

1 Introduction

There has been a large shift in the paradigm of automated manufacturing in the past ten to twenty years. Previously it was equated with dedicated systems producing large volumes of a single product at high speed. The overriding theory being that if a large enough quantity of products could be produced at a high enough rate for a long enough time, then the cost of the equipment could be justified and a significant portion of the market could be satisfied. Secondary benefits, including reduced labor and more consistent quality, were added bonuses but not the driving factors. However, this view no longer holds true. Smaller lot sizes, shorter times to market, increased product quality, and lower manufacturing costs are typical of the requirements of a modern manufacturing facility. In the face of the above constraints, hard automation systems are not feasible. They simply take too much time to design, setup, and install, and carry too high a cost to be economically justifiable for smaller lot sizes. What is required is a rapidly reconfigurable automation system that is capable of manufacturing a wide variety of products. This can be accomplished through the repeated use of a basic infrastructure coupled with quickly exchangeable modules specific to each particular assembly. A basic infrastructure allows a capital investment to be recovered over the life of many different products while modules encapsulate hardware, software, and processes specific to a particular assembly. Together they create a flexible assembly system which may be rapidly reconfigured for the manufacture of vastly different products.

Agile manufacturing has benefits, but how important is it for manufacturers to embrace the new technologies? After comparing US manufacturing with the rest of the world and discussing US deficiencies, Richard Ligus in *Industrial Engineering* [1] wrote the following:

As a result, factories are clumsy in moving parts on the factory floor, too slow in introducing new products to respond to market demands, stumbling in execution of production, and severe quality problems exist. What's the consequence? Losing business.

Another supporter of the agile paradigm, Terrence Schmoyer, executive director of the Agile Manufacturing Enterprise Forum, wrote [2]:

Agile manufacturing provides the ability to thrive and prosper in a competitive environment of continuous and unanticipated change and to respond rapidly to changing markets.

Linda K. Schuch [3], contributing editor to *Assembly*, again sums up this fact in her article on rapidly changing flexible assembly technology:

With product life cycles as short as nine months, manufacturers can no longer afford to use conventional assembly-system-development strategies, which can take up to two years. Nor can manufacturers depend on assembly systems that have been designed for specific products.

In addition to economic justification, customer satisfaction can also be a driving factor. *Automotive Engineering* [4] uses the following definition for agile manufacturing:

The agile manufacturer is the fastest to market, with the lowest total cost and the greatest ability to meet varied customer requirements. The final measure is the ability to “delight” the customer.

Consumer's expectations of product quality, time to new product design introduction, and final product cost have changed. Customers continue to demand higher quality products for reduced prices with improved product designs at quicker intervals, a goal which cannot be reached using traditional automation techniques.

Several companies have already fully embraced this technology, in effect becoming the benchmark by which others are evaluating their own implementations. Perhaps the most successful and technologically advanced system is Motorola's automated pager line for a new product, code-named *Fusion* [5]. This line is capable of assembling pagers specific to a single customer's request in real time. There is no need to retool or change hardware. The system begins by marking a unique serial number on each circuit board and tracking that board throughout the system. Each workstation reads the serial number and performs the correct and required operation. While Motorola's line deals specifically with electronic devices, Panasonic has developed a

custom production line for manufacturing bicycle frames to customer specifications [6]. The customer can choose from a variety of frame types and sizes, request the type of components, and specify the paint scheme and colors. Combined, there are over 11 million different combinations of bikes which can be produced. At the factory, each bike is assembled in CAD to test the frame's design, then assigned a unique tracking number. A master craftsman oversees the production of the bike throughout the manufacturing process to ensure the automated equipment is producing a quality product. In approximately 10 days, the customer receives a bike custom-built exactly to his/her specifications.

In a more general sense several companies, Adept Technology Inc., Sony Factory Automation, and Sieko Robots, are marketing flexible manufacturing systems. These systems are not designed for any particular product as were the two previous examples, but are designed to be generic manufacturing machines applicable to a wide variety of different tasks. Adept refers to their system as *Rapid Deployment Automation* [7]. Their system is comprised of standard robots, controllers, and vision-based flexible feeders which can be combined in a wide variety of layouts to satisfy many different automation requirements. Adept also offers a graphical simulation tool, Rapid [8], which can help speed the design of new automation systems. Sony's *SMART (Sony Multi Assembly Robot Technology)* [9] system uses a similar technique in which standardized components are available to be arranged into whatever assembly system is needed. Like Adept's system, standard components include a robotic workcell, multi-turret end effectors, and a flexible feeding system. Seiko describes their products as *Agile Enabled* [10]. They include linear elements, controllers, and a vision system designed to be rapidly constructed into a fully functional, vision-driven assembly system.

