Int J Adv Manuf Technol (2007) 34: 430–439
DOI 10.1007/s00170-006-0615-2

ORIGINAL ARTICLE

Reuven Katz

Design principles of reconfigurable machines

Received: 6 October 2005 / Accepted: 10 April 2006 / Published online: 8 June 2006

Abstract Reconfigurable machines form a new class of machines that are designed around a specific part family of products and allow rapid change in their structure. They are designed to allow changes in machine configuration according to changes in production requirements. The reconfiguration may be related to changes in machine functionality or its scalability, i.e., the change in production volumes or speed of operation. Reconfigurable machines represent a new class of machines that bridges the gap between the high flexibility and high cost of totally flexible machines and the low flexibility and low cost of fully dedicated machines. The design principles of reconfigurable machines follow a similar philosophy, which was derived for reconfigurable manufacturing systems, and present an approach for the design of machines to be used mainly in high-volume production lines. This paper introduces design principles for reconfigurable machines, which may be applied in different fields of manufacturing. Based on these design principles, three types of reconfigurable machines were designed for various types of production operations such as: machining, inspection and assembly. This paper shows how the suggested design principles were utilized in the design of several full-scale machine prototypes and tested experimentally.

Keywords Machine design · Reconfigurable machines (RM) · Reconfigurable manufacturing systems (RMS) · Reconfigurable machine tool (RMT) · Reconfigurable inspection machine (RIM) · Reconfigurable assembly machine (RAM)

Abbreviations RM: Reconfigurable machine · RMS: Reconfigurable manufacturing systems · RMT: Reconfigurable machine tool · RIM: Reconfigurable inspection machine · RAM: Reconfigurable assembly machine · DMS: Dedicated manufacturing systems · FMS: Flexible manufacturing systems · ERC/RMS: Engineering Research Center for Reconfigurable Manufacturing Systems · CNC: Computer numeric control · CMM: Coordinate measurement machine · FRF: Frequency response function · FFT: Fast Fourier transform

R. Katz (✉)
NSF Engineering Research Center for Reconfigurable Manufacturing Systems, University of Michigan,
Ann Arbor, MI, USA
e-mail: reuven@umich.edu
Tel.: +1-734-7630956
Fax: +1-734-6150312

1 Introduction

The two main traditional methods utilized by manufacturing industries in the production of medium- and high-volume parts are dedicated manufacturing systems (DMS) [1, 2] and flexible manufacturing systems (FMS) [3–5]. DMS is used when part production volumes are high and constant, and the part does not change. FMS is used when the required quantities are relatively lower and many modifications in the part design are foreseen, or more than one type of product is produced on the same line simultaneously. An innovative approach of customized manufacturing, termed reconfigurable manufacturing systems (RMS) is described in [6]. The main advantage of this new approach is the customized flexibility of the system to produce a “part family” of products with lower investment cost than an FMS. A set of core characteristics: modularity, scalability, integrability, convertibility, customization and diagnosibility comprises the heart of an RMS [7]. A typical RMS includes both conventional flexible machines and a new type of machine called the reconfigurable machine (RM) on its production line.

Typically, a dedicated machine used in a DMS is designed around a *specific part* that is mass produced. It is designed to perform a single operation with high reliability and repeatability, and high productivity and therefore is relatively simple and less expensive. Machines that are used in an FMS are designed to perform most operations in a flexible manner. These flexible machines are computer numerical controlled (CNC) and can produce many *different parts* by changing their computer programs. Since reliability, repeatability and high productivity are required for mass production lines, flexible machines designed for high volume production are relatively expensive. In contrast, the RM is designed for customized flexibility, i.e., the flexibility needed to produce a particular *part family* [7]. The RM can perform a pre-designed set of required operations as specified for the specific part family with high reliability, repeatability and high productivity. The limited, customized flexibility allows reduction of investment costs on the one hand and fast response when a product changes on the other, both representing economical benefits.

The innovative idea of RMS and its six core characteristics was originally developed for "systems", namely, mass production lines. Development of new design principles based on RMS philosophy was required in order to design RMs. These machines are to be used on RMS lines, thereby extending the RMS concept from a system level to the machine level.

In the literature, several general principles of machine design have been proposed and discussed. For example, Doubbel describes principles of embodiment design such as: principle of division of tasks, force and energy transmission, as well as safety and reliability principles [8]. Norton defines engineering design as "The process of applying the various techniques and scientific principles for the purpose of defining a device, a process or a system in sufficient detail to permit its realization" and also describes the phases of the design process [9]. Suh presents a thorough discussion of the design process in engineering using mathematical tools and shows examples of machine design [10]. He presents the design equation that relates the functional requirements vector {FR} to the design parameters {DP} vector using the design matrix [A]. Using this approach, he studies different cases of coupled design, redundant design and ideal design. Other researchers focus on design principles of machines which are used primarily for manufacturing. Altintas presents fundamental principles of designing CNC machine tools [11]. It includes sizing and selecting drive motors, configuration of physical structure and modeling of servo control. Design principles of CNC machine tools were also presented in detail by Koren [12]. Design principles of machining systems as well as an upgradeable multi spindle RM are discussed in [13]. RM design concepts are studied in [14] with the goal of developing "modular reconfigurable machine". As stated there, the key characteristics of modular machine design were focused on decomposition, standardization and exchangeability. According to [15], the design of RMS is based on a construction kit principle that enables it to adjust to new production requirements by substitution, addition or removal of machine systems. A synthesis methodology for designing reconfigurable machine tools (RMT) [16, 17] takes a set of functional requirements and a set of process plans as the input and generates a set of kinematically viable RMTs to meet the given specifications. A thorough study of machine tools scalability in the context of RMS is presented and discussed in [18]. Current studies are focused on improving dynamic design capabilities of RMTs [19] and on a modular approach for RMT servo axis modeling [20]. The derived machine tool models can be used for design and control of RMT servo axes. When high volumes of parts are produced, there is a need for rapid and low cost inspection equipment for measuring geometrical and dimensional tolerances as well as surface quality. Typically, dedicated gages that are designed for high precision and high repeatability are expensive and are not flexible to product changes [21]. Therefore, manufacturers prefer using flexible coordinate measuring machines (CMM) that can measure many different parts or features [22]. An interesting application of the general design principles proposed by Suh [10] demonstrates a methodology for selecting a measuring system for inspection of mechanical parts [23]. Utilizing this methodology, the authors selected a flexible CMM-based system for completing their task.

