Minifactory: A Precision Assembly System Adaptable to the Product Life Cycle

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ABSTRACT

Automated product assembly systems are traditionally designed with the intent that they will be operated with few significant changes for as long as the product is being manufactured. This approach to factory design and programming has many undesirable qualities which have motivated the development of more "flexible" systems. In an effort to improve agility, different types of flexibility have been integrated into factory designs. Specifically, automated assembly systems have been endowed with the ability to assemble differing products by means of computer-controlled robots, and to accommodate variations in parts locations and dimensions by means of sensing.

The product life cycle (PLC) is a standard four-stage model of the performance of a product from the time that it is first introduced in the marketplace until the time that it is discontinued. Manufacturers can improve their return on investment by adapting the production process to the PLC. We are developing two concepts to enable manufacturers to more readily achieve this goal: the Agile Assembly Architecture (AAA), an abstract framework for distributed modular automation; and minifactory, our physical instantiation of this architecture for the assembly of precision electro-mechanical devices. By examining the requirements which each PLC stage places upon the production system, we identify characteristics of factory design and programming which are appropriate for that stage. As the product transitions from one stage to the next, the factory design and programming should also transition from one embodiment to the next in order to achieve the best return on investment. Modularity of the factory components, highly flexible product transport mechanisms, and a high level of distributed intelligence are key characteristics of minifactory that enable this adaptation.

Keywords: factory automation, precision assembly, product life cycle, modular factory, automated manufacturing, flexible manufacturing, minifactory, agility

1. INTRODUCTION

The term "agile" has come to be used to characterize a company which can quickly adapt both its manufacturing and marketing processes in order to suit the current marketplace. In the engineering literature, production flexibility has been identified as a means to adapt to the uncertainties of the manufacturing process including product variations and changes, and variations and uncertainties in parts dimensions and locations. As a result, considerable research has been conducted to design manufacturing systems which embody manufacturing flexibility[1]. Analogously, marketing publications have identified marketing flexibility as a means to adapt to the uncertainties of the marketplace. Marketing uncertainties are external influences beyond the control of the individual organization; for example, changes in customer demands and competitor's strategies. Flexibility in the marketing process can be used as a defensive strategy to desensitize an organization to unexpected marketing conditions[2]. In this paper, we apply an established model for understanding marketing uncertainties—the product life cycle—to identify appropriate adaptations of the manufacturing process in order to improve the agility and return on investment for the business.

Our work centers upon two ideas: the Agile Assembly Architecture (AAA), an abstract framework for distributed modular automation; and minifactory, our physical instantiation of this architecture for the assembly of precision electro-mechanical devices. The motivation for the design of minifactory has been that the time-to-obsolescence of precision electro-mechanical products such as disk drives, CD players and pagers is shrinking. Factory setup and changeover becomes a significant portion of product costs when the time-to-obsolescence is short. Thus, minifactory has been proposed to reduce the time and effort needed for factory setup and changeover. Moreover, we propose that the principles underlying the minifactory system are beneficial for a multitude of products with life cycles of varying durations.

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We describe the product life cycle and minifactory in Sections 2 and 3, respectively. Then in Section 4, we discuss how factory personnel can easily adapt a minifactory system to the four stages of the product life cycle.

2. THE PRODUCT LIFE CYCLE

The concept of a product life cycle (PLC) having distinct definable stages is well accepted in the marketing literature[3,4]. Through the careful observation of the sales history of numerous commercial products over time, business experts have realized that most products undergo a characteristic sequence of stages from the time the product is first introduced into the market until the time it is withdrawn. The PLC model has been used by marketers as a tool for deciding the best methods for offering, presenting, distributing and selling their product. Thus by understanding the stage of the PLC which the product is in, the company can attempt to maximize profits by appropriately adapting the marketing strategy.

