The Development of an Automated Production System

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THE DEVELOPMENT OF AN AUTOMATED PRODUCTION SYSTEM

BY

BRIAN M. CARDINAL
B.S., University of Lowell, 1981

THESIS
Submitted in partial fulfillment of the requirements for the degree of Master of Science in the Graduate Studies Program of the College of Engineering University of Central Florida Orlando, Florida

Summer Term 1984
ABSTRACT

This paper describes the development of an automated production system recently completed by the Martin Marietta Aerospace Division, Orlando, Florida, for the assembly, inspection and test of printed circuit boards. The project began in January 1981 with the purpose of increasing the then existing production capability and to create the building block for the total automation of the printed circuit board assembly area of the plant in Ocala, Florida.

The system was implemented using a combination of off the shelf equipment modified and integrated to create a single production system. The system employs much of the new production philosophies tailored to meet the particular needs of Martin Marietta and to fulfill present production requirements as well as future production projections.

During the development and implementation of this project, flexibility within the team was required to accommodate for the unforeseen problems which surfaced. The actual work required to perform this task far exceeded the expectations of the team and the company. This document covers all facets of this project, from inception to operation, and describes the problems encountered and lessons learned throughout the project.
ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to the following people for their support and patience during the development of this paper: Dr. John Biegel, Robert Gundal, Arthur Harding, Norman Marler, Lisa Sanders, and Ken Sizemore.

I would like to thank the Martin Marietta Corporation for allowing me to participate in the Industrial Fellowship Program to pursue my Masters Degree in Industrial Engineering at the University of Central Florida.
PREFACE

The automated production system discussed in this paper was an active project of the Martin Marietta Corporation and is now in use at the Printed Circuit Board Manufacturing facility of Martin Marietta in Ocala, Florida. I had the privilege of working on this project throughout the design, development, and implementation of the system.
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GLOSSARY

ACTGR - ACTivate GRoup
ATFER - Archival TransFER
CAD - Computer Aided Design
CAM - Computer Aided Manufacturing
CCD - Charged Coupled Device
CCONT - Central CONTROL
CNC - Computer Numerical Control
CPS - Central Processing System
CPVP - Circular Pipeline Video Processor
DBACQ - Data Base ACquisition
DIP - Dual In-line Package
DNC - Direct Numerical Control
DS - Distributed Systems
E/O - Electro/Optical
FCD - Fixed Center Distance
FMS - Flexible Manufacturing System
FREND - FRiENDly FRont END
GEAR - Group Editor/Analyzer/Reporter
GETBD - GET Bad board Data
GT - Group Technology
HELPR - error message HELPeR
IC - Integrated Circuit
IRR - Internal Rate of Return
GLOSSARY (continued)

LCC - Local Control Center
LCCLU - Local Control Center Logical Unit tester
MISOU - MISinsertion report OUtput
NC - Numerical Control
PCB - Printed Circuit Board
PCPRT - Printed Circuit board report PRinTer
VCD - Variable Center Distance
INTRODUCTION

When automation is thought of in the manufacturing world, people usually have in mind the machine shop or the assembly of mechanical parts. In electrical assembly the first thing that comes to mind is the assembly of motors or generators. Not much has been written on the fabrication and assembly of printed circuit boards. The reason for this is the lack of general knowledge in this field of manufacturing. Usually an engineer's first exposure to printed circuit board manufacturing is after he/she has gone into industry.

The printed circuit board assembly is present in a majority of government contracts. These assemblies form the intelligence of a weapons system. In order to be competitive it is essential to develop the capability to produce circuit board assemblies as reliably and inexpensively as possible. This is the reason for the development of the automated production system to be discussed. This project's prime objective was to upgrade an existing capability, to become a center of excellence in the circuit board assembly field.

In general, a circuit board assembly is made up of many parts assembled on a printed circuit board. The unpopulated board is the mounting surface for the components. The
circuit board is made from sheet(s) of base material, usually copper clad fiberglass, with electrical conductors etched onto the copper clad surface. The purpose of the conductors are to allow a method of connecting components to create an electrical network. A hole is drilled into the board and plated with conductive material to allow interconnection of layers of material. The hole is also used to assemble the leads of a component to the circuit board. This enables the electrical connection of the component to the layers of material.

The development of a base line is essential in the upgrading of an existing capability. This required a product survey. Then a strong definition of the existing production facility was formed. Once this was done a set of goals and objectives were established. This gave the starting point as well as the finishing point. The next step was to determine a path to meet the objectives set forth.

A concept was developed based on experience and industry surveys. These surveys looked at two areas, equipment availability and industry approaches. A proven method or combination of several proven methods was considered a safe approach. The equipment and associated budget required to undertake the task was determined and a justification of the plan was made. The justification was accomplished by determining a cash flow for a specified period of time. The next step was to calculate
an expected savings based on the existing method versus the proposed method. The cash flow was then input into an IRR (internal rate of return) calculation to determine if the project would be cost effective.

The system design and architecture was developed to establish a plan to complete the task. A schedule was created for the plan, to determine the time and man power requirements. The initial plan was to create two separate tasks, the assembly and soldering, and the inspection. The two groups acquired the expertise to complete the tasks as separate entities.

Since the major components of the system had been determined, the next step was to develop a scheme to control the individual parts in order to create a system. The plan was to have a computer control the individual elements. This network would also have the capability to interface with existing computer systems used in the present production process. Whenever possible standard software and hardware was employed to simplify as well as reduce the cost of the task.

As the project progressed the system went through several changes. In addition to these changes it was necessary to standardize parts of the product to optimize the system capabilities. This increased the original scope and changed the original concept. This program affected the product along with the process. Since the system was not in production at this time, the standardization process
was performed by the group developing the system. With this approach, the man power necessary to maintain product at existing levels was not affected.

The most important step and usually the least considered is the integration. The integration occurs when individual parts are connected to become a system. Three areas required the majority of the effort, communication between computers, mechanical transitions between machines, and operator interface. At this point all the theory becomes a reality. Once completed the project becomes a system. The final step was to run production to determine if the system worked and if the project was a success. The final test was done in two steps, a sample run of 'dummy' parts and a pilot run of production parts.

At the completion of the project a final analysis was performed to evaluate the approach to determine its effectiveness and to highlight the shortcomings to avoid the same mistakes in future projects. An additional study is underway to determine possible enhancements and further resolution of existing problems.
BACKGROUND

Product Description

A strong definition of the product to be assembled is an essential first step in the development of an automated system. Before this production line was considered, a survey was made of the products presently being produced as well as products expected to be made in the future. A study was performed to determine the mix of parts for circuit board assemblies present in the products. It was found that the product had many variations to be considered.

The first of these was the unassembled circuit board. It was determined that the circuit boards to be produced had two basic shapes, round and rectangular. Additionally they varied in thickness from .031 inches to .093 inches. The outer dimension ranged from 2 inches by 2 inches to 7 inches by 10 inches. In addition the boards were either double sided or multilayered. If the board is multilayered it has a tendency to warp. This warpage is due to the interlamination movement of the several thin layers of material that make up the board.

There are many part types used in the production of an electronic system. For the purpose of automatic assembly the primary concern is the physical dimension of these
parts. The reason for this will become apparent as discussion proceeds. Parts are grouped into five major types: axial-leaded components, radial-leaded components, dual in-line packages (DIPs), ribbon-leaded components and hardware.

Typical axial-leaded components are shown in Figure 2.1. This type of component is the most widely used in the industry today. The most important dimensions to be considered are, the body diameter, the body length, the lead diameter and the spacing between holes in the circuit board. The right angle bend of the lead into the circuit board is needed to create a stress relief for the solder joint. This stress relief is necessary for the electronic system to operate without failure under large fluctuations in temperature.

