

Methodology for Configuring Desktop 3-axis Parallel Kinematic Machine

Saša Živanović

Research Assistant
University of Belgrade
Faculty of Mechanical Engineering

Miloš Glavonjić

Full Professor
University of Belgrade
Faculty of Mechanical Engineering

Zoran Dimić

Research Assistant
LOLA Institute, Belgrade

Configuring machine tools is a complex task which involves the use of huge spectra of conceptions, methods, models, calculations, technologies, simulations, control, programming, techno-economy. The paper presents the IDEF methodology for functional configuring of new machine tools, with an example of this methodology application for desktop 3-axis parallel kinematic machine. The paper describes the structure of the machine, modeling approach, and control and programming system based on PC Linux platform with real-time extension and EMC2 (the Enhanced Machine Controller) software system. Desktop 3-axis parallel kinematic machine (PKM) has been verified by successful making of the first prototype.

Keywords: configure, IDEF, control, parallel kinematic machine.

1. INTRODUCTION

The term configure is particularly common in the world of computer technology, for example, it is said to configure computers, network, server, protocols, user accounts, etc. Today, the concept of design and construction of the machine tool is unthinkable without computers, and the term configure has entered in this area. Modern machine tools are very complex mechatronical systems. The capability and efficiency of a machine tool are mainly determined by its kinematics, structural dynamics, computer numerical control system and the machining process [1].

The proposed definition of configuring machine tools is as follows: Configuring a new machine tool is a process of functional completion on the basis of the conception of machine tools, using standard and special (calculated and made) components, kinematics and the open architecture control. For the new machine tool, some of the new general methodology for configuring is always useful. The description of the process of configuring a new machine tool requires methodology, general enough for the designer, no matter which machine tool it is.

This approach would use the computer as a processor model of a machine tool, in which the models were subjected to various transformations. They would then be received at the exit of the virtual (digital) prototype machine tool, which can be considered reliable enough to immediately start the production. The virtual prototype of machine tool is computer simulation model of the physical product that can be presented, analysed and tested like a real machine [1].

This paper discusses the application of the methodology of configuring the parallel kinematic machines (PKM). Industrial adoption of the PKM may be eased by availability of methodologies, and integrated tools enable the PKM analysis of any

configuration for a short time, providing the key data needed to design a machine. The PKM design, a methodology, supported by powerful, integrated software tools is given in the works [2,3]. This paper presents the IDEF methodology of functional configuring of new machine tools.

2. IDEF FUNCTIONAL MODELING METHODOLOGY

In configuring new machine tools the Integration Definition Function Modeling (IDEF0) methodology [4,5] is applied. During the 1970s, the U.S. Air Force Program for Integrated Computer Aided Manufacturing (ICAM) sought to increase manufacturing productivity through systematic application of computer technology. The ICAM program identified the need for better analysis and communication techniques for people involved in improving manufacturing productivity. As a result, the ICAM program developed a series of techniques known as the IDEF (ICAM Definition) techniques which included IDEF0 methodology too, which is used here.

The IDEF0 is used to produce a "function model". A function model is a structured representation of the functions, activities or processes within the modeled system or subject area [4].

The IDEF0 is a methodology based on combined graphics and text that are presented in an organized and systematic way to gain understanding, support analysis, provide logic for potential changes, specify requirements, or support systems level design and integration activities. An IDEF0 model is composed of a hierarchical series of diagrams that gradually display increasing levels of detail describing functions and their interfaces within the context of a system [4].

The IDEF0 model diagram displayed in Figure 1 is based on a simple syntax. Inputs are shown as arrows entering the left side of the activity box, while the outputs are shown as exiting arrows on the right side of the box. Controls are displayed as arrows entering the top of the box, and mechanisms are displayed as arrows entering from the bottom of the box. Inputs, controls, outputs and mechanisms (ICOMs) are all referred to as concepts [5].

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Correspondence to: Sasa Zivanovic, M.Sc.
Faculty of Mechanical Engineering,
Kraljice Marije 16, 11120 Belgrade 35, Serbia
E-mail: szivanovic@mas.bg.ac.rs

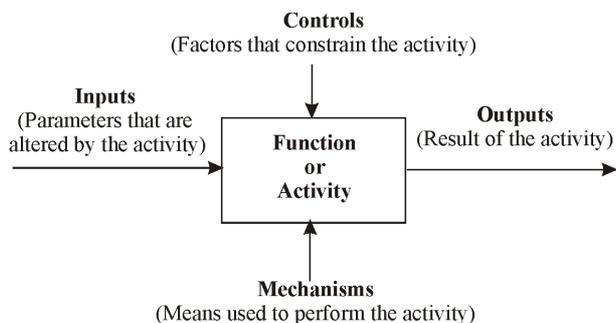


Figure 1. Basic IDEF0 Syntax [5]

A strategy for organizing the development of IDEF0 models is the notion of the hierarchical decomposition of activities. A box in an IDEF0 model, after all, represents the boundaries drawn around some activity. Inside the box is the breakdown of that activity into smaller activities, which together comprise the box at a higher level. This hierarchical structure helps the practitioner to keep the scope of the model within the boundaries represented by the decomposition of the activity, as shown in Figure 2.

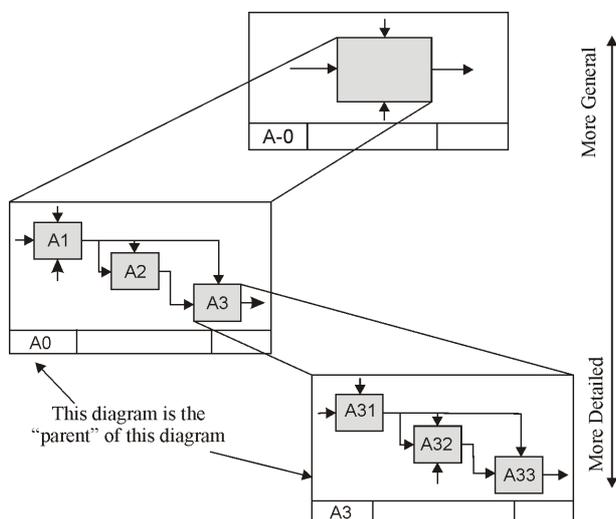


Figure 2. Decomposition construction of an IDEF0 model [5]

This organizational strategy is also useful for hiding the unnecessary complexity from view until a more indepth understanding is required.