The PLC is depicted in Figure 1. The sales of a typical successful product for the time period between when it is introduced and when it is withdrawn from the market are plotted. Only the curve shape is of importance in this discussion because the relative duration of each stage may vary widely from product to product. Except for certain fad and fashion merchandise, this relationship has been observed to apply to all types of products including paper, VCRs, and automobiles. Each of the four product life cycle stages, introductory, growth, maturity and decline will be described in sequence. We will discuss the typical behavior of sales, product modification, and production costs for each stage. The typical behavior of many other marketing variables such as target market, price, profits, competitors, and brand loyalty can be found in the marketing literature.
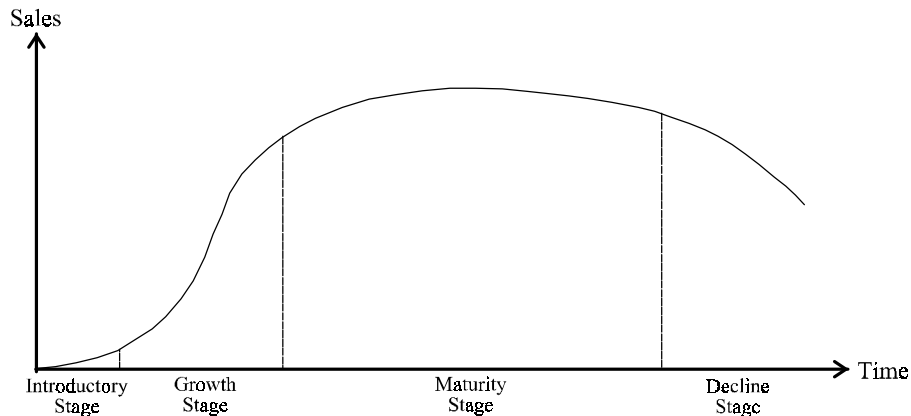

Figure 1: The Product Life Cycle

Even before the introductory stage is entered, a product must successfully complete conception, and an incubation period of product development[4]. Although these prior stages do not directly impact our discussion of the PLC, the time and resources expended during those stages will play major roles in the company's approach to product introduction. Specifically, the first to market a particular product will have the best chances of recovering these pre-introductory expenses.

The introductory stage is characterized by slow sales growth. Production volume is low disallowing economies of scale. Flexible but inefficient production equipment is usually applied because demand uncertainty forces manufacturers to use existing equipment rather than investing in new specialized machinery. Often functional problems with the product are discovered and production changes are relatively frequent during this period. For these reasons, production costs tend to be high and so is the product price. More often than not, the business incurs losses during this stage.

The growth stage is a time of rapidly increasing sales. It is a signal that the product has been accepted in the marketplace. The stage can actually be divided into two substages; the first characterized by an increasing rate of sales growth and the second characterized by a decreasing rate of sales growth. The increased sales volume allows the exploitation of economies of scale and provides the revenues for the purchase of new, more efficient, production equipment. As a result, the costs of production are higher in absolute terms but lower in per product terms. Prices can be dropped which further increases sales by opening new markets from lower-income customers. Profits can be high and competitors are quick to enter the market with competing products at this time. In fact, the greatest competition occurs in the growth stage. The intense competition eventually forces prices and profits down, and by the end of this stage many of the competitors have

dropped out. Production is frequently adjusted during this stage as competitors try to improve or enhance their products to gain a competitive advantage. It is towards the end of the growth stage that product differentiation begins to segment the market. The survivors of this stage will need a full product line across multiple market segments in order to stably reach the maturity stage.

A relatively constant sales volume characterizes the maturity stage. Once all markets for this product have been saturated, sales tend to approach a constant level. Prices, profits, and production costs are stabilized also. Most production changes are esthetic rather than functional ones in an effort to persuade consumers to purchase new products before old ones have reached the end of their usefulness. A broad product line must be continually maintained to service a spectrum of the largely segmented market.