1.1 Definition

The first question that arises when attempting to describe an agile manufacturing system is a definition for the term *agile manufacturing*. There are currently many definitions of agile manufacturing.

Many people seem to define agile manufacturing in terms of the “buzzword” programs they have implemented. [11]

This quote sums up the haphazard convention of defining agility rather well. Below are additional definitions given to the term *agile manufacturing*.

Agility: The measure of a manufacturer’s ability to react fast to sudden, unpredictable change in customer demand for its products and services and make a profit. [12]

Industries are embracing the concepts of agile manufacturing, which favor nimble principles over the aging techniques of mass production. [13]

[Agile manufacturing] refers to the ability to produce so-called custom-engineered or custom-specific parts usually in short production runs or one-of-a-kind batches. [14]

The buzzwords are “lean”, to describe efficient, un wasteful, less costly manufacturing; “agile”, said of a manufacturing system’s speed in reconfiguring itself to meet changing demands; and “flexible”, meaning the system’s ability to adjust to customers’ preferences. [15]

Agile Manufacturing System: a system that can fabricate different objects simultaneously, without having to be shutdown for retooling. [16]

Agile manufacturing assimilates the full range of flexible production technologies, along with the lessons learned from total quality management, “just-in-time” production and “lean” production. [17]

The term agile has even been applied to the business and management sector as well.

The word “agility” has popped into the business jargon over the last several years... There is a growing number of companies that are making agility part of the focus of their strategic business plans and road maps. [18]

The only common theme among the various definitions is the ability to manufacture a variety of similar products based on current customer needs. In this dissertation, agility is defined as:

The ability to accomplish rapid changeover between the manufacture of different assemblies utilizing essentially the same workcell and allow the rapid introduction of new products with little or no workcell downtime.

This definition is especially appropriate for light mechanical assembly, which is the focus of this research. *Light Mechanical Assembly*, as defined here, is the assembly of products from discrete, moderate-sized components to form a more functional whole. While there is no hard limit placed on *size* or *weight*, a good approximation would be no larger than a few inches in size and no heavier than could be easily manipulated by a commercially-available table-top robot.

1.2 Factory of the Future

Consider the following hypothetical situation in which a factory is built consisting of similar robotic workcells. A workcell may be defined as the required group of equipment for performing light mechanical assembly. Most of the workcells are connected using a generic conveyor system and are used for production. Several of the workcells, separate from the rest of the production system, are designated as setup workcells and used to introduce new products into the system. The factory is used to produce a wide variety of products, which are ordered in small lot sizes with no regularity. When an order for a product is received, the first available workcell is setup and begins to fill the order. The next order arrives and is inserted into the next available workcell, which begins producing that product.

The requirement is the *encapsulation* of product specific hardware and software. By modularizing all assembly-specific components and software, the separate modules may be re-deployed to fit current production needs. The term “encapsulation” first became prevalent in regards to object-oriented software which was written using

constructs that wrapped data structures and functions into modules which could only be accessed through a standard, pre-defined interface. While it is important for workcell control software to employ object-oriented design techniques, the concept of encapsulation can also be applied to workcell hardware. In relation to the physical, it means designing assembly-specific hardware to be self-contained and to only allow access through a standard, pre-defined interface. For example, a particular gripper quick-change adaptor is selected for use. Then all grippers are required to interact with the rest of the system by using the pneumatic, electric, and mechanical connections provided by that adaptor. The pre-defined interface of the adaptor encapsulates the gripper such that any workcell using that type of gripper adaptor is capable of using the gripper.

