FEATURE

Vision, Principles and Impact of Reconfigurable Manufacturing Systems

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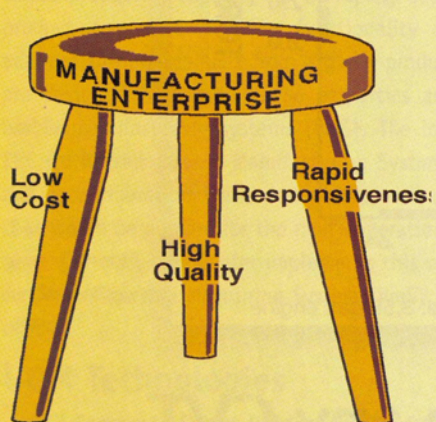

Figure 1: Basic Foundations of Manufacturing

Introduction

Cost, Quality, and Responsiveness are the three foundations on which every manufacturing company stands [Figure 1]. Low Cost has been an economic goal since the introduction of mass production in the 1920s. High Quality is an economic goal associated with the lean manufacturing paradigm [6], and more recently has been the focus of Six Sigma [5]. Cost-effective Responsiveness is achieved by reconfigurable manufacturing [3].

For manufacturing companies to be competitive in the global economy, these three goals are equally important. Like a 3–legged stool that needs equally strong legs to be stable, a manufacturing enterprise should strive towards low cost, high quality and rapid responsiveness.

One basic difference among these paradigms is that Lean Manufacturing and Six Sigma deal with improving the system operations. By contrast, Mass Production and Reconfigurable Manufacturing focus on new ways of designing production systems as well as operating them.

Reconfigurable Manufacturing

At the heart of a Reconfigurable Manufacturing System (RMS) is a set of core characteristics, as defined below:

Modularity – the compartmentalization of operational functions and requirements into quantifiable units that can be transacted between alternate production schemes to achieve the most optimal arrangement to fit a given set of needs.

Scalability—the ability to easily change existing production capacity by rearranging an existing production system and/or changing the production capacity of reconfigurable components (e.g., machines) within that system.

Integrability – the ability to integrate modules rapidly and precisely by a set of mechanical, informational, and control interfaces that enable integration and communication.

Convertibility—the ability to easily transform the functionality of existing systems, machines, and controls to suit new production requirements.

Customization – the ability to adapt the customized (non-general) flexibility of production systems and machines to meet new requirements with a family of similar products.

Diagnosibility—the ability to automatically read the current state of a system and controls so as to detect and diagnose the root-cause of defects, and subsequently correct operational defects quickly.

When these characteristics are embedded in the system design, a high

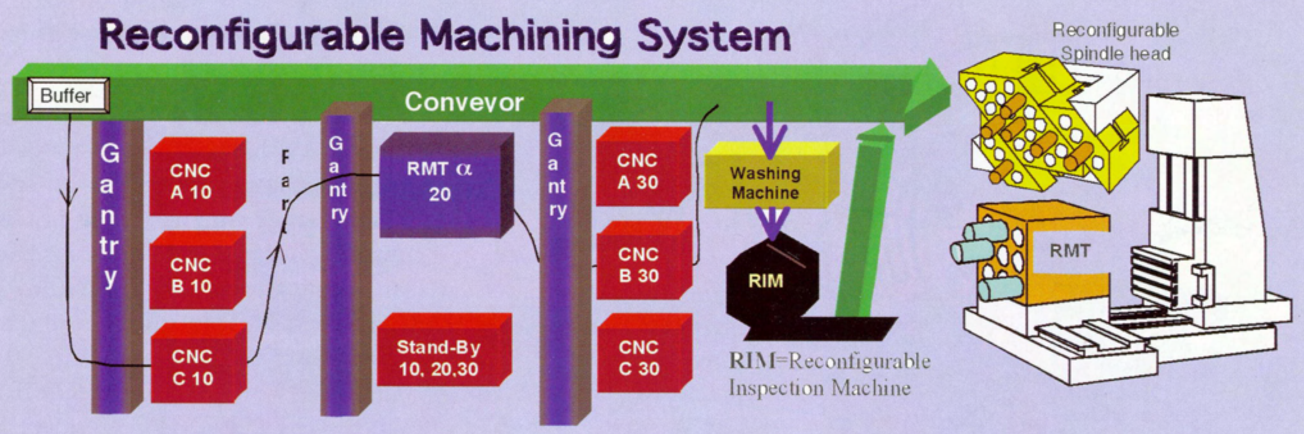

Figure 2: Reconfigurable Machining System

degree of reconfigurability is achieved. Furthermore, they enable the RMS to serve as a cost-effective compromise between the low productivity but high flexibility of flexible systems, and the ultra-high productivity but low flexibility of dedicated lines.