The IDEF0 is particularly useful in this context because it allows consistent multi-level models to be created. These multi-level models progressively reveal more details at each level, with each individual level being simple to understand in comparison to the complexity of the whole enterprise model [5].

3. CONCEPT OF 3-AXIS PARALEL KINEMATIC MILLING MACHINE

Compared with conventional machine tools, parallel kinematic machine (PKM) has many advantages, e.g. higher stiffness and higher force-to-weight ratio. This is regarded as a revolutionary concept for machine tools. Many research works about diverse aspects of PKM have been published but they are still R&D topic in many laboratories.

It is well-known that the shape and volume of the workspace are one of the greatest weaknesses of parallel

kinematic machine tools. Hexaglide and Triaglide mechanisms [6] are examples where workspace extension is achieved by elongating one axis as a principal motion axis that is a common feature of all Cartesian machines. With the idea of principal axis of motion in mind, a new 3-*dof* spatial parallel mechanism for horizontal and vertical milling machines has been developed [7,8]. The concept of mechanism model is shown in Figure 3. The mechanism consists of the mobile platform, three joint parallelograms c_1 , c_2 and c_3 , and a stationary base with two parallel guideways.

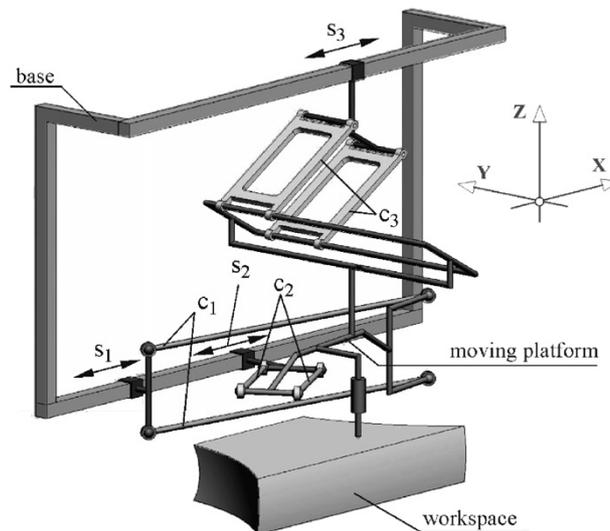


Figure 3. Concept of the parallel mechanism pn101 [8]

Two crossed parallelograms c_1 and c_2 , with spherical and/or universal, i.e., cardan joints, are connected with one of their ends to the mobile platform, and with their other ends to the independent sliders s_1 and s_2 which, with a common guideway, make two powered and controlled translatory joints.

The third joint parallelogram c_3 is connected with one of its ends, through passive rotating and translatory joints to the mobile platform. Its other end is connected with rotating joints to the slider s_3 , which makes, with the second guideway, the third powered and controlled translatory joint. The actuation of sliders s_1 , s_2 and s_3 offers three degrees of freedom to the mobile platform, i.e., the tool, so that the platform in its motion through the space retains constant orientation.

The influence of mechanism structure on the workspace shape and volume is reflected in the following [7,8]:

- The parallel guideways provide:
 - arbitrary workspace length in X direction, and
 - regular workspace shape on its boundaries in Y direction, i.e., $Y_{\min} = \text{constant}$ and $Y_{\max} = \text{constant}$.
- The crossing of joint parallelograms c_1 and c_2 provides:
 - decreasing of guideway lengths for the same X dimension of workspace, and
 - smaller curvature on X_{\min} and X_{\max} workspace borders.
- Passive translatory *dof* or joint in Y direction provides:
 - decoupling of platform motions in Z and Y directions, and

- Exceptional workspace regularity with $Z_{\min} = \text{constant}$ and $Z_{\max} = \text{constant}$ on its borders for each of $Y_{\min} \leq Y \leq Y_{\max}$.

In comparison with similar developed mechanisms it has several advantages such as: rather regular shape of the workspace (slightly modified block) similar to serial machines; greater stiffness by nature of struts arrangement; good force and speed ratio through the entire mechanism workspace. The variance of mechanism structure and design solutions enables a wide range of applications for vertical and horizontal 3-axis milling machines, as described in [7,8], where first developed vertical milling machine prototype has been presented, Fig. 4.



Figure 4. Experimental vertical milling machine, first industrial prototype LOLA pn101_4 V.1 [7]

3.1 Desktop 3-axis parallel kinematic machine

Today, unfortunately, a great majority of research institutes, university laboratories and companies have no PKM. The reason, obviously, is the high cost of education and training for a new technology, such as PKM.

In order to contribute to acquiring practical experiences in modeling, design, control, programming, and the use of PKM, functional simulator of parallel kinematic milling machine has been first developed [9] and then a low-cost desktop educational 3-axis parallel kinematic milling machine [10] is suggested.

The developed educational desktop 3-axis parallel kinematic milling machine is based on a newly developed 3-DOF spatial parallel mechanism [11]. This mechanism was first used for successful development of experimental vertical milling machine prototype described in detail in [7,8]. On the basis of several-years' experience in developing vertical milling machine prototype, we arrived at the conclusion that based on the same mechanism a low-cost desktop educational 3-axis parallel kinematic milling machine, Fig. 5, can be developed as a help in the process of acquiring basic experiences in the field of PKM.

The paper describes the methodology of configuring, the structure of mechanism, developed experimental prototype of educational desktop 3-axis parallel kinematic milling machine, and control and programming system based on PC Linux platform with

real-time extension and EMC2 software system [12,13]. The design model for the desktop 3-axis PKM is shown in Figure 4.

