

A MONOGRAPH FOR AUTOMATED ASSEMBLY RESEARCH

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(ABSTRACT)

The emergence of manufacturing automation to deal with decreased productivity and shorter product market-life is very evident in the area of assembly. Correspondingly, a wealth of researchers dedicate considerable efforts to advancing automated assembly technology. The purpose of this thesis is to provide a comprehensive monograph for the research. This thesis has categorized the current research efforts into eight research categories: rationalization techniques, design for assembly, representation, sequencing, system configuration, equipment, parts mating and joining, and a category for issues with a global impact. Each is described in terms of an explanation of the research in the category, the key researchers in the area, and suggestions for future research. Additionally, a database has been developed to capture characteristic research from each of these categories. This monograph coupled with the associated database, will assist automated assembly researchers in understanding the breadth of issues facing the research community. Additionally, it will provide researchers with a 'first-look' document and literature review for those interested in automated assembly.

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1. CHAPTER 1

INTRODUCTION

1.1. BACKGROUND

Languishing productivity in the United States is an issue of serious domestic regard. There is a growing concern that manufacturing in the United States is no longer competitive with other countries in the global market-place [86,338]. Automation offers a solution to many problems associated with low productivity [305]. Consequently, many industries have become conscious of the potential impact of automation on their economic well-being and perhaps even their survival [137].

Within the field of automation exists the area of automated assembly. A great deal of documentation expounds on the potential advantages of automated assembly to reverse the slide into low productivity [46,86,126,263]. Manual assembly typically accounts for between 40 and 60 percent of total production time [9,47,236]. One-third of the workforce of a manufacturing organization is normally involved in assembly tasks [86]. Furthermore, assembly costs often account for 50 percent of total manufacturing costs [46,339]. Together, the potential for reducing labor costs coupled with the associated indirect cost savings suggest the appropriateness of automated assembly as a means to increase productivity.

Both automatic assembly research and automated assembly development demand a great amount of attention. The International Conference on Assembly Automation convenes yearly to discuss topical matters (1980 - present). Major expositions exist to display advances in hardware (e.g., Assembly Technology Expos). Additionally, most major annual manufacturing conferences and expositions dedicate presentations, sessions and floorspace to automated assembly issues and equipment (e.g., AUTOFACT, NAMRC, ROBOTS, VISION, International Symposium on Industrial Robots, International Conference on Simulation in Manufacturing, etc.). Finally, automated assembly issues are presented at other annual major engineering conferences such as: International Conference on Industrial Engineering, IEEE Conference on Robotics and Automation, ASME Design Technical Conference - Flexible Assembly Systems, etc.

1.2. PROBLEM STATEMENT

Although automated assembly research issues demand attention as a result of the drive to increase productivity, the area itself is still in relative infancy [263]. Introductory documents that focus exclusively on automated assembly are at best - sparse. Any in-depth study of automated assembly research literature leaves researchers searching for some cohesive organization to the volumes of literature which surround the subject. Additionally, information about the myriad of problems facing automated assembly researchers and developers is, at best, randomly scattered throughout the volumes of literature.

Admittedly, some literary works focus on assembly; certain ones even focus on automated assembly [46,47,126,172,236,254,260,263]. Nevertheless, each is

limited according to the authors intended audience and personal agenda. Evidence of this is revealed in the diversity of the major headings listed in the tables of contents of the above cited automated assembly tradebooks. Certain areas are discussed in one document but are excluded in others. Neither these books, nor other individual documents, attempt to enumerate all the subjects associated with the entire spectrum of automated assembly topics/research.

Furthermore, any close analysis of the contents of conference proceedings merely compounds the problem of trying to understand the breadth of issues facing automated assembly researchers. As with the tradebooks, it is impossible to discern a global focus for automated assembly research from the literature presented. Simply take note of the diversity of topics presented at each of the eleven International Conferences on Assembly Automation. Research literature has been presented by the foremost experts on subjects ranging from assembly design, to vision for assembly, to peg-in-hole techniques. However, none of the documents guide the reader to an understanding of the 'big picture'. Furthermore, direction cannot be inferred by any single conference collection or the group of eleven conferences when taken as a whole. Finally, to exacerbate the problem further, an abundance of innovative automated assembly research literature is presented outside of the few conferences that concentrate on assembly (e.g., International Electronics Packaging Conference, Midwest Symposium on Circuits and Systems) [67,182,212,222,342].

Most articles addressing automated assembly issues provide some guidance for research [26,181,215,269]. Yet, the direction is understandably limited to the particular area presented in the literature. A few works give some general

direction [32,298] for other automated assembly research, but they are insufficient. Documentation does not exist that expressly identifies and isolates potential research areas. Moreover very little effort has been devoted to identifying areas of potential research issues for industrial developers. Accordingly, a comprehensive document is needed to provide structure and cohesion to the literature and add some direction for researchers interested in automated assembly.

1.3. PURPOSE/OBJECTIVE

The scope of this research included a thorough study of all aspects of automated assembly research. Specifically, an in-depth literature review of all scientific and application research ongoing at educational/research institutes, government agencies, and within manufacturing organizations has been conducted.

Correspondingly, the objective of this thesis is to document and categorize the available literature into a coherent monograph on automated assembly research. This thesis provides structure and cohesion to the volumes of literature that are available in the area of automated assembly. The monograph fills a much needed niche for those researchers looking to understand the 'big picture' in automated assembly. The organization and categorization is the contribution to the overall 'body of knowledge'. The monograph includes an explanation of each major and minor category, accompanied by listings of the major researchers in the category, discussion of the current issues in the area, and general suggestions for where future research resources should be directed.

As a natural by-product of the literature review, an extensive database for automated assembly research has resulted. This database is captured on a commercial software package which possesses a multitude of search options to include keyword searching, author searching, etc. Appendix 1 will briefly address the origins of the contents of the database, provide a keyword list, and outline some of the features of the software.

1.4. PRESENTATION METHODOLOGY

The body of the thesis will begin with definitions of assembly and automated assembly, followed by a brief general historical account of automated assembly and a discussion of the need for automation in assembly (within the Literature Review). Next, the players in the automated assembly arena will be briefly discussed and explanations of the various automated assembly systems provided. Additionally, the Literature Review will include an extensive listing of various research efforts which is organized by areas. The methodology will explain the process used to arrive at the final categories. Finally, the research categories will be presented.

Each category will be described in terms of combinations of the following: background/explanation, a brief recapitulation of the well-written research institutions/individuals, present research focuses, and needs/problem areas. The explanation will loosely define the category and outline the type of research ongoing in the particular category. The text on the research institutions will give the reader a re-examination of some of the major contributors who have done research in the past as well as those who are currently contributing. Finally,

current focuses and areas for future research will be outlined to provide insight into possible areas for additional research.

1.5. SCOPE AND LIMITATIONS

'Assembly' can be a rather nebulous concept when viewed from total world perspective. The term itself has different meanings in different organizations (e.g., assembly denotes a different meaning in the construction industry than it does in a manufacturing company). Consequently, the discussion in this thesis will be limited to automated assembly as it has an impact on the mechanical engineering and electronics manufacturing fields.

The thesis will not attempt to address larger categories of generic 'assembly' research (e.g., design for assembly, parts mating, research topics unique to manual assembly, etc.) unless they also pertain to automated assembly. In fact, the thesis will be further limited towards research into flexible automated assembly and its close variations (i.e., semi-flexible, programmable, etc.). Since most of the developments surrounding specialized automated assembly are application oriented, discussion of research in specialized (fixed) automated assembly will not be included. Additionally, no attempt will be made to suggest what type of research should be done at Virginia Polytechnic Institute and State University or any other university. Potentially, this document will provide necessary direction for any future research projects and equipment acquisitions to interested researchers.

The research emphasis is to synthesize the assemblage of research subjects into a coherent monograph for use by individuals interested in automated assembly. The thesis will provide the reader with an introduction to the 'world' of automated assembly research. Its unique feature will be its outline of the 'big picture' of automated assembly research capturing the breadth of diversity which exists in this enormous field. The author's lack of special expertise in any one specific area, along with the absence of any bias due to a specific agenda, will allow the document to serve as a generalized document.

The literature presented in the Literature Review does not presume to be all inclusive. Rather, the articles which make up the Literature Review are a representative set from a far larger set. This group is indicative of the types of research being done in the automated assembly arena. The area/literature has been studied in sufficient depth to draw conclusions as to the categories necessary to capture all present research efforts. Moreover, the validation process corroborated the results of the category formulation process.

1.6. THE BIG PICTURE

This thesis fits into an overall scheme of research being conducted by the Manufacturing and Automation Research Laboratory at Virginia Polytechnic Institute and State University. However, its potential uses breach the confines of a single institution.

This monograph and its accompanying database is designed to serve as a 'first-look' resource for future automated assembly researchers. Using the overall

categorization provided, researchers can narrow their anticipated research efforts to an area of interest based on their goals, available equipment (software and hardware), and the fundamentals outlined in each category. Armed with this information, the researcher can plan future research. Once a researcher decides on an area for research, this document will serve as a basis to build upon prior to more in-depth literature reviews and study. This bottoms-up approach can save valuable time and resources.

2. CHAPTER 2

LITERATURE REVIEW

The Literature Review is broken into three sections. In the first section, definitions of key terms, a brief summary of the historical origin of automated assembly and an explanation of the need for automated assembly are provided for background. An explanation of the 'players' involved in automated assembly research follows. Next, explanations of the types of automated assembly systems are furnished to provide a basis for understanding the various types of system configurations. All of these have been developed from a sundry of written works and are structured specifically for this thesis. Finally, the remaining reviewed literature is grouped into research areas for presentation. Remember, the material outlined within the areas does not represent an 'all inclusive' list of automated assembly research. Rather, it includes a select collection of works from the larger set available under each heading. The choices are indicative of the research being conducted in all of the many different 'areas' of research.

2.1. BACKGROUND

During this research, it has been necessary to synthesize the definitions of many terms (e.g., area names, the type of systems, etc.). Understandably, the definitions of the two following terms are essential to an understanding of the subject area: assembly and automated assembly (specialized and flexible). These

definitions and, equally important, the justification for automated assembly follow in the next three sections.

2.1.1. WHAT IS ASSEMBLY?

Assembly becomes necessary when the design effort cannot simplify the product into a one piece element. Assembly is the complex process by which a product gradually attains its final form and shape through a series of operations [9,269]. These operations are designed to unite machined parts into components, sub-assemblies, and eventually the final product [9]. The sequential addition of components not only creates a more complex product but adds value at each station [113]. Although assembly cannot occur until parts are gathered and organized, the main function of assembly is to join components, formless material, and sub-assemblies into a final conglomerate product [9].

Common assembly operations include mechanical fastening (using screws, nuts, bolts, rivets, etc.), welding, brazing, and bonding by adhesives [113]. There are two major approaches to assembly: manual assembly and automated assembly (see Figure 1).

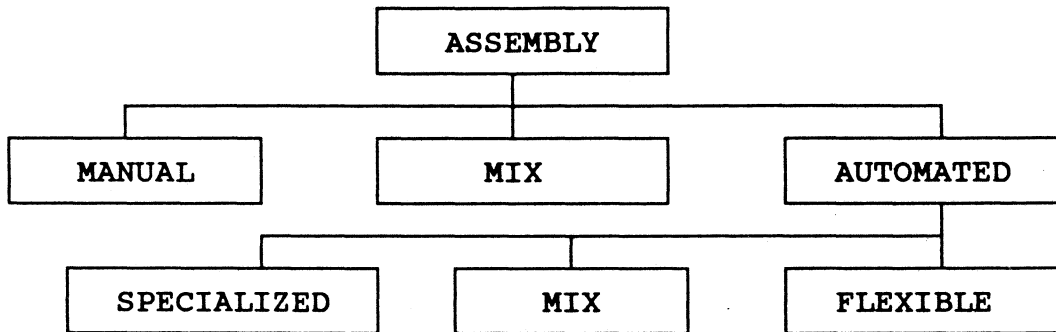


FIGURE 1
APPROACHES TO ASSEMBLY

2.1.1.1. MANUAL ASSEMBLY

Typically manual assembly operations use low cost laborers equipped with simple jigs and fixtures [260]. Laborers use the various bonding options to join the various parts and subassemblies together into a usable product. Humans are extremely adept at assembly. Their flexibility and dexterity are difficult to equal/duplicate [236,263,336]. Unfortunately, their performance is laborious to document and difficult hold to a standard [336]. Nevertheless, in cases where volume and capital investment are low, manual assembly remains the chosen method for complex operations requiring detailed inspection, diverse manipulation, and precision [263,336]. In addition, since manual assembly is almost always an option (a rare exception - certain clean room operations with thin wafers), it remains the prevalent form of assembly.

