AUTOMATIC TOOL-CHANGING WITHIN THE RECONFIGURABLE MANUFACTURING SYSTEMS PARADIGM

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ABSTRACT

Reconfigurable manufacturing systems were developed as a proposed solution to the varying market and customer requirements present in today's global market. The systems are designed to offer adaptability in machining functions and processes. This adaptive capability requires access to a selection of tools. The development of reconfigurable manufacturing systems has mainly been focused on the machine tools themselves. Methods of supplying tools to these machines need to be researched. This paper does so, presenting a tool-changing unit that offers a solution to this need. It then discusses the enabling technologies that would allow for automatic integration and diagnostic abilities of the unit.

OPSOMMING

Herkonfigureerbare vervaardingstelsels is ontwikkel as 'n voorgestelde oplossing vir die varierende mark- en klantbehoeftes in die hedendaagse globale mark. Die stelsels is ontwikkel om aanpasbaarheid te bied ten opsigte van masjineringsfunksies en –prosesse. Hierdie aanpasbare vermoëns vereis egter toegang tot 'n verskeidenheid van gereedskapstukke. Die ontwikkeling van herkonfigureerbare vervaardigingstelsels het egter hoofsaaklik gefokus op die gereedskapstukke. Die wyse waarop hierdie gereedskapstukke beskikbaar gestel word aan die masjinerie moet egter nagevors word. Hierdie artikel doen juis dit en stel 'n eenheid voor vir die ruiling van gereedskapstukke. Voorts word die tegnologieë bespreek wat automatiese integrasie moontlik maak en diagnostiese vermoëns verskaf.

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1. INTRODUCTION

Modern manufacturing demands require that producers adjust rapidly to changes in the market. These changes could be in the form of variations in production volume and/or mix. Customers are also demanding customised parts and products. This makes it necessary to have even more flexible manufacturing systems than are currently available. In response to this manufacturing climate, researchers developed the concept of ‘reconfigurable manufacturing systems’ in the mid- to late-1990s [1].

Reconfigurable manufacturing systems are designed at the outset to offer adaptability in both hardware and software. They are required to be able to respond to the varying manufacturing demands that exist in the current industrial environment. The machine tools that make up these systems must be able to deliver an array of functionality and processing capability. A selection of tools is therefore required to perform these operations. This necessitates rapid tool-changing to promote an efficient and cost effective manufacturing process. Along with this, the reconfiguration of the manufacturing equipment gives rise to the need for an in-process calibration procedure to ensure machining accuracy and timely part production. Reconfigurable machine tools will not be able to effectively function without an adaptable tool supply system.

Reconfigurable manufacturing systems (RMS) have six core characteristics [2], [15]: modularity; integrability; customisation; convertability; scalability; and diagnosability. When designing systems within this paradigm, a conscious effort must be made to keep to these specifications.

A subset of RMS known as ‘modular reconfigurable machines’ has been researched and formulated [3]. While the other characteristics of RMS design have not been neglected, this subset emphasises modular building blocks as the foundation for varying the system’s output, functionality, and degrees of freedom. It is within this subset and framework that a tool-changing module was developed, constructed, and tested in order to explore a solution to the problem of providing a reconfigurable manufacturing system with an automatic tool-changing capability.

Modern manufacturing equipment typically includes a tool-changing unit built into the system. In the field of modular reconfigurable machines, tool-changing units will be designed as one of the modules available to potential customers. It is therefore important that tool-changing units can be effectively integrated into the manufacturing system. Other machining modules, such as those that add an extra degree of freedom, will predominantly have hardware interfaces with the system. A tool-changing unit may not have this advantage, as it may be cumbersome and unnecessary to design a hardware interface for a module that does not specifically require rigidity constraints within the system.

This paper details the current development of a tool-changing unit, and also discusses the technologies necessary to improve its integration into the broader manufacturing system. Aspects that would allow the unit to perform a diagnostic analyis of the tools it stores is also discussed.

2. CURRENT WORK IN THE FIELD

A comprehensive state-of-the-art survey performed by Bi, Lang, Verner & Orban in 2007 [4] gives a clear breakdown of the development of reconfigurable machines, including the research emphasis up to that point. The paper categorises the work done into the areas of:

1) Reconfigurable machining systems
2) Reconfigurable fixturing systems
3) Reconfigurable assembling systems
4) Reconfigurable material handling systems

5) Reconfigurable inspecting and calibrating systems

It is evident from the above that extensive research has been conducted in the field of reconfigurable manufacturing systems and reconfigurable manufacturing tools. There is still a need to develop formal design methodologies for these types of tools [5].