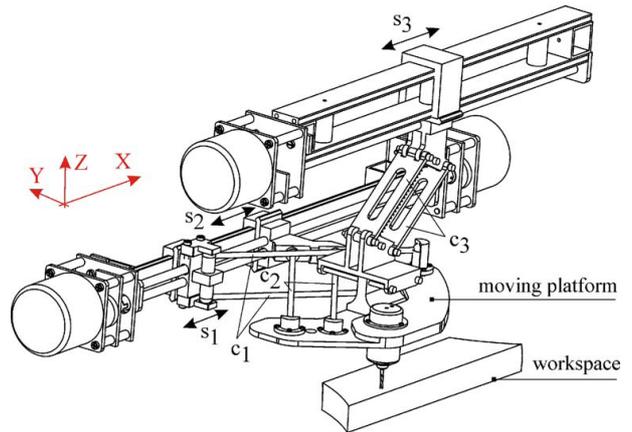


Figure 5. Design of mechanism's model for pn101_st V.1 [14]

4. METHODOLOGY OF FUNCTIONAL CONFIGURING MACHINE TOOL

The basic idea is to build an integrated design environment for configuring – that will enable a concurrent synthesis of the physical machine structure, the virtual machine – for validation, visualization and off-line programming, and control algorithms [2].

Functional model for configuring the new machine tool is a structural presentation function, activity or process modeling, which can be viewed at several different levels. The result of applying IDEF0 methodology to configure the machine tool is a model which consists of a set of hierarchical diagrams with text descriptions, Fig. 6.

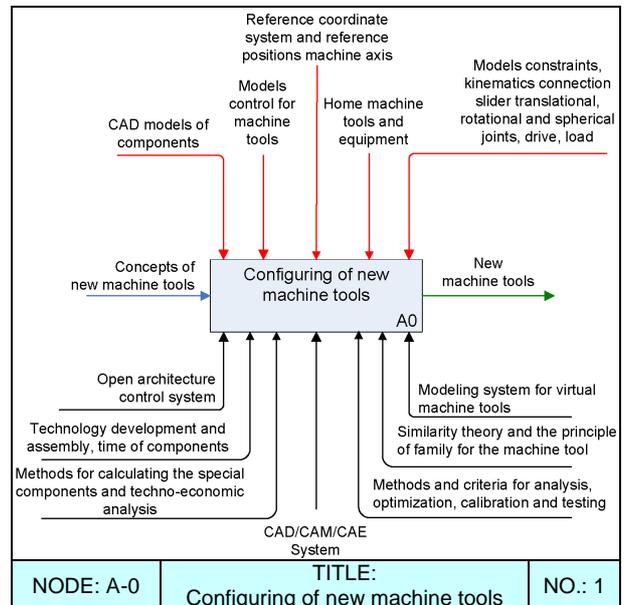


Figure 6. View diagram A-0

Configuring the new machine tool is a complex task that involves the use of a wide range of different conceptions of machine tools at the input of the general functional block. After the transformation to follow in the functional block of the output you get a new machine tool.

Arrows on the upper side of the controls initial can be described in the following way:

- CAD models of standard components with the purchasing price,
- models of machine tool control,
- a reference coordinate system of machine tools (standard) and the reference position of each axis of machines,
- available home machines and other equipment that will be used for the production of new machine tools, with the price of their privacy,
- kinematics models limit connections, drives, and load on the machine tool.

Control mechanisms that perform the appropriate transformation in the functional blocks, entering from the bottom, can be described as follows:

- CAD/CAM/CAE system, the environment for the design, project planning, design, programming, simulation of a new machine tool,
- open architecture control system with real-time extension,
- methods for calculating special components,
- technology of special components and the time of technology and assembly with the necessary time,
- techno-economic analysis,
- modeling system for virtual machine tools,
- similarity theory and the principle of family, planning for the production as the family of machine tools,
- methods and criteria for the implementation of analysis, optimization, calibration and testing of machine tools.

A more detailed diagram A-0 (Fig. 6) provides the basic flow of activities to configure the new machine tools; it is shown in Figure 7a.

The basic flow of activities are:

- A1 – Design of the machine and the establishment of the necessary model,
- A2 – Configuring the control,
- A3 – Analysis and simulation of the model,
- A4 – Making of machine tool and test work.

For example, a more detailed diagram A4 is shown in Figure 7b.

4.1 One example application of this methodology

One application of this methodology, from Figure 6, shown on the example of configuring desktop 3-axis parallel kinematic machines, is given in Figure 8. The input to this methodology is patent Triaxial spatial parallel mechanism, pn101 [11]. Several different concepts were discussed and pn101_4 was adopted as a starting conception for the desktop version of 3-axis parallel kinematic machine. The PC Linux platform with real-time extension was deployed for control and EMC software system [12,13]. For the modeling of virtual machine, Python program language was used. For modeling, design, simulation and programming, CAD/CAM/CAE system Pro/Engineer, Wild Fire 4 was applied.

A full decomposition of the activities, Fig. 6, in configuring new machine tools with an example of application of this methodology for desktop 3-axes parallel kinematic machine is summarized in Table 1.

Table 1. A full decomposition of functional configuring activities

A1.	<i>Design machine pn101_st V.1 and the establishment of the necessary model</i>	
	A11.	Selection and design of machine components
	A12.	Project of a complete machine tool
	A13.	Configure family machine tools
	A14.	Techno-economics of machine tool
A2.	<i>Configuring Control for pn101_st V.1</i>	
	A21.	Control modeling for machine pn101_st V.1
	A22.	Integration of model control into EMC
	A23.	Simulation of CNC system in EMC
	A24.	Configuring virtual machine simulator of pn101_st V.1
	A25.	Integration of control systems into EMC
A3.	<i>Analysis and simulation of the model</i>	
	A31.	Formation of the model for CAE and optimization
	A32.	CAE analysis
	A33.	Optimization of the model
A4.	<i>Make pn101_st V.1 and test work</i>	
	A41.	Development of special components and subcomponents
	A42.	Assembly of machine tool
	A43.	Calibration of machine tool
	A44.	Testing and trial work of machine tool

Example, the basic flow of activities to configure the desktop 3-axis parallel kinematic machine pn101_st V.1 is shown in Figure 8a. It can also show a detailed diagram of each sub-function. So, Figure 8b displays a more functional block A2: Configuring control for pn101_st V.1.