![Axial-Leaded Component Definition](image)

**Fig. 2.1 Axial-Leaded Component Definition**
Some of the most commonly used radial-leaded components are shown in Figure 2.2. The radial-leaded component requires less space for mounting to the circuit board than a comparable axial-leaded component. The most important features to be considered are; the shape and size of the body, the number of leads, the lead spacing and the lead diameter. The radial-leaded components can be assembled into the board in two ways, this is shown in Figure 2.3. The first method is to assemble the component flush to the circuit board; the second is to bend the leads to allow for stress relief.

The dual in-line package (DIP) was developed to assemble an integrated circuit (IC) to a circuit board. The IC is mounted inside the package and wires are bonded to the leads. The DIP is then hermetically sealed. There are three predominant types of component configurations; the radius lead, the side brazed and the bottom brazed lead. The differences are shown in Figure 2.4. The important variables to be considered for automatic assembly are, the number of leads, the body length, height and width and the spacing between the rows of leads. The spacing of leads within a row is an industry standard of 0.100 inches. In the case of the radius lead and the side-brazed lead the component body is mounted flush to the circuit board. The bottom brazed DIP body is mounted off the board to a dimension equal to the distance of the lead radius.
Fig. 2.2 Radial-Leaded Component Definition

Fig. 2.3 Radial-Leaded Mounting
Fig. 2.4 Dual In-Line Package Component Definitions
Ribbon-leaded components are similar to DIPs in that they provide a method for assembling ICs to a circuit board. The difference is that the leads are flat and mounted on the top of the circuit board. This is shown in Figure 2.5. The important dimensions are the body size, the number of leads and the number of sides where the leads are present. The leads are formed to create a stress relief.

Fig. 2.5 Ribbon-Leaded Component Definition
The final group of parts to be discussed is the hardware used on a circuit board. These parts usually make up less than 10% of all the parts found on a circuit board and therefore provide little impact on justification for automation. This category includes terminals, eyelets, and rivets. They are primarily used to affix a component or other part to the circuit board. The terminal is used for either nominal components or for wire termination. A nominal component is used when the exact value can not be determined until after test, the terminal facilitates this procedure. Wires are connected to terminals to accommodate engineering changes and to interconnect the circuit board to other devices. Eyelets may also be used for connecting wires to the circuit board however, this make the board more susceptible to damage. The rivet is used to mechanically fasten a part to the circuit board. Some examples are connectors, component clips, heatsinks and brackets. The rivet can be replaced by a screw and nut when strength is more important than size and weight. Some examples of hardware are shown in Figure 2.6.

The parts discussed comprise the majority of possible parts found on a circuit board and present the highest possibility for justifying automation. When considering automated assembly the major characteristic of a part, mechanical or electrical, is the physical configuration of that part. The parts configuration affects the tooling required to automatically feed and assemble it.
Fig. 2.6 Hardware Examples

Eyelet

Rivet

Terminal

Terminal
Existing Process

The existing process of assembling a circuit board was predominantly by manual operations. This was due to the small quantities on the production contracts. Automation was not cost-effective for individual contracts or across several contracts. Production engineering decided that the circuit board production area would be manual and the operators would build from the engineering drawing.

As the number of contracts increased, stand alone pieces of automation were justified. The equipment consisted of a variable center distance axial-lead insertion machine, an axial-lead sequencing machine, a DIP insertion machine, an automatic flow soldering machine and an in-line degreaser. Each of the machines required a person to operate and/or monitor the equipment continuously during production. The insertion machines were numerically controlled (NC), requiring a mylar tape to download the data as well as an operator to load and unload the circuit board. At that time, this was the only equipment available to perform these operations. Although not fully automated, it was considerably faster than manual operations. The manual operations consisted of hardware installation, component assembly, hand soldering and inspection. These manual operations were necessary because of the limitations of the automatic equipment.
The flow though the production area began with component preparation. This operation prepared the components for assembly. The most important step was to sequence the axial-leaded components prior to automatic insertion. The assembly machine required a presequenced tape of components to ensure that each component was assembled in the correct location. The automated equipment could only move the circuit board to a specified location under the insertion head. The head would then cut the component from the tape, form the leads, insert it into the holes, and cut and clinch the leads. The DIP inserter sequenced the parts during part insertion. Once the parts were prepared correctly they went in a stock room.

The next step in the process was to create kits for automatic insertion. A kit is made up of a 'lot' of circuit boards and associated parts. A 'lot' of circuit boards is a group of boards with the same part number. Thus multiple boards could be run with a single set-up operation. A kit must be made for each lot of circuit boards and each machine, if there were two machines. After the kit was created, it was given to the operator to be used in the automatic assembly process. The operator retrieved the NC tape that corresponded to the circuit board part number and it was read into the machine. The parts were loaded into the machine. The operator began by loading a board onto the X-Y table, the
machine went through its cycle and the operator unloaded the finish board replacing it with a new one. The cycle was repeated until all the parts were inserted. The kit was then returned to stock where it was rekitted for the next operation. The rekitting added the components for the next step in the process to the 'lot' of circuit boards, with some components already inserted, and the new kit was released to the production floor.

The next step in the process was the manual assembly, where the operators assembled all the components that the automated equipment could not assemble. This employed several operators and a conveyor belt to create a paced line. This paced line was difficult to balance for the different boards. This paced line finish assembled the circuit board and prepared them for soldering. The soldering operation used an in-line wave solder machine. The machine was setup for the particular circuit board to be soldered. The setup included wave height, conveyor speed and preheat temperature. The machine was setup in stages along a conveyor. The cleaned and baked board was placed in a fixture to hold it flat and parallel to the stages. The fixture was then placed on the conveyor with the bottom of the circuit board exposed to the working stages of the solder machine. The first stage applied flux to promote solderability. The next stage preheated the circuit board to a sufficiently high temperature to avoid thermal shock to the board when it was exposed to
the molten solder of the wave. The final stage of the machine passed the circuit board over the solder wave. A solder wave is created when the molten solder is pumped through a precisely designed nozzle.

Directly after soldering the circuit board went through a cleaning operation. The board was placed on a conveyor which carried it through the in-line solvent cleaner. Inside the machine, solvents were sprayed onto the board to remove flux and other contaminates from the soldering operation.

The final steps in the assembly were the manual inspection, touch-up and test. These steps will be discussed later. The most important consideration was the handling necessary to assemble a circuit board. Excessive handling drives up the cost of the assembly and increases the possibility of damage.
GOALS AND OBJECTIVES

The primary objective in building the line, was to make it the most advanced circuit board assembly facility in the aerospace industry. In addition to this, the highest levels of productivity and reliability were to be maintained. The system was to be fully integrated to allow total control of the process at all times. The individual components as well as the total system were to be the most advanced equipment available. It would be a center of excellence where all the company's circuit boards would be produced.

The phrase most commonly used when discussing this system was "state of the art". This is defined as the highest level of usable technology. During the period of the conceptual design of the system there were two state of the art system approaches to automation, the flexible manufacturing system (FMS) and the in-line or Detroit system. The FMS was a relatively new concept in production based solely on theory. The in-line system had been used for many years, in the automotive industry. The key was to determine which approach best suited itself to the assembly of circuit boards.

The FMS system is the integration of several NC and/or CNC controlled machines, automated material handling and a
computer to control the material handling and the individual machines. "A flexible manufacturing system (FMS) consists of a group of processing stations (usually NC machines) connected together by an automated workpart handling system. The FMS is capable of processing a variety of different part types simultaneously under NC program control at the various work stations."(Groover 1980)

The in-line system consists of a series of work stations, usually in a straight line, with automatic material handling to integrate the system. The stations work independently of each other. The ideal system would be designed so that the process time of the individual stations are equal.

