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Modular Reconfigurable Machines Incorporating Modular Open Architecture Control

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Abstract- The Reconfigurable Manufacturing System (RMS) paradigm has been formulated to encapsulate methodologies that enable manufacturing systems to display a variability of system functionality and capacity in response to constantly changing production requirements. The formulation of a new class of production machinery, Modular Reconfigurable Machines (MRMs), for RMS is presented. By virtue of their fully modular nature these machines are able to display a variability of machining functions and cutting degrees of freedom on a single platform. A corresponding modular Open Architecture Control (OAC) system is presented. OAC overcomes the inflexibility of fixed proprietary automation, ensuring that MRMs provide the reconfigurability and extensibility necessary to meet the demands of modern manufacturing.

Index terms – Reconfigurable Manufacturing Systems, Modular Reconfigurable Machines, Open Architecture Control, Modular Machine Control

I. INTRODUCTION

Reconfigurable Manufacturing Systems (RMS) is a new class of manufacturing systems, having been created to overcome the inadequacies of previous manufacturing paradigms [1]. These inadequacies entail the inability to cope with the rapid introduction of new products, fluctuating consumer demands and provision for Mass Customization Manufacturing (MCM) [2]. The following is a definition of RMSs offered by Koren et al [3]:

A Reconfigurable Manufacturing System (RMS) is a system that combines the advantages of DMS and FMS by designing it at the outset for rapid change in structure, as well as in its machines and controls, in order to quickly adjust production capacity and functionality in response to market or product changes.

The formulation of a new manufacturing paradigm required the reengineering of the production machinery, which are to impart defining characteristics to the system. Dedicated Machine Tools (DMTs) are characteristic of Dedicated Manufacturing Systems (DMS) while Computer Numerically Controlled Machines (CNC) are characteristic of Flexible Manufacturing Systems (FMS) [4, 5]. The failing in both these systems can be traced to the nature of the production machinery employed in each. DMTs are rigid machine tools, being designed for the production of a single product; these machines are robust and cost effective. DMTs however, limit a system as a whole to the production of a small variety of products. CNC machines, on the contrary, are designed to be general purpose, thereby imparting high flexibility to FMS; nonetheless these machines often possess excessive functionality, resulting in FMS being an expensive system with a longer payback period than DMS [1, 6]. Presently DMT and CNC machine controllers are proprietary in nature. Proprietary controllers are expensive to upgrade and present hindrance in interfacing a machine with a higher control system [7].

This paper presents the formulation of Modular Reconfigurable Machine (MRM) tools for RMS, a new class of production machines, which by virtue of their modular characteristics offer the reconfigurability required by RMS to provide a rapid response to market or product changes. Outlined are the methodologies for MRM design from mechanical, electronic and control perspectives. In enhancing the extensibility of the machines controller, the development of a modular real time Open Architecture Controller (OAC) has been initiated. OAC systems aim at eliminating the problem of “vendor lock in” thereby making upgrades and alterations to the system easier and more cost effective. OAC further enables communication between the MRM and higher control systems, an essential capability for RMS.

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II. RELATED WORK

A. Reconfigurable Machinery- Related work

Having identified the inadequacies of conventional machine tools, researchers at the Engineering Research Center for Reconfigurable Machining Systems (University of Michigan) developed a new generation of machines called Reconfigurable Machine Tools (RMT). The design of RMTs began with the conception of a library of machine modules [8]. The notion of designing machinery from a library of modules is critical in shortening the machine development process. A methodology developed by Moon and Kota [8,9] makes use of Screw Theory and Graph Theory to transform a given set of machining operations into a kinematically viable machine tool whereby the necessary precompiled parameterized library modules are identified for the synthesis of the machine. This methodology was applied to the development of the world's first RMT: the Arch Type RMT. The machine was designed around a family of engine blocks to be machined (V6 and V8) and displayed reconfigurability in terms of the angle of inclination of the cutting tool. The machine was capable of either drilling or milling operations on the various inclined surfaces of the engine blocks [10]. Although being designed from a library of machine modules the Arch Type RMT did not exhibit modularity, in the sense that machine modules could be added and deleted from the platform to enhance or diminish the machines functionality. MRM technology has been developed on principles established in RMT technology; however the key distinction between both is the design orientation. Unlike RMT's, MRM technology is not part family orientated. The *fully modular* nature of the machine, including the modular OAC system, permits the machine to be adapted to the production of multiple part families, while still being customizable to the machining task at hand.

B. Open architecture control

Open Architecture Controllers (OAC) are aimed at eliminating the problem of implementation by creating a flexible control system, which can be attached to a wide variety of machine tools. The advent of faster processors for personal computers (PCs) and a general reduction in their prices have increased the use of PC-based controllers. PC based controllers are generally flexible, open and can be easily integrated into multiple manufacturing configurations [11]. They also offer faster design cycles, lower down time with the aid of diagnostic and simulation tools. These attributes help in enhancing productivity and reduce maintenance costs.

