ASSEMBLY AUTOMATION AND PRODUCT DESIGN

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OTHER VOLUMES IN PREPARATION

Preface

Portions of this book are based on a book published in 1968 under the title *Mechanized Assembly* by G. Boothroyd and A. H. Redford. In a further edition, entitled *Automatic Assembly* by G. Boothroyd, C. Poli, and L. E. Murch, the original material developed at the University of Salford in England was updated with work carried out at the University of Massachusetts. In those days, it was felt that manufacturing engineers and designers wished to learn about automatic assembly since it appeared to provide a means of improving productivity and competitiveness. Since 1980, however, my colleague, Peter Dewhurst, and I have developed a subject that holds much greater promise for productivity improvement and cost reduction, namely, design for assembly. Our techniques have become widely used and have helped numerous companies introduce new and extremely competitive product designs.

This new text, therefore, includes detailed discussions of design for assembly and, thus, the subject of assembly automation is considered in parallel with that of product design.

Clearly, the first step in considering automation of assembly processes should be careful analysis of the product design for ease of automatic assembly. In addition, analysis of the product for ease of manual assembly should be carried out in order to provide the basis for economic comparisons of automation. Indeed, it is often found that if a product is designed appropriately, manual assembly is so inexpensive that automation cannot be justified. Thus, a whole chapter is devoted to design for manual assembly. Another chapter is devoted to design for high-speed automatic and robot assembly, and a third chapter deals with electronics assembly.

The remaining material has been updated or rewritten as necessary—particularly to reflect interest in the use of general-purpose assembly robots.

The book is intended to appeal to manufacturing and product engineers as well as to engineering students in colleges and universities.

I wish to thank Dr. A. H. Redford for his kind permission to use material published in the original book, *Mechanized Assembly*, and Dr. P. Dewhurst for his contributions to the subject of design for assembly. I also wish to thank Lori Allen and Joanne Pasquazzi for typing the manuscript.

Geoffrey Boothroyd

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Introduction

Since the beginning of the nineteenth century, the increasing need for finished goods in large quantities, especially in the armaments industries, has led engineers to search for and to develop new methods of manufacture or production. As a result of developments in the various manufacturing processes, it is now possible to mass-produce high-quality durable goods at low cost. One of the more important manufacturing processes is the assembly process that is required when two or more component parts are to be secured together.

The history of assembly process development is closely related to the history of the development of mass-production methods. The pioneers of mass production are also the pioneers of modern assembly techniques. Their ideas and concepts have brought significant improvements in the assembly methods employed in high-volume production.

However, although many aspects of manufacturing engineering, especially the parts fabrication processes, have been revolutionized by the application of automation, the technology of the basic assembly process has failed to keep pace. Table 1.1 shows that, in the United States, the percentage of the total labor force involved in the assembly process varies from about 20% for the manufacture of farm machinery to almost 60% for the manufacture of telephone and telegraph equipment. Because of this, assembly costs often account for more than 50% of the total manufacturing costs.

Table 1.1 Percentage of Production Workers Involved in Assembly

Industry	Percentage of workers involved in assembly
Motor vehicles	45.6
Aircraft	25.6
Telephone and telegraph	58.9
Farm machinery	20.1
Household refrigerators and freezers	32.0
Typewriters	35.9
Household cooking equipment	38.1
Motorcycles, bicycles, and parts	26.3

Source: 1967 Census of Manufacturers
U.S. Bureau of the Census

Although, during the last few decades, efforts have been made to reduce assembly costs by the application of high-speed automation and, more recently, by the use of assembly robots, success has been quite limited, and many assembly workers are still using the same basic tools as those employed at the time of the Industrial Revolution.

1.1 HISTORICAL DEVELOPMENT OF THE ASSEMBLY PROCESS

In the early days, the manufacture of the parts and their fitting and assembly were carried out by craftsmen who learned their trade as indentured apprentices. Each part would be tailored to fit its mating parts. Consequently, it was necessary for a craftsman to be an expert in all the various aspects of manufacture and assembly, and training a new craftsman was a long and expensive task. The scale of production was often limited by the availability of trained craftsmen rather than by the demand for the product. This problem was compounded by the reluctance of the craft guilds to increase the number of workers in a particular craft.

The conduct of war, however, requires reliable weapons in large quantities In 1798, the United States needed a large supply of muskets, and federal arsenals could not meet the demand. Because war with the French was imminent it was not possible to obtain additional supplies from Europe. Eli Whitney, now recognized as one of the pioneers of mass production, offered to contract to make 10,000 muskets in 28 months. Although it took 10½ years to complete the contract, Whitney's novel ideas on mass production had been successfully proved At first Whitney designed templates for each part, but he could not find machinists capable of following the contours. Next, he developed a milling machine that could follow the templates but hand-fitting of the parts was still necessary. Eventually, the factory at New Haven, Connecticut, built especially for the manufacture of the muskets, contained machines for producing interchangeable parts. These machines reduced the skills required by the various workers and allowed significant increases in the rate of production. In a historic demonstration in 1801, Whitney surprised his distinguished visitors when he assembled a musket lock after selecting a set of parts from a random heap.

The results of Eli Whitney's work brought about three primary developments in manufacturing methods. First, parts were manufactured on machines, resulting in consistently higher quality than that of handmade parts. These parts were not interchangeable and, as a consequence, assembly work was simplified. Second, the accuracy of the final product could be maintained at a higher standard; and, third, production rates could be significantly increased. These concepts became known as the American system of manufacture.