The goal of this paper is to introduce and explain the design principles of RMs. These design principles follow the concepts and vision of the RMS philosophy presented in [6, 7] and introduce a complete set of practical design principles. Based on these design principles, several RMs were designed. The paper presents three examples of such machines designed for machining, inspection and assembly operations. We explain how the design principles are reflected in the actual design of each machine. Metal cutting, metrology and assembly represent different manufacturing operations; however, similar design principles have been used to design RMs for each of these operations. Two full-scale prototypes of RMs were built (Sections 3 and 4). These RMs were experimentally tested to evaluate their reconfigurability features as well as their functional performance. The paper briefly describes some of these studies and refers the readers to more complete documentation of our research efforts.

Section 2 presents and explains the design principles of RMs. Sections 3, 4 and 5 describe each RM that was designed based on the design principles discussed in Section 2. First a brief description of the machine is provided. Then, the application of the design principles during the design phase as well as the studies and validation performed for each machine is discussed. Section 6 summarizes the paper and presents concluding remarks.

2 Design principles

An RM is a machine that is specifically designed to handle product variants within a specific part family. A good design of an RM is a design that makes it proficient in handling changes and simplifies the changeover procedure.

The design principles of RMs follow the philosophy of reconfigurable manufacturing systems. RMs are designed mainly for mass production applications. RMs are designed to allow customized flexibility and a cost-effective production and inspection of a family of parts.

A machine is classified as an RM if its design follows the necessary principle and several of the primary principles stated below.

Necessary principle:

1. A reconfigurable machine is designed around a specific *part family* of products.

Primary principles:

2. A reconfigurable machine is designed for *customized flexibility* only.
3. A reconfigurable machine is designed for easy and rapid *convertibility*.
4. A reconfigurable machine is designed for *scalability*: allows addition or removal of elements that increase productivity or efficiency of operation.
5. A reconfigurable machine is designed to allow reconfiguration of the machine to operate at several locations along the production line performing different tasks at different locations, using the *same basic structure*.
6. A reconfigurable machine should be designed applying *modularity* concepts, namely, using common "building blocks" and common interfaces.

Clarifying remarks:

1. The first principle is necessary in defining a machine as a RM. The other five principles are the key principles that specify the essence of RMs.
2. Part family, in principle 1, is a set of parts with similar characteristics. A characteristic is a distinguishable property of a part e.g. material, geometry, shape or color. Similarity can be difficult to measure depending on the property. Two parts can be similar based on one set of properties, but different when a second set is considered. When machined parts are considered, the choice of geometric and shape properties is common. Cylinder heads for different engines may be regarded a part family. Similarly, several types of engine blocks can form a part family. However, a cylinder head and an engine block of the same engine may not belong to the same part family. Rigorous definitions and discussion of part families can be found in [24]. The definition of a part family in our context is broad to allow each manufacturing business to define its own part family and design a RM according to its specific needs.
3. Customized flexibility, mentioned in principle 2, means that a machine possesses only a limited amount of flexibility related to several specific features as required from the design specifications. General flexibility means that a single flexible machine can deal with a large variety of features such as in a computer numerically controlled (CNC) machine tool or in a general-purpose coordinate measurement machine (CMM).
4. The third principle of "easy and rapid convertibility" suggests that the configuration should be designed to allow easy and fast change of machine elements, rapid addition or removal of elements and quick set up time. The designer should design means for rapid reconfiguration of the machine in advance. He or she should decide how to allow fast access to fasteners and connectors, how to design several optional locations for different machine elements and how to automate the process in order to speed it up and keep it precise.
5. Principle 5 refers to the requirement that the basic structural design of a RM will allow changeable configurations in order to place the machine at different locations along the production line. At each location the RM will be configured to perform specific tasks that are required for that location. In other words the same basic RM may include different structural (hardware) elements such as spindles, sensors or grippers as well as different software configurations.
6. Design for modularity is a broad principle related to the good practice of machine design in general. In our context, modularity should allow efficient reconfigurability of the machine. Standard electrical, mechanical, control and software interfaces should allow rapid integration of common elements or "building blocks" which were designed or selected in advance.

3 Reconfigurable machine tool (RMT)

The researchers at the ERC/RMS suggested an innovative concept of a machine tool [25] and developed and studied several RMT concepts. Two of them have been built, demonstrated and are currently used for research [26, 27]. In this paper we will focus on one machine only, the "arch type RMT" [27].

3.1 Brief description of the arch type RMT

The arch type RMT, shown in Fig. 1a, was built around a part family of products with inclined surfaces, which exist in some automotive engine blocks or cylinder heads. It was designed for a mass production line for both milling and drilling on inclined surfaces.

The machine tool has three controlled degrees of freedom along its column, along the spindle axis and along the table axis. One additional passive motion is the angular reconfiguration motion of the spindle, which allows reconfiguring the spindle's angular position into five pre-designed locations to allow machining on different inclined surfaces. Therefore, the arch type RMT is a non-orthogonal machine that may have different characteristics at each configuration of the machine.

The machine is designed to drill and mill on an inclined surface in such a way that the tool is perpendicular to the surface.