When the sales volume begins to continually reduce, the product has entered the decline stage. Regular esthetic changes can no longer maintain sales levels and are thus discontinued. The product line is reduced as specific product incarnations are dropped for lack of sufficient sales. The economies of scale no longer accrue and production costs begin to increase. Eventually, when profits can not longer be reasonably maintained, the product line is discontinued.

3. MINIFACTORY OVERVIEW

A basic understanding of the minifactory system is a prerequisite to our discussion of adapting production to the product life cycle. Our goal is to produce a system that enables fast and easy deployment and changeover. To afford both analytic tractability and design practicality we have deliberately restricted the scope of capabilities we wish a minifactory to perform. Thus, we have limited the scope of operation to assembly and processing tasks requiring four or fewer degrees-of-freedom. We foresee minifactory based systems being capable of four-degree-of-freedom vertical insertion tasks with micron-level accuracy. Simple integration of overhead processing (*e.g.*, laser processing or material/glue deposition) should be facilitated, and basic factory design and programming (also redesign and reprogramming) should be possible in less than a week.

To provide these capabilities, a minifactory consists of a potentially large collection of mechanically, computationally, and algorithmically distributed robotic modules which we will refer to as agents[d]. In Figure 2 are shown several agents including couriers, overhead manipulators and overhead processing stations. Also shown is a typical product being carried by a courier and a manipulator holding a part that is ready to be assembled to the product. Each agent in a minifactory is responsible for providing a minimum level of cooperation and communication in order to participate in the most basic minifactory operations, thus providing a guaranteed level of inter-agent operability. Each agent, which we foresee being provided by a variety of agent vendors, will have a collection of built-in high-level capabilities. The user need not program these capabilities explicitly; instead, the user will specify only the desired intermediate tasks and the parameters required for the agent to achieve those tasks.

The hope is that the process of designing and programming complex high-precision assembly systems can be simplified through the use of factory-wide standard procedures, protocols, and well structured agent autonomy. A standardized AAA design and programming tool, the *interface tool*, will allow a user to select agents from vendors on the Internet and program them in a simulated factory environment with high confidence that an actual factory will perform similarly. This will be accomplished by requiring each minifactory-compliant agent to both provide an accurate representation of its own operation, and calibrate itself with respect to the rest of the system by exploring its local environment. These capabilities enable a high level of simulation fidelity and run-time robustness, facilitating the transition between simulation and reality.

The most obvious departure from traditional robotic assembly systems and one of the most obvious embodiments of our philosophy of factory level integration is our choice to integrate product transfer and local manipulation. As such, we have eschewed the traditional use of SCARA manipulators coupled with part conveyor systems and local fixtures. As depicted in Figure 2, we have chosen to make use of cooperating two-degree-of-freedom manipulators and planar couriers moving over a high-precision platen surface, both capable of micron level precision. The couriers are thus responsible both for product transport within the factory and for transiently forming cooperative four-DOF robots with stationary manipulators to perform parts and materials manipulation. This approach to providing four-DOF capability has a number of

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[d] By agent we explicitly mean a mechanically, computational, and algorithmically modular manufacturing entity, *e.g.* a robot and its associated computer, capable of both communication and physical interaction with its peers.

advantages[6,7] and incorporates simple and standard mechanisms for the inclusion of semi-custom processing elements (*e.g.* screwdrivers, orbital head formers, glue dispensers, laser processors, etc.).
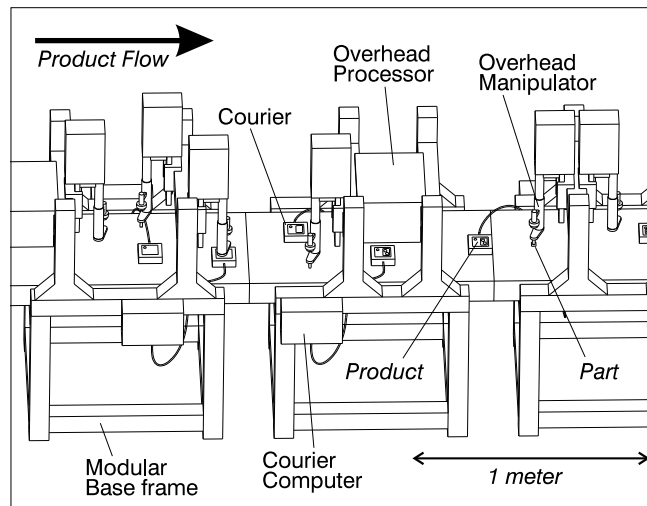