In recent years, organizations like Open Systems Architecture for Controls within Automation systems (OSACA), Open Modular Architectures Controllers (OMAC) and academic institutions like University of Michigan and University of British Columbia have either drawn standards or developed an open architecture controller for machine tools. Most controllers of this nature are implemented using PC's supporting a real-time operating system (OS), including the utilization of communication networks such as PROFIBUS and SERCOS. Peripheral devices such as digital signal processing (DSP) boards and microcontrollers are then used for low-level processing and I/O operations. Although several controllers have been successfully implemented, much work is still needed in improving the openness and real-time performance.

C. Real time performance

Machine tools require robust real-time motion control capabilities in which time constraints are critical to maintaining the accuracy and integrity of a product. PC based Real-Time Operating Systems (RTOS) are generally implemented as the real-time system of choice [12]. RTOS have the ability to: schedule tasks according to performance critical priority, quickly recover from errors, provide fast switching between tasks and most significantly, they are extensible. Further advantages include reduction in sizes and overheads. The presence of characteristics like multi-threadedness, preemptability, thread priority, predictable thread synchronization mechanisms, priority inheritance and predefined latencies (predictable) in an operating system makes PC based RTOS suitable for real time machine control. Thus far RTOS like the QNX and other UNIX based OS have been implemented and tested in manufacturing situations.

III. MRM – MECHANICAL ASPECTS

Modular Reconfigurable Machines (MRMs) are *fully* modular in nature. The mechanical modules, from which an MRM is created, have the ability to be assembled in a "building block" fashion. This permits the mechanical modules to be assembled in multiple configurations, providing a variation of the machining Degrees of Freedom (DOF) and machining functions on a single platform. The primary stage in the development of a MRM is the synthesis of a library of precompiled mechanical modules, from which only the necessary modules are selected to provide the required machine configuration. The complete library of modules represents a general machining solution to a manufacturer; a customized solution may be derived through the purchasing of a subset of library modules, according to the machine functionality required. Future enhancements may be made to a machining platform through purchasing of additional modules.

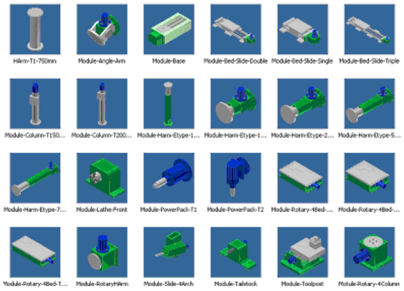

Figure3.1: A library of mechanical modules for MRMs

A. Module Types

Modules within a library are classified into three categories: *Function, Motion and Accessory.* Function modules are interchangeable modules that provide a machining process. Each function enables one of the following machining processes: Drilling, Milling, Tapping, Boring, Grinding, Polishing Engraving and Turning. The functionality of a machine tool is reconfigured through the variation of function modules as the end effectors of a system. Fig 3.2 illustrates this.

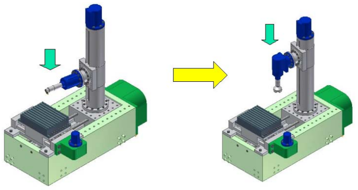

Figure: 3.2. A Reconfiguration of Machining Functionality

Motion modules are modules that contribute to the Degrees of Freedom (DOF) possessed by a machine tool. The platform developed possessed a minimum of three DOF (translations along the X, Y and Z axes of a Cartesian coordinate system). Additional motion enhancement modules were then created enabling a variability of: 3, 4, 5 and 6 DOF on a single platform. Each additional DOF is added through the integration of a Motion Module. In total eight different kinematical configurations were achievable on a single platform. Such reconfigurability has thus far not been displayed by commercial machine tools or academic prototypes. Fig 3.3 illustrates the reconfiguration of machining DOF through the integration of a Motion Module. The third class of modules used in the assembly of an MRM is Accessory Modules. These modules are not directly involved in the cutting process; however they are essential to the successful completion of a task. Such modules include work clamps and work piece stabilizers.

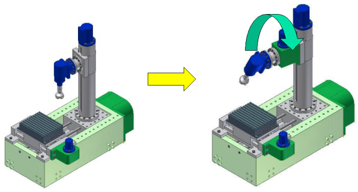

Figure: 3.3. A Reconfiguration of Machining DOF

B. Module Architecture

All modules within the library possess three types of standardized interfaces that enable the integration of modules in a building block fashion. These are standardized mechanical, power and control interfaces. Standardized mechanical interfaces facilitate physical interconnectivity between modules. A standardized mechanical interface further allows multiple types of modules to be connected to a single interface enabling a reconfiguration of machine topology. Each module contains a DC motor and other mechanical actuation gear that enables the module to provide a required motion. Power to the mechanical actuation gear is supplied via the standardized power interface. This allows the module to be connected to external motor control circuitry performing PWM. Embedded within each Motion Module was a three channel 500 PPR encoder, facilitating position control. Function Modules contained a dual axis accelerometer for vibration sensory feedback. All sensory information is fed back to external control circuitry via the standardized control interface. Control circuitry is housed externally to each module. The choice not to embed intelligence within a module was based on ease of accessibility to control circuitry for upgrades and repairs.

