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Virtual Machine Models in Electronics Assembly

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Abstract

Electronics assembly systems are increasingly automated and capital intensive. As technology progresses, the circuit cards produced by such systems are more complex, and there is a greater level of product customization. These factors translate into significant challenges in production system design and operation. In the design stage, one must be able to predict system performance accurately. In production, equipment must operate efficiently and be able to react in a robust manner to minimize potential disruptions.

The first step in addressing these challenges is to develop high fidelity models of production equipment (e.g., machines which place components on circuit cards). We are currently using Virtual NC to develop such models, which can be used to study the effect of different component placement sequences and different equipment setup configurations on machine cycle time. Eventually, we plan to integrate these models with optimization heuristics designed to solve the difficult problem of determining a component placement sequence and equipment configuration to minimize cycle time for production of a given circuit card type. This integrated toolset will allow a manufacturing engineer to determine near-optimal sequences and configurations, and then determine the resulting cycle times via detailed simulation.

In this paper, we discuss the concepts underlying our virtual machine models, present progress to date, and describe plans for future research. This research is being conducted at the Virtual Factory Lab at the Georgia Institute of Technology.

Biographies

Douglas A. Bodner is a research engineer in the School of Industrial and Systems Engineering at the Georgia Institute of Technology. His research involves developing generic modeling representations for manufacturing systems, applying new computing technologies and paradigms to the study of manufacturing systems, and developing integrated sets of modeling and analysis tools for manufacturing systems design and improvement.

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Andrew McLaughlin received the Bachelor of Science in Mechanical Engineering from the United States Military Academy in 1991, whereupon he was commissioned as a Field Artillery officer. After spending five years in the Army and receiving the rank of Captain, he returned to graduate school at Georgia Tech, where he is pursuing Masters degrees in Mechanical Engineering and Management.

Mark L. Spearman is an associate professor in the School of Industrial and Systems Engineering at the Georgia Institute of Technology. He received the Ph.D. degree from Texas A&M University in 1986. His research addresses the need for improved manufacturing models and production control methods.

Chen Zhou is an associate professor in the School of Industrial and Systems Engineering at the Georgia Institute of Technology. His research interests include manufacturing systems control and analysis. In system control, his interests include equipment interface problems, and in system analysis, his interests include dimensional measurement and dispatching strategies.

Introduction

As electronic products proliferate in the marketplace, it is increasingly important to produce electronic elements quickly and inexpensively. To do so, however, is not an easy proposition. There are a number of complex equipment design and configuration problems that must be solved first. For example, given that a system must produce a certain type of electronic element, how does one assign production operations to machines, and how does one configure the equipment hardware and software to operate most efficiently? Likewise, how does one design a machine so that it operates in an efficient manner, with a minimal number of run-time errors?

This research effort focuses on the assembly of printed circuit boards (PCBs). Circuit boards are used in a wide array of electronic products, ranging from computers, to automobiles, to toasters. A PCB is characterized by a substrate (i.e., a board) onto which a variety of electronic components are attached. Electronic components include capacitors, resistors, integrated circuits, etc. Components are placed on a board by highly automated placement machines. The type of placement machine studied here uses surface mount technology (SMT) for attaching components to a board.

Electronic products are becoming more sophisticated and complex. As a result, components and even circuit boards themselves are becoming smaller and more intricate. In addition, there is a pronounced trend toward product variety and customization. Manufacturers, therefore, often must produce a number of different board types on the same placement machines. These considerations increase the complexity of equipment design and operation problems.

Due to product size, intricacy and complexity, PCB assembly equipment is highly automated and capital-intensive. There is a need for high fidelity models to study equipment performance off-line, to aid with equipment design and configuration decisions. In the design stage, these models can be used to prototype a proposed equipment design and predict its performance. In operation, these models can be used to evaluate various equipment configuration alternatives. The performance metric of interest is cycle time (i.e., the time needed by a machine to perform its operations on a PCB).

This paper describes the development of high fidelity simulation models of individual placement machines (i.e., "virtual machine models") using Virtual NC . This work is being done at the Virtual Factory Lab at the Georgia Institute of Technology. The remainder of the paper is organized as follows. First, the class of placement machines to be modeled is described. Next, the problems to be solved with the models are discussed, and the virtual machine model concept and implementation are detailed. At this point, the virtual machine model serves as a tool for what-if analysis (e.g., testing different pre-specified equipment configuration alternatives). The paper concludes with a brief discussion of future plans. The first is to integrate optimization heuristics with the virtual machine model. Such heuristics would generate equipment configurations, which would then be tested with detailed simulation. The second is to implement capability that would allow the model to be driven by a pre-recorded stream of data from actual production equipment.