2.1.1.2. AUTOMATED ASSEMBLY

Automated assembly is the alternative assembly approach. This form can be divided into two sub-types: specialized assembly and flexible assembly. In addition to the possibility of saving money, automated assembly exists to address some of the deficiencies inherent in the performance of the human assembler [336]. Nevertheless, automated assembly presents many challenges of its own.

2.1.1.2.1. SPECIALIZED AUTOMATED ASSEMBLY

The first type of automated assembly is specialized (or fixed) automated assembly. Specialized assembly is the traditionally thought of type of assembly automation which uses dedicated devices to assemble massive quantities of products. These products normally enjoy stable design and long market life (e.g., bottling, electronic devices, video cassettes, etc.) [41,260,339]. Dedicated machines execute the operations normally performed by the human assembler. Specialized assembly is extremely efficient and has uniform performance if parts quality is good [260,336]. Still, specialized assembly is expensive because each task requires its own dedicated apparatus. Such investments must be amortized across production quantities in the millions to ensure economic viability [260,263,336]. This makes small batch assembly with specialized assembly equipment impossible from an economic, as well as, a practical sense [46,291].

2.1.1.2.2. FLEXIBLE AUTOMATED ASSEMBLY

Flexible assembly is a hybrid of sorts, offering some of the flexibility of manual assembly with the uniform results of specialized assembly [260,336]. In this type of assembly, robots and other types of versatile machinery are used to execute the assembly tasks. As with specialized automation the capital investment is costly; however, the assembly devices (normally robots) are versatile and not limited to one specific function [260,336]. Its inherent flexibility makes this form of assembly a practicable alternative for batch production. Nevertheless, drawbacks are also associated with flexible automated assembly (e.g., the need to integrate humans to accomplish certain difficult to duplicate tasks).

2.1.2. AUTOMATED ASSEMBLY DEFINED

A simple definition of automated assembly is not easy to draft. Frank J. Riley - a recognized expert in the field - offers the definition below.

Automatic assembly may be interpreted as the mechanized placement of individual discrete components into a specific spatial relationship to form an end item with some specified function. This automatic progressive placement of one component after another may include the orientation of components from bulk storage, the retrieval of oriented components from storage, the fabrication of components on the assembly line, the monitoring of the physical placement of each component, the joining of the components to form the assembly, and inspection for functionality of the assembled product [126]. (Or somewhat simply : automatic assembly is the repetitive assembly of manufactured products by use of programmed or sequentially controlled mechanisms [263]).

As suggested here, the concept of automated assembly encompasses more than the perfunctory tasks of having a machine perform tasks identical to the human laborer. The additional peripheral equipment and operations associated with automated assembly are numerous [113,260,263,336]. While this additional equipment enables quicker product assembly, it also requires additional attention and generate added problems and expenses. Yet, serious consideration of widespread automated assembly would be impossible without the breakthroughs in equipment that perform such tasks as automated parts feeding, orientation, and delivery.

Automated assembly requires precision, repeatability, and variety of motion [263]. Sophisticated gripper devices which sometimes themselves play an active role in one of the assembly steps are often indispensable. Automated assembly does not enjoy the luxury afforded to some automated manufacturing devices.

Some automated manufacturing operations can offer such advantages as improved weld quality or elimination of hazardous conditions to warrant their acquisition. However, since for the most part assembly operations are not dangerous or dirty, the only practicable justification for automated assembly is increased speed and efficiency or improved accuracy.

Although earlier distinction was made between specialized and flexible assembly, generally they will be addressed as a single topic. Except in cases where it provides substantial clarification, most researchers do not attempt to differentiate between specialized and flexible assembly - the term automated assembly encompasses both. Furthermore, the term 'automated assembly' has been chosen as opposed to - automatic assembly, programmable assembly, assembly automation or robotic assembly - as a generic concept. Later if variations in this terminology are made, they will be deliberately used to convey a different meaning.

2.1.3. A BRIEF HISTORY OF AUTOMATED ASSEMBLY

Prior to the late 18th century the complete assembly of a product was performed by a single craftsman. Additionally, that same individual normally manufactured each individual part. The scale of production was limited by the availability of skilled tradesman rather than demand.

However, in 1798 Eli Whitney introduced the concept of mass production with the introduction of interchangeable parts for musket production. This novel concept coupled with Oliver Evans' concept of conveying materials from one

location to another through the use of conveyors in 1793, were the building blocks for assembly automation.

Elihu Root's notion of 'divide work and multiply output' further advanced the workforce's capability to handle large volume assembly contracts with minimal training. Frederick Winslow Taylor's time and motion study methods improved overall performance by ensuring all necessary equipment was in the optimal location for the worker to carry out the required assembly tasks.

Nonetheless, the most significant contributions to the field of automated assembly were made by Henry Ford. He added his own ideas of those of the aforementioned innovators to develop on the first mass assembly operations. In Ford's own words his principles for assembly are as follows:

First, place the tools and the men in the sequence of operations so that each part shall travel the least distance whilst in the process of finishing.

Second, use work slides or some other form of carrier so that when a workman completes his operation he drops the parts always in the same place which must always be the most convenient place to his hand and if possible have gravity carry the part to the next workman.

Third, use sliding assembly lines by which the parts to be assembled are delivered at convenient intervals, spaced to make it easier to work on them.

His principles of assembly as applied to the production of the Model T Ford provided the foundation for today's operator assembled manufacturing facilities.

As a logical progression to Ford's assembly line, mechanical devices have replaced operators. Automatic workheads have replaced workers performing

simple tasks. Robots have now been added and more and more complicated/versatile assembly equipment is being developed. Nevertheless, mechanized devices have not fully replaced operators. Instead, except in a very few instances, they augment or supplement manual lines where they will continue to work side by side with human operators for the foreseeable future.

2.1.4. WHY AUTOMATED ASSEMBLY

As mentioned in the Introduction, the move towards automation as a means to increase productivity is gaining momentum. Increasing the use of automated assembly can potentially contribute to this effort. The problems associated with present assembly techniques are self-evident: assembly tasks occupy one-third of the workforce, account for 40-60 percent of total production time, and are responsible for 50 percent of the total manufacturing costs [9,46,86,339]. Alone, the potential reduction in labor and the associated indirect costs, suggest the appropriateness of automated assembly.

In recent years most developments in the manufacturing arena have been in the area of component manufacture. For a myriad of reasons automated assembly developments have been slow and the technology has failed to make significant market penetration [260,263]. Foremost is that automated equipment is a totally optional purchase [263]. Additionally, most non-assembly operations cannot be performed without the aid of equipment [339]. Conversely, most assembly operations can be performed manually. Moreover, automated assembly equipment generally does not add to the value or design requirements of the product (unlike machine tools, packaging devices, transfer mechanisms, finishing

tools, etc., which do). Finally, in the U.S., engineers focus on product design and assume manufacturing will figure out how to make the product - while in countries like Japan their primary focus is on designing an efficient manufacturing process and then feeding it with products designed to manufacture [64]. These factors all point to an apparent lack of appreciation for the impact of assembly and they have contributed to lack of substantial gains in market penetration.

Fortunately, the many other potential advantages associated with automated assembly are generating greater interest. Improved product quality, reduced assembly costs, greater job satisfaction, improved working conditions, increased productivity, increased reliability, uniform quality, and increased competitiveness represent just a few reasons [263,339]. Quality has become the driving force behind the move to automated assembly. As evidence, vendors no longer build **assembly machines**, they build **assembly** and **test systems** today. Just look at warranties on car components. What were once one year warranties are now from five to seven years. Nevertheless, except for in a few special circumstances, reducing costs remains the most compelling reason - for without cost reduction, automation is superfluous [263,234].

Despite automated assembly's shallow market penetration, the potential for savings is growing [260]. Unlike during the introductory years when automated assembly systems were designed to assemble products that already existed, the systems of today are designed for future products. Designers and researchers are focusing more on requirement-driven systems rather than solution-based systems [298]. As the advances in research are adopted by manufacturing, the technology

will continue to make strides forward. Finally, Bloch and Conrad point out several myths about the relationship between quality and productivity which must be dispelled and offer compelling incentive for automated assembly [34].

The first is that quality is an extra, a luxury desirable to the extent it is feasible. In fact, quality is an essential requirement and does not come in increments - low quality is not an acceptable or meaningful standard.

The second is that quality is not quantifiable - that it is a subjective judgement by the consumer. It is, in fact, precisely measurable.

The third is that quality is expensive. That is a short-term management attitude that ignores the long-term savings achieved through quality management.

Finally, there are many misconceptions about the causes of poor quality. By ignoring measures such as error rates, scrap, and other indicators of the integrity of the design and manufacturing process, this myth attributes poor quality to lazy workers, labor-management disputes, and other environmental factors.

The ability of automated assembly to satisfy these demands relating to improved quality is yet another justification for its implementation.

2.2. THE PLAYERS

2.2.1. UNIVERSITIES

Universities continue to contribute significantly to automated assembly research. Although much of the early automated assembly research was done in-house at some of the major manufacturing firms (IBM, Westinghouse, etc.), much of the current efforts are spearheaded by institutes of higher learning. Numerous colleges and universities are contributing as the Literature Review will illustrate. A few of the many major research hubs are listed below.

First, at the University of Massachusetts and now the University of Rhode Island, Boothroyd and Dewhurst have made great advances in the area of design for assembly. Their handbooks on design for assembly coupled with numerous books on the subject are widely cited by other researchers and provide valuable insight. To complement their work, they have devised computer-aided design for assembly software [43] and have presented papers on the economic rationalization of assembly automation [41,42].

Another group of major contributors is at the Charles Stark Laboratory which is associated with the Massachusetts Institute of Technology. Nevins and Whitney pioneered the area of remote center compliance devices and continue to address part mating/joining issues [113,260,263,336,337]. Gustavson has done much of the work in the area of rationalization techniques for automated assembly [115,117]. A team of Stark Draper researchers devised the "Strategic Approach to Product Design and Analysis of Integrated Manufacturing Systems" for a National Academy of Engineering project that outlines a process to implement integrated product and process design [338]. In addition, some of these same researchers recently presented material on automated assembly in clean room environments [269].

At the Linkoping Institute of Technology in Sweden, a major division is focused on systems for automated assembly. Their main research efforts are concentrated on programming, adaptability, sensor development (optical, force and tactile), and off-line programming to include artificial intelligence methods. Their collective efforts are geared to automated assembly advances and their

researchers have published numerous research results at several major conferences [222].

Countless other research developments originate in universities. Notwithstanding, some reluctance still exists towards the undertaking of automated assembly research. The root of this hesitation can be linked to the adverse stigma surrounding academic research that is closely connected to industrial application - 'non-basic research'[34]. This remains a continuing problem. As a result, community colleges and 2 year technical universities are receiving much of the attention and funds from industry and government because of their inhibition towards this culpability.

2.2.2. INDUSTRY

The actual number of industrial organizations active in the furtherance of automated assembly research is difficult to assess. Large companies such as IBM, GE, Honeywell, and the automobile industries, remain as research leaders. However, many other companies no longer have substantive in-house research capability. Regrettably, since most of the research done by industrial organizations is not public domain, it is difficult to evaluate what proprietary successes may have occurred. Still and all, it would be prudent to infer that successful applications (e.g., automated assembly of computer hard disks, automobile relays, air-bag systems, etc.) were preceded by extensive research.

IBM has been responsible for numerous automated assembly application (assumedly based on proprietary research) innovations. Contributions include

their IBM 7565 Manufacturing System for Assembly and the early development of the AML Language for Robots. IBM has also developed automated assembly systems to produce everything from word processors [254], to ribbon cartridges to the PS2 personal computer [162].

Specialized automated assembly vendors dominate the application arena. Most are well versed in the capabilities and limitations of their equipment. They have field tested units for specific problems and can adapt successful past designs to meet current problems [263]. Nevertheless, since they normally cater to the development and refinement of relatively inflexible specialized systems designed for specific customers - they do not play a large role in the research arena.

The needs of the manufacturing industry spawn research. Specifically, the major user of automatically assembled products (e.g., relays, fuses, wiper motors, etc.) continues to be the automakers. The automotive industry has long been a virtual driver of the assembly industry [32]. Consequently, their interests and funding impact significantly on research advances.

2.2.3. U.S. GOVERNMENT

Governmental agencies continue to provide much of the funding for research. Nevertheless, a national policy for automation or manufacturing does not exist. Additionally, the government does not publish any comprehensive documentation indicating the needs researchers should address. All this elimi-

nates any potential evolution of synergy from the numerous research and development projects ongoing throughout the United States.

