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Reconfigurable Manufacturing System for Agile Mass Customization Manufacturing

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Abstract: Manufacturing companies are facing three challenges: low cost production of product, high quality standard and rapid responsiveness to customer requirements. These three goals are equally important for the manufacturing companies who want to be competitive in the global economy. Reconfigurable machining system facilitate the demand for Mass Customization Manufacturing, (MCM). The reconfigurable machining system is a subsystem of Reconfigurable Manufacturing System (RMS), which falls within the scope of Agile Manufacturing (AM). AM provides the ability to accomplish rapid changeover between manufacturing processes for different assemblies.

Keywords: RMS, AM, 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 i.e. Mass Customization Manufacturing (MCM). Some manufacturing techniques used that have been used to achieve MCM are based on the principles of Flexible Manufacturing and Dedicated Manufacturing production [Goebel, 2005]. To achieve MCM, the concept of Reconfigurable Manufacturing System (RMS) was introduced and it has three key capabilities: rapid changeover between products, rapid introduction of new products and unattended operation. The relationship between these manufacturing techniques is illustrated in Fig.1. 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 re-tooling.

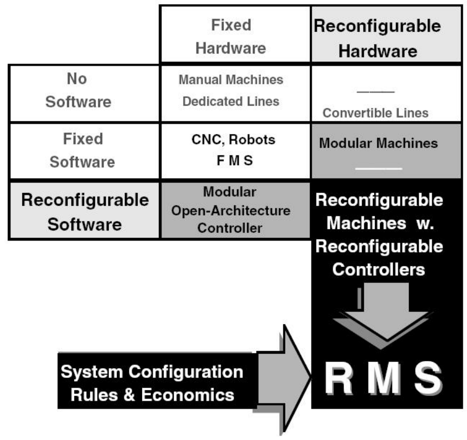


Fig.1: The comparison of three kinds of manufacturing systems [Handbook]

The research presented in this paper is focused on the design of modular machine for reconfigurable machining system. This is one of the subsystems that was into the Computer Integrated Manufacturing (CIM) cell developed at the University of Kwa-Zulu Natal. The research addressed the design of the subsystem of 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. The design of the subsystem allowed for rapid reconfiguration of RMS that increased system efficiency and significantly minimized manufacturing downtime.

Another issue that was addressed is the development of some kinds of automated machines (as illustrated in Fig.2). One is modular machine design for reconfigurable machining system for 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. The control system allowed for the operation of different subsystems within RMS.

Fig.1 describes the four integral components (①, ②,③and④) 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

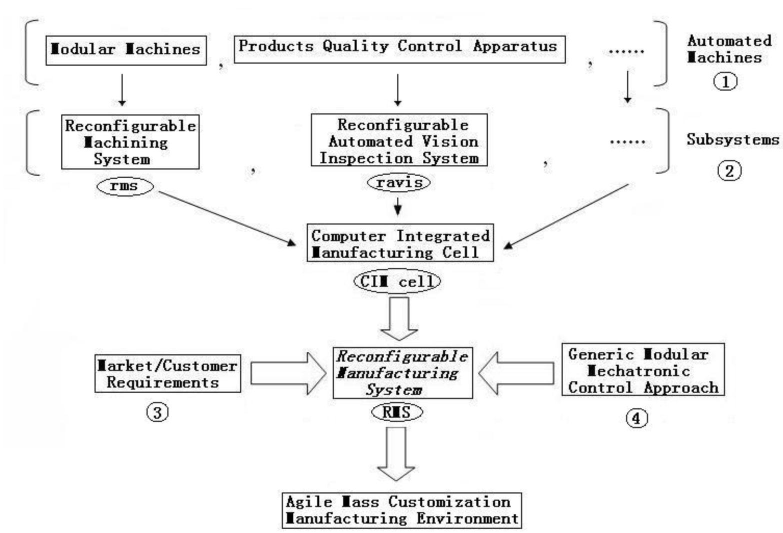


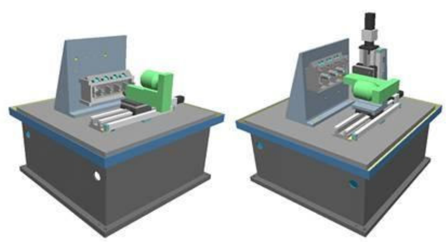
Fig.2: Diagrammatic representation of Agile Mass Customization Manufacturing Environment

competitive (i.e. low cost), and have exceptional quality. Different automated machines can be reconfigured 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 to 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.

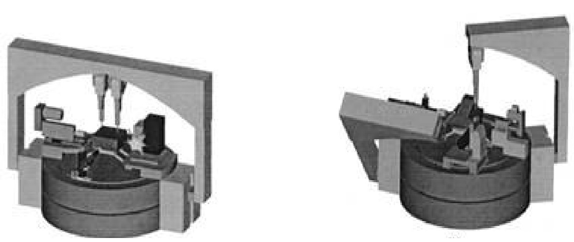
2. Reconfigurable machining system

To realize this concept of reconfigurable machining system modular machines 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. Examples of these are illustrated in figures 3 and 4. An exhaustive list of such machines is no presented in this paper.