The production quantities and the mix of part types dictate which system is best suited for a particular application. The in-line method is best used in high production rates with very few part types. The system is usually designed for a specific part and requires a major tooling change-over which shuts the line down. The FMS is made for medium production rates and a moderate number of part types. This type of system is based on group technology principles (GT) where parts are grouped into families of like parts. The use of GT enables designers to make the system cost effective. When low volume per part type and a large number of parts exist, stand alone or "islands of automation" are considered to be the most cost effective method.
The concept of controlling individual machines with the aid of a host computer was new. This allowed more control over the entire process than ever before. Large quantities of data can be manipulated to compensate for fluctuations in the process. Individual pieces of equipment are built with self-contained microprocessors to control the operation of the machine. The operator inputs a program using predetermined commands to allow the machine to operate. The data must be in a fixed format but this format varied from machine type to machine type. There was no interaction between individual machines. The host computer enabled data to be formatted for a specific machine at the floor, automatically, without creating a duplicate data base for different machines.

As a total concept the system was to be modular in design, allowing for flexibility to handle future needs. The capability of being used as a building block for the "factory of the future" was essential. The capability to grow to meet the needs of a dynamic industry and increase the level of automation as technology became available was a high-level concern.
CONCEPT DEVELOPMENT

The equipment available to perform the automatic assembly of the type of parts discussed, have two major design differences. The first is random access versus the presquencing of components. One type has the ability to select a component at random just prior to the insertion operation. The other type requires the components to be presquenced in a separate operation performed off-line before the insertion operation. The second design difference is that the machine that uses presequence components requires an operator to load and unload the circuit board. The other type can be purchased with automatic board handling equipment. The detailed capabilities of these machines will be discussed later.

Equipment is available to assemble all the part groups discussed earlier except the ribbon-leaded components. Further study indicated it would not be cost effective to pursue the automation of the installation of ribbon-leaded components. These components were phased out of the product lines, because of the intricate handling required to place them reliably.

The industry approach has been to purchase stand-alone pieces of equipment to assemble the individual part groups. An operator is required to operate each piece of equipment.
A new approach by a Japanese manufacturer is to link the machines together with automatic board handling. This allows the operator more time because it is no longer necessary to load and unload the circuit boards. The operator would then be able to operate more than one machine. This approach is not widely accepted in the aerospace industry because of the "buy American" philosophy and because it is a new concept.

The system was to be designed to allow for several different products to be built with minimal changeover or setup required. At the time, there were three distinctly different product lines being assembled and projections showed in excess of ten product lines in the near future. This created a problem due to the different requirements of the individual product lines. The products will be used in different environments and will be subjected to variations in physical requirements.

To perform the cost justification of the system, a conceptual design was developed to determine an estimated cost and performance, because of the possibility of new equipment becoming available in the near future. The conceptual design was made up of automated workstations connected with automatic material handling equipment to form an in-line system. Each station was to be computer controlled to perform its task and the overall system was to be computer controlled. The system would be fully integrated to allow complete control of the process and the
individual boards to be processed. The work stations would consist of one station to assemble each of the part groups discussed. Additionally, stations were available to solder, clean and inspect the completed circuit board. The line had two off-line automated areas to which the circuit boards would be routed for further processing. These areas include the robot assembly of non-standard parts and the final automatic test area. The system had two levels of computer control, the host computer for data management and the local control centers for interfacing the work stations and the host computer. An conceptual drawing of the system is shown in Figure 4.1.

The cost justification for the system with the exception of the off-line robotics and the automatic test module was established. The design and cost justification of the off-line robotics and the automatic test module would be performed separate from the basic system. The basic system was grouped into two sections to perform the justification. The first group included the assembly equipment, soldering equipment, cleaning equipment and the process control. The second group encompassed the inspection work stations. The funds required to build the line are shown in Table 4.1.
Fig. 4.1 System Conceptual Design
TABLE 4.1 Investment Requirements

<table>
<thead>
<tr>
<th>1981 INVESTMENTS</th>
<th>CAPITAL (000$)</th>
<th>MANPOWER (000$)</th>
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<tr>
<td>AUTO LOADER</td>
<td>15.2</td>
<td></td>
</tr>
<tr>
<td>DIP INserter</td>
<td>130.0</td>
<td></td>
</tr>
<tr>
<td>AXIAL INSERTER</td>
<td>200.0</td>
<td></td>
</tr>
<tr>
<td>RADIAL INSERTER</td>
<td>105.0</td>
<td></td>
</tr>
<tr>
<td>AUTO UNLOADER</td>
<td>15.2</td>
<td></td>
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<tr>
<td>HANDLING EQUIPMENT</td>
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<td>section</td>
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<td>WAVE SOLDER</td>
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<td>labor</td>
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<td>CLEANER</td>
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<td>SOLDER MASK</td>
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<td>INTEGRATION</td>
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<td>COMPUTER</td>
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<td>AUTO INSPECTION</td>
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<td>539.6</td>
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<td>* ROBOTICS</td>
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<tr>
<td>* AUTO TEST</td>
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<td><strong>1150.5</strong></td>
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TOTAL INVESTMENT: 4857.5

* NOT INCLUDED IN COST SAVINGS

From the survey discussed earlier, a table of circuit board build quantities per program per year is shown in Table 4.2.

TABLE 4.2
Insertable Circuit Boards/Program/Year to be Processed on the System

<table>
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To develop a cost comparison between the then current method and the automated method, the current cost per circuit board per program was calculated. This cost included only the labor requirements to build and inspect the assembly. The remaining processing time was not included because that time would be the same using either method. The cost for the proposed method were derived from the cost for the existing method. This was done by subtracting out the processing time of all the parts to be processed by the new system. The remaining labor quantities for all the circuit boards were summed and the labor corresponding to three operators working full time per year on a single shift was added to this value. The raw processing times were multiplied by a labor rate and a learning curve based on experience gained through building the circuit boards in the past. This curve varied in slope between the existing method and the proposed method because of the increased use of automation. This curve showed that the proposed system would become more productive faster because less operator interaction will be required to assemble a circuit board. Table 4.3 shows the net savings per year and the depreciation schedule of the capital investment and the net cash flow.

The results of the cash flow were input into a computer program to calculate the internal rate of return (IRR). The IRR was compared to the minimum acceptable rate of
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<td>7310.8</td>
<td>8996.0</td>
<td>9406.5</td>
<td>10091.9</td>
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<td>8024.5</td>
<td>8758.8</td>
<td>9768.1</td>
<td>33764.7</td>
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</table>

return (MARR) to determine if the project would be cost effective. When justifying a piece of capital equipment for use on a government contract the savings realized are not always converted directly to profit. This depends on the agreement in the individual contract. This is called savings sharing, where the government shares the saving with the company. Since this system included several programs to justify the capital expenditure, the share ratio varied. In some cases the company was allowed 100% of the savings in other case they were allowed as little as 20% of the savings. Additionally the savings share ratio varied from year to year on a given contract. The amount of change is not predictable and could not be accounted for in the IRR. Table 4.4 shows the IRRs for the different amounts of saving that could be converted to profit.
TABLE 4.4
IRR vs. Percent Savings Shared

SAVINGS CONVERTED TO PROFIT

<table>
<thead>
<tr>
<th></th>
<th>100%</th>
<th>50%</th>
<th>20%</th>
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</thead>
<tbody>
<tr>
<td>IRR</td>
<td>54%</td>
<td>34%</td>
<td>17%</td>
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</table>

At the time of the analyses, the most widely used share curve was the 70/30. This means that the company receives 70% of the savings. The government was starting to make new contracts in the reverse or 30/70. In order to be conservative, a 50% share ratio with a corresponding IRR of 34% was used.
Once the project was approved, the equipment selection process began. The first step was to select assembly equipment that best met the concept developed for the cost justification. The existing equipment was stand-alone insertion machines built by the Universal Equipment Company. The first thought was to use the same brand so that the experience gained might result in an easier transition into the automated line. Universal had begun to modify their standard equipment to use automatic board handling and to create an inline system. They had not completed this task at the time of the equipment selection process. The only company with the automatic board handling capability was the Panasonic Company. The Panasonic equipment had a new concept in parts feeding known as random access. The parts can be selected randomly during the insertion operation. The method commonly used is to sequence the parts in a separate operation. The most important difference between the two methods is that with random access if a part is not inserted correctly, that part can be removed and the machine can repeat the step and insert a new part. The other method will only allow the operator to clear the bad part and skip over it. The incomplete circuit board then requires an additional rework.
step where a person would insert the missing part manually. Due to the handling of the parts and the tolerance of both the machine and the circuit board this condition may occur as much as 15% of the time. The concept required a single work station for the part groups discuss earlier. This was possible for all the stations using either supplier, with the exception of the axial-lead components. The Universal machine can insert a variety of sizes and lead spacings. The Panasonic can only insert a single lead spacing with limited variation in body size.

