The Technology Base for Agile Manufacturing

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The effective use of information is a critical problem faced by manufacturing organizations that must respond quickly to market changes. As product runs become shorter, rapid and efficient development of product manufacturing facilities becomes crucial to commercial success. Effective information utilization is a key element to successfully meeting these requirements. This paper reviews opportunities for developing technical solutions to information utilization problems within a manufacturing enterprise, and outlines a research agenda for solving these problems.

1 Introduction

Agile manufacturing is being heralded as the key to successful competition in today's marketplace, supplanting traditional mass production techniques. As always, the successful economic competitor is the one who produces the right product at the right price. What has changed is the marketplace — consumers no longer want a generic product at the lowest price. The increasing reality of the world as a single market is forcing suppliers to deal with more varied demands, niche markets, and most importantly, more competitors. Agility in manufacturing is the the ability to respond to small production quantities, short development cycles and product lifetimes, and increased product variety. The manufacturer who successfully adopts these skills will be more responsive to changing customer desires and will be rewarded with a larger market share.

It is our view that although there are important process development issues, success in agile manufacturing will center on effectively utilizing information in the manufacturing organization. As product cycles and production quantities shrink, product costs become increasingly dominated by non-recurring engineering costs — the upfront engineering. Furthermore, efficient information control is a critical contributor to determining time-to-market, another increasingly important issue in today's marketplace. The successful producer is the one who recognizes the importance in developing, analyzing, and utilizing information.

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The manufacturer that ties its future productivity to the utilization of information also opens an opportunity to free itself from current resource-based growth constraints. As long as competitiveness is closely tied to physical goods, a mature industry finds its fate tied to changes in resource availability or to the incremental improvements of a mature technology. By linking its future to information utilization, the agile enterprise benefits from the inherently unlimited nature of an abstract commodity, information. Further, information technology is currently improving at a very high rate, allowing information to be processed at rapidly declining costs.

Sandia's Intelligent Systems and Robotics Center (ISRC) has created a program in Information-Driven Manufacturing to focus efforts on the effective control and utilization of information in the manufacturing environment. We have identified automatic planning and programming, and sensor- and model-based control as key technologies required to overcome the impediments to agility inherent in current generation manufacturing equipment. We have chosen assembly of electromechanical components to motivate our research in agile manufacturing. This subset of manufacturing tasks is important both for its major role in manufacturing, and because many of the key issues to be resolved in electro-mechanical assembly are representative of analogous problems elsewhere in the manufacturing process.

In classic economic tradition, we will draw upon the example of the Acme Widget Company to build a scenario for agile manufacturing. Through this example we will illustrate the path of information flow in the manufacturing process and explore how better utilization of that information translates into greater agility. We will also identify the important research issues that require resolution to create the highly agile enterprise.

2 The Acme Widget Company

Acme Widget is a world-leader in the design and manufacture of — widgets. Market research has identified significant consumer interest in widgets with a Super Turbo feature. Fortunately, the technology required to produce Super Turbo Widgets has been developed by researchers in Acme's basement. Now Acme's problem is to manufacture the new Super Turbo Widgets and bring them to the marketplace before their competitor, Vile Enterprises. We will follow the design and production of this new product with an eye toward where information is generated and utilized.

Acme researchers have produced a prototype Super Turbo Widget, but this prototype must be refined into a commercial product design and then manufactured. The engineering department develops a candidate design, and the drawings are sent to the prototyping shop. Based on tests with the early units, engineering makes a number of design changes to remove slight performance glitches, and new prototypes are built. After several such cycles, the design is frozen and sent to production engineering.

The basic technology of the Super Turbo Widget is the same as the ordinary widget, so production engineering's primary task is to develop tooling and set up the new production line. Production engineering develops an assembly line plan, and notices that several inverting stations are required that seem extraneous. By inserting screws A12–A16 from the opposite direction, several of these inverting stations may be omitted, reducing manufacturing costs. Production engineering sends the drawings back to design engineering and requests the design change.

Design engineering implements the requested change, which requires cutting new dies for some of the stamped parts. Production engineering then resumes work. An initial batch of parts is fabricated, and assembly line construction begins. Initial trials reveal that the hole spacing on part X3Y is too tight for the high-speed insertion machines, requiring either a design change or a significant cost penalty along with reduced production rate. This hole spacing is not critical to widget performance, so the design is again modified by design engineering.

Finally the unit goes into volume production. During the initial production runs, the workstation for part G42Z jams 15% of the time, causing spoilage that interrupts production and eradicates profits. Apparently there is a slight difference between the injection-molded production version of part G42Z and the machined prototypes used in the initial workstation trials. Production engineers study the situation, and are eventually able to adjust and modify the workstation tooling to prevent the problem.