Placement Machine Description

A placement machine is a complex electromechanical device. Since this research addresses cycle time issues, the primary focus is on the logistical characteristics of the machine. These are the characteristics that impact the time needed for placement of components on a board, and that also impact the time needed to load and unload a board from the machine's work position. Therefore, the focus centers on the mechanisms that place components on the circuit board, how they are configured, and how they operate during board assembly. A schematic of the type of placement machine considered here is illustrated below in Fig. 1.

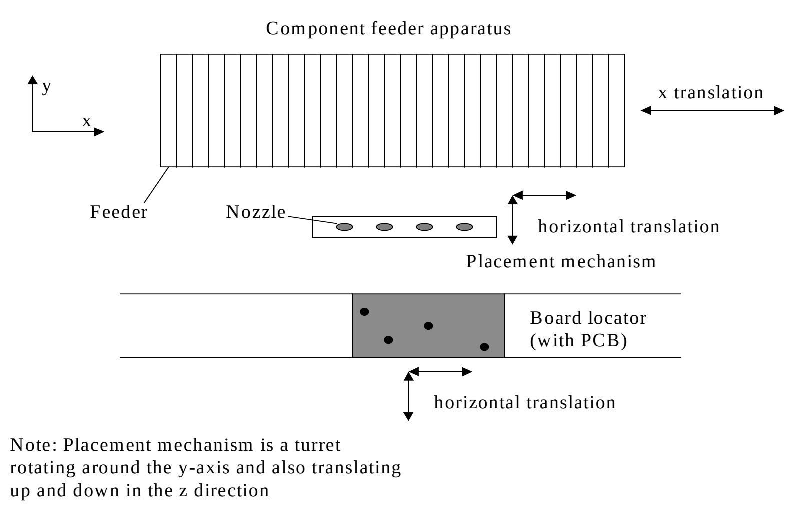

Fig. 1 – Abstract representation of placement machine mechanisms

From a logistical perspective, a placement machine has three fundamental mechanisms that interact to assemble components onto a circuit card.

- A *board locator* aligns the board substrate into proper position and holds it during component placement. In some machines, the board locator moves the board during assembly so that it is positioned properly for placement of a component. As shown in Fig. 1, this movement is in the horizontal (x-y) plane.
- *Component feeders* contain the different components that the machine must assemble onto the board. Each feeder contains components of a particular type. Often, the components in a feeder are contained in a reel. When a component is removed from the reel for placement, the feeder mechanism advances the next component on the reel into the removal, or "pick" position. In some machines, the component feeder apparatus moves in the x-direction so that feeder of the component type to be removed next is in a pre-defined "pick" position.
- A *placement mechanism* picks components from the feeder slots and then attaches them to the board at designated locations. This mechanism is a rotating turret consisting of a number of placement heads that pick and then place the components. Each placement head has a nozzle that picks a component using a vacuum. While it holds a component, a head may perform other operations on it such as rotation, tweezing, or inspection. The placement mechanism can move in the x-y plane as it translates from the component feeders to the PCB, and it also moves in the z-direction when picking or placing components.

This project uses a particular type of machine as a proof-of-concept model. In this machine, the board locator remains stationary during component placement. The component feeder apparatus is likewise stationary. The placement mechanism performs all movement needed to transport components from the feeders to their locations on the board. The placement mechanism is housed within a gantry-like apparatus that translates in the y-direction, from the component feeders to the board locator, along two rails. The placement mechanism, or turret, translates in the x-direction and also rotates along the y-axis.

In making a series of component placements, the turret loads a pre-determined sequence of components at the component feeders onto each of its placement heads. Then, the apparatus moves in the x-y plane so that it is located over the board. It deposits the components in the same sequence onto their designated locations on the board. The gantry and the turret move simultaneously and independently in the x- and y-directions. Thus, their movement is characterized by a Chebyshev distance metric.