3.2 Application of RM design principles in arch type RMT

Principle 1 The arch type RMT was built for a part family with inclined surfaces found in V6 and V8 automotive cylinder heads shown in Fig. 2. During manufacturing of

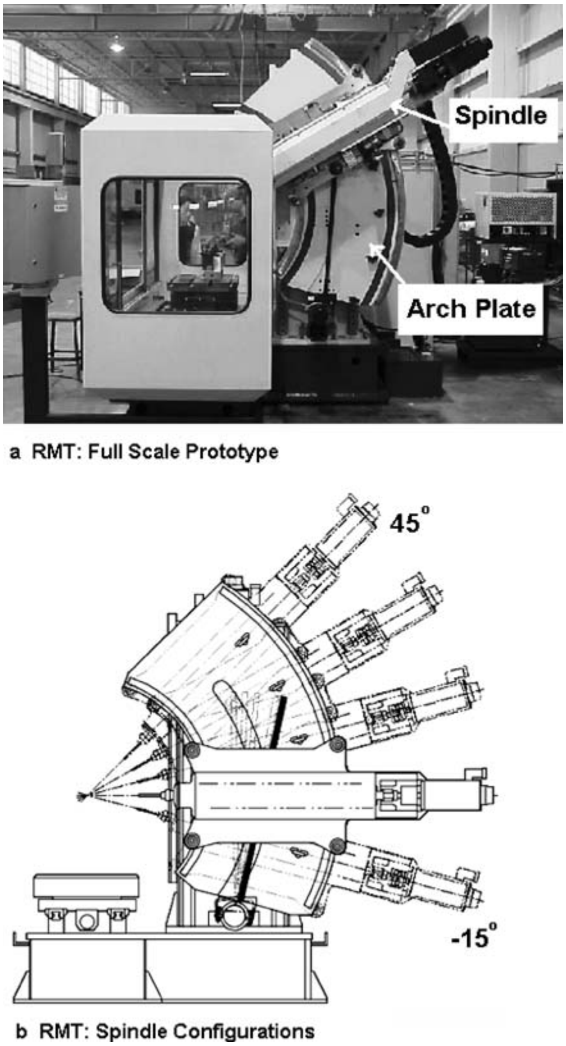


Fig. 1 Arch type RMT

these parts there is a need for drilling, tapping or milling on inclined surfaces. Currently, typical dedicated production lines are designed for mass production of one specific part. The machines that operate on dedicated lines are dedicated as well, i.e. are built at one specific angle and perform a single set of operations such as milling or drilling. The introduction of the Arch Type RMT will allow changing a dedicated production line to a reconfigurable line that will allow production of a family of parts with different inclination angles without replacing machines.

Principle 2 The arch type RMT was built for customized flexibility only. The inclination angle might be changed between −15 degrees up to 45 degrees in steps of 15 degrees as shown in Fig. 1b.

Principle 3 The arch type RMT was designed for rapid and easy convertibility by moving the spindle from one angle to another by means of a motorized mechanism and by fixing it at a precise location. When the motor brings the spindle to its required location the spindle is rested on

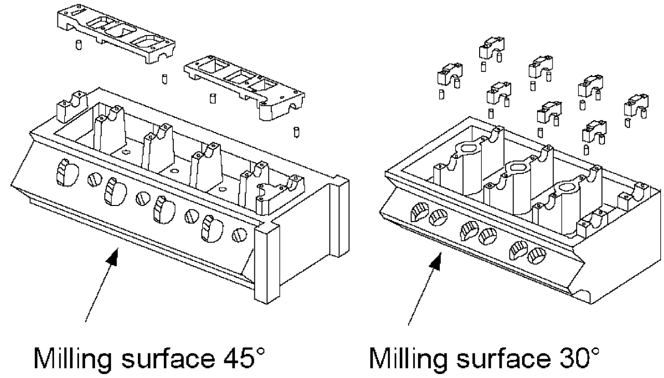


Fig. 2 RMT part family – two automotive cylinder heads: V-8 (left) and V-6 (right) [26]

positioning blocks that are attached to the arch plate and bolted to have better structural rigidity and precision.

Principle 5 At one location along the production line, the arch type RMT is capable of milling on an inclined surface and at another location, it is capable of drilling or tapping.

3.3 Study and validation of arch type RMT design

Our key concern at the design phase of the RMT was the dynamic stability of the machine tool and how the performance will be affected by moving a large mass of the spindle from horizontal location to 45 degrees location. Once the machine was built, dynamic characteristics of the RMT were experimentally validated using hammer tests and cutting tests [18]. It was shown after analysis of these experimental results that the dominant frequency in the machine's tool frequency response function (FRF) came from the tool holder assembly, at above 600 Hz., regardless of spindle angular position. Figure 3a shows analytically derived stability lobes for cutting at 0 and 45 degrees. Point "a" represents stable cutting conditions and point "b" unstable conditions. We have performed cutting experiments using the parameters indicated by points "a" and "b". Figure 3b shows the fast Fourier transform (FFT) of cutting force in feed direction during stable machining in horizontal position. Figure 3c shows the FFT of cutting force in feed direction during unstable machining also in a horizontal position. During unstable cutting, we get a clear signal around 650Hz which corresponds to the tool holder mode. Similar cutting experiments were repeated at 45 degrees inclination and the results showed similar characteristics. The results interestingly showed that the reconfiguration of machine structure does not affect arch type RMT stability.