At last Acme is producing Super Turbo Widgets without a hitch. Unfortunately, Vile Enterprises introduced its new Extra Turbo Whatsit two months earlier, and has already sold 20,000 units. It is unclear whether Acme will ever be able to gain a significant market share in the wake of Vile's head start.

3 Analysis of the Scenario

The scenario demonstrates a basic cycle consisting of design → fabricate → test → repeat. In our example we had an "inner loop" between engineering and prototyping that we traversed several times. There is another inner loop in the production engineering area. Finally, there is an outer loop containing these two inner loops. There are three basic methods that we can apply to shorten the time to get to market — fewer times around each loop, concurrent execution of the loops, and faster execution of the steps inside each loop. The first and last methods also lead to reduced non-recurring engineering costs.

Acme could have exploited all three of these methods by using information effectively. For example, production engineering's initial trials showed that modifying the X3Y hole spacing could reduce manufacturing costs; if this information about the limitations of the manufacturing equipment was discovered at design time, an entire cycle between design and production engineering could have been avoided. Further, if design engineering had released interim design information, then production engineering could have begun assembly line development concurrently. Finally, better analysis tools could have helped both design and production engineering identify and resolve problems more rapidly, thus shortening the time required for each step.

Inadequate use of information was central to Acme's problems. The most significant problems were related to information *content* rather than information *flow*. For example, the failure of the G42Z workstation resulted from subtleties in the interaction between the workstation and the parts it manipulated. This workstation design was sensitive to differences between machined and injection-molded parts, but this information was not known until production began, at which point the workstation began to fail. This is an example where critical information was simply not available until late in the design/production cycle.

Despite the close similarity of the manufacturing processes for the ordinary and Super Turbo Widgets, the scenario shows how inadequate information utilization during design and manufacturing development can substantially affect the eventual profitability of the product.

4 A Research Agenda for Agile Manufacturing

The Acme widget scenario showed two opportunities for using information to increase manufacturing agility: by allowing work to proceed concurrently, and by providing early detection of problems. There is also a third approach: by using information on-line to provide process capabilities not available otherwise. These new process capabilities may eliminate problems and reduce the need for complex design analysis.

In the following sections we outline an agenda of research required to support the information-based agile enterprise. The outline provides the broad brushstrokes of what will be a long-term effort by many participants. Within Sandia's Intelligent Systems and Robotics Center we have created the Information-Driven Manufacturing Project to develop technology to support each of these approaches, ultimately in concert. The following sections will review these approaches, the research problems they entail, and some of Sandia's efforts toward their solution.

4.1 Allowing Concurrent Work

One method of reducing the time required to take a product to market is to perform product design and manufacturing development concurrently. This requires good communication between design and manufacturing groups, and frequent exchange of design information between groups. Information exchange adds overhead to the efforts of both groups; if this overhead becomes too large, then the benefits of concurrent engineering are lost.

Successfully implementing concurrent engineering in a manufacturing organization involves significant human factors and management issues. However, there are technical challenges as well. These include the development of efficient communication techniques that minimize the overhead associated with concurrent engineering. Supporting this communication electronically could produce substantial benefits, but some difficult problems must be confronted. For example, distributed design representations must be developed that will allow a design to be modified by many designers spread throughout a manufacturing organization, while preventing one designer from inadvertently corrupting another designer's work. Further, the design representation must allow each designer to view relevant aspects of the design; for example, one designer may wish to check for part interference during the expected motions of a mechanism, while a second designer may focus on the mechanism's hydraulic control system. At the same time these activities are proceeding, a production engineer may be seeking ways to reduce the complexity of assembling the mechanism. Each of these analysis problems requires numerous analysis-specific details describing the design. If these views are not seamlessly integrated, then concurrent engineering is compromised because the implications of design changes are more difficult to transmit between groups.

We can break the problem of developing concurrent engineering tools into two basic components: representation and communication. The representation component requires that the design database support each designer's view of the design problem. In the example of the previous paragraph, the representation must support analysis of kinematic linkages, geometric sweeping operations for interference checking, a model of hydraulic performance, and the geometric and physical information needed for assembly analysis. The communication component requires software that allows multiple designers to effectively access the data simultaneously. This software must facilitate efficient communication of design details and intent, and prevent conflicts between design modifications.

Past work has addressed many of these issues. Representations have been developed for geometric analysis, including kinematic pairs and sweeping operations [Leu *et al.* 1986; Hoffmann 1989; Joskowicz 1989; Rossignac and Requicha 1986]. Special-purpose representations have also been developed for modeling hydraulic systems and other design aspects. However, representations that support manufacturing process analysis require further development; these must be completed before an integrated multiple-view design representation may be developed. There has also been work addressing the communication component of the problem [Kannapan and Marshek 1991]. Past work in computer networks, transaction-based databases, and multiple-user concurrency and version control all shed light on the issues that must be addressed to successfully implement a concurrent engineering system.

