Reconfigurable Manufacturing Systems and Their Enabling Technologies

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Abstract

A reconfigurable manufacturing system (RMS) is designed for rapid adjustment of production capacity and functionality in response to new market conditions and new process technology. It has several distinct characteristics including: modularity, integrability, customization, convertibility, and diagnosability. There are a number of key interrelated technologies that should be developed and implemented to achieve these characteristics. This paper examines and identifies these technologies.

After a brief description of the RMSs and their goals, aspects of reconfiguration (reconfigurable system, software, controller, machine, and process) are explained; this provides one with a better understanding of the enabling technologies of RMSs. Then some of the issues related to technology requirements of RMSs at the system and machine design levels, and ramp-up time reduction are explained. The paper is concluded with descriptions of some of the future research directions for RMSs.

1. Introduction

New technological developments and market demands have major impacts on manufacturing. As a result, several shifts in focus of manufacturing processes can be observed; they can be conveniently divided into three major epochs: (1) Pre-computer numerical control, (2) computer numerical control (CNC), and (3) knowledge epochs (Mehrabi and Ulsoy 1997-a; Mehrabi, Ulsoy and Koren, 1998). In the Pre-CNC epochs (i.e., before the 70's), the emphasis was on increased production rate; there was small demand for product variations and the market was characterized by local competition. This was changed to cost reduction, and emphasize on improved product quality in the CNC epoch (i.e., the 70's and 80's); manufacturing was dramatically affected by the invention of CNC machines as they provide more accurate control and means for increasing product variety. In the knowledge epoch (i.e., starting in the 90's), the focus has shifted to responsiveness of a manufacturing system. This period is characterized by intensified global competition, high-pace of technological innovations and enormous progress in computer and information technology (Jaikumar, 1993; Mehrabi and Ulsoy, 1997-a; Mehrabi, Ulsoy and Koren, 1998). Rapid progress was made in areas such as management information systems, development of software/application programs for various purposes, advances in communication systems (hardware and software), and penetration of computer technology in various fields (Gyorki, 1989; Sheridan, 1989; Beckert, 1990; Teresko, 1990). Therefore, global competition and information technology are the driving forces behind recent changes in manufacturing. These conditions require a responsive manufacturing system that could be rapidly designed, able to convert quickly to the production of new product models, able to adjust capacity quickly, able to integrate process technology and to produce an increased variety of products in unpredictable quantities.

As reported by (G.H. Lee, 1997; Garro and Martin, 1993), underlying components and structure of a manufacturing system significantly affect its ability to be reconfigured for rapid and cost effective production of new products. In their study, it is shown that modular design of machine tools provide the manufacturing systems with necessary tools for quick integration and restructuring as required for rapid response to the fluctuating market. On close examination of the manufacturing techniques introduced so far (e.g., FMSs, lean, JIT), one observes that they do not posses a modular structure in terms of software and hardware; therefore, they are not always flexible enough and can not accommodate rapid changes.

The same views are strongly supported by the results of recent surveys carried out in Japan and US to assess accomplishments of some of the available manufacturing systems (e.g., flexible manufacturing systems) and user satisfactions with their performance (J. Lee, 1997; Ulsoy and Heytler, 1997; Mehrabi *et al*. 1998). The results indicate that some manufacturers have lost interest in FMSs, and FMS sales have been dropping (J. Lee, 1997). Software complexity, lack of reconfigurability, investment cost, maintenance cost and rapid obsoleteness are among the dominant factors in making FMSs not very attractive (J. Lee, 1997; G.H. Lee, 1997; Ulsoy and Heytler, 1997; Mehrabi *et al*. 1998). As a result, and due to demands of manufacturers, new approaches to design of manufacturing systems are proposed which are substantially different from conventional methods. For example, the so called "Holonic Manufacturing Systems (HMSs)" have been introduced (J. Lee, 1997) by the Japanese firms to address the needs of industry. The underlying design philosophy of HMSs (bottom-up design) is totally different from FMSs (top-down design). In another study (G.H.Lee, 1997), the simultaneous design of products and manufacturing systems is proposed to enhance the overall reconfigurability of production.

The concept of reconfigurable manufacturing system (RMS) was introduced to address new challenges in modern manufacturing systems. Such a system can be rapidly created using basic process modules —hardware and software— that can be re-integrated quickly and reliably. Reconfiguration allows adding, removing, or modifying specific process capabilities, controls, software, or machine structure (see Figure 1) to adjust production capacity in response to changing market demands or technology. For a manufacturing system to be readily reconfigurable, the system must possess certain key characteristics. These include: modularity (design all system components, both software and hardware, to be modular), integrability (design systems and components for both ready integration and future introduction of new technology), convertibility (allow quick changeover between existing products and quick system adaptability for future products), diagnosability (identify quickly the sources of quality and reliability problems that occur in large systems), and customization (design the system capability and flexibility (hardware and controls) to match the application (product family)). As shown in Figure 2, there are many aspects of reconfiguration. These include various configurations of the production system (e.g., serial, parallel, hybrid), reconfiguration of the factory communication software, configuration of new machine controllers, building blocks and configuration of modular machines, modular process and modular tooling.

