected, the machine head will discard it into the trash bin.

Different nozzle sizes are required for the various types of component packaging. An automatic nozzle change system is used to ensure that the correct nozzle