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Modular Mechatronic Control of Reconfigurable Manufacturing System for Mass Customization Manufacturing

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Abstract
Manufacturing companies are faced with the challenge of unpredictable, high frequency market changes in both local and international markets. There is a need for greater, more effective responsiveness by manufacturers to change their manufacturing processes. Many manufacturing techniques are based on the principles of Flexible Manufacturing and Dedicated Manufacturing for mass production. Reconfigurable Manufacturing Systems, (RMS), is a manufacturing system that can provide for Mass Customization, (MCM). This has lead to research on the concept, design and equipment implementation for RMS. RMS requires three key capabilities: rapid changeover between products, rapid introduction to new products and unattended operation. The relationship between these manufacturing techniques has been investigated. Research has been focused on the design of Reconfigurable Modular Machine, (RMM), for RMS. The research has addressed the design of subsystems for RMM by using the generic modular mechatronic control. This approach includes modular machine controller hardware, software, mechanical design and generic "plug-and-play" capability. These design of subsystems allowed for rapid reconfiguration of RMS that increased system efficiency and significantly minimized manufacturing change over downtime.

Keywords
RMS, MCM, modular mechatronic control

1 INTRODUCTION

Manufacturing companies of today are faced with the challenge of unpredictable, high frequency market changes in both local and international markets. There is a need for greater, more effective responsiveness by manufacturers to change their manufacturing processes Mass Customization Manufacturing, (MCM). There are some manufacturing techniques used that are based on the principles of Flexible Manufacturing and Dedicated Manufacturing production [3].To fulfill these purposes, the concept of Reconfigurable Manufacturing System, (RMS), was introduced and it has three key capabilities: rapid changeover between products, rapid introduction to new products and unattended operation. The relationship between these manufacturing techniques is illustrated in Figure1. RMS falls within the scope of Agile Manufacturing, (AM). AM requires the use of technologies that can be used to manufacture and check product quality within a variety of family products without extensive retooling.

Research has been focused on the design of: modular machine for reconfigurable machining system which is one of subsystems and was integrated into a Computer Integrated Manufacturing (CIM) cell. The research addressed the design of subsystem of Reconfigurable Manufacturing System, (RMS), by using the generic modular mechatronic control approach. This approach includes modular machine controller hardware, software, mechanical design and generic "plug-and-play" capability. These designs of subsystem allowed for rapid reconfiguration of reconfigurable machining system that increased system efficiency and significantly minimized manufacturing downtime.

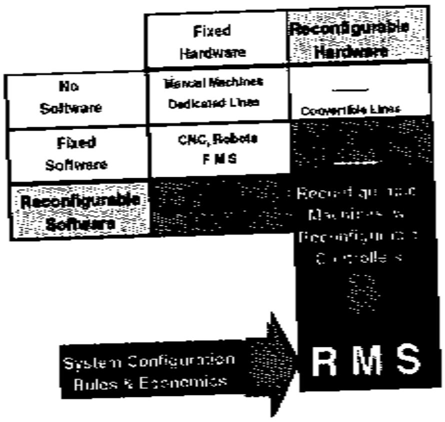


Figure 1 - The comparison of three kinds of manufacturing systems [9].

The objectives of the research project (as illustrated in Figure 2) were to develop some kinds of automated machines. One is Reconfigurable Modular Machine, (RMM), design for reconfigurable machining system that was able to Mass Customization Manufacturing, (MCM). A reconfigurable machining system design was focused on three key characteristics: decomposition, standardization and exchangeability. This subsystem was controlled by a generic modular mechatronic control system design. The control system allowed for the operation of different subsystems within RMS.

