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DESIGN OF GENERIC MODULAR RECONFIGURABLE PLATFORMS (GMRPS) FOR A PRODUCT-ORIENTED MICRO MANUFACTURING SYSTEM

Xizhi Sun, Kai Cheng

School of Engineering and Design, Brunel University, Uxbridge, UB8 3PH, UK xizhi.sun@brunel.ac.uk, kai.cheng@brunel.ac.uk

Abstract

With the proposition of the concept of product-service systems, many manufacturers are focusing on selling services or functionality rather than products. Industrial production is shifting production models from mass production to mass customization and highly personalized needs. As a result, there is a tendency for manufacturing system suppliers to develop product-oriented systems to responsively cope with the dynamic fast moving competitive market. The key features of such a manufacturing system are the reconfigurability and adaptability, which can enable the system respond to the changeable needs of customers quickly and adaptively. Therefore, one of the challenges for the micro manufacturing system provider has been the design of a reconfigurable machine platform which will provide the functionalities and flexibility required by the product-oriented systems.

In this paper, a new micro manufacturing platform, i.e. a generic modular reconfigurable platform (GMRP) is proposed in order to provide an effective means for fabrication of high quality micro products at low cost in a responsive manner. The GMRP-based system aims to be a product-oriented reconfigurable, highly responsive manufacturing system particularly for high value nano/micro manufacturing purposes. To reuse components and decrease material consumption, GMRP is characterized by hybrid micro manufacturing processes, modularity of key components, and reconfigurability of machine platforms and key components. Furthermore, a practical methodology for the design of reconfigurable machine platforms is discussed against the requirements from product-driven micro manufacturing and its extension for adaptive production.

Keywords: Product-oriented micro manufacturing, reconfigurable manufacturing, micro manufacturing system.

1.0 Introduction

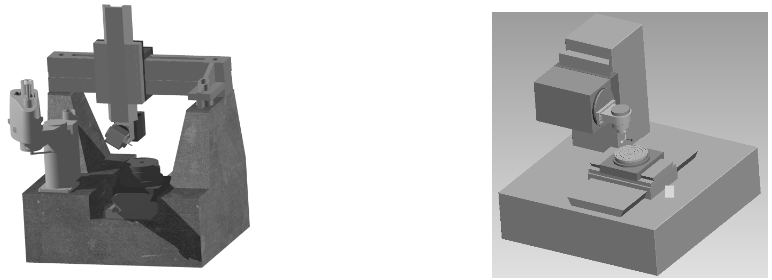
The concept of product-service systems has been proposed for one decade or so as a possible solution to unlink environmental pressure from economic growth. Godekoop et al [1] defined a product-service system as "a marketable set of products and services capable of jointly fulfilling a user's need and has a lower environmental impact than traditional business models". The key idea behind product-service systems is that consumers' specific needs can be met more properly by using service engineering to meet some needs rather than a merely physical object. Product-service systems respond more appropriately to the current demands than the conventional systems of mass production because of the flexibility of customers' demands in current vibrant market place. This is an evolution of the economic transition away from standardized and mass production towards flexibility, mass-customization and markets driven by quality, innovative products and added value rather than cost [2-5]. Therefore, most advanced manufacturing companies are shifting their business strategy from traditional business model towards services-oriented or functionality-driven instead of merely products.

Three types of product-service system have been proposed by Aleksejs Azarenko for machine tool industries. They are product-oriented product-service system, use-oriented product-service system and result-oriented product-service system [6-7]. To meet the variable needs of different customers and providing suitable services, design of a modular reconfigurable machine tool is therefore essential for the success of the proposed industrial product-service systems. It can be argued that the key features of such systems are their modularity and reconfigurability, which will lead to responsive and cost effective solutions to dynamically changing competitive global market. This of course equally applies to micro manufacturing systems because of the system cost, complexity and high value manufacturing in nature. In deed, the current challenges for the micro manufacturing include the hybrid manufacturing capability, reconfigurability, modularity, adaptability and energy/resource efficient. Therefore, a generic modular reconfigurable micro manufacturing platform is in deeded for fulfilling the essential needs above. Such kind of machine platform will play as a basic but key modular unit to provide the functionalities and flexibility required by the product-oriented production systems.

