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Mechatronic Design of A Reconfigurable Machining Machine

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Abstract—**The paper deals with the integration of mechanical and control aspects involved in the design of a novel 4-DOF reconfigurable machining machine (RMM). Its modular mechanical structure and control system are conceived in order to obtain the reasonable flexibility and reconfigurability in performing a series of machining tasks around a product family. Reconfigurable machines bridge the gap between two types of conventional machining machines: the fully flexible machining machines and the totally dedicated machining machines. The application of the integrated mechatronic design approach and its application advantages are detailed in this paper. A full-scale RMM prototype has been built; its hardware and software layouts are presented as well. The experimental results compared with the traditional drilling/milling machine performance are also discussed.**

I. INTRODUCTION

Two types of conventional manufacturing system are mainly utilized by manufacturing companies. The dedicated manufacturing system (DMS) which is designed for high part production volumes and the flexible manufacturing system (FMS) which is used to deal with the relatively lower part production volumes and more part feature changes. In order to cope with the modern mass customized manufacturing environment, a new type of manufacturing system called reconfigurable manufacturing system (RMS) was introduced by Y. Koren in 1997 [1]. The advantages of this new manufacturing system are: reasonable flexibility and acceptable cost compared with the redundant flexibility and high cost which FMS is suffering; higher reconfigurability compared with the DMS. The same as the role of dedicated machines like drilling and milling machines in a DMS and computer numerical controlled (CNC) machines in a FMS, a typical RMS consists of a series of reconfigurable machines: reconfigurable machining machine (RMM), reconfigurable inspection machine (RIM) and etc. which is shown in Figure 1. Normally, the dedicated machine used in a DMS is specifically designed for a single part that would be mass produced. It can perform a unique operation with high reliability, high repeatability and high productivity. As a result its structure is relatively simple and its cost is always less expensive. On the contrary, the CNC machine used in a FMS is designed to produce as many as different parts that would be mass produced. It should perform multiple operations with the same high reliability, repeatability and productivity as dedicated machine does. Due to the reasons of redundant flexibilities and so on, the cost of CNC is extremely expensive.

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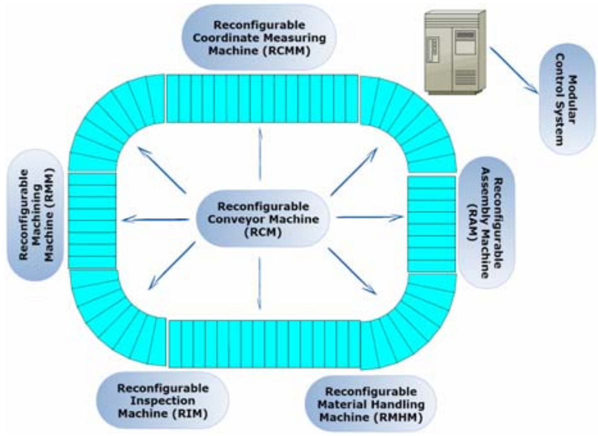

Fig. 1. RMS cell.

The design of RMM requires broad knowledge of machine design, machine tool design, kinematics modeling and dynamics analysis. According to the literature research, there is no comprehensive theory or design methodology that is directly applicable to the RMM design. The concept of reconfiguration has been used in related fields including fixture design, assembly system design and reconfigurable robots. Shirinzadeh [2] developed a CAD based reconfigurable fixture design methodology. Hollis [3] developed a robotic reconfigurable assembly system. Researchers involved in reconfigurable robots have developed several design methodologies and some can be applied to the design of RMM [4]. Researchers at the Carnegie Mellon University developed RMMS (Reconfigurable Modular Manipulator System) [5]. They identified the characteristics of reconfigurable machine design as a task based design and developed a design methodology for reconfigurable manipulators from the kinematics task requirements [6] [7]. I.-M. Chen [8] applied the theory of graphs to the design of reconfigurable manipulators and proposed the concept of Assembly Incident Matrix. By manipulating the graphs, Chen generates all possible configurations which could fulfill the kinematics requirements [9]. As a result, there is a need to have an effective design approach for reconfigurable machines design so that it can bridge the gap between the dedicated machines and the CNC machines.