The Cost-Effectiveness of RMS

is achieved through:

- Adjustable resources that enable system scalability in response to changing market demands and system convertibility to new products of the same part family. Resources may be adjusted at the system level (e.g., adding machines) and at the machine level (changing machine hardware and control software).
- Customized flexibility for a part family that can allow for (1) optimal mix between CNC and dedicated machines in a system, and (2) multi-tool operation on a CNC-type machine, thereby multiplying the productivity of the machine.

The definition of a reconfigurable manufacturing system is, therefore, as follows [3]:

A Reconfigurable Manufacturing System (RMS) is one designed at the outset for rapid change in its structure, as well as its hardware and software components, in order to quickly adjust its production capacity and functionality within a part family in response to sudden market changes or intrinsic system changes.

Vision and Scope

The vision of transforming the manufacturing industry in the 21st Century by introducing next generation technology —a living, evolving factory— the reconfigurable manufacturing system (RMS), was the basis of our proposal to NSF to form the Engineering Research Center for Reconfigurable Manufacturing Systems (ERC/RMS) that will build the scientific base for responsive, reconfigurable systems (see http://erc.engin.umich.edu). The Center, we proposed, would develop RMS design, economic evaluation, and reconfiguration methodologies that could be applied to several manufacturing domains (i.e., RMS), but would implement them just on machining systems (i.e., RmS) in our testbed. This vision has been thoroughly reviewed during the last summer, and still found to be very compelling now.

Responsive systems are systems whose production capacity is adjustable to fluctuations in product demand and whose functionality is adaptable to product variety. The vision of the reconfigurable manufacturing paradigm may be summarized by

Exactly the Functionality and Capacity Needed . . .

. . . Exactly When Needed

The ERC/RMS introduced the concept of reconfigurability and is developing a generic reconfiguration science base to realize this vision. The Center's testbed and case studies are primarily focused on reconfigurable machining systems (RMS), which are a special case of RMS that is the Center's overall vision. During the last two years we have broadened the Center research to also include projects related to assembly and semiconductor fabrications.

Example of a Reconfigurable Machining System

We would like to give an example of a reconfigurable machining system. Imagine a part α that can be completed in three operations: Op. 10 = milling straight surfaces with a 3-axis horizontal milling machine (CNC 10); Op. 20 = drilling of many holes

