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Programming of 3-Axis Hybrid Kinematics CNC Machine for Rapid Prototyping Using Subtractive and Additive Processes

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***Abstract*— The paper presents the programming and program verification on a 3-axis hybrid kinematics CNC machine for rapid prototyping using subtractive and additive processes. The original hybrid (parallel-serial) 3-axis O-X glide mechanism developed to build a rapid prototyping machine and multifunctional machine tools is presented. The paper analyzes the available programming software, which can be one of the standard CAD/CAM systems or a specialized CAM system, for subtractive processes, i.e. desktop milling. For the additive processes, the software for generating G code based on the STL file as well as the possibility of simulating the machine when working is considered. To verify the program, the simulation of material removal for subtractive processes as well as the simulation of material addition for additive processes were considered. The paper presents the prototype of a hybrid kinematics CNC machine and some of the results of testing with an open control system based on the LinuxCNC.**

***Keywords*— programming, subtractive processes, additive processes, CAD/CAM, program verification, virtual machine, O-X glide mechanism**

I. INTRODUCTION

The development of industrial production in the 21st century is focused on the improvement of production systems by developing new structural and control concepts. As their basic production unit, machine tools are the subject of constant improvement. That primarily refers to the improvement of the mechanical structure, electric power components, and control. To improve the production characteristics of machine tools for a long period, numerous scientific and commercial researches are performed. That includes the improvement of their kinematic structure [1]. As a result, many machine tools with parallel and hybrid kinematic structures have been developed in the last few decades. This mechanical structure with the application of principles of reconfigurable design provides a significant improvement in operational characteristics and increases the flexibility of production processes, which is extremely important in production systems adaptable to specific production conditions. The basic problem of the applications of such machine tools is the need for the realization of complex mathematical calculations related to direct and inverse kinematics of mechanisms in real-time.

The paper presents the process of programming and verification of the original CNC machine based on O-X glide mechanism. His hybrid kinematic structure [2-7] is suitable for using in the processes of machining or adding materials. The paper analyzes programming procedures, appropriate software, as well as verification of drivers on the physical prototype and virtual simulation of the machine tool.

II. BASIC CONCEPT OF 3-AXIS HYBRID KINEMATICS CNC MACHINE FOR RAPID PROTOTYPING

The basis of the machine tool with the hybrid kinematic structure presented in the paper is the original O-X glide mechanism which contains a plane parallel mechanism with dual configuration (O and X configurations) and one serial axis that provides a translation mechanism. The machine was designed to improve the concept of machine tools intended for rapid prototyping using multiple machining methods. Figure 1 shows the initial concept of a machine with hybrid kinematics and design solution, in positions with stretched (O) and crossed (X) configurations of O-X structure [1,6].