Recently, it is proposed that the emergence of "point-of-care" service systems as a major model for the future of healthcare. Similarly, in the manufacturing domain, there is a swing back from the existing largely centralized manufacturing model to a more distributed manufacturing model that co-exits with the centralized model [8] [9] [10]. That means manufacturing service location will move to the point of consumption from factories in the future. Therefore, the proposed reconfigurable machine platform for product-service system should not only have the ability to provide product-oriented manufacturing but also can enable the micro manufacturing to take place at the "point-of-use" in a timely and economic fashion.

It is against such a background that this paper has proposed a new micro manufacturing platform, i.e. a generic modular reconfigurable platform (GMRP), to provide an effective means for fabrication of high value micro products including customer goods, automotive optics and medical devices, etc. at low cost in a responsive manner. The GMRP has the potential to satisfy the dynamic fast moving demands and the applications of "point-of-use". The GMRP features hybrid micro manufacturing processes, modularity of key components, reuse of machine components, reduced material consumption, and reconfigurability of machine platforms and key components. Furthermore, this paper also proposes and discusses a practical methodology for the design of reconfigurable machine platforms for product-oriented micro manufacturing systems intended as a key element of industrial product-service system.

2.0 GMRP Conception



(a) (b)

Fig.1 Virtual models of two GMRP configurations

As shown through the viral models in Fig.1, two GMRP configurations have been proposed by the authors. Each GMRP is a bench-top hybrid processing machine designed for industrial feasible nano/micro manufacturing. The base of each platform is generic, and manufacturers can add, change, or remove modular components such as spindles, slideways, tool holders, etc., forming a specified nano/micro hybrid machine as new components/ products manufacturing is required. Moreover, a GMRP is modular and reconfigurable in structure, so it can thus be used as a generic machine unit for forming a product-oriented micro manufacturing system at low cost.

2.1 Hybrid Manufacturing Capability

Micro components/products are normally integrated products with different materials and of diverse micro features, which make it necessary for manufacturers to possess hybrid micromachining ability to cope with varied features and materials. The GMRP has hybrid manufacturing capability aiming to broaden the limits of its application and to improve the product manufacturing quality. As illustrated in Fig. 2, the GMRP may integrate many micro processes such as micro-electrical discharge machining (EDM), micro grinding, micro milling, micro drilling, etc. because of their similar kinematic configurations. The seamless integration of micromachining processes on a GMRP will lead to predictability, producibility and productivity of nano/micro manufacturing, with the capability to be adaptive, which is essential for the future industrial product-service system.

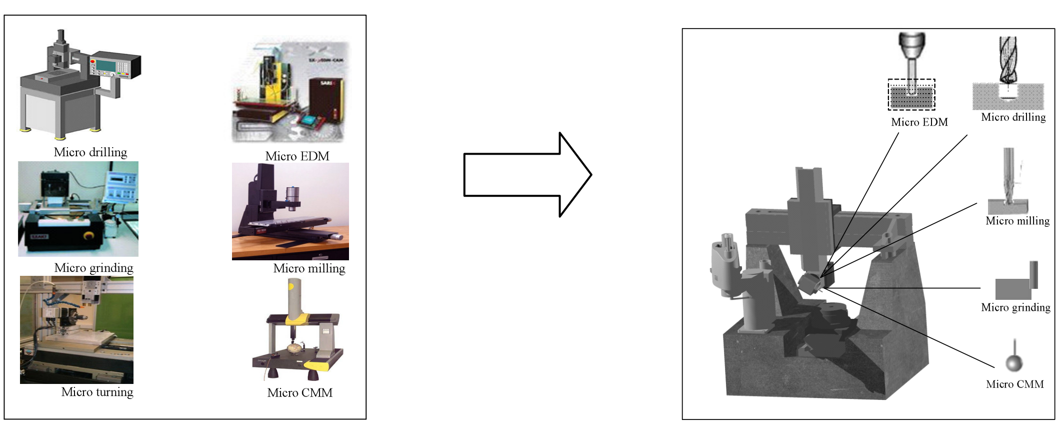


Fig.2 Hybrid manufacturing capability of a GMRP

2.2 Machine Platform and Modularity

Modular structure and reconfiguration are required for industrial product-service system which can appropriately responds to personalised individual needs low-costly and quickly. Modularity is one solution for micro manufacturing systems to outlive the products they were originally designed for. The manufacturer can easily configure the platform and later reconfigure it to meet customer's future needs [11]. Modularity is also a cost-efficient solution, and makes later upgrades or modifications to the platform easier.

