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FLEXIBLE AUTOMATION

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Description

Flexible automation (FA) is a type of manufacturing automation which exhibits some form of 'flexibility'. Most commonly this flexibility is the capability of making different products in a short time frame. This 'process flexibility' allows the production of different part types within their overlapping life-cycles. A different type of flexibility exhibited with flexible automation is the production of a part type through its multiple subsequent product generations. Clearly, there are several manifestations of 'flexibility'. The objectives of this article are to expose the reader to the basic forms of flexible automation, demonstrate the differences between these technologies and dedicated equipment, and discuss their effectiveness in supporting an appropriate manufacturing strategy.

Flexible automation allows the capability of producing a variety of part types in small or unit batch sizes. Although FA consists of various combinations of technology, flexible automation most typically takes the form of machining systems, that is, manufacturing systems where material is removed from a workpiece in some organized manner to achieve a pre-specified design. The flexibility comes from the programmability of the computers. Flexible automation is also observed in assembly systems, where the complexity of the many contingencies needs to be catered for in the various attachment and insertion processes. The most prominent form of flexible assembly is observed in the electronics industry, where flexible machines (automated surface mount technologies) are used to populate printed circuit boards with integrated circuits and other componentry. In this instance, manufacturers have found the machines' accuracy and reliability to be sufficient to warrant the significant investment cost. Overall, however, manufacturers tend to prefer to use automation for the fabrication side of production, and leave assembly to human operators who can adapt to a greater variety of changing circumstances more rapidly and easily than machines. In this article, our discussion of flexible automation is primarily focused on machining systems.

The building block of flexible automation is the computer numerical controlled (CNC) machine tool which is typically augmented by automated materials handling systems, centralized controlling computers, automated storage and retrieval systems, and human operators. The variety of installations of flexible automation are numerous. Some typical configurations are discussed below. A CNC machine tool is a self-contained machine where the tool cutting movements, spindle speeds, tool exchange, and other operations are controlled by a part program executed by the computer controller based at the machine tool. The spindle is a spinning device which holds the tool used to cut into the workpiece. There are analogous conventional machine tools (e.g., lathes, drill presses, milling machines) to their computer-controlled counterparts. However, the operation of these conventional tools is typically done by skilled craftsmen for each part machined. There can be variation to some specifications between subsequent parts on a conventional tool, whereas this variation is decreased on CNC machine tools. The elimination of this variation is one objective (benefit) of automating the discrete part production process.

Further benefits include a reduction in required floorspace, reduced delivery and production leadtimes, higher utilization, increased quality, and smoother implementation of changes and improvements in product designs. Another significant benefit is achieving mass production scale with a machine tool able to produce parts identical to one another, but with also the scope to switch production between part types of different designs. This latter capability comes from having the part programs stored in the local memory or being downloaded from a centralized storage device. Effectively, this is seen as a step towards gaining the benefits of both mass production and job shop customization, commonly known as mass customization. Mass customization refers to the practice of producing single parts to individual modifications of part type designs, but can also refer to producing batch sizes greater than one. Flexible automation is recognized as a means to help achieve mass customization.

Flexible automation is created when the CNC machine tools are augmented by ancillary equipment, such as automated materials handling systems, automated inspection, and central controllers. The materials handling systems are responsible for loading and unloading parts from the machines, transporting parts between machines in the system, handling work-in-process inventory storage, and handling additional parts introduced into the system, such as subassemblies. These materials handling systems could consist of robot arms, conveyors, automated guided vehicles, and gravity feed chutes. Most commonly, a combination of these technologies are used with human operators at some stage introducing unworked parts into the system and removing finished parts from the system.

Another aspect of flexible automation is the usage of multiple cutting tools to perform each operation on a part and the automatic changing of cutting tools at each CNC machine tool. A magazine containing cutting tools is located at each machine and tools are automatically changed (i.e., without human intervention) as the part program dictates. Typical tool magazines can hold 30-90 tools. The selection of which tools should be loaded into which magazine is known as the loading problem, one of several production planning problems (see Stecke, 1983) that a manager of flexible automation must contend with when operating a flexible automated machining system. Occasionally, centralized tool magazines permit sharing of tools between various machine tools, potentially reducing the total tooling cost. However, this requires additional tool transportation devices and a more difficult coordination activity by the central computer system.