Figure 2: Basic Components of a Minifactory

In further contrast to traditional automation systems, there is no centralized controller describing the global operation of a minifactory. Rather, each agent, whether it be a courier, manipulator, or other custom module, is an independent entity executing its own program. Thus, the overall minifactory behavior results from the interaction of agents with each other and their physical environments.

To simplify the daunting task of developing the distributed programs necessary to operate a minifactory, three key features of the system will be exploited. First, task-based abstractions will be used to allow agents to be programmed with a minimal level of dependence on the explicit behavior of their peers. Second, each agent will be able to robustly execute their task directed programs by ensuring their proper calibration with respect to relevant features in the minifactory. Finally, these two ideas combine with the ability of agents to provide accurate physical and behavioral models to the simulation system included in the interface tool, allowing for the production of virtual minifactory systems that accurately reflect potential physical minifactory systems. The overall effect is to provide a design and programming environment that enables the rapid development of well debugged distributed systems which are both themselves modular and programmed in a modular fashion, enabling local changes in factory configuration to be made with only local modifications to the factory programs.

To facilitate this highly agile model of factory design, deployment, and modification, the interface tool—the primary channel for interaction with a minifactory—will be a graphical point-and-click simulation environment. Using this tool, personnel can view, manipulate, and interact with 3-dimensional representations of alternative factory designs. Ultimately, we foresee a minifactory system being designed and programmed by personnel who have expertise in the assembly problem at hand, but little detailed expertise in minifactory programming.

4. FACTORY ADAPTATIONS TO THE PRODUCT LIFE CYCLE

4.1 Overview

With the background information from the two previous sections, we may now begin to envision how adaptations of the assembly system can be achieved in each stage of the PLC in an attempt to maximize the return on investment. Each adaptation, whether it is a design or a programming change, can be gracefully transitioned into the operating factory by personnel using the interface tool. First, the adaptation can be developed in a simulated factory environment. Then, one element at a time, the new hardware and/or software can be introduced into the actual factory.

4.2 Introductory Stage Adaptations

The desired characteristics of factory design and programming in the introductory stage are fast setup, minimal investment, and frequent modification. Fast setup is critically important because of the host of benefits that accrue to the first company to introduce a new product in the marketplace. Because of the uncertainty of sales and the typically low sales

volume in the introductory stage, a manufacturer will limit his investment in the production process to the bare essentials. Frequent adjustments to both the product and the process are typically required in the introductory stage to respond to customer needs and ensure proper product operation.

Fast setup of minifactory is facilitated by its interface tool, modular nature, and distributed intelligence. The interface tool makes factory design fast and easy. With direct Internet integration, agent models are obtained in seconds and the actual hardware is obtainable in a few days. Because all modules have standardized mechanical and electrical interfaces, factory construction is simply a matter of positioning the components, tightening the clamps and mating the utility connectors. Communications and coordination between agents are built-in distributed capabilities independent of each component's position in the factory network. High level built-in capabilities for task execution make agent programming fast and simple.

Frequent modification of the factory design is as easy to accomplish as the original design using the interface tool. Because the program for each agent is local and because each one has built-in capabilities to handle new situations, programming of new or changed factory components remains a straightforward local task.