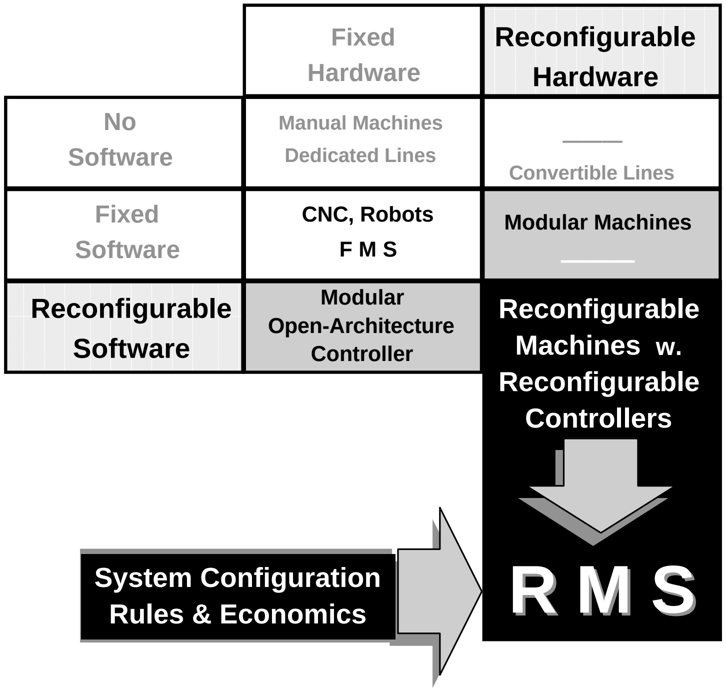


Figure1. Comparison of the key hardware and software features of manufacturing systems

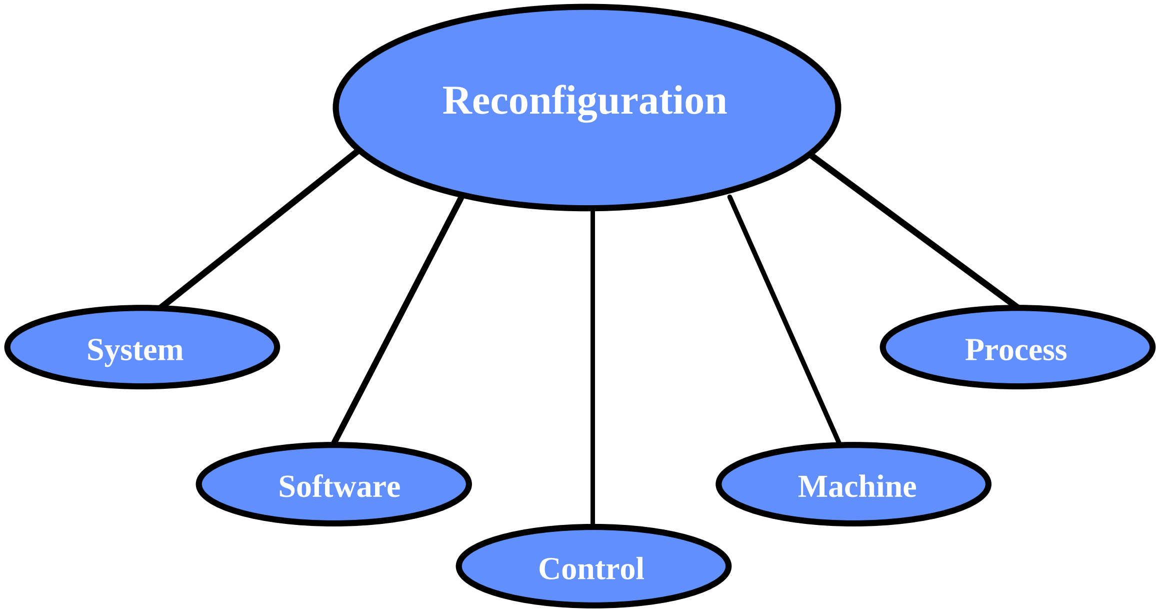


Figure.2 Aspects of reconfiguration (reconfigurable system, software, controller, machine, and process) for RMSs

To achieve the goals of reconfigurable manufacturing systems, there are several key enabling technologies that should be developed and implemented to realize the benefits of RMSs. The following sections are devoted to review of these technologies and the ways they contribute to success of RMSs.

2. Technologies for Reconfigurable Machining Systems

At the system level, there can be several system configurations for production of the same part family. Development of the necessary tools and methodologies to design the system, and evaluation of various configurations (based on life-cycle economics, quality, system reliability, and preferences of decision maker(s)) is needed. As far as system software/hardware architecture is concerned, it should have certain features to support the five key characteristics of RMS. It should have a modular structure and be "open" such that upgrading and customization of the system is practical while integration of new software is possible. Control of RMSs is another important subject to be studied. By noting that the system configuration changes (based on market demand), the parameters of the production machines such as damping, mass, and inertia will change accordingly. Therefore, the controller should have the ability to reconfigure and adapt itself to these new conditions.