The DIP insertion station was built by the Panasonic company. The machine is equipped with an X-Y positioning table and automatic board handling. The operation is microprocessor controlled internal to the machine. The machine has 80 separate programmable part locations. Each of these locations can hold fifteen tubes of parts with the ability to discard an empty tube and replace it with a full one. A tube is a plastic container for DIPs to handle them without damage. The tube is commonly used in the industry for shipping the parts. The machine is capable of inserting the three part shapes discussed earlier using two heads. The first will insert radius leaded DIPs, the other inserts the side brazed and bottom brazed DIPs. The machine can insert DIPs with 6 to 22 leads spaced at .300 inches from row to row. The dry cycle speed of the machine is 4800 components per hour with a 99.4% reliability. Dry cycle is defined as the machine operating without parts and
X-Y movement less than one inch between insertions.

The axial-leaded component insertion station originally was to have been a Universal stand-alone machine. The automatic circuit board handling was to have been designed in-house and the sequencing machine was to be connected to the Universal machine to eliminate the handling of the parts between the operations. The Universal machine had a microprocessor and an X-Y positioning table. The sequencer had 80 programmable parts locations to feed parts from tape. The taped part is a standard parts handling method used in the industry. The machine can insert a variety of parts conforming to the drawing shown in Figure 5.1. The machine is capable of inserting 10,000 components per hour with a reliability of 99.5%. This concept was changed to use two Panasonic machines, one a fixed center distance machine (FCD), the other an in-house modification of a fixed center distance machine to a variable center distance (VCD) machine. This will be discussed in detail in the System Growth and Change Section.

The radial-leaded component work station is a Panasonic system with automatic board handling. The machine is microprocessor controlled with an X-Y positioning table. The equipment has 31 programmable part storage locations that hold taped components. The taping of radial-leaded components is standard in industry. Figure 5.2 shows the part configurations that are insertable by the radial-leaded inserter. This machine is capable of inserting 4200
<table>
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<tr>
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<tr>
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<tr>
<td>Wire Diameter</td>
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Fig. 5.1 Universal Axial-Leaded Specification

Fig. 5.2 Radial-Leaded Components
components per hour with a reliability of 99.2%.

The circuit board handling equipment, at the beginning and end of the assembly equipment as well as between the different machines, is standard Panasonic. The beginning of the line has a board loading station. This station loads a circuit board for a magazine to the conveyor of the DIP insertion machine. The loader communicates with the DIP machine to determine when a circuit board is required. The board is extracted from the magazine and the magazine then indexes to the next position. This operation is repeated as the DIP machine requires. When a magazine is empty the loader can shuttle the exhausted magazine out and replace it with a full one. The loader has the capacity to hold five magazines at one time, two full with circuit boards, two empty and one in process. An operator is required to load full magazines and remove empty ones.

A magazine buffer is used between each of the insertion machines to compensate between the different machine throughputs. This was supplied by Panasonic. The buffer works as an in-process queue, employing last-in, first-out stocking philosophy. The buffer communicates with both the machine feeding it and the one emptying it.

At the end of the insertion machines a circuit board unloader/stocker is used. This machine is similar to the loading machine but works in reverse. The unloader accepts inserted circuit boards from the radial-leaded machine and stocks them in a magazine. The magazines are circulated in
the machine to expand its capabilities. At this point in the line the circuit boards are taken to the off-line area for further processing. Work stations are set up to manually or semi-automatically assemble parts to the circuit board that are not done with the automatic machines.

The circuit boards are returned to the line for further processing. At this point all the parts of the circuit board that can be exposed to the chemicals and the heat of solder and cleaning have been assembled. The circuit boards are placed in a magazine and placed onto a loading machine as in the beginning of the line. The next work station is the solder mask machine. This machine applies a temporary solder mask at predetermined hole locations on the circuit board. The material inhibits solder flow during the wave soldering process. These holes are used to assemble the components that can not be exposed to wave soldering or cleaning. If the holes were to be soldered, the person who assembles the components later would have to remove the solder and could possibly damage the circuit board in the process. This is a standard Panasonic machine without the mechanism needed to insert components. It has the board handling, an X-Y positioning table and a microprocessor. The mechanism and associated control to apply the solder mask material is an in-house design.

The board is then passed to the wave solder machine to automatically solder the circuit board. The wave solder
machine is microprocessor controlled to allow the adjustment of specific parameters for the different circuit board types to be processed. These parameters are, preheat temperature, conveyor speed and solder temperature. The machine was supplied by the Electrovert Company.

From the wave solder machine the circuit board continues to the in-line degreaser which removes flux and contaminates from the circuit board. The machine was supplied by the Baron Blakslee company. It uses a solvent solution of Trichlorethane 1,1,1. The circuit board is placed on a conveyor and the is passed through a series of spray nozzles to clean the board. The cleaning solution is reclaimed through a distilling process to remove the contaminates and reuse the solvent.

The last section of the line is an electro-optical inspection station that inspects the underside of the circuit boards for solder flaws. It uses a principle know as feature extraction to first define the feature and then determine whether or not flaws exist. This method requires no data base. Some of the flaws are, excessive solder, too little solder, open circuit, contamination, delamination, exposed copper, foreign material, poor wetting, solder bridges, blow holes and icicles. The system looks at the solder side of the circuit board with a charged couple device (CCD) camera. The output image of the camera is digitized and inputted into a circular pipeline video processor (CPVP). This processes the image through several
algorithms to determine the type and location of the flaws. The handling equipment and the X-Y positioning table is the same as used for the solder mask station. The mounting of the camera and the design and build of the CPVP was done in-house. This same technology was used to develop a stand-alone inspection station for the inspection of the bare circuit board. This station inspects the completed circuit board before assembly and the inner layers prior to lamination. The detail station uses a Bridgeport mill without the milling head for X-Y positioning. The inspection equipment is similar to the assembly inspection station except the algorithms are different. This station inspects for annular rings, circuit to edge spacing, open circuits, conductor spacing, conductor width, delamination, contamination, hole count, hole size, insufficient plating and markings. The detail inspection station uses a Reis robot to position the panel on the Bridgeport. Figure 5.3 shows a block layout of the station.
Fig. 5.3  E/O Detail Station Layout
The system control is made up of a network of Hewlett-Packard (HP) computer equipment. This equipment communicates with the microprocessors in the work stations. The control system is made up of three levels of control, a Central Processing System (CPS), a Local Control Center (LCC), and the microprocessors in the individual machines. The CPS is a data management system which communicates to the LCC. The purpose is the storage of circuit board-specific information necessary to operate the individual NC machines. The LCC passes the data stored in the CPS to the NC machines through RS-232-C cables as the machines require it. The LCC monitors the operation of the NC machines to compile data for output into management reports. The LCC is an execute-only system made up of an HP1000F CPU and a 16 megabyte disc drive with a video display terminal and three 8 port multiplexers. The CPS is a disc based, multi-programming system made up of an HP1000F CPU, two 120 megabyte disc drives, two magnetic tape drives and three terminals, two video display and one printing. The duplication of equipment is to create a redundant system to avoid line shut-downs because of equipment failure. The CPS is connected to the LCC using the Hewlett-Packard distributed system (DS) network.