Different levels of assembly accuracy can be achieved by different factory designs and programs. High accuracy manipulations may require extra sensors and sensing operations, or extra aligning motions. In order to quickly implement a traditional automated assembly system, a designer may avoid these accuracy enhancing complications during the introductory stage. Methods of automated inspection and error detection may similarly be eschewed in the introductory stage for the same reason. In contrast, high level sensing, aligning, inspection and error detection capabilities are built into minifactory components and are always readily available for use. The designer of a minifactory system need only choose the functions desired and adjust the parameters required for operation. In this way, complicated accuracy enhancing manipulations may be introduced into the factory earlier than is traditionally possible.

Some assembly operations may be so complicated that the application of traditional automation equipment would simply require too long to setup for responding to a profitable, but time-limited, marketing opportunity. In such a case, a company would be forced to rely upon manual assembly (if this is a viable option) or risk the possibility that their competitors might respond to the opportunity unchallenged. A company with minifactory capabilities could respond to marketing opportunities which require complicated factory setups within limited time windows. Although complete automation of production is often preferred, a minifactory system does not preclude the inclusion of manual assembly, inspection, or processing steps in the factory.

Keeping investments in production low during the introductory stage is difficult. Minifactory-compliant equipment may be more costly than traditional equipment because of the stringent precision and intelligence requirements. The high accuracy machining, high precision sensors and actuators, and high throughput processors needed for agent designs will contribute to higher costs for these components. However, the total cost of a system includes both the costs of the equipment and the costs for system integration, and system integration is notoriously expensive, comparable to or greater than the equipment itself. Although traditional manufacturing equipment may be less costly than minifactory equipment, the total cost of a minifactory system may be less than the total cost of a system using traditional automation because integration will be a simpler, lower cost activity.

4.3 Growth Stage Adaptations

Once a product has entered its growth stage, the manufacturer has sufficient justification to invest further in the production process. Moreover, because of rapidly increasing sales, production facilities must be expanded to keep pace. The primary defining characteristic of the growth stage is increasing factory capacity. Quality improvements are prevalent as a result of the competition between companies in this stage. Production of product variations are also desired because the growth stage is the time when most of the market fragmentation occurs.

A principal means of increasing factory capacity is by adding parallel production lines to the factory. Minifactory facilitates the fast setup of these new lines as previously discussed. With multiple agents negotiating for limited shared resources, the serial flows of product assembly may be replaced by more complex conditional motions. The flexible transport afforded by couriers on platens contributes greatly to the ease with which changes in the factory configuration or changes in the process sequence can be made because these changes can be confined to software. The high level of built in intelligence and the autonomous ability to self-calibrate allows agents to adjust to the addition, reconfiguration, or removal of factory components.

Minifactory personnel can continually improve product quality by taking full advantage of the built-in capabilities of agents for inspection, error detection, and recording process data. Such quality improvements are much more difficult to realize using traditional automation equipment because custom hardware and software must be developed.

As the market for a product fragments into more and more specialized markets, an agile manufacturer with minifactory-compliant equipment is able to quickly test and enter the emerging niche markets. Programming for the assembly of multiple different products on the same production line requires additional effort. However, this complexity is not difficult to implement for a minifactory system because each courier has sufficient built-in capabilities to keep track of the specific needs of the subassembly which it carries.

4.4 Maturity Stage Adaptations

In the maturity stage, the manufacturer is attempting to maintain its market share by infrequent esthetic changes and quality improvements. Production capacity is generally adequate for handling the demand, so factory personnel may focus more upon increasing the efficiency of the process. Reductions in execution time, increases in reliability and increases in yield will contribute to enhanced efficiency levels. Monitoring and data collection done in the growth stage can play a major role in determining how improvements in quality and efficiency can be made.

Quality improvements can become evident by close inspection of collected process data. Minifactory has a decided advantage over traditional automation systems in that high precision is a built-in property of all factory components. Couriers may travel the length of a factory and maintain micron level precision at any location along the way. This contrasts greatly with prior factory systems which can achieve high precision only at specific locations where special-purpose positioning devices are used.