In the modular machine arena, libraries of mechanical components have predominantly focused on motion and function modules [3]. Motion modules allow the degrees of freedom of the machine to be varied from a single degree of freedom – such as in a drilling machine – to a machine with a full six degrees of freedom. Function modules, on the other hand, deliver the machining process functions such as milling, boring, drilling, and turning.

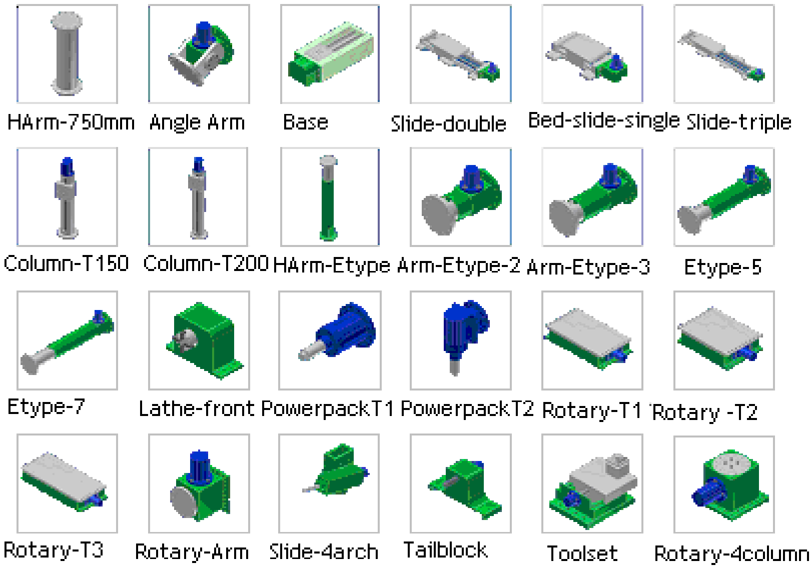

Figure 1: An example of a library of modules for modular reconfigurable machines (adapted from [3])

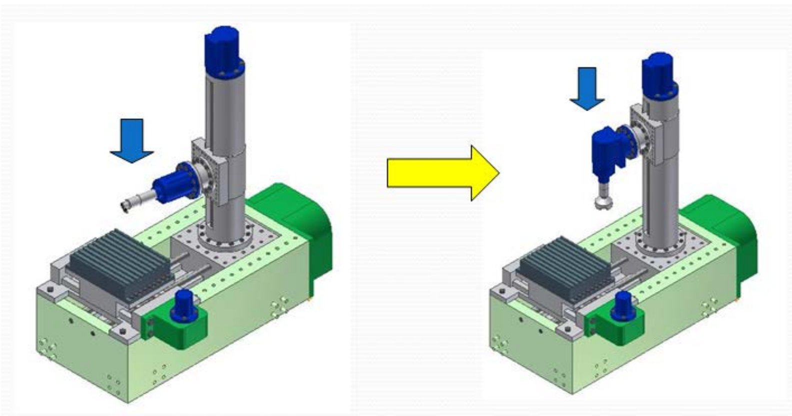

Figure 2: Using different modules to vary a machine's functionality [3]

A third category of modules, called accessory modules, are parts such as clamps and stabilisers. They might not have an active role in the cutting process, but they are critical to ensuring successful production. Tool storage and exchange systems may fall into this category, but the authors suggest that they should form part of a fourth set of modules called auxiliary modules. Auxiliary modules may also not form a direct part of the machining process, but they would add extra functionality to the machines, aiding the efficiency and quality of production. These modules might also include tool monitoring and quality control modules.

In the South African context, research has been completed by Estment, Gorlach & Wiens [7] in the area of adding an automatic tool changer and spindle to a reconfigurable machine tool. The machine tool was a gantry type CNC machine delivering 2.5 axis machining. The emphasis of the research was on the successful integration of these two new modules with the existing machine. Mach 3 CNC programming software was used to generate the required G code. The tool changer module was mounted directly on the gantry machine bed, using a part of the machine that was not required for the workspace.