During component pick-up, the turret rotates so that each head can pick a component, and the turret adjusts its position along the x-axis so that the placement head can pick a component from the appropriate feeder. Likewise, during component placement, the turret rotates so that each head can place its component on the board, and the gantry apparatus adjusts its horizontal position so that the placement head is directly over the appropriate position on the board. When picking and placing components, the turret moves down and then returns up (i.e., in the z-direction). The placement mechanism uses a vision guidance system in placing components. This guidance system can introduce some uncertainty in the time needed to make a placement.

Components have varying sizes. Size is important in arranging the components within the component feeder areas. Obviously, larger components require more room in the feeder area. This is important because there is often limited room in the component feeder area. If there is not enough room to house all component types that a machine needs to produce its assigned board types, the feeder arrangement within the machine must be physically reconfigured between production runs of different board types. Also, large components require large nozzles on the placement head. Hence, if the arrangement of nozzle sizes on the placement head does not match the component sizes for a given sub-sequence of component pick-ups, the placement heads must skip picking up a component. This results in idle placement nozzles and obviously has a negative impact on cycle time.

Problem Specification

The basic problem of interest here is two-fold. The first problem is to develop an accurate and high fidelity representation of the machine with animation. The second problem is to characterize the cycle time problem and develop a model that one may use easily to test different equipment configurations.

Modeling Issues

Clearly, the model must represent the three mechanisms that interact to perform component placement. It must also represent components and PCBs. Additionally, it must account for the conveyor mechanism, which loads boards into the machine and then takes them from the machine after assembly is performed. Finally, it must represent the static frame of the machine. In addition to the three dimensional geometries of these elements, the model must capture their dynamic behavior and their interactions.

Virtual NC provides many useful modeling constructs that allow the representation of these elements, their behavior and interaction. The main difficulty is gathering the data needed to run the model. The geometries associated with the machine and PCBs can be measured fairly easily. However, the movement times for the various mechanisms are not so easily measured. These times must account for the acceleration and deceleration profiles of each moving mechanism. These profiles may not be readily available from the machine specification. If this is the case, the modeler must perform significant data gathering to obtain the profiles.

The specific type of machine modeled here does not have a moving component feeder apparatus or board locator. Hence, the modeler needs only to be concerned with representing the dynamic behavior of the placement mechanism. In other applications, though, the board locator and component feeder apparatus may move. In these cases, the three mechanisms move concurrently, and the interactions between them are not straightforward [2]. For instance, a component can be picked only when the feeder apparatus and the placement mechanism have stopped moving. Likewise, a component can be placed only when the board locator and the placement mechanism have stopped moving. Often, machines perform simultaneous pick and placement. The coordination of these activities must be captured in the model.

The Cycle Time Minimization Problem

Cycle time can be expressed as the sum of three items: loading the board into the board locator, placing the components, and then unloading the board. The loading operation includes time needed to align the board properly for placement. Generally, loading and unloading times are not overly complex, and do not vary. Component placement time depends on a number of things and can vary significantly. Hence, it is the focus of the minimization problem.

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A single placement machine may attach hundreds of components to a single board. In general, a placement machine is assigned a certain set of components to attach to a board. Other placement machines in an assembly system are assigned other sets of components to place on the board. There is a hierarchy of decision problems to be solved in developing a process plan and equipment configuration for assembly of the various board types to be produced. McGinnis *et al.* [5] define the problem hierarchy as shown in Fig. 2.