5. DEVELOPMENT OF DESKTOP 3-AXIS PKM, FIRST PROTOTYPE

Using previous experience in the field of PKM and successfully developed first experimental prototype of vertical milling machine based on newly developed mechanism [7,8], there emerged an idea about developing a low-cost desktop educational 3-axis parallel kinematic milling machine. Initially, it was concluded that the developed mechanism is suitable in both design and technological respect.

The first step was to set the goals that can be summed up as follows:

- it is a low-cost desktop educational machine,
- it can machine soft materials,
- it is programmable in a common way,
- it is fully safe for user-beginners.

Using the thus determined goals, elaboration of the concept involved:

- dimensional analysis of the desktop machine and its workspace,

- conception of basic units with the choice of possible solutions.

Those two steps are strongly synergetic, because care had to be taken of the previously set goals and

constraints, such as: that it is a desktop machine, that main components (step motors, leadscrews, sliding guideways, joints, etc) can be easily procured, that all other components can be built in a laboratory.

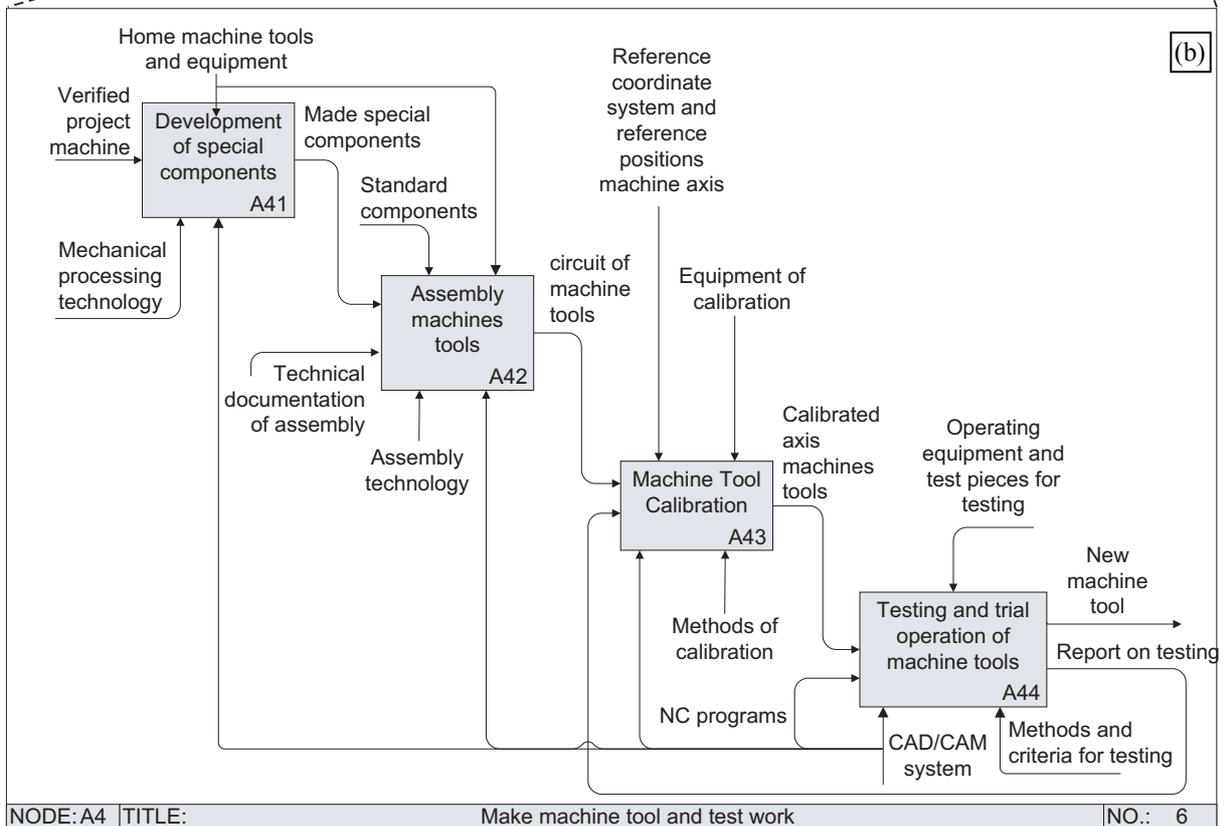
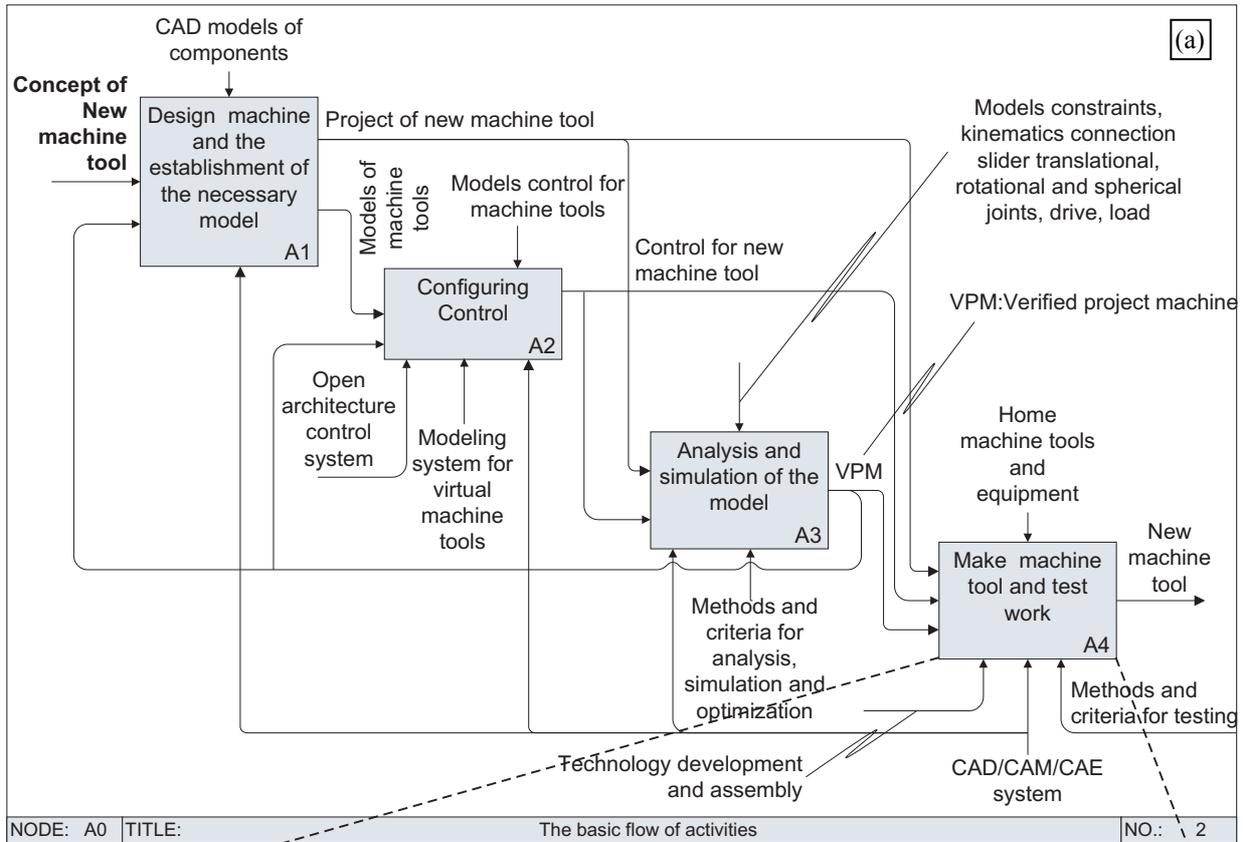