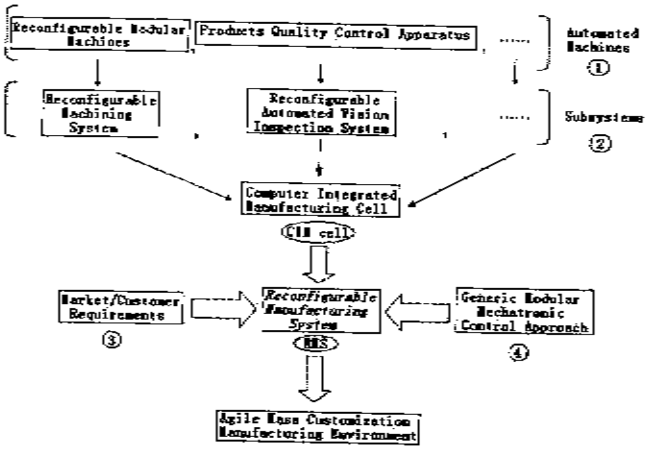


Figure 2 - Diagrammatic representation of Agile Mass Customization Manufacturing Environment.

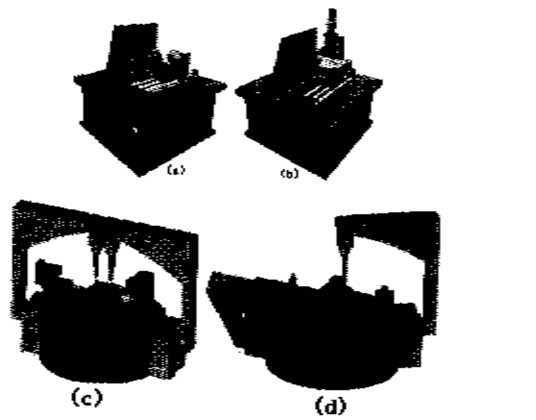
Figure 1 describes the four integral components (①, ②, ③ and ④) leading to the implementation of reconfigurable manufacturing, as well as outlining the core principals of Agile MCM environment. The market/customer requirements are those of custom made products manufactured in a mass production environment. The finished product should be competitive, (low cost), and have exceptional quality standards. Different automated machines can be reconfigurable to do multiple tasks for production of various assemblies. These automated machines consist of different subsystems which are the key components of the RMS.

The generic modular mechatronic control system included motion and communication design and implementation. This allowed the subsystems can be controlled automatically via PC level programming. A generic "plug-and-play" system should provide the facility for control to be interchangeable with various automated machines. This produced uniformity amongst the machines and reduced the downtime in cases of malfunction.

2 RMM DESIGN FOR RMS

To realize this concept of Reconfigurable Manufacturing System RMM must fulfil various functions through the combination of distinct building blocks, modules, etc. Various modular machines have been proposed as models and built up machines. These are illustrated in Figure 3.

The purpose of the design of the reconfigurable machining system was to provide the capacity and functionality for the machining operation. The core engineering method needed for machine-level design was that of a systematic design of modular machines. [5] The design of the machine utilized a library of machine modules which provided a plat-



(a)Two axis configuration (b) Three axis configuration (c) Initial configuration (d) After reconfiguration

Figure 3 - Few configurations of the prototype modular machines [12].

form for fundamental motion analysis. A set of RMMs could be connected together to generate the new type of machining system: reconfigurable machining system.

There were three key aspects for the design of the modular machine: manufacturing requirements, control requirements and mechanical requirements.

2.1 Manufacturing Requirements

- Dedicated Manufacturing System, (DMS): Designed for narrowly defined production requirements (normally one part at large volume) that are supposed to remain constant over the lifetime of the machining system. This system is custom-designed to machine a specific set of features at a constant cycle time. It would not cost-effectively accommodate the rapidly changes in production requirements.
- Flexible Manufacturing System, (FMS): Designed for loosely defined production requirements that are supposed to significantly change in an unknown manner over time. FMS often has the excessive capacity to fulfil the undefined production requirements which causes the customer to pay for unneeded capabilities.
- Reconfigurable Manufacturing System, (RMS): Designed for MCM requirements. It cost-effectively combines the attractive feature of DMS and FMS: robust performance and the ability to accommodate new production requirements. The RMS is structured by a series of modular machines which can be changed of the machining operations during a short time and at a low cost so that the whole RMS can meet the rapidly changing market requirements. [12]

