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MACHINING SIMULATION OF VIRTUAL RECONFIGURABLE 5-AXIS MACHINE TOOL

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Abstract: This paper presents configuring of a virtual reconfigurable 5-axis machine tool for the purpose of realizing the simulation of the machine according to the running program. Machining simulation is realized in the CAD/CAM environment, when the machine works according to the CL files based running program, and in the STEP-NC Machine environment, when the machine works according to the STEP-NC format based running program. In this way, a possibility of program verification for the machine is obtained, which includes a complete virtual model of the machine configured with the corresponding kinematic relations. Verification of the virtual machine, in both environments, has been done by simulations of machining several test workpieces based on the running program.
Keywords: simulation, reconfigurable 5-axis machine tool, CAD/CAM, STEP-NC

1. INTRODUCTION

The machining simulations of the virtual machine prototype, when it works according to the running program, is a broad topic and includes the complete models of the machining process, the structure of the machine, the actuators, the kinematic subsystem, etc. [1]. All of these models have to be integrated into some software systems, which allows part of the virtual production [2,3]. Such researches are intensive at the Faculty of Mechanical Engineering in Belgrade and many results have been achieved, including machining simulation of mini-laboratory and desktop 3-axis parallel kinematic milling machine [4], machining simulation of 2-axis wire electrical discharge machine [5], machining simulation of CNC lathe [6], machining simulation of 5-axis machine tool [7], etc.

This paper describes a virtual machining system based on virtual prototypes of 5-axis machine tools from the class of reconfigurable machine tools, discussed in paper [8], and includes only the kinematic simulation of the machine that allows the motion of a virtual model as a system of rigid bodies in two environments: CAD/CAM system PTC Creo 2.0 [9] and STEP-NC Machine [10].

According to [11], the concept of reconfigurable machine tools means a system of constituent elements, i.e. a modular system, by which a larger number of different machines can be completed, each of them being a new structure. The paper presents reconfigurable machines with high cumulative processes and with one or two spindles. Tool change is not the subject of this research, nor are the other items of equipment for such machines, except the necessary programming system. Reconfigurable machining system in this paper is based on the concepts of reconfigurable machine tools, which are typical of CNC lathes with milling option and for CNC milling machines with turning option. In the foreground is a reconfigurable machine type such as CNC lathes with milling option, which are justified with statistically more frequent axial symmetrical parts included in the production programs of various manufacturers. In this way, it allows for performing the process of turning and milling with the same base on the same machine, thus achieving continuity of the machining process with high quality.
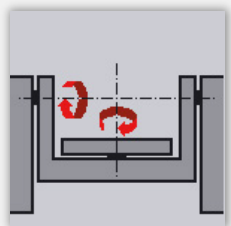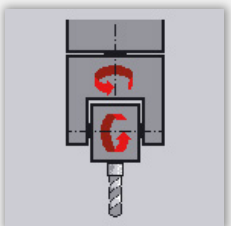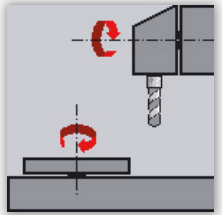
2. CONCEPTIONS OF RECONFIGURABLE 5-AXIS MACHINE TOOLS

In order to facilitate considerations of different concepts of machine tools, it is suitable to take advantage of some of the ways of describing their structure. Machine tools may be formally described by conventional structural formulas, as shown in Figure 1. Based on the description of the machine by the

structural formula, it is possible to establish a lot of different concepts, for which initial concepts for further analysis can be configured and selection of the best solutions according to some criteria can be made. For this paper, the machine concepts chosen can cover different groups of machine tools (GM1, GM2 and GM3), Figure 1.

W	OM	T	W	OM	T	W	OM	T
A'B'	Fixed base O and axes: X, Y, Z of the basic structure of 3-axis machine tool in all mutual configurations.	-	-	Fixed base O and axes: X, Y, Z of the basic structure of 3-axis machine tool in all mutual configurations.	AB	A'	Fixed base O and axes: X, Y, Z of the basic structure of 3-axis machine tool in all mutual configurations.	B
B'A'		-	-		BA	B'		A
A'C'		-	-		AC	A'		C
C'A'		-	-		CA	C'		A
B'C'		-	-		BC	B'		C
C'B'		-	-		CB	C'		B

GM1: Group of machines which have rotary axis only on the workpiece side. The machines are horizontal or vertical.	GM2: Group of machines which have rotary axis only on the tool side. The machines are horizontal or vertical.	GM3: Group of machines which have one rotary axis on the tool side, and one rotary axis on the workpiece side. The machines are horizontal or vertical.