Given the state of the art, a sound approach to developing effective concurrent engineering systems is to develop the necessary specific representations to support analysis of manufacturing processes, integrate these and other representations to produce an integrated multiple-view design representation, and develop a system that will allow several users to work simultaneously with a design using the integrated representation. The near-term research goals of the Sandia ISRC will address the first of these problems by developing the representations required to support early problem detection and on-line control of manufacturing processes. Integrating these representations will be addressed in the longer term.

4.2 Early Problem Detection

One of the key lessons of the Acme scenario is that it becomes increasingly expensive to resolve problems as the development process proceeds. Further, the later a problem is discovered, the greater the delay that results from solving the problem. Thus, early detection of problems in the product or its manufacturing facility could reduce non-recurring engineering costs while simultaneously bringing the product more quickly to the market. In other cases these techniques may show that manufacturing costs will erode profits, allowing a manufacturer to cancel a project before the sunk costs become too great.

Problems may occur in a variety of places. The product may fail to perform its desired function reliably. Basic part fabrication processes may produce high scrap rates. Assembly machines may jam or improperly assemble parts. To maximize the agility of the manufacturing enterprise, we would like to detect problems as early as possible in each of these areas. In this section, we will focus on problems that occur in the assembly stage. This is due to the inherent difficulty of predicting these problems, their prevalence in manufacturing applications, and their relative insensitivity to the fabrication technology used to produce the component parts. The goal of the research agenda outlined here is to develop analysis techniques that can combine the information inherent in the design model with information regarding manufacturing capabilities to predict manufacturing problems.

Assembly problems may occur on a macroscopic or microscopic level. On the macroscopic level, the intrinsic product design may force additional manipulation and assembly operations that increase manufacturing costs (such as the extra inverting stations needed in our Acme Widget scenario). Analyzing assembly strategies early in the design process may suggest relatively simple design changes that may dramatically reduce the number of required assembly operations and yield substantial manufacturing cost savings. This benefit could be maximized by performing an assembly analysis frequently during the design process, but this is impeded by the inherent difficulty of a detailed assembly analysis. The number of possible assembly sequences grows exponentially with the number of parts, and complex feasibility constraints must be evaluated to discriminate between feasible and infeasible assembly plans. Further, these constraints depend on details of the assembly line and its tooling, which may be modified to improve assembly efficiency. These complications discourage frequent assembly analysis; tools to aid this analysis would allow manufacturing organizations to simplify product assembly operations before design changes become prohibitively expensive.

The problem of automatic assembly sequence analysis has been studied for several years. The 1992 IEEE Conference on Robotics and Automation sponsored a workshop on this topic; the notes to this workshop provide a snapshot of the state of the art [Lee *et al.* 1992]. More accessible references include [Fahlman 1974; Lieberman and Wesley 1977; Boothroyd and Dewhurst 1986; Wolter 1988; Strip and Maciejewski 1990; Defazio *et al.* 1990; Homem de Mello and Lee 1991]. These efforts have produced several prototype assembly planning and analysis systems, and have also identified a variety of open problems that must be solved to support general assembly analysis. These include developing planners that accept geometric CAD models as input, implementing search procedures that effectively cope with the combinatorial explosion of design alternatives, developing methods for combining geometric and physical process constraints in the assembly analysis, and implementing reconfigurable procedures for generating output process specifications and machine-executable code. The Sandia ISRC will continue to address these problems in future work.

Assembly problems may also occur at a finer level of detail. In addition to laying out the simplest possible sequence of assembly operations, manufacturing engineers must implement assembly lines that reliably carry out each operation. This is at once critical and difficult. Due to the serial nature of assembly lines, the reliability of the entire line hinges on the reliability of each individual operation. Assuring this reliability is very difficult to do in advance, since part-handling operations often involve subtle mechanical processes that are hard to understand and predict. The Acme example contains an instance of this — the inability to reliably feed part G42Z because of variations induced in the fabrication stage. Currently a manufacturing engineer is forced to employ trial-and-error methods after parts and tooling have been fabricated, which delays assembly line implementation and leads to late (expensive) design changes. Tools that help identify reliability problems early on would help manufacturing organizations avoid these delays and their associated cost.

Research on issues at this microscopic scale are generally referred to as *fine motion planning* [Lozano-Pérez *et al.* 1984]. This research strives to simultaneously consider task geometry, physics, and uncertainty to automatically analyze and construct robust assembly tasks. Much of the early work in this area studied issues related to specific assembly tasks, such as peg-in-hole assembly [Whitney 1982; Erdmann 1986; Donald 1988; Strip 1989; Caine *et al.* 1989]. Other work has addressed tasks more closely related to part feeding and presentation [Erdmann and Mason 1986; Peshkin and Sanderson 1988; Goldberg *et al.* 1991; Boothroyd 1992; Brost 1992; Schimmels and Peshkin 1992]. These results have improved our ability to automatically analyze assembly tasks, but much work remains. Open problems include the development of robust analysis procedures that may be applied to a variety of tasks, definition of practical models of task uncertainty, and calibration of the physical accuracy of the analysis output. Future ISRC research will address these problems.