2.2 Control Requirements

- CNC controllers: Typical CNC controllers posses comprehensive architectures (hardware and software) to provide processing flexibility; however not all of the built-in functionality may be used. Furthermore these components cannot be cost-effectively upgraded because of the unnecessary costs are incurred due to software development, installation and maintenance.

- RMM Controllers: Design based on the concept of open-architecture. In open-architecture control, both software components and hardware components are modular. This generic modular mechatronic controller for modular machine allows the machine can be reconfigured when market/customer requirements change or new technology becomes available. [5]

2.3 Mechanical Requirements

Designed for a machine to meet the productivity and quality demands of an operation, it must fulfil a variety of requirements including the ability to produce the specified motions and satisfy the part tolerance specifications. There are two key aspects during the mechanical-level design of modular machine: Kinematic Viability and Structural Stiffness [7]. Good kinematic viability makes the machine perform the various motions required to produce the needed features. Reliable structural stiffness of machine can decrease the possibility of geometric errors.

Examples of part family from the market/customer requirements are as in Figure 4:

Figure 4 - Part family: two kinds of engine blocks.

A CAD/CAM software package (Unigraphics) was used to produce a module library. According to the different market/customer requirements, different prototypes of modular machines were designed and analysed in the virtual computer environment. It is showed in Figure 5.

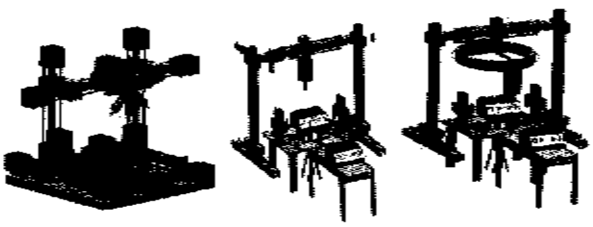


Figure 5 - MR^{2}G modular machine conceptual design

According to the conceptual design, MR^{2}G research group built a real modular machine with modular mechatronic control system. The RMM is assembled from a module library in the computer environment and its modular structure (in both hardware and software) allows is to be converted in a cost-effective method when the market/customer requirements change. The following figures show the different components of MR^{2}G RMM.

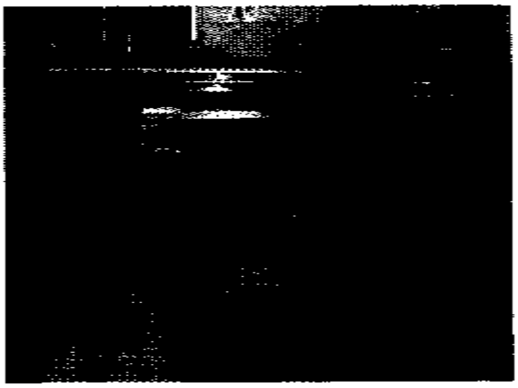


Figure 6 - Part transfer components for RMM.

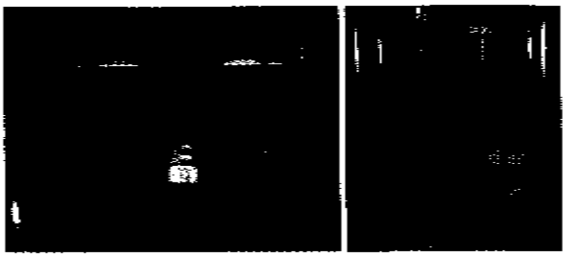


Figure 7 - Lifting table and clamping component for RMM.