The central computer system is another feature of flexible automation systems. The central computer system differs from the local computer controller that resides at an individual processing machine in the system in that it has an integrative role of managing the overall operation of the system as well. The responsibilities of the central computer can be divided into off-line and real-time activities. Typical off-line activities include effective planning and scheduling for the most productive use of the system during a given production period. Typical real-time activities include monitoring the operation of the system, adapting the schedule and production plans when problems arise, and alerting personnel when catastrophic failure occurs. The degree of 'intelligence' and automatic control in the computer system varies greatly across systems, with various levels of human intervention common in all systems. When the central computer system is also responsible for downloading the part programs to the workstations, the system is known as distributed numerical control.

Other ancillary equipment that is contained in flexible automation systems is some automated inspection system that checks the location of either the raw part, the specifications of the finished part, or some intermediate version of the part, commonly several of these. Video cameras and automated gauges can verify whether the part adheres to some pre-determined quality standard and alert the central computer if a part falls outside of the specifications. Another form of flexible automation is seen primarily in the semi-conductor industry, surface mount technologies. These machines are used to 'populate' printed circuit boards (PCBs) with integrated circuits and other componentry. Typically the components in question are presented to the machine on large reels which are loaded onto the surface mount machine. The PCBs pass alongside or though the machine, a component is extracted from the reel, and a gantry arm places the component into a specified location on the PCB. Sometimes the PCB itself is attached to the gantry arm and is moved to a location where the component is inserted into its correct position. The board is then moved along a conveyor to the next component loading position. The component locations are stored in computer memory and the CNC gantry and inserter locate themselves according to this information. Different PCB designs can follow one another through the surface mount machine without disrupting the machine so long as there is sufficient commonality of components or capacity to load different component reels.

Due to the level of automation and presumed consistency, if a single part fails to meet specifications, this is a signal that some problem that could affect many parts could exist. This could be a faulty fixture, materials handling device, or worn or damaged tool. How the central computer deals with the situation depends upon the level of autonomy granted it. Most systems will merely alert their human overseers. However, others will take action, checking various possible sources for the problem. The amount of artificial intelligence (AI) built into most industrial systems today is fairly low, largely limited to image processing and monitoring activities rather than management of contingencies. These machine vision systems typically consist of a video camera, lighting, computer-based artificial intelligence to analyze and filter the image into a recognizable form, and a monitor to display the image and process status (Cohen and Apte, 1997). The use of AI is likely to expand as the adaptive control hardware technology improves. In the future, opportunities will exist for problems to be prevented before they occur. For example, tool wear can be monitored and new tools substituted before a frail tool has the opportunity to damage a part in production. Limited applications such as these are beginning to appear in practice.

While most of the discussion has concerned flexible *machining* systems because of their prevalence, it is appropriate to briefly discuss other forms of flexible automation. Industrial robots can be used for purposes other than merely to handle parts. They can perform various welding functions, inspection, and assembly. If equipped with the appropriate monitoring and sensing devices, they can perform quite sophisticated and dexterous functions. For example, a spot-welding robot arm on an automotive production line can move more quickly across an entire vehicle, performing more consistent and rapid welds than a human operator. The flexible robot can recognize the vehicle type by some sensing technology (e.g., by identifying the fixture type) or from sequencing information from the central computer, and adapt the weld location and sequence from car model to car model. Such robots are usually trained by an operator manually moving the robot arm in a learning mode, where the x-y-z Cartesian coordinates of the robot arm's position, the various arm-segment angles, and joint rotations are recorded for use in real production.

Flexible automation can be configured in several different ways to achieve different production objectives. For example, a flexible cell is typically a single CNC machine tool possibly with automated materials handling system, and can make many part types at low volumes, sometimes one-off prototypes of products. Another form is where CNC machine tools can be lined serially with a conveyor for part movement in a 'transfer line' arrangement, to get a high throughput of a limited number of part types. A flexible manufacturing system is typically more elaborate in design, involving several CNCs doing different sets of operations, linked together logically by computer communications and physically by materials handling devices. These systems can be operated in different ways. For example, sometimes several machines perform identical operations for reasons of system balance and/or redundancy during periods of machine failure. This then allows different routes for parts through the system.

Historical Perspective

Flexible automation is a form of manufacturing technology which is the culmination of a long evolution of production automation. The development path of industrial automation as we know it has largely occurred during the twentieth century.