Legend: W -workpiece; OM is a basic structure of machine tool with 3-axis mechanism and with fixed base O; T - tool,; A, B, C are rotary axes; X, Y, Z are translational axes. If the machine is horizontal, then the stationary member is denoted by H and by V if vertical; GM1, GM2 and GM3 are groups of machines with a similar structural formula.

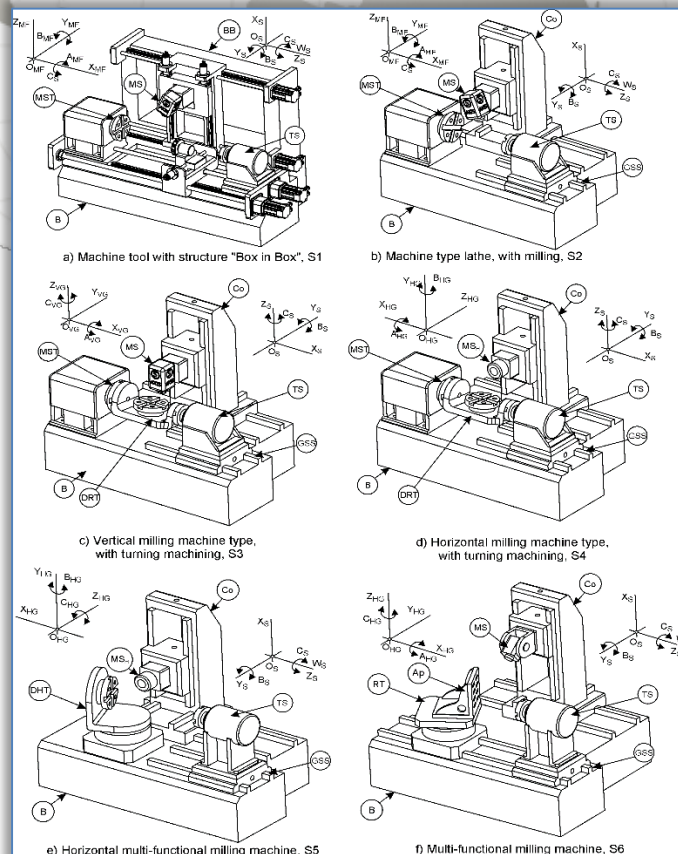Figure 1. Description of the 5-axis machine tools with structural formulas

a) Machine tool with structure "Box in Box", S1

b) Machine type lathe, with milling, S2

c) Vertical milling machine type, with turning machining, S3

d) Horizontal milling machine type, with turning machining, S4

e) Horizontal multi-functional milling machine, S5

f) Multi-functional milling machine, S6

Figure 2. Concepts of reconfigurable 5- axis machine tools

Legend: B: base; DRT: dual rotary table; DHT: dual horizontal rotary table; MS: milling spindle; TS: Turning spindle; BB: "Box in Box" Co: column; MST: multifunctional single table; RT: rotary table, Ap: Angle plate, (O$_{VG}$, O$_{HG}$, O$_{MF}$, O$_S$): coordinate systems of vertical and horizontal milling machines, multifunctional machines and lathes; MS$_H$: horizontal spindle; GSS: guides for the second spindle; A, B, C: rotations

This paper observes only the 5-axis milling machines with serial kinematics, and these machines have three translatory and two rotary movements. According to the standard, basic rotary feed movements are marked with A, B and C, where A is rotation about the axis X, B is about the axis Y, and C is about the axis Z. Five-axis machine tool has two of these three rotations. The structural formulas of these 5-axis milling machines is given in Figure 1. In these formulas, the basic machine is a part of the mechanism with translatory axes and fixed base, which is described as a variant of the layout of axes OXYZ, XOYZ, XOZY ... in all mutual sequences. Rotary axes on the machine can be just on the tool side, or just on the workpiece side, or one rotary axis on the tool side, and one rotary axis on the workpiece side. According to the scheme presented in Figure 1, very many structural formulas can be configured for different machines, in particular for the horizontal, or in particular for vertical machines.