Figure 7. View diagram A0 and A4

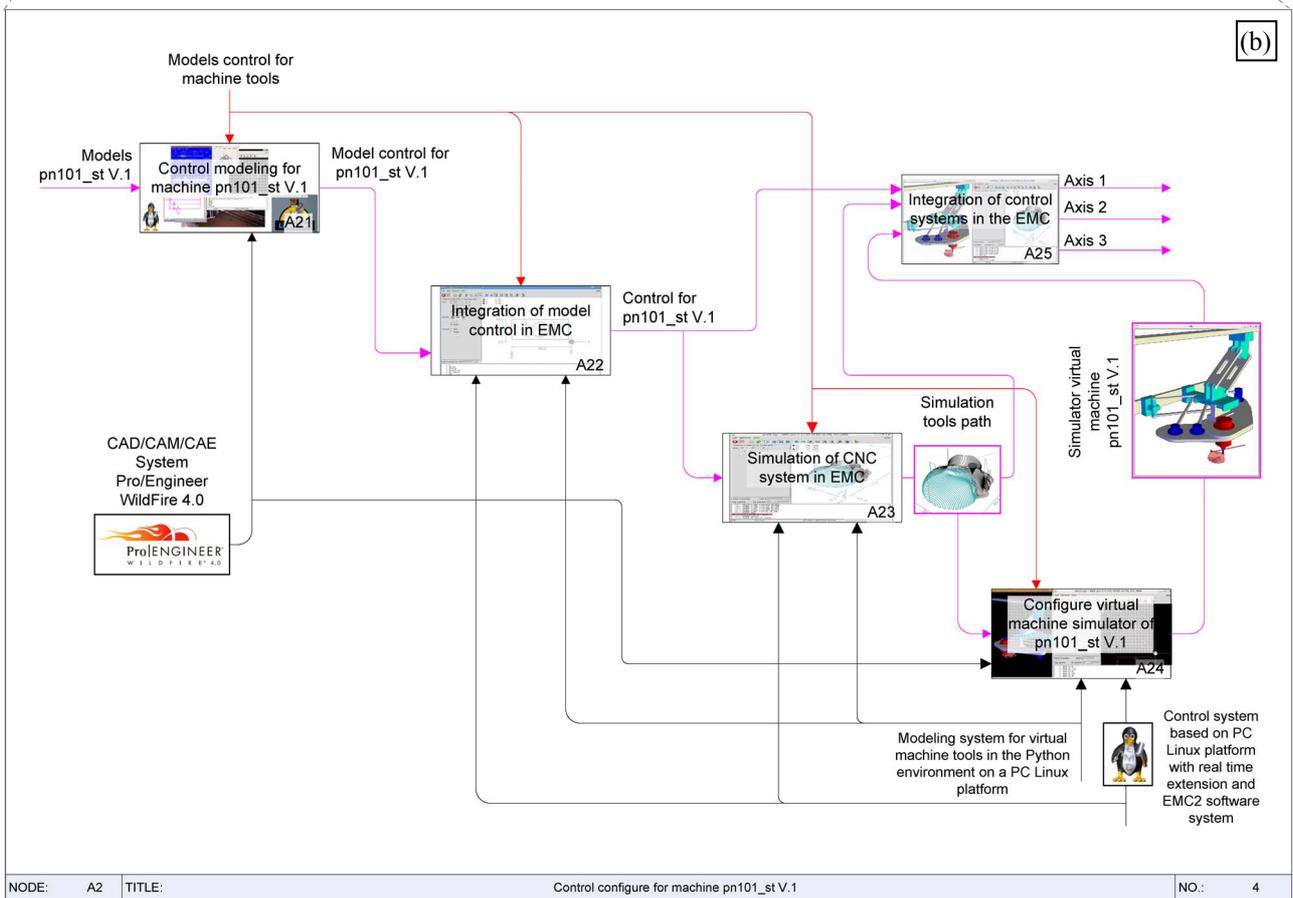
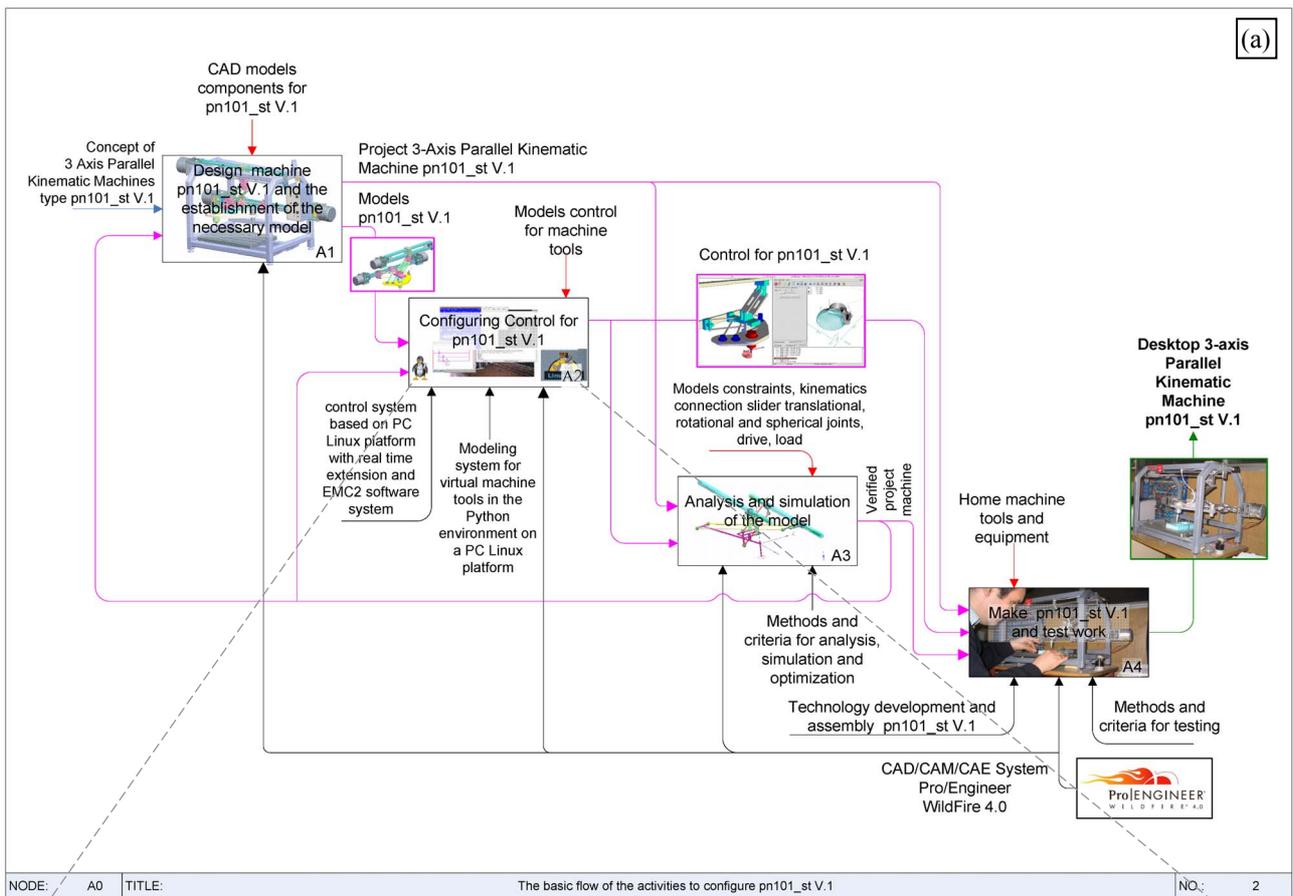


Figure 8. View diagram A0-Basic flow of activities and A2 – Control configure for machine pn101_st V.1

The analysis evidenced that scale factor 5, compared to the first experimental industrial size milling machine prototype [7,8], would be an optimal solution because the machine would be desktop and would have 5 times smaller overall sizes and 5 times smaller workspace overall sizes, retaining all advantages of the mechanism used. Those dimensions also provide for applying the existing low-cost components as well as building of other components in our laboratory.

Figure 9 shows CAD model of developed desktop educational 3-axis parallel kinematic milling machine that all necessary technical documentation has been generated from.