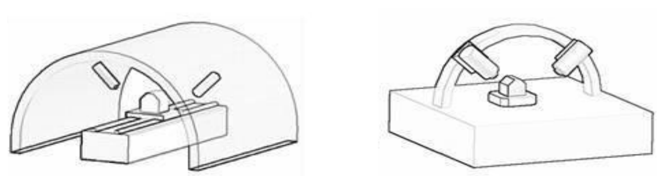


(a) Two axis (b) Three axis

Fig. 3: Two configurations of the prototype modular machines. [Moon and Kota, 1998]



(a) Initial configuration (b) After reconfiguration



(c)Tunnel shaper machine (d) Double arch configuration conceptual design

Fig. 4: Modular machines' conceptual design from other research groups [Reuven and Moon, 2000].

3. Design of Reconfigurable machining system

The purpose of the design of the RMS 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 [Koren and Kota, 1999]. The design of the machine utilized a library of machine modules which provided a platform for fundamental motion analysis. A set of modular machines could be connected together to generate the new type of machining system, producing a reconfigurable machining system.

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

3.1 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 fulfill the undefined production requirements which causes the customer to pay for unneeded capabilities.

Reconfigurable machining system: 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 [Reuven and Moon, 2000].

3.2 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 that are incurred due to software development, installation and maintenance.

Modular machine 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 [Koren and Kota, 1999].

3.3 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** [Landers, 2000]. 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 products/components from the market/customer requirements are as in Fig.5. The part families have been assigned using the requirements of kinematic viability and structural stiffness analysis of the RMS. These in turn define the products' features and manufacturing processes.

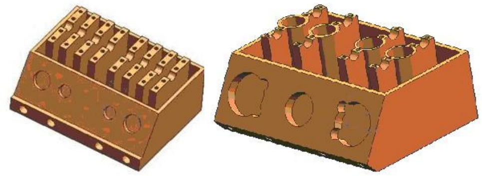


Fig. 5: Part family: two kinds of engine blocks

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 Fig.6.

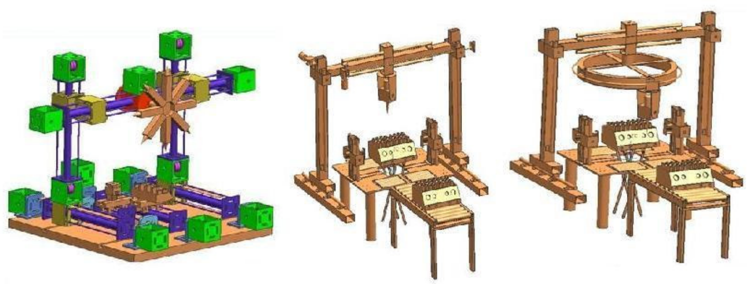


Fig. 6: MR^2G modular machine conceptual design

The modular machine is assembled from a module library 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.

4. Reconfigurable machining system for Agile Mass Customization Manufacturing environment

4.1 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-fulfillment processes that can manage anticipated change with precision while providing fast and flexible response to unanticipated changes [Fulkerson, 1997]. 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.

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 2.3.

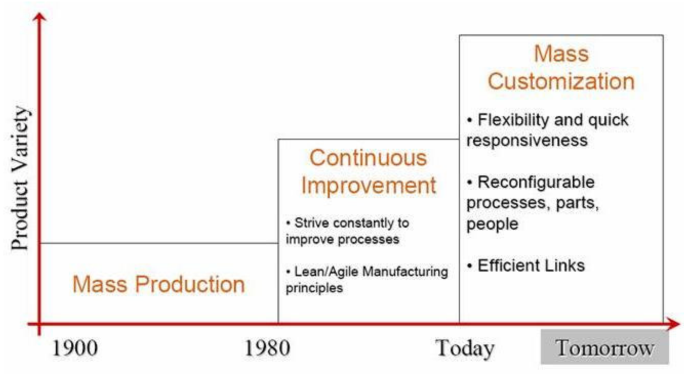


Fig. 7: From mass production to mass customization (MC).

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 [Pine, 1993]. 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 [Ruddy, 2002]. 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 [Felton, 2001]. 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 [FMS FOR MCM].

4.2 Reconfigurable machining system 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) reconfigurable machining system, and 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 reconfigure the system, developing and integrating new functions when necessary.

The reconfigurable machining system is based on generic modular mechatronic controlled and mechanically modular machines in addition to other value-added, automatic, reconfigurable product quality inspection and material handling facilities. The reconfigurability 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.

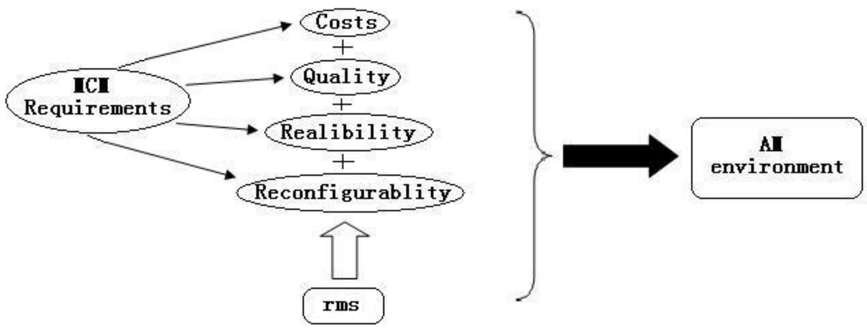


Fig.8: MCM requirements for rms in Agile MCM environment

5. Reconfigurable Machine Using Modular Mechatronic Control

The RMS 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 [Potgieter and Bright, 2002]. 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 reconfiguring 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. A H-Bridge setup 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 [Grabowski and Paredis, 2002]. 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.

6. 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.

7. CONCLUSION

The research developed reconfigurable modular machines 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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