The initial considered concepts of reconfigurable 5-axis machine tools are shown in Figure 2. In Figure 2 a mark was added for coordinate systems of the machine, as well as the one for basic elements of their structure in the legend at the bottom of the figure. A total of six different variants of the structure: S1, S2, S3, S4, S5 and S6 is presented. The alternatives to the column design for each machine are shown either as a "Box and Box" (as in Figure 2a), or as a classical column (Figure 2b, c, d, e, f). According to the analysis of the basic components of the considered machine tools from Figure 2, a modular system of reconfigurable hardware is established, which is described using morphological matrix, as shown in [8]. This approach allows for efficient configuring of different conceptions, based on a common base module, and obtaining virtual prototypes for further analysis. This paper considers the kinematics simulation of the machine tool when machine works according to the running program. Each machine is configured in the CAD/CAM environment, with corresponding kinematic relations of movable machine elements, which enables the simulation of the machine working based on the running program. Table 1 presents typical examples of reconfigurable five-axis machine, referring to the concept given in Figure 2.

Table 1. Typical concepts of reconfigurable and multifunctional machine tools

N	Description of the machine tool conception	Characteristics	Typical purposes
1	Vertical machine tool (Fig. 2a), Box in box Column, with one rotary axis on the tool side - B-axis, and one rotary axis on the workpiece side, A-axis. Machine type GM3, Fig.1.	Good access tool to workpiece. Small surface of the footprint machine. High rigidity.	Small workpieces. Blades and other parts.
2	Vertical machine tool (Fig. 2b) with one rotary axis on the tool side - B-axis, and one rotary axis on the workpiece side, A-axis. Machine type GM3, Fig.1.	Good access tool to workpiece. Small surface of the footprint machine. Good rigidity.	Small workpieces. Blades and other parts.
3	Vertical machine tool (Fig. 2c), with two rotary axes on the workpiece side - A and C axes. Machine type GM1, Fig.1.	Good access tool to workpiece. Small surface of the footprint machine. Good rigidity.	Small varied workpieces. In small series.
4	Horizontal machine tool (Fig. 2d), with two rotary axes on the workpiece side - A and B axes. Machine type GM1, Fig.1.	Good work space for the reception of bigger parts and machining with five sides. Good rigidity.	Larger impellers. Workpieces with machining with five sides.
5	Horizontal machine tool (Fig. 2e), with two rotary axes on the workpiece side - B and C axes. Machine type GM1, Fig.1.	Highspeed machine tools. Less risk of collision in the work of machines.	Impellers. Turbine rotors. Different cutting tools.
6	Horizontal machine tool (Fig. 2f), with one rotary axis on the tool side - A-axis, and one rotary axis on the workpiece side, C-axis. Machine type GM3, Fig.1.	Reception of larger and heavier parts. Good base for the workpiece. Good rigidity.	Wokpieces of larger dimensions. Workpieces with thin walls.

The development of the 5-axis reconfigurable machine tools involves the objectives such as: (i) developing low-cost desktop machine tools, (ii) taking advantage of built machine and/or virtual prototypes for research and education, (iii) completing the control system by using open architecture control, (iv) considered machines can be programmed by G-code or using the STEP-NC program, (v) preparing an adequate environment for programming based on G-code or based on the STEP-NC standard, (vi) preparing virtual prototypes of machines for the simulation purposes when the machine works by running program in both of these environments (CAD/CAM and STEP-NC).

3. MACHINING SIMULATION IN THE CAD/CAM ENVIRONMENT

Machining simulation that uses the virtual machine tool is the safest and the most cost-effective way for multi-axis program verification. In this section, chosen environment for programming with four

examples of virtual prototype of machine tools (S2, S3, S5 and S6) is shown, with simulation example of convex calotte machining, Figure 3. Conventional programming system was used and for this case it was PTC Creo 2.0 [9] CAD/CAM system.