The arch type RMT was designed as a non-orthogonal machine tool, except when in horizontal position. At the design phase, a thorough study of the control problem associated with this design concept was performed [28]. A new type of cross-coupling controller was suggested. The stability of the control system was investigated, and

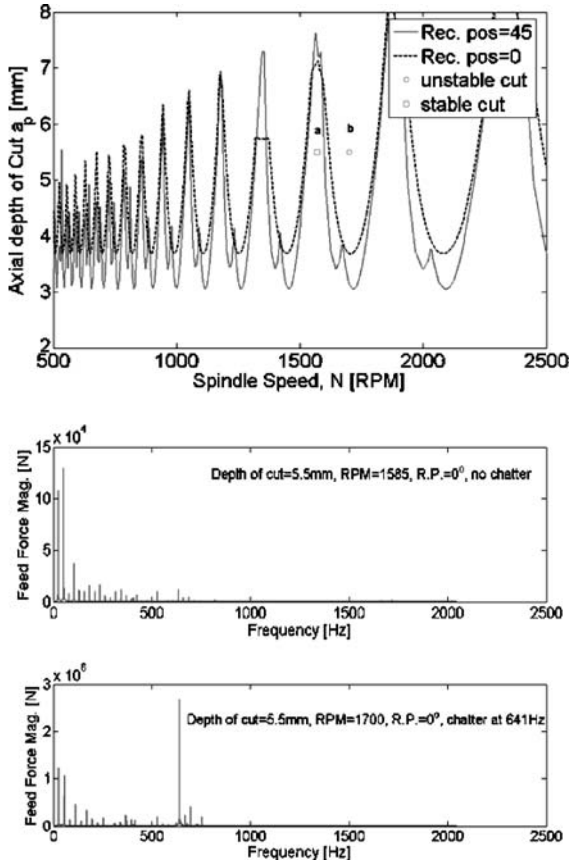


Fig. 3 RMT dynamic characteristics

simulation was used to compare different types of controllers.

The arch type RMT was designed for rapid and easy convertibility. The process of moving the spindle from −15 degrees angle to 45 degrees by means of a motorized linear stage and fixing it at a precise location was tested. It takes less than 5 min to complete the reconfiguration process in the laboratory.

The arch type RMT is capable of drilling on a surface with 45 degrees inclination at one location along the production line and another similar arch type RMT just differently configured is capable of milling on a surface with −15 degrees inclination in a different location.

In the design phase there was a plan to introduce modularity features to the Arch Type RMT by using standard interfaces in order to enable easy spindles exchangeability. We have not succeeded in this effort since it required close cooperation with spindles supplier. An outstanding example of modular design of spindle interfaces for machine tools is presented in [15], where the spindle has standard interfaces for: power, media, data, alignment and tool change that allowed the development of the "multi coupling" concept that utilizes modularity principles.

4 Reconfigurable inspection machine (RIM)

4.1 Brief description

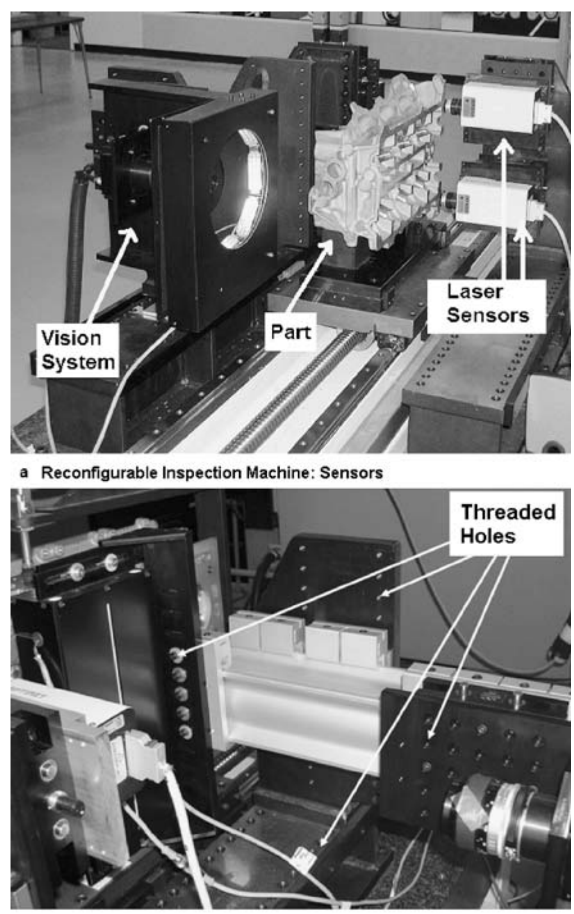
The reconfigurable inspection machine (RIM) was designed for rapid, in-process, inspection of the machined features of a part family of cylinder heads.

The RIM has been originally developed for measuring geometric features such as: flatness, parallelism and profile associated with the cover and joint faces of an engine cylinder head [29–31].

Under a different configuration, by adding a machine vision system to the structure, the RIM also allows inspection of cylinder head surfaces for pores and other surface texture imperfections.

The RIM uses non-contact measurement methods based on commercial laser sensors and high-definition line-scan cameras in conjunction with computer vision technology and other commercially available non-contact sensors. A prototype of the RIM is shown in Fig. 4a.

The inspected part moves along a linear axis and passes the sensors on a servo-driven single-axis motion stage that is equipped with a high-precision linear scale of 1 μm accuracy. The velocity of the motion stage, as well as the probe sampling frequency, can be varied in accordance to



a Reconfigurable Inspection Machine: Sensors

b Reconfigurable Inspection Machine: Convertibility Features

Fig. 4 Reconfigurable inspection machine the required sampling density and inspection cycle time. The linear position along the axis of travel is recorded for each measurement point, which enables a precise mapping of the part surface without being affected by variations in the motion stage velocity.

The RIM is intended for use in an industrial environment. It is located adjacent to the machining line with a total cycle time including part transfer equal to that of the machining line, which is assumed to be around 40 seconds. Radio Frequency (RF) technology was demonstrated in the laboratory for reading the RF tag located on the part fixture to identify the specific part number to be evaluated. Upon completion of the measurements and feature evaluations, the results of the evaluation were stored on the RF tag and on the RIM database. A bock diagram of the RIM system architecture is presented in Fig. 5.

