NISTIR 4368

THE NEED FOR RESEARCH IN ELECTRONICS ASSEMBLY TECHNOLOGY

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Abstract— The National Institute of Standards and Technology assisted the Harry Diamond Laboratories in an effort to develop plans for a new program of research in electronics assembly technology. The need for research was investigated in the domains of precision engineering, system integration and process control. Rather than engineering design problems, the emphasis was on principles, techniques and standards that could help eliminate obstacles to widespread adoption of state-of-the-art technology in assembly plants. Current popular assembly methods as well as emerging new trends were studied. Research projects are recommended in the areas of (1) flexibility of equipment, (2) precision handling of components, (3) equipment interfaces, (4) equipment programmability, and (5) statistical process control.

Introduction

The Harry Diamond Laboratories (HDL), a research agency of the United States Army, is identifying projects and subjects to be addressed as part of a new program. The aim of the program is to advance the state of the art in areas concerning automated assembly of electronics for military applications. The Automated Production Technology Division at the National Institute of Standards and Technology (NIST) is working in conjunction with HDL, and is primarily concerned with precision engineering, system integration, and process control.

The initial efforts in this program were to gather information on current problems and trends, to investigate the need for research in the stated areas. NIST participated in this phase of the program by means of literature searches, plant visits and discussions with personnel in industry, universities, and government agencies. This report is an overview of the findings and recommendations in the NIST areas of concern. Statements of significant conclusions from this investigation will be shown in *italic type* throughout this report.

Several electronics assembly plants were visited, and still others were studied through interviews with plant managers and reviews of reports. The main purpose of the plant studies was to identify technological problems that might be solved through research. Since certain plant managers granted interviews only after being assured that information regarding their company circumstances and strategies would not be made public, this report does not identify plants by name. However, the basic plant descriptions necessary for understanding points made in this report are provided in Appendix B.

Shortcomings of Currently Available Technology

New technological advances are always needed to fill the gaps that discourage widespread use of available technology, as well as to enable steps to be taken toward even further developments. Thus, regardless of the state of the art, research is always important.

The Current Need for Research

New problems in electronics assembly have arisen with recent technology. For high-density leaded components, for example, processes for lead forming, soldering, repairing, and conformal coating are among the areas that must be accommodated with new technological developments. Leadless surface mount technology (SMT) component carriers having 20-mil (a "mil" is 0.001 inch), 15-mil and even 10-mil spacing between pad centers present new bonding challenges. Although some research is being done in these and similar areas, solutions are elusive, and much is left to be done. Plant H, for example, is working on particular problems involving the assembly of 120- and 240-lead SMT devices with 20 and 25 mils between lead centers. Although experiments succeed in assembling 20-mil center devices, so far they do not succeed in meeting the military specifications that require "no overhang."

Modernization does not necessarily imply automation. Although there are several arguments against extensive automation (to be discussed later), the solutions to a good deal of assembly problems do require automation. High-density packages such as those mentioned above cannot be assembled reliably by hand due to their need for precise locating and placing. Assembly robots in experiments at Plant H require the guidance of a vision system to line up high-density packages with mounting pads. Perhaps the best argument in favor of automation is that quality can be controlled by controlling the processes used in the factory, and process control works well with automated processes.

Inspection and rework are largely done manually only because automated techniques are not sufficiently reliable. Plant D does 100% visual inspection of every solder joint. Most boards produced there have 2000 or more joints per side, and the few defects that are typically found per side are re-soldered manually.

A well-automated facility should be capable of assembling products on demand, thus allowing significantly reduced inventories. Large inventories reduce the return on a product. Managers at Plant E say that 30% of the value of the product per year is the cost of storing, and that any strategy to reduce inventories is worth serious consideration.

Although many plant managers believe that automation is a good idea, they do not always find a desirable degree of automation achievable. Plant D personnel believe that more automation of their facilities and procedures would result in better efficiency. But they cannot afford the investment of time (or money; see the section on "Other Issues") that modernization would require, and they feel that the current operations are efficient enough. They say that they look forward to direct loading of computer-aided design (CAD) data into automatic insertion equipment because it would minimize the possibility of error and eliminate the need for planning certain processes. But a consequence of this particular change will be a dependency on CAD, which most of their operations are not ready for.

Bottlenecks to Automation

It seems that after a certain level of automation is reached in any facility, the benefit of further automation is questionable at best. After that level has been achieved, the more automated a facility becomes—that is, the less the need for human participation in the operation of the facility—the greater the cost with respect to any benefit. At Plant H, the philosophy on this issue is worded, "Do not automate assembly for automation's sake." There are situations where manual processes make more sense.

At Plant J only about 60% of assembly is automated—where it is cost-effective. Sometimes it is more feasible to perform certain tasks manually even though available automated facilities are capable of accomplishing the tasks. Some automatic equipment, the component insertion equipment for example, is used only when the volume of production is great enough to amortize the setup expense. And even though testing is 95% automated, the determination of the problems that cause boards to fail tests requires human procedures and judgement.

The Plant F staff have scaled back plans for automation of their printed wiring assembly facility because more use of robotics means more expense, more materials handling challenges and more difficulty with process planning. The revised plans will assign a human operator to each of the facility workstations.

Since this trend of diminishing benefit with increasing automation is so common, is advanced automation an unimportant area for research? In some cases, reasons for limiting automation may be absolute consequences of general manufacturing principles. But in certain cases, arguments against automation are valid only in the context of the current state of the art, and may be rendered baseless by new research. *Research needs to identify the cases in which certain technological constraints, and not any natural laws, are responsible for the prevalence of this trend, and to discover how to manipulate such constraints.*

When any production facility is to be modernized, it is commonly expected that automation will beget higher profits through better quality, faster throughput, greater machine utilization, and lower work-in-process inventory. Among the reasons that these expectations are seldom met, however, are (1) these technologies are not well understood; (2) integration is more difficult than originally thought; (3) increased flexibility leads to more complex control problems; and (4) current scheduling strategies are inadequate to deal with the problems created by this new, dynamic manufacturing environment. Research in these key areas can open the way to make the goals of modernization more achievable through automation.