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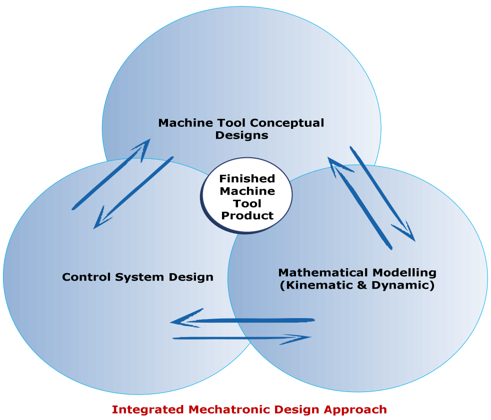
II. Design and Optimization

A. RMM Design Approach

Classical machine tool design consists of two sequential aspects of optimization: mechanical structure and control system. Normally, designer will start with machine mechanicals design by using CAD tools such as SolidWorks. Once the designer completes the CAD model and finish building a full scale physical machine, electrical and control engineers will lay out the electrical system and program the machine controller. The design team will perform the experimental test on the physical model integrated with control system. Any problems at this phase that require reworking on the control system or even redesigning the machine elements can lead to long delays and increase extra expenses which can significantly influence the difference between profit and loss for machine tool builders. However this design approach is still widely used among the machine tool builders in spite of its less effectiveness. In order to solve this problem, in this paper we utilized a novel approach termed mechatronic design for RMM building. Mechatronic is a combination of multidisciplinary engineering fields: computer engineering, control engineering, electronic engineering, mechanical engineering and etc. The mechatronic design approach can overcome the disadvantages that tradition design approach is suffering by connecting machine design tools and creating a virtual machine prototype before the full scale physical machine is built. The comparison between the conventional machine tool design approach and the integrated mechatronic design methodology is shown in Figure 2.

A virtual machine prototype is a 3D CAD model of the machine that interacts with a machine controller simulation to visualize and test machine behavior. Based on such 3D model, machine designers can test and improve their machine designs in a computer environment before establishing any physical components as shown in Figure 3.



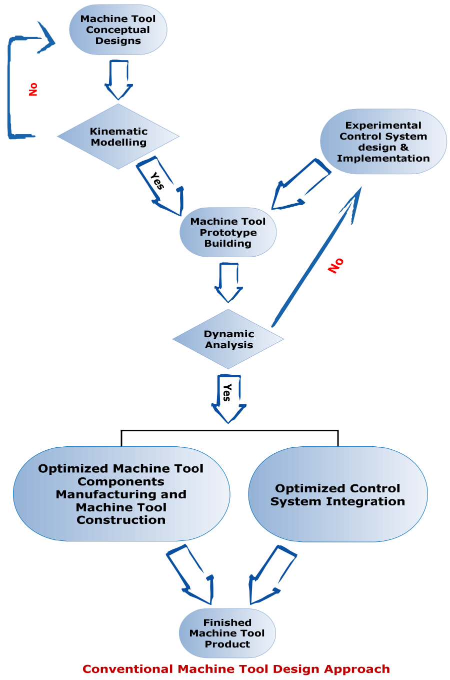


Fig. 2. Comparison between the conventional approach and the mechatronic approach.

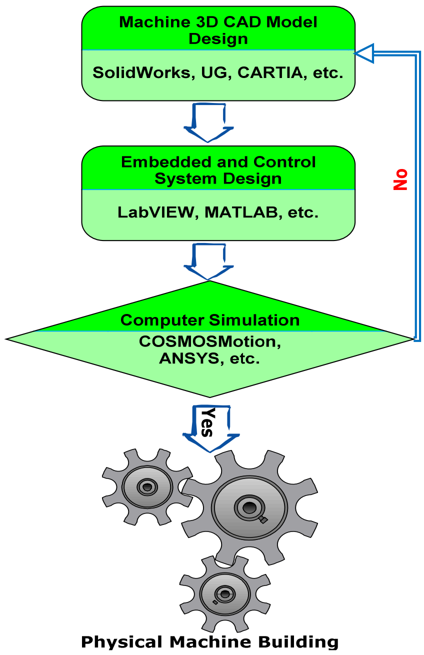


Fig. 3. Graphical machine tool design.

B. Machining Requirements Clarification and Machining Operation Plan

The first step of RMM design is the work piece machining requirements clarification. Each requirement includes a series of machining operations and each operation represents a kind of machine tool motion type. Some typical motion types are defined as follows:

- *RMM Tool Point Motion (TPM)*: An RMM TPM is the movement among different consecutive tool positions which are represented by a series of points in space;

- *RMM Tool Machining Motion (TMM)*: An RMM TMM collects all RMM TPMs which are involved in the same machining feature (hole, slot, etc.). All of TPMs have the same directions (x axis, y axis, etc.) and perform the same machining task (drilling, milling, etc.);
- *RMM Tool Machining Motion Family (TMMF)*: An RMM TMMF is the collection of a series of machining motions among different work pieces which can share the same motion types.