4.2 Application of RM design principles in RIM

Principle 1 The RIM was built around a part family of engine cylinder heads that during mass-production need in-line inspection. Typical parts that belong to this part family are shown in Fig. 6. These engine cylinder heads were produced by different companies for different types of engines. However, all of them have common characteristic features such as precisely machined flat surfaces, prismatic shape and a series of threaded holes.

Principle 2 The RIM was built for customized flexibility only. The machine is capable of measuring various features of cylinder heads of various sizes; however, it is not designed to measure all features of one part or to measure other parts that are not from the same part family.

Principle 3 The RIM is designed for rapid and easy convertibility by adding sensors when needed and by changing the location of existing sensors as required for inspection of different parts or different features of the same part.

Principle 4 The RIM was designed to be scalable, i.e., to allow mounting of different probes at different locations prepared at the outset. The scalability enables efficient measurements of different features.

Principle 5 The RIM is capable of measuring surface flatness at one location along the production line and measuring distance between two features centers at another location along the line as presented schematically in Fig. 7.

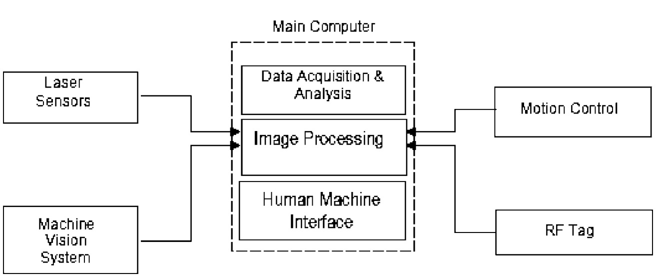


Fig. 5 RIM system architecture

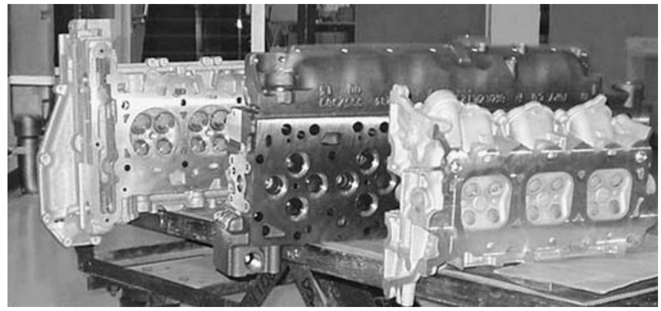


Fig. 6 RIM part family of engine cylinder heads

4.3 Study and validation of RIM design

In this section, we demonstrate the RM design principles and their implementation as reflected in RIM design. Also, RIM performance as a non-contact inspection machine was experimentally validated.

The reconfigurable inspection machine was designed around a part family of engine cylinder heads as explained earlier. To measure each of the heads, different fixtures were designed and used. For each head, the location of the laser sensors as well as the position of the vision system were reconfigured to capture all features of interest.

The RIM can measure geometrical and dimensional features such as: flatness of a surface and parallelism between two surfaces, distance between surfaces distance between edges and related dimensional features. The RIM is not designed, however, to measure the roundness of parts, since roundness is not relevant for inspecting cylinder heads, which are prismatic parts. We have tested experimentally the quality of RIM measurements. Table 1 presents RIM repeatability experimental results tested in nominal condition when measuring a reference part. The measurements show good nominal repeatability of the RIM.

Currently, the coordinate measurement machine (CMM), is the standard tool for industrial inspection of machined parts. It uses a touch-probe with a 0.5 to 2.0-mm diameter ball. Utilizing the ConoProbe sensor on RIM, its laser beam has a typical diameter of 20μm. Therefore, one can expect different readings when using these two types of sensors on machined surface with a non-perfect surface finish. In order to compare RIM measurement results with the results of a coordinate measurement machine (CMM), the "virtual ball" method was developed and implemented [32]. It provides the interpretations of non-contact laser measurements as if they have been performed by a CMM touch-probe. A comparison between measurements from the RIM and a CMM, and repeatability results from the RIM are presented in [33].

Figure 4b shows a typical design-for-convertibility of the RIM structure and fixtures. The design included a series

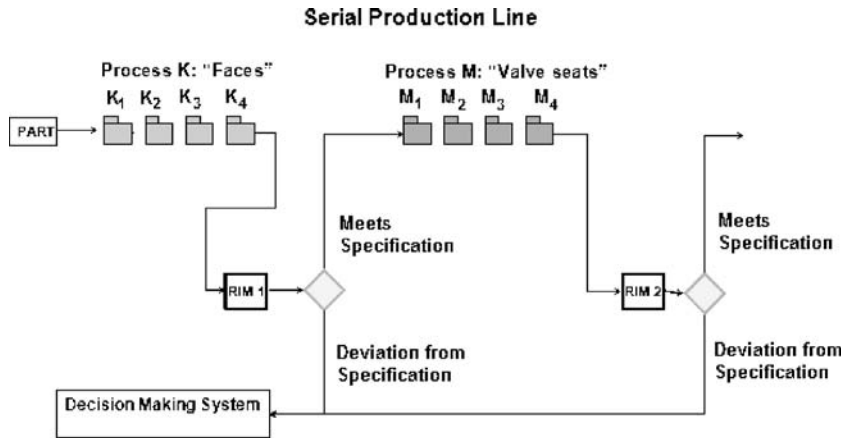


Fig. 7 RIM integration on production line

of threaded holes to allow fast and easy relocation of various sensors and accessories needed for inspection. While measuring different features on different types of cylinder heads, we have changed the fixtures and the location of the sensors many times. A typical time period required for relocation of sensors when different heads are measured is less than an hour. The calibration process of the sensors following reconfiguration process of the RIM [34] was successfully tested in the laboratory.