Depending on the chosen machine configuration, NC program can be prepared by an appropriate postprocessor for each of them, using the generator of postprocessor, which adapts the G-code format to the specific machine tool.
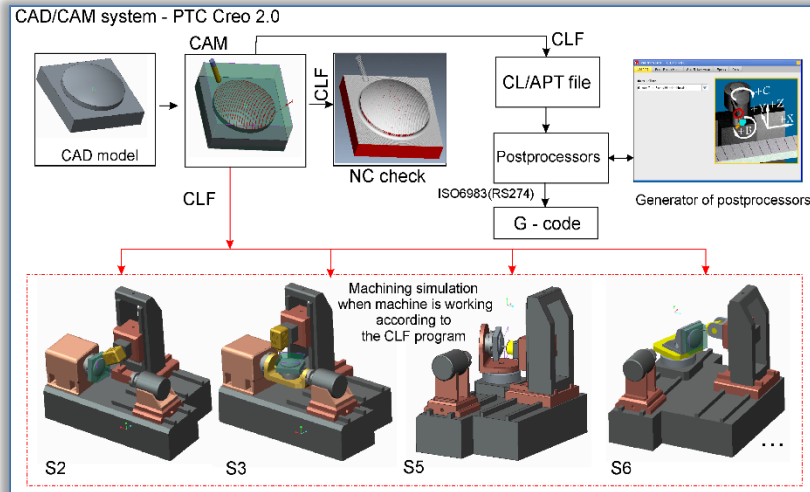

Figure 3. Programming system with possibility of simulation of reconfigurable 5-axis machine tool based on CLF in the CAD / CAM environment
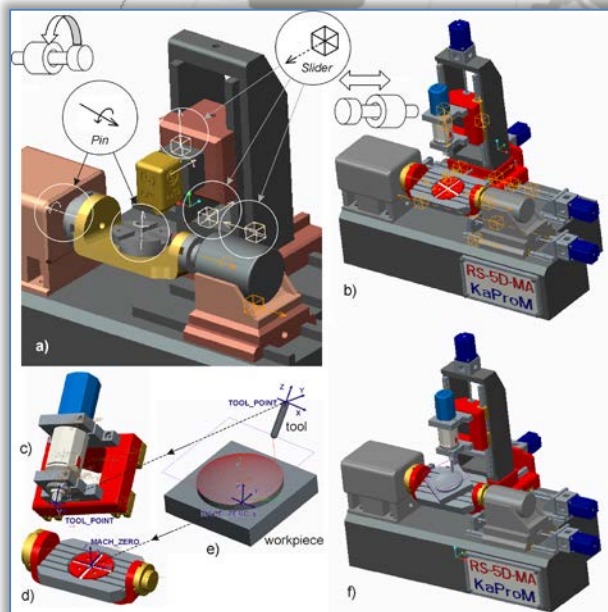

Figure 4. Kinematic relationships, coordinate systems and machining simulation for one of the variant machines

Machining simulation, i.e. simulation of virtual prototype kinematics, allows movements of modeled segments, with the tool at the end of kinematic chain, with the tool tip drawing the tool path, as a result of the execution of a given program in the CLF format [6-10]. In Figure 4, the concept of machine S3 is shown, with the vertical direction of the main spindle and with two rotary axes of the workpiece (A and C). For preparation of the model for simulation, the corresponding kinematic connections (Slider-type) are used for translational movements along the X, Y and Z axes of the basic machines (OM) according to Figure 1. For the rotations of the workpiece A and C, the Pin-type kinematic connection was used, Figure 4a.

For a simplified conceptual model from Figure 4a, the virtual prototype with chosen components for machine construction is already prepared, with all the kinematic relations, Figure 4b. Workpiece coordinate systems, denoted as MACH_ZERO, and tool coordinate systems, denoted as TOOL_POINT, are shown in Figures 4c, d, e. Workpiece coordinate systems are located on the table of the machine and on the workpiece, while tool coordinate systems are on the head of the main spindle and on the tool. Running the simulation of the machine is performed using Machine Play option. According to pre-defined coordinate systems and their matching, the workpiece is placed on a table, and tool is placed in the machine spindle. Machining simulation in the example of convex calotte machining for machine tool from Figure 4b is shown in Figure 4f.

Various methods for NC program verification are: the toolpath simulation, the material removal simulation (NC Check) and the machining simulation according to the tool path based on CLF. This last type of simulation is also very interesting in developing new machine concepts and gives insight into the possible collision between machine parts and workpiece, in the absence of physical prototype and for program verification in the CAD/CAM environment.