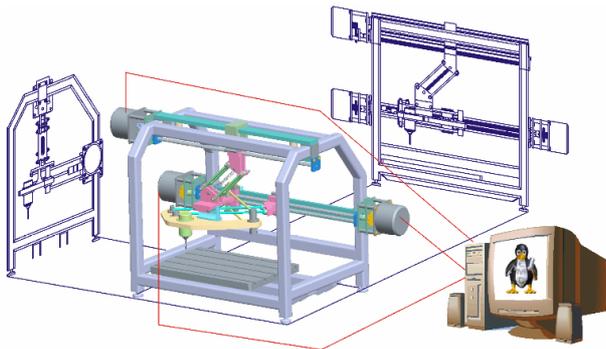


Figure 9. CAD model of desktop 3-axis PKM

Since geometric model of desktop educational milling machine is identical to the model of developed industrial size milling machine prototype [7,8], workspace of desktop milling machine is shown in Figure 10.

Control and programming system is based on PC Linux platform with real-time extension and EMC2 software system for computer control of machine tools, robots, hexapods, etc. EMC2 was initially created by NIST (the National Institute of Standards and Technology) and is free software released under the terms of the GPL (General Public License) [12,13]. Based on inverse and direct kinematics module [14], it

is programmed in C language and is integrated into EMC2 software system.