To demonstrate scalability of the system, the RIM was tested with a differing number of sensors. We started with two laser sensors for surface flatness inspection and we increased the number of laser sensors to four when measuring parallelism [35]. We also applied machine vision systems based on a line scanning camera and used both the 4 K and 8 K pixels versions. We could use each type of sensor separately or together in parallel during the scan of the cylinder head surface. One important application of the vision system was measuring surface defects such as casting originated pores on machined surfaces [36]. A typical image of pores on cylinder head surface is shown in Fig. 8. Figure 8a shows a pore which is connected to an edge of a machined feature while Fig. 8b presents an "isolated pore". For each pore of interest we can analyze its size and the location relative to some given datum. Based on our porosity inspection research, one of ERC/RMS industrial partners is currently building a full-scale machine to be located and used on a production line of cylinder heads replacing visual inspection.

5 Reconfigurable assembly machine

5.1 Brief description

The reconfigurable assembly machine (RAM) described in this paper is an assembly machine for automotive heat exchangers (radiators) [37]. Dr. M. Mehrabi and his graduate students have conducted a study and conceptually designed the RAM together with an ERC/RMS industrial partner.

Heat exchangers are rectangular matrices comprising tubes and fins bordered by headers and side supports as shown in Fig. 9. The assembly process starts by feeding tubes and fins to the core-builder area. The tubes are in the form of stacks that are fed into the core-builder whereas the fins are supplied in trays that contain the required number of fins per radiator. The machine then places one tube followed by one fin from the respective sources and the process iterates till the required quantity of fins and tubes is reached. The collection of tubes and fins that are loosely held together is termed as a '*loose matrix*'. This loose matrix is then transferred to the final assembly area where it is capped with side supports and headers after being compressed to the correct dimensions and checked for alignment. The tubes are to be pressed into the slots provided in the headers and therefore their alignment is fairly important. The finished product received from the final assembly area is termed as the '*core*'. Before the core can be removed from the assembly area, it is constrained by

Table 1 Repeatability measurements performed on a reference part

Inspection number	Width	Parallelism	Joint face flatness	Cover face flatness
1	118,975.1	9.3	9.5	9.3
2	118,975.1	8.7	8.7	8.8
3	118,975.2	8.8	8.7	8.7
4	118,975.1	8.5	8.4	8.5
5	118,975.1	10.1	9.3	9.5
Mean value	118,975.1	9.1	8.9	9.0
Repeatability (range)	0.1	1.5	1.1	1.0

Values are in µm. (Repeatability is defined as the difference between the max and min values in the range defined by the five inspections performed)

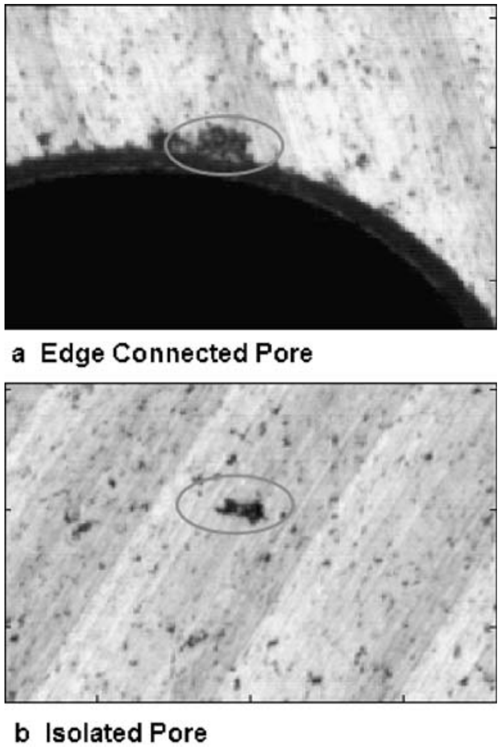


Fig. 8 Porosity on machined surface

the use of brass frames. A new pick and place mechanism was designed to perform the task of placing the headers and side supports into the assembly fixtures. The design of the new reconfigurable pick and place mechanism led to drastic reduction in final assembly time. The conceptual design of the core-builder is presented in Fig. 10.

The similarities between various products are based on geometrical features. A greater width results in a greater number of tubes and fins. An existing assembly machine can assemble heat exchangers in 45 to 60 s. The design goal of the RAM was to reduce assembly time to 30 s and allow assembly of various types of heat exchangers that belong to the same part family utilizing reconfigurable design principles.

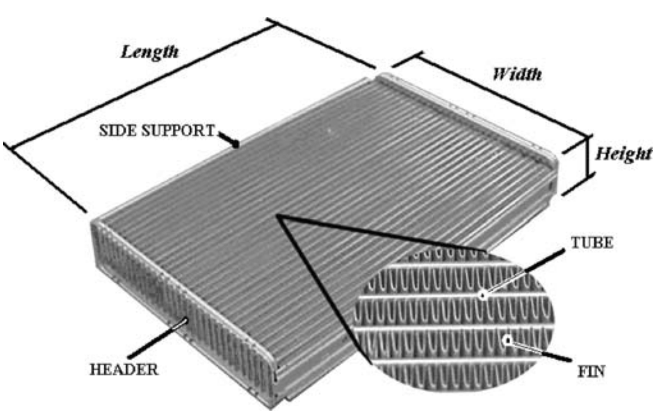


Fig. 9 Heat exchanger [37]