Automation has long been the dream of engineers and scientists, whereby the simple, dirty, repetitive, and dangerous tasks traditionally done by people, could be undertaken by machines. This vision has been extended to complex physical, computational, and analytical tasks. Advances in technologies allowed the vision to become reality with many aspects of personal, administrative, industrial, and logistic activities now partially or fully automated. Initially, automation was *fixed*, where it could perform a single task, or small set of tasks, efficiently and effectively, but changing this task set was difficult, costly, or impossible. However, a feature common to many types of fixed automation is rigidity. Fixed automation commonly can do a small set of well-defined tasks particularly well, but has trouble doing anything else, without significant and time-consuming intervention from human operators.

Historically, automation as a substitute for general human activity exists with various tools and apparatus as varied as the Gutenberg printing press in 15th century Germany to the Watt steam engine of 18th century England with many other more and less sophisticated examples before and since. Automation as a substitute of mechanical, electronic, or computational apparatus for human activity in an organized industrial context can be traced to the 18th century. This Industrial Revolution superseded the existing craft and cottage industries, forming great urban factories which could utilize cheap power from steam engines in a single location. The technological and organizational advances originating during this period became commonplace and the roots of modern industry were formed.

The formation of extensive railroads is credited with spawning modern American industry (Hopp and Spearman, 1996). The automotive industry, that would later be one of the proponents of first fixed, then flexible, automation experienced the creation of large, vertically integrated, and conglomerated corporations early in the 20th century in the form of Ford and General Motors, itself an amalgamation of several smaller auto manufacturers. It was within these companies, primarily Ford in 1913, for which the mechanization of production generated tremendous competitive strength leading to mass production of a previously craft-generated product. This resulted in the automobile becoming affordable for the average American, greatly expanding the market and growth opportunities. Scale economics dominated the industry for much of the century until competitive pressures, primarily from Japan, forced the American auto industry to partially change their focus to one of product variety and quick response to market needs. The emergence of the new flexible automation technologies enabled a more agile approach to cater to these pressures.

The birth of numerical control (NC), resulting from the combination of conventional machine tools and computers in the 1940s, is credited to John Parsons (Chang, Wysk, and Wang, 1998) with further development done at MIT, funded by the U.S. Air Force. The first fully fledged NC machine tool which could machine complex chapes was developed in 1952 at MIT. Parson used punched cards containing programs which delivered instructions to hardwired machine tools. The hardwired controller was succeeded by an

NC controller and the punched cards gave way to paper tape. These machine tools evolved into NC machine centers that could drill, bore, and mill, and developments during the 1960s included automated tool changers and indexing work tables (Viswanadham and Narahari, 1992).

Parallel developments in computing technologies resulted in much progress in the NC controller, allowing a centralized controller to issue commands to numerous numerical control machine tools. This *direct numerical control* was appropriate when the available computing technology was bulky and expensive. However, as electronics and computers became miniaturized it became possible to place computer controllers within each machine tool, with a central controller responsible for a smaller array of operations, mostly real-time monitoring at the system level, with advancements in local area networks. One of the earliest fully fledged flexible manufacturing systems was developed by the Sunstrand Corporation in 1965. It involved eight NC machine tools with a computer automated roller conveyor. Although it did not have much process flexibility, it marked the advent of flexible automation where part programs for different part types could now be loaded quickly into local microprocessors and production could switch between different part types often without significant setup. Automated movement was done using relay switches. Developments since have been mostly refinements in the technologies and expansions to cover a greater variety of machine tools. The technology is far more robust and significant cost reductions have resulted.