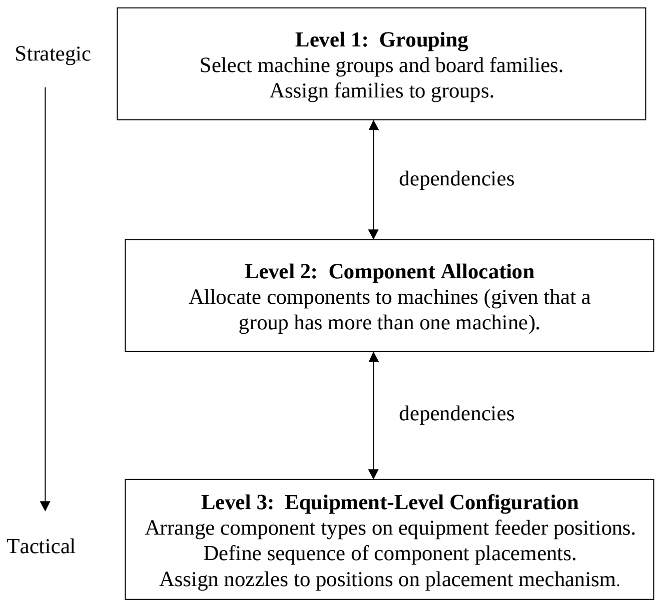

Fig. 2 – Cycle time minimization problem hierarchy

Typically, the objective of the grouping and component allocation problems is to balance workload across an assembly line. This dynamic line balancing problem is difficult to solve. Since this research focuses on one machine, the assumption is that solutions to the grouping and component allocation problems are already specified. Of course, these may be in the form of several alternatives to be tested by a simulation consisting of several virtual machine models. A single virtual machine model is developed for purposes of solving the component feeder arrangement, nozzle assignment and placement sequencing problems for one machine. Each of these problems can have a significant impact on the cycle time because each has an impact on the travel time of the three relevant mechanisms and hence on the time needed to place components.

In solving the component feeder arrangement problem, the goal is to assign component types to feeder positions so that travel time of the placement heads and component feeder apparatus (if relevant) is minimized. In solving the placement sequencing problem, the goal is to define a sequence of components to be placed on the board so that the travel time of the placement mechanism and the board locator (if relevant) are minimized. In solving the nozzle assignment problem, the goal is to assign nozzle sizes to placement nozzles such that the number of idle placement nozzles is minimized over the set of placements to be made. Component feeder arrangement and nozzle assignment are equipment configuration problems (i.e. hardware configuration). Placement sequencing is a software configuration problem because it involves only changing the program to be executed by the machine. In general, these three problems are intractable when formulated independently as optimization problems (i.e., integer programs) [1], [3], [4]. However, there are dependencies between these problems that make them even more difficult to solve, since they are related by the placement mechanism movement.

It should be pointed out that many placement machines have the capability to compute solutions to the placement sequencing problem before production, given an equipment configuration. These solutions are based on heuristics that typically are proprietary in nature.

Model Configuration Issues

The solutions derived for the feeder arrangement, nozzle assignment and placement sequencing problems are in most cases sub-optimal. In addition, heuristics used to determine the solutions may make assumptions not met in practice. For example, the optimization model may not capture acceleration and deceleration effects because it assumes that travel time is a linear function of distance. Hence, simulation analysis potentially is an important tool in cycle time minimization.

The virtual machine model is to be used to test cycle time performance of various solutions to the problems associated with minimizing cycle time. This is similar in concept to research done by Tirpak [6] and Ahmadi *et al.* [2]. In providing such a platform for what-if analysis, it is clear that there must be a straightforward way for someone to configure a model. That is, one must be able to specify different feeder arrangements, nozzle assignments and placement sequences fairly easily.

Virtual Machine Model

A virtual machine model is a highly detailed model of a placement machine used for off-line design and operational analysis. It is characterized by a technically accurate representation of the machine's structure and behavior and by a realistic animation of the machine. Virtual NC was selected because it provides the necessary constructs to build models of a machine and animate them.

Representation of the Machine Elements

The PCB is defined as a workpiece, while the mechanisms of the placement machine are defined as devices. The model has five different axes of movement:

- The gantry moves the *y*-direction across two static rails.
- The placement turret moves in the *x*-direction within the gantry.
- The nozzles and the placement turret perform *z*-direction movement to pick and place components.
- The turret rotates about the *y*-axis when it picks (or places) a sub-sequence of components.
- Each nozzle rotates independently about the *z*-axis so that it can place a component in the correct orientation for placement on the board.

These axes of movement are defined in the MIMIC file. The placement machine is actually modeled as a milling machine, since the placement operations are closer in nature to milling operations than to the other choice, turning operations. Thus, each nozzle on the placement mechanism has a cutting tool attached to it. This cutting tool cuts out a portion of the PCB during model execution to represent placement of a component. The cut-out section on the PCB is specified to be the same size as the component that it represents.

The MIMIC functions read in various files that specify the configuration of the machine and the set of component placements to be made. The *feeder arrangement file*, for example, specifies the location of each feeder within the feeder apparatus and the type of component held by the feeder. *The component placement file* contains information for each component to be placed on the board. This information includes the feeder that contains the needed component type, the precise location on the board where the component is to be placed (given in Cartesian coordinates), and an orientation for the placement (given in degrees, e.g., 90). The *component size file* specifies the dimensions of each component type.