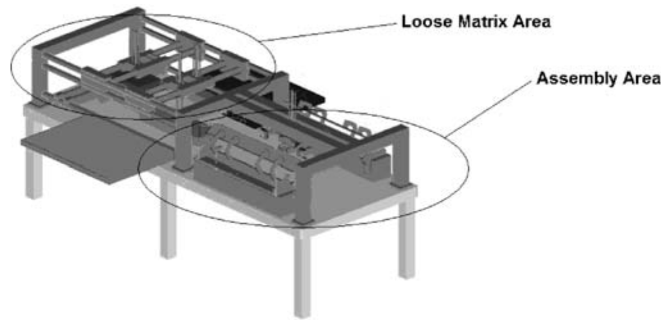


Fig. 10 The core-builder [37]

5.2 Application of RM design principles in RAM

Principle 1 The RAM was designed around a part family of heat exchangers with different dimensions and different numbers of fins and tubes. It is an assembly machine used by automotive radiators manufacturers. Many different types of radiators, which could be assembled by RAM, were identified and classified into three main groups that define the "part family" [37]. This topic will be further explained in the next section.

Principle 2 The machine was designed for customized flexibility as it can perform only some of the assembly tasks related to core-building of these heat exchangers that belong to the defined part family.

Principle 3 The RAM was designed for rapid convertibility to allow the assembly of different sizes of heat exchangers. Replacing the automated core builder elements such as the pick and place mechanism and the loose matrix grippers, allows assembly of different types and sizes of products.

Principle 6 The RAM was designed to use different modules or building blocks that are integrated into the assembly machine to allow the assembly of different parts. Modular elements of pick and place devices and grippers were designed for different sizes of heat exchangers.

5.3 Study and validation of RAM design

The RAM team has studied the characteristics of a typical core-builder that our industrial partner has designed and

Table 2 RAM-part family [25]

Subgroups	Length	Width	Total products
1	20	20	27
2	20	20–32	100
3	20–30 1/2	20	219
rejected			45

built for its customers. The team investigated this core-builder's functionality and tried to understand its limitations and improve them.

The study led to the conclusion that the productivity of the existing core-builder is constrained by elevated changeover and cycle times. Therefore, the goal was to minimize changeover time and hence reduce the idle state of the system. The constraint to productivity formed by the changeover time can be addressed effectively by making the machine reconfigurable. As previously stated, RMs are specifically designed to handle changes within a part family. Their modular design significantly contributes towards the reduction in changeover time. The changeovers in RAM are reduced to the interchanging of modules instead of the many adjustments needed in the existing assembly machines, when assembling different products.

The first step in the design of a RM is a clear identification of the part family. Using our industrial partner's products catalog, 398 radiators were classified and grouped. Combinations of product features were studied in order to establish a relationship between the product characteristics. The information for this study consisted of product features such as model, length, width, height, number of rows and car that uses it. These relationships were utilized to define part families depending on the characteristics that are more imperative to machine architecture. The study of these relationships concluded that the length and the width are the most important parameters that affect the reconfigurability of the machine to the greatest extent.

As a result of this study [38], three main subgroups define the RAM part family, and a few rejected products were identified as listed in Table 2. With the newly structured part family, the number of required modules has reduced to three; each of them takes care of one sub group, whereas still more than 90% of the product range was covered. If the design of the modules is based on this part family definition then the resulting machine will handle changes within product sub group without requiring changeover at all, and if the change is across a part family then the changeover will be restricted to a change of a module. Hence, extended changeover time that leads to large downtimes, can be avoided. The easy changes across the part family represent a good example of design for convertibility. The design principles and the study of RAM were not validated experimentally since the machine was not built.

6 Summary and conclusions

This paper outlines the importance of design principles for RMs. Based on the design principles presented in this paper, the ideas presented in the RMT and RIM patents [25, 29] were realized. Each of the full-scale RMs was experimentally tested for the validation of reconfiguration principles as well as for sound functional performance. The prototypes described in the paper currently serve as research platforms.

The main contributions of this paper are as follows:

– The RMS vision was refined into concrete machine design principles for the design of RMs that can be used in a manufacturing system.
– The generality of application of these principles was demonstrated in various manufacturing domains such as machining, assembly and metrology.
– The importance of the aforementioned design principles was validated for RMs.
– Studies that demonstrate reconfigurability and good performance of the RMs that used the design principles for RMs were presented.

The conclusions of our study are as follows:

– RMs represent a new class of machines that are designed mainly for high-volume production applications. They bridge the gap between the flexible machines and the dedicated machines.
– Not all design principles presented in this paper must be reflected in the design of each specific RM. However, the principle of a machine that is designed around a part family is a necessary condition and should be reflected in the design.
– The design principles were demonstrated in the design of reconfigurable machining, inspection and assembly machines; however, this philosophy is general and may be applied to other domains of machine design.
– The design principles of RMs and RMS follow a similar philosophy.
– RMs enable production of different products that belong to the same part family by allowing rapid and efficient pre-designed changes of a machine's configuration.
– The design principles of RMs are focused mainly on the functionality of these machines and are important in the phase of conceptual design. The detailed design of a RM follows concepts similar to any other machine design.
– The suggested design principles do not contradict any traditional design principles related to the good practice of machine design.

Acknowledgements The author would like to thank Prof. Y. Koren for his RMS vision and his remarks to this paper and to the teams of researchers and graduate students who participated in the RMT, RIM and RAM projects. The author would like to thank V. Srivatsan, J. Duphia and Dr. P. Spicer for their feedback and remarks to this paper. The author also gratefully acknowledges the financial support of the NSF Engineering Research Center for Reconfigurable Machining Systems (NSF Grant EEC95-92125) at the University of Michigan.