By encapsulating all specialized hardware and software, any workcell is capable of being used to fill any order. When an order for a new product is received, specialized hardware is manufactured and tested and specialized software developed and debugged on one of the setup workcells. After the process is functional, the assembly may be shifted to the next available workcell in the factory. In this manner, orders are filled as they arrive by the first available workcell. If a particular product's assembly was more complicated and required n workcells to complete the task, the conveyor system would be used to transfer partially completed sub-assemblies between the workcells. The next time the product was ordered, the first n available workcells could be used. Since all the workcells are connected using the conveyor, it would not matter physically if the same workcells were used for the assembly since the conveyor can transfer sub-assemblies between any workcell.

The above situation is an interesting mental exercise and prompts further examination. How can a production system such as this be implemented? What has to be in place before a factory like the one described can be brought on-line? Further study of the problem yields some insights into the requirements of a flexible assembly factory. Specifically, "What are the features necessary to realize a *Factory of the Future*"?

Reprogrammable Part Manipulator. This usually is an industrial robot, but in the general sense, what is needed is a generic manipulator which can be programmed to perform a number of pick-and-place or assembly operations at any position within its working envelope. Since any workcell may be used to perform any assembly, it cannot be know a priori what type of assembly each particular workcell will be doing at any given time. Therefore it is necessary that each workcell be equipped with a manipulator that is capable of performing a wide variety of tasks.

Flexible Parts Feeders. Since, by definition, assembly is the conversion of many parts into one useful product, it is necessary to present the bulk parts needed for assembly to the workcells. Conventional feeding methods, such as bowl feeders, are specialized in nature and are simply too component-specific for use in a generic workcell. They are designed, built, and tuned for a particular part. If any property of the part (mass, mass distribution, size, material) is altered, the feeder becomes useless. In the hypothetical factory, any workcell can be used for any assembly, so a parts feeder capable of feeding a wide variety of parts with little or no alteration is needed.

While it would be possible to encapsulate each feeder and introduce it into the system as a module, there are several flaws with this thinking. First, feeders are expensive pieces of equipment and it would not be justifiable, from an economic standpoint, to purchase a new one for each part fed. Secondly, the lead time associated with a new feeder can be long and therefore violates the second half of the adopted definition of agile: “rapid introduction of new products with little or no workcell downtime.” Lastly, feeders can be rather large pieces of equipment. Allocating the storage space for a feeder for each part ever assembled at the factory would quickly fill up a large amount of storage space.

Current trends in flexible feeding are toward using vision-based systems, but other solutions, such as carrier-based feeders (GPAX Tape and Reel system [19], for

example) also fit the definition. Without flexible parts feeders, it would be impossible to assemble any product at any workcell.

Rapidly Reconfigurable Hardware. Many assemblies contain operations which are impractical or impossible to perform using a common industrial robot. For example, parts may need to be stamped together, requiring more force than the robot is capable of producing. A nut may need to be run on a threaded rod, requiring a range of motion beyond the capability of the robot. A sub-assembly may need to be inverted so that additional parts may be added to its bottom. While it may be possible for a robot to accomplish some of the preceding tasks, time may also be a factor. It may be required to produce parts at a rate greater than possible if only the robot is used. In all these cases, dedicated hardware can accomplish the task quickly and more reliably than a robot. For this hardware to be useful it must be capable of being rapidly introduced into the workcell as well as be capable of operating at any of the workstations. This requires that each workcell have an area which includes a standard mounting scheme, power connector, and control/sensor connector for interfacing quickly and cleanly with the dedicated hardware.

Generic Conveyor System. If an assembly process is too complex for a single robot to perform, it is necessary to use multiple workcells to complete the task. A structure must be in place to transport sub-assemblies between workcells. Since any workcell is capable of performing any assembly task, it is necessary for all the workcells to be interconnected by the conveyor system. The form of the conveyor is left intentionally vague. It could be a simple, pallet-based conveyor system, such as those manufactured by Bosch Automation [20] or Lanco Systems [21], or could be as complex as a fleet of autonomous vehicles moving between the workcells. The requirement is that a sub-assembly at any workcell can be transferred to any other workcell. Each workcell, therefore, must have an area, within the reach of the manipulator, into which the conveyor may deliver parts.