We can improve efficiency by combining similar tasks at one manipulator. As with other changes, this type of change is a simple matter of reprogramming the manipulator and removing the equipment no longer needed. If previously acquired data shows that reoccurring patterns of resource scheduling are forcing couriers off of a fast serial visit to the process stations, we can adjust the spacing and order of the process stations to reduce transport times. Programming of parallel motions for collaborating agents should be included to reduce execution time. Minifactory programmers can reduce the execution time of certain tasks by finely tuning the parameters of those tasks. If couriers are often required to queue up for a resource at a particular manipulator, another manipulator may be added. These changes should be motivated by inspection of the data from the operating factory or on simulations of the factory. Improvements in accuracy and reliability of the process will increase the yield and can allow the elimination of some of the sensing and inspection operations used by the factory. The combined effect of these improvements will be an increase in the throughput of the system.

It is interesting to note that while the efficiency of a minifactory can be improved by appropriate design and programming, the maximum efficiency of minifactory is limited because components are made for general-purpose operation and because the courier tethers limit the number of couriers which can operate in a given vacinity. Because components are general-purpose, some capabilities of each component will remain unused for any specific installation. Also, because couriers cannot travel over the tethers of other couriers, some potential parallel activities will not be possible. Hard automation, where products are made by custom designed machines, may be more efficient than a minifactory system for production in the maturity stage. However, a product would be less likely to reach the maturity stage if the company committed to hard automation in the introductory or growth stages. A commitment to a minifactory system does not preclude the incorporation of hard automation within the factory.

4.5 Decline Stage Adaptations

By the time a product is known to have entered its decline stage, a manufacturer is unlikely to invest in improvements or expansions of the process. Instead, attention should be focused upon the future of the business and the next product line. Reuse or sharing of the equipment may begin in an effort to smoothly discontinue the declining product while introducing a new product from the same family or a completely different one.

It is expected that adaptations of the process for the declining product will be limited to the removal of underutilized factory components and the conversion of components for production of new products. The removed factory components can be reused or replaced by different components needed for the next product line. For a time, new products and old can be manufactured on the same factory sharing portions of the process. The aforementioned advantages of distributed control makes this sharing of equipment easy to implement. At the point when the declining product fails to be economically viable, it may be discontinued, and the remaining factory components will be converted for the new products.

Minifactory's modularity and the manageable physical size of components provides for the added advantage of production portability. Facilitated portability of the entire production system offers the manufacturer another option for dealing with the decline stage. Instead of utilizing the company's main production facilities for a product whose sales are declining, a company can choose to contract with a third party to handle production of the product until it is discontinued. The entire production process can then be quickly disassembled, transported and reassembled at the new production location with a minimum of difficulty.

5. CONCLUSIONS

The product life cycle has been used by marketers as a useful model for relating the sales volume of a typical successful product to marketing variables over time. We have discussed how the PLC model can also be used by companies to improve their return on investment through the agile adaptation of factory design and programming. In the first introductory stage of a product's life cycle, factory design and programming should be completed quickly with minimal investment in labor and equipment. Once product sales rise into the growth stage, the factory can be adapted for higher capacities. As the market saturates and sales stabilize, the maturity stage is entered and adaptations can be directed towards increasing factory accuracy, reliability and throughput. Continuous quality enhancing adaptations can also be implemented in these first three stages. Finally, in the decline stage, the manufacturer can adapt the system by gracefully transitioning resources from the declining product to other products in the same family or completely new offerings.

We have identified characteristics of factory design and programming which facilitate the adaptation of production to the PLC. Factory equipment and software needs to be modular with common mechanical, electrical, and communications interfaces. Software to operate and coordinate factory components must be distributed with a high level of built in capabilities. Design and programming of the factory by personnel with little expertise must be facilitated by a graphical interface tool. Also, it is beneficial to incorporate a highly flexible transport system. Minifactory is a proposed system for precision assembly that embodies these characteristics. Minifactory principles can be applied to a multitude of different manufacturing systems to allow the factory design and programming to be adapted to the PLC.

ACKNOWLEDGEMENTS

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