3. THE DEVELOPMENT OF A STAND-ALONE TOOL-CHANGING MODULE

The Mechatronics and Robotics Research Group (MR^{2}G) of the University of KwaZulu-Natal has developed a tool-changing unit that presents a solution to the need for an autonomous module that offers a selection of tools to a reconfigurable manufacturing system. This section describes the specifications imposed on the design, and gives an overview of the various components that make up the unit.

3.1 The design specifications of the module

The first specification to be decided upon was the working space that the tool changer should cover. After a survey of typical production machines, it was concluded that the tool changer should be able to cover the 60th percentile of machine working area sizes. This would represent a good portion of commercially available machines. This requirement translates into a working area for the tool changer of 600 x 300 x 450mm above the worktable. The tool changer also had to occupy no more than 1.5m^3.

The next consideration was the carrying capacity of the unit, along with the requirement for the speed of the tool exchange. The unit was required to house at least six industry standard tool holders and perform a tool change within 30 seconds.

Initially, it was thought to design the module around a BT-30 tool holder; but upon further investigation it was found that the BT-40 holder was more common in the South African manufacturing environment. The tool changer was therefore designed to handle a tool weight of up to 5kg and have an accuracy of 2mm at the tool insertion point.

3.2 The selection of the design concept

Various methods of exchanging tools are commercially available in the manufacturing environment. Five conceptual designs were generated and considered for the development of the unit. A rotating carousel, a design that is widely implemented on CNC machines, was the emerging concept.

A graphical depiction of the structure and motion of the tool-changing concept is shown in Figure 3. The BT40 tool holders are suspended from the carousel using pull studs. Magnets are used to keep them in place during carousel rotation. The carousel, linear actuators, and gripper arm are capable of providing:

a) storage and appropriate selection of the required tools
b) translational motion to exchange the tools between the carousel and the manufacturing spindle
c) rotation to allow for spindles that may be at an angle
d) vertical motion to allow flexibility for different tool holders and for mounting the tool in the spindle and retrieving it.

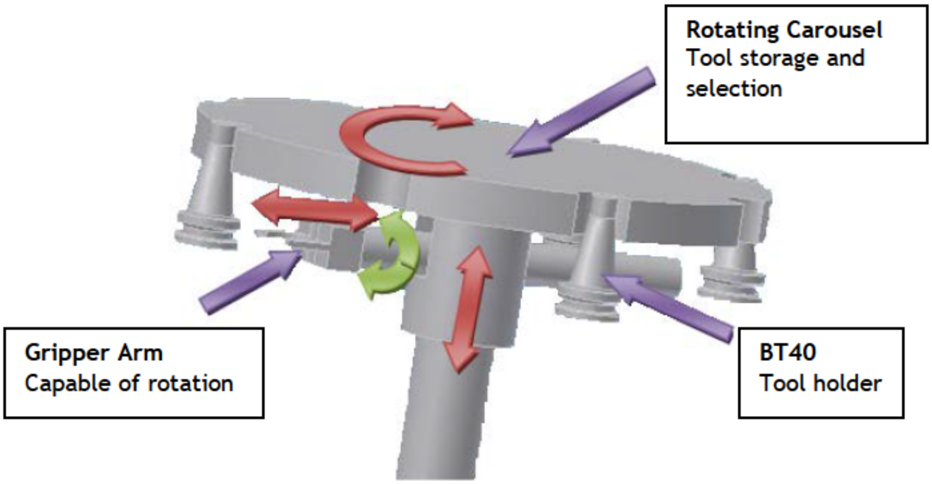

Figure 3: Tool-changing module concept [10]

3.3 The core structure of the unit

The tool changer was designed to be an autonomous module within a reconfigurable manufacturing system. It was therefore important to design a unit that would provide adequate stability during the tool-changing process. The tool changer would also need to be self-reliant, because it would be critical that it not depend on other structures for stability. A structurally-autonomous module would offer the user the advantage of flexibility: the unit could easily be used on several different machines without concern about the structural surroundings. No hardware interface would be required between the tool changer and the machine it was interacting with, as the tool-changing unit would form a complete module in the RMS environment.

The final design used a 6mm-thick mild steel 'rolled can' to form the core of the structure. The 'can' would produce the structural strength of the machine as well as provide room for some of the inner mechanical workings of the unit. It was mounted on four adjustable legs that provided stability as well as the necessary height adjustment. The skeletal structure can be seen in Figure 4.