Strategic Perspective

Upon its rise to popularity, flexible automation was hailed as a remedy for the competitive challenges that modern manufacturing was encountering including increasing quality standards, shortening product life cycles, and greater demand for product variety (Hill, 1994). Some disappointment resulted from these great expectations. Some commentators suggested that the problem lay in the strategic mis-use of the systems. For example, Hayes and Jaikumar (1988) suggested that managers using these new technologies in the same manner in which they used their previous conventional technologies were destined for disaster, stressing a new mindset was necessary to experience the 'revolutionary' benefits these new flexible systems promised. New modes of operation and organization were needed to begin approaching the optimistic expectations the managers first had. Indeed, Hayes and Clark (1986) observe that productivity can fall for significant periods after the introduction of new production technologies, but this can be tempered by appropriate management and reorganization. In fact, Jaikumar (1986) observed a difference in the early usage (late 1970s, early 1980s) of these technologies between certain Japanese and American manufacturers. He suggested that the flexible systems in Japan were used more for their flexible benefits than were the systems in America. He suggested Japanese managers introduced more products into their systems every year than their American counterparts, and simultaneously produced more part types at lower volumes. Significantly, the Japanese manufacturers also had fewer problems financially justifying the technologies than the American manufacturers. This suggested that the Japanese manufacturers may have gained a headstart in implementing and using the systems compared with the Americans. This would concur with subsequent evidence of an improved American performance with these technologies, indicating that this misuse was recognized and addressed. Hill (1994) suggests that a great deal of disappointment resulted from managers investing in 'flexible' equipment believing that the possession of new production technologies would result in a 'strategic response' to competitive pressures, citing several instances where companies made unwise investment choices. One lesson appears to be that flexible automation is appropriate when its capabilities (e.g., producing multiple part types in medium volumes) are aligned with the company's needs and defined manufacturing and technology strategies. Upton (1995a) believes that flexibility is largely drawn from the managerial emphasis on it and cooperation between management and experienced operators, with the production technology not particularly crucial at all.

Much has been written about the economic justification of flexible technologies (see Son, 1992). There has been evidence to suggest conventional justification techniques are inappropriate for flexible automation (Kaplan, 1986) and much activity has been directed at attempting to capture the more quantifiably elusive benefits of flexible technologies. Foremost among these benefits is the flexibility of making multiple products simultaneously, and many authors have attempted to capture and characterize this flexibility through mathematical programming models (e.g., Fine and Freund, 1990), real option models (Trigeorgis, 1996), and empirical studies (e.g., Upton, 1995b).

Technology Perspective

There is an obvious difference between flexible automation and the conventional equipment in hardware. Not so obvious is the change in management practice required to secure the benefits of the new technologies. This change was not fully appreciated initially, and early performance of flexible automation in America was lacklustre. These changes extend to the planning processes needed to operate flexible automation. Stecke (1983) identified five production planning problems necessary for effective operation of flexible manufacturing systems. Much subsequent research into FMSs has addressed one or more of these problems of grouping machines, selecting part types, choosing relative mixes of products, allocating system resources to part types, and determining appropriate tool magazine loading strategies. These are challenges faced by production managers of flexible automation that are driven by the technology; dedicated technologies which handle a single product do not encounter similar problems.

The difference in approach to the management of flexible automation is exhibited by the 'flexible approach' part type selection method (Stecke and Kim, 1991) to achieve workload balance across machines and to maximize utilization. This approach of dynamically allocating and adding part types into the production mix is shown to be superior to a batch method of allocation when the stochastic demands of products are independent.

With all the advantages that existing flexible automation offer, a legitimate question is to ask why all manufacturing is not done on such equipment. One reason is that dedicated equipment is generally faster, operation by operation, than flexible automation, and often more appropriate in high-volume environments. Another reason is that there is a cost premium in the acquisition and operation of flexible automation over dedicated systems. Also, for all the tumult about the 'agility' of flexible automation, the ability to *easily* modify the systems to accommodate entirely new part types is limited. Therefore, the next phase of flexible automation appears to be the development of reconfigurable manufacturing systems (RMSs), where the technology (Koren and Ulsoy, 1997: 1) "is one designed for rapid adjustment of production capacity and functionality, in response to new circumstances, by rearrangement or change of its components". An example of a reconfigurable machine is one that, say, mills and drills, but currently is not capable of turning. Where there is a future desire for such a capability, this "reconfigurable" machine can easily, quickly, and cheaply be reconfigured to acquire the new turning capability. Although RMS technology does not currently exist, newly constructed hardware and software tools promise the easy production of newly introduced part types on these manufacturing systems. Another example of RMS hardware would be a milling machine where there is scope for addition of several spindles that can be arranged in numerous configurations, in an absolute and relative positional sense. This permits tool and workpiece orientations in machining even more varied and versatile than in five-axis milling machines. For example, it may be possible to have multiple milling tools operating on a single workpiece from different directions. The development of the hardware, the software, and the science of reconfiguration is ongoing.

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