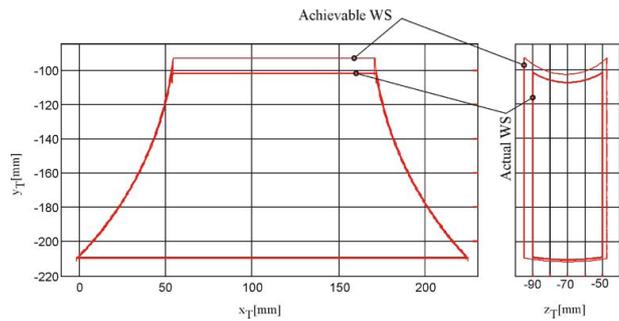


Figure 10. Workspace of desktop milling machine

Part programming is very conventional, with the use of a postprocessor to convert CL file into G code. During G-code loading, EMC2 software performs cutter path verification. Since this is an educational system with a complex kinematics, a virtual machine was included in the control and programming system too. Virtual machine is designed by using several classes predefined in object-oriented programming language Python. When the program starts running, G-code instructions are executed in real time and generated control signals are directed to a real and/or virtual machine. The virtual machine makes possible simulation of the real machine for the user, i.e., verification of the program in desktop machine workspace, Fig. 11.

Virtual machine is characterized by:

- validation of the part program generated by a commercial CAM software,
- on-line visualization,
- off-line programming of the machine.

On the basis of the adopted concept and design parameters, the first low-cost desktop educational 3-axis parallel kinematic milling machine has been built and tested in our Laboratory, Fig. 12.

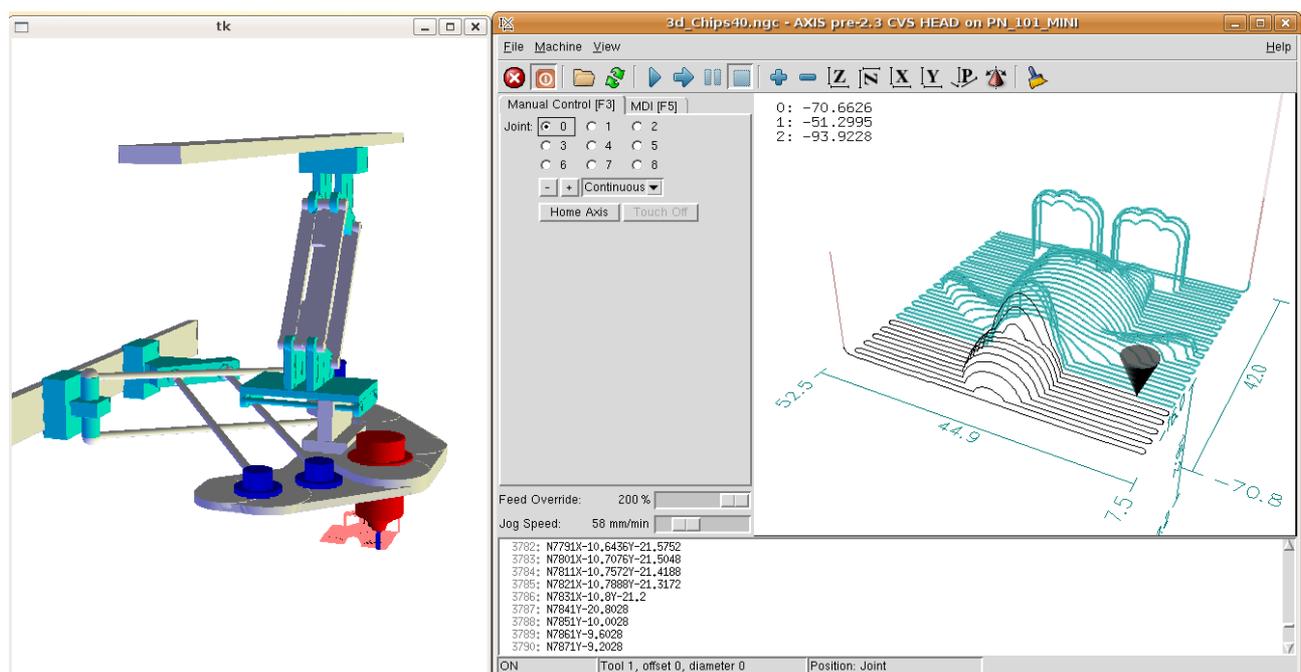


Figure 11. Virtual machine and simulation of tool path in EMC (AXIS environment)

According to the overall dimensions and estimated accuracy of developed desktop milling machine prototype basic calibration is performed on machining center during the assembly process.



Figure 12. Desktop 3-axis parallel kinematics machine, first prototype pn101_st V.1

After preliminary geometric tests, the processing of the test pieces and contours follows, Fig. 13.

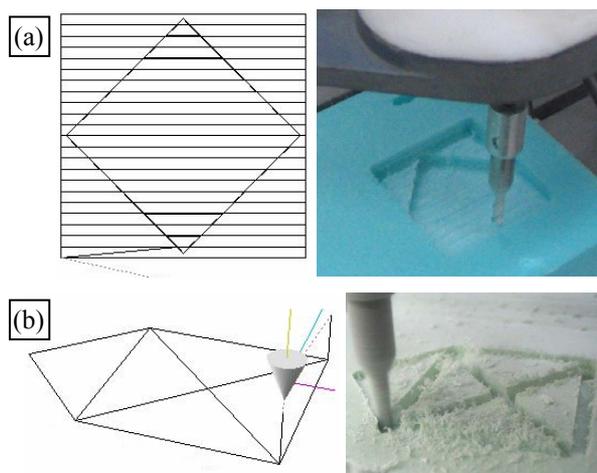


Figure 13. Simulation tool path and machined test pieces

6. CONCLUSION

This paper presented a functional model of configuring the new machine tool as a result of applying IDEF0

methodology. The application of IDEF0 methodology proved to be very successful in describing the functions and activities during the configuration process. This methodology is applied to different objects, such as desktop 3-axis parallel kinematic machine pn101_st V.1 (at the level of physical prototype), and desktop parallel kinematic machine pn101_st V.2 (at the level of virtual machine tool), Fig. 14.