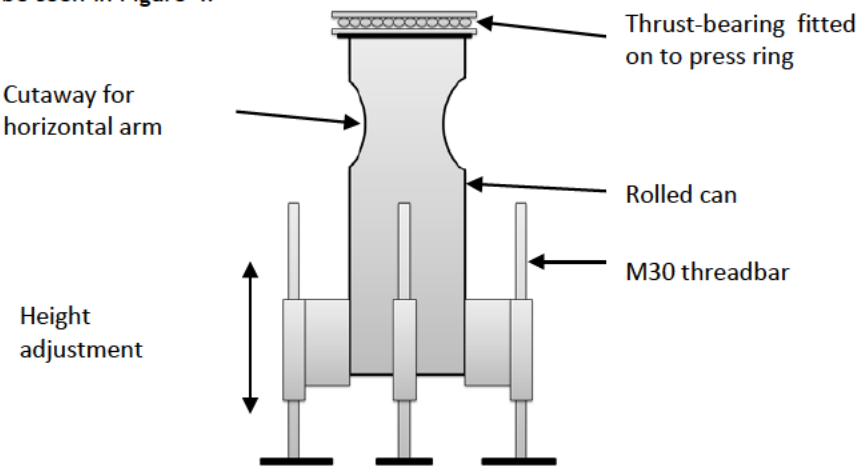

Figure 4: The skeletal structure of the tool changer (adapted from [6])

3.4 The tool transfer system

The tool transfer system is responsible for the required motions of the tools to and from the carousel and the spindle. Four degrees of freedom were needed from the tool-changing unit in order to transfer the tool effectively. The first required motion would be the rotation of the carousel. This would provide for the exchange of the different tools to and from the gripper position. The second would be the needed horizontal motion to move the tool away from the storage carousel and towards the spindle. The tool would also then need some form of vertical actuation to lift the tool into the spindle - the third degree of freedom.

A unique feature of this tool-changing unit is that it offers a fourth motion not commonly found in other tool-changing systems. This is the rotation of the tool about the horizontal axis so that the tool-changing unit can be used with a machine that uses a spindle at a non-orthogonal fixed angle. This added flexibility increases the unit's ability to interact with a greater range of machines.

In terms of the structural setup of the system, a thrust bearing was placed at the top of the core structure of the unit. The carousel was then mounted on the bearing and a geared 12V DC motor was used to drive the carousel. A DC motor was also used to drive the worm gear that would provide the rotation of the gripper arm.

For the horizontal and vertical actuation, two linear actuators manufactured by Festo were used. The actuation was delivered through electric ball screw spindle drives. DC servo motors were chosen to drive the spindles due to their small size and relatively high torque. Figure 5 shows the configuration of the two spindle drives and their directions of actuation. The larger horizontal drive delivers 300mm of translation, while the vertical drive provides the necessary 100mm to ensure adequate insertion of the tool into the spindle.

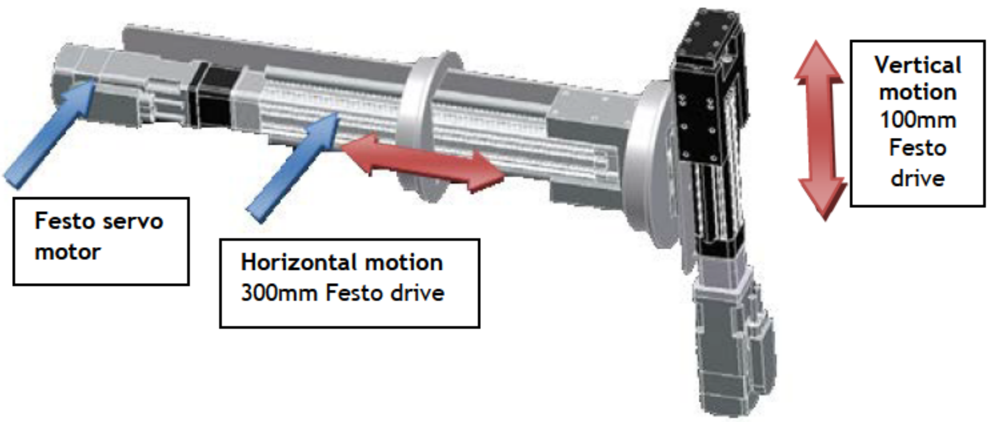

Figure 5: Spindle drive configuration (adapted from [6])

3.5 Controlling the unit

The control system plays a vital role in integrating all the aspects of the unit so that it functions successfully. It also acts as the link between the user and the machine, allowing the user to interact with the module and produce the desired results.