Equipment Interfaces

Some modern plant configurations have assembly equipment controlled by a central computer, or cell controller. Plant J considers the information transfer system to be the most important part of the plant. For a plant to adapt to such a style of operation, a major issue to resolve is the kinds of hardware and software interfaces to be used between equipment and controllers. Requirements for interfacing differ depending on the equipment and computers between which communication is desired. RS-232 hardware connections are common, but far from universal. Furthermore, software—not only communications protocols, but also data formats—is unique to the combination of equipment being linked.

Various data interchange format standards are currently under development, such as EDIF (Electronic Design Interchange Format), VHDL (VHSIC Hardware Design Language), PDES (Product Data Exchange Specification), IGES (Initial Graphics Exchange Specification) and the IPC (Institute for Interconnecting and Packaging Electronic Circuits) D35x series. The scope of each overlaps with others, and harmonization meetings to resolve the situation are in progress.

Several interface standards, covering, to various extents, hardware and software, are also under development. Included are the SEMI Equipment Communications Standard (SECS; see Figure 1), the Manufacturing Automation Protocol (MAP) and the Technical and Office Protocol (TOP).

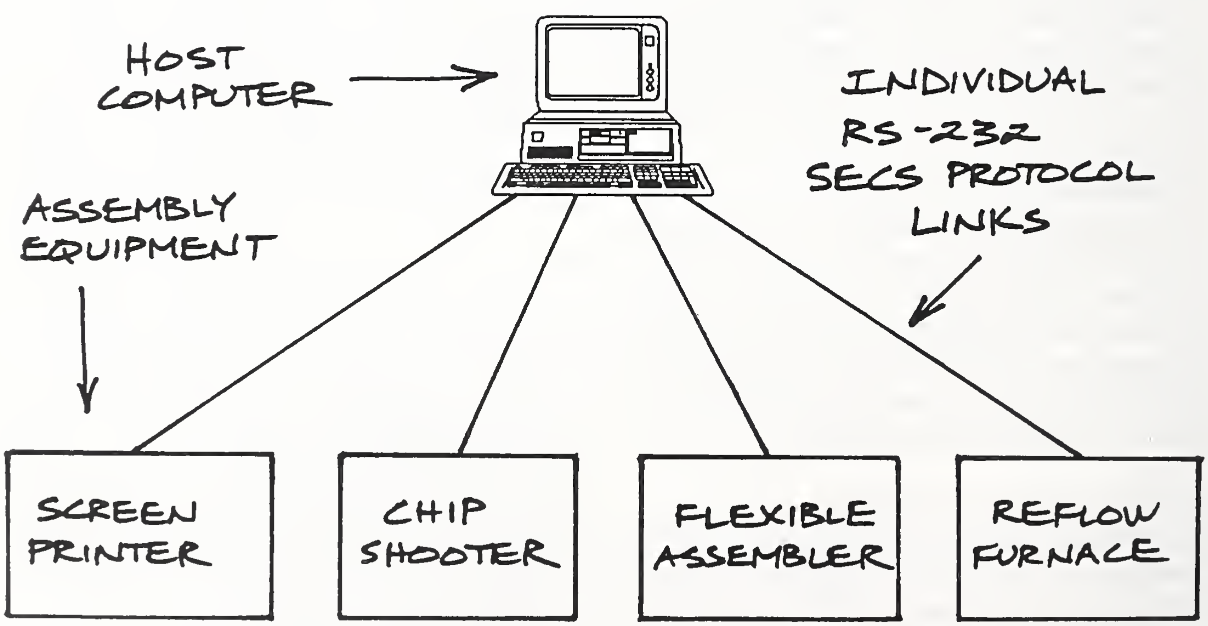

FIGURE 1: ***Typical host-controlled assembly line topology using the SECS protocol.***

Plants with integrated facilities have found that these standards, in their existing forms, may be helpful to a certain extent, but that each task of interfacing their equipment has had needs that required original solutions. Custom interfaces for each situation often lead to further integration difficulties. Plant engineers express a desire for comprehensive interface specifications in the near term, even if they may be more narrow in scope than the long term standards that are currently under development.

Equipment Programmability

At many modern facilities, as much equipment programming as possible is done off-line, as an alternative to the process-disruptive procedures of teach-programming. According to several plant managers, programming the flexible automated equipment is often the aspect of adapting it to different tasks that is found to be most difficult and time-consuming. When the managers of a facility meet this obstacle, it is not only infeasible to consider more extensive automation, but it is reasonable to wonder whether the current level of automation should be scaled back. In some cases the off-line programming is so cumbersome that it nearly offsets the benefit of having automated equipment. *The problems of programmability are a barrier to automation.*

A reason for programming difficulty is that, since the program code for the last task must typically be replaced entirely, regardless of its similarity to the requirements for the next task, a completely new program must be developed for each application. Programming procedures are commonly too complex. As much software as possible should be saved from one application to another; code should be ported across application boundaries. A "permanent," formal means of ensuring completeness should also be available.

If a general system for significantly simplifying the programming of automated equipment were developed, implementation of further advancements in facility automation would become more practical.

Statistical Process Control

Statistical process control (SPC) is an approach to monitoring processes and controlling key variables to ensure that measures of output quality are within acceptable limits. Among the benefits of SPC are reduced scrap and rework, higher yields, higher quality and lower inspection costs. But most importantly, SPC provides a baseline measurement of a process from which operators can detect when and where non-random variations occur.

Unfortunately, for electronics assembly, parameters to be measured for SPC seem to be poorly understood, and measurement techniques are not well developed. Several plants studied claim to be using SPC, but are not. Some are practicing statistical *quality* control, but concern themselves only with attributes of completed assemblies rather than process variables; and others collect in-process data for later analysis, but do not actually control any processes on the basis of data collected.