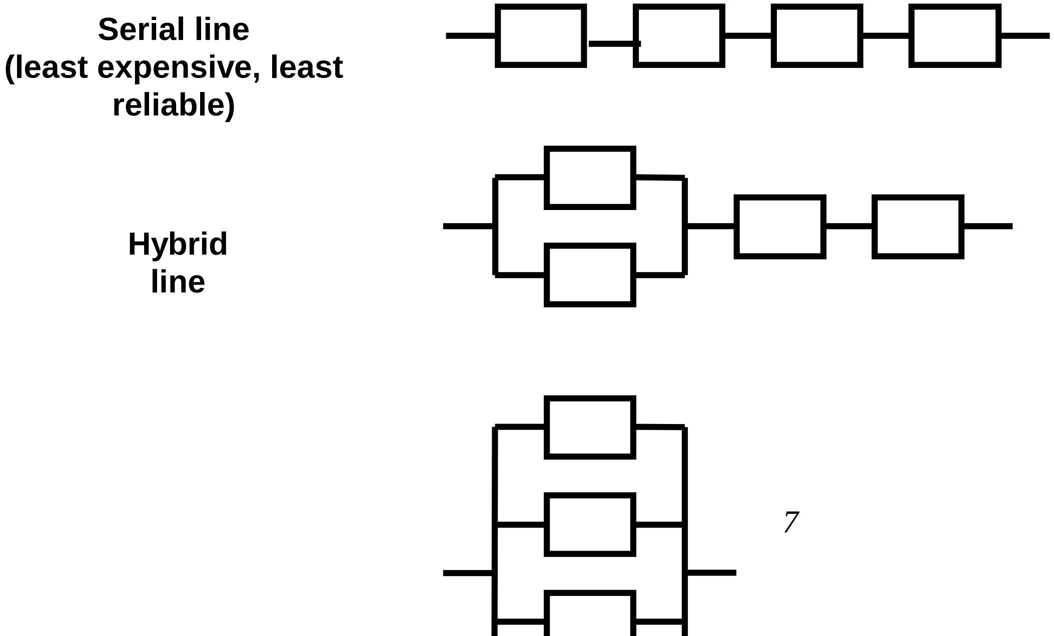
Development of a unified approach for design and construction of reconfigurable machine-tool systems is another important challenge in the design of RMS. Like any other design problem, a compromise should be made among certain variables of the system. The RMS design problem is, however, quite complex since the number of variables is large.

Reduction in lead time requires the adoption of CAD techniques for production systems, and that the system be readily diagnosed for reliability and product quality problems. Rapid restructuring of a system requires component design for reusability and quick integration. Ease of upgrading requires that the components be designed for substitution, and that the system be designed for integration of new technology and new functionality.

The following sub-sections provide a more detailed review of the technology requirements of RMSs. They include system design and configuration for RMSs, their software and communications requirements, control and monitoring, machine design aspects of RMSs, processes and tooling, and intelligent sensors and multi-sensor data fusion for system reliability and safety.

2.1. System Designs and Configuration Aspects of RMSs

There are number of steps involved in manufacturing of a part from its conceptualization to production; including product design, process planning, production system design, and process control. Computers are used extensively in all these stages to make the process easier and faster. As a result, there are many software tools available such as computer aided design, process planning, computer aided manufacturing, etc. However in spite of all these developments, there is not a systematic approach to their integration and implementation, and each stage is done separately with little interaction with the rest of the system. Also, most of these developments assume a unique and predefined configuration for the machines (Cho, 1994). RMSs offer a dynamic configuration and each one has its own advantages/disadvantages in terms of cost, quality, and reliability of the system. For example, a system with serial configuration (see Figure 3) of the machines has minimum cost but it is less reliable; however, when the same machines are arranged in parallel the system becomes more reliable but it becomes more expensive too. Therefore it is possible to compromise between these two extreme cases and design a hybrid system (see Figure 3) which is optimized in terms of cost, quality, and reliability. Literature survey suggests that there is a need for either development of new theories and approaches or adoption of some of existing concepts to systematic design and optimization of production systems. At the system level, design and selection of an optimal machining system configuration for a particular product family requires new methodologies, as the research to date on optimal machining system design is quite limited. Evaluation of machining configurations should be based on preferences of decision makers and take into account factors such as quality, cost, timing and part variation. A literature survey suggests that in-depth studies of some of the issues related to system integration for RMS. — e.g., integration rules, economic evaluation of alternative configurations, cost models, analysis and selection of machining



Parallel line
(most expensive, easy to add
functionality)

Figure3. Several possible configurations with four machines

systems, and the design of configurations to achieve minimum idle time and optimal system productivity (Klutke and Lawrence, 1991; Klutke and Wortman, 1996)— are needed. Some existing techniques, such as life-cycle economic modeling and Imprecisely Specified Multi-Attribute Utility Theory (White and Sykes 1986; White and Anendaligam, 1993) can be adapted to this class of problems. As an RMS can have many configurations, it is important to clearly observe the effects of changes in the system configuration on factors such as part quality, and system productivity, reliability, and cost of the system (Sood *et al.* 1993; Hassan, 1994). A survey of the literature suggests that, there is a need for development of new underlying theories, or extension of existing theories and concepts, to resolve these issues in the context of RMS. For example, to produce high-quality products, it is necessary to locate sources of product quality variation. A method previously used for automotive body assembly — the Stream-of-Variation theory — can be extended to trace back quality problems in machining to their manufacturing sources (Hu, 1997).

2.2. Software/Hardware Architecture Aspects of RMSs

An integral part of RMSs is the software required to handle tasks at various levels such as control, monitoring and communications among mechanical, electrical and electronic components (at low level) as well as higher levels tasks such as process planning, user interface, process control, data collection/report from the process, etc. Therefore, the structure and functionality of the communication and control software is very critical and directly affects the performance of the entire system. From the economic point of view, approximately 25% of the total initial cost of a machine-tool is attributed to the software development. The modular nature of RMSs requires that the software/hardware of the system be in a modular form; i.e., consist of separate entities totally decoupled from the rest of the system such that addition/modification of a component is possible. Furthermore, it should be extensible (i.e., be able to respond to new features, environments, and requirements), modifiable/reusable (easy to modify and usable in different programs, if necessary), and most importantly reconfigurable (able to accommodate different configurations and to support internal/external interactions of modules without modifications in the software). As reported, (Pritschow and Muller, 1997), object-oriented programming is a reasonable choice as already has been used in other areas for real-time control applications (Awad *et al*. 1996). Equally important is the hardware architecture that should be compatible and responsive to the properties of the software (mentioned above), interacting in harmony to support the essential features of RMSs.