The circuit board is equipped with a bar code label to identify the part number, serial number and the revision level. The bar code used is a twenty character, high density code 3 of 9 label. Each work station in the line
has one or both types of bar code readers, a fixed reader and a wand reader. The fixed reader is mounted on the input conveyor of the work stations to read the bar code on the circuit board as it passes to the X-Y positioning table or in the case of the cleaner and wave solder machine before it begins the process. This information is sent to the LCC to prompt the loading of NC data to the machine via RS-232-C communication line. The fixed readers were supplied by the Control Laser Company. The wand readers are used on the machines which require component parts to setup the machine. Each group of the same part number has a bar code to identify that parts. The bar code has the part number and a lot number for traceability. The operator reads the bar code as the parts are setup on the machine. This information is sent to the LCC via a RS-232-C communication line. The wand readers are equipped with an alpha-numeric key pad for backup of the wand reader and communication between the operator and the LCC. These readers were supplied by the Burr Brown Company.

A block diagram of the system is shown in Figure 5.4.
HAND HELD SCAN & TERMINAL
PC BOARD SCANNER

CENTRAL PROCESSOR

TEST

TEST

SOLDER

OTHER EQUIPMENT

CLEANING

INSERTION

INSERTION

Fig. 5.4 Base System Illustration
CONTROL SYSTEM DEVELOPMENT

The data necessary to operate the system is developed in a process external to the control system. The component descriptions and associated hole locations on the circuit board are part of a data base developed by the design process. The transforming of this data as well as the formatting is accomplished in two steps. The first step is to merge two files together. The first file is the computer aided design file (CAD), which is a list of reference designators versus hole locations for all the parts on the board. The second file contains the part numbers and their electrical and physical dimensions. The parts are given a code to determine which insertion machine will insert it or whether the part is to be assembled in the off-line area. A magnetic tape of this data for a group of boards is loaded into a computer aided manufacturing (CAM) system.

The second step is the CAM system, which plots the data on a Computervision graphics system for further processing. A program was developed to order the parts for the individual machines to achieve the highest percent of insertability. The order in the process flow which the machines are to operate is fixed. The order of the parts to be inserted on a machine is made at this stage. The CAM
system takes into account the tooling footprint and the previously assembled parts to make the sequence and avoid machine and/or part damage. In addition, the system can determine the sequence of a group of parts to determine the best order to insert the maximum number of those parts. This data is outputted to a magnetic tape and then inputted into the production system's CPS.

To further reduce the setup requirements of the system a "standard panel size" is used. The detailed description of the panel will be discussed later. In general, the panel design is fixed in size and the circuit board is within the outer limits. Depending on the size of the circuit board, multiple boards can be placed on the panel.

The control system is made up of several software modules to process the data and communicate to the equipment described earlier. Figure 6.1 shows the communication lines for the control system. The software modules and a brief description of each are listed below.

ACTGR Activates a group selected by the operator by passing new pending group ID to BADBD through class I/O. Allows for modification of machine exclusion data for a group. Prints the Machine Setup Report (parts shortage, machine exclusion, and reference designator exclusion) and the Group Parts Requirement Report (for each insertion machine).
Fig. 6.1 Communication System
ATFER Transfers the archival information from disc to magnetic tape and removes unneeded records from the archival files, panel info data file, missing component file, misinsertion file, group production file, and group cross reference file, and purges unneeded setup requirements and variance requirement files. Prints the Aged Panel Report, which shows the board ID numbers stored on the disk which are over three months old.

CCONT Control program at the central processor to shut down or start up the system and the machine programs. Provides the capability to pass boards through and stop boards on a machine. Provides status on all of the system programs.

DBACQ Data base acquisition/update program. Allows the operator to modify and update the data base. Prints the Data Base Acquisition Program Processing Summary report.

FREND Friendly FRont END. This program provides the operator with a friendly environment for starting and stopping the rest of the programs in the system.

GEAR Group Editor/Analyzer/Reporter. Assists in the group scheduling. Establishes setup instructions for the operators. Makes up files for use by the
NC machine process control programs. Runs ACTGR in batch mode to print out reports. Also prints the Part Number Binning Survey By Machine Type report.

GETBD Gets good/bad board status and transmits it to BADBD. Allows for addition of a board ID number to the control system or for modification of the good/bad board status of an existing board. Prints the New Badboard Panel ID and Status Number report.

HELPR Provides easy access to help data for the control system errors.

LCCLU Program used by System Manager only, to match system LUs, program names, and NC machines.

MACHINE PROGRAMS Controls the NC machines and all peripherals (Wands, Laser Scanners, etc.).

MISOU Outputs misinsertion data to the printer on the CPS. Prints the Reference Designator report sorted by the number of misinsertions. The operator may choose between a long or short form for the report.

PCPRT Prints out insertion machine data for the group selected.

The flow of data through the programs is shown in Figure 6.2 and described in the remainder of this section.
Fig. 6.2  Computer System Data Flow
The magnetic tape produced by the CAM operation is processed by DBACQ to produce a data base at the CPS. In order to produce circuit boards with this system it is necessary to first establish a "group", which is defined to be a quantity of 1 to 10 different circuit board assembly numbers, all of which may be processed through the assembly system without requiring more than one setup per insertion machine. This is accomplished by running GEAR. GEAR, by reading the data bases and through interactive decision making, will create a Setup Requirements File, a Setup Variance File, and create/modify Printed Circuit Board (PCB) Panel Data Files. The computer operator inputs circuit board assembly numbers into GEAR, which then determines whether or not these assemblies can be processed as a group (i.e. all the components for all the circuit boards can fit on each of the machines at one time). The Setup Requirements File is a list component part numbers and quantity per machine for a group determined by GEAR. The Setup Variance File contains data for the group on insertion machine exclusions and component part exclusions for each board. The PCB Panel Data File is a circuit board specific file comprised of the NC data for each of the machines to process the circuit board.

Once the Requirements, Variance, and Panel files have been created, the CCONT module is used. This module is used to start the system programs. When the system programs have been started, program ACTGR is run. ACTGR
allows the computer operator to modify a group for production. The computer operator inputs the machines that will not be run or the components that are not available for the run due to shortages. Once the group has been modified, the operator can activate the group for production. ACTGR prints the Machine Setup Report and the Group Parts Requirement Report for each of the insertion machines. This reports tell the machine operator which component part numbers and quantity are required for for each of the insertion machines. The next system program to be run is GETBD. GETBD takes the inputted good/bad board data and transmits it to BADBD. The good/bad board data refers to the panel. In the case of a panel with multiple circuit boards, this data is the number of boards on a panel as well as which ones have passed both inspection and test and are to be processed.

At this point in the data flow the information is present to process the circuit board panels for the group. The program CCONT starts the machine programs to begin interaction between the LCC and the individual devices. The machine operator can begin setting up the machines and loading the magazines of panels. The machine operator reads a bar code label as the component parts are loaded on the machines. When complete, the control system will verify that all the parts necessary to process the group have been loaded. If a component is missing, the control system will send a message to the machine operator via the
display on the wand reader to correct the discrepancy. This procedure is performed for each of the machines using one machine operator or several at the same time.

Once the first machine is set up correctly, that machine sends a panel request message to the preceding piece of handling equipment. A panel is placed on the conveyor underneath the fixed bar code reader. The reader transmits the information read on the bar code to the LCC. If the bar code label is not read, an error message is sent to the display of the wand reader to prompt the machine operator to take corrective action. If the label is read correctly, the LCC requests the appropriate NC data for that assembly number and the machine it is residing on. When the NC data is transmitted, the LCC gives a start command to the machine to begin the operation. The machine will complete the panel without operator intervention unless an error occurs. If an error occurs, the LCC will prompt the operator to take corrective action via the wand reader display. The machine is then restarted by the machine operator and proceeds until the machine has completed the panel. The machine will remove the panel from the X-Y positioning table, then waits for a new panel to start the cycle over. This procedure is the same for each of the insertion machines. At the completion of the production run of panels, the program CCONT is used to turn off the machine programs and the machines will no longer be under computer control.
During the operation of the line, data for two reports will be accumulated. The Misinsertion Report contains the reference designator of the component parts that were misinserted on a given circuit board. This report informs production control of the parts used in addition to the ones required for the circuit board. The Missing Component Report for a circuit board gives a list of reference designators that were not assembled during the process due to parts shortages and unrecoverable misinsertions. After a week's production, the ATFER module is used to transfer this data to a magnetic tape for archiving.
SYSTEM GROWTH AND CHANGE

During the creation of this system, several planned and unplanned design efforts were required. These designs were completed in-house by the group responsible for the development of the system. The unplanned efforts consisted of the modifications of vendor equipment to meet the specifications of the company for circuit board assemblies. The vendor was unwilling to modify the standard design of the equipment to meet the necessary requirements.