Although SPC is not a new practice, it has mainly been applied to fabrication of parts rather than assembly of parts; and also, more to mechanical products than electronics. Assembly of electronics is obviously a crucial area in the production of technological goods. Since quality control *is* a serious problem in electronics assembly, there is much to be gained through the widespread successful use of SPC.

Where SPC programs have been applied in U.S. industry, they are often found lacking; commonly due to (1) misunderstanding of the objectives that were intended for statistical control charts, (2) similar approaches and techniques towards the control of short runs that are only valid for high-volume production and vice-versa, and (3) lack of suitable techniques providing adequate interpretation of statistical estimates. Many quality managers, engineers and inspectors are unaware of the limitations of conventional methods of SPC charting and the likelihood of erroneous data representation and interpretation. Classification, terminology and definitions in the area of SPC applied to electronics assembly operations are still very obscure. These are problems encountered by personnel who have implemented some sort of SPC system; however, it is much more common that an SPC program is desired, but never begun because of more basic problems such as what factors to monitor, how to measure them, how to determine meaningful control limits, etc.

While SPC may be used to keep a process under control, it does not engineer quality into the process. There is a need to optimize processes before SPC is implemented, so that the need for process corrections is minimized. To design processes that are robust to external or uncontrollable sources of variation, more assembly plants need to apply methods of experimental design. These methods are used to determine where the controllable variables of a process should be set so that the quality characteristic (see Figure 2) is centered at the nominal dimension and has minimum variability from product to product, regardless of the levels taken on by the uncontrollable input variables.

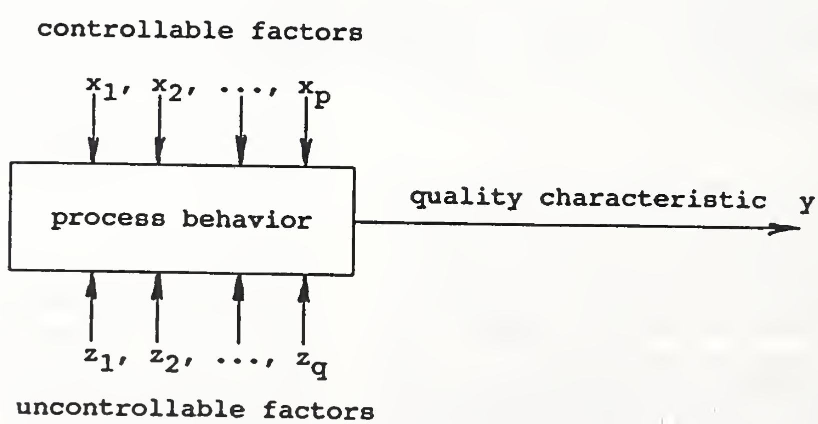

FIGURE 2: *Schematic representation of a process.* Sets of controllable and uncontrollable factors (inputs) interact to produce a response (output)—a functional or quality characteristic of the end product. Experimental design methods may be used to determine the values of $x_1, x_2, \ldots, x_p$ which yield the optimum value of y.

Many SPC training and educational programs are dedicated only to basic statistical procedures, not to assembly-related statistical knowledge. But implementation problems are not due as much to a lack of understanding quality-control statistics as they are to understanding how to use them effectively. *There is a very clear need for practical guidelines which are specific to electronics assembly.*

Other Issues

Managers of several plants explained a number of barriers to facility modernization that dealt with practical requirements of the transition rather than with technical issues. For example, consider the portion of Plant D operations which is sustained by cycles of one-year government contracts. The plant cannot risk making a contract bid that includes the cost of facility improvements which are not specified in the contract. Therefore, the plant can afford to modernize its operations only if the required time and money are provided by contract. However, even though the responsible government personnel agree that modernization is a good idea, they never consider it important enough to write the necessary provisions into the contracts. The existence of such problems is important to note even though, being outside the scope of the HDL program, they will not be discussed here; but strategies to overcome such obstacles must be devised before it will be realistic to expect widespread adoption of recommendations to upgrade plant operations.

Suggested Research Areas

In the cases of the most modern plants studied, the implemented solutions to problems in such areas as precision handling of components, equipment programmability and equipment interfaces were unique and, usually, applicable only to their very specific situations. Still, many related problems remain even in those situations, and most importantly, general methodology for such capability is needed. Several research recommendations involving the most prominent problems in the NIST areas of concern will now be listed.

Flexibility of Equipment

Perhaps there are some fundamental reasons why assembly equipment is not more flexible. If so, *research should aim to overcome such obstacles to flexibility.* The more flexible the capabilities of any item of equipment, the more desirable the equipment is. Having more flexible equipment minimizes the need for many separate items of equipment, some of which would likely be under-utilized.

Machines with the possibility, and for which assembly plant engineers express the desirability, to acquire additional functionality should be identified. *Barriers to flexibility should be studied with the intention of integrating additional technology, new or existing, to adapt particular machines to performing functions that were previously found only on multiple machines.* Experiments must be performed on prototypes to demonstrate the feasibility of the principles.

Precision Handling of Components

Research is necessary to develop innovative applications of machine vision for assembly and test. Vision systems allow more precise handling of components. Better precision is required for at least two reasons:

- high-density packages present new problems with lead forming and assembly; and

- off-line programming requires that automated insertion of components be done precisely.

Because it is necessary for a satisfactory degree of automation, off-line programming is strongly preferred over teach programming. If more effective vision (or other) techniques allow precise locating and placing of components without advance experimentation, then more equipment can be developed with the ability to be programmed off-line, and a higher level of automation is more feasible.

Machine vision techniques resulting from recent research must be experimentally adapted to prototype pick-and-place machines.

Equipment Interfaces

There is a great need for software interface standards for electronics assembly equipment. It seems probable that hardware interfaces are being sufficiently addressed by existing efforts.