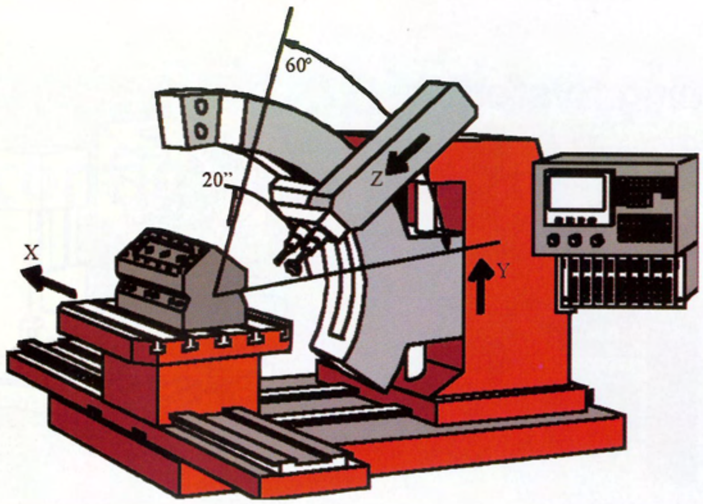

Figure 3: Arch-Type Machining

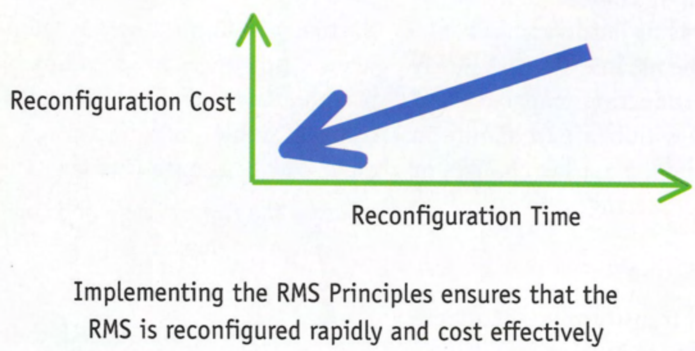

Figure 4: Reconfigurable Time and Cost Relation

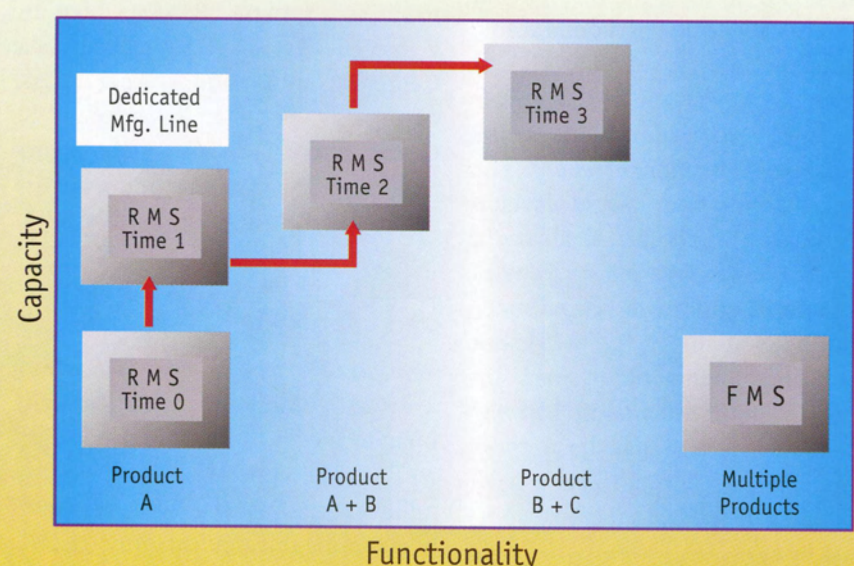

Figure 5: Capacity/Functionality Benefits of RMS over DML and RMS

perpendicular to the machined surfaces; Op. 30 = Milling of features, which can be done only after drilling the holes (CNC 30).

One possible system configuration is shown in Figure 2 that shows a 3-stage machining system plus an additional stage in which in-process inspection is performed. CNC A-10 is an identical machine to CNC B-10 and CNC C-10, and all three of these machines can perform Op. 10. Similarly, CNC A-30 is identical to CNC B-30 and CNC C-30. Identical machines (that are loaded and unloaded with a gantry) are added in parallel to adjust the system capacity to the required designed volume of annual parts.

The drilling of the holes (e.g., 15 holes, some with different diameters) could be done in CNCs 10, but it would be time consuming (positioning and drilling of 15 holes plus tool changing) which, in turn would require adding more machines in parallel in Op. 10 to supply the needed demand, and consequently the cost would be increased. Therefore, the drilling operation is separated, and is being performed by a Reconfigurable Machine Tool (RMT) that can drill 15 holes simultaneously. This is a very rapid operation, and therefore only one RMT machine is required in Op. 20, while in the other stages three CNC machines are needed.

If another part β has to be also produced on the same system in a batch-type operation, then the system is stopped for a short period (e.g., 20 minutes) to perform spindle-head change, such that the new hole-pattern fits the part geometry. If a random part production is needed, then an additional RMT-β has to be added in the second stage, and part routing would be done according to the part type. (The random part production requirement is more expensive.)