Rapidly Changeable Grippers. As a product is being assembled, a robot must handle parts as they are retrieved from flexible parts feeders. While one could envision a generic dextrous hand used for part manipulation, such technology, while commercially available [22], is not currently applicable to production floor requirements. Speed and economic considerations generally dictate that simple pneumatic grippers be used. It then becomes necessary to quickly mount the grippers to any manipulator at any workcell. This system must be capable of rigidly and accurately securing the grippers to the manipulator. It also must pass power and control/sensor signals between the grippers and the workcells control system. While this at first appears to fall under the category of *Rapidly Reconfigurable Hardware*, the distinction lies in use. The grippers are tools used by the robot at a particular workcell to handle and manipulate parts. Hardware is rigidly mounted, does not move relative to the robot's base, and is generally used to fixture parts during assembly or perform operations the robot cannot.

Vision System. An agile manufacturing system must permit rapid reconfiguration for a different product. A vision system allows the manipulator to quickly register the location of objects as they enter the workcell. After changing from one product to another, the manipulator may "look around" in its work envelope to find any new dedicated assembly hardware. A vision system is also usually an integrated part of a flexible parts feeder.

Software and Control. It is also necessary to construct the software system such that it is capable of performing any given assembly at any workcell. This type of system demands a distributed, multi-layered control approach. Each sub-system must be responsible for those below it and report to the system above it. If an emergency stop (E-stop) is pressed at a single workcell, for instance, there is no reason for another workcell to shutdown as well. This condition should be handled by the local controller and only propagated to a higher controller if it is impossible to resolve the problem without intervention. An overall controller, a *factory manager*, would be responsible for

overseeing all operations, but control of individual assembly cells would be handled by a local controller. It would be the responsibility of the factory manager to ensure the proper software was transferred to each workcell for a particular assembly and that the conveyor controller was properly initiated and able to serve requests from each workcell.

Correctly Designed Products. One of the most often overlooked, and possibly most important, feature in an assembly system is the design of the parts and products which they make. While it is possible to automate almost any assembly, quite often a small design change can make the difference between a product which is easy and reliable to assemble and one which constantly requires operator intervention. These design changes, if made during product development, cost little and often are not even noticeable in the final design. However, they make a vast difference in the reliability of the assembly process. This process of redesign in the light of automated assembly is referred to as *Design for Manufacture and Assembly* or DFMA™ [23].

Returning to the hypothetical factory and using the components described above, the following would be a normal scenario for producing a product. First an order would be received and the first available workcell chosen. The modular tables containing any specialized hardware would be retrieved and mounted in the workcell. After registering the worktable into its world coordinate system using the vision system, the robot would know the fixture locations and be able to use them. A gripper containing the necessary end effectors would be attached to the robot using a quick connector. Tool offsets would be used to describe the geometry of the gripper to the robot so that it could be used to manipulate parts. Flexible feeders would be filled with component parts needed to produce the product and present those parts to the robot for assembly. As products were finished, they would be placed onto a pallet, also registered into the robot's world coordinate system using the vision system. When a pallet was filled it would be taken to another location to be unloaded by the conveyor system. A central factory controller

would be responsible for downloading the correct programs to the robot's controller which would guide the particular assembly.

1.3 Agile Manufacturing at CWRU

A prototype agile manufacturing workcell has been constructed at CWRU so that research may be conducted with real hardware [24][25][26]. Without a physical system for testing, many of the processes and techniques described later in the dissertation would be purely speculative and not directly applicable to real-world manufacturing situations. The following section discusses the design of the manufacturing system.

1.3.1 Workcell Overview

The standard workcell at CWRU (Figure 1-1 and Figure 1-2) consists of a Bosch flexible material-handling system, two Adept 550 robots, several flexible parts feeders, an Adept MV controller, a single-board computer with a real-time operating system (RTOS), an AdeptOne robot with an MC controller, and an AdeptOne robot with a Cimatrix controller. A central feature of the workcell is the Bosch conveyor system. It is responsible for transferring the partially-completed sub-assemblies between the assembly robots and for carrying finished assemblies to the unloading robot. The two Adept 550 robots have been mounted on pedestals near each conveyor spur (described below). Pallets with specialized parts fixtures are used to carry the sub-assemblies as well as the finished assemblies throughout the system. A safety cage encloses the entire workcell. This protects operators from malfunctions and serves as the mounting frame for the overhead cameras.