The National Science Foundation frequently teams with universities and industry to study a myriad of topics. Their Design and Manufacturing Systems Division exists to support research that will deepen understanding of modern manufacturing to include innovative assembly procedures [223]. A catalyst for manufacturing research, the National Science Foundation has also formed the Engineering Research Centers and the Basic Science and Technology Centers to provide opportunities to work outside of traditional boundaries and into the needs of the future [34].

Funded projects include the work done by Whitney and Nevins at the Charles Stark Draper Laboratories on peg-in-hole insertion [161], the Adaptable-Programmable Assembly System developed in conjunction with Westinghouse Electric Corporation [113], numerous projects done at the University of Texas at Austin [312,313], and many others. The United States Commerce Department also has a program for advancing manufacturing innovations. Both are interested in the furtherance of the state of art in assembly technology.

Finally, the Department of Defense is a major source for research funds. Most of their allocated research funds go to the resolution of specific research shortcomings as well as application problems. Their considerable interest in flexible automated assembly is fueled by their customary requirements for relatively low volume production.

The goals and obstacles of assembly automation research remain universal. Abroad, researchers have similar interests in the area of automated assembly to their colleagues in the United States. Noteworthy successes in innumerable different topics can be isolated to researchers in specific countries. In fact, certain nations are considered global leaders in specific research and development areas.

Notably, major differences exist in the degree of participation by the governments of the individual nations. For instance, some nations - like Singapore- have a national policy of increased automation under which substantial tax advantages are afforded to companies that increase automation [237]. Organizations literally cannot afford not to automate. (It should be noted that Singapore has a goal of leading the way in manufacturing in the Southeast Asia triangle and negative unemployment to kindle its interests.)

Additionally, the European nations actively promote cooperation in automation under EUREKA projects like EEACP, ESPRIT, ALVEY, BRITE, and RACE. EUREKA was established to combat the increasing threat to their industries by the Pacific basin countries and the United States. Of particular interest to automated assembly is a current project known as FAMOS (Flexible Automated Montage of Systems). Its goal is not research based - its intent is aimed at developing flexible automated assembly designed to produce 'real products for real profit'[215,216]. Solidarity like this has yet to arise within the United States.

2.3. THE SYSTEMS

The explanations given below attempt to simplify the types of automated assembly systems (they are peculiar to this research).

2.3.1. SPECIALIZED (MECHANIZED) ASSEMBLY

Specialized machines (often referred to as 'fixed automation') are designed to assemble products with few or no projected modifications [339]. All specialized automated assembly systems can be categorized as one, or a mix of more than one, type of system: single station, synchronous, non-synchronous, and/or continuous [113,336,339]. All four incorporate the sequential build up of the product as it travels through the stations. Most inefficiencies result from poor parts quality [260,263,339]. Some product variety within a family is possible; however, there quickly becomes a point where it is uneconomic to accommodate the variations.

Single-station machines are used when a specific operation has to be performed many times on one or a few parts. Tooling is usually uncomplicated, and the single-station machines are many times coupled to function in multi-station assembly systems [339].

With synchronous systems, individual parts and components are supplied and assembled at a constant rate at fixed individual stations. Rotary indexing machines are the most common type, but in-line and carousel machines also share the market. Cycle time is dependent on the slowest operation within the

line [263,339]. There are size limitations due to the physics involved with rotary machines and additional limitations for the in-line types. Additionally, duplication of slower operations is not possible due to the inherent sequential nature of these systems. Their main affliction is that the entire system stops when any of the various mechanisms stops (e.g., jammed parts) [260].

The stations in a non-synchronous (or free transfer) system operate independently. Imbalances are accommodated in storage buffers between stations [339]. Consequently, if there are enough parts in a particular buffer, that station need not operate. Though these systems are slower than the synchronous ones, they allow for duplication of any individual station which unnecessarily increases cycle time by a substantial amount [339]. They are best suited for situations where station assembly times vary widely.

The final types are continuous systems. The product is assembled while moving at a constant speed on a pallet or another type of work carrier [339]. High production rates are possible because indexing time is eliminated. Automobile assembly lines are the most prominent example of continuous systems.

2.3.2. FLEXIBLE (ROBOTIC) ASSEMBLY

It is becoming increasingly difficult to justify special-purpose assembly equipment with its inbuilt inflexibility except in mass-production cases where the product has sufficient volume and a long market life. Seventy-five percent of all assembly is now batch type assembly [260,113]. This is due to the increase in

demand for product variety and the rise in the number of products that are subject to frequent and numerous design changes.

The solution to these new demands is flexible automated assembly [339]. Ideally, a flexible system can assemble different products (or at least different models of a product) from a family of products with little or no tool change. Classification of types of flexible systems is uncommon. Although their design will normally follow the same design as the specialized systems (single station, synchronous, etc.), the absence of groups of common features dissuades classification. Later, it will be shown that a great deal of research revolves around the area of system configuration for automated assembly. Some literature is given to a further breakdown into areas defined as programmable and adaptable; however, there is no consistency to the use of these terms. Consequently, the term 'flexible' will be used throughout this thesis since additional resolution would not prove useful.

A good example of a single station flexible system is a Selective Compliance Assembly Robot Arm (SCARA) device used to insert components on a printed circuit board. Unlike in a specialized assembly system, many similar operations are performed by a single device (the robot). This type of a system could assemble many different printed circuit boards. Correspondingly, a flexible line assembly system can be thought of as a series of single-station systems connected by transfer mechanisms with parts presentation devices interspersed.

Applications of flexible automated assembly are limited only by the ability of researchers to design or redesign products for compatibility with the process.

Although they are generally slower than specialized systems, they are ideal for low to medium volume requirements where product mixes within a family of products are susceptible to variations [46,291]. (The term robot will be used generically when referring to the 'assembler' in flexible assembly). Additionally, whereas industrial robots are usually designed on the assumption that their environment is highly structured and ordered, current and future automated assembly systems are projected to operate in a far less structured environment.

2.4. THE AREAS

One of the more challenging tasks is to discern between research and application. Research can be thought of as scholarly or scientific investigation or inquiry for the 'generic' sake of broadening the body of knowledge. Conversely, application advances and application research concentrate on putting knowledge to some special use or purpose. Simply stated, the main difference is that application research is initiated with an anticipated outcome.

Since, by necessity, much of the research done in this field is multi-disciplinary, it is often difficult to differentiate between one area and another. Also, it is frequently impossible to determine where the research ends and the application begins. Consequently, the thesis will not attempt to prove indisputably that any citation is 'true' research or that a topic may not also fit into another category. The only contention is that these categories are sufficient. Fortunately, since these distinctions are not the overall purpose of this study, it should not detract from the usefulness of the thesis.

The below-listed ten areas seem to capture the abundance of research in automated assembly: rationalization techniques, design for assembly, representation, sequencing, system configuration equipment, vision and sensors, parts mating/joining, printed circuit board assembly, and global research. The remainder of the research literature will be organized and presented in these groups. As stated earlier, the research captured here is merely a representative set of past/recent research in each area.

2.4.1. RATIONALIZATION TECHNIQUES

The first area includes research aimed at developing techniques to rationalize the adoption of automated assembly technology in a manufacturing organization. The current standard techniques for the rationalization of most manufacturing equipment (e.g. machining equipment) does not adequately account for multitude of savings associated with automated assembly systems. The rationalization techniques reviewed are either based on cost savings or some other tangible benefits.

2.4.1.1. COST BASED

Computerized techniques for the evaluation of capital investments are the norm. Proposals normally follow a bottom-up trail with the manufacturing engineer shouldering the burden of showing savings and developing a budget to push the proposal up the chain. Most standard accounting packages are not sufficiently robust to analyze adequately the implementation of automated assembly technology. Justifying automated assembly based on direct labor cost

reduction is extremely difficult. Researchers believe common measures such as direct labor replacement are not the best method for increasing the efficiency of a manufacturing process. Consequently, alternative rationalization techniques are frequently presented to encourage the expansion of automated assembly use by supplying supporters with models to convince management of the equipment's merits. The core issue is to ensure that alternatives and options are studied analytically rather than intuitively [87].

Gustavson classifies all potential resources in terms of fixed and variable unit costs to quantitatively evaluate the most economical system for production [115,117]. Others use combinations of terms such as pay-back criterion, net present value calculations, and internal rate of return [227] to appraise the alternatives. Researchers at Imperial College concentrate on methods to validate the cost-effectiveness of assembly by robots to assist users without sufficient resources for such an endeavor [284]. They have developed a method based on the 'principle of fixity' in which optimality is based on cycle-time, production volume, and shifts worked [285]. Boothroyd assists developers by presenting mathematical models based on variables that apply to common assembly systems to describe economical performance [41]. Lotter has developed a 4-stage method to determine the most economic method for assembly as well as the associated optimum production [184].

Computer Aided Manufacturing - International (CAM - I) is heading a consortium of approximately 35 organizations (governmental, industrial, and selected universities and accounting firms) in an effort to develop a standard body of knowledge about cost-management practices for an automated

environment called Cost Management System (CMS) [339]. Also, Grondahl's research presents eight reasons for flexible automatic assembly which are connected to direct benefits that are quantifiable in term of savings. He contends the main benefits are from set-up time reductions and batch size reductions [112].

2.4.1.2. OTHER

Some rationalization techniques use other than cost reduction to justify the implementation of automated assembly equipment. One such method defines assembly processes as a function of the relationship between parts and tools and uses this relationship as an evaluation method to recommend automation [12]. Another is based on a company's need to compete in the global market [171]. Finally, a new strategy for improving productivity is proposed by researchers at the Charles Stark Draper Laboratories as a rationalization for the addition of automated assembly equipment. The strategy is based on using the assembly process as the focal point and integrator of all the complex decisions required to create a producible product. The ideas are grouped into two areas: 1) design of product and 2) design and operation of manufacturing systems [338].

2.4.2. DESIGN FOR AUTOMATED ASSEMBLY

Design for assembly considerations are not always given proper priority during the life cycle development of a product. Granted, from a practical side, design for assembly must normally take a back seat to design for functional requirements, aesthetic considerations, and cost of fabrication and material

[265]. Nevertheless, many researcher and manufacturers believe assembly oriented product design demands that assembly costs be given more stature when considering a products overall cost [26]. This is why a great deal of research and discussion revolves around this topic.

Although almost all the researchers who currently publish tradebooks on automated assembly present design for assembly techniques [86,236,254,260], three researchers originate the bulk of innovative methods and considerations. These key players are Myrup Andreasean and the team of Goeffery Boothroyd and Peter Dewhurst. These individuals (especially Boothroyd and Andreasean) have written extensively on the subject and are recognized as the foremost experts [8,9,39,40,41,43,44,46,47]. Andreasean's design tools closely parallel those of Boothroyd and Dewhurst. Together, the approaches of these three researchers are cited by most other researchers and form the basis for most of the follow-on research and applications.

Boothroyd and Dewhurst are presently working at the University of Rhode Island. For the past two plus decades they have investigated the area of design for assembly. While at the University of Massachusetts Amherst they published a progression of handbooks on automated assembly. Two of them - Feeding and Orienting Techniques for Small Parts and Design for Assembly - form the basis of documentation on their research. As a follow-on to this research, they created an interactive software system that allows analysis of product design for ease of automated or manual assembly [43]. The software eliminates the tedious task of collecting data from classification sheets and reduces routine errors. Their design for assembly techniques are component-oriented and entail a procedure of

quantifying of each components suitability followed by the summation of the total score for the assembly [8].

Andriasean is from Denmark and has written several tradebooks on this subject. His methods have been developed in accordance with 'downstream approaches' based on the realization that the design is disposed with the product [8]. He has expanded his design for assembly rules to include their application to Computer Integrated Manufacturing (CIM) system creation and operation [215].

Other contributors include researchers at Stark Draper Laboratories who affirm a similar grouping with their 'bottom-up' and 'top-down' classifications. The 'bottom-up' method is an empirical approach containing a two phase process: study followed by implementation. The 'top-down' approach is based on analytical management science aided by the mathematical programming of ADES (a software device) [336]. In another concept developed by Piatak and Kimball, the researchers attempt to reduce the redundancy associated with Mechanical Computer Aided Engineering (MCAE). Classes of objects are modeled rather than the objects themselves to eliminate work. These researchers illustrate how the ten thousand keystrokes required to build a stipulated solid geometry and finite element model can be captured by only fifty [248]. Although this technique is not uniquely oriented towards automated assembly, its obvious advantages for flexible assembly systems bear some consideration.