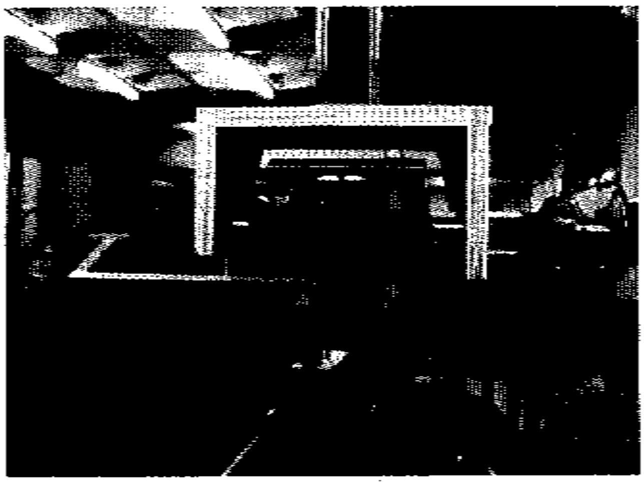


Figure 8 - Auto-tool changing component for RMM.

Figure 9 - Modular mechatronic control card and case for RMM.

3 RMS FOR AGILE MASS CUSTOMIZATION MANUFACTURING

3.1 Mass Customization Manufacturing (MCM)

With significantly shortened product life cycles, manufacturers have found that they can no longer capture market share and gain higher profit by producing large volumes of a standard product for a mass market. Success in manufacturing requires the adoption of methods in customer-acquisition and order-fulfilment processes that can manage anticipate change with precision while providing a fast and flexible response to unanticipated changes [2]. Many companies are confronted with the challenge of changing their strategic orientations to meet demands of the current market place. Mass Customization Manufacturing, (MCM), is a solution to this challenge.

Mass Customization Manufacturing (MCM) has been gaining recognition as an industrial revolution in the 21st century. Just as mass production was crucial to manufacturing in the 20th century, MCM will be the key to economic growth in the 21st century as shown in Figure 10.

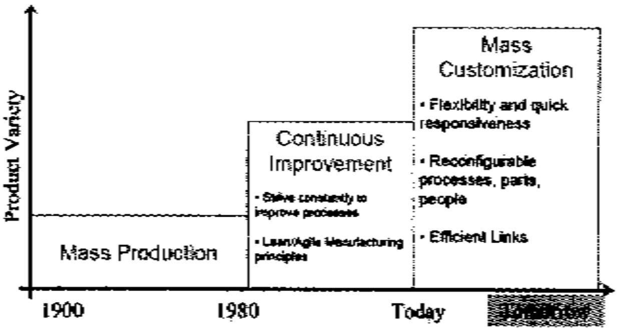


Figure 10 - From mass production to Mass Customization (MC) [6].

The concept of MCM was first expounded formally in the book "Future Perfect" by Stanley M. Davis in 1987. In 1993, Joseph Pine gave MCM a clear definition as a strategy that sought to exploit the need to support greater product variety and individualization [10]. The goal of MCM is to produce and deliver customized products at mass production costs and speed.

In recent years, advantages in Computer Aided Design (CAD), Product Data Management (PDM), and computer network control technologies have made mass customization no longer legend, but closer than ever [13]. The word "personalization/customization" will take on more applications: personal families, personal food (food designed to maximize custom diet needs), personal clothing (clothing sized to individual bodies and fabricated to personal climate and skin needs), and personal (customer-designed) cars [1]. MCM competent manufacturers will enjoy superior market share and greater profit margins, and it is the promise of these economic incentives that will compel other manufacturers to move to MCM sooner than later.