A literature survey reveals that CNC machines have been equipped with proprietary control systems; i.e., the users do not have access to the controller and further modifications/enhancements of the system (by the users) are either impossible or very costly. This has significantly hindered the applications of efficient control algorithms, addition of new sensors for process improvement/monitoring purposes, and has suppressed the automation of the entire production system (Pritschow and Muller, 1997; Proctor and Albus, 1997). This type of controller is unable to support the basic characteristics of RMSs such as convertibility, integrability, etc. To achieve them, the

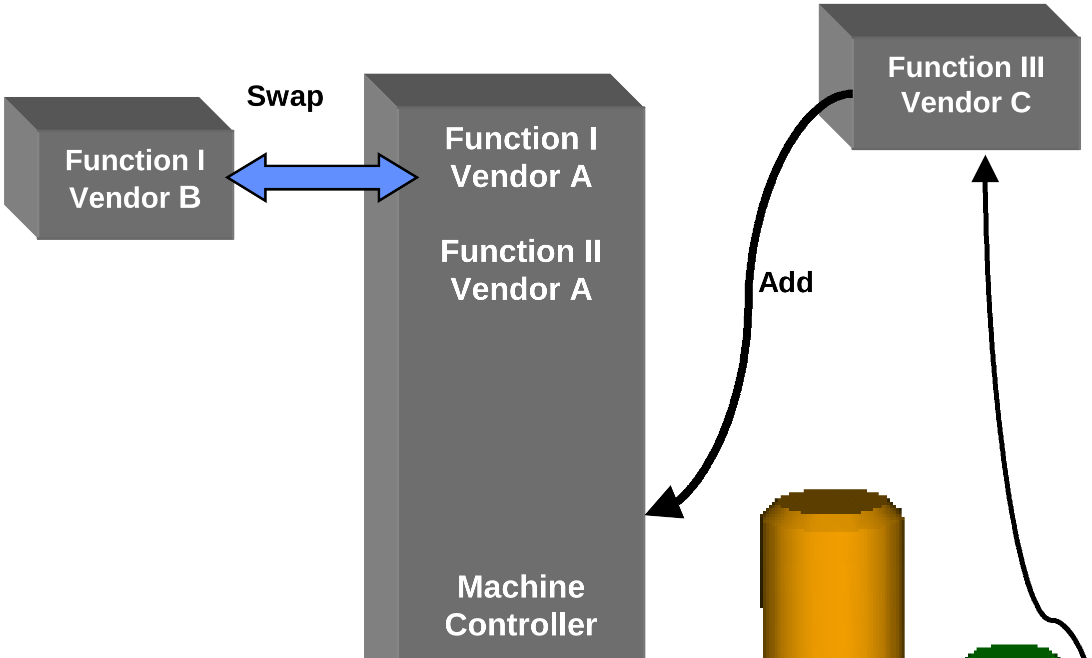


Figure 4. Open-Architecture principle in machine tool control systems

system should be open (Birla and Shin, 1995; Wright and Greenfeld, 1990; Wright *et al*. 1991; Pritschow and Muller, 1997; Proctor and Albus, 1997) to allow continuous upgrading and possess an "open architecture" (see Figure 4) to accommodate the above features (Duffie and Bollinger, 1980; Dilts*et al.* 1991; Duffie and Prabhu, 1994; Ardekani and Yellowley, 1996). It should be mentioned that a unified definition for "open-architecture systems" does not exist. What is meant by "openness" and what are the domain of the "systems" depend on how they are viewed. Probably, the clauses "open-architecture/open systems" have been the most overused and misinterpreted phrases in history of control/automation systems (software/hardware). In this regard, some similarities can be observed between the application and interpretation of the phrases "open-architecture systems" and "computer-integrated manufacturing (CIM)" (Bedworth*et al*. 1991) which was at a similar stage of development in the 80's. In spite of all the ongoing debates (Owen, 1995; Proctor and Albus, 1997), it seems reasonable to state that an open-architecture control system should posses the common capabilities and functionality offered by standard platforms such as standard computing architecture (ISA/VME Bus), standard processors (Intel 1x86/Motorola 680x0/PowerPC), standard operating system (Windows NT/Unix), and standard languages (C/C++, Visual C++/Basic, etc.).

A survey of the open architecture machine-tool control literature reveals that there are a number of projects underway with different objectives such as Enhanced Machine

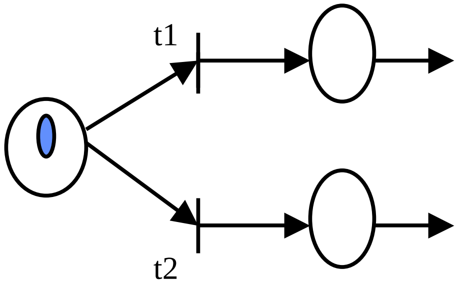
Controller (EMC) at Sandia National Labs, industry-government collaborative programs such as Big three Open Modular Control (OMAC), Oasys, and Icon (Owen, 1995). The National Institute of Standards and Technology (NIST) has proposed and implemented a reference model architecture for real-time control systems (RCS Reference Model) (Proctor and Micholski, 1993; Proctor and Albus, 1997). Based on that model, and to address industrial requirements, the Next Generation Controller (NGC) Program — sponsored by the US Air Force, and executed by Martin Marietta— prepared the Specifications for Open System Architecture Standard (Wright Laboratory Report, 1994). The University of Michigan (UM) has contributed to the development of next-generation machine controllers by effectively creating an open and readily modifiable control system for CNC machines. Issues such as distributed networks, design of hierarchical controllers, and their software structures have been investigated (Koren *et al.* 1998; Koren and Lo, 1992; Pasek *et al*. 1995; Ulsoy and Koren, 1993; Koren *et al.* 1996; Park *et al*. 1996; Zhou *et al.* 1996; Kim and Shin, 1997). The largest-scale projects in the field of control software (in Europe) is the Open System Architecture for Controls within Automation (OSACA) system (Pritschow and Muller, 1997). Also noteworthy are projects on the design of reconfigurable real-time software at Carnegie Mellon University (Stewart, 1993), OSEC (in Japan), at the University of British Columbia—where a hierarchical multiprocessor and motion control system has been designed (Altintas and Munasinghe, 1994; Altintas and Munasinghe, 1996).