2.4.3. REPRESENTATION (SIMULATION AND MODELING)

Simulation and modelling are the two major types of assembly cell representation research being conducted. It is the desire of manufacturing community to have the means available to study automated assembly cell dynamics off-line to determine potential device collisions, sensor positioning, possible insertion/joining conflicts, and a myriad of other interactions. Researchers are investigating means to scrutinize inner cell activities, communications between cells, etc. without resorting to trials.

At SUNY of Buffalo, a system for automated assembly of planer closed loop mechanisms has been developed. Given a set of mechanism components in unassembled position and orientation, this system will automatically calculate the assembly transformation matrices for each component such that a feasible configuration of the mechanism is obtained [119]. In Belguim, LOLA (Leuven Off-line Language) is used to generate off-line robot programs with geometrical data from a CAD-database [290]. Bajcsy and Tsikos advocate assembly via disassembly to learn about representation of objects [22]. At IBM Japan, researchers have described an algorithm for collision detection between moving objects in simulation [273].

Research has also produced a model which provides an analytical calculation of robotic assembly reliability over a workspace. It includes assembly operations performed in any plane or orientation [98]. Furthermore, the same two researchers (GAO and Wells) created a simulation model and procedure to

determine robot accuracy and repeatability of position and orientation to determine the reliability of any robotic assembly operation [99].

At Stanford University, a method for modeling dextrous manipulation with sliding objects has been developed to assist assembly researchers. The approach which also uses compliance is useful for describing how a grasp will behave in the presence of external forces (e.g., when and how the fingertips will slide) and for planning how to control the fingers so that the grasped object will follow a desired trajectory. The analysis is then extended to general three-dimensional grasps with sliding and non-sliding fingers [157].

Finally, a team composed of researchers from Purdue and Sandia National Laboratories have devised their own system for automating mechanical assembly. ARCHIMEDES is a prototype mechanical assembly system which generates assembly programs from CAD model input. It offers an off-line system for generating assembly instructions from CAD solid models [304].

2.4.4. SEQUENCING

Conventional assembly systems are serial in nature where parts are sequentially assembled on to one base object. However, many widely different chronologies are available to assemble even the most simple items. Understanding how to produce the available options and how to select the 'best' sequence is an endeavor embarked upon by the researchers in this area.

One researcher poses an alternative - sub-batch assembly where parts of the same type are assembled to a number of base objects. This is well suited for small volume assembly in that it reduces the number of robots needed [15].

In other research, a rule-based system has been developed for selection of the most suitable automated assembly sequence. The exploited rule set has been compiled and structured with experienced shop floor engineers and offers more general application on a wide variety of parts [7]. A computerized system for sequencing has been developed by the University of Erlangen-Nuremberg to eliminate intuitive planning for programmable assembly [93]. SAGA is an interactive software for the automatic elaboration of assembly sequences developed in France [48].

Defazio and Whitney demonstrated 818 theoretical assembly sequences for a product consisting of 11 parts which they finally reduced to 2 feasible methods [79]. Also, at Texas A&M, a Rule-based technique for exploding views and assembly sequences was developed [171]. Finally, Khosla and Mattikali developed a method for determining assembly sequences from 3-D models [165].

2.4.5. SYSTEM CONFIGURATION

As mentioned earlier, selection of the proper system configuration for flexible automated assembly systems demands close attention. As assembly systems try to accommodate wider product family ranges, the choice of the proper assortment of equipment and its subsequent arrangement is critical to ensure flexibility.

Westinghouse Electric Corporation with funding from the National Science Foundation furthered research into the advancement of the state of the art in automated batch assembly with the Adaptable-Programmable Assembly System (APAS). The system consisted of six computer controlled workstations (robots at four of the six), transfer conveyors, sensors, fixtures with tooling, and parts presentation equipment. Conclusions included the realization that adaptable-programmable assembly is feasible, inspection must be done at each station, design for assembly is essential, and that future systems probably will need to be a combination of fixed automation and robotics [113].

Whitney's research suggests a system to determine the technical requirements of stations before selecting robots, sensors, computers and other equipment. It starts with an examination of workcell geometry and moves on to accuracy and repeatability issues [336]. Csakvary proposes a system selection method based on a managerial process followed by an analytical evaluation for selection of equipment ranging from feeders to manipulators [73]. Additionally, another group developed a procedure based on workspaces, kinematic manipulability and dynamic manipulability of robots, and trajectories of the end-effectors to optimize design and operations in a multi-robot-assembly work cell [123].

In their study of system configuration, researchers at Hitachi developed an experimental travelling assembly robot system for flexible assembly featuring a reduction in cycle time due to simultaneous assembly and parts transfer [135]. Another group of researchers performed assembly of identical products while

varying the manipulator type/grouping to investigate the effects of varying configurations [23].

2.4.6. EQUIPMENT

Considerable effort goes into the development of equipment for automated assembly equipment. This area of research evolves from specific demands by manufacturing organizations as well as the desire to produce generic equipment for yet undefined needs. It is very difficult to discern between applications and research when dealing with equipment advances; nevertheless, some characteristic research is presented below in sub-area order: parts presentation and handling equipment, manipulator development, and end-effector advancement.

2.4.6.1. PARTS PRESENTATION AND HANDLING

It should always be remembered that component manufacture and assembly are unavoidably connected. Processing sector deficiencies will inevitably cause assembly problems. It is generally accepted that given quality parts, the efficiency of any type of automated assembly system is almost totally dependent upon proper parts handling and presentation [260]. Consequently, proper part presentation is essential to automated assembly. The acceptable interface between the assembly equipment and the parts is the feeder. Although standard vibratory bowl feeders are quickly maturing and thus dominate the industry, research is being done to develop alternatives which increase flexibility.

An example alternative is the development of an on-line reconfigurable parts feeder developed at Intelligent Automation Systems Inc. The system does not require any special tooling and is capable of feeding a wide variety of shapes and sizes [107]. A computer based system that determines the most appropriate automated assembly parts presentation method for a part has also been developed. Given a description of the part, the system performs feasibility and economic analyses of several parts presentation techniques [96].

Redford has outlined the basic system requirements for a generic materials handling system which is quickly reconfigurable and of low cost. His research also points out that top-down high technology approaches are not appropriate for the development of most automated assembly equipment. Rather, he suggests the use of bottom-up methodologies where the objective is to develop equipment with limited commercial applications as the only viable option available to industrial developers [259]. In Belgium, a general loading module consisting of a robot, an input site, sensors, and a positioning station has been developed for the feeding of assembly cells [179]. In addition, Boneschanscher has created a task assigner that divides batches into similar 'repeating sets' to deal with limited buffer capacities while minimizing assembly time [37].

Finally, research is also being done in 'bin-picking' - attempting to reestablish parts orientation from a bulk condition - as an alternative to feeders. Two researchers at Linkoping University use the center of mass and the orientation of the principal axes of inertia of a given rigid object to determine its position and orientation. Taking this information from static and dynamic loading, they attempt to tackle the problems associated with 'bin-picking' [296].

2.4.6.2. MANIPULATORS

Manipulators tend to be electrically, pneumatically or hydraulically actuated [339]. Servo electric drive mechanisms are the most popular [339]. Manipulator research is scattered across a multitude of purposes. Of concern here is the research that has direct application to the advancement of automated assembly. Research in this area includes devices that affect automated assembly control systems, hardware, and programming. Developments vary from the design of a Spherical SCARA robot [335], to a parallel manipulator for assembly [339], to a device that is suspended by three wires (maintaining seven degrees of freedom) designed for heavy part assembly [14]. Additionally, researchers at the Fraunhofer-Institute for Manufacturing in Germany have designed a flexible assembly cell that will execute interference fits as needed [329].

Other examples include a parallel topology manipulating system developed in a left-handed mode. It allows for complex assembly operations using both active and passive finite compliant motions coupled with an articulated manipulation gripper mounted on a conventional manipulator [33]. Rathmill presents papers in his book on five different manipulators developed for automated assembly operations (the DEA PRAGMA A3000, the SCARA family of robots, a special purpose Hatachi robot, the YESMAN, and the ASEA robot) [254]. Recently, an intelligent robot system with integrated computer simulation and some heuristic capabilities demonstrated its abilities by assembling a jigsaw puzzle [229].

As an example of a control system, the hierarchical, knowledge-based approach developed by Finnish researchers provides for control while maintaining a degree of autonomy for the individual elements in the assembly cell [128]. In addition, another researcher has proposed an 'open' control architecture for control of assembly systems as an interface for the differing equipment available from assembly vendors [211]. Further research has been done to deal with the control of cooperating robots in a flexible assembly cell that solves task scheduling by transforming the problem into a multi-objective optimization problem [302]. These examples, as well as an abundance of other research, are geared towards the development of interface systems to compensate for the absence of a common language for assembly robots and equipment. In fact, research is leaning toward hierarchical planning systems which allow engineers to teach multiple robots and program peripheral devices off-line. Another example is the ARI (Assembly Robot with Intelligence) planning system project by Toshiba which generates robot programs automatically [306].

Error recovery and compensation research also invades the control research area. Day, places all accuracy errors into five categories for analysis: environmental, parametric, measurement, computational, and application [77]. Zorkany has developed an off-line approach to automatically compensate for positioning errors due to robot inaccuracy and object location variations [350].

Although 'languages' are not traditionally referred to as 'equipment', their development is placed in this area because of their close connection with equipment. The Adept Company has developed a software package, Assembly and Information Management System (AIM), which allows assembly robots to

be programmed using task-level statements. They contend this system greatly simplifies the integration, programming, and operation of robotic assembly cells [289]. Along the same lines, MODULA-2 provides a universal programming system which makes it possible to program different machines off-line in one common language [57]. Researchers at Penn State developed MCL (Manufacturing Control Language) as a possible answer to incompatibility problems [343]. The SONY Corporation has developed a programming language called LUNA for its new 4-axes high-speed assembly robot [146]. Finally, research at Osaka University in Japan is geared towards construction of an assembly system language which translates rough task specifications written in natural language (English) and expands each instruction into a sequence of basic assembly operation that can be carried out by a robot [1].

2.4.6.3. END EFFECTORS (GRIPPERS)

If areas were selected on the volume of research alone, this area could be a primary area instead of a sub-area. As with the area of manipulators, end-effector research which poses solutions to automatic assembly problems are the ones of interest. The term end effector is normally associated with flexible assembly. Included in this group are grippers, holders and other tools for handling components.

End effectors for automatic assembly vary in their design and often in their application. A recently developed programmable gripper claims to eliminate time normally wasted during tool change while removing the need to design parts to accommodate standard gripper configuration [190]. The Closed Loop

Assembly Micro - Positioner (CLAMP) Docking end effector allows lower accuracy robots to achieve high accuracy during assembly operations through the use of a docking apparatus [84]. Other types of research include items such as an odd-shaped component inserter for printed circuit board assembly. It eliminates the need for manual insertion of non- radial/axial components [61,209].

Other research steers away from gripper design itself, and concentrates on grasping considerations for handling mechanical components. One researcher uses (1) the physical properties of the components to be grasped, and (2) the task condition, along with (3) the type of insertion and (4) the position and orientation of the components, to determine grasping strategies for end-effectors [224].

Work is also being done on a tactile sensitive hand and its control algorithm for a bin picking robots that could detect the position and orientation of cylindrical workpieces stored in a bin. These type of end-effectors could have a profound effect on reducing the need for some parts presentation equipment [136]. Tooling for robotic assembly is also included in this area. An example is the development of a special auto-screwdriver to increase the inherent versatility of assembly robots [333].

2.4.7. VISION AND SENSORS

Most assembly machines are built without sensor capacity or vision. Vision and sensors clearly play an important role in the assembly process. Often

inspection can be increased to 100 percent offering substantial improvement over the quality attained using traditional sampling techniques [113,263,339]. Additionally, each step of the assembly process can be checked/verified during the process (in-line sequential inspection), rather than at the end of the assembly line.

Sensors can prevent damage due to incorrect assembly, relate relative positioning of parts, and provide automatic identification of random parts to name but a few capabilities. Types include tactile and non-contact (pneumatic, ultrasonic, proximity, optical) devices [339]. Research includes investigation into the possibility of creating both contact and non-contact sensors which determine soft versus rigid contact, sliding, rolling, and mating. Additionally, research into mechanisms for force sensing, velocity sensing, and functional sensing benefit the automation expansion.

