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Reconfigurable Micro-Machine Tool Design for Desktop Machining Micro-factories

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Abstract:
Nowadays, the micro-factory concept of downsizing production systems is essential to manufacturing small products in sustainable growth. Concerning this, this paper presents the developments accomplished during the recent years at Tecnológico de Monterrey (Mexico) introducing new findings related to the design of reconfigurable micro-machine tools for micro-factories. It shows the framework related to the conceptualization of micro-factories for manufacturing system layouts based-on reconfigurable micro-machine tools, identifying the basic steps. The methodology for designing reconfigurable micro-machine tools is exposed, and a reconfigurable first-generation CNC micro- machine tool for micro-factories, is designed and tested, using the Universal Numerical Control concept.

Keywords:
Desktop, micro-factories, reconfigurable micro machine tool, CNC, micro manufacturing.

1. INTRODUCTION

Since the end of last century, there is a continuous and intensive technological improvement in manufacturing systems. The globalization of the world economy has meant that current manufacturing systems are subjected to increased production in small batches, increasing the flexibility of the systems, reducing production costs and improving product quality. In the recent world, there are many small mechanical parts and products that are used for mobile phones, medical devices, home appliances, and so on. However, manufacturing systems for those devices are large and complex. So, manufacturing systems should be small as possible within satisfying requirements in the production (Mishima, 2010).

There is a growing need for fast, direct and mass manufacturing of miniaturized functional products from metals, polymers, composites, and ceramics. The demand for miniaturized meso (1-10 mm) - micro (1-1000 µm) devices with high aspect ratios and superior surfaces has been rapidly increasing in aerospace, automotive, biomedical, optical, military and micro-electronics packaging industries (Koc, 2011). Today, the miniaturized production systems, i.e. micro and desktop factories, are widely studied in several universities and research centres around the world (Tanaka, 2001) (Honegger, 2006) (Ramírez-Cadena, 2012). This trend of development is supported by the commitment of governments and large-scale companies to move towards more environmental friendly production. Mini, micro and desktop factories are expected to decrease the factory floor space, reduce energy consumption and improve material and resource utilization which is strongly supporting the new sustainable manufacturing paradigm (Heikkila, 2010).

There is a need for more cost effective and adaptable production solutions for miniaturised products. One promising approach to meet the market demands bases on so called desktop factories. They inherently offer a sustainable and energy efficient solution for the assembly of meso- and microsized parts. The realisation of adaptable automation solutions based on desktop factories under the paradigm of Evolvable Production Systems (EPS) leads to the question of downscaling the implementation following the EPS guidelines (Hofmann, 2011).

The micro-factory concept advocates miniaturizing production equipment and systems to match product dimensions. The micro-factory concept for downsizing production systems is essential to manufacturing small products in sustainable growth. It is just entering the phase of practical application, following concept building and trial development in the 90s and the first decade of the new century. Further research and development are needed to realize the effectiveness of miniaturized systems in practical use (Okazaki, 2010).

This paper summarizes the developments accomplished during the recent years at Tecnológico de Monterrey (Mexico) introducing new findings related to the design of reconfigurable micro-machine tools (RμM^{2}T) for micro-factories. First, the framework related to the conceptualization of micro-factories manufacturing system layouts based-on RμM^{2}T is presented on Section two. Section three deals with the methodology for designing reconfigurable micro-machine tools. Section four explores the feasibility of applying the methodology proposed. For this purpose, a reconfigurable first-generation CNC micro- machine tool, was designed and tested. Section five shows the description of the Universal Numerical Control for Desktop Micro-factories. Section six discusses the layouts of the micro-factory based-on reconfigurable micro-machine tools developed. Section seven concludes the paper.

2. FRAMEWORK RELATED TO THE CONCEPTUALIZATION OF MICRO-FACTORIES MANUFACTURING SYSTEM LAYOUTS

Micro-factories have a set of specific characteristics that distinguish it from the classical manufacturing systems (Tanaka, 2001). The most relevant ones for this research area are:

(1) Significant reduction in terms of power consumption by decreasing the size of the manufacturing system.
(2) Reduction of inertial forces due to the low weight and technological characteristics of the components of micro-manufacturing system.
(3) Flexibility of micro-manufacturing systems increases because layouts of the production system can be easily changed compared with to those of conventional systems.