IV. KINEMATIC MODELLING

Each mechanical module possesses two standardized mechanical interfaces (Rear and Front). The first stage in the kinematic modeling of a MRM is the placement of coordinate systems at the centre of both interfaces of a module. The placement of the coordinate system on an interface must be such that it will coincide with the coordinate systems of adjacent module interfaces, once all modules have been assembled into a viable machine tool. This permits each module to be described by a transformation matrix M_n that relates the two coordinate systems placed on either interface. Module transformation matrices may then be concatenated in order of assembly from the cutting tool to the work bed, yielding a final matrix that describes the position of the cutting tool relative to a global reference on the worktable. The Forward Kinematical model is given by:

$$T_{tool}^{worktable} = M_1 M_2 M_3 \ldots M_n \tag{1}$$

From (1), equations for the end effecter position $S(\theta_n,T_n)$ are derived, where θ and T are the rotations and translations of the system. $S(\theta_n,T_n)$ is given by:

$$S(\theta_n,T_n) = \begin{bmatrix} x(\theta,T) \\ y(\theta,T) \\ Z(\theta,T) \end{bmatrix} \tag{2}$$

Due to the multiple kinematic configurations achievable, analytical solutions to the inverse kinematic problem of MRMs are not feasible. Instead an iterative Jacobian solution was integrated into the controller. Such a solution easily facilitates the control of multiple configurations of the machine tool. Based on the research of Kang [12], the method of Damped Least Squares was selected for integration into the IK controller. The algorithm for DLS is as follows:

1) Calculate the error between current and target positions based on current joint values
$$error = t - S \tag{3}$$
2) Calculate the Jacobian matrix using current joint values
$$J = \frac{\partial S_i}{\partial(\theta,T)_J} \tag{4}$$
3) Calculate the change in joint values using the DLS formula
$$\Delta\theta = J^T (JJ^T + \lambda^2 I)^{-1} \times error \tag{5}$$
Where λ is a preselected damping constant

4) Update values for joint angles
$$\theta = \Delta\theta + \theta \tag{6}$$

5) Repeat steps until the error between current and target position is negligible.

This algorithm was coded into the Open Architecture Controller (OAC), and further enabled the machining of contours that cannot be expressed or programmed using conventional CNC programming languages.

V. CONTROL ARCHITECTURE

A. Control Hardware

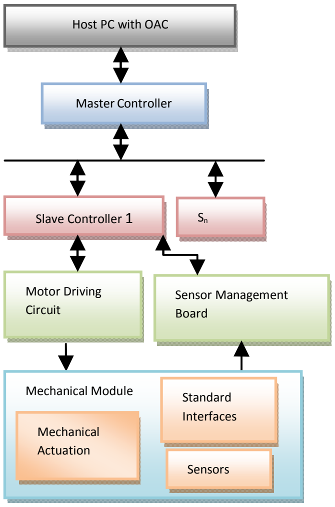

Figure 5.1 Hardware Schematic of system

At the head of the control system is a Host PC supporting the OAC system. The Host PC is responsible for all calculations involving inverse kinematics and calculations related to the trajectory of the tool. The OAC interfaces with a Master Control Module via USB. The Master Control Module is an ATmega32 based micro controller board, responsible for the management of instructions to Slave Control Modules. Slave modules are networked together on an I2C network; up to 128 slave modules may be connected. Individual slave modules map to mechanical modules on a 1:1 basis. For each new mechanical module integrated into an MRM platform a corresponding slave module is added to the network. Slave modules are ATmega 32 based and receive instructions on distance to move and speed of movement, or in the case of a Function Module, simply the cutting speed. Slave modules provide a PWM control signal to H-Bridge motor driving circuits as well as receive feedback from a Sensor Management Board, which is dedicated to each mechanical module. Feedback from the sensor management board is via UART. These boards are ATmega 8 based and are responsible for analyzing feedback from the 500PPR encoders embedded in each mechanical module.

Illustrated by Fig 5.1 is the complete electronic hardware architecture of the control system. The system is fully modular and distributed. The modularity of the system facilitates scalability, whereby the processing potential of the controller may be increased as outlined. The distributed nature of the system improves maintainability, promoting cost effective repairs and upgrades.