NIST has been cooperating with Microelectronics Computer-Integrated Manufacturing (MICROCIM), a Navy program, in the development of a uniform specification to communicate data between any computerized process equipment and a local computer which controls equipment operations. (See Figure 3.) The objective of the project, called Communications Protocol for Microelectronics CIM (informally called Meet-in-the-PC), is to overcome the current shortcomings of MAP/TOP, SECS, and other available interface standards by creating a near-term interim standard intended to converge with and be superceded by national standards (such as MAP/TOP).

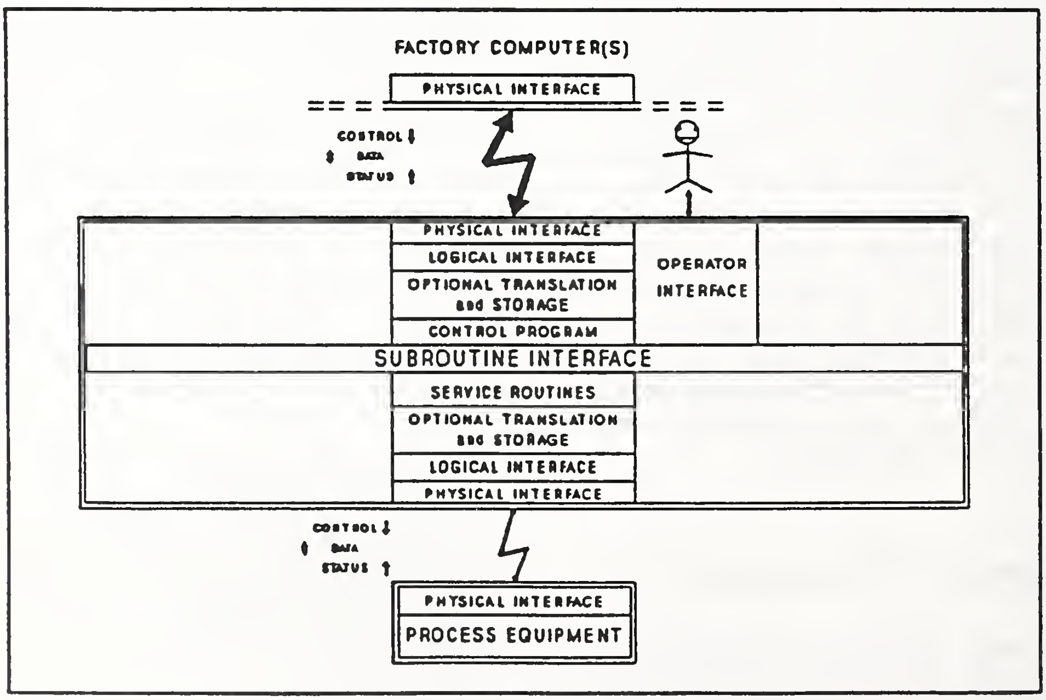

FIGURE 3: *Possible architecture for "Meet-in-the-PC" interface.*

Although this effort is already under way, much of the emphasis so far has been on hardware and electrical interfaces, and the software solutions will require creative contributions of many parties over a long period of time.

Equipment Programmability

A proposed solution for the problem of programmability is the development of a very high-level programming language that can serve as an environment for all of the various languages that each item of equipment in a system may require. To coordinate the development of programs of each type in the system, such an environment must allow the user to create (1) generic definitions of assembly operations, and (2) definitions of devices in terms of their generic operations. These kinds of definitions will configure the environment for a specific system of equipment, effectively creating a model of the system to be programmed. Then, in systematic accord with the model, a programming procedure can be designed, interfacing to the language requirements of each item of equipment.

All this need be done only once for a specific system. The resulting procedure for the system will allow the user to program the system in a formal and systematic way that will ensure completeness of each program. And, even if the resulting "program" will be decomposed into several individual programs, each in the language of the item of equipment for which it is intended, this decomposition will be invisible to the user. He need not even be concerned that the system consists of different components. The permanent programming procedure will ensure completeness of the programs and may be used repeatedly as long as the physical system remains configured according to the model.

The *AMPLE* system, a programming language environment developed at NIST, is intended to solve similar problems in the area of automated mechanical fabrication workstations. If generic operations for the different areas of electronics assembly can be defined with sufficient generality, then *AMPLE* can be configured to accommodate typical as well as worst-case programming challenges, and a programming environment for electronics assembly could be proposed as a general solution for simplifying programming. If appropriate equipment is provided, then prototype software modules can be developed for test and evaluation of the proposed software environment.

Statistical Process Control

Since SPC has not been in widespread use in electronics assembly, problems must now be solved that had no former need to be acknowledged. *New measurement techniques need to be developed for certain unique assessments of quality.* For example, a nondestructive measurement of gull wing height (stand-off height resulting after lead forming of certain surface mount devices) will require reading a height sensor at the time when there is an acceptable balance between an applied force comparable to that of installation, and an elastic deformation of the leads. (See Figure 4.) Uniformity of lead spacing is another example of many measurement challenges that must be met. Another unique class of problems will address statistical assessment of quality in terms of discrete instead of continuous characteristics.

Practical applications of SPC procedures need to be more specifically and systematically established, especially in regard to correlating the quality of end products with process parameter measurements.

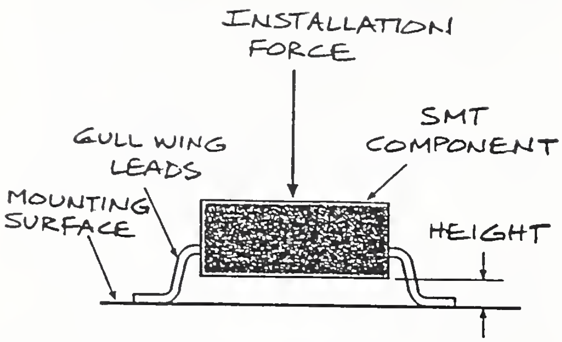

FIGURE 4: ***Gull Wing Height.*** This end view of a flat pack shows the problem measurement.