An RMM machining operation plan contains information that consists of machining operation parameters and machine tool motion for a machining feature family. A text form of the machining operation plan is listed in Table I. A typical machining operation plan includes some of the following parameters:

- *Machining Type*: At this stage, different machining operation types would be considered, classified and analyzed such as drilling, milling, grinding, turning, reaming, etc. In this paper, only drilling and milling operation will be considered;
- *Machining Characteristic*: machining time, feed rate, material, tool type, etc.;
- *Setting Up*: Initial position of the tools' tip and the orientations of work piece at each step;
- *Tool Tip Machining Position*: tool tip's location during the machining procedure;
- *Work Piece Feature*: tool cutting trajectory selection.

TABLE I
MACHINING OPERATION PLAN

Unit: mm, N, sec		
Part No.:	A	B
Type of Material:	Wood	Wood
Initial Position:	(0, 0, 0, -100, -70, -100)	(0, 0, 0, 150, -50, -125)
Machining Procedure:	1	1
Tool Type:	Drilling	Drilling
Tool Initial Position:	Drill #5	Drilling #5
Feed Rate:	0.2	0.2
⋮	⋮	⋮
Feed to Position n:	(0, 0, 0, -100, -70, -100)	(0, 0, 0, 150, -50, -125)
Machining Procedure:	2	2
Machining Type:	Milling	Milling
⋮	⋮	⋮

C. RMM Mechanical Design

In this section, Graph Theory was used to represent RMM's topological and functional structure. A graph consists of nodes and edges. By using two basic nodes as shown in Figure 4, an example RMM that has work table, base, column frame and tool head can be illustrated in Figure 5. Figure 5 shows two types of reconfiguration can be achieved by using same mechanical modules.

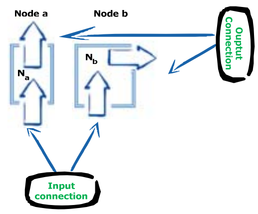


Fig. 4. Basic nodes.

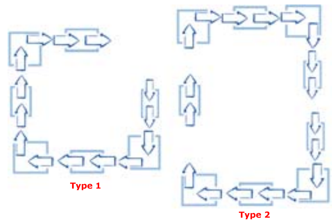


Fig. 5. Two types of reconfiguration.

In this paper, we define three types of basic mechanical modules: Module I, Module II and Module III. Among these three basic modules, different combination of DOF and movement can be created as shown in Table II.

TABLE II
MODULE COMBINATION

	Module I	Module II	Module III
Module I	1	2	3
Module II	2	1	2
Module III	3	2	1

Arrow means the direction of movement;
Number means the degree of freedom (DOF).

In SolidWorks, a series of modules have been created for RMM design. Based on the graph theory, an RMM module selection procedure can be illustrated in Figure 6.

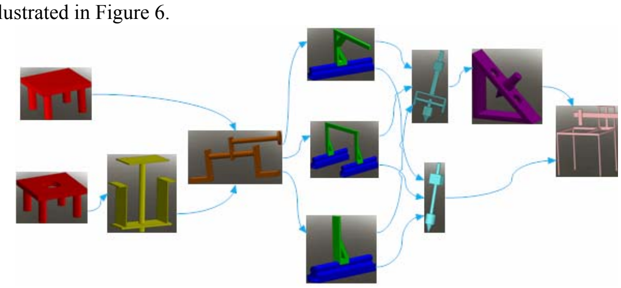


Fig. 6. Module selection graph.

Based on the university research lab environment, a set of suitable modules have been selected and manufactured. The full scale RMM and its integration with RCM and RIM are shown in Figure 7.

Fig. 7. Full scale RMM.

D. RMM Control System Design

The PC-based control system for the RMM was implemented using an Eagle MicroDAQ Data Acquisition Box USB-120A as illustrated in Figure 8. Based on its corresponding EDR software developer's kit, a series of customized digital I/O operations can be programmed.