Based-on previous analysis, the next sub-sections shows a framework related to the conceptualization of micro-factories manufacturing system layouts based on RμM^{2}T, that can be implemented in the advanced development production system, on-site manufacturing system or mobile manufacturing system (Figure 1).

The framework consists of four stages. Step A begins the process of searching for the information needed for decision-making, regarding whether or not to develop a micro-factory. If the decision is to build a micro-factory, it goes to step B. At this stage are created different possible configurations of the micro machine tools that conform the micro-factory, according to the established requirements. Stage C defines the different layouts that could form the micro factory according to the identified needs. Finally, stage D makes the process of monitoring needs in order to reconfigure the micro-factory in terms of the new needs identified.

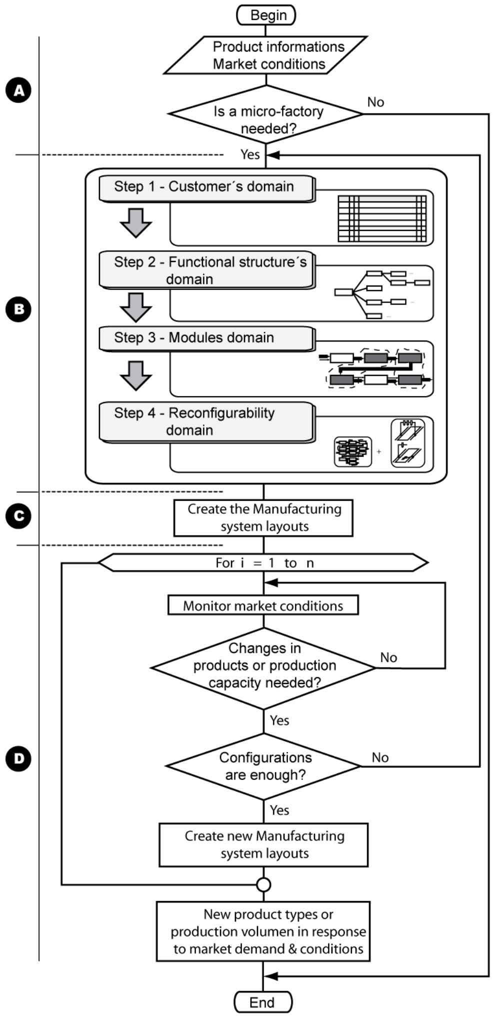

Fig. 1. Framework of micro-factories manufacturing system layouts based-on RμM^{2}T

2.1 Stage A: Product informations & Market conditions

The first stage of the proposed framework (Figure 1) includes the study of all micro-scale products to be processed by the micro-factory and the different technological conditions to be met. It is important to identify the family of features that will be machined into the micro-factory, since the RμM^{2}Ts will respond to this family of features. At this point you should take the decision on the construction of the micro-factory. If so, we continue with the design of RμM^{2}Ts that make up the micro-factory.

2.2 Stage B: Design of reconfigurable micro-machine tools

This stage is the focus of this article and is the key to the development of micro-factories with reconfigurable manufacturing systems (Figure 1). The design of RμM^{2}T guarantees in terms of machining the complete reconfigurability of the manufacturing system. The different configurations of RμM^{2}T obtained at this stage, satisfy the conditions set on stage A, relative to the family of features of micro parts. This aspect will be discussed in more details in section 3.

2.3 *Stage C: Create de manufacturing system layouts*

At this stage, from the different concepts of μRM²T that are obtained in the previous stage, different types of manufacturing system layouts are identified. At the same time, it must evaluate which one best satisfies the requirements of production defined on stage A.

2.4 *Stage D: Response to changes in the market conditions*

Once you have defined the most appropriate manufacturing system layout and the micro-factory is operational, it should be handled in a continuous process of monitoring the market. In case of identifying changes in the family of features of micro parts or need to change the production capacity, then it must assess whether the established RμM²T configurations can meet these changes. If so, we will proceed to consider new manufacturing system layouts. If not, you must return to stage B to obtain new configurations of RμM²Ts. This process is repeated until new manufacturing system layouts are obtained that meet market requirements.