Specific guidelines for answering the following questions should be established for classes of machines with specific functions.

- What parameters should be measured (because they have bearing on the quality of the product)?
- What suggested techniques for measuring the recommended SPC parameters should be adopted?
- How to correlate measured variables with the quality of the product so that practical control limits may be derived?

The following objectives are suggested for a research project on SPC:

1. Develop recommended techniques for measuring the parameters that will need to be monitored. (Verification that each list of such parameters is sufficient or complete will be part of the third objective, below.)
2. Generalize the steps for designing experiments to maximize process efficiency.
3. Generalize SPC procedures for processes within project scope.
4. Formulate a general approach to planning the implementation of a new SPC program in a plant.

Experiments on example equipment would support the final recommendations of the project. The result of this research could be a handbook, "SPC Handbook for Electronics Assembly."

Approach to Research

Most of the tasks outlined above will require study of and experimentation with example assembly equipment. Especially because of the facility integration issues, the NIST Automated Manufacturing Research Facility (AMRF) is an ideal environment in which to establish a cell of experimental electronics assembly workstations. Such a cell could serve as a testbed for interface standards, programming system prototypes and precision control of manipulators. Equipment could be outfitted for experiments with vision systems, SPC and functional versatility.

HDL would also use the work cell to conduct research other than that mentioned in this report. This would provide an excellent opportunity for HDL personnel to benefit from NIST experience with the AMRF, and gain expertise on approaches to factory automation research. The experience at the NIST electronics assembly cell would be a valuable first step to the eventual establishment of a manufacturing sciences laboratory at HDL to test, certify and promote widespread adoption of new processes.

It is possible to have additional access to equipment through "microfactories"—the cooperative operation of contractor-operated testbeds.

There are many options for arrangements for getting started with the research suggested here; but it is most important to make every effort to investigate the possibilities and then proceed to the solutions.

Appendix A:
A Research Plan

The following research plan was written to be essentially independent of this report. Therefore, for clarity, certain information from the text of the report is repeated in the research plan.

Research Plan:

Development of Methodology for Implementing Statistical Process Control in Automated Electronics Assembly Plants

Abstract— This research plan is proposed to be a collaborative undertaking between the Harry Diamond Laboratories and the National Institute of Standards and Technology. The objective is to find solutions to several research problems which are obstacles to effectively implementing statistical process control and experimental design methods in automated electronics assembly plants. Promotion of the results of this research will allow widespread adoption of advanced quality control practices in industry, and thus enable the U.S. to take a better position against foreign competition. The final product of the project will be a published practical guide to implementing the procedures studied.

Introduction

Improving product quality and reducing production costs are essential to maintain a competitive manufacturing position. Many have attributed the decline in U.S. competitiveness to our failure to improve the quality/cost characteristics of our products as quickly as our competitors have. In the face of worldwide competitive pressure, American business cannot afford to overlook the benefits of advanced quality control methods. To a significant degree, the competitive edge that Japan has on the manufacture of quality products is attributable to the use of statistical methods in quality control—particularly statistical process control (SPC).

SPC is an approach to controlling and improving a process via systematic feedback on product characteristics and process variables. SPC raises a flag before a process goes out of control, helping to define problems and ultimately fix them. Through the elimination of special or assignable causes, and by making changes in the process to remove common or chronic causes of variation, all processes can benefit from SPC. Among the benefits are reduced scrap and rework, higher yields, higher quality and lower inspection costs. But most importantly, SPC provides a baseline measurement of a process from which operators can detect when and where non-random variations occur. Once SPC is mastered, a substantial portion of productivity and quality losses should disappear.

According to a report[1] by the U.S. Office of Naval Research on quality control practices in Japan, U.S. research emphasizes general results that can be applied to many situations, while in Japan, research on particular conditions related to particular products is emphasized. The report recommends that U.S. government agencies that fund research accelerate their funding of systems research in quality technology generic to *particular industries.* Such systems research would make use of a laboratory process test bed and a team approach involving engineers, computer specialists and statisticians, and would be oriented toward producing a technology for process design and optimization.

It is probably well understood by the majority of U.S. manufacturers that SPC should be implemented in their operations, but it is generally very poorly understood how to effectively implement SPC on any particular production lines. Research must be done and practical knowledge disseminated to promote effective use of SPC wherever possible. The need for better established techniques and guidelines is especially great in certain specific areas to which SPC has hardly been adopted. Automated assembly of electronics is a key field in this category. Research to establish practical, effective SPC procedures in the area of automated assembly of electronics would clearly advance the competitive position of the U.S. in the world arena of technological productivity.

Background

Unlike SPC, which aims to prevent poor quality by keeping processes within control limits, traditional quality control efforts emphasize the detection of poor quality in end products. Statistical *quality* control (SQC) is a class of methods that ensures the quality of products, but the means do not necessarily include SPC. Off-line inspection procedures and sampling plans used in usual SQC practices can not be applied to SPC because they do not have an interface with assembly process control.

To the small degree that SPC is established in the U.S., it is mainly applied to fabrication of parts rather than assembly of parts; and also, more to mechanical products than electronics. Assembly of electronics is obviously a crucial area in the production of technological goods. Since quality control *is* a serious problem in electronics assembly, there is much to be gained through the widespread successful use of SPC.

Some reasons for the failure of SPC programs include (1) misunderstanding of the objectives that were intended for statistical control charts; (2) similar approaches and techniques towards the control of short runs that are only valid for high-volume production and vice-versa; and (3) lack of suitable techniques providing adequate interpretation of statistical estimates. A great deal of quality managers, engineers and inspectors are unaware of the limitations of conventional methods of SPC charting and

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[1] Bowman, K.O.; Hopp, T.H.; Kacker, R.N.; and Lundegard, R.J. "Statistical Quality Control Technology in Japan," *Scientific Information Bulletin,* Department of the Navy Office of Naval Research Far East (U.S.), 15(1): 57-73; Jan-Mar 1990.

the likelihood of erroneous data representation and interpretation. Classification, terminology and definitions in the area of SPC applied to electronics assembly operations are still very obscure. These are problems encountered by personnel who have implemented some sort of SPC system; however, it is much more common that an SPC program is desired, but never begun because of more basic problems such as what factors to monitor, how to measure them, how to determine meaningful control limits, etc.