The planned design tasks included the axial-leaded station, the solder mask station, and the electro/optical inspection stations.

The axial-lead insertion station as discussed earlier, is made up of two separate machines. One machine will insert axial-leaded components at fixed center distance (FCD). The other has the ability to insert the components at a variety of center distances. The term for this is a variable center distance (VCD) machine. The VCD machine can adjust the tooling to bend the wire leads of a component to a programmed distance. The purpose of using the two machines in the system is to increase the throughput of the system. The FCD is capable of inserting components at a rate of 7200 per hour. The VCD can insert 3600 components per hour. The VCD requires more time to
make the adjustment for the different lead spacings. The FCD machine is set at .500 inches lead spacing. Of the components to be inserted, 80% of the axial-lead components are assembled at the .500 inch lead spacing.

The VCD design is based on the standard Panasonic FCD. The concept was to take an FCD insertion head and cut it in half. A stepping motor is connected to an adjustment screw which varies the distance between the two halves of the head. The same method was planned for the cut and clinch anvil. A third stepping motor was also employed to adjust the distance off the circuit board the head would travel. This compensates for the different body diameters of the components. The FCD head uses a pneumatic cylinder to activate some of the mechanization to perform the insert, therefore it was impossible to physically cut the head in half. An effort was required to design the two side of the head, each having the necessary cylinders. An application for a patent on these mechanisms has been submitted.

The controller for the three stepping motors, is an Intel 8085 microprocessor. Three motor interface circuit cards are used to control the stepping motors. Additionally an RS-232-C communication bus is line used to communicate to both the internal Panasonic microprocessor and the LCC. Since additional data is required to operate the stepping motors, the data string for each step in the operation had to be increased. The standard data string
has three axes of control, the X-Y position of the circuit board, and the location of the parts bin to pick the part, from (0-20). The control of the VCD requires two more axes, the center distance between the holes, and the depth stop of the head. This added data is tacked onto the end of the standard data string. The LCC transmits the data to the VCD controller first. The controller strips off the added data and passes the remainder to the Panasonic controller. The VCD controller can also inhibit the operation of the modified Panasonic machine to wait for the adjustment of the three stepping motors between steps in the operation. The VCD controller also monitors the status of the Panasonic to enable coordination between the two microprocessors.

The solder mask machine is a Panasonic based design with several additions. The Panasonic machine is an FCD machine without the insertion head and anvil. The material applied is Solder Mask from the D.C. Atkins and Sons Company, catalog number 311. The applicator is a pneumatically activated valve with a disposable needle. The valve is mounted on a bracket with a cam follower. The cam follower rides on a cam connected to a stepping motor. The stepping motor makes one revolution per cycle. The cam is designed to lower the needle to the board surface, the valve is turned on, and the needle fluctuates up and down three times to draw the material to the circuit board surface. The material is piped from a reservoir to the
valve assembly. This reservoir is airtight, pressurized and constantly mixes the masking material. The pneumatic valve is activated by a control box from the Electron Fusion Device company. This box turns the valve on and off. The time delay for this switching cycle is variable. The control box is also equipped with a vacuum draw back for the valve to avoid dripping. This vacuum is create by a venturi affect of the input pressure. Figure 7.1 is a diagram of the pneumatics.

A second controller is used to coordinate the Panasonic microprocessor and the valve controls. This controller is a logic based fixed sequence system. The primary function of the controller is to simulate the electrical feedback of an insertion head normally present on the machine. The controller allows for adjustments to fine tune the process. An added feature to the machine was the use of a one milliwatt Metrologic laser to verify the application of the material. The laser sends a beam of light to a mirror which reflects it to the hole location. If the hole is not blocked, the laser light activates a receiver that sends a signal to the Panasonic microprocessor and an error condition is indicated. This error is treated the same way as a misinsertion on an insertion machine. The operator can press a button and repeat the last step in the operation. An application for a patent has been filed for the solder mask machine.
Input Pressure

Material
Reservoir

Input Pressure

Valve Control

On
Off

Diaphragm Valve

Needle

Fig. 7.1 Solder Mask Machine Pneumatic Diagram
The electro/optical (EO) inspection stations are similar in design. They vary in the method of automatic material handling. The solder inspection station uses a Panasonic FCD machine similar to the solder mask system. The fabricated panel inspection system uses a Bridgeport CNC mill without the milling head for X-Y positioning of the panel. A Reis robot is used to pickup the uninspected panel and load it on the mill. After the inspection operation, the robot removes the panel and places it on a tray.

The solder inspection station has two CCD cameras mounted directly over the X-Y positioning table of the Panasonic machine. A set program is input into the Panasonic microprocessor to step the circuit board panel underneath the cameras for processing. The cameras look at an area of approximately .500 by .500 inches known as a mosaic. A mosaic is made up of 512 by 512 pixels. A pixel is the smallest element that a picture is divided into, approximately .001 by .001 inches. That mosaic size represents the zoom optic operating in the narrowest field of view. Both mosaic size and pixel size can be increased by the zoom ratio. As the zoom ratio is increased the resolution of the system decreases.

The CCD cameras input the image into the CPVP for processing. The CPVP is made up of several algorithms to first define the image and then to analyse the results to determine the flaws. The CPVP processes the data through
the algorithms in parallel whenever possible to increase the throughput of the system. The CPVP is designed for any type of image processing and can be tailored to a specific application.

The solder inspection station is controlled by an Hewlett Packard HP9836 microcomputer. The controller coordinates the Panasonic microprocessor, the CPVP and the cameras. There is no interface between the LCC and the HP9836.

The detail inspection station works the same as the solder inspection station. Since a detail panel is approximately twice the size of an assembly panel the detail station has four cameras. The controller interfaces with the Bridgeport mill and the Reis robot instead of the Panasonic. The LCC has no computer link with this system either. Both stations print out a report for each part inspected that lists the type of flaw and the location on the panel. This report, along with the inspected panels, is sent to an off-line area for rework.

The unplanned design efforts mention consist of the three remaining Panasonic machines. The DIP insertion machine required modifications to the cut and clinch mechanism. The remaining lead length after cut and clinch was too long. The leads extended over the annular ring of the plated-through hole. Figure 7.2 shows an example of this condition. The Panasonic design uses lever action to activate the cutters. The lever first cuts the leads then
bends the remaining portion to approximately a 45 degree angle. After observing the action, it was found that the cutters had a radius. This radius would push up on the board and increase the length of the remaining lead. The radius was ground to eliminate the pushing up of the board.

Fig. 7.2 DIP Lead Condition
The FCD axial-lead insertion machine had a similar problem. The cause was not the same. In this case the spacing between the two cutting surfaces was too large. This condition caused the lead to bend prior to the cutting action and resulted in the same condition as the DIP machine. Figure 7.3 shows a diagram of the condition. The solution was to decrease the spacing between the two cutting edges by moving the fixed cutter toward the cutting lever.