2.3 Machine Platform and Reconfigurability

According to the definition of product-service system, key factors for the success of product-service system should include: to customize solutions to meet specific customer needs and to create new functions or to make unique combinations of functions. Consequently, GMRP is designed highly reconfigurable in order to be adaptive to the introduction of new technologies, manufacturing changes and mobility requirements.

Mechanical reconfigurability GMRP is able to be easily reconfigured for changes due to its modular components and modules. For example, reconfigurability for changes of products and processes is achieved by changing machine modules, such as spindle units, rotary tables, and linear slideways, with different sizes, accuracy and functionalities.

Electrical reconfigurability Electrical installation at the GMRP can be reconfigured by choosing modules from the library of electrical components and hardware. This library possibly includes rotary motors, linear motors with diverse specifications, encoders and amplifiers. Rotary motors, for example, can be replaced with linear motors to get better motion performance and neat design of the drive and actuation system. Different types of encoder are also possible to be selected to reconfigure the system for different level of performance requirements.

Control system reconfigurability Similar to reconfiguring machine modules and electrical systems, control systems are also capable of being reconfigured by selecting needed software modules (e.g., servo control algorithms, interpolators) and hardware modules (controllers) in the development of open-ended control architecture. Selection of control modules is directly influenced by the electrical components.

2.4 Formation of a Product-oriented Micro Manufacturing System

Fig.3 depicts that a micro manufacturing system formed with GMRPs can be developed to fabricate various micro products, covering the full process chain from different machining operations (e.g. micro milling, drilling, EDM) through inspection (e.g. micro CMM) to the final assembly. Such a system can be used to produce high quality products competitively due to its reconfigurability, modularity and adaptivity, offering excellent responsiveness, short lead time, low cost and mass customization. In this micro manufacturing system, each GMRP can be configured as a specified functional machine by choosing corresponding modular components from the library of modules, which greatly reduces the set up and the cost of the whole manufacturing system. The system is highly flexible and can be easily reconfigured and reused because of the adoption of GMRPs.

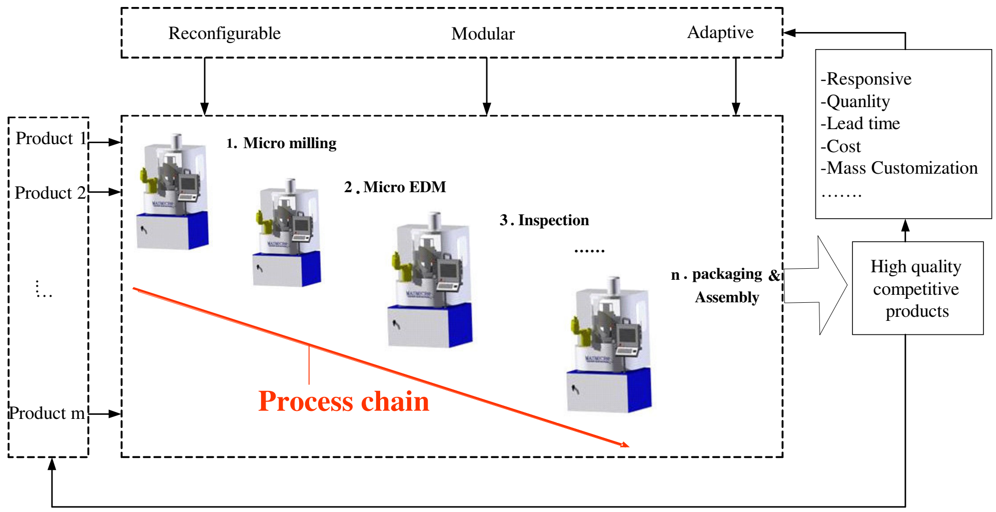


Fig. 3 Principle of a product-oriented micro manufacturing system

3.0 Design Methodology of GMRP

The GMRP-based system aims to be a product-oriented reconfigurable, highly responsive manufacturing system particularly for high value nano/micro manufacturing purposes. The methodology of the design of GMRP is illustrated in Fig. 4.