4. MACHINING SIMULATION IN THE STEP-NC MACHINE ENVIRONMENT

Nowadays a new standard, informally known as STEP-NC (Standard for Product Model Data Exchange for Numerical Control), is being used as the basis for developing the next generation of CNC controller for a new generation of machine tools. These new standards are ISO 14649 and ISO 10303 AP 238. In the field of machine tool programming an open challenge is a new programming method using standard known as STEP-NC. The development of this new programming method has started, but it is still an unfinished work. The subject of this paper is machining simulation based on STEP-NC program, using software, to verify the program before its execution on CNC machine tool [12].

Machining simulation for the considered 5-axis reconfigurable machines is realized in the STEP-NC Machine software [10], which supports the programming of machine tools based on the STEP-NC standard, as a new programming method of CNC machine tools. In this programming method, technological primitives on the workpiece are denoted as objects (Features), and if the preparation of programs for the machining uses these objects without using alphanumeric text, then this programming method is usually referred to as an object programming method. However, classical programming (G-code) is still in use, and object-oriented programming method (known as STEP-NC) has not been introduced to the full extent [12]. These two methods exist concurrently.

Virtual machine tool is able to interpret the STEP-NC program in the STEP-NC Machine software environment. For importing the arbitrary created machine in the STEP-NC environment, it is necessary to apply the following procedure: a) prepare a CAD model of the machine tool; b) make an export model of the machine in the STEP format by the protocol AP203 or AP214; c) prepare XML file: (i) machine name, (ii) control algorithm, (iii) name of the STEP file machine, (iv) description of the machine base structure, which is stationary, (v) description of the tool side structure, (vi) defining placement location for the tool, (vii) description of the workpiece side structure, (viii) defining placement location for the workpiece, (ix) description of NC axes and their feeds [13].

Preparation for the use of a new programming method applying the STEP-NC standard included, in this paper, the configuration and integration of virtual machines in such way that they can be run according to the program in the STEP-NC format, in the STEP-NC Machine software environment. For example, machines S3 and S5 in Figure 2 were prepared as virtual prototypes that can work in the environment of STEP-NC Machine according to the STEP-NC program, Figure 5.

5. CONCLUSION

The paper presents the concept of the development of a class of reconfigurable 5-axis machine tools, which includes an analysis of the configured virtual prototypes by machining simulation in their working environments for programming. Two such environments have been considered: PTC Creo CAD/CAM system and STEP-NC Machine.

For the chosen representatives of considered reconfigurable 5-axis machine tools, machining simulation was carried out by running the program for its verification and detection of possible collisions during machining process: in the case when the machine is programmed in a common way in the CAD/CAM environment, as well as in the

Figure 5. Reconfigurable 5-axis machine tools in STEP-NC Machine environment

case when the machine is programmed by the new programming method using the STEP-NC Machine environment.

Machining simulation by running the program is possible thanks to the applied modelling of the machine mechanism with all kinematic connections between components that enable the motion of the entire virtual model as a system of rigid bodies.

Research in the field of reconfigurable machine tools is important for further research on multi-axis machining and reconfigurable 5-axis machine tools, as well as for education in programming, which is particularly important for educational institutions in the acquisition of knowledge about the complex reconfigurable multi-axis machines.
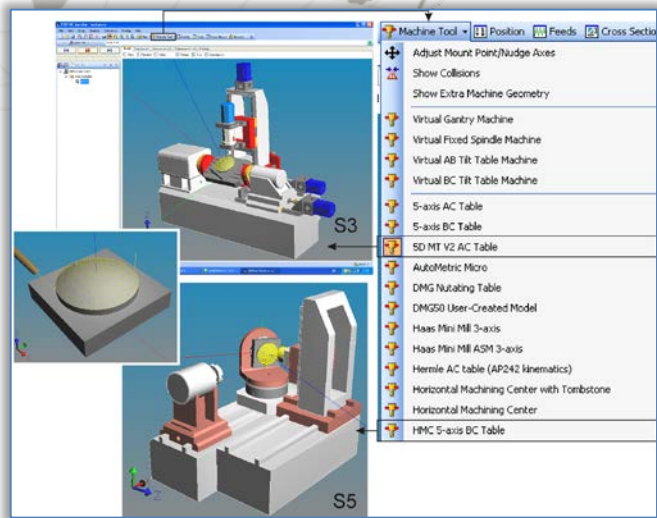
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