Fig. 7.3 Axial Lead Condition
The radial machine had the same problem as the FCD machine. The same solution was incorporated. In addition to the cutter problem, the radial machine had a "footprint" problem. The footprint is the tooling required to insert a part which interferes with parts already inserted. The Panasonic design employed lead guides to insert the parts. These lead guides came in contact with the top surface of the circuit board and required a set area on the circuit board to be free of components. A diagram of the lead guides is shown in Figure 7.4. The lead guides allow the machine to insert a wide variety of radial component types. Some part types, such as the disc capacitor, have a wide tolerance range for the body shape. This makes it

\[ \text{Fig. 7.4 Radial Machine Insertion Guides} \]
difficult to grip the part accurate enough to locate the leads in the holes. The components that are insert by this machine have only two configurations as shown in Figure 7.5. These body configurations can be gripped accurately and be inserted without the lead guides. Modifications were made to the gripper to eliminate skewing of the parts prior to insertion. Additionally, the cutters used to cut the component from the tape during the cycle were modified to cut the leads to the correct center distance.

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</table>

Fig. 7.5 Radial Component Specification (inches)
The last modification to be made was the standardization of the panel size to be run on the machine. Although the systems automatic material handling can be adjusted for various circuit board sizes, this operation was very time consuming and tedious. The solution was to develop a standard panel size in which the circuit board will be within the outer boundaries. The size of this panel relates directly to the panel used to fabricate the circuit boards. To reduce the material handling and minimize the setup required in the fabrication process, the circuit boards are made on three panel sizes. The three sizes are 12 by 18, 14 by 18, and 24 by 18 inches. The standard assembly panel is 8 by 11.7 to 12.7 inches. The panel size is approximately one half of a 12 by 18 and a 14 by 18 panel and one quarter the size of a 18 by 24 panel. Figure 7.6 shows the dimensions of the standard panel size with two circuit boards inlaid. The tooling hole locations are fixed with respect to each other and to the leading and the bottom edges. The machines position the panel prior to loading on the X-Y positioning table with the leading edge of the panel. To load the panel, the machine activates a finger which locates the panel and pulls it on to the table. Once on the table, two tooling pins are cam activated to precisely locate and position the panel.
Fig. 7.6 Standardized Panel Design
INTEGRATION AND IMPLEMENTATION

At this stage of the development process, all the individual pieces of equipment were tied together to form the integrated system. The equipment was set up and communication lines and hardware interfaces were proved out to prepare for the initial run of production. The most important part of this phase was to insure that the circuit board was handled reliably throughout the line.

Automatic circuit board handling techniques between the different vendor machines were designed and implemented at this point. The first interface is between the Panasonic automatic handling equipment used on the solder mask machine and the conveyor of the Electrovert wave solder machine. This interface extracts a panel from the magazine on the buffer proceeding the solder mask machine and loads it on the conveyor of the wave solder machine. The wave solder machine conveyor is on an angle which can vary from 3 to 9 degrees. This will change the entrance level of the machine since the angle adjustment pivots at the rear of the machine. The interface must interact with the controller of the buffer to insure that it does not attempt to extract a panel while the solder mask machine is loading a panel. This interface was built by the Applied Robotics Company. The system is pneumatically driven and controlled
by a General Electric Series One controller. The interface has a pneumatic cylinder which extends into the magazine of the buffer underneath the panel, the controller signals the buffer to index and the panel is then pulled out. The interface then raises and adjusts to a fixed angle setting to match the wave solder conveyor. A pneumatic cylinder then pushes the panel onto the wave solder conveyor. This cycle is repeated until the buffer is exhausted.

The next interface is between the exit of the wave solder machine and the entrance of the inline degreaser. This interface was relatively straightforward. The only consideration was the slight difference in height between the two conveyors. For this interface a straight conveyor on a slight angle was used. The conveyor speed matched that of the wave solder machine and cleaning machine. As a panel exits the wave solder, it continues onto the interface conveyor and enters the cleaner.

The interface between the exit of the cleaner and the buffer preceding the E/O inspection station was also supplied by the Applied Robotics Company. The cleaner has a fifteen inch wide mesh conveyor which may allow the panel to shift slightly. The exit height of the cleaner is approximately one foot above the entrance level of the magazine on the buffer. The interface must communicate with the controller of the buffer to insure that it does not attempt to insert a panel into the buffer at the same time the E/O inspection station is removing one. The
interface has a wide flat belt which can accept a panel that has shifted. At the exit end of the conveyor, fingers are used to realign the panel. The interface has tandem rollers on each side to accept the panel from the conveyor and load it on a platter. Once the panel has made a switch on the platter, the platter lowers to the buffer entrance height. A cylinder is then activated to push the panel into the magazine on the buffer. The controller signals the buffer to index for the next panel. The conveyor on the interface has a stop on the exit end to hold a panel until the platter has returned to the ready position to repeat the cycle.

Prior to the integration of the system, most of the software modules had been written. These modules were designed under the assumption that each of the pieces of equipment which required computer interface would operate as the vendor stated in the specifications. This was not the case and it created a need to modify the machines and/or the software modules. The machine modifications were performed by the vendor after the equipment had been delivered. The most important modifications were to the Panasonic insertion machines. A list of commands were given that could be initiated remotely by the computer. The software modules were based on this list and therefore it was imperative that they function correctly. After many vendor visits these problems still exist and will be discussed later. In addition to the command errors,
messages from the Panasonic machine to describe the condition of the machine after an error occurred were not consistent. Depending on the error, contradictory messages were sent to the LCC which made it impossible for the LCC to prompt the machine operator to take corrective action. This will be discussed in the next section.

Once the unforeseen "bugs" were resolved it was time to prepare the system for production. The first step was to purchase parts that best simulate the parts used in production. These parts were run initially to correctly set up the individual machines to avoid damage when the production parts were to be run. This also helped to fully understand the operation of the machines and to aid in training the operators at a later date.

After the machines were correctly set up, the system, including computer interaction, was proven out and the software modules were debugged. The next step was the initial run of production material. This was known as the "pilot line". It did not include either of the E/O inspection stations, they were to be proven out separately and then integrated separately. For the pilot line, two circuit board assemblies were used. Twenty five panels of two circuit boards each were made for both the assemblies. The panels were loaded into one magazine for each of the assembly numbers. After running the GEAR software module it was determined that the two assembly numbers could not be run as a group. This made it possible to check the
software to make sure it could determine the change of
groups and prompt the machine operator to setup the
machines for the second group. The only unexpected bug was
that the optical switches used to signal the fixed bar code
readers that a panel was present, would reflect the solder
plating on the panel. This created a false state and the
fixed readers would signal the LCC that a panel had gone by
but that it could not read the label. The solution was to
use a nonreflective light switch, such as a LED to send the
signal.
UNRESOLVED PROBLEMS/LESSONS LEARNED

Presently the system still contains some unresolved problems that must be solved to achieve the goals set during the concept development. During the development of the system, lessons were learned that might prove to be invaluable in future automation development projects.

The Panasonic software problems have not been fully resolved. The two machines affected are the DIP inserter and the radial-lead inserter. The insertion cycle of these machines are similar and the same problems exist. The conflicting error messages are due to the operation of the machines. The insertion cycle of these two machines retrieves a part for the next insertion while it inserts the part of the current insertion. This means that a component cycle is not the same as a machine cycle. The two axial-lead insertion machines retrieve a part and insert it in the same cycle. The correct time in the microprocessor to update the machine status is no longer straightforward, which causes errors when reading the state of the microprocessor. Panasonic is presently working on resolving these problems. In the meantime "work-arounds" have been created to allow the machines to be functional. This includes giving the machine operator the responsibility of determining the error that occurred.
The two commands that are not presently functional are the C5STSK and the C5UP. The C5STSK command tells the machine to skip the present insertion which caused an error and continue in the sequence. The machine operator must now determine when this is necessary and activate the machine at the control panel. The C5UP command is used when the last panel has been inserted on a particular machine and that panel is to be passed to the next machine. The machine operator now must activate a switch, that normally the next panel would activate, to trick the machine into removing the panel. The Panasonic company is presently working on these problems.