References

1. Mehrabi MG, Ulsoy AG, Koren Y (2000) Reconfigurable manufacturing systems: key to future manufacturing. J Intell Manuf 11(4):403–419
2. Altiok T (1996) Analysis of manufacturing systems. Springer, Berlin Heidelberg New York

3. Kaighobadi M, Venkatesh K (1993) Flexible manufacturing systems: an overview. Int J Oper Manage 14(4):26–49
4. Mehrabi MG, Ulsoy AG, Koren Y, Heytler P, (2002) Trends and perspectives in flexible and reconfigurable manufacturing systems. J Intell Manuf 13(2):135–146
5. Sethi AK, Sethi SP (1990) Flexibility in manufacturing: a survey. Int J Flex Manuf Syst 2:289–328
6. Koren Y, Jovane F, Heisel U, Pritschow G, Ulsoy G, VanBrussel H (1999) Reconfigurable manufacturing systems. Keynote paper. CIRP Annals 2:6–12
7. Koren Y, Ulsoy AG (2002) Vision, principles and impact of reconfigurable manufacturing systems. Powertrain International, pp 14–21
8. Doubbel H (1994) Handbook of mechanical engineering. Springer, Berlin Heidelberg New York
9. Norton RL (2000) Machine design an integrated approach. Prentice-Hall, New York
10. Suh NP (1990) The principles of design. Oxford University Press, Oxford
11. Altintas Y (2000) Manufacturing automation: metal cutting mechanics, machine tool vibrations, and CNC design. Cambridge University Press, Cambridge
12. Koren Y (1983) Computer control of manufacturing systems. McGraw-Hill, New York
13. Spicer P, Koren Y, Shpitalni M, Yip-Hoi D (2002) Design principles for machining system configurations. CIRP Ann Manuf Technol 51:275–280
14. Bright G, Xing B, Craig S (2005) Modular machine design for reconfigurable manufacturing. 3rd CIRP Conference on RMS, Ann Arbor, MI
15. Abele E, Worn A, Stroh C, Elzenheimer J (2005) Multi machining technology integration in RMS, 3rd CIRP Intl. Conference on RMS '05, Ann Arbor, MI
16. Moon YM, Kota S (2002) Design of reconfigurable machine tools. ASME J Manuf Sci Eng 124:480–483
17. Moon YM, Kota S (2002) Generalized kinematic modeling of reconfigurable machine tools. ASME J Mech Des 124:47–51
18. Spicer P, Yip-Hoi D, Koren Y (2005) Scalable reconfigurable equipment design principles. Int J Prod Res 43(22):4839–4852
19. Dhupia J, Powalka B, Katz R, Ulsoy AG (2005) Effect of reconfiguration degrees of freedom on dynamics of a machine tool. 3rd CIRP Intl. Conference on RMS '05, Ann Arbor, MI
20. Ersal T, Stein JL, Louca LS (2004) A modular modeling approach for the design of reconfigurable machine tools. Proc ASME IMECE '04, Anaheim, CA
21. Farago F, Curtis MA (1994) Handbook of dimensional measurement. Industrial Press Inc.
22. Bosch JA (ed) (1995) Coordinate measuring machines and systems. Marcel Dekker, New York
23. Coelho AG, Mourao AF, Navas HG (2004) A rational way to select a measuring system for mechanical parts inspection. Proc of ICAD '04, Seoul, Korea
24. Ramesh M, Yip-Hoi D, Dutta D (2001) Feature-based shape similarity measurement for retrieval of mechanical parts. J Comput Inf Sci Eng 1:245–256
25. Koren Y, Kota S (1999) Reconfigurable machine tool. US Patent # 5,943,750
26. Landers RG, Min BK, Koren Y (2001) Reconfigurable machine tools. Ann CIRP 50:269–274
27. Katz R, Chung H (1999) Design of an experimental arch type reconfigurable machine tool. Proc 2000 JUSFA, 2000 Japan-USA Symposium on Flexible Automation, July 23–26, 2000, Ann Arbor, MI
28. Katz R, Yook J, Koren Y (2004) Control of reconfigurable machine tool. ASME J Dyn Syst Meas Control 126:397–405
29. Koren Y, Katz R (2003) Reconfigurable apparatus and method for Inspection during a Manufacturing Process. US Patent # 6,567,162
30. Katz R, Zuteck MG, Koren Y (2002) Rapid inspection and error-tracing methodology for machining production lines. CIRP ICME '02, Ischia (Naples), Italy
31. Katz R, Zuteck MG, Koren Y (2002) Reconfigurable inspection machine for machining production lines. Proc Global Power Train Conference 2002, Ann Arbor, MI
32. Barhak J, Katz R (2003) Interpretation of laser measurements produced by the reconfigurable inspection machine using the "virtual ball" method. Proc CIRP- 2nd Intl. Conference on RMS '03, Ann Arbor, MI
33. Barhak J, Katz R (2004) Rapid non-contact measurements of engine cylinder heads with the reconfigurable inspection machine. CIRP ICME '04, Sorrento, Italy
34. Gupta A, Segall S, Katz R (2004) Motion stage error compensation technique with verification methodology for a reconfigurable inspection machine. ASME Proc 2004 Japan-USA Symposium on Flexible Automation
35. Barhak J, Djurdjanovic D, Spicer P, Katz R (2005) Integration of reconfigurable inspection with stream of variations methodology. Int J Mach Tools Manuf 45(4–5):407–419
36. Kalyanaraman A, Katz R, Lock T, Spicer P, Warlick Z, (2004) Cylinder head surface porosity inspection. University of Michigan, ERC/RMS TR-051-04
37. Bair N, Kidwai T, Koren Y, Mehrabi M, Wayne S, Prater L (2002) Design of a reconfigurable assembly system for manufacturing heat exchangers. Japan-USA Symposium on Flexible Manufacturing, July14–19, Hiroshima
38. Kidwai T (2002) Design of a reconfigurable core-builder: an assembly machine for heat exchangers. University of Michigan, ERC/RMS-TR-056-05