Many SPC training and educational programs are dedicated only to basic statistical procedures, not to assembly-related statistical knowledge. But implementation problems are not due as much to a lack of understanding quality control statistics as they are to understanding how to use them effectively. There is a very clear need for practical guidelines which are specific to electronics assembly.

There is a further need to optimize processes before SPC is implemented, so that the need for process corrections is minimized. Experimental design is a technique of actively varying the parameters affecting a process, to determine interactions between variables. Once such relationships are understood, process efficiency may be maximized by manipulating the controllable factors. Therefore, this project proposal addresses process optimization problems as well as SPC problems.

Uniqueness of Problems

Since SPC has not been in widespread use in electronics assembly, problems must now be solved that had no former need to be acknowledged. New measurement techniques need to be developed for certain unique assessments of quality. For example, a nondestructive measurement of gull wing height (stand-off height resulting after lead forming of certain surface mount devices) will require reading a height sensor at the time when there is an acceptable balance between an applied force comparable to that of installation, and an elastic deformation of the leads. (See Figure 1 in the accompanying report.) Uniformity of lead spacing is another example of many measurement challenges that must be met. Another unique class of problems will address statistical assessment of quality in terms of discrete instead of continuous characteristics.

The problems that need to be solved deal mainly with measurement and evaluation procedures, areas in which the National Institute of Standards and Technology is especially qualified. Although the benefit of solving the prevalent problems is obvious, the individual industries in the position to benefit are not in the position to fund and conduct research or to establish standard guidelines with applicability extending beyond their immediate concerns. It is appropriate, then, for the benefit of national productivity, that government agencies support the required research.

Project Objectives

This project will develop practical guidelines for implementation of SPC in electronics assembly plants. The end objective is to publish a guide that contains specific procedures for specific types of equipment and operations involved in automated assembly of electronics.

The means of accomplishing the objectives of the project will include industry cooperation with "microfactories," and research agreements with universities. The microfactory concept is an arrangement with private companies to use certain of their production facilities to conduct research and development experiments. When a company provides access to a microfactory, even though normal operations will be disrupted somewhat, the inconvenience should be offset by the eventual benefit that will result from the research program.

Following is a list of project objectives. Each objective pertains to each major type of process involved in electronics assembly. (Examples of processes are component insertion, lead cutting and clinching, lead tinning, wave soldering, vapor phase soldering, wire bonding, and the various types of solder-joint inspection.)

1. **Develop recommended techniques for measuring the parameters that will need to be monitored.** Describe appropriate methods of data collection and representation.

2. **Generalize the steps for designing experiments to maximize process efficiency.** A process must have the potential to produce high-quality results before SPC is implemented. While SPC may be used to keep a process under control, it does not engineer quality into the process. Statistical experimental design methods are extremely useful in the characterization, control, and optimization of industrial processes. Using approximation models that empirically describe a system's behavior, experimental designs can be used to improve quality by helping to design or adjust the assembly process. They determine where the controllable variables of a process should be set so that the quality characteristic (see Figure 2 in the accompanying report) is centered at the nominal dimension and has minimum variability from product to product, regardless of the levels taken on by the uncontrollable input variables. This would produce a process design that is robust to external or uncontrollable sources of variation.

   Two specific techniques of process optimization have been widely used effectively: response surface methods and Taguchi methods (although in certain cases other methods may be simpler and more efficient). The application of these techniques to the cases of concern for this project will be studied and the steps generalized.

3. **Generalize SPC procedures for processes within project scope.** Included will be explanations of how to accomplish the following tasks.

   A. Mathematically define and statistically quantify process capability. The extent of capability studies must be decided in advance.

B. Perform the fundamental physical modeling of the processes. Specify all the parameters which are involved, and note those which will need to be monitored. Identify the key areas of process output—i.e., measures of quality—for each major type of process. Define quality losses in terms of variables (continuous quantities such as temperature or weight) and attributes (discrete characteristics such as an open or closed circuit). Develop methods for calculating and analyzing quality losses, including the ability to accurately estimate the current quality status and to predict changes. Procedures should detect sources and types of product variation. Decide on rational sub-grouping of all observations.

   A special challenge in modeling electronics assembly processes will be the treatment of attributes. Since most types of processes for which SPC has been successfully implemented involve more variables and fewer attributes than many electronics assembly processes, principles of statistical control by attributes have not been well developed.

C. Decide the most effective techniques of data reduction and error analysis, including correlation, regression and mathematical modeling. Select the appropriate statistical techniques for short and long production runs. Include in the steps for data analysis a forecast capable of determining the time and sample size for the next inspection. Calculate the values of control limits and construct control charts. Provide means to signal the time to stop production and indicate possible corrective actions.

   Specify requirements of analysis software needed in the SPC system, including statistical techniques and functional requirements. Manual charting cannot compete with a dedicated software program which contains a set of all the necessary statistical tests and estimates and is capable of automatic data reduction and modeling.

4. **Formulate a general approach to planning the implementation of a new SPC program in a plant.** Guidelines will be developed for a plant to plan (1) stages of gradual implementation from simple procedures to increasing levels of sophistication; (2) how to balance available human and financial resources carefully to match the scope of the SPC program and the anticipated results; and (3) what kind of training personnel must undergo.

Sequence of Project Milestones

1. Develop descriptive list of processes and equipment to be addressed.

2. Establish microfactory agreements with industry.

3. Establish research agreements with universities.

4. Develop measurement techniques and data collection procedures.

5. Using experimental design, optimize processes on each microfactory facility. Generalize the steps for all the processes of interest.