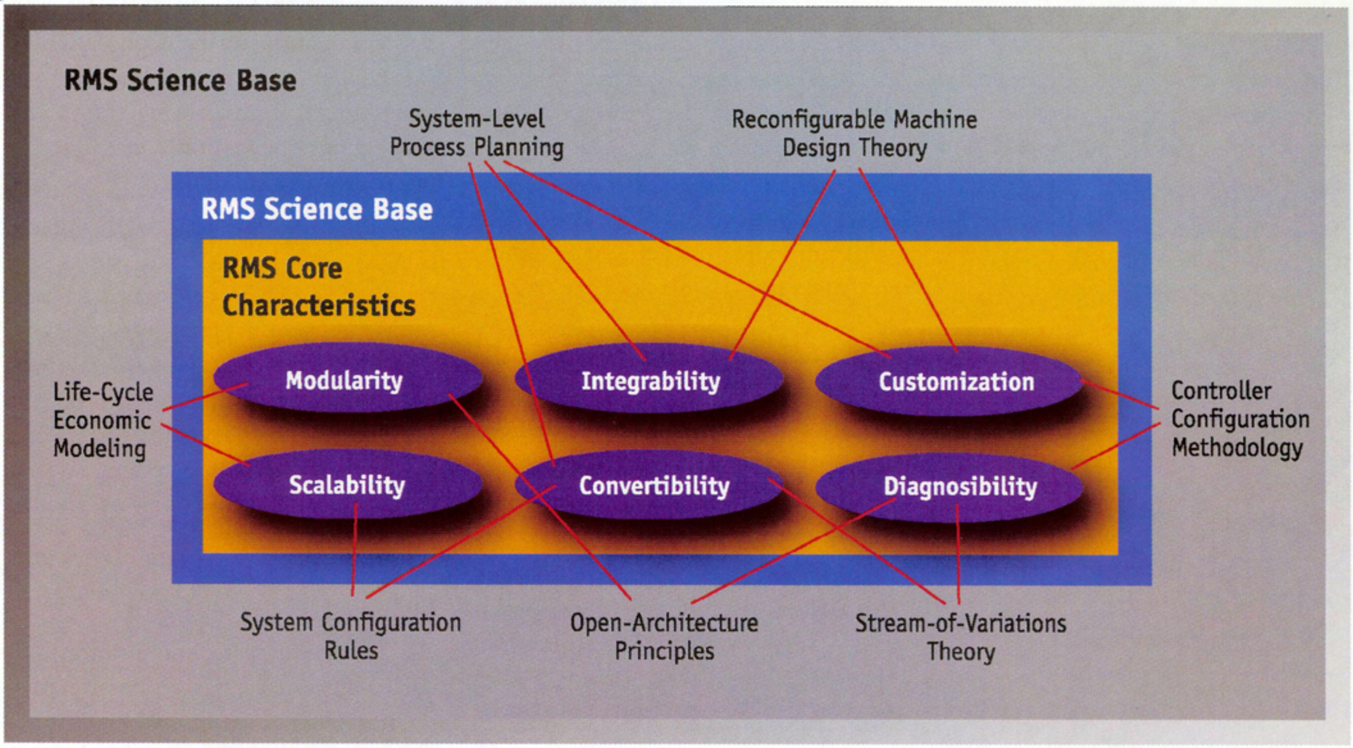

Figure 6: RMS Science Base

The part may move in this system through several routes (9 in this example). This has an advantage in cases of machine failure – an alternate route keeps the system running, while in a serial line configuration (with no buffers), for example, each machine failure stops the line. Nevertheless, if the RMT fails, the system stops. One option to keep the system running in such cases is to add a Stand-By general-purpose CNC in the second stage, which provides a safety capacity for this system. This CNC can be utilized as a stand-by machine not only to Op. 20, but also to Op. 10 and Op. 30, with the appropriate change in the part routing. (The utilization of the stand-by machine would require using different process plans.) One may conclude that more alternate routes for a part to be produced on a system enhances its capability to cope with unexpected events, or in our term, enhances the system reconfigurability.

In this example we introduced one class of RMTs – a class by which the system capacity is adjusted in a cost-effective manner. Another class of RMTs is one in which the functionality of the machine may be rapidly adjusted. An example of this class is our Arch-type machine, that although having only 3 controlled axes, can drill and mill surfaces at inclined angles The angle can be changed during a short reconfiguration period (3 minutes). The operation of this machine can be demonstrated in our testbed.

RMS Principles

Reconfigurability can be achieved in any production system, if time and cost are not considered. But in order to perform cost-effective and rapid reconfiguration, the design and operation of reconfigurable manufacturing systems must be based on several RMS principles:

1. To enhance the responsiveness of a manufacturing system, the RMS core characteristics should be embedded in the entire system as well as in its components (mechanical, communications and controls).
2. The RMS contains adjustable production resources to respond to imminent needs.
    - The RMS capacity is rapidly scalable in small, optimal increments.
    - The RMS functionality is rapidly adaptable to the production of new parts.
3. The RMS is designed around a part family, with just the customized flexibility needed for producing all parts of this part family.
4. The RMS contains an economic mix of flexible and dedicated equipment, as well as Reconfigurable Machine Tools whose functionality and productivity can be readily changed when needed.
5. Continual monitoring and diagnostics is embedded in the RMS modules to enhance its response to a fault or quality/productivity degradation.