B. PC Based Open Architecture Control

The PC based control architecture of the system is based on the OSACA reference model illustrated in Fig 5.2. Real-time (RT) Linux has been selected as the RTOS. In addition to being an open source platform, RT-Linux has short scheduling and interrupt latencies [11]

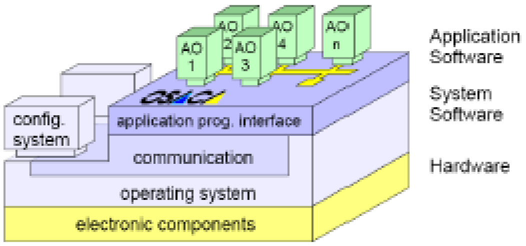

Figure 5.2 The OSACA reference model

RT-Linux has been shown to have a worst case scheduling latency of 25 µsec on a 300MHz and 128 MB Pentium II machine. The host PC of the MRM platform has a processor of speed of 2 GHz and is equipped with 1GB of RAM.

VI. CONTROL IMPLEMENTATION

The control functions were distributed between micro controller and PC levels. Proper structuring of the software was ensured through use of structures and styles where a system was decomposed into subsystems and consideration made on the interaction of the resultant subsystems. A good architectural style ensured a well coordinated, synchronised and properly functioning system. A combination of styles normally creates a more robust system. Key identifying characteristics in a style include flow of data within a system, mode of transmission and good synchronicity. Each architectural style has its own advantages and disadvantages but for this particular project data abstraction and object oriented style were the focus in software implementation. This style is characterised by encapsulation of data and its primitive operations into abstract data called objects [13]. The ability of an object to hide its representation from the clients makes it possible to change the implementation without affecting the client. The bundling of a set of accessing routines with the data they manipulate enables programmers to decompose problems into a collection of interacting agents. C++, an object-oriented programming language was used for the implementation. The hardware implementation discussed, adopted the hierarchical architecture, which promoted reconfigurability. Furthermore, proper positioning of sensors in MRM modules, and properly implemented data transmission prevented communications delays while simultaneously enhancing the real-time characteristics of the system

VII. DISCUSSION

A. Reconfigurability

The MRM platform displayed a variability of eight processing functions on a single platform. In addition to the cutting processes the platform further displayed eight different kinematical configurations. In total 64 different reconfigured states were achievable on a single platform. Reconfigurability of this level in a machine tool will effectively enable RMS to provide a reconfiguration of overall system functionality according to changes in production requirements.

B. Accuracy and Repeatability

The sensory infrastructure of each MRM Motion Module included an encoder capable of a pulse count of five hundred pulses per revolution. In modules providing a rotary motion the encoders were coupled directly to the output shaft thereby reducing mechanical errors in the angular positioning feedback loop. Individual rotary Motion Modules possessed a control resolution of 0.72^{o}. Linear acting Motion Modules possesses an average control resolution of 0.005mm, an accuracy of 0.032mm and repeatability of 0.054mm. When modules were assembled the cumulative machining accuracy and repeatability of the MRM platform was found to be unsatisfactory. A typical CNC machine has a repeatability figure of 0.008mm [14]. Poor accuracy and repeatability figures were attributed to errors in the mechanical assembly of MRMs. Such errors were expected due to the modular nature of such machine tools. The rigid mechanical architectures of conventional DMTs and CNC machines impart superb accuracy to these machines. Further research is to be conducted on two fronts in the improvement of MRM accuracy. The first path of research will be conducted into methodologies for MRM assembly, which will reduce errors during the mechanical reconfiguration process. The second path of research will be conducted into machine calibration techniques that will allow the controller to absorb errors in the mechanical configuration. This will provide accurate positioning of the machine tool relative to the prescribed global reference frame on the machine worktable.

C. Spindle Power and Cutter Sizes

The self-contained nature of individual modules required that the motors powering the cutting tools be housed within individual Function Modules, thereby limiting motor sizes and cutting power. A reduction in motor cutting speeds and torques invariably imposed limitations on the sizes of the cutting tools installed on the platform, resulting in the MRM platform displaying smaller machining capacities in comparison to similar sized CNC machines.

VIII. CONCLUSION

The RMS paradigm has been developed in response to global manufacturing challenges. In addressing these challenges a manufacturing system is required to quickly adjust system functionality and production capacity in accordance to changing production requirements. In facilitating system responsiveness RMS requires that production machinery be readily reconfigurable at hardware and software level. This paper presented Modular Reconfigurable Machines, a new class of production machines that incorporate Open Architecture Control in order to meet the requirements of RMS. The paper presented the methodologies employed at mechanical, electronic hardware and software levels of the machines design, including architectural and algorithmic details of the machines control system. In total 64 different functional and kinematical combination states were achieved by a single platform. Although further improvements to the accuracy of MRM technology are required, the level of reconfigurability achieved has verified that MRMs possess the necessary characteristics required for implementation in RMS.

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