One assembly system incorporates a force sensor and a 3-D vision sensor to enable an assembly robot to pick up components that do not have a fixed three-dimensional position and mount them correctly on a printed circuit board [310]. Another system can reduce the difference between the achieved and desired pose of an object by simultaneously measuring the position and orientation within .0005 inches and .1 mill-radians [318]. Its uses 'include data' for algorithms that increase robot performance. At the University of Toronto, they have developed a non-contact electro-optical orientation sensor to overcome unexpected object-location variation problems [242]. Additionally, they have developed a robotic electro-optical distance sensor [241]. Their goal is to incorporate these two a tactile-force sensor into one multi-purpose sensor [242].

Vision researchers are also busy developing systems that can increase the flexibility of assembly systems. Areas include the evolution of higher-resolution vision systems and associated algorithms for range data to determine identities and positions of parts during assembly [151]. Neural networks are being developed for recognition of part orientation [181]. Systems are being simplified to increase speed through feature extraction methods which require less discrete data processing and reduce errors due to reflections [156]. At Digital Equipment Company they have developed a Grey Scale vision system for real-time inspection and assembly [191].

2.4.8. PARTS MATING/JOINING

Proper parts mating and joining is a problem that plagues both the manual and automated assembler. However, in the case of manual assembly the worker is very adept at identifying and compensating for any improper mating\joining. Unfortunately, the faculties employed by the human assembler to identify and compensate for irregularities are difficult to mimic in machinery.

Research varies from the general - describing the force/torque reactions [334] - to the very specific. Researchers at Sandia National Laboratories looked further into the peg-in-hole problem using geometric analysis and hybrid force position control. Their research expanded the types of peg-in-hole analyzed to include a wide variety of shaped pegs (including some non-convex) [305]. Other work has been done to create models that ensure the tolerances on mating parts of a assembly are compatible to the precision of the assembly robot by measuring the associated 'probability of successful assembly' [166].

Additional work in this area, done by Whitney at the Massachusetts Institute of Technology (MIT), examines the relationship between part shape and the ease of assembly. Also at MIT, Asada and Hirai have developed a model-based approach for the in-process monitoring of assembly operations. They use force and displacement information to estimate the state of the assembly process [18]. Caine uses his model to show the effect of (1) a chamfer's degree of curvature and (2) the location of the peg-tip versus the hole, on the reliability of insertion operations [60]. Further efforts include a three-axis force sensing systems [221], as well as a system that uses feature extraction and multivariate data-analysis to monitor parts mating developed by the Xerox Corporation. Xerox has created a learning set of known mating forces and compares them to unknown ones to eliminate the need for some inspection [97].

Hennessey has showed the existence of minimum energy chamfers which led to the classification of different assembly phases and an examination of the "insertion force versus depth plot" to better understand joining force actions [129]. Additionally, a group of researchers is working on a six degrees-of-freedom structure which uses hybrid position-force (passive and active mechanisms) in tandem control algorithms [256]. Also at Japan's Kogakuin University, researchers have introduced an insertion procedure using vibration to combat some of the problems associated with RCC devices [231].

Parts joining is a follow-on operation to parts mating. Once the parts are mated, additional steps are taken to ensure that the parts will maintain the

desired relationship to each other. Advances in research on fasteners, adhesives, etc. and their associated dispensing equipment are enabling automated assembly users to accommodate increasingly more diverse products [94].

2.4.9. PRINTED CIRCUIT BOARD ASSEMBLY

An expansive area of automated assembly research is the automating of printed circuit board assembly. Many factors impact on the choice of automated assembly techniques, including the determination of into which type of system the board will be employed (i.e., whether it be an inexpensive transistor radio or a space vehicle). Determining (1) what these factors are, (2) which apply to particular products and (3) how best to accommodate the specific needs of each product, is one of the tasks the printed circuit board researcher must address.

It becomes evident that this area is in itself a microcosm of the general field of automated assembly research (i.e., the majority of the research in this area is not peculiar to printed circuit boards - it has applications across much of the larger spectrum of automated assembly research).

As with the general topic of automated assembly research, work is being conducted to devise rationalization techniques for using automated printed circuit board assembly [91,100]. Additionally, research geared to develop expert systems can also be found in this area. One researcher uses a patchwork-based expert system composed of focus control blocks, and rule-firing heuristics to perform Computer Aided Process Planning specifically for PCB assembly [326]. Moreover, as in the overall assembly area, research is being done to produce

manipulators useful in printed circuit board assembly. An example is the '3d Link' mechanism designed by the NEC Corporation for clean room operations [315].

The arrival of surface mount technology has increased the already extensive list of demands placed on the printed circuit board assembler. Much attention is being placed on methods to accomplish this difficult procedure. To meet these demands, researchers at UAS Automation Systems have developed an approach using a generic cell for the data-driven placement of fine pitch chip carriers [75].

Component insertion is another problem from the list of printed circuit board research topics. As in other areas, it is very difficult to emulate the prowess of the manual assemblers. The ability of humans to accurately insert small leads into tight holes (e.g. a .020 diameter wire a .021 hole) is impossible to reliability match. Other problems such as the difficulty of automated machinery to insert parts from multiple axes also pose tough obstacles for researchers [265].

Just as research into better fasteners is increasing in the general automated assembly area, advances in adhesives, soldering and cleaning techniques, and test and inspection procedures demand a great deal of attention in the literature for this area [94]. Moreover, given that humans continue to be the largest uncontrolled source of particulates in clean rooms [269], researchers are looking to automated systems as a solution to the elimination of these contaminants [238,269,303].

The move towards flexible assembly for printed circuit boards is also realizing more attention with the advent of the need to produce smaller, more diverse batches using many different combinations of components [75,100]. As an example, small companies like the Plessey Business Systems are faced with the task of producing 750,000 wiring assemblies per year involving 1,000 varieties and 128 million components in batch sizes of one to a few hundred [317]. Flexible automated assembly may be the only alternative to manual assembly for PCB assembly.

2.4.10. GLOBAL

Research is also ongoing in generalized areas with connections to automated assembly. The Toyota Company presents its 'Ten Commandments' for automated assembly lines in support of its organization's production system [208]. Some research centers have developed methods to evaluate the feasibility of automated assembly through in-house studies [161].

Another group of researchers posed the Strategic Approach to Product Design (SAPD) as an alternate multistep process to integrate product with process design and eliminate compartmentalization. The process advocates linkage between industry and universities and the squelching of misgivings towards the appropriateness of manufacturing research. Additionally, the process suggests that education institutions dispense with teaching the traditional linear manufacturing system concept because of its excessive compartmentalization. They contend that manufacturing processes (to include automated assembly)

require an understanding of interdependent decision making which is presently not being advocated with enough emphasis [338].

Finally, FANUC provides a glimpse into the future with its unattended factory using flexible automated manufacturing. Although it is not totally unmanned, the reduction in numbers went from 108 people and 32 robots assembling 6,000 motors per month, to 60 people and 101 robots assembling 10,000 motors per month [320].

3. CHAPTER 3

THE CATEGORIES

The research methodology used to develop the categories was rather rudimentary. After an extensive literature search of all written material pertaining to automated assembly, a first review resulted in separation of research areas of interest from the application efforts. Next, initial categories were formulated. The initial categories were then challenged to see if they could be: 1) condensed and/or eliminated, 2) needed to be expanded or changed, 3) were actually subordinate to others, or 4) could in anyway be modified as the knowledge base expanded. After this alignment, the categories were finalized. The concluding phase included a thorough validation of the monograph using the assembled literature and all other information that had been recently added to the database.

The final categories/sub-categories are listed below:

- RATIONALIZATION TECHNIQUES
- DESIGN FOR ASSEMBLY
- REPRESENTATION (SIMULATION AND MODELING)
- SEQUENCING
- SYSTEM CONFIGURATION
- EQUIPMENT
- PARTS PRESENTATION

FIXTURES

MANIPULATORS

LANGUAGES

CONTROLLERS

END EFFECTORS

VISION

SENSORS

- PARTS MATING AND JOINING

- GLOBAL

The presentation order for these categories does not presuppose a chronology of events for automating the assembly process (that is beyond the scope of this research). Such a chronology would entail a great deal of separate research. Great debate could arise simply over the determination of whether or not many of the activities associated with these category names should occur simultaneously when automating assembly. Furthermore, distinction between activities is sometimes clouded by recognized overlaps in the research within separate categories and the interdependency of one advance on another. Therefore, the categories are arranged in the order above simply to facilitate ease of reading and understanding.

The word 'category' will be the primary term used. In context, it will be synonymous with 'area', 'grouping', and 'assemblage'. Understandably, these words will be used interchangeably to provide literary variety. Current issues and future areas will be discussed as they pertain to the overall category label. This

'generic' discussion will eliminate some subjectivity which may unnecessarily narrow the discussions.

As stated in Section 1.5, the automated assembly research is limited to the assembly of small mechanical devices and electrical equipment. In this chapter, the categories will attempt to capture this pair as a single entity; however, differences that are unique to electronic assembly will be noted. By incorporating the research from both areas of interest into a single set of categories, continuity is gained.

Each category will be described in terms of combinations of the following: background/explanation, a brief reiteration of the well-written research institutions/individuals, present research focuses, and needs/problem areas. The explanation will somewhat define the category and outline the type of research common to the particular category. The text on the researchers institutions will give the reader a re-examination of the major contributors who have done research in the past as well as those who are currently contributing. Finally, the current focuses and areas for future research will be outlined to provide some general insight into possible areas for additional research.

Let it be noted that this chapter is not designed to stand alone. Chapter 2 (Literature Review) remains indispensable to Chapter 3 (The Categories). Although citations to some of the references in Chapter 2 will be repeated in Chapter 3, Chapter 3 cannot be considered as an autonomous document. The reader may need to refer back to research in Chapter 2 for detailed research listings.

The reviewed literature is also assembled in a database as described in Appendix 1. Included with these research articles is an extensive complimentary collection of automated assembly research articles not examined during the validation process. Together they constitute a near exhaustive list of automated assembly research as of the date of this thesis.

3.1. RATIONALIZATION TECHNIQUES

3.1.1. BACKGROUND

There is no universally agreed upon best method for justifying the use of automated assembly mechanisms or their associated equipment [339]. However, it is generally agreed that the time-established conventional methods are no longer adequate [192,227,235]. Most current methods do not take into account savings due to indirect labor reduction, warranty and liability claim reduction, elimination of cyclical hiring overhead, and/or inventory reduction to list a few. Additionally, in the case of flexible automation, traditional methods do not account for the savings connected with the added capability to customize products and the associated rapid response to new product developments.

The reluctance of some managers to accept that short periods of return can only be expected when the alternate existing manual method was inefficient and overly expensive only compounds the problem. A fine point is made by Grondahl who states that economic rationalization is not primarily a question of choosing the best investment analysis model, rather it is to decide which effects

or benefits should be analyzed. This is because the benefits from automated assembly depend heavily on how the automation is used [112].

Furthermore, few companies want to understand the overall capital investment associated with automated assembly equipment. As an example, they are often unwilling to spend the extra money for the higher quality parts needed by the feeders. Regrettably, they have unrealistic expectations about the intelligence and adaptability of the robots and other peripheral equipment and refuse to come full circle and invest sufficient capital to ensure success.

In older industries (where automated assembly may be implemented), the basis of competition is production efficiency. In newer industries, product innovation, quality, and advanced technology are the decisive factors which lead to market share and profits. Both types of industries can potentially benefit from the incorporation of automated assembly. The only remaining obstacle is to eliminate the often times undocumented, intuitive, and judgmental decision making process employed by many companies. To accomplish this, a higher level of understanding of the rationalization process is needed.

3.1.2. EXPLANATION

This category encompasses the entire gambit of research which concentrates on quantitative (cost based) and qualitative rationalization techniques for the adoption of automated assembly. Additionally, justification techniques are also included for analysis of the effectiveness of systems in operation. Much of the research incorporates some overlap with the system configuration category in

that the research in each category often attempts to address both issues simultaneously. Since, for most products direct labor is 10% of product cost, that area alone is too small to justify the time and capital necessary to incorporate automated assembly technology [41]. Therefore, the research includes a laundry list of ideas that suggest methods to ensure proper weight is given to potential savings outside of direct labor reductions.

Additionally, this category includes work that is specifically geared towards rationalizing assembly automation for printed circuit boards. While some of the rationalization research for automated assembly is generic enough to cover any type of system, printed circuit board assembly equipment rationalization often times requires separate analysis. These research efforts recognize the unique features of printed circuit board equipment and the corresponding problems and adds to the list of reasons for implementing automation and the savings associated with them.