The workcell is controlled by a dual VME bus control system. An Adept MV controller performs motion and vision processing while communicating with a second VME bus through a reflective memory network [27]. The second bus contains a single-board computer which controls the overall workcell, including the conveyor system, and

the flexible parts feeders. This permits the use of a real-time operating system and software development in C or C++.

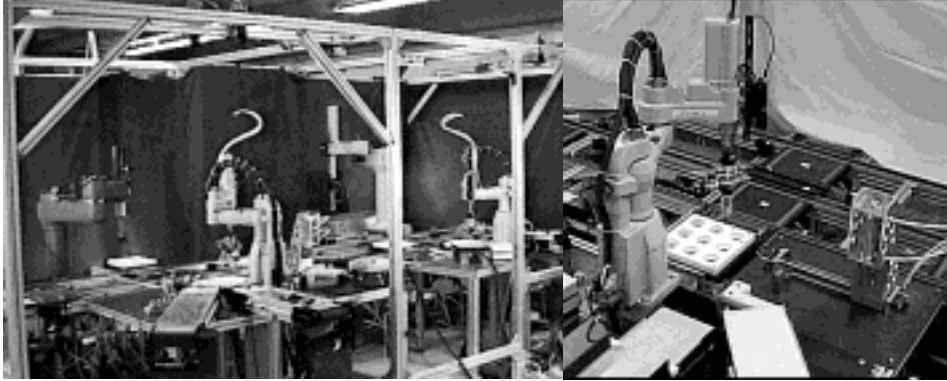


Figure 1-1: Two Views of the CWRU Agile Manufacturing Cell

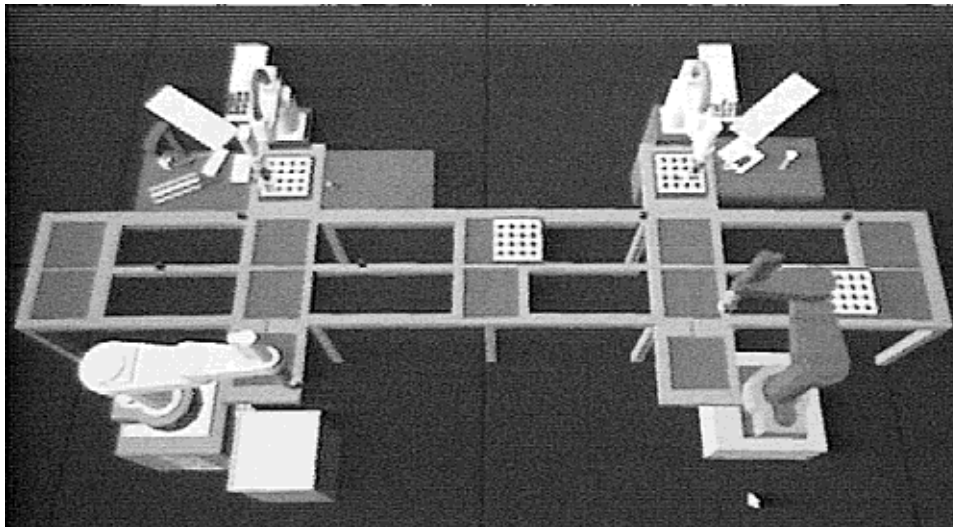


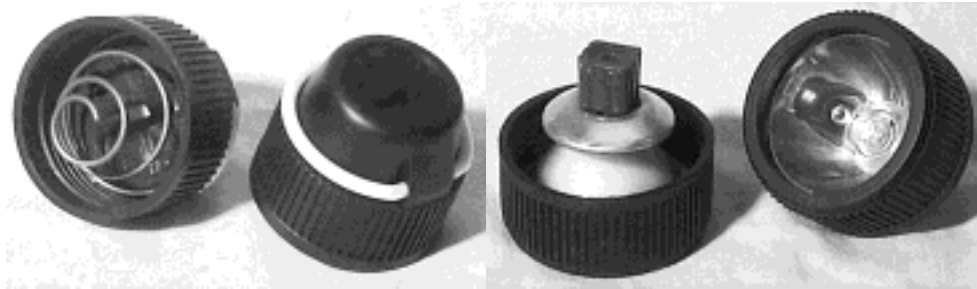
Figure 1-2: Simulation View of the CWRU Agile Manufacturing Cell

Specialized hardware such as presses and grippers are encapsulated on interchangeable worktables and end effector quick connectors. These modular worktables and grippers can be quickly swapped for rapid changeover of manufactured components.