6. Outline the steps to define process capability.

7. Determine recommended modeling techniques; apply to microfactories.

8. Develop data analysis and software recommendations.

9. Develop a general implementation plan for assembly plants.

10. Publish a guide summarizing all recommendations.

Resources Required

1. Project Personnel Requirements (total: 12 man-years)

   (1) Senior Level Computer Scientist

   (1) Mechanical Engineer

   (1) Senior Level Electronics Engineer

   (1) Electronics Technician

   (1) Senior Level Research Statistician

   (1) Statistics Assistant

2. University Support

   (1) Graduate Student (Statistics)

   (1) Graduate Student (Systems Engineering)

3. Industry Support

   (2) Microfactory Attendants, one at each site (one-fifth time)

   (4) Advisory Panelists, including Quality Control Specialists

4. Equipment Needed

   - Two microfactory facilities of diverse types

- Computer and instrumentation equipment for each microfactory site
- Computer equipment for data analysis
- Analysis software (several packages for experimentation)

Appendix B:
PLANTS INVESTIGATED

Plant A: A $60 million fully automated and computer-integrated facility for low-volume, high-mix SMT assembly (40,000 types of components; 200 components per circuit board assembly; 1000 types of circuit board assemblies; 50,000 assemblies per year).

Plant B: An experimental prototype low-volume, high-mix SMT facility completed in November 1987 and subsequently dismantled. An elaborate study to develop an integrated conceptual plan for the full range of electronics assembly operations preceded this prototype facility, which was constructed to validate some of the concepts developed in the study.

Plant C: A plant for a large computer manufacturer, although this particular plant produces electronics assemblies only for products other than computers.

Plant D: A plant for a large diversified commercial manufacturer. In addition to other products, this plant makes SMT assemblies for other major electronics products manufacturers. Flat packs with leads spaced on 25-mil centers are typical. There is prominent use of automation. For the most part, a production run of any particular board involves a minimum of 60,000 placements (of components); but there are also special rooms dedicated to low-volume work and prototypes.

Plant E: A plant for a large diversified commercial manufacturer. This particular plant is a small operation compared to others the company has. In addition to commercial products, it also works on small military contracts for high-volume manufacture of electronics products. Most processes are automated, loading and SPC measurements being exceptions.

Plant F: A facility currently under construction, to produce printed wiring assemblies containing through-hole and/or SMT components. Average lot size will be five, and throughput will be 15,000 assemblies per year. The special feature of the system will be its acceptance of PDES data files as input. Otherwise, there will be no research; advanced performance capability will be achieved with commercial equipment and applications packages. Completion is expected by mid-1990.

Plant G: An experimental prototype facility for the assembly of through-hole components onto printed circuit boards. The facility was completed in May 1987, and was subsequently dismantled. It was designed for fast production of parts on demand, in lot sizes as small as one.

Plant H: A large private operation dedicated to military contracts—especially electronic systems research, development and production. Printed circuit assembly facilities feature a wide range of capabilities, including automatic insertion of 8- through 24-lead DIP integrated circuits into printed circuit boards and planar arrays; numerically controlled multiple fixturing and cut-and-clinch machines; automatic back panel wiring; robotic pick-and-place machines; and electro-optical systems assembly and test. Flexible circuits and integrated multilayer/flexible cable boards are also produced. Wave and vapor phase soldering techniques are used.

Plant J: An automated computer-integrated robot-based facility designed for the broad mix, small lot size and high change rate of defense electronics products. Serving as production support for Plant H, this plant is set up especially to assemble, solder, inspect and test two different types of assemblies: high-density printed circuit boards with flat-pack SMT components (100 components per side, 9000 interconnections on a board); and the other boards with through-hole components. It does not produce boards that combine both through-hole and surface mount technology.

Plant K: A detailed theoretical model of an electronics assembly plant, resulting from a study conducted under a Tri-Services program that concluded in 1984.

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Glossary

assignable cause— A process *factor* which contributes to variation in a product characteristic, and which is feasible to detect and identify.

attribute— A "go or no-go" observation; a characteristic which is appraised in terms of whether it meets or does not meet a given requirement. For example, a feature may be either present or absent; or a unit may be either effective or defective.

bonding— The forming of an interconnection on the surface of a bare semiconductor *chip*, or an interconnection between the wire leading from such a chip and a *mounting pad* on a board; generally referring to the thermal compression or ultrasonic bonding process in chip-and-wire hybrids.

bonding pad— A relatively large metallic area at the edge of an integrated-circuit *chip*. This area is connected through a thin metallic strip to some specific circuit point to which an external connection is to be made.

capability— (Not a preferred term; see *process capability.)*

chip— 1. (In reference to a resistor or capacitor:) A *lead*less *component* having a small, ceramic substrate as a base, thus distinguished from through-hole components. **2.** (In reference to integrated circuits:) A single substrate on which all the active and passive circuit elements have been fabricated in situ using one or all of the semiconductor techniques of diffusion, passivation, masking, photoresist, and epitaxial growth.

common causes— Random sources of process variations, which cannot be altered without changing the basic process itself.

component— The preferred term for a discrete electrical element such as a resistor, capacitor, transistor, etc.

component carriers— *Lead*ed or leadless *packaging* of electronic *components*, having input and output terminals around the perimeter.

conformal coat— A coating that completely covers a printed circuit board to protect the board and its *components* from voltage breakdowns, corrosive gases, corrosive chemicals, solvent damage, electrical failure, micro-organisms, physical abuse and other detrimental effects.

control chart— A graphic record on which are plotted statistical measures obtained from successive or sequential samples of products or services, used to evaluate whether a process is in a *state of statistical control.*

control limits— The limits on a *control chart* between which the statistical measures obtained from a sample will lie when the process is in a *state of statistical control.*

DIP (Dual In-line Package)— An *insertion*-mountable *package* having a row of extended I/O pins on two opposing sides. The extended pins are typically mounted through a hole in a printed wiring board. DIPs are generally used to package integrated circuits.