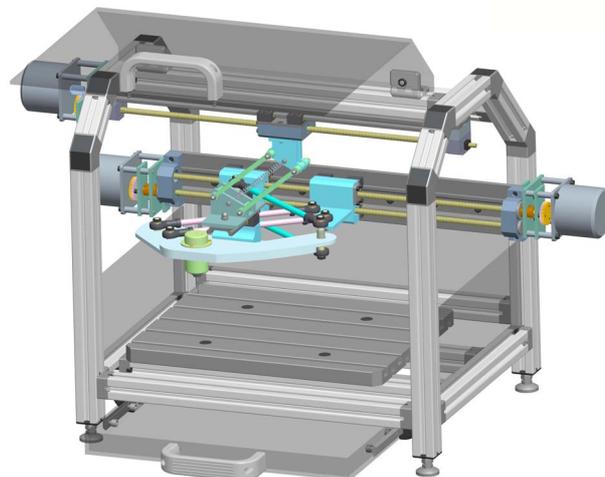


Figure 14. Desktop 3 axis parallel kinematic machines pn101_st V.2 (with standard components)

In order to contribute to acquiring experience in modelling, design, control, programming and use of PKM, a low-cost desktop educational 3-axis parallel kinematic milling machine is proposed. The developed desktop educational parallel kinematic milling machine is based on newly developed 3-dof spatial parallel mechanism with specific advantages in comparison with similar mechanisms. The developed low-cost desktop educational parallel kinematic milling machine could be comprehensive and sophisticated didactic facility. The laboratories, universities and schools may find a planned commercial version of this machine.

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REFERENCES

- [1] Altintas, Y., Brecher, M., Weck, M. and Witt, S.: Virtual machine tool, CIRP Annals – Manufacturing Technology, Vol. 54, No. 2, pp. 115-138, 2005.
- [2] Molinari Tosatti, L., Bianchi, G., Fassi, I., Boër, C.R. and Jovane, F.: An integrated methodology for the design of parallel kinematic machines (PKM), CIRP Annals – Manufacturing Technology, Vol. 47, No. 1, pp. 341-345, 1998.
- [3] Giacomo Bianchi, Irene Fassi, I., Lorenzo Molinari Tosatti, A virtual prototyping environment for Parallel kinematic machine analysis and design, in: *Proceedings of the Year 2000 Parallel Kinematic Machines International Conference (2000-PKM-IC)*, 13-15.09.2000, Ann Arbor, USA, pp. 99-108.

- [4] *Integration Definition for Information Modeling (IDEFIX)*, Federal Information Processing Standards Publication 184, National Institute of Standards and Technology, 1993.
- [5] Kim, S.-H. and Jang K.-J.: Designing performance analysis and IDEF0 for enterprise modelling in BPR, *International Journal of Production Economics*, Vol. 76, No. 2, pp. 121-133, 2002.
- [6] Hebsacker, M., Trieb, T., Zirn, O. and Honegger, M.: Hexaglide 6 dof and Triaglide 3 dof parallel manipulators, in: Boer, C.R., Molinari-Tosatti, L. and Smith, K.S. (Eds.): *Parallel Kinematic Machines: Theoretical Aspects and Industrial Requirements*, Springer, London, pp. 345-355, 1999.
- [7] Milutinovic, D.S., Glavonjic, M., Kvrjic, V. and Zivanovic, S.: A new 3-DOF spatial parallel mechanism for milling machines with long X travel, *CIRP Annals – Manufacturing Technology*, Vol. 54, No. 1, pp. 345-348, 2005.
- [8] Glavonjic, M. and Milutinovic, D.: Parallel structured milling machines with long X travel, *Robotics and Computer-Integrated Manufacturing*, Vol. 24, No. 3, pp. 310-320, 2008.
- [9] Glavonjic, M., Milutinovic, D. and Zivanovic, S.: Functional simulator of 3-axis parallel kinematic milling machine, *The International Journal of Advanced Manufacturing Technology*, Vol. 42, No. 7-8, pp. 813-821, 2009.
- [10] Milutinovic, D., Glavonjic, M., Zivanovic, S., Dimic, Z. and Kvrjic, V.: Mini educational 3-axis parallel kinematic milling machine, in: *Proceedings of the 3rd International Conference on Manufacturing Engineering (ICMEN)*, 01-03.10.2008, Kallithea of Chalkidiki, Greece, pp. 463-474.
- [11] Glavonjic, M., Milutinovic, D. and Kvrjic, V.: Triaxial spatial parallel mechanism, machine tool and industrial robot with this mechanism, Publication of patent application number 645/04, in: *Intellectual Property Gazette (GIS) No5*, Department of Intellectual Property, Belgrade, pp. 1095-1096, 2006.
- [12] EMC – Enhanced Machine Controller, <http://www.linuxcnc.org>
- [13] NIST – National Institute of Standards and Technology, <http://www.nist.gov>
- [14] Glavonjic, M., Milutinovic, D., Zivanovic, S., Dimic, Z. and Kvrjic, V.: Desktop 3-axis parallel kinematic milling machine, *The International Journal of Advanced Manufacturing Technology*, Article in Press.

**МЕТОДОЛОГИЈА ЗА КОНФИГУРИСАЊЕ
СТОНЕ ТРООСНЕ МАШИНЕ СА
ПАРАЛЕЛНОМ КИНЕМАТИКОМ**

**Саша Живановић, Милош Главоњић, Зоран
Димић**

Конфигурисање нових машина алатки је комплексан задатак који укључује коришћење широког спектра концепција, метода, модела, прорачуна, технологија, симулација, управљања, програмирања и технономије. У раду се представља методологија функционалног конфигурисања нових машина алатки, са примером примене ове методологије на конкретан пример стоне троосне машине са паралелном кинематиком. Овај рад описује структуру машине, приступ моделирању и конфигурисање система управљања и програмирања базираног на *EMC* системском софтверу, који ради под *Linux* оперативним системом у реалном времену. Стона глодалица је верификована успешном изградњом првог прототипа.