3. METHODOLOGY FOR DESIGN RECONFIGURABLE MICRO-MACHINE TOOLS

In this research, a RμM²T refers to a micro-machine whose structural liaison permit quickly, customize more than one possible machining function (i.e. like turning, drilling and milling) configuration, in respond to a particular family parts' features. The RμM²T must satisfy at least the following properties: reconfigurable modularity, scalability and/or convertibility. The conceptualization of the design methodology for design of RμM²T, must be represented by four main steps (Figure 1). Each step has a specific function and a variety of sequential activities. Each main step must be executed following the prescribed order.

3.1 *Step 1: Customer's domain*

The first step of the methodology (Figure 2) allows accomplishing the customer's domain. This domain has the purpose of collecting the appropriate information from customers (a more detailed and thorough process that the one performed in stage A), related to the purpose and characteristics of the RμM²T and the micro-parts to be machined. To explore this domain, the methodology proposes a first activity, associated to the identification of the operational needs of the micro-machine tools and the micro-parts.

The main needs must be catalogued in: accuracy of the micro-machines and the micro-parts to be machined, structural characteristic of the micro-machines, vibration characteristics, preliminary kinematic analysis, thermal performance, and so forth.

The second activity starting from the identified operational characteristics. It's carried out a characterization of a family of micro-parts that should be mechanized on the micro-factory. The most important elements to keep in mind in this analysis are: the production volumes to perform, the basic technological processes that RμM²T must have, the main machined features of a family of micro-parts, the basic elements related to the tool paths

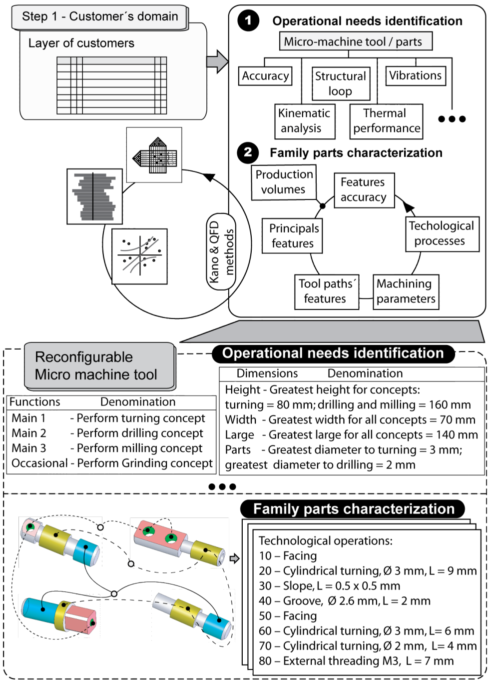

Fig. 2. Customer's domain step of the methodology

and the variability of the machined features parameters of a family of micro-parts.

These two activities of this domain should be analysed with tools that allow a qualitative analysis of the customer needs (Kano & QFD Methods), with the objective of identifying the weaknesses and strengths in the definition of the initial parameters of the micro-machine tools.

3.2 *Step 2: Functional structure's domain*

The second step of the methodology (see Figure 3) permits to carry out the functional structure's domain. This domain has the purpose of transforming the customer needs analysed in the previous step, in a functional structure of the RμM²T. The main elements that influence in the determination of the functional structure of the RμM²T are the technological processes defined in the step one of the methodology. This domain includes two key activities. The first one, is related to the identification of the operating modes of the RμM²T. Each operating mode characterizes the functionalities of the RμM²T, in response to the range of the technological processes defined. For each mode of operation, we have to identify the global function and set up the functional decomposition. Once concluded this process, we have a set of functional structures, in response to each mode of operation. This domain is significant for the methodology, because it states the necessary functional base, that is used in the following steps to find out the reconfigurability of the RμM²T.