3.5.1 System modelling approach

The accurate modelling of a system is a significant step in ensuring accurate control. It is also important to try to model the system as efficiently as possible, to avoid excessive computation.

There are several approaches that can be taken when attempting to model a robotic system. The focus of the model is to be able to identify the position of the end effecter.

One of the approaches is to view the position of the end effecter as a cumulative output of the positions of the various degrees of freedom (inputs) of the system. In order to model the system, a mathematical function containing all of the inputs is used to calculate the output. This approach may lead to a complex mathematical function, requiring significant computing power. Although that may be seen as a disadvantage, there are applications where it is beneficial. This option only requires a single control loop, and the end effecter error is seen as a mean error distributed through the entire system. This is advantageous in situations where there are excessive degrees of freedom, or where several different combinations of the inputs give rise to the same output. It is also a useful approach when working with degrees of freedom containing similar hardware with similar tolerances.

An alternative approach – and the one that was used for the tool changer – differs from the previous concept in that each degree of freedom is considered as its own system with its own errors. This model separately examines the error generated by each degree of freedom, and reduces the errors individually. The model works well in a system where the degrees of freedom are not directly linked together in affecting the output position. An example of such a system is one with three orthogonal axes or fewer. The mathematical calculations are, as a result, significantly reduced; but the system requires a separate control loop for each degree of freedom.

This type of model was a good solution for the tool changer, as each degree of freedom is independent of the others in its effect on the desired output. To have each error calculated separately was useful in this application, since the unit consisted of degrees of freedom of varying tolerances. The high accuracies of the Festo drives could be taken advantage of, and would not be affected by the other less accurate parts of the unit.

3.5.2 General control system description

A requirement of the tool-changing unit's control system was that it be efficiently integrated into a broader manufacturing system. The control architecture used commercially-available software and hardware in its development.

User interaction with the unit was achieved through the use of a graphical user interface (GUI) programmed to run on a Windows XP PC. The PC then used serial (RS232) and USB connections to communicate with two Atmel AVR Atmega 32 microcontrollers. The microcontrollers were used to control the two 12V DC wiper motors that drove the carousel and the worm gear that generated the rotation of the horizontal axis. The switch that powered the gripper solenoid for locking the grippers was also controlled by the microcontrollers. One of the microcontrollers was used for the pulse counting of the encoders and the angular velocity data generation routines. The other was used for the pulse width modulation (PWM) and the PID controller routines. Incremental encoders were used to provide the required feedback from the motors.

The Festo drives were coupled with proprietary controllers that initially had to be set up through the Festo configuration tool (FCT). The FCT could be used to generate a position table as well as velocity profiles. Once this data was stored on the controllers, digital I/O was used for the PC to communicate which point the drives should move to. The two Festo controllers were also linked to the PC via RS232.