The methodology consists of four important parts, namely, design interface, knowledge base, design engine and component library, which may be basically regarded as a design expert system.

The design interface provides a user-friendly HCI for accessing different modules and functionalities. Through the interface, the designer will be able to specify the design requirements according to the customer needs such as the type of machining, the number of axis of the machine tool, etc. (Fig. 5). The system will use the knowledge base to display relevant design suggestions and/or solutions (Fig. 6) for designer to choose suitable design options or parameters. The interface presents an integrated platform for the interactive design process.

The rule-based knowledge base is the essential element of the system, which stores and represents the expert knowledge of good designers. It is implemented as a part of a standard expert system. The design engine is largely based the axiomatic design theory, which will be detailed in the next section.

The component library is basically a database to support the design process. The detailed information of the components will be used for analysis and evaluation of different design configurations in the design engine and knowledge base. They will also be directly used in the representation and display of actual designed modules or systems (Fig. 7).

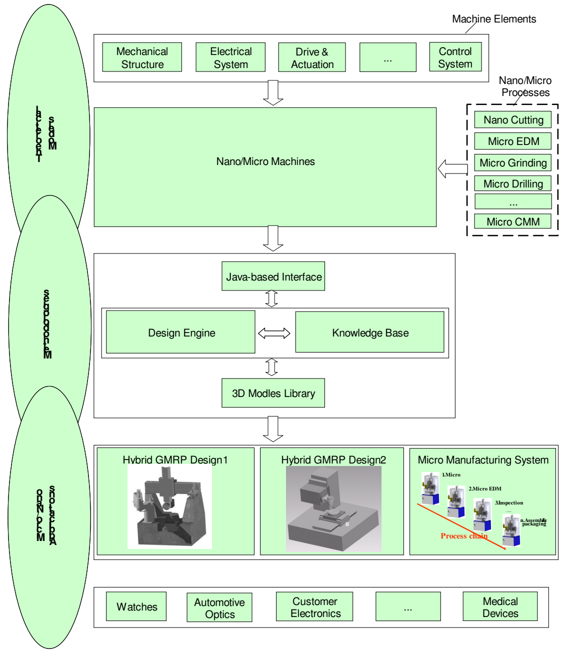


Fig. 4 GMRP and micro manufacturing architecture

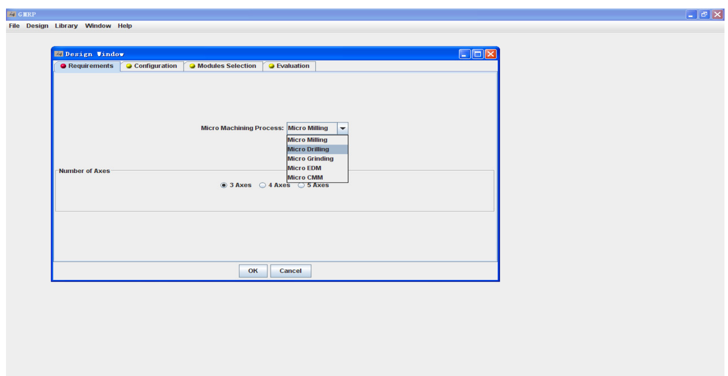


Fig. 5 Design requirements interface

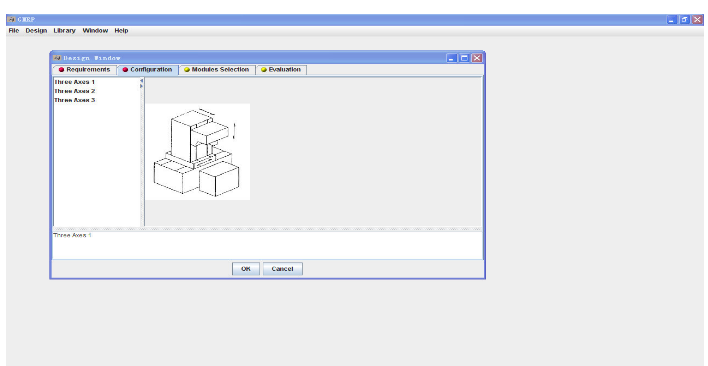