3.3 *Step 3: Modules domain*

The third step of the methodology (see Figure 4) let the transformation of the set of functional structures obtained in the previous step, in modular identification of the RμM²T (modules domain). The domain comprises three main activities. Primarily, we proposed to analyse the functional decomposition of each mode of operation and

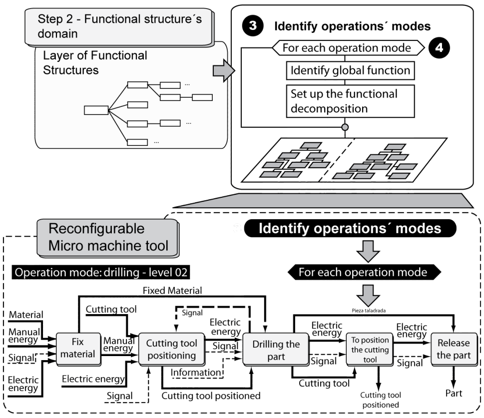

Fig. 3. Functional structure's domain step of the methodology

your related functional structure, to obtain a map with the main functions of the RμM^{2}T, view from different contexts.

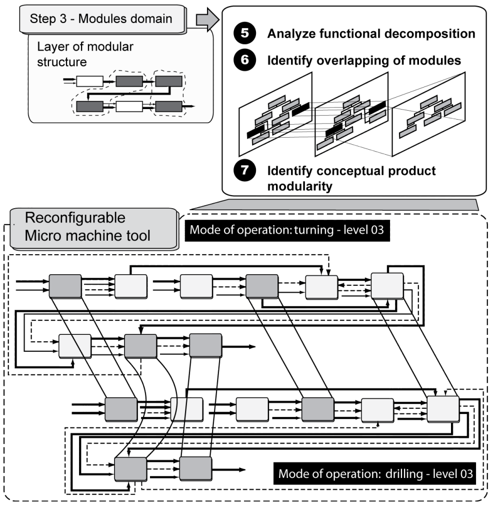

Fig. 4. Modules domain step of the methodology

The second activity includes the identification of the overlapping of modules. It consists in the comparison of each functional structure with the others, to recognize the similar functions of the RμM^{2}T and analyse the degree of dependence.

This activity is carried out recursively to the previous one. The third activity is focused on the identification of the RμM^{2}T modularity. This is the hub of the methodology, because it identifies one of the main properties of the reconfigurability concept, the reconfigurability modularity (Pérez, 2004) of the micro-machine tool.

3.4 Step 4: Reconfigurability domain

The fourth step of the methodology (Figure 5) allows the identification of the reconfigurability of the RμM^{2}T and is a key factor of the methodology. It's based-on a new method, denominated method to assess the conceptual reconfigurability of micro machine tools (MAcRM^{2}T). This method supports the identification of the ranges of variability of each micro-machine tool function, the definition of the different concepts of the RμM^{2}T, and allows the evaluation of the reconfigurability properties. The MAcRM^{2}T method is based-on a 3D-cube, where each face is used to specific purpose. In each activity, every face has a particular role and can be moved or rotated to obtain a precise intention. This domain covers three key activities. The first one, the definition of reconfigurability ranges, that allows the identification of the ranges of variability of each variant of function versus the technological possibilities defined in the customer's domain. The face α states all functions of the MAcRM^{2}T obtained in the modules domain, and their principle of solutions. The face β communicates the different technological processes which the reconfigurable micro-machine tool must be performed. If the designer matches each one of the technological process with the different principle of solutions of each function, he obtains the face γ, that allows the identification of the ranges of variability of each variant of function. The second activity of this domain, undergoes the definition of the reconfigurability concepts, permits the definition of the different concepts of MAcRM^{2}T, starting from the systematic combination of the principles of solution of the face α, and fulfilling the restrictions defined by the ranges of variability (face γ). In this activity, the face α articulates the systematic combination of the principle of solutions of each function, to obtain the different concepts of the MAcRM^{2}T. Each one of the concepts must satisfy at the same time, all the conditions exposed on face γ.

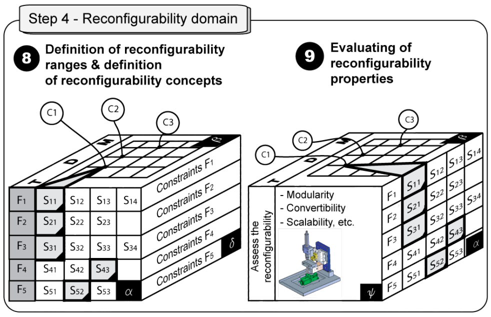

Fig. 5. Reconfigurability domain step of the methodology

At the same time, from assessing the modularity of the MAcRM^{2}T, this step facilitates the definition of the minimum number of active axe-of-motion needed to provide the flexibility to produce a part family, ensuring the customized characteristic of flexibility.