6. In general, shorter manufacturing systems (i.e., smaller number of stages) are more reconfigurable, but they require higher investment cost in machine functionality.

7. In general, systems with a large number of alternative routes to produce a part are more reconfigurable, but they require higher investment cost in the material-handling system.

8. The RMS possesses cost-effective safety capacity and stand-by functionality that is utilized to cope with unpredictable events.

9. Decision-making capability is embedded in the RMS to reduce its response time to unpredictable events.

10. The organization of the manpower that operates the RMS is structured according to the RMS core characteristics and includes people and teams (modules) that are dedicated to particular tasks as well as people and teams that are flexible in their assignments.

A manufacturing company that possesses responsive production systems designed according to these principles can respond quickly to short windows of opportunity for new products, and can cope with unpredictable, high-frequency market changes as well as with unpredictable equipment failure in the system.

Reconfiguration Science Base

The ERC/RMS is the world intellectual leader in the development of fundamental knowledge concerning reconfigurable systems, and cooperates with other world-wide centers to promote its use in application domains other than machining (e.g., assembly and semiconductor fabrication) (Figure 7).

The Center is taking the lead in developing a new reconfiguration science base, defined as a set of methodologies that enable the implementation of the RMS principles which, in turn, facilitate rapid and economic reconfiguration, The science base will have a potential widespread impact even beyond manufacturing Consequently, the benefits will not be confined to machining systems, but will be spread throughout the nation's manufacturing sector and beyond.

Both the dedicated manufacturing line (DML) and the FMS are static systems. The DML is designed to produce one product at large capacity. The FMS can produce several products but, because of its high cost, it is designed for low capacity. The RMS is a dynamic, evolving system, so that its capacity and functionality change in time, as needed (Figure 5).

Goals

We believe that reconfiguration science will form the basis for a vital production technology in this era of global market competitiveness — that it will evolve into an entirely new manufacturing field with enduring benefits for the US economy and society. The RMS Center is the world leader in developing the knowledge and science-

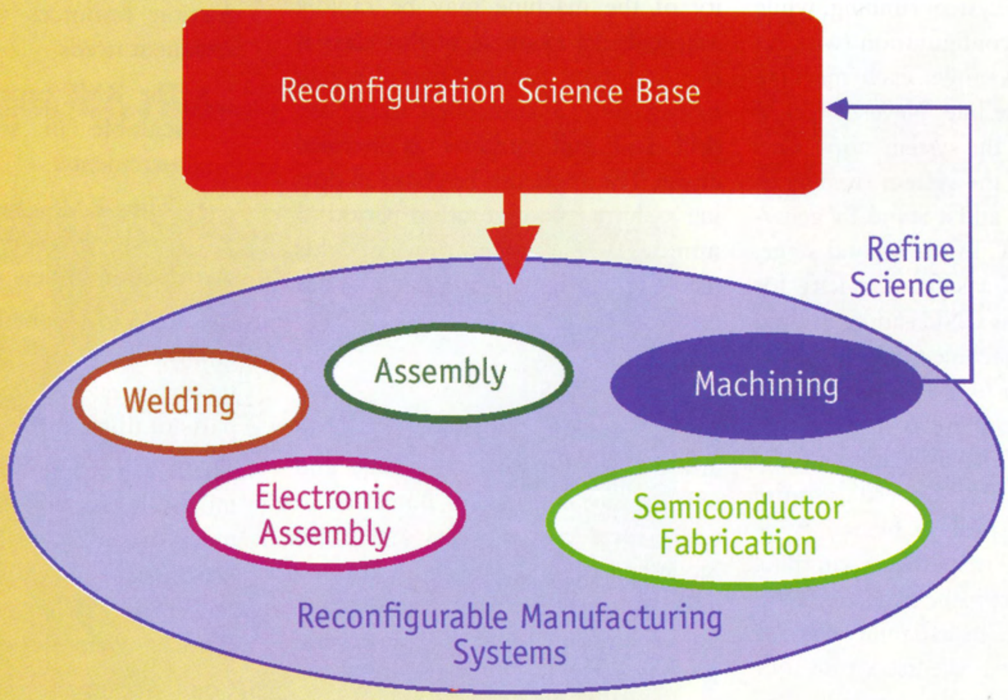

Figure 7: Principles of Reconfigurability

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base for this field, including:

- Development of computer-aided design (CAD) techniques and mathematical tools for the systematic design of manufacturing systems and their economic evaluation,
- Creation of a new generation of reconfigurable machines and reconfigurable controllers, as well as methodologies and software tools for their design.
- Reduction in ramp-up time after installation or reconfiguration of manufacturing systems by developing system root-cause analysis tools and on-line part measurement methodology.

These three components are being integrated into a testbed facility for testing and obtaining feedback for refining the science base. In addition, the Center is developing educational materials and courses, so that the knowledge base for reconfigurable systems engineering can be disseminated to industry and to other universities. Let us elaborate on these points.

CAD for Manufacturing Systems

The most effective way to accelerate the time-to-market for new products is by reconfiguring existing manufacturing systems, which must be done rapidly, efficiently, and in a systematic way. The only way to take economic advantage of the dramatic reduction of product development time achieved by computer-aided design (CAD) is to develop CAD for the design of the manufacturing systems that produce the products as well as for their efficient reconfiguration. This task, although more difficult than the development of CAD for products, will have an unprecedented impact on all manufacturing industries, and, in turn, on the economy. Developing CAD for manufacturing systems will be perhaps the most substantial contribution of the ERC/RMS to science and the national economy.

Economic Evaluation

If we take into account the entire life-cycle cost of a production system, reconfigurable systems may be less expensive than dedicated lines or flexible manufacturing systems. The main factor that makes the RMS less expensive is that, unlike the other types of systems, the RMS is installed with exactly the production capacity and functionality needed, and may be upgraded (in terms of both capacity and functionality) in the future, exactly when needed. However, mathematical tools are needed to compute the optimal reconfiguration intervals and to assess the optimal mix of reconfigurable capacity in the manufacturing process.

Reconfigurable Machines

The main components of RmS are CNC machines and Reconfigurable Machine Tools (RMTs) – a new type of modular machine that has a changeable structure that enables the adjustment of its resources (e.g., adding a second spindle unit) according to the need. The reconfigurable machine tool (RMT) is a hybrid between a dedicated machine that is designed to machine just one part type with high efficiency, and a CNC machine that has "general flexibility" and can produce a variety of types of parts. The RMT is designed around a part family, and therefore it can utilize programmable, multiple-tool spindles that drill simultaneously, and/or a special geometry to machine a particular part, with adjustment period between different parts of the same part family, thereby providing "customized flexibility." Adjusting the machine to new part geometry within the part family requires a short conversion time (e.g., 20 minutes).

Reconfigurable Controllers

We predicted in our original proposal that industrial control will evolve in a manner similar to that of desktop computer hardware and software. There will be companies producing hardware platforms, companies developing industrial control software, and companies developing generic software tools that can enable users to: (1) integrate their proprietary control modules into configurable user-tailored controllers and (2) write and debug their control code for large systems (i. e., replacement of ladder diagrams). Out of this will grow a new software industry of system integrators. With the aid of these software tools, the control design of new and reconfigured plants will be done systematically, which, in turn, will create major savings generated by shorter design time and shorter ramp-up time for control systems.

Ramp-Up Time

Rapid ramp-up is very important for any manufacturing system since, during this period, following installation, full-volume production at required quality levels is not achieved. However, ramp-up becomes critical in RMSs, which, by their nature, must go through many processes of reconfiguration and subsequent calibration and ramp-up periods during their lifetime. If rapid ramp-up is not achieved, the RMS cannot meet expectations and it is not advantageous. The ramp-up period can be dramatically shortened by using two complementary methods: (1) diagnostics based on process knowledge and statistics embedded in components and propagating to the system level, and (2) new real-time part dimension measurement technology combined with systematic calibration of machines. Integration of these two methods enables a systematic identification of the sources of part quality problems through "intelligent" root-cause analysis.