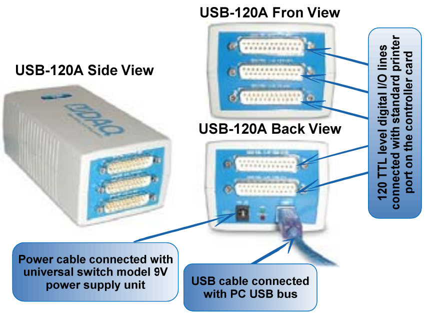


Fig. 8. DAQ box.

One of the most important aspects of RMM control system is the motor control. The Pulse Width Modulation (PWM) principle is widely used in motor control field. This principle operates by applying the full supply voltage to the motor for short pulses of variable duration. This is done by timing the opening and closing of high frequency switch. In practice a power MOSFET (Metal-Oxide Field-Effect Transistor) is used to do this switching. A signal similar to the waveform desired across the motor is sent to the gate of the MOSFET, which is either open or closed with the signal to its gate being high (~11V) or low (~0V). However, the disadvantage of the PWM circuit is that it does not provide for direction reversal of the motor rotation. So in the case of RMM motor control, we would utilize a separate circuit which has a Double-Pole Double-Throw (DPDT) relay configured specifically for polarity changing of the voltage fed to the motor, or by combining PWM with an H-bridge circuit which is shown in Figure 9.

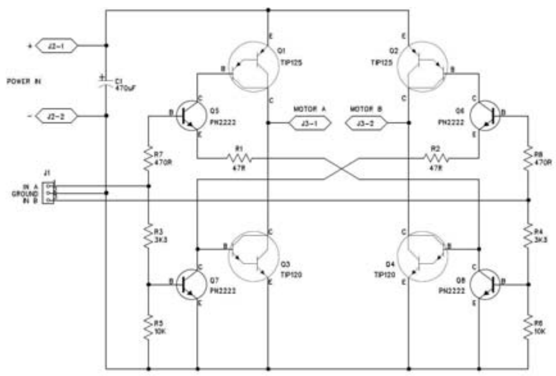


Fig. 9. H-Bridge drive circuit [10].

As shown in Figure 9, there are two level compatible inputs, IN A and IN B, and two outputs, MOTOR A and MOTOR B. If IN A is brought to high, output MOTOR A goes high and MOTOR B goes low. The motor goes in one direction. If IN B is driven, the opposite happens and the motor runs in the opposite direction. If both inputs are low, the motor is not driven and can freely "coast", and the circuit consumes no power. If both inputs are brought to high, the motor is shorted and braking occurs.

The mathematical model of DC motor can be expressed by the following equations and the control Simulink diagram is also illustrated in Figure 9:

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + e_a, \text{ where } e_a = K\omega_m$$

$$T_e = J\frac{d\omega_m}{dt} + T_L \text{sign}(\omega_m) + B_m\omega_m, \text{ where } T_e = Ki_a$$

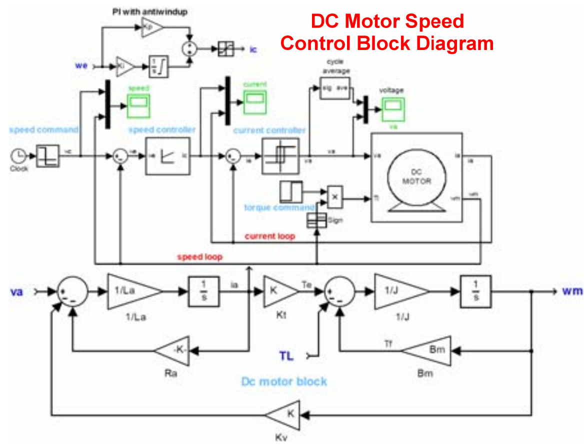


Fig. 10. DC motor speed control block diagram.

Based on MATLAB/Simulink simulation, a motor controller card has been made in the research lab as shown in Figure 11.

Fig. 11. PWM motor controller card.

In keeping with the modular control protocol, the development of RMM control system was decomposed into four control modules as follows:

- Automatic Part Transfer System (APTS) control module;
- Automatic Part Clamping/Rotating System (APC/RS) control module;
- Automatic Part Lifting System (APLS) control module;
- Automatic Tool Changing System (ATCS) control module.

In this paper, we only discuss the APTS control module design for example. The APTS movement requires the generation of 4 activation signals to control the DC motor in order to implement control decisions as shown in Figure 12.

The control decisions are made based on the feedback information collected from the APTS using 6 feedback signals as shown in Figure 12. The activation and feedback signals for the APTS are listed in Table II and Table III respectively.