By this way, it is guaranteed that each concept fulfils the technological conditions expressed through the technological possibilities. Once finished the systematic combination of the principles of solution following the previous considerations, a set of refined concepts is obtained by the technological conditions.

4. RECONFIGURABLE MICROMACHINE FOR A MICRO-FACTORY

The objective of the test bed was to explore the feasibility of applying the proposed methodology. For this purpose, a reconfigurable first-generation CNC micro- machine tool, was designed and tested.

4.1 Step 1: Collect information to fulfil customer's domain

First of all, was applied the Kano's method to know the behaviour of the customer needs and the QFD's method to systematically take the desires down to the level of detailed operations. After that, the operational needs based-on a survey of the customers was recognized (Figure 2).

The typology of the customer needs was structured in functions, dimensions, geometric characteristics, kinematic conditions, modularity, costs, and so forth. The main functions of the micro machine tool were identified: turning, drilling, milling and occasionally grinding. The maximum dimensions that could have the micro machine tool were 25 x 30 x 50 cm for all configurations in the micro-factory. The geometrical features of the families of micro-parts that should predominate are: processes of turning, drilling and milling. The kinematic conditions were set as high stiffness and decreased number of possible links in the kinematic chain of micro-machine tool in its different configurations. Was established as a requirement to ensure high modularity in the system and all at a reasonable cost. Then, was preparing the family parts characterization ensuring high modularity.

4.2 Step 2: Transform the customer's need in a functional structure of the micro machine tool

The aim of this domain is to obtain a set of functional structures starting from the identification of the operation modes. The main operating modes, casual and accidental, were identified as modes of operation of the RμM^{2}T, . In this case, they were identified three main operation modes: (a) turning; (b) drilling; and (c) milling. Was identified as an occasional mode of operation the grinding technological operation.

Having identified the main operating modes, functional structures is constructed by levels for each of them, starting with the main function of the RμM^{2}T up to a level of functional structure that meets the design requirements. This operation should be made for each operation mode and with the number of levels that it is considered appropriate. In the Figure 3, it is shown the case of the functional structure for the operation mode of drilling, in the second level of stratification. Once all functions have been decomposed to a given level, the last layer will represent the sub-functions that are more related to the final structure of the micro machine tool.

4.3 Step 3: Transform the functional structures in modular identification

The basic characteristic of the RμM^{2}T is their modular construction, which is neither completely functional, nor completely constructive, but rather possesses reconfigurability oriented modularity. Reconfigurable modularity (Pérez, 2004) refers to a set of principles and rules that define a family of machines or products, to the manner and shape in which modules are standardized and their respective interfaces. These modules allow modifications to the structural and functional configuration of the machine, in such a way that significant changes to product form and demand can be accommodated.

Based-on this concept, the modules domain (Figure 4) pull out the intrinsic modularity of the micro machine tool, because visualize the connection among the functions of each functional structure of each operation mode, in each level of stratification. In this step is analysed the decomposition of the functional structure of the last level of stratification of each main mode of operation. This analysis provides the identification of modules that match in each main operation mode. In this way the conceptual modules of the micro machine tool are able to identify, from the functional structures obtained in the previous step.

4.4 Step 4: Identify the reconfigurability of the machine

The core of the proposed methodology is the domain of reconfigurability (Figure 5), because it transforms the visualization of the connection among functions in engineering information related to the principles of solutions, concepts and the evaluation of the properties of the reconfigurability. Following the activities proposed by the MAcRM^{2}T method in Figure 5, we can find firstly, the definition of the reconfigurability ranges of each variant of function. In the analysed case, in the face α of the 3D-cube we can observe the principles of solutions to the main functions of the RμM^{2}T. The information contained in the α phase is the same as offering traditional morphological matrix, which establishes a link between functions and principles of solution.