The above discussion separates the macroscopic and microscopic aspects of an assembly problem. The macroscopic analysis addresses the assembly sequence and overall assembly plan, while the microscopic analysis addresses the details of each individual assembly operation. In reality, these issues are coupled — the choice of assembly sequence can simplify or complicate the required assembly operations, and details of each assembly operation can affect the feasibility of a given assembly sequence. An ultimate goal of our research in information-driven manufacturing is to produce an integrated assembly analysis tool that supports early problem detection by simultaneously considering both macroscopic and microscopic aspects of an assembly problem.

4.3 On-Line Process Control

The previous sections have described two methods for using information to reduce the time to implement a desired manufacturing line — by supporting concurrent work and early problem detection. Both methods have the benefit that, given a fixed set of problems to solve in order to implement a desired assembly line, they accelerate the process of solving these problems.

A third approach is to reduce the number of problems that must be solved by increasing the capabilities of the assembly process itself. One method is to use information to make on-line process adjustments at production time. For example, consider the problem of mating two parts. A standard approach is to place one part precisely in a fixture, and then attach the second part using a placement device that expects the first part to be repeatably placed. Implementing this strategy requires the development of a fixture and fixture-placement operation that places the first part in a highly-repeatable position; the details of this operation must be carefully evaluated by a manufacturing engineer. An alternative would be to place the first part in a simple clamping device, measure the part's true position, and modify the second part's insertion motion in response to the measured position. If the sensing/motion modification device is easy to reprogram for the new task, then this approach reduces the effort required to develop the assembly line because the need for a detailed repeatable fixture analysis is eliminated. Additional cost savings arise because a part-specific custom fixture does not need to be constructed, and part tolerances relevant only to the fixturing operation may be relaxed.

On-line control of manufacturing processes can also produce cost savings by allowing changes to the technology used to manufacture parts. For example, sometimes a weld between two parts must be ground flush with the surrounding surface to eliminate stress risers on an assembly that is subject to high strain. The exact surface position is not critical, but the surface smoothness is critical. Precise grinding machines may be used to smooth out the weld to the required tolerance, but these machines also require a precise surface position and shape, thereby imposing additional tolerance specifications that result purely from manufacturing considerations. If on-line sensing is used to sense the surface position and adjust the grinding operation accordingly, then these additional tolerance specifications are no longer required. This may allow the parts to be cast instead of machined, yielding substantial cost savings.

These examples illustrate ways to employ the use of information during process execution, thereby simplifying the up-front information analysis required. Adequately using information on-line requires good sensors, means for interpreting sensor data, methods for controlling actuation devices based on the interpreted sensor results, and a simple method for re-programming the sensing/control device to execute a new task.

The use of on-line sensing to compensate for process variations has been applied to a variety of manufacturing processes. For example, active force control has been applied to compensate for part and fixturing inaccuracies during assembly operations [Whitney 1977]. Force control has also been used in conjunction with high-resolution capacitive sensors to allow tight-tolerance finishing operations on metal parts in significantly less time than competing technologies [Selleck and Loucks 1990]. Machine vision has been used to locate parts that are difficult to feed mechanically [Regalbuto 1991]. The challenge in each of these cases is to make the on-line sensing/control system flexible and easy to re-program. Future research at the ISRC will continue to develop sensors, control systems, and user interfaces to support flexible on-line process control.

5 Conclusion

We have seen that effective information utilization is a critical issue in agile manufacturing. Although there are numerous issues in process and tool development that will significantly impact agility in production, the most important changes will come from shifting our attention from the hardware in a plant to the information used to design and manufacture a new product. It is only through good information utilization that we can achieve better productivity in the non-recurring engineering costs, which are becoming increasingly important as product life cycles shorten. In addition, effective information utilization will shorten product development time, which is essential as the number and variety of competitors grows. On the factory floor, information-based control will change the way in which machines and processes work. As more of the process versatility becomes embedded in real-time controllers, we will be able to add previously unimagined capabilities to smart machines at low marginal cost.

Information-driven manufacturing methods use information to efficiently implement a successful manufacturing facility. In this paper we have identified an agenda of research topics whose resolution is necessary to make these methods a reality. The outlined research program will require a dedicated effort by many researchers from a variety of organizations. Like many others throughout the world, we in the ISRC are working on pieces of the puzzle. We recognize the critical importance of collaborating with others ranging from leading edge research organizations to down-in-the-trenches production engineers. We invite these collaborations as we continue to develop tools to support information-driven production.

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