2.3. Measurement and Control Aspects of RMSs

The measurement and control systems for RMSs should be able to support its key characteristics. Currently commercially available controllers allow only limited access by users; in fact, a majority of industrial controllers (e.g., axis motion controllers) have a fixed control structure (e.g., traditional PID). This is the bottle neck for the existing controllers which makes them unsuitable for RMSs. Therefore, more studies for the design of proper PC-based control systems and their architecture (software/hardware) are needed(Proctor and Albus, 1997). As pointed out by (Proctor and Albus, 1997), PC-based control systems for machine-tools will revolutionize the manufacturing systems very much in the same way that PC did for office automation. There are reports of recent efforts in the industrial sector by realizing the importance of this problem and trying to find proper solutions (Baab, 1996; Hollenback, 1996). Some of the companies who are actively involved in development of PC-Based controllers are Allen-Bradley , Cincinnati Milacron, Cranfield Technologies, HP Trellis, Wizdom Controls, and Icon, to name a few.

On the other hand, while the control algorithms used in CNC machines are primitive, in academia during the last two decades there have been reports of research achievements on the application of advanced control policies to machining processes(Ulsoy *et al.* 1983; Daneshmend and Pak, 1986; Watanabe, 1986; Ulsoy and Koren, 1989), on-line tool wear measurement and estimation (Danai and Ulsoy 1987; Wright and Bourne 1988), multi-sensor systems are employed to report on a number of process variables, such as temperature, forces, and tool wear, (Lan and Dornfeld, 1984; Stein and Shin, 1986; Lee, 1987b; Rangwala and Dornfeld, 1990; Chow and Wright, 1994), and the selection of proper control strategies (Furness *et al*. 1996). But most of them are not utilized in the current industrial controllers and in particular in CNC machines because of the reasons stated above.

The same view is valid for programmable logic controllers (PLC). To date, programmable logic controllers (PLC) have been used in industrial automation to control and monitor discrete event systems. However, the needs of industrial automation and manufacturing systems have changed dramatically due to recent developments in information management systems. The new requirements are mostly dictated by the capabilities of manufacturing machines and components in terms of communicating with the rest of the system, their upgrading and easy modifications, versatility and programming languages. The fact that PLCs were originally designed to replace the hard-wired relay logic (Batten, 1994) used in control of machinery, suggests that they have limited capabilities in this regard and in general they suffer from limited capabilities for on-line operations (the entire system should be stopped to download a new logic program), slow communications between PC and PLC (mostly done through serial port), no standardization of the software for communications at high/low level and often very expensive, not open to the users (i.e., every vendor has his own components which does not fit the others), overall costs of the system is very high (the costs for user interface and their software, components are very expensive as compared to PC-based systems), and limitations on the programming language used. These are the bottlenecks with available PLCs which make them not very suitable for RMSs. The functionality of PLCs can be enhanced, however, by proper implementation of available I/O boards (and compatible software) on a much more compact and industrial PC platform such as PC/104 (its form factor is very small while has the same functionality as a PC; i.e., in terms of communications and other functions) at fairly low costs. Many



(a) Conflict: if t1 fires, t2 is not enabled and visa versa

(b) Concurrency: t1and t2 can be fired independently

Figure 5. Examples of modeling capabilities of Petri nets

industrial control companies are delivering PC-based systems (hardware/software) for implementing PLC functions (Owen, 1995); also, progress is being made in integrating the functional logic (discrete) of PLCs and machine-tools motion control (continuous) by utilizing modeling capabilities of Petri nets (see Figure 5)(Park *et al*. 1998; Jackman *et al.* 1997; Linn *et al.* 1997). Another critical issue in design of RMSs and other modern intelligent manufacturing systems is communication. So far, networking and data communication between CNC controller/PLC or PLC/PLC have been done through proprietary networks (similar situation as with controllers); i.e., related communication systems, protocols, and software/hardware are not open to the users/other vendors. Therefore, further system enhancements are severely restricted (in some cases, means of serial communication is provided; but the speed of communication is not fast which makes them unfit for real-time applications). Cost is another important issue. Lets consider a set of sensors/devices communicating with a central computer/controller. Traditionally, they should be hard-wired to the central controller/PLC; therefore the costs associated with wiring, connections, control cabinet, space, labor , maintenance and trouble shooting are quite high. With a proper communication system, the same sensor/device is connected to a network (locally) which takes care of all data reporting and condition monitoring of the entire manufacturing system. A literature survey suggests that there are reports of recent development of built-in intelligent control devices and communication networks such as Devicenet (Proctor and Albus, 1997; Paula, 1997). Also, progress is made in development of standard terminology for message and instruction sets such as Manufacturing Message Specification (MMS) which are necessary for shop floor communication (Hollingum, 1987). In Devicenet network, local devices have built-in intelligence (with little cost) and their communication capabilities are enhanced. Therefore, control decisions/actions are made locally and the entire control system for manufacturing is decentralized.