experimental design— A systematic approach to determining cause-and-effect relationships between controllable process *factors* and measures of output performance. With an understanding of how to actively manipulate the factors, process performance may be optimized.

factor (statistical sense)— A variable characteristic or condition which is likely to affect the *response* of a process.

flat pack— **1.** A flat, rectangular integrated-circuit or hybrid-circuit *package* with a row of coplanar ribbon wire *leads* extending from each long side. **2.** A semiconductor network encapsulated in a thin, rectangular package, with the necessary connecting leads projecting from two or four edges of the unit. Both styles of flat packs are designed for *gull wing* lead forming for *surface mounting.*

gull wing— A *lead* form where leads exit the sides of a *package* body from a plane near the center of the part, turn downward to just below the body, then turn outward to form feet for reflow solder mounting. The appearance of such a lead resembles a gull's wing bent downward in flight.

high density— (referring to electronic circuits) Having significantly more circuitry per unit area than more common boards or *packages.* This implies the use of packages with high *lead* counts, and consequently fine lead pitch (center-to-center spacing of $\leq$ 25 mils).

insertion— Placement of a *component* on a board in the position where it is to be soldered or otherwise *bonded.*

interface— A boundary between two devices, functions, or combinations of devices and functions, which provides (mediates) interactions between the entities on either side. An interface specification must cover both physical and software considerations.

lead— A small conducting post extending from a *component,* forming an interconnect facility when *inserted* in or on a printed wiring board.

microfactory— A subset of production facilities within a factory to which access is provided for the conduct of research by an outside organization.

mounting pad— A metallized site for attachment of either a *lead* of a *component* or a conductor of a leadless component.

off-line programming— The process of developing instructions for an item of equipment without the need to interfere with productive operation of the equipment. Normal productive operation unrelated to the programming task could take place even during programming. Compare with the definition of *teach programming.*

overhang (of a lead)— The portion of a *lead,* e.g., a *gull wing,* which extends beyond its mating *mounting pad.*

package— Housing containing integrated circuits, using any of the various mounting technologies: through-hole, (e.g., *DIPs*), *surface mount* (e.g., plastic *lead*ed-*chip* carriers, small-outline integrated circuits or fine-pitch devices such as quad *flat packs*), tape-automated *bonding*, chip-on-board package, etc.

PDES— Product Data Exchange using STEP (Standard for The Exchange of Product model data), being developed by a voluntary standards group with industry-wide participation. PDES data exchange will permit communication among dissimilar computer-aided design and computer-aided manufacturing systems, numerical control machines, finite element methods, etc., and will include product life cycle application data, assemblies, user-defined data, and information on constraints and dependencies.

pick-and-place machine— An automated or semiautomated machine used for picking *SMT components* from specified delivery mechanisms and placing them at programmed locations on a printed wiring assembly. A robot which can perform pick-and-place tasks differs from a pick-and-place machine in that it can be programmed to perform certain other types of tasks as well.

process capability— The limits of inherent variability that may be expected from a production process working at the settings, speeds, materials inputs, and other operating arrangements specified.

quality characteristic— A quantitative measure of the properties of a product or service that bear on its ability to satisfy given needs.

quality loss— A decrease in the potential value of the *quality characteristic* of a process.

rational sub-grouping— Classification of observations into small groups within which it is believed that *assignable causes* are constant and into which observations can be subdivided in the carrying out of certain methods of statistical analysis.

regression— The procedure of determining estimates of coefficients in a mathematical model and determining their relative importance in quantifying the total variation in the response variable.

response (of a process)— The output of a process in terms of characteristics of the end product.

response surface— An empirically-based representation of the expected *response* of a process at particular combinations of *factors*. This is a means to determine the factor levels that give optimum response.

state of statistical control— A state of a process wherein the variations among the observed sampling results from the process can be attributed to a constant system of chance causes.

statistical process control (SPC)— An approach to monitoring processes and controlling key variables to ensure that measures of output quality are within acceptable limits.

statistical quality control— The part of quality control procedures—i.e., operational techniques and activities used to satisfy quality requirements—in which statistical techniques are used.

surface mount technology (SMT)— The technology of planar assembly (as opposed to through-hole or *chip*-and-wire mounting) of electronic *components* onto printed circuit boards, or onto hybrid printed interconnect substrates. SMT differs from conventional through-hole technology in that the components do not have *leads* intended to extend into holes drilled in the printed circuit board; rather, the leads, if any, are to be bonded to the *mounting pads* on the board surface.

Taguchi methods— A specific set of statistical methods to design quality into processes.

teach programming— The process of developing instructions for a item of equipment by taking it through the actual procedure of the task to be programmed, and recording each step.

vapor phase soldering— A method of using a vapor blanket above a boiling fluid to heat up parts to be joined, and melt previously applied solder to form bonds on a circuit assembly.

variable— A representation of a value with possibilities along a continuous scale, such as weight in pounds, resistance in ohms or moisture content in percent. This usage of the term *variable* is in contrast to the term *attribute*.

wave soldering— A method of moving a board across a wave of molten solder, momentarily immersing the underside so that *leads* extending through holes in the board from *components* on the top side, as well as *SMT* components glued to the underside, are simultaneously soldered to the board.

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The National Institute of Standards and Technology assisted the Harry Diamond Laboratories in an effort to develop plans for a new program of research in electronics assembly technology. The need for research was investigated in the domains of precision engineering, system integration and process control. Rather than engineering design problems, the emphasis was on principles, techniques and standards that could help eliminate obstacles to widespread adoption of state-of-the-art technology in assembly plants. Current popular assembly methods as well as emerging new trends were studied. Research projects are recommended in the areas of (1) flexibility of equipment, (2) precision handling of components, (3) equipment interfaces, (4) equipment programmability, and (5) statistical process control.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

electronics assembly; equipment interfaces; high-density electronics components; off-line programming; printed wiring assemblies; statistical process control; surface mount technology

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