The feedback information for the APTS was collected using the position feedback sensor technique. A VB 6.0 project, APTS control *module.vbp*, was developed to implement the APTS control algorithm.

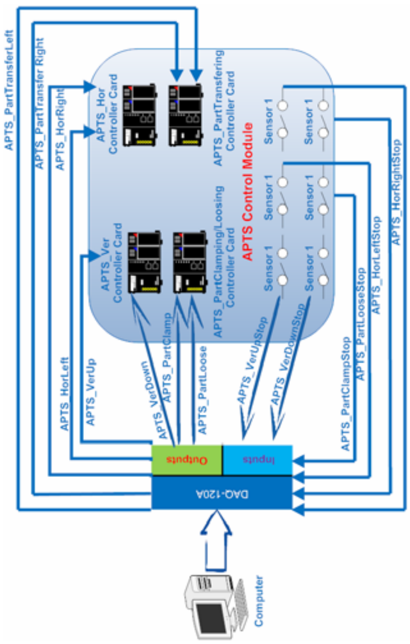


Fig. 12. APTS control module diagam.

TABLE III
APTS CONTROL MODULE ACTIVATION SIGNALS

Name:	Control Function	Port	Pin Number	EDR Code
APTS_VerUp:	Lift up the part from the conveyor	0	10	0, 2
APTS_VerDown:	Move the part back to the conveyor	0	11	0, 3
APTS_PartClamping:	Clamp the part	0	100	0, 4
APTS_PartLoosing:	Loose the part	0	1100	0, 12
APTS_PartTransferLeft:	Transfer the part to the APLS	0	10000	0, 16
APTS_PartTransferRight:	Transfer the part to the conveyor	0	110000	0, 48
APTS_HorLeft:	Locate the part onto the lifting table	0	1000000	0, 64
APTS_HorRight:	Locate the part onto the conveyor	0	11000000	0, 192

TABLE IV
APTS CONTROL MODULE FEEDBACK SIGNALS

Name:	Control Function	Port	Pin Number	EDR Code
APTS_VerUpStop:	Detect VerUp stop signal	14	10	14, 2
APTS_VerDownStop:	Detect VerDown stop signal	14	11	14, 3
APTS_HorLeftStop:	Detect HorLeft stop signal	14	100	14, 4
APTS_HorRightStop:	Detect HorRight stop signal	14	1100	14, 12
APTS_PartClampStop:	Detect PartClamp stop signal	14	10000	14, 16
APTS_PartLooseStop:	Detect PartLoose stop signal	14	110000	14, 48

III. EXPERIMENTAL TEST AND CONCLUSION

Due to the modular mechanical structure of RMM, we applied motion accuracy test based on each sub-system's performance. The dimension of the lifting table is 800mm x 600mm. The motion accuracy test results of APTS, APC/RS, APLS and ATCS are illustrated in the following tables.

TABLE V
APTS MOTION ACCURACY TEST RESULTS

Axes	Central Point Displacement (mm)										Averge Errors (mm)
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	
X-Axis	+0.7	-0.6	+0.5	-0.5	+0.7	+0.5	+0.6	-0.8	+0.7	-0.7	0.63
Y-Axis	+0.5	+0.8	+0.5	-0.5	+0.7	-0.9	+0.5	+0.7	+0.8	+0.5	0.64

TABLE VI
APC/RS MOTION ACCURACY TEST RESULTS

	APC/RS-function 1: Clockwise Rotation										
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Averge Errors
Anticipated Angle (°)	30	30	45	45	90	90	135	135	180	180	
Test Displacement (°)	+0.6	+0.7	+0.5	-0.8	+0.8	1.5	+0.9	+1.2	+0.9	+0.8	0.93
	APC/RS-function 2: Counter-Clockwise Rotation										Averge Errors
Anticipated Angle (°)	30	30	45	45	90	90	135	135	180	180	
Test Displacement (°)	+0.6	+0.7	+0.5	-0.8	+0.8	1.5	+0.9	+1.2	+0.9	+0.8	0.93

TABLE VII
APLS MOTION ACCURACY TEST RESULTS

Axes	Central Point Displacement (mm)										Averge Errors (mm)
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	
Z-Axis	+0.7	-0.6	+0.5	-0.5	+0.7	+0.5	+0.6	-0.8	+0.7	-0.7	0.63

TABLE VIII
ATCS MOTION ACCURACY TEST RESULTS

	ATCS-function 1: Clockwise Rotation										
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Averge Errors
Anticipated Angle (°)	30	30	45	45	90	90	135	135	180	180	
Test Displacement (°)	+0.6	+0.7	+0.5	-0.8	+0.8	1.5	+0.9	+1.2	+0.9	+0.8	0.93

In this paper, drilling and milling are two machining functions that have been tested on RMM. The machining cycle time and the machining accuracy comparisons between traditional single-spindle drilling machine/traditional vertical milling machine and RMM are also illustrated in the following figures.