Oliver Evans' concept of conveying materials from one place to another without manual effort led eventually to further developments in automation for assembly. In 1793, Evans used three types of conveyors in an automatic flour mill that required only two operators. The first operator poured grain into a hopper, and the second filled sacks with the flour produced by the mill. All the intermediate operations were carried out automatically, with conveyors carrying the material from operation to operation.

A significant contribution to the development of assembly methods was made by Elihu Root. In 1849, Root joined the company that was producing Colt six-shooters. Even though, at that time, the various operations of assembling the component parts were quite simple, he divided these operations into basic units that could be completed more quickly and with less chance of error. Root's division of operations gave rise to the concept "Divide the work and multiply the output." Using this principle, assembly work was reduced to basic operations and, with only short periods of worker training, high efficiencies could be obtained.

Frederick Winslow Taylor was probably the first person to introduce the methods of time and motion study to manufacturing technology. The object was to save the worker's time and energy by making sure that the work and all things associated with the work were placed in the best positions for carrying out the required tasks. Taylor also discovered that any worker has an optimum speed of working which, if exceeded, results in a reduction in overall performance.

Undoubtedly, the principal contributor to the development of modern production and assembly methods was Henry Ford. He described his principles of assembly in the following words:

First, place the tools and then the men in the sequence of the 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 part 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 parts to be assembled are delivered at convenient intervals, spaced to make it easier to work on them.

These principles were gradually applied in the production of the Model T Ford automobile.

The modern assembly-line technique was first employed in the assembly of a flywheel magneto. In the original method, one operator assembled a magneto in 20 min. It was found that when the process was divided into 29 individual operations, carried out by different workers situated at assembly stations spaced along an assembly line, the total assembly time was reduced to 13 min, 10 sec. When the height of the assembly line was raised by 8 in., the time was reduced to 5 min, which was only one fourth of the time required in the original process of assembly. This result encouraged Henry Ford to utilize his system of assembly in other departments of the factory, which were producing subassemblies for the car. Subsequently, this brought a continuous and rapidly increasing flow of subassemblies to those working on the main car assembly. It was found that these workers could not cope with the increased load, and it soon became clear that the main assembly would also have to be carried out on an assembly line. At first, the movement of the main assemblies was achieved simply by pulling them by a rope from station to station. However, even this development produced the amazing result of a reduction in the total time of assembly from 12 hr, 28 min, to 5 hr, 50 min. Eventually, a power-driven endless conveyor was installed; it was flush with the floor and wide enough to accommodate a chassis. Space was provided for workers either to sit or stand while they carried out their operations, and the conveyor moved at a speed of 6 ft/min past 45 separate workstations. With the introduction of this conveyor, the total assembly time was reduced to 93 min. Further improvements led to an even shorter overall assembly time and, eventually, a production rate of one car every 10 sec of the working day was achieved.

Although Ford's target of production had been exceeded, and the overall quality of the product had improved considerably, the assembled products sometimes varied from the precise standards of the hand-built prototypes. Eventually, Ford adopted a method of isolating difficulties and correcting them in advance before actual mass production began. The method was basically to set up a pilot plant, where a complete assembly line was installed, using exactly the same tools, templates, forming devices, gauges, and even the same labor skills that would eventually be used for mass production. This method has now become standard practice for all large assembly plants.

The type of assembly system described above is usually referred to as a manual assembly line, and it is still the most common method of assembling mass- or large-batch-produced products. Since the beginning of the twentieth century, however, methods of replacing manual assembly workers by mechanical devices have been introduced. These devices take the form of automatic assembly devices or workheads with part-feeding mechanisms and, more recently, robots with part trays.

Thus, in the beginning, automated screwdrivers, nut runners, riveters, spot-welding heads, and pick-and-place mechanisms were positioned on transfer devices that moved the assemblies from station to station. Each workhead was supplied with oriented parts, either from a magazine or from an automatic feeding and orienting device—usually a vibratory bowl feeder. The special single-purpose workheads could continually repeat the same operation, usually taking no more than a few seconds. This meant that completed assemblies were produced at rates on the order of 10–30/min. For two-shift working, this translates into an annual production volume of several million.

Automation of this type was usually referred to as mechanization and, because it could be applied only in mass production, its development was closely tied to certain industries: for example, those manufacturing armaments, automobiles, watches and clocks, and other consumer products. Mechanization was used in the manufacture of those individual items such as light bulbs and safety pins that are produced in large quantities. It was probably the process industries, however,—for example, the food, drug, and cosmetic industries—that were the first to apply mechanization on a large scale.

Recent estimates of the proportion of mass-produced durable goods to the total production of durable goods range from 15 to 20%. It is not surprising, therefore, that only about 5% of products are automatically assembled, the remainder being assembled manually. As a result, since World War II, increasing attention has been given to the possibility of using robots in assembly work. It was felt that, because robots are basically versatile and reprogrammable, they could be applied in small- and medium-batch manufacturing situations, which form over 80% of all manufacture.

According to Schwartz [1], George Deval, Jr., patented a programmable transfer device in 1954, which served as the basis for the modern industrial robot. By 1965, several licenses had been issued, and specifications had been outlined for the first modern industrial robot, the Unimate [2]. In 1962, the Unimate Mark 1 prototype was built.

The first uses of industrial robots were in materials handling such as die-casting and punch-press operations and, by 1968, they started to be used in