2.4. Machine Design Aspects of RMSs

Modular form and dynamic structure (in terms of configuration) of RMSs makes the design of their components a highly complex issue. In conventional design of machines and in particular machine-tools, their elements were optimized based on a unique and predefined architecture. Therefore, the major task was to optimize a machine for a specific configuration (i.e., at machine level). However, an RMS can be created (according to requirements) from some basic modules the so called “building blocks” (Moon and Kota, 1998) (see Figure 6). Therefore, since there are more than one configuration of the machine, optimization should be made for several possible configurations which is much more involved than a single configuration. There are reports of modular fixture design and programmable clamps to firmly hold a component (Cutkosky *et al.* 1982). For example, in the latter based on fixturing characteristics of commonly used fixtures, an approach is introduced for design of modular fixtures. However, it should be noticed that clamps and fixtures are considered to be auxiliary equipment of machine-tools and dynamics involved is not a major factor in their design.

Another challenge in mechanical design of RMSs is specification of the extent of modularity that is required for a process. In other words, what are the building blocks of a reconfigurable machining system which produces the most efficient and optimized system. In a report by (Rogers and Bottaci, 1997), the principle modules (mechanical) are considered to be processing subsystems (i.e., process machine primitives), actuator elements (used to move the axis of a machine or build simple material and component transfer system), and tooling and fixtures (to support a specific configuration). But, a specific approach is not provided as how to design the system.

To support the characteristics of RMSs, there is a need to develop a new theory –which we call Reconfiguration Design Theory – for topological synthesis of reconfigurable machines, optimization of machine chains-of-motion and structure, and analysis of the associated problems (such as wear, vibration, and stiffness). Such a theory should be capable of analyzing and estimating the machine accuracy and repeatability once different modules of the machine (e.g., machine structure, tool-support, spindle, working-holding table, etc.) are identified. In this regard, there are reports of achievements on the synthesis of machining systems (Kota and Chiou, 1994) which can be extended to the design of generic building blocks, conceptual design, and their simulation.

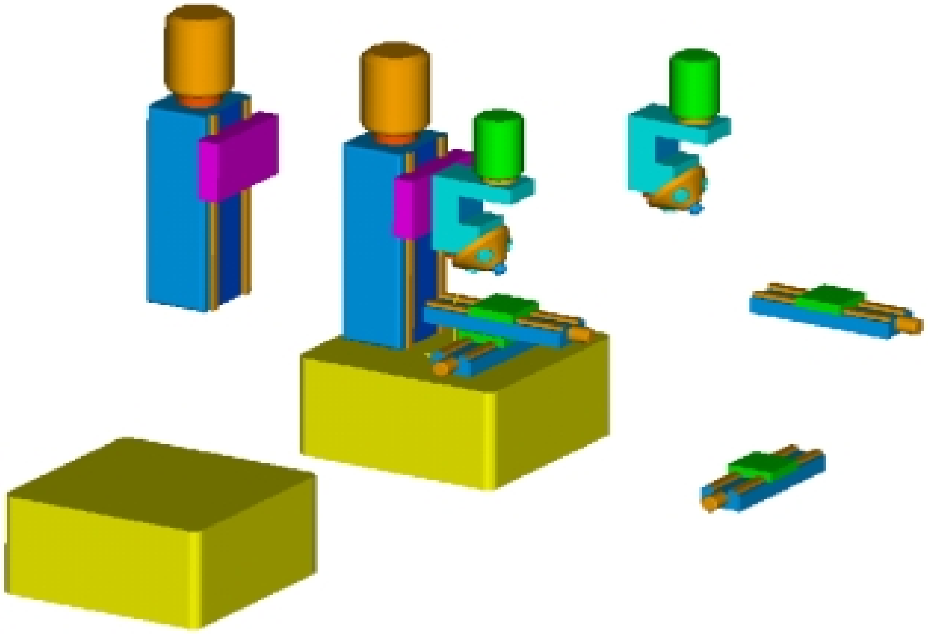
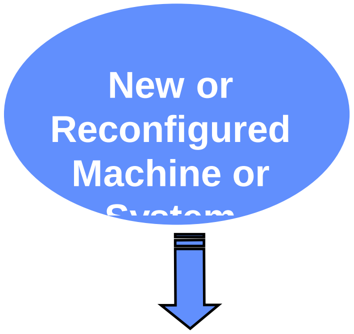