3.2 RMS for MCM

There are many challenges for MCM, the followings are important: 1) keeping costs low to match those of standardized items, 2) achieve high quality production of high variety of products, 3) making these products available in a timely fashion to customers. So in order to fulfill mass customization, there are two research areas needed to be done: 1) Product Design For Mass Customization (DFMC), 2) Manufacturing Systems design for MCM. In this research, we just address the design of manufacturing systems for MCM

A "responsive" manufacturing system is one that can quickly reconfigure itself to allow flexibility not only in producing new products but also in changing the system itself. Such systems will necessitate the use of highly sophisticated manufacturing systems that are flexible, extensible and re-usable. There are two components which are very important for the new manufacturing systems design: 1) RMM design 2) generic modular mechatronic control systems.

The design of the new manufacturing systems for MCM is an extension of the customer-centered concept in fabrication. Success in MCM is achieved by swiftly reconfiguring operations, processes, and business relationships with respect to customers' individual needs and dynamic manufacturing requirements. It is thus critical to development a manufacturing system that will achieve this goal. A competitive manufacturing system is expected to have enough reconfigurablity to respond to small batches of customer demand. Because the construction of any new production line is a large investment, current production lines must be able to be reconfigured to keep up with increased frequency of new product designs. In MCM, each unpredictable feature demanded by customers is considered an opportunity, whereas current system capabilities may not be able to support new customer requirements. The key to adjusting the manufacturing capability successfully is to reconfigurable the system, developing and integrating new functions when necessary.

The RMS is based on generic modular mechatronic controlled modular machines in addition to other value-added, automatic, reconfigurable product quality inspection and material handling facilities. The reconfigurablity within RMS serves to satisfy demands for a relatively diverse range of products with a small to medium batch size production. Compared with other manufacturing systems, more part varieties are produced in a mass-customized agile production environment, and manufacturing requirements are often dynamically changed. In addition, customer orders come through more randomly with different delivery dates. Thus, RMS for MCM has sufficient reconfigurability and rapid response capability to deal with Agile MCM environment.

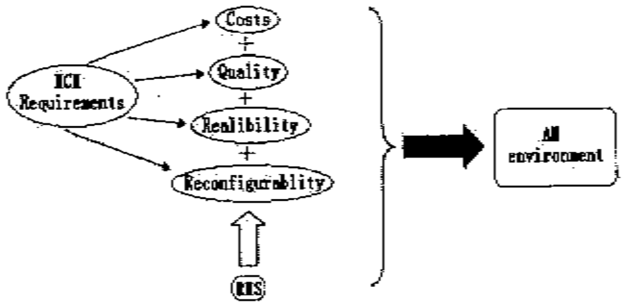


Figure 11 - MCM requirements for reconfigurable machining system in Agile MCM environment.

4 RMM CONTROL BY USING MODULAR MECHATRONIC CONTROL APPROACH

The Reconfigurable Modular Machine, (RMM), is controlled by computer-based technology. Since the advent of the microprocessor, computer-based technologies have made it possible to improve productivity, reduce manufacturing costs, and produce higher quality goods. [11] The development of the microprocessor has seen the use of automated machines for many applications. RMS generally consists of a number of subsystems. These subsystems are sometimes not flexible enough to reconfigure their elements or processes in order to produce custom products.

One of the main objectives of the research was to develop a low-cost generic modular mechatronic "plug-and-play" controller for the control of subsystems. The subsystems were required to demonstrate modularity and flexibility. Ultimately, a truly flexible modular mechatronic controller would not only be low cost, but would also allow for the selection of any particular motorized system through software, and thus have the controller appropriately reconfigures itself. This means that a large-scale RMS with series of subsystems could be controlled from a single central PC. This would allow for fast set-up times without any mismatches between hardware and software.

The generic control system for the RMS made use of modular mechatronic actuators. These contained all the necessary on-board electronics to facilitate motion and communication. This design for the generic modular control card evolved from the realization that all automation processes make use of motors and sensors (encoders, limit switches, etc) in various configurations. Standardizing these configurations through software control made it possible to research and develop generic "plug-and-play" control modules. The main objective of these modules was to allow for rapid changeover between different manufacturing machine processes and assemblies.