3.1.3. RESEARCHERS

The Charles Stark Draper Laboratory at the Massachusetts Institute of Technology generates an abundance of the research on this subject. In particular, Gustavson has written numerous papers on the subject [115,116,117]. His research centers around evaluation based on unit costs (fixed and variable), that is used to determine a 'cross-over point' for the adoption of automated assembly in lieu of other types. Nevertheless, no one organization dominates this research category. Universities, companies, and research institutes alike produce varied independent methods and strategies to rationalize the use of automated

assembly equipment [41,87,112,117,142,144,192,227,284]. Boothroyd provides mathematical models to describe economic performance of assembly systems [41]. Poli describes both the equations and nomograms developed in order to provide a fast and easy way of estimating the approximate capital investment requirements for various assembly systems [251]. Carlisle contends 30% to 50% of plant capacity is associated with overhead and proposes a technique based upon the decrease in unit cost associated with increased capacity [64]. Troxler and Blank's research recognizes that the decision factors are tangible as well as intangible and supplies relevant strategic, tactical, and operational decision factors for consideration [316]. Finally, Scott and Husband have created an 'orthodox hierarchy design' to estimate the cost-effectiveness of introducing robots, select the best layout, and choose the most suitable areas for implementation coupled with a principle of 'fixity' to derive a robot's cost-effectiveness for assembly [284,285,286]. The Literature Review as well as the database include an extensive list of other methods and tools.

3.1.4. CURRENT/FUTURE ISSUES

Future issues follow from the current ones. At present the need that predominates this category is simply the inadequacy of present rationalization techniques to account for the myriad of related affects of adopting automated assembly equipment. Methods need to continue to compare the assembly costs of a given product by means of various assembly systems (manual, specialized, or flexible systems) at an early stage in the decision process. Issues include answering the question of how much does an increase in market share reflect in the estimation of savings associated with the implementation of automated

assembly equipment. Another is to what degree are indirect labor costs affected. Techniques need to account for potential profits associated with improved deliveries, uniform quality, and strategic pricing capabilities. The cost of equipment changeover time as well as workstation efficiency are two more important factors when rationalizing the use of equipment.

Additionally, methods must include the benefits associated with reduced warranty expenses, reduced liability exposure, and the security associated with the objectivity afforded by automated inspection (especially in today's age of regulation). Production and inventory control considerations are receiving more attention with the advent of Just-In-Time discussions, but still fail to take a prominent position in rationalization considerations. Finally, the decline in manufacturing skills associated with future generations of workers must be taken into account in any set of equations.

Once a single system, or many specialized ones (e.g. one for the printed circuit board assemblers, one for automotive assemblers, etc.) is developed peculiar to this endeavor, education to promote recognition of the inadequacy of present systems and acceptance of the new ones must naturally follow. Many decision makers still fail to recognize the inadequacies of traditional techniques; consequently, an awareness program is necessary to focus on the pitfalls of present systems and expose better methods. Subsequently, (or perhaps, concurrently) effort must focus on accounting for the increased flexibility of future systems. As automated assembly systems become more adaptable, the techniques must account for these added flexibilities. Estimates must include the effects of changes in product design and multi-product assembly.

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techniques are applied to their fullest potential, assembly may be eliminated or at least simplified to the point where the requirement of machines to duplicate the dexterity and versatility of human assemblers is not longer cumbersome. Design for automated assembly techniques offer guidelines for ensuring assembly is given proper consideration during the design phase.

Research efforts in this category, focus on the development of tools or techniques which accomplish one of the following:

- a. Simplification of design
- b. Ease of assembly

Simplification of design deals with the desire to minimize the number of parts necessary in a product. Ease of assembly techniques supplement motion time studies to reduce the difficulties connected with handling, feeding, orienting, inserting, and joining operations [9].

Most research concentrates on the ease of assembly. Quantitative methods fall into one of three groups: Assembly Evaluation Method (AEM), Boothroyd/Dewhurst Method, or combinations of the two [8,45,205].

AEM, commonly known as the Hatachi method, uses assembly element symbols that are selected from a small array of possible choices. Combinations of the symbols represent the complete assembly operation for a particular part. Penalty points associated with each symbol are substituted into an equation, resulting in a numerical rating for the design. The higher the rating, the better

the design.

The Boothroyd/Dewhurst method follows two steps. The first step involves the application of criteria to each part to determine whether it should be separate from all the other parts in the assembly. The second step provides an estimate of the handling and assembly costs for each part using automated assembly.

Other methods vary considerably, but ultimately contribute to one of the above stated goals: simplification of design or ease of assembly.

3.2.3. RESEARCHERS

As discussed in the Literature Review, the team of Boothroyd with Dewhurst at the University of Rhode Island and Andreason are considered the foremost experts in this field. However, as with rationalization techniques, almost all universities, companies, etc. expound their own individual set of techniques [21,48,64,199,265]. Nevertheless, it seems that all other techniques are simply variations or modifications of research first proposed/developed by the above mentioned researchers. Also, included are techniques which specifically provide for assembly of printed circuit boards.

3.2.4. CURRENT ISSUES/AREAS FOR FUTURE RESEARCH

The current issues and future needs are identical in this area. Since progress in this area can occur virtually independent of other advances in other

areas, lags between current and future needs are minimal.

One major issue has arisen due to the greater emphasis placed on properly using design for assembly principles: Is the continual use of automated assembly really necessary for a given product? The proper use of design for assembly techniques makes it extremely difficult to justify automated assembly equipment for certain products. In fact, many organizations have had to re-visit their decisions to use automated equipment once their product has been redesigned using the improved design for assembly tools (e.g., it may be that the use of snap-in fasteners to replace screws in a product makes manual assembly faster than automated assembly).

Nonetheless, there still exists a great need for design for **automated** assembly tools for a multitude of products. Boothroyd appropriately defines the global difficulty with reference to the classic Chicken and Egg Dilemma. The production process cannot be well defined until the assembly is designed, but the assembly cannot be well designed until the process is defined. The challenge in formulating design for automated assembly techniques is to understand this conflict and realize that design can be assessed for suitability prior to establishing the details of the assembly process [44].

The most significant area for improvement is in the further development of general guidelines for product design of products for flexible assembly. Considering the disparate nature of flexible assembly systems it is difficult to generalize design considerations. Additionally, techniques need to more fully address their applicability to **automated** assembly and evolve as the capabilities of end-

effectors, fixtures, fasteners, etc. improve. Finally, work is needed to incorporate the abundance of existing CAD/CAM information for a product into a process-driven design for assembly procedure [199].

3.3. REPRESENTATION (SIMULATION AND MODELING)

3.3.1. BACKGROUND

Models for the fabrication of parts are generally good. However, models for automating the assembly process have lagged behind. Assembly is an inherently integrative process. It is important to identify what capabilities are essential for assembly, not what capabilities people have that make them good at assembly [260]. Correspondingly, modeling (kinematic, dynamic, quantitative, qualitative, solid, etc.) and cell simulations offer valuable insight into the automated assembly process. Mechanical devices (e.g., feeders, conveyors, grippers) can be simulated as well as man machine interactions, parts presentation, mating operations, and the assembly process itself. These activities provide system developers non-destructive analysis options which cannot be economically gained otherwise.

3.3.2. EXPLANATION

Included in this category are modeling tools, simulation programs, and other representation implements covering the entire spectrum of devices involved in the study of work cell dynamics. This encompasses kinematic,

geometric, and dynamic models for mechanical devices (feeders, grippers, fixtures, conveyors, etc.), man-machine interaction, and solid modeling of parts and assembly processes (including presentation, mating, and assembly) research. Research like that of Bajcsy and Tsidos is typical. They attempt to represent objects (after disassembly into parts) in order to evaluate which features are innate and what are derived from the environment [22]. Other indicative research includes, a study on the effects of assembly conditions which looks at the assembly sequence, the assignment of parts to arms, gripper changing, and robot unloading of completed assemblies to determine if a product is compatible with robotic assembly methods [65]. Additionally, models which estimate the assembly accuracy/reliability over a robot workspace and offer a design approach for the reliability design of robotic assembly operations are included [98], as well as ones that obtain the statistical characteristics of the accuracy and repeatability data [99]. Lastly, a system which automatically calculates the assembly transformation matrices from a set of unassembled mechanisms for each component such that a feasible configuration of the mechanisms is obtained exemplifies work in this category [119].

Cell simulation is also fundamental to this category. Research into systems for the simulation of spatial constraints, production requirements, the structural relationships of parts of an assembly, and the physical properties of the work cell are included in this category. Path planning research and artificial intelligence for simulation are also research efforts within this area. In general, the category includes all representation instruments designed to learn more about the dynamics of automated assembly cells/systems. A final example is the simulation software launched by ISTEEL which displays the operation of a plant

while it is running to reduce development time of assembly plant design alternatives [105]. Although not directed specifically at automated assembly situations, this system can be a valuable tool for researchers.

3.3.3. RESEARCHERS

There are no standout research institutes in this category. As is evidenced by the breadth of research contained in the category and suggested by the diversity seen in the Literature Review, the area is much too disparate for any one organization to dominate. Accordingly, research is being done at many of the aforementioned research facilities. To illustrate this point, a few examples of the diverse research being done follows. Samples include the development of SIMBED. SIMBED is a simulation model which incorporates the logic necessary to represent four FMS/FAS subsystems: 1) assembly workstations, 2) product routing decisions, 3) inventory and inventory policies, and 4) material handling. The parametric structure of the simulation model reduces simulation development time for evaluating system interactions in a flexible assembly system [163]. Also significant may be the development of Archimedes. This system is a prototype mechanical assembly system which generates assembly programs for a CAD model input [304]. A final example is the research into causal modeling for automated assembly. The approach centers around giving the model the ability to 'reason'. Such a model contains both structural and behavioral knowledge of workcells [122].

3.3.4. CURRENT ISSUES/AREAS FOR FUTURE RESEARCH

The need for continual research to represent the growing dynamics in automated assembly work cells through models and simulation is extremely urgent. Continued research is needed to evaluate the countless equipment interactions. Interactions for modeling and investigation include the delays that arise when one arm waits for the other to complete a task in cells where two manipulators work together at a single fixture. Additionally, the interaction between feeders and escapement devices is also of primary concern because of downtime. Models of these junctures can be used to anticipate problems. In general, work is needed to embed in computer models the relevant knowledge about the domain that the system is dealing with in an effort to free the programmer from envisioning all the possible outcomes of a situation and having provide all the appropriate actions to ensure proper assembly [122].

Additionally, simulation models are needed to scrutinize the workcell as a whole. Simulation platforms need to be created which allow researchers and engineers to develop and study workcells prior to capital investment. Models need to be developed that mirror sensor activity in real-time so that cell dynamics can be studied more closely. Moreover, work is required to analyze and understand the behavior of human operators such that the required skills can be duplicated or substituted for by automation equipment. Operators and programmers must be able to detect and prevent collisions of moving and stationary objects off-line.

Among this almost endless list of needs is the desire for improved off-line programming methods. These methods should permit complex robot programs to be developed from design data with the aid of the integration and advancement of CAD/CAE/CAM software which can be downloaded directly to the assembly workstation for the required assembly tasks [113]. With shop floor programming for small-sized batches being extremely time and cost consuming, off-line graphical simulation systems are essential. In commercial CAD systems, assemblies are typically generated in a semi-manual procedure that requires tedious determination of location and orientation of each component that is prone to error [119]. Work to automate this process needs to continue. Especially in the case of complex geometries, direct data transfer from a CAD database can further improve the efficiency of robot programming. Ideally the development of a CAD-system capable of treating the complete production process is warranted. Their application thus far in the electronics assembly field (especially with printed circuit board assembly) have greatly increased the productivity of small batch assembly.

Another major issue for future research is task planning. At the present time, most planning is done by a programmer who decides the sequence, order of operations, and layout. The resultant plan usually has many surprises even for simple operations with as few as two robots. Graphics, simulation and planning tools are a necessity to improve this procedure. Finally, artificial intelligence will hopefully continue to further penetrate the research agenda with further development of expert systems for cell mimicing.

3.4. SEQUENCING

3.4.1. BACKGROUND

Sequencing has always been of interest to assembly researchers. Accordingly, the order in which a product is assembled is a topic of concern for automated assembly researchers [339]. As with Design for Automated Assembly, researchers realize that automated assembly equipment does not, nor is it intended to, exactly duplicate the actions of the hands of a human assembler. This forces sequence researchers to make differing concessions when developing automated assembly sequences. Often, the assembly sequence for mechanized assembly will be quite different from any existing manual sequence. Procedures such as those that require two hands or the flipping over of an unstable subassembly, may be difficult to automate or time wasters [336] and thus eliminated.

3.4.2. EXPLANATION

Normally direct planning of assembly operations is very complicated. Accordingly, it requires an expert user. Sequencing has a significant impact on the entire assembly process. Choices affect fixturing requirements and can add to or reduce potential in-process damage. Additionally, the sequence can impacts on in-process testing and may be helpful in re-work considerations. Sequencing undoubtedly has a significant impact on unit cost. The main problem is selecting the best order from the large number of possible sequences while

dealing with the drastic effects of even slight design changes. This category contains all the research connected with the study of this problem.