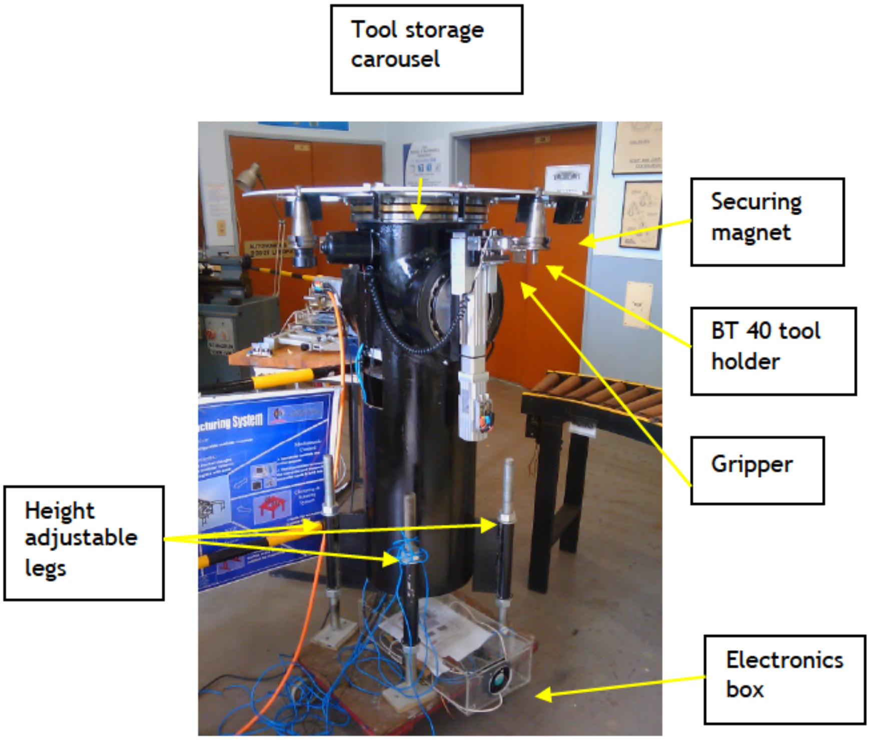

Figure 6: The completed tool changer (adapted from [10])

4. DISCUSSION OF THE EXPERIMENT

The various degrees of freedom were tested individually and then run together as a complete unit using the developed GUI. The tool changer was able to deliver on the required specifications, but there were some limitations that needed to be addressed in order to improve the unit's capabilities and performance. A successful tool change was performed in less than the required 30 seconds.

The first important limitation was the Festo linear actuators. They had to be programmed to a set position table before integration with the rest of the system. This meant that the various positions of the gripper relative to the machine it was interacting with had to be known ahead of time - or that the machine would be in down-time while the tool-changing positions were taught and programmed in. Once programmed, the Festo drives, along with their corresponding controllers, proved to be a very accurate source of motion. The repeatability and accuracy of the drives was 0.2mm.

The rotation about the horizontal axis also revealed some complications. The torque demands on the motor varied as the angle was changed. This resulted in an accuracy of only 2 degrees being realised for this degree of freedom.

In terms of accuracy, the rotating carousel yielded good results. Low speeds were required to avoid gear kickback, but the carousel was accurate to within 1.5mm along the circumference. It also displayed a repeatability of 1mm. The initial design specifications of the unit were that it could carry six tool holders. In the end, the carousel contained eight slots with room for several more should the need arise.

5. ENABLING TECHNOLOGIES FOR AUTOMATIC INTEGRATION OF THE TOOL CHANGER INTO THE MANUFACTURING SYSTEM

In order for the unit to deliver automatic tool-changing in a reconfigurable manufacturing system environment, the core RMS characteristic of *integrability* with respect to the tool changer needs to be addressed. One method of applying this characteristic practically is to enable the unit to have an automatic calibration capability. Further research will investigate the tool changer's ability to exhibit diagnostic features, thereby improving its *diagnosability.*

5.1 Calibration and integrability

Integrability defines the efficiency with which different components in a reconfigurable system can be added to each other or to the system as a whole. Its definition, according to Mehrabi [8] and ElMaraghy [9], implies integration with the current system as well as an ability to be integrated into future systems with future technologies. Therefore, for a higher level of integrability, one not only has to consider the current configuration of a system: future configurations also have to be taken into account. Designs of reconfigurable machines need to be forward-thinking, and highly reconfigurable modules will be able to adapt to future changes without having to be rebuilt or redesigned.

Integrability affects the time required to reconfigure a machine, which in turn affects the life-cycle cost of the equipment [2]. It is concerned with both the hardware and the software components of a module [1].

The tool changer is a mechatronic system. There are two primary factors that affect the accuracy of mechatronic tools. They are:

a) the precision of the mechanical components;
b) the ability of the software and control architecture to adjust and correct errors [11].

The tool changer is required to form part of a reconfigurable manufacturing system – a system designed to be changed and adapted to suit different manufacturing demands. It can therefore be seen that the level of integrability of the unit will depend largely on its ability to be efficiently re-calibrated to a different configuration or machine.

A typical robot calibration process takes place in four stages [12], [13]. A brief description of each stage is given below:

a) **Modelling** – The robot/machine must first be mathematically modelled in order to relate its functioning to its control system
b) **Measurement** - The end effecter positions are then measured and compared with the predicted positions of the mathematical model
c) **Identification** – This is the process of identifying how the degrees of freedom or joint angles affect the position of the end effecter
d) **Compensation** – The software commands are then reprogrammed to allow for accurate correlation between the user's input and the resulting output.