A standard electrical motor provided the essential power to move the various axes of the machine. An H-Bridge set up utilizing Pulse Width Modulation, (PWM), provided speed and direction control for the electrical motors. PWM is a technique used by most microprocessors and other controllers to control an output voltage at any value between power rails. It consists of a pulse train whose duty cycle was varied so that it created variable "on" and "off" states. The average output value approximates the same percentage as the "on" voltage. [Krar and Arthur, 2003] By varying the DC voltage supplied to the motors, different speed settings were achieved. Power was supplied to the generic mechatronic controller card using a standard power source (±12VDC). The logic power for the encoders and the microprocessors (PIC) were reduced to 5VDC using voltage regulation on the controller card.

Two types of encoder setups were utilized for monitoring the running operation of the motors. Firstly, incremental quadrature encoders were used. This encoder generated two output signals by using two LED's and phototransistors, positioned 90° out of phase. By evaluating which signal was leading, the direction of rotation of the encoder disc could be determined. This encoder setup produced results of modern industrial incremental encoders by the means of a square wave. [4] Further analysis of the environment in which the reconfigurable machine would be operated in produced results that quadrature incremental encoders were not necessary. The use of single incremental encoders was therefore adopted. Direction of the motors, either forward or reverse would be known prior to operation through program commands. Using single encoders freed up I/O pins on the generic control card, allowed for more encoders and limit switches to be directly implemented onto the board.

The generic control card module was designed to independently control three motors, namely x, y, z-axes of any machine. As the objective of the project was to provide a modular reconfigurable system with the possibility of easily expanding to control more motors, a jumper system was adapted to successfully daisy chain more cards together. The cards were modular, being able to plug directly into a racking system with a USB (Universal Serial Bus) communication to a central computer station. The motor controller consisted of three relay switches. These were utilised rather than the H-Bridges due to their robust design and ease of availability (cost). The final card used three PIC16F88, one for each motor, for its onboard computing and communication protocols. The USB communication was implemented by using and FT232 UART USB chip. The USB communication resulted in the card achieving "plug-and-play" status as well as having the advantage that many generic controller cards could be plugged into one USB ports.

5 SYSTEM PERFORMANCE

When the entire system was assembled, control of the modular machine and product quality control apparatus was possible. The generic modular controller card needs to have more software development to fully achieve its' maximum potential.

Other systems investigated such as dedicated interface cards and DAQ boxes do not have the flexibility of the described system. They are also limited to the number of devices that can be monitored and controlled. The generic mechatronic controller cards provided the necessary flexibility and control to provide an adaptable RMS.

The mechatronic hardware layer for a RMS was developed for reconfigurable modular machine. It included design, prototyping, testing and validation of electronic hardware and associated driver software. The research into modular mechatronic controller cards showed that various machines, including those in a reconfigurable environment could be controlled via computer and reconfigured via software rather than hardware.

Research into more sophisticated control techniques is also an area for further development. Future work would include the development of other subsystems so as to integrate it with a computer aided manufacturing (CAM) package for materials handling and assembly. The software will also be developed with a library of available robots and motor driven devices so that the system can easily be configured to drive different devices, thus allowing seamless integration into an Agile MCM environment.

6 CONCLUSION

The research developed a RMM that were able to MCM. A standard platform was selected and implemented. The platform's simplicity and ability to be easily modified, to perform various tasks in a reconfigurable environment, provided the ideal test bed. The engine block was used as the part family.

Designing the modular machine required modeling the modular components in a computer aided design (CAD) software package, Unigraphics (UG) and Solid Edge. This provided a machine design that was modeled and analyzed in a computer simulation environment. Furthermore Rapid Prototyping technology enhanced the design procedure by manufacturing a small scale physical 3D model. Design changes were easily accommodated by producing new prototypes. This approach allowed for the feasibility of modular machines to be analyzed in the real world, while significantly reducing production costs and times.

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