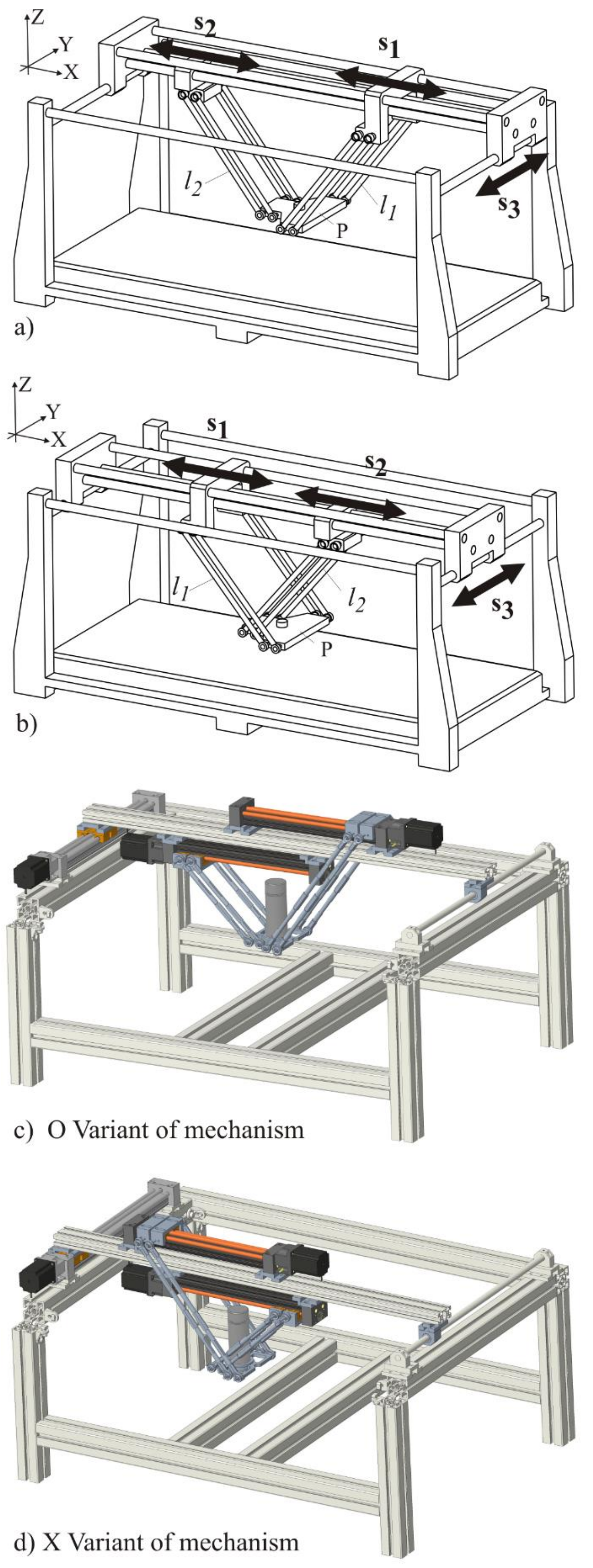


Fig. 1. Initial hybrid O-X glide mechanism and design solution

The parallel mechanism consists of a planar structure containing a movable platform, which is connected to rods of constant length via spherical joints. At the other end, the rods are connected to the corresponding sliders by rotating joints (with one degree of freedom), each of which moves according to its guide. To increase the autonomy of the slider movement, they are positioned at different distances, in the direction of the vertical axis, which enables their passing in the plane, as well as the movement of the mechanism, in the extended (O) and crossed (X) position [6].

A parallel mechanism enables movements in the (XZ) plane, using sliders s1 and s2, while the linear movement of the entire parallel mechanism is realized by a serial axis s3, on the support structure. The moving platform provided three degrees of freedom and moved with a constant orientation of the tool in the workspaces of the machine. This concept of the machine enables a wide range of applications for (i) vertical 3-axis milling machine; (ii) laser engraving machine; (iii) machine for additive manufacturing [7].

In this paper, the programming and program verification of this machine for rapid prototyping, using subtractive and additive processes analyzed.

III. Programming and Program Verification

This chapter provides basic information about the established programming environment, including a virtual machine for tool path verification in CAD/CAM system PTC Creo, as well as information about programming based on STL files for subtractive processes i.e. desktop milling [8].

Generating of the model, i.e. STL file, and appropriate toolpath before fabrication of the physical models using subtracting technology can be done using any CAD/CAM systems (Creo, Catia,…) or specialized software for the rapid manufacturing (based on STL), which allows pre-machining layer by layer and finally finishing.

Another aspect of implementation is additive processes and the establishing programming environment for programming the 3-axis hybrid kinematics CNC machine, with the illustration of simulation of adding material, as well as machine simulation when in realizing the path for adding material.

A. Programming in CAD/CAM system PTC Creo

As basic programming software for 3-axis hybrid kinematics CNC machine based on O-X glide mechanism could be used available CAD/CAM solutions. For programming can use available CAD/CAM systems like PTC Creo or Catia, in which a virtual prototype of the machine has been developed. This paper use PTC creo for programming and machine simulation. Figure 2 shows the basic structure of programming systems. Verification of the program can be realized by: simulation of tool paths, material removal simulation, and machine simulation when virtual machine working using program CLF (Cutter Location File). The process of postprocessing of tool path is the same as for conventional 3 axis machine tools, according to ISO 6983 standard.

As an example for simulation, a test part was chosen based on standard parts for testing CNC machine tools. This programming method was verified by the machining of this trial part shown in Chapter IV.

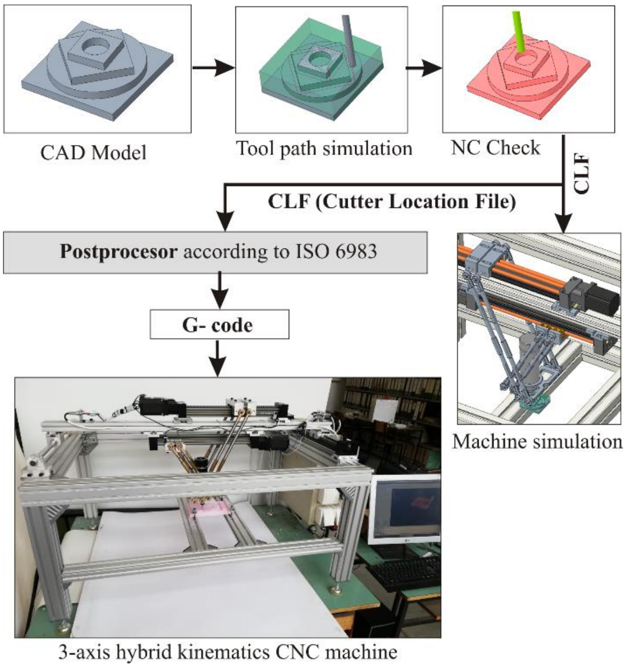


Fig. 2. Basic structure of programming system using CAD/CAM system

B. *Machine simulation in the CAD/CAM system*

PTC Creo software system supports all stages of programming, modeling, and machine simulation based on the virtual machine model. The mentioned phases can be expressed as [6,8]: (i) modeling and assembly the mechanism with defined kinematic connections, (ii) definition of ranges in kinematic connections, (iii) manual interactive inspection of defined virtual kinematic connections, (iv) creating a video file of tool path simulation on a virtual machine for presentation.