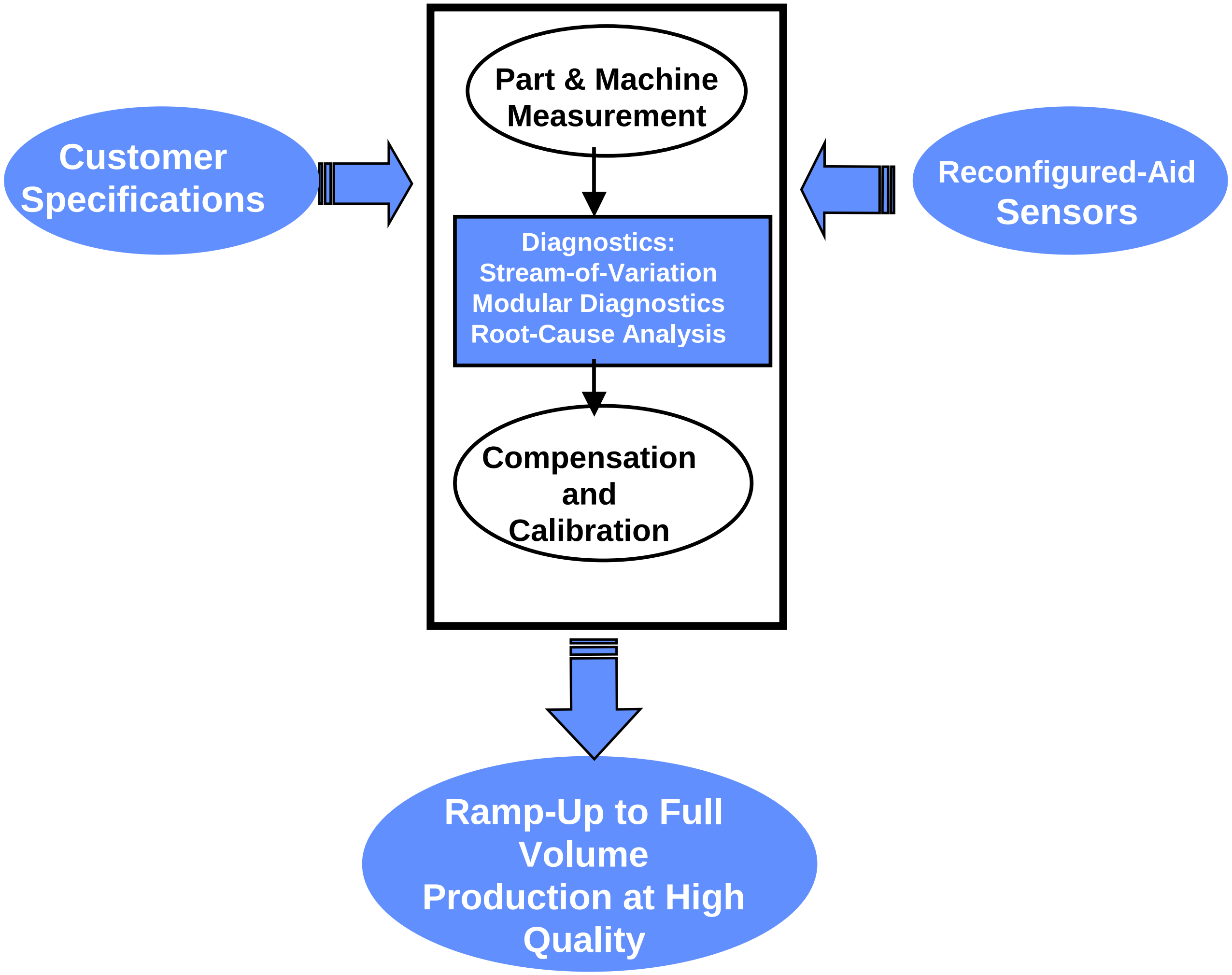
Figure 6. Examples of building blocks of reconfigurable machining systems

2.5. Process and Tooling Aspects of RMSs

After the RMS is reconfigured, the production system must typically be "fine-tuned" before it can consistently produce at the required quality and production volume. This is referred to as ramp-up, and it takes a long time (months or even years) with traditional production systems. For RMS to be practical, ramp-up time should be significantly reduced for both new and reconfigured systems. This objective requires diagnostics, calibration, and ramp-up methodologies (see Figure 7).

One of the key factors in evaluating the product quality is precision in machining. To achieve that, the cutting operation is tightly controlled by using real-time data collected from sensors located at different locations of workpiece, tool, and machine-tool (Rao, 1986; Kannatey-Asibu, 1987; Rivin and Kang, 1992; Rivin, 1994; Ni, 1993). Also, some measurements are made for process monitoring purposes with the objectives of preventing irreparable damages to the workpiece and the machine (Li and Albestawi, 1996). In general, real-time measurements of the following variable are required: dimensional errors, quality of surface finish, thermal deformations during machining, and dynamic deformations of the workpiece; chatter vibration, cutting force, condition of the