5.2 Automatic calibration of the tool changer

The tool changer will need to be able to adjust to a new reconfiguration of equipment, or it may even be required to service a different machine altogether. As mentioned earlier, its integrability will be affected by its ability to be re-calibrated to the new environment. Re-calibration must not only be possible, but also efficient. The more efficiently the unit is able to be calibrated, the more integrable it becomes.

Accurate sensors are the key to calibrating the unit. Often calibration is performed with the use of additional sensors or specialised equipment. As this equipment is not usually required for a machine's day-to-day running, it is a suitable solution for machines that do not need to be calibrated very often. In a reconfigurable system, however, it may be difficult to predict how often calibration may be needed. The solution is therefore to have the sensors built into the machine. The number and accuracy of the sensors will mainly be limited by financial constraints [14].

There is an additional benefit to having an automatically-calibrated machine: it could be programmed offline [16]. This would significantly reduce the down-time of equipment during a reconfiguration. It would also have the knock-on effect of reducing ramp-up time; and a new product might gain a competitive edge by being brought to the market that much sooner.

In industry, a majority of robots are programmed using the 'teach' method. The end effecter is placed in position for each of its required motions. These positions are then recorded and used to produce the program for the desired function of the machine. While the benefit of this procedure is that an inverse kinematic model is not required to produce a program, teaching the robot is very time-consuming. This method may be advantageous in some circumstances, but for reconfigurable systems it may lead to excessive amounts of equipment down-time.

In terms of the tool-changing unit under discussion, one of the limitations mentioned previously has a significant effect on its ease of calibration and hence its integrability. The machine had to be taught the required positions in order to effect a tool change. This would mean either that the unit would have to be positioned in exactly the same position relative to each machine tool, or reconfiguration. That might not be possible in every circumstance, in which case the unit would have to have a new position table configured. This would drastically increase reconfiguration time.

High integrability of the unit would allow it to be positioned within a reasonable working range of the machine it would be interacting with, and for it to detect its necessary working positions automatically. Further work on this project will explore ways to make this a reality.

Due to the constant reduction in the price of electronics, and the common availability of sophisticated equipment, location-sensing technologies are easily accessible [17]. These technologies will be researched and an appropriate solution developed to increase the tool changer's ability to calibrate itself automatically. Further research will integrate the tool-changing unit with a 5-axis modular reconfigurable machine that has been developed by the research group.

5.3 Improving the unit's diagnosability

Diagnosability has two facets. The first is defined by a system's ability to ascertain the causes of poor part quality, and then to be able to adjust in order to produce the acceptable parts. The second facet is the system's ability to detect failure or damage in the machine itself [1], [2].

It is important for the tool changer to be able to detect factors that would reduce part quality. For this unit there are two specific areas that would significantly improve its diagnosability:

a) **Tool location** – This is the machine's knowledge of which tool is in which place in the storage carousel.
b) **Tool wear** – This is the machine's knowledge of the working condition of each tool.

Currently the operator has to enter which tool is housed in which slot in the carousel manually. If the unit had an automatic method of detecting this, it would speed up reconfiguration time and hence production. Solutions to this will be researched as the project continues.

Tool wear has a more direct effect on the quality of the products produced. Therefore it would be a great advantage to the system if the tool changer had an automatic method of detecting the condition of the tools it houses. A large amount of research has gone into this important field, realising significant savings for manufacturers [18], [19]. Many methods are currently available to detect the condition of machine tools accurately; and modern laser techniques are even able to detect tool condition through a stream of coolant [20], [21]. Such solutions will be added to the tool changer to give it a tool monitoring capacity.

6. CONCLUSION

Reconfigurable manufacturing systems research is ongoing, and many aspects of these types of systems have been examined. Owing to the modular requirement of these systems, modules that offer machines a selection of tools and that automatically adjust to reconfigurations of the system need to be developed.

One such module is currently being developed by the Mechatronics and Robotics Research Group of the University of KwaZulu-Natal. The main structure and functioning of the unit has been constructed. It was able to implement a simulated tool change within 30 seconds. The tool changer was able to house 8 BT 40 tool holders, and was an autonomous unit that required no other structures for support.

Technologies that aid the automatic calibration of the tool changer are still to be implemented. These enhancements will be used to enable the unit to interact with a 5-axis modular reconfigurable machine.

7. ACKNOWLEDGEMENTS

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