Most methods fall into one of two groups. The first, and most prevalent method, revolves around knowledge bases built from assembly and disassembly trials. This group uses these trials with heuristics and some theoretical knowledge to develop a list of possible sequences and subsequently choose the best one [171]. The other smaller group, uses algorithmic means to choose the most appropriate sequence.

Nevertheless, other methods do exist which suggest the best sequence from the larger group of possible sequences. An example is the rule based system developed in concert with shop floor engineers which relies on disassembly information to determine the valid assembly sequences [7]. Another is the sub-batch assembly approach used by Arnstrom and Grondahl [15]. Although it does not focus on sequence selection, it offers an alternative to reduce the sequencing considerations associated with conventional methods.

3.4.3. RESEARCHERS

As this is still a moderately new area for **automated** assembly planners, researchers are again scattered across an array of organizations [15,48,124,149,164,171,250]. Of particular note are Defazio and Whitney at the Charles Stark Draper Laboratories. Their work developing aids for the design and choice of assembly sequences has provided a good basis for other researchers [79,80]. Complementing their work is that conducted by Bourjault.

Much of Defazio's and Whitney's work is based on some of his earlier work. Both Bourjault and the Defazio and Whitney team characterize the assembly process by a sequence of states. Additionally, they both use sets of questions whose answers lead to establishment conditions from which one can construct directed graphs. The main difference is the set questions used by each. Bourjault and Lambert have also developed a software system called SAGA to generate all possible sequences. They use the generated list as a part of a three step method for analysis of automated assembly system implementation [48].

Additionally, a great deal of research is being done by de Mello at RPI and Sanderson at Carnegie Mellon University. They have created a system which uses AND/OR graphs and a group of other algorithms for the automatic generation of assembly sequences [202,272,273,274]. C.L. Chen at Purdue has used pattern matching [66] and a graph partitioning approach [67] to generate assembly sequences. Pinedo has completed theoretical research which dealt mainly with the development of polynomial time algorithms for certain jobshop scheduling problems, with the determination of the computational complexity of the scheduling problems for which no polynomial algorithms could be found, and the development of heuristics and their worst case analysis for such problems [250]. Also, a knowledge-based method for determining assembly sequences using a CAD data base is in use [102].

One research group has developed a system that is able to accept a sequence of instruction in English and expand each instruction into a sequence of basic assembly operations. The system tries to generate a sequence by assuming the most promising assumption selected from a set of plausible ones

or the default. When the trial results in failure, then a more plausible assumption than the old one will be generated [1]. Other work by Heemskerk uses a new technique for grouping parts (clustering) and a new method for representing assembly sequences (the Layered Assembly State Transition Diagram) [124,125]. Finally, C.L.P. Chen at Wright State has written of his precedence knowledge acquisition system for sequence generation [68].

3.4.4. CURRENT ISSUES/AREAS FOR FUTURE RESEARCH

The future issues revolve around traditional difficulties, yet the consequences of proper sequencing have increased. Whereas in a manual setting where changes can be more readily accommodated, enormous amounts of capital are at stake as automated assembly equipment purchase is based largely on the sequence selected. Ideally a standard method for decomposing assembly tasks is needed to compliment modelling research. Additionally, researchers need to continue to classify the different mating conditions and develop sorting rules for three dimensional assembly situations to further the development of useful sequencing models. Difficulties lie in the increasing complexity and capabilities of automated assembly equipment (i.e. the number of possible sequences increase). Therefore, computer sequencing solutions are necessary to speed up the process and accommodate the increased number of in-process product design changes.

3.5. SYSTEM CONFIGURATION

3.5.1. BACKGROUND/EXPLANATION

A great deal has been written concerning the need for flexible assembly systems [194,217,291,330]. Potential users of automated assembly systems need to perform a macro examination of the equipment needed to support the product under consideration. System configuration research is geared to address this need. The current research is directed towards flexible systems much more than special systems. Flexible systems employ production equipment (robots, sensors, computers, etc.) that is readily commercially available and recyclable which lowers overall costs [293].

Since special systems are purposely designed for a single family of products by a vendor, room for expanding the product line and its associated body of knowledge is almost nonexistent. However, flexible systems are intended to meet varying product lines and require careful examination of hardware and software modularity, layout of cells and stations, and communications between apparatus. Many factors influence the selection process: volume, product life, cost of handling, insertion, and inspection equipment, production rate, size and weight of parts, complexity of the design, etc. Andreasen contends that system flexibility is dependent on both product design and layout considerations and warns that since these two activities are normally performed by different people, flexibility is often left unattended [10]. Thus, methods for designing flexible systems are being developed. Expert systems are becoming the norm for selecting equipment for entire systems.

3.5.2. RESEARCHERS

Many players participate in the development of considerations for system configuration. Most of the literature is centered on the development of generic systems capable of accommodating a group of products. As there is no leading research expert, in fact, much of the research is drawn from reversed engineering. That is, as more companies adopt/implement equipment (with or without researcher assistance), the techniques are developed as an after-product based on the lessons learned during the decision process. An example is the automated assembly system described by Arnstrom and Grondahl. They present research dealing with the philosophy behind the system (of both economical and technical nature) and describe the system concept and technical solutions employed for system configuration [16]. Likewise, Papinski describes his considerations for system configuration based on their MARK II flexible, high-speed automatic system for low volume, small batch assembly [239].

Other research includes a procedure based on workspaces, kinematic manipulability and dynamic manipulability of the robots and trajectories of the end effectors to design a multi-robot-assembly work cell [123]. Additionally, researchers at Production Engineering Research Association in the U.K. define versatility requirements and describe characteristics of programmable assembly machines to assist in system configuration decisions [127]. And a group of Czechoslovakian researchers provide technical and economical analysis of modular assembly systems based on their experiences with systems in that country [25].

The leading experts in specialized system configuration include the Bodine Company and Adept. They expound the increasing modularity of 'hard' automation as an answer to the broad spectrum of assembly requirements. They contend that if specialized (fixed) automated assembly configuration is given proper consideration in the early stages, the system possesses more inherent flexibility than most believe.

3.5.3. CURRENT ISSUES/AREAS FOR FUTURE RESEARCH

Above all flexibility is the desire of manufacturers. The days of high-speed dedicated machines are, by and large, past. Lot sizes are smaller, the number and diversity of parts and components is increasing; thus, the need for systems that can produce customer tailored lots is multiplying. What is needed is a system that can literally be changed over on the fly. Systems that reduce setup time for short-lived manufactured parts are essential in a competitive world market. System configuration research needs to examine how general equipment components (feeders, fixtures, jigs, tools, arms, end effectors, sensors, computers, etc.) should be [293].

Accordingly, researchers are looking into system configurations that can accommodate this demand for more flexibility. The push in manufacturing is towards JIT and the associated need to produce varying quantities (e.g., 5 of this, and 500 of that, then 20 of this). Without flexibility, the risk exists that machines will be down more than they are running because of changeover. Accordingly, automated assembly system configuration experts must take into consideration the need for systems with quick changeover. Research needs to

continue towards modularity of software and hardware components. Additionally, system configuration research needs to look at programmable transfer mechanisms and station modules and the corresponding communications within the system. In general, research needs to center around devising expert systems (or heuristic systems) which incorporate provisions for selecting the proper type of equipment and correct amount of flexibility (to include manipulator selection, sensor selection, etc.) to accommodate the intended product. Integral to that ends, will be work like that being done by the Robot Classification Work Group of the International Federation of Robotic Industries to develop internationally recognized robot classifications. Their work to classify robots by type, target industries, application area, and population category will prove essential to future system configuration researchers [351].

3.6 EQUIPMENT

3.6.1. BACKGROUND

An apparent area for automated assembly research is the development of the tools for execution. It is extremely difficult to discern between research and applications when discussing this area. Fortunately, the distinction is somewhat superfluous since most of the applications were immediately proceeded by the associated research. The explanation of the characteristics of the research in this category will be of lesser importance than the outlining of areas for future development and research.

The following sub-categories capture the research in this category: parts presentation equipment, fixtures, manipulators, languages, controllers/control algorithms, end effectors, vision equipment and sensors. A careful examination of the specific equipment requirements for automating the assembly of any product is crucial to its initial and future success. The advances and needs of the various pieces of automated assembly equipment are very much intertwined with and interdependent in relation to one another. In fact, more and more equipment research is geared to the development of **systems** for automated assembly (e.g. a manipulator, with a language, sensors, an end effector, etc.) [146,229,256,347]. The words 'assembly system' are replacing 'assembly machines'. Unfortunately, not enough work is being done to develop and accept appropriate standards for equipment communications and other interfaces.

3.6.2. EXPLANATION/CURRENT ISSUES AND FUTURE RESEARCH

Parts Presentation. Parts feeding remains the largest bottleneck in automated assembly [32]. Parts presentation researchers are interested in improving current methods for the transfer of parts from their 'reception' state to an acceptable condition for the assembly machine/system. These 'reception' states vary from an unorganized bin of washers to an aligned strip of resistors. Most industrial robots are designed on the assumption that their environment is predefined and understood. Consequently, much research effort has been expended to ensure parts are presented in well defined positions and orientations. Usually this requires many separate specialized devices such as conveyors, magazines and feeders (which unfortunately increases complexity and costs). The general problem is how to pick up jumbled parts from a bin. The ideal

equipment should be able to accept parts in any bulk state and be able to properly present the parts in any desired position and orientation. Possible solutions include: feeding parts in trays, using magazines, kitting, etc. Although all research in this subcategory does not specifically address 'bin-picking', the research is appropriately geared towards the development of flexible, 'bin picking' devices and their peripherals or other systems that do not require extraordinary sorting. The ability to program the feeder is also desirable. Generally, all research in this area centers around the movement of parts from their arrival state to the assembly machine.

Fixtures. The time and costs associated with the fabrication of fixtures for automated assembly is an area venerable to cost savings. Research concentrates on designing flexible fixturing that can be used for a multitude of operations. Ideally, a system that eliminates the need for sensors by creating a standard family of fixtures that are easily reconfigurable and possibly remotely driven is desired. The future should hold fixtureless or 'generic' fixturing to ease the changeover problems associated with small batch assembly.

Manipulators. Manipulator research is geared towards the 'third generation' of robots. The "first generation" (still in wide use) performs tasks that are stored in the system's memory, and have basic sensors that make them slightly aware of their surroundings. The "second generation", currently in development, are sensor-based robots that supply the robot controller with sensory data that enables the robot to react to a changing environment. The future holds the "third generation" that will be completely autonomous and super-intelligent, having the capability to remember the solutions to a previous problem, as well

as the ability to learn from acquired knowledge [2]. Quality motion and precision are also desired from future generations of manipulators which should possess sufficient compatibility to work with other manipulators in the same work space without complicated add-on control mechanisms. Additionally, as automated assembly becomes an established solution to clean room contamination problems, work should continue in the development of better robots for clean room use to accommodate assembly of items such as disk drives.

Languages. Language research must yield a common manipulator language. Unfortunately, because of language barriers, each manipulator stands in isolation from the surrounding equipment [299]. Researchers recognize that most assembly robots are still programmed using forms of teach pendant in lieu of other methods. However, researchers continue to search for the quintessential: 1) a standard language able to be used with any assembly robot, that 2) can be programmed off-line by the same level of worker that presently does programming, 3) can communicate with other factory machinery, and 4) is robust enough to deal with assembly tasks rather than the movements necessary for assembly [114]. Languages must be fast, reliable, redundant, fault tolerant, modular, layered, etc. Additionally, work is being done to develop more task level programming techniques where robot actions can be specified by their effects on objects rather than a sequence of manipulator motions connected to task accomplishment [245].

Controls. Control research concentrates on providing an open type interface between parts presentation equipment, assembly machines (e.g. manipulators), and other various peripheral equipment. These researchers are

trying to bridge the existing gaps created by the non-standard robot languages/control algorithms, nonstandard communication protocols, etc., all of which inhibit coordination and interfacing between devices within a cell as well as between workcells. Future standard interfaces should extend to include sensors, vision systems, command centers, parts presentation equipment, and other devices within the workcell.

Additionally, work is needed to provide real-time control of devices as well as real-time monitoring of system performance. Also a real need exists for the ability to dynamically make adjustments from a work cell controller. Naturally, this would entail the ability to sense and recover from errors and make adjustments as needed. All of these tasks need continual formalization into a structured decision making system with hierarchical control. Ideally systems which can take advantage of a machines ability to make inferences are desirable.