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Accomplishments

RMS technology requires a systems approach to creating new knowledge for the design and operation of reconfigurable manufacturing systems. Several elements of this new body of knowledge, which we call "the reconfiguration science base," have already been developed.

- Given a part family, volume, and mix, a System-Level Process Planner suggests alternative system configurations and compares their productivity, part quality, convertibility, and scalability options.
- A Life-Cycle Economic Modeling methodology, based on blending dynamic programming with option theory, recommends the system that will be optimally profitable during its lifetime.
- A Reconfigurable Machine Tool (RMT) design methodology allows machines to be systematically designed, starting from the features to be machined on a family of parts. A new arch-type RMT, which has been designed and built, forms the basis for a new direction in machine research.
- A logic control design methodology for sequencing and coordination control of large manufacturing systems results in reconfigurable and formally verifiable controllers that can be implemented on industrial PLCs.
- A Stream-of-Variations (SoV) methodology based on blending state-space control theory with in-process statistics forms a new theoretical approach for systematic ramp-up time reduction.
- A measurement Scheme Selection methodology for modular machines and large systems ensures that the quality of the finished parts is economically optimal. (The development of a new In-process Reconfigurable Inspection Machine is underway.)

Broad Impact of RMS: Changing the Relationships between Builders and Users

With RMS deployment, the original supplier (i.e., builder or integrator) of the system will implement also the reconfiguration process and integrate new technology into existing systems. This, in turn, will change the nature of the relationships between equipment suppliers and users of RMS technology. It will prompt the development of enduring strategic relationships (rather than one-time sales) in which the suppliers frequently reconfigure systems for users and continuously integrate profitable upgrades, allowing users to rapidly capture rising market demand, comply with government regulations and supply better products to customers.

Furthermore, proximity between the plant where an RMS is installed and the location of the machine builder will become extremely important. To enable quick reconfiguration, North American users will have to buy all their machining systems from US builders. The users will have a business interest in maintaining a strong domestic machine tool industry. Therefore, the new reconfigurable technology may enable the US to once again become a world leader in the machine tool industry.

Commercial Reconfigurable Machines

Several of the ERC/RMS industry members have started to build and advertise their products as Reconfigurable Machines (e.g., Masco Machines in Cleveland, and CELCON – Cellular Concepts in Detroit). Livernois Engineering is seeking our expertise to jointly develop a conceptual design of reconfigurable assembly machine for car heat exchangers, which their US (e.g., Delphi) and European customers are very excited to see realized. The February 2002 issue of Mechanical Engineering magazine [1] featured an article describing reconfigurable manufacturing of connecting rods by a small supplier firm, Tri-Way. Our new Arch-Type Reconfigurable Machine will be displayed in the IMTS in Chicago in September, and boost interest in RMTs even more.

US Patents. The Center is protecting several of its inventions by patents. Five US patents have been granted and five new applications have been filed. Three of our patents, "Reconfigurable Machine Tools," "Reconfigurable Manufacturing Systems," and "Reconfigurable Logic Controller" form the cornerstones of designing RMSs. Although the full impact of these patents will only be observed about 10 years from now, we believe that our patent "Reconfigurable Machine Tools," issued in 1998, inspired the creation of a new modular machining center for engine block production by Ingersoll Milling Machines [2].

Center's Software Transfer to Industry. The ERC/RMS has started to deliver beta-version system design software packages to the end-users. In particular these are software packages aimed at enhancing system productivity, such as our line balancing algorithm and PAMS (Performance Analysis of Manufacturing Systems). Software for ramp-up time reduction, based upon our stream-of-variation theory, has been developed and validated in the testbed. We are now planning the first in-plant evaluations of this software with Ford and one of its suppliers, Citation.

Stream-of-Variations Impact

The development and implementation of the SoV in assembly (supported by NIST/ATP) has made a significant impact in industry. The SoV methodology, however, has not been implemented yet in machining plants.

Nevertheless, during the last few years approximately 20 papers have been published (or submitted) on various aspects of the SoV topic. In 2001, four of these papers received the BEST Paper award from ASME Mfg Division, ASME Design Division, INFORMS QSR Section, and NAMRC. Furthermore, four former ERC students/researchers (Judy Jin, Yu Ding, Darek Ceglarek, and Shiyu Zhou) who worked on the SoV topic have joined or will join the faculty in top industrial engineering departments in the US, which will enhance the deployment of the SoV methodology.