The configured virtual machine includes the possibility of virtual prototype elements movements as a rigid body system. That configuration can be used in the simulation of the tool path [5]. For this possibility need to define all kinematic connections between components. The required kinematic connections for the considered 3-axis hybrid kinematic machine are three translations (s1, s2, and s3) with slider type of connection, and 16 rotary joints with pin-type connection, at the points of connection the parallel mechanism rods with the moving platform and sliders [6], Fig.3a.

After defining the kinematic connections on the moving parts of the machines, it is necessary to make a connection between the coordinate systems on the workpiece and the tool and the virtual machine within the used CAD/CAM system (PTC Creo). Virtual machine tools need defining coordinate system MACH_ZERO, on the machine table and TOOL_POINT on front of the main spindle (Fig. 3b,c). Also, workpiece and tool have the same coordinate systems. By matching the appropriate coordinate systems of tools and workpieces is possible to prepare a set-up for simulation [6].

After that, the virtual machine is ready to simulate according to the program, based on CLF, by using the Machine Play option, whereby the machine simulation shown in Fig.3d could be obtained.

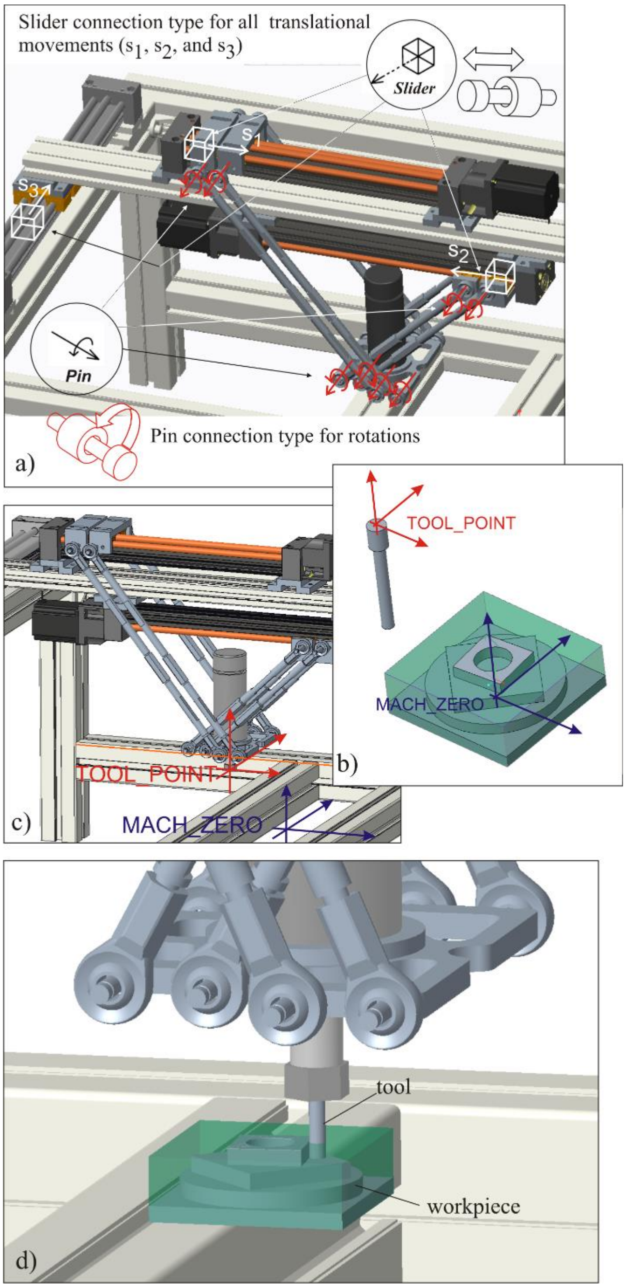


Fig. 3. Virtual machine simulation in CAD/CAM environment with defined kinematic links and coordinate systems

C. *Programming in CAM based on STL files*

The typical process for subtractive technology in rapid prototyping is also known as desktop milling. This procedure involves the following steps: (1) CAD modeling of prototype; (2) STL conversion; (3) Loading of STL file in CAM system; (4) planning roughing and finishing strategy for milling; (4) generating adequate G-code; (5) G-code verification with material removal simulation; (7) Fabrication of prototype using desktop milling [8].

There are many specialized software packages for machining based on STL files. Some of them are CUT3D, Deskproto, MeshCAM, etc. These software packages are easy to use and fast generation of roughing and finishing tool paths. These software packages enable the loading of the model in the STL format, orientating of model for machining, tool selection, choosing machining strategies for roughing and finishing