End Effectors. Serving as the 'action instruments' for the manipulator, end effectors have the difficult task of trying to emulate the human hand. The final and most important interface between the robot and the work cell is the end effector. It is where the capabilities of the robot are either utilized or abused [214]. The greatest need in end-effector research is to develop the technology to enable end effectors to accommodate a wide variety of parts (within certain family guidelines) in varying orientations. Versatility is the desire of the user [113]. A need also exists for standard and specialized tooling that is adaptable to robot-grippers. It seems ridiculous to use a 400-lb robotic arm as a replacement for a human/arm using a paint spray gun. Answers may include anthropomorphic devices using hands with three or more fingers. Advances in tooling could

also enable the manipulator to perform more complex tasks moving away from its typical role as a transportation/holding device. Additionally, work is also needed to develop small end effectors for drilling holes and installing rivets and fasteners in difficult access areas.

Vision. The problems associated with vision are extremely complex. The basic function of vision systems is positioning (e.g. to recognize discrete parts with random orientation). Bajcsy and Tsikos introduce the problem well with the following short excerpt:

Perceptual activity is exploratory, probing, searching; percepts do not simply fall onto sensors as rain falls onto the ground. We do not just see, we look. And in the course of looking, our pupils adjust to the level of illumination, our eyes converge or diverge, we move our heads or change our position to get a better view of something, and sometimes we even put on spectacles [157].

Obviously, vision systems need to emulate the human in as many ways as possible. Furthermore, work in this area needs to focus on enhancing the capability of systems to deal with conditions where 'scene' knowledge does not exist. This will involve the continual development of specialized computer hardware and software.

Sensors. Ideally, it is desirable to develop non-contact sensors with improved transducers to enable them to sense the slightest minimum contact. These sensors need fast signal processing capability and to be able to perform in a uninstrutive environment. The most advanced features would include the capacity to detect soft contact versus rigid contact. Higher levels of information (force, velocity, acceleration, etc.) need to be received and digested by future

sensors such that they can predict the condition of the system at a low level and communicate the information back to the control system.

Other futuristic capabilities include, in-process 3D inspection at production speed, improved force sensing, detection of sliding, rolling, imminent jamming, as well as real-time sensing of parts orientation and location. Although tasks such as the recognition of welds, correction of weld path deviations and tool wear sensing are routine [28], calibration and test methods for sensor verification are essential to future systems. As with most other equipment, standardization of connections, software interfaces, etc. will be necessary before many advances can occur.

A natural consequence of the incorporation of visual and tactile sensors in assembly is to use this capability for quality control [19]. Defective parts/products could be discarded, marked for special considerations, or most usefully, the system could be self-correcting - i.e. identify the problem and reinsert the item such that the system corrects identified deficiencies. One of the more overwhelming problems is the synthesis of the abundance of feedback signals generated by the sensors and the eventual translation of this data into forms that over devices can be used directly.

3.7. PARTS MATING AND JOINING

3.7.1. BACKGROUND

Parts mating and parts joining are the two primary types of processes performed during assembly [227]. While both processes contain requirements that are conducive to automated assembly equipment, others must be performed by machining equipment (especially in the case of flexible assembly). The final result of the assembly process depends on the quality of the parts to be assembled and on the correct performance of every single operation [334]. It is desirable to ensure assembly will occur without regard to tolerances (random assembly). Selective assembly of components with tight tolerances is time consuming and normally cost prohibitive [154].

Parts mating can be defined as bringing a part into the physical relationship specified in the design by butting, overlapping, insertion, or other means [297]. This task - trying to match the relative positions of the mating parts - has traditionally been a major obstacle. Positional errors caused by numerous inaccuracies in the assembly system and the tolerances associated with parts manufacture cause unexpected interference and prevent proper assembly.

3.7.2 EXPLANATION

Four types of operations generalize the fundamentals of parts mating [113].

Peg-in-Hole- requires 6 degrees of freedom for square parts and 5 degrees of freedom for round parts.

Hole-on-Peg- bearing or gear on a shaft

Multiple Peg-in-Hole - e.g. microchip with many feet

Stacking- several components are placed on top of one another with no pins or other locating devices.

Nevins and Whitney see assembly as a geometric problem: if parts were identical and perfectly made/positioned - assembly would always be successful and free of excessive mating forces [161]. They have described the process of inserting a peg into a chamfered hole in terms of the insertion funnel (experiencing one point and two point contact), and the wedging and jamming of parts. Their research specifies the conditions for ensuring successful mating in terms of part geometry, friction coefficient and arrangement of the applied forces [113]. Based on this description, compliance devices have been developed.

All research in this category is based on efforts to overcome the problems associated with these operations. Additionally, the category includes research designed to reduce the associated root problems (e.g. chamfer design). The explanations below describe some of the methods for compensating for mating difficulties.

The three methods of compensating for this unwanted contact are: active, passive, and remote center compliance. Active devices attempt to zero out applied forces with electromechanical devices that move the grippers [339]. The two most common alternatives for active compensation are wrist/pedestal force sensing and reaction force sensing at the joint drives of the manipulator. Both use contact-force information. Their effectiveness is sometimes limited by the speed of the system to respond to the information (especially in the absence of auxiliary equipment).

Passive compliance incorporates mechanical devices whose geometry and elasticity are designed to allow temporary structural deformations in both translation and rotation in response to forces and moments [260,339]. Instead of rigidly locating parts, a degree of compliance is introduced into the assembly system which deforms under the influence of the assembly forces, thus reducing the misalignment [140].

The final method (remote center compliance) was devised at the Draper Laboratory by Nevins and Whitney. Remote center compliance devices operate under the principle that if you can locate the center of the compliance device close to the tip of the mating peg, its first linkage allows the latter to rotate about the center if it is angularly misaligned with the hole, while the second linkage permits linear translation if lateral error occurs [260]. This method has become a widely accepted method for inserting a pin into a chamfered hole. Added improvements have come from Rebman and Miller who designed an adjustable RCC in 1980 that vastly improved the original design and De Fazio

who furthered the concept with the use of geometric deflection to serve as an error vector signal for closed-loop control also in 1980 [113].

Parts joining is a follow-on operation to parts mating. Once the parts are mated, additional steps are taken to ensure that the parts will maintain the desired relationship to each other. Seven different operations define the type of processes that might be used to maintain these relationships: fastening screws, retainers, press fits, welding and related joining methods, adhesives, crimping (includes rivets and staking), and sewing [113]. With the emergence of good design for automated assembly, the need for new joining devices is growing (especially in the area of adhesives). (Sewing is not an area covered by this document due to the scope of the industries of interest. However, automated assembly is making a good deal of headway in the garment industry).

3.7.3. RESEARCHERS

As shown above, most of the early work was done at the Charles Stark Draper Laboratories by Defazio and Whitney. They continue to 'tweak' their RCC design and write on mating/joining problems. In 1986, they presented their Instrumented Remote Center Compliance device which permits construction of algorithms that combine active and passive behavior to utilize the best features of both [78].

Sandia National Labs [305] and others [256] are also deeply involved in hybrid control to solve the problems with joining. Also of interest is the work by Asada and Hirai using symbolic-level force feedback to determine the contact

state from sensory information such as force and displacement [18]. Likewise, the research by Peugeot on air stream compliance [59] and that by IBM and RPI on an electrorheological fluid for a compliance effector [63] offer alternative compliance solutions. Finally, work centered around compliance with a vibratory wrist for prismatic parts is being done in Korea to overcome the more pronounced asymmetry of prismatic parts geometry [155]. Additional research is scattered as shown in the Literature Review and database.

3.7.4. CURRENT ISSUES/AREAS FOR FUTURE RESEARCH

Yet to be developed are insertion methods using a combination of compliance and vibration. Also needed are new passive and active compliance devices and programmable fixtures to allow for vertical parts mating. Another yet to be explored area is the development of a worktable to act as a passive compliance device as opposed to the end effector. Generally, the problems of tomorrow will not be unique to the future; consequently, most of the research needs to center around the same issues as today's.

3.8. GLOBAL

This category includes two types of research. One type is research that is in its infancy where not enough has been done to date to warrant a separate category. The Toyota Company's development of its 'Ten Commandments' for automated assembly lines characterizes this type of research [208]. Additionally, this category includes significant one-of-a-kind and/or once-only research that

does not fit into other categories. The work at the Charles Stark Draper Laboratories on the Strategic Approach to Product Design (SAPD) [338] and the development of the unattended factory by FANUC are good examples [338]. Understandably, there are no established experts in this category or suggestions for improvements. However, its existence is essential to capture noteworthy research that fits one of the two above listed guidelines which would otherwise go unnoticed.

4. CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

Recalling that the purpose of this monograph is to provide structure and organization to this field of research, this (quasi-sequential) organization of categories captures the breadth of research areas and allows the reader to put the research into perspective. After a careful analysis of the multitude of research topics, categories were formulated, refined and validated. The Literature Review includes a representative set of the research efforts geared towards the advancement of automated assembly research. Definitions of key terms have been provided along with insight into the particular 'players' involved in automated assembly endeavors. The chosen categories capture the substance of the extensive research efforts. The categories embody research ranging from the rationalization of automated to innovations in equipment design. This document should serve as an excellent introductory document for any automated assembly researcher.

The base categories should never become obsolete. Since they form the foundation for all other research, they will remain essential to an overall understanding of the enormity of automated assembly issues. Nevertheless, as the field of automated assembly matures, categories will need to be added.

Additionally, sub-categories will become necessary as the amount of research in the base categories increases.

The technique used to develop this monograph was based on an externally based investigation. The difficulty with a study of this nature (developing a monograph for such a broad subject) is being able to remain general enough to include all the associated research being conducted that relates to the subjects. One recommendation below suggests that the process be reversed.

Recommendations include expanding the literature search and adding pertinent articles to the database. Keywords should be expanded and finalized. Efforts should include remaining abreast of new research at identified research hubs (e.g. Charles Stark Draper Laboratories, IBM, Honeywell, etc.)

Another recommendation is to reverse the analysis - i.e., conduct an inward looking outward study by area to further validate the final category list. This study could be conducted as a by-product of future in-depth research done in any of the eight categories. Using the category information and individual area literature reviews, over time, a researcher could perform a detailed review to expand the peripheral issues linked to each category while ensuring the breadth of the category is sufficient.

Additionally, work should be initiated to contact the leading experts in each category to ensure the database contains any up-to-date research projects. Furthermore, some of the experts should be queried about their opinion on the adequacy of the categories proposed in this thesis as a further validation step.

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APPENDIX 1

THE DATABASE

So far thousands of articles on automated assembly have been collected. References were gathered from the following sources: Index of Scientific Technical Proceedings (Conference Proceedings Index) 1984-1991, the Science Citation Index (General Index), a Society of Manufacturing Engineers (SME) INTIME search (CD ROM for Technical Papers, Tradebooks, Journal Articles, etc., published by SME) as of 8 December 1990, the Directory of Published Proceedings Index, the National Technical Information Service (CD ROM for Government Funded Research), VTLS (Tradebooks) as of 24 July 1991, Knowledge Index (DIALOG Services on line search of Engineering Index) as of 27 July 1991, and several other miscellaneous sources. This search has netted the pertinent articles from the ICAA (1-11), the ISIR (13-19), ROBOTS 7-12, NAMRC 14-17, to list some of the most frequently referenced.

From this conglomeration numerous articles have been extracted to form the basis of the Literature Review. The database is separated into two parts. Reference numbers 1-350 include articles referenced in the thesis of used in the validation process, while numbers 350-2400 include yet-to-be reviewed articles collected from the above sources. All-in-all this collection of works stands as a good initial literature review for any automated assembly researcher.

The software used is PAPHYRUS. PAPHYRUS is a Bibliography System system designed to store reference collections. Its capabilities include: import/export, word processor access, and keyword, title, author, publication year, etc. search capability. Keyword merge capabilities will facilitate any changes/additions to the category/sub-category names.

Key words are listed below:

SEQUENCE

SYSTEM CONFIG

MANIPULATORS

END EFFECTORS

PARTS PRESENTATION

ROI (Rationalization)

JOIN (Parts Joining and Mating)

LANGUAGES

CONTROL

VISION

SENSORS

MODELS (Representation and Modelling/Simulation)

DFA (Design for Assembly)

PCB (Printed Circuit Board)

GENERAL

APPLICATION (includes Case Studies)

PLAYERS

GLOBAL

Also included as keywords are the various research location names (e.g. Stark Draper, IBM, Univ of Hull, etc.). As the database grows, searches by research organization/location and authors will increase in value.

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