1.3.2 Workcell Capabilities

The agility of the workcell has been demonstrated using two simple assemblies. A common flashlight bottomcap and headcap were chosen as typical assembly tasks

because they were inexpensive and readily available in moderate quantities from local sources. The bottomcap assembly consisted of 4 components and the headcap assembly consisted of 5 components. Figure 1-3 shows both completed assemblies while Figure 1-4 shows the assembly drawings. Overall, the complete bottomcap assembly is about 1 1/2 inches in diameter and 1 inch in height. The completed headcap assembly is about 2 inches in diameter and 1 1/2 inches in height.



Bottomcap Assembly

Headcap Assembly

Figure 1-3: Completed Assemblies

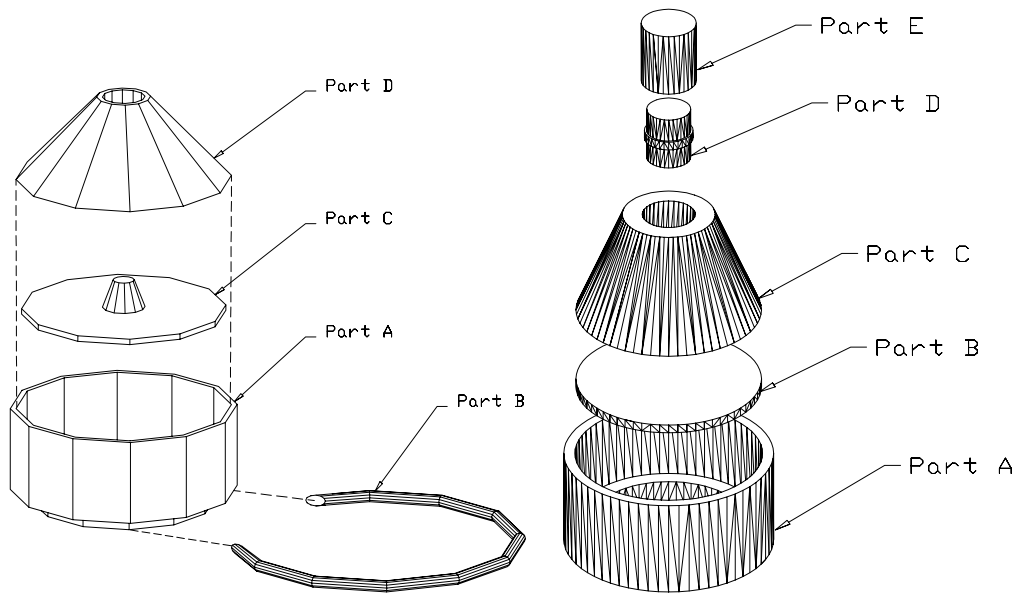


Figure 1-4: Assembly Views

1.3.3 Mechanical Workcell Components

1.3.3.1 *Safety Cage*

The safety cage is constructed of Bosch extruded aluminum. This structure serves two purposes. First, it encloses the workcell and discourages people from entering the assembly system. It also protects the user from flying objects (in the case of a malfunction). The second major function of the safety cage is to hold the overhead cameras. The cage was designed to be stiff so that the overhead cameras would remain still during mechanical operation. Cameras are mounted over both robot workstations for part feeding.

Precision, rigid, six degree-of-freedom camera mounts were designed and constructed. During system setup, it is necessary to align the cameras over the vision window of the flexible parts feeders. This must be done to a high degree of accuracy. The camera's optical axis needs to be precisely aligned so as to be perpendicular to the vision window. The vision window then needs to be aligned in the camera's field of view. The mount allowed easy and independent adjustment of the camera during installation.

1.3.3.2 *Conveyor System*

The conveyor used for the assembly system is a model T2 manufactured by Bosch. Pallets are circulated on two main conveyor sections. These straight sections are parallel to each other and operate in opposite directions. Pallets are transferred between the two sections by means of Lift Transfer Units (LTU's). These units are standard Bosch accessories for the T2 conveyor system. The transfer stations on the ends of the conveyor are uni-directional (transfers must always start on the same belt and end on the other belt). There is also a third connection between the two main conveyor sections at their mid-point. This transfer station is bi-directional (transfers may begin or end on either belt). This allows the pallets to be "shuffled" (their order can be changed) during operation.