The current model performs a simple algorithm to determine a placement sequence for the components, based on these input files. The input files are based on standard recipe file format (SRFF), which is a standard developed by the Surface Mount Equipment Manufacturer's Association (SMEMA). The basic ideas behind SRFF are (i) to provide a uniform format for production files across different machines and (ii) to provide a way for the relevant machine locations to be specified relative to a standard referencing system. Further work needs to be done on the model to realize the full benefits of SRFF.

In addition to the dynamic elements of the machine, the static elements are also represented. These include the base of the machine (i.e., the frame), the rails on which the gantry apparatus moves and the conveyor rails on which the PCB moves. The PCB is moved via Command Line Interpreter (CLI) code to simulate loading and unloading of the board.

Use of the Virtual Machine Model

The virtual machine model can be used to select between multiple alternatives for machine configuration. The modeler performs this task by modifying the input files. In addition, it can be used to prototype a proposed design for a machine over a variety of configurations and board types to be produced. A screen capture of the virtual machine model is shown below in Fig. 3.

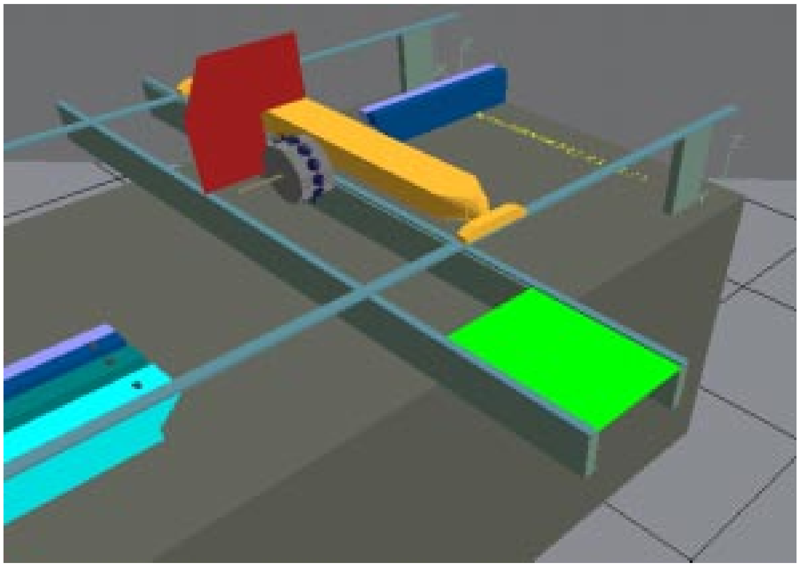

Fig. 3 – Screen capture of the placement machine model

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The screen capture shows the component feeders at the lower left corner, the placement mechanism and the associated gantry apparatus in the upper center, and the board being loaded via a conveyor from the lower right. In addition, it shows the rails that guide the gantry in its *y*-direction movement.

Conclusions and Future Work

This paper has focused on the development of a virtual machine model of an electronic assembly placement machine. This model is useful because it allows one to test different component feeder arrangements or placement sequences off-line, to determine the resulting machine cycle time. Expanded to include a number of virtual machine models, plus the material handling linkages between them, the virtual machine model concept can be used to test the throughput of an assembly system and the impact of higher-level decisions such as component allocation to machines.

Future work includes two important projects. First, in addition to the current "what-if" analysis capabilities of the model, the plan is to integrate prescriptive modeling capability. This prescriptive modeling capability would be in the form of optimization heuristics to provide solutions to the placement sequencing, nozzle assignment and feeder arrangement problems. Once a solution to these problems is given, the detailed simulation model can be used to assess the cycle time and judge the relative worth of the solution. Aside from algorithm development for the needed heuristics, the key technical challenge is to develop a data representation for the system that supports formulations for both the simulation model and the optimization model.

The second project is to develop capability for the virtual machine model to be driven by a GEM-compliant datastream. GEM (Generic Equipment Model) is an emerging standard for equipment operation, originally developed in the semiconductor industry. It facilitates the development of equipment control and communication software. The idea here is to be able to use the animation model for real-time monitoring and for real-time display of equipment operation. The key technical challenge here is to develop efficient and robust algorithms to process the information-intensive GEM datastream to enable real-time operation of the model.

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