The dimension of the experimental workpiece is 170mm x 170mm x 100mm as shown in Figure 13 and the material is wood.

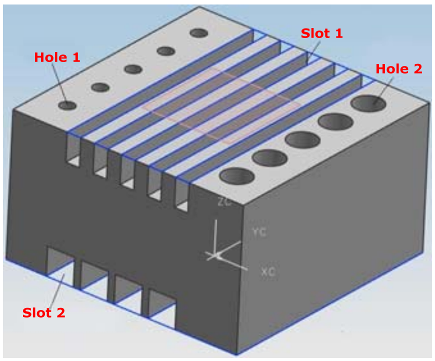


Fig. 13. Experimental workpiece.

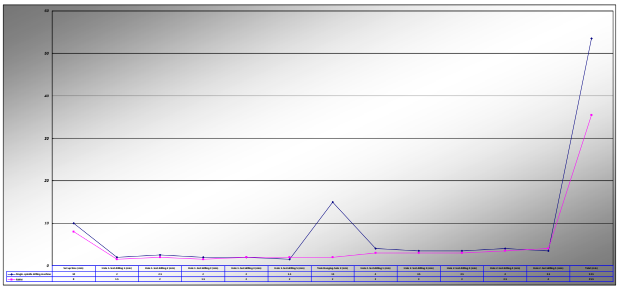


Fig. 14. Cycle time comparison between the traditional single spindle drilling machine and RMM.

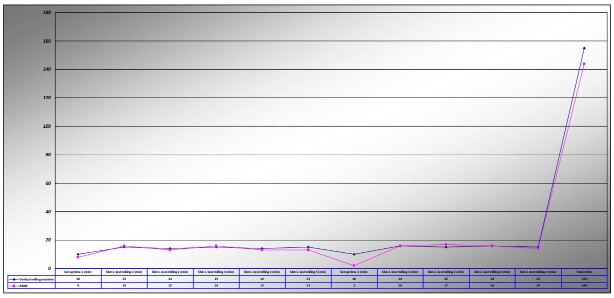


Fig. 15. Cycle time comparison between the traditional milling machine and RMM.

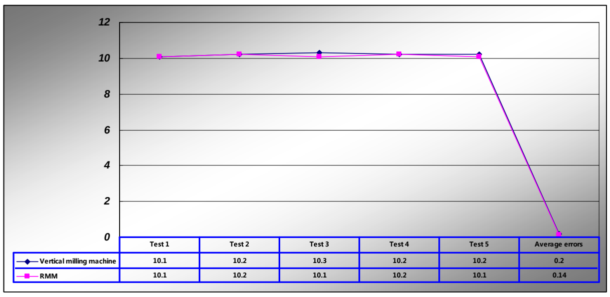


Fig. 16. Milling accuracy comparison.

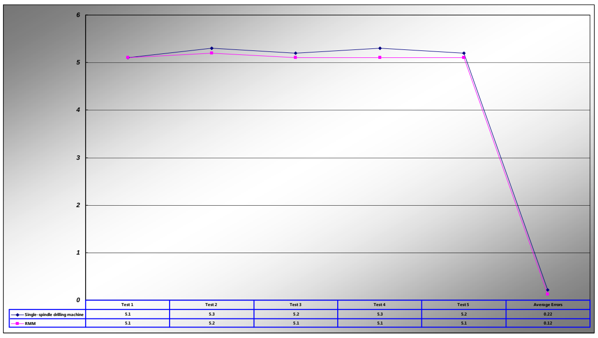


Fig. 17. Dilling accuracy comparison.

IV. CONCLUSION

In this paper, a full scale RMM has been designed, controlled and experimental tested by using mechatronic design approach. It is found that this approach has significant advantages compared with the traditional method. In addition, the experimental test results show that RMM can achieve a better performance than conventional drilling/milling machine.

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