A new concept seen on the conveyor is the use of short “spur lines”. The spur is simply an extension built off the main line of the conveyor which houses a single LTU. By placing an LTU in the main line opposite the spur, pallets may be removed from the main line and placed within the reach of a robot so that the flow of the main line is not blocked during assembly. This allows the flow of the main conveyor line to be maintained while a robot performs an assembly at the pallet. Pallets entering a spur are registered in the robot’s world coordinate frame by an arm-mounted camera, allowing the robot to place/remove parts on/from the pallet and avoiding the expense of mechanical registration.

1.3.3.3 Workcell Layout

Five concepts were generated for the positioning of the robots in the standard workcell. Some of the factors considered in the placement of the robots included: reach of the robot relative to the pallet on the spurs, placement of the parts feeders within the work envelope of the robot, placement of the feeders so that they physically fit in the allotted floor space, and position of the assembly area relative to the feeders within the work envelope of the robot (this will have a dramatic impact upon the speed of the assembly). The design of the final layout positioned the robot in-line with and facing the spur with its dead space oriented directly away from the workcell. The parts feeders enter the robot work envelope from both sides at the back of the robot’s reach. To the left and right in front of the robot are two areas for modular worktables. Approximately half the area of the worktable is within reach of the robot. By using a pneumatic slide (or other part transport device), components may be moved to dedicated hardware located outside of the robot’s envelope, thereby reducing the possibility of a robot/hardware collision. Figure 1-5 shows an overhead view of the workcell layout.

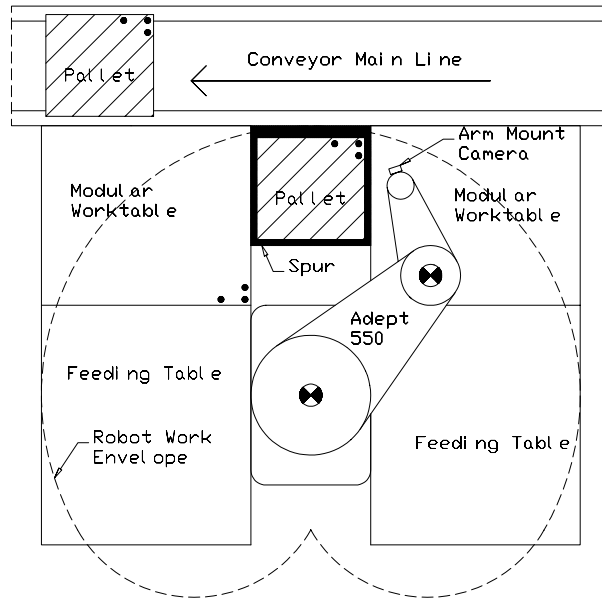


Figure 1-5: Agile Manufacturing Workcell Layout

1.3.3.4 Modular Work Tables

Modular worktables have been designed to facilitate the rapid-changeover of dedicated assembly hardware. By mounting the required hardware on a removable table and attaching that table to the workcell, the assembly hardware can be easily interchanged. When a table is installed at a workstation, the robot locates the table in its World Coordinate System (WCS) using the vision system. Locations on the tables necessary for assembly are defined in a table relative frame of reference, so that once the pose of the table is known in the WCS the assembly locations can be determined in the WCS. The solenoids, vacuum generator, and other hardware which drive the assembly hardware are mounted on the bottom of the table. An electrical enclosure, containing a modular plug connection to the table components, is mounted on the bottom of the table. Some tables are completely passive and do not require pneumatic or electric connections, greatly simplifying their construction.

1.3.3.5 *Grippers*

A quick connector is mounted on the flange of each robot so that modular grippers may be used. Given the small payload (5 kg.) of the Adept 550 robot, a small quick connector designed and sold by ATI Industrial Automation, model “Light-5A” [28], was selected. This connector allows six independent air lines and ten independent electrical connections to pass through. The connector and its mating part (which is attached to each gripper) is lightweight and well suited for use on Adept 550 robots.