Once it has completed the filling process of the α phase, then are located the different main modes of operation of the micro machine tool in the β phase. The face β of the 3D-cube express the technological processes that the RμM^{2}T must be performed, i.e. turning, drilling and milling, represented by T, D and M respectively in the Figure 5. Following the procedure of MAcRM^{2}T method, once it has concluded the completeness of phase β must be completed the γ phase. This step consists in performing a process of linking each one of the functions of the α face with each one of the main modes of operation of the micro machine tool represented in the β phase.

The face γ represent the simultaneous analysis of the faces α and β respectively, and manifest the ranges of variability of each variant of function. This ranges represent restrictions to the following activity of this domain, therefore, they are the firsts conditions to obtain the required reconfigurability of the RμM^{2}T. Secondly, we can construct the different concepts of the RμM^{2}T. Using the principles of solutions of the face α, we are able to use the systematic combination of these principles, like the usual morphological method, only that in each combination, it will be proven that it fulfils the restrictions obtained in the face γ. Following these recommendations, we obtained the set of RμM^{2}T concepts in the face β. These concepts take in an implicit way, the first restrictions that support the identification of the reconfigurability of the micro machine tool.

The concepts reflected in the β face of the MAcRM^{2}T method satisfy both the functional requirements established in stage A, such as restrictions or ranges of variability of the main modes of operation of the micro machine tool set on the face γ. In Figure 5, it's shown two of the possible concepts of the RμM^{2}T that they accomplish the technological conditions of the customer needs: the turning, drilling and milling technological processes.

5. UNIVERSAL NUMERICAL CONTROL

The automatic control of the prototype of the reconfigurable micro-machine tools for micro factories is based on a platform of open resources with a data acquisition board PIO-D48U for a PCI bus. This setting controls the micro-machine tools and also serve as an interface to the application of Universal Numerical Control (UNC).

The UNC is a modular control system that can be adapted to any machine tool and has movable components. The UNC is a communication module that enables the use of various hardware signals and modifies or select the type of interpolation or GUI required. It has a modular architecture consisting of functional units or modules of software applications that perform specific tasks required by the user or process (Ramírez-Cadena, 2012).

The interface has two modes, automatic and manual. The automatic mode is able to process a G code program and interact with the actuators through the control board. Manual mode is mainly to make strategic adjustments to the automatic mode.

6. MANUFACTURING SYSTEM LAYOUTS FOR THE MICRO-FACTORY

In this section, is shown the layouts of the micro-factory based-on reconfigurable micro-machine tools, like the RμM^{2}T developed.

A Reconfigurable Manufacturing System (RMS) (Koren, 1999) is designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements. According to this definition, an RMS is expected not only to accommodate for the production of a variety of products, which are grouped into families, but also it must give a positive response to new products introduced within each family. A critical decision in this process is the selection of the system configuration. The arrangement of the processing-units in series, in parallel, or in different hybrid configurations, has a profound effect on factors such as product quality variations, overall system productivity, the ease of adding incremental production capacity, and cost.

Selecting the optimal solution from the large number of possible alternatives (more than 2n-1 for n machines) requires the development of new configuration rules. Next, the required operations are distributed across the machines in a balanced manner by a system-level process planner. Finally, life-cycle economic modeling that estimates the system cost during its entire life-time, and accounts for future product changes and uncertainty in market conditions, must be used to select among the feasible manufacturing system alternatives (Koren, 1999). Three feasible system configurations were drawn, based-on the features of the micro-part's family. A serial line (I) with three RμM^{2}T. This configuration produces lowest reliability, acceptable micro-part quality and low investment cost. The second configuration (II) is formed by two parallel micro-cells, each with three RμM^{2}T in series. This configuration produces acceptable reliability and best micro-part quality. The last configuration (III) is formed by two serial micro-cells, each with three RμM^{2}T in parallel. This configuration produces the best reliability, large quality variance and the easiest to add incremental capacity.

The MAcRM^{2}T is completely adapted to the RMS concepts in the micro-factory, because can be adapted to any configuration of the proposed layouts.

7. CONCLUSIONS

The framework of micro-factories for manufacturing system layouts based-on reconfigurable micro-machine tools, allows the generation of layouts for micro-factories, based-on RμM^{2}T. The methodology for designing reconfigurable micro-machine tools was exposed. The RμM^{2}T enable the possibility to have completely reconfigurable micro-manufacturing systems, adapting to different conditions and demands of micro production systems.

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