Education and Outreach

The essence of reconfigurable systems is design for the future, where the future is unknown and can be only projected. This principle, when applied to engineering education, may open a new approach in solving engineering design problems. We have developed a new undergraduate Manufacturing Systems Concentration at the University of Michigan, with its supporting courses, that aims at introducing this approach. The ERC helps to attract a talented and diverse group of students to the area of manufacturing. Our outreach to K-12 students specifically targets underrepresented groups, involving Detroit area junior-high-school and high-school students. We also reach out to general public through our museum exhibits.

New Graduate Courses

Our two new graduate courses have begun to achieve national attention. The course "Reconfiguration Science-Base" was taught in Winter 2002 to 60 students, over half of them at remote industry sites in the US and Mexico. The course "Agile, Reconfigurable Manufacturing" was taught simultaneously here and at Wayne State University, and other institutions expressed interest in the same course. We would like to add that in the April 2002 Edition of the Best Graduate School Rankings, published by US News and World Reports, the UM Mechanical Engineering graduate Program was ranked second, and "Industrial/ Manufacturing" Engineering was also ranked second among 145 US graduate programs that provided data to calculate rankings. This is the highest ranking that the ME graduate program has received ever! There is no doubt that the reputation and accomplishments of the ERC/RMS played a major role in this high ranking of the ME and the Manufacturing programs. We are certain that this high ranking will attract even better students to our graduate programs.

Worldwide Impact

Our presentation in China about the ERC/RMS in 1997 influenced the creation of a similar center there, and our 1999 CIRP keynote paper on "Reconfigurable Manufacturing Systems" served as a catalyst to start intensive research on reconfigurable manufacturing in Canada (London and Hamilton), Germany (Stuttgart), and Italy (Milan and Palermo). A keynote paper on RMS and a plenary paper on RMS and RMTs were presented at the 2000 Japan-USA Symposium and the 2000 Japan Machine Tool Show. The CIRP " 1st International Conference on Reconfigurable Manufacturing," hosted by our Center in 2001, attracted 160 participants from 14 countries, of which 80 were from industry (Canada, Germany, Japan, Italy, and the US). This conference has been a remarkable milestone that demonstrated the Center impact on academia and industry. However, it is difficult to evaluate the long-range impact of a new technology on the marketplace and the educational infrastructure after only five and a half years of operation. We believe that RMS – a new research field initiated by us with obvious benefits to industry and society – will continue to grow over time. This assertion is supported by a Delphi study, summarized in the U.S. National Research Council's Visionary Manufacturing Challenges for 2020 [4], which identified "adaptable and reconfigurable systems" as the number one priority technology in manufacturing for 2020. We are confident that only a few years from now the term "reconfigurable" will be used frequently both in manufacturing and other disciplines, and that system, machine, and control reconfigurability will be basic requirements for new manufacturing systems.

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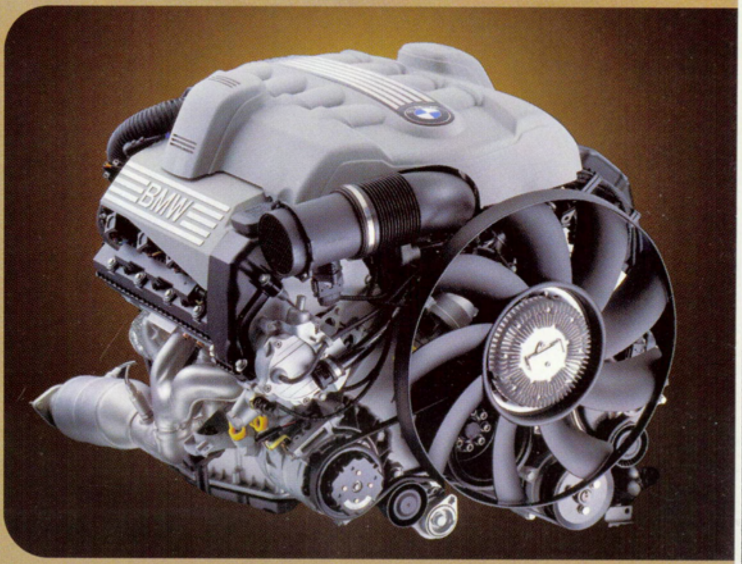

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