Air lines which power the grippers on the robots are routed internally in the quill of the robot which eliminates dangling hoses around the end effector. A special connector was fabricated to allow the hoses to pass from the inside of the quill to the outside of the quick-connector where they are attached. The hoses are protected where they pass through the top of link three using shrink wrap.

1.4 Organization of this Dissertation

The remainder of this dissertation is composed of four chapters, introduced below. Each chapter deals with a specific area of an agile manufacturing workcell.

1.4.1 Flexible Feeding

Flexible parts feeders are key components of an agile workcell. As previously mentioned, dedicated feeding techniques are too constrained for a flexible workcell and a more general, flexible approach is needed. An added benefit of flexible feeding is its immunity to jamming. It has been reported that bowl feeders are responsible for as much as 50% of the downtime of industrial automation systems [29]. By using a flexible approach, this downtime can be avoided.

In Chapter 2 of the dissertation, the design of the CWRU feeder will be discussed. The original design decisions will be discussed as well as subsequent revisions. A comparison with other commercially available flexible feeders will also be examined. A discussion of feeder testing procedures is included and feeder throughput results for

various components will be presented. Finally, the statistical properties of the feeder are examined. Recommendations for future work are discussed in the conclusions section.

1.4.2 Workcell Modularity

Designing a workcell to be modular is important if agility is to be achieved. The only way to enable both the rapid changeover between different assemblies and the use of dedicated hardware is to encapsulate the specialized hardware on modular tables and grippers on quick-change tool adaptors. By encapsulating the assembly-specific hardware, rapid reconfiguration of the workcell is possible.

The second half of modularity is defining and teaching tool offsets that allow the use of the modular hardware in any generic workcell. While it may be possible to rapidly replace modular hardware and grippers, if a complete re-teaching of tool offsets and assembly locations is required before production can begin the system is still not agile. The offsets in the system must be designed such that once they have been taught, they do not need to be re-taught. The modular assembly hardware should be capable of being placed into a physically different workcell and still function using the same offsets.

In Chapter 3 of the dissertation, a method of determining and using offsets is presented. First, an overview of homogeneous transforms is presented followed by a discussion of possible methods of defining offsets. Next the proposed method is described in more detail. Finally, results from testing the method are presented. The CWRU workcell was used for this testing. The test consisted of setting up an example assembly at one of the robot workstations and determining all necessary offsets then moving the assembly to another workstation and running the system without re-teaching offsets, while under observation. The headcap assembly was used for testing.

1.4.3 Design For Manufacturing and Assembly

The design of the parts being assembled in the workcell can have a profound effect on the performance of the system. Often times a small change in the geometry of the part can have a profound influence on its manufacturability. While much has been

published previously on the subject of design for manufacture, little has been presented in regards to assembly in an agile workcell. This type of assembly, given the modular nature of the components and flexible feeding can present unique challenges to the design of a product.

Chapter 4 of this dissertation is separated into several parts. First, previous work is presented. Second, design guidelines are presented which deal with design for manufacture and assembly in three agile related areas: design for assembly in an agile workcell, design for flexible feeding, and design for vision recognition. Finally, as an example of the guidelines, the redesign of a commercially-available product is discussed.

1.4.4 Robot Grippers

Chapter 5 presents the final topic, the design of grippers for agile manufacturing. The design of grippers for robotic assembly is, in general, one of the most important yet most often overlooked portions of workcell design. Specific to agile manufacturing, the design of grippers has some extra challenges. First, in order to decrease the cycle time of the system, it is often advantageous to design the grippers to grasp multiple parts with a single set of gripper jaws. This eliminates the time needed to perform tool changes. Second, using a flexible feeder has several major implications on the design of grippers because the parts are presented in a random fashion. Designing gripper fingers which are unnecessarily large can significantly decrease the throughput of the system. Since the flexible feeder uses a vision system, additional uncertainty can be introduced into the part locations due to inaccuracies in the vision system. Grippers need to be capable of accurately retrieving parts despite error in the pick-up location.

This chapter of the dissertation discusses guidelines for the design of grippers and then discusses the design of grippers currently in use in the CWRU workcell and in Eaton's Reconfigurable Assembly Cell in light of these guidelines. Seventeen different grippers are discussed and examined. Additionally, the design of a rotary jaw gripper,

needed to rotate parts from stable feeding orientations to assembly orientations, is also discussed.