Fig. 6 Recommend design solutions

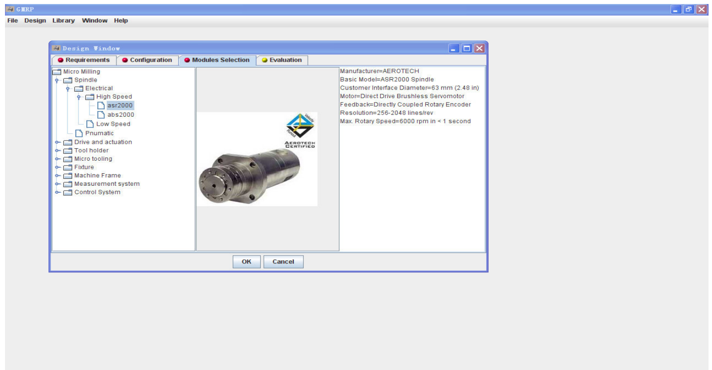


Fig. 7 Detail information of components

3.1 Extended Axiomatic Design

Axiomatic design is a design methodology which systematically processes information between and within four design domains: the consumer domain, the functional domain, the physical domain and the process domain. The domain structure and the specific domains in micro manufacturing of various micro parts are illustrated schematically in Fig. 8. The domain to the left relative to the domain on the right represents "what we want to achieve," whereas the domain on the right represents the design solution, "how we propose to satisfy the requirements specified in the left domain" [12].

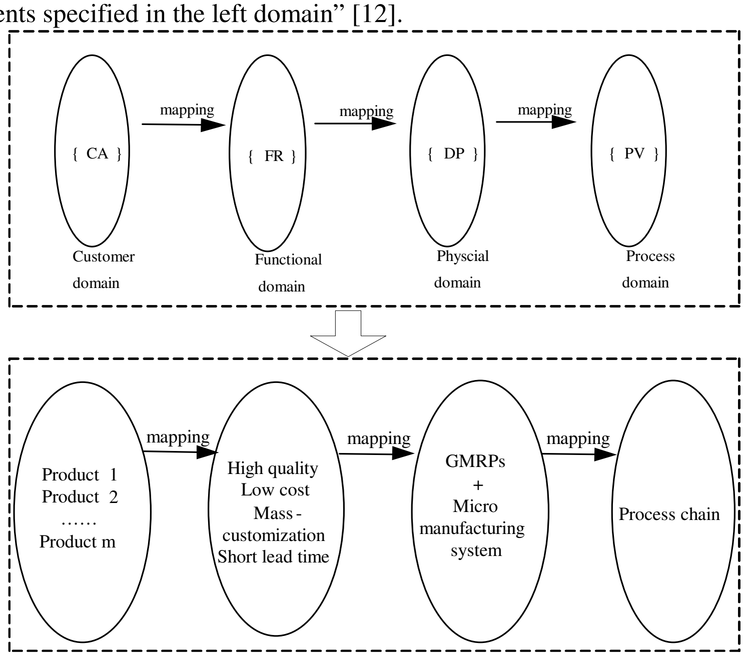


Fig. 8 Four domains of the micro manufacturing of various micro parts

Customer needs is described in the customer domain by the vector {CAs}. In the functional domain, the customer needs are translated to functional requirements {FRs). To satisfy the specified FRs, design parameters {DPs} in the physical domain are conceived. Finally, to produce the product specified in terms of DPs, we develop a process that is characterized by process variables {PVs} in the process domain [12-14]. In the micro manufacturing field, what customer need are various micro parts, so the micro manufacturing system has to be able to offer high quality, low cost and customized products. In the physical domain, GMRPs and GMRPs based micro manufacturing system are designed to provide the needs required in function domain.