Customer Specifications

Part & Machine Measurement

Diagnostics:
Stream-of-Variation
Modular Diagnostics
Root-Cause Analysis

Compensation and Calibration

Reconfigured-Aid Sensors

Ramp-Up to Full Volume Production at High Quality

Figure 7. Ramp-Up Methodology for
Reconfigurable Manufacturing Systems

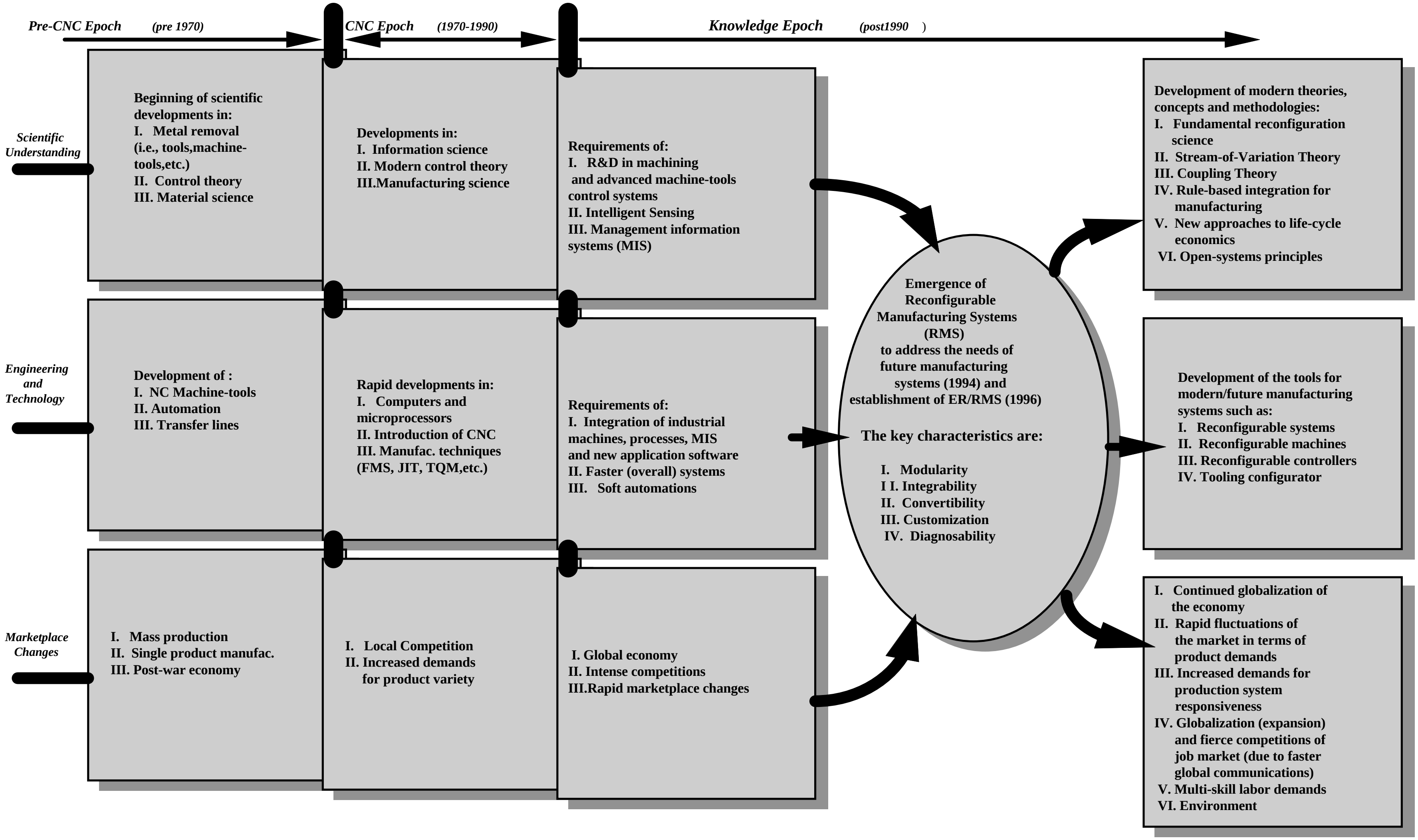


Figure 8. The Key Role of Reconfigurable Manufacturing Systems (RMSs) in Future Manufacturing

chip, and identification of the cutting for process monitoring (Chrysolouris *et al.* 1992); thermal deformation, dynamic deformation of the machine elements, and structural vibration of the machine-tool (Ferreira and Liu, 1986) and wear, failure, and thermal deformations of the tool (Rao, 1986; Li and Albestawi, 1996).

Regardless of the type of process, there are several key components in modern intelligent sensor-based machine monitoring systems including: data-acquisition system which consists of sensors and signal conditioning systems for collecting (remote/local; software/hardware; on/off line) data (for monitoring and reliability estimation), signal processing techniques to extract valid data (software), and decision making (software) routine to analyze the data and classify the results (software). In essence, the entire process of control and monitoring is very similar to the actions of humans and ideally, should duplicate the response of an experienced and efficient machine operator. Further details of general description and classifications of the sensors (contact/non-contact), techniques of measurements (direct/ indirect) and sensor-data fusion (to improve the accuracy and reliability) and their features and limitations are provided in (Mehrabi and Ulsoy, 1997-b).

3. Future Trends/Research Directions

It is very difficult to forecast long term trends for manufacturing systems, since the changes are happening at a very fast pace. However, it is possible to extrapolate future trends from the current situation by analyzing and specifying the key drivers behind the changes. Certainly, availability and distribution of information plays an important role in this transition and it is considered as one of the key drivers. In this regard, there are needs for improvements and standardization of various components (such as data interfaces, protocols, communication systems, etc.) so that data can be transferred to the desired location at a faster rate.

There have been reports of several studies relevant to future manufacturing technologies, processes, and machine-tools (Agility Forum, 1997; Aronson, 1997; Ashley, 1997). They have all agreed that manufacturing should be viewed, designed and optimized as a system (as a whole) to achieve the required responsiveness (i.e., shorter lead-time and ramp-up time). In this regard, there is a need for fundamental understanding of manufacturing processes, equipment, and technologies and their relations to the rapidly changing market.

There are many research efforts underway, however, we are still at the beginning of a new era of modern manufacturing systems and there are many barriers to their advancement (Agility Forum, 1997). As reported, there is a lack of available tools and methodologies to analyze the trade-off among processes, equipment, life-cycle costs, and initial investment. Also, there is a lack of effective communication among product designers, process designers and machine-tool designers as it is necessary for design of an optimized manufacturing system.

Advances in manufacturing will not occur without the proper machine-tools and equipment. Machine-tools are going under some fundamental changes in terms of their structure (modular structure), components (controllers, hardware/software, spindles, tooling, sensors, etc.); therefore, new theories, design concepts and methodologies should be developed for these purposes (see Figure 8) (Garro and Martin, 1993; Aronson, 1997; Ashley, 1997; Rogers and Bottaci,1997). These changes are fundamental to the success of future Reconfigurable Manufacturing Systems (RMSs).

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