The E/O inspection stations have not yet been proven out and made functional. Work has temporarily stopped on the solder inspection station to allow total concentration on the detail station. It was felt that it would be better to complete one station fully than to work on both at the same time and delay the operation of both. The most significant problem on the detail station is the rate of false alarms. Over 50% of the flaws presently detected were false alarms. This is due to several problems. The first problem is the resolution of the cameras used. Although the cameras have a maximum resolution of .001 inches, the actual output resolution through the CPVP is approximately .003 inches. This is caused by the jitter created by the analog to digital (A/D) converter used to convert the analog signal of the camera to a digital signal.
for processing through the CPVP. Additionally losses occur within the CPVP algorithms. An example is the width of a conductor run. The requirement is that a nick in the run must be less than 20% of the width. If the width is .010 inches and the resolution is .003 inches, the best determination is whether it is greater than 30%. To compensate for the inaccuracy, modifications were made in the algorithms to accommodate the error. This failed. The lighting added to the problem. A scheme to create uniform lighting over the wide range of background darknesses has not been fully developed. The background material is the fiberglass used as the base material for the circuit boards. The process and the variation in lots from the manufacturers create a wide range of darknesses.

The final problem of the E/O inspection station is in the case where a feature on a panel that comes between two mosaics. In this situation a portion of the feature is present in two or more mosaics. Work is continuing in the algorithm development to first define the feature using data from more than one mosaic and second to be able to determine if a flaw exists.

The E/O inspection stations are an example of a lesson learned. Although optical inspection is a viable method for circuit boards, the use of feature extraction techniques is still relatively new. The systems available for optical inspection require a large data base and compare the panel or image to a "known good" image. To
maintain this data base a large computer is needed and the comparison process is slow. The approach on the E/O inspection stations was to use the technology of target recognition. Target recognition is the ability to optically view an area of land and determine whether potential targets exist and what these targets are. The government has done extensive research in this field and is in the process of building aircraft systems having this technology. It was felt that this technology could be converted easily for use in the inspection of circuit boards. Such was not the case. The amount of front end research was understated and resulted in schedule slips. The lesson learned was not to schedule technology breakthroughs for use in production systems.

The modification of the Panasonic axial-lead insertion machine to give variable center distance capabilities, cost more than anticipated. The reason was the design and fabrication of the controller. The controller is an Intel 8085 microprocessor. The Panasonic machine uses the same microprocessor. The plan was to use the VCD controller to expand and interact with the Panasonic microprocessor. This meant modifying the software of the Panasonic microprocessor to drive the VCD controller. The modification of this software, using the available documentation provided with the machine, was impossible. The fabrication of the VCD controller was near completion when this determination was made. Since the VCD controller
was microprocessor based the solution was to use it as a separate microprocessor and to monitor the Panasonic microprocessor. The concept of building a microprocessor for this application instead of purchasing one was not cost effective, but since the fabrication was near completion this was the prudent course at the time.

The development of an automated production system of this magnitude should interface directly with the area of the plant were this system will operate. For this system, the development was performed by a satellite group not directly responsible for the production area. This in itself is not a bad concept. It allows the group to fully utilize their resources for the completion of the project instead of solving the every day problems of the production floor. The problem arises when the group responsible for the production area does not concern itself with the project because the project is not presently impacting production. A company must establish and maintain strong ties between the production group and the automation group to insure that present as well as future problems are considered in the development of automation. In the development of this automated production system these ties were not established and thus modifications of the system were required to accommodate the previously unsurfaced problems.
FUTURE ADDITIONS AND RESEARCH

This system was conceived as the first step in the development of an automated factory. Many avenues exist to expand this system into that factory. Voids within the processes can be automated and tied into the system. The system has the ability to grow into other areas of the circuit board manufacturing facility. Future efforts are to identify the areas of expansion and then develop a plan to achieve this growth.

The system presently has an offline section in the middle where components that can not be assembled on the automated machines are assembled to the circuit boards. These component types are used in small quantities and automation can not be cost justified. In order to automate, less expensive equipment must be used. Presently most of these components are assembled using a semi-automatic method. This method uses an X-Y positioning table to move the circuit board under a light that projects a light symbol at the location were the component is to be assembled. The symbol corresponds to the component type and highlights characteristics such as polarity. The operator picks the component from a tray and inserts it. A foot pedal is then activated to cut and clinch the lead and index the circuit board to the next location. This method
is faster and more reliable than manual methods, but still requires the operator to handle each of the components. Additionally the components require a prepping operation to cut and bend the leads to the correct configuration prior to the assembly operation. This area is planned to be automated using robotics. Design efforts are under way to eliminate multiple part configurations for the same component types. It is hoped that this will reduce the automation required to handle the different parts. Once this is completed, an exercise will begin to determine the requirements of the area and to develop concepts to automate.

The final step in producing a circuit board is to test to see if it functions properly. Extensive work in this field has been done in the past decade. The method most commonly used is to automate the test cycle and allow an operator to load and unload the circuit board. The test stations are usually designed for a specific circuit board. The planned approach is to automate the material handling and connect it to the system after the E/O inspection station. The test stations will be designed for families of boards to eliminate like test stations. These stations will be able to load and unload the circuit boards from the test fixture. Additional automated material handling will take the failures to a rework area and the good circuit boards to the next higher assembly operation.

The CAD/CAM/automated system interface uses magnetic
tape to send data from one system to the next. The plan is to first connect the system together and then allow the computer operator of the automated system to perform the operations at the CPS just prior to the operation of the system. A graphics tube can be used to verify the first time acquisition of data for a specific circuit board. This system can be expanded to write and maintain the process instructions for the circuit boards that are used by manufacturing personnel.

The development of the E/O stations and its resulting technology offer the greatest opportunity for major benefits within the factory. This development will provide a means to inspect not only printed circuit cards and their associated processes but, will allow automated inspection of machined parts, coatings, plating, welding, assemblies, and most factory processes now inspected visually. The area of inspection within the factory is rapidly becoming one of the most labor intensive areas as the processes themselves become automated. The recent advances such as the CPVP type technology and the appropriate programs are now providing the needed technology to replace the visual inspector's tedious task. The technology of the CPVP is readily expandable for use with differing sensors to provide the automation intelligence required of the inspection task.

The automated production system discussed is a major undertaking for any company. The most significant part of the system is the expandability. Once the system is
functional, the expansion can be performed in sections to minimize the capital burden on the company.
SUMMARY

The overall goals for the automated production system can be summarized as follows.

* Flexibility
* Building block for an automated factory
* State of the art
* Increased capability
* Increased reliability
* Reduced cost of end products
* Increased productivity
* Center of excellence

The automated production system combines the philosophies of FMS and in-line high production systems to remain flexible while providing medium to high production capabilities. Modifications of the group technology principles are used in the GEAR program to allow multiple board types to be processed with a single system setup.

The system was designed to be a building block for a totally automated factory. Enhancements to the system are already being designed to expand the capabilities of the system to encompass other areas of the printed circuit board assembly process. The basic system now functional is the only such system with the flexibility and abilities to process the wide range of product required of this facility. The
system was designed using the most recently available equipment and technologies to make the system "state of the art".

Since the system has been in production for a short period of time, no data is available to substantiate the increased productivity and reliability expected of the system. Since the system requires less operator handling of the material, the reliability and quality of the product is expected to increase. The reduced cost of the end products is anticipated to be no lower than 80% of the original justification figures, which would still be cost effective.

Efforts are underway for the corporation to have all printed circuit boards to be produced by the company manufactured by this system, making the system the firm foundation for a "Center of Excellence" in the printed circuit board facility. Contracts are also being negotiated to manufacture circuit boards for other companies.

Although the automated production system still has some unresolved problems, the corporation is confident that these problems will be resolved to satisfactorily meet the expectations of the system. This automated system was the largest and most complex automation development project ever undertaken by the corporation. Future tasks will benefit by the lessons learned on this project.
BIBLIOGRAPHY