Process chains in process domain can provide the fabrication of products required by customers. The mapping process between the domains can be expressed mathematically in terms of the characteristic vectors that define the design goals and design solutions. The relationship between functional requirements {FR} and design parameters {DP} which satisfy the functional requirements can be written as:

$$\{FR\} = [A]\ \{DP\} \tag{1}$$

where [A] is a design matrix for design process.

Two axioms that govern the design process in axiomatic design are stated as:
Axiom 1: The Independence Axiom. Maintain the independence of the FRs.
Axiom 2: The Information Axiom. Minimize the information content of the design.

Independence axiom states that the independence of functional requirements must always be maintained. It means that when there is two or more FRs, the design solution must be such that each one of the FRs can be satisfied without affecting the other FRs.

Information axiom states that among those designs that satisfy the Independence Axiom, the design that has the smallest information content is the best design because it requires the least amount of information to achieve the design goals. Information content I for a given FR is defined in terms of the probability P of satisfying FR:

$$I = \log_2 \frac{1}{P} = -\log_2 P \tag{2}$$

The information content for an entire system I_{sys} with m FRs is

$$I_{sys} = -\log_2 P_{\{m\}} \tag{3}$$

where $P_{\{m\}}$ is the joint probability that all m FRs are satisfied.

In simple cases where the distributions can be approximated as uniform distributions, equation (2) may be expressed as:

$$I = \log_2 \left(\frac{System\ Range}{Common\ Range} \right) \tag{4}$$

where System Range and Common Range are defined in Fig. 9. The Design Range corresponds to the required tolerances.

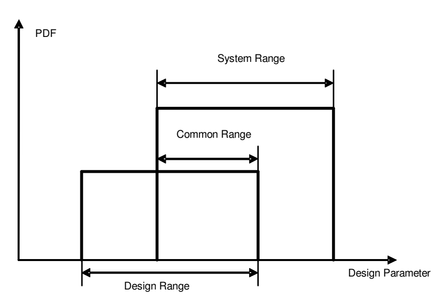


Fig. 9 Probability distribution of a system parameter

3.2 Application of Axiomatic Design

A number of corollaries can be derived from the above two axioms and some of them are very relevant to the design discussed in this paper, i.e.

Corollary 2: Minimization of FRs.
Corollary 3: Integration of physical parts.
Corollary 4: Use of standardization
Corollary 6: Largest tolerance.
Corollary 7: Uncoupled design with less information.

They can be directly used to guide the design process. A typical design process based upon the axiomatic design theory is as follows [15]:

Step 1: Establishment of design goals to satisfy a given set of perceived needs.
Step 2: Conceptualization of design solutions.
Step 3: Analysis of the proposed solution.
Step 4: Selection of the best design from among those proposed.
Step 5: Implementation.

For the design of GMRP, the customer needs can be therefore identified as:
CA1=reconfigurable
CA2=highly responsive
CA3=nano/micro manufacturing

These needs can be further translated into functional requirements:
FR1=machining functions
FR2=flexibility
FR3=accuracy
FR4=machining volume

The functional requirements can be each related to a design parameter:
DP1=machine type
DP2=set up time
DP3=accuracy of machine
DP4=maximal machinable part volume

It is possible to determine the mathematical relationship between the functional requirements and design parameters:

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ X & 0 & X & X \\ X & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \end{Bmatrix} \tag{5}$$

The first axiom has been used in the generation of the design parameters due to characteristics of design matrix of equation (5). Given these design parameters, there are many feasible solutions. The second axiom may be used to select the best design using the information content measure, calculated based upon equation (4) when system range and common range are known.

The functional requirements and design parameters could be further expanded into a hierarchical structure with the design parameter decomposition corresponding to the functional requirements decomposition. One obvious way of decomposition is a top down approach from the whole system through subsystems down to component level.

4.0 Conclusions

This paper has presented a generic modular reconfigurable platform (GMRP) intended for a product-service system in micro manufacturing, as well as its design methodology based upon the axiomatic design theory. The axiomatic design offers many benefits and can subsequently lead to optimum design.

The methodology is currently being implemented. The implementation is based on Java-based interface, axiomatic design and integration knowledge-base and 3D models library. The design and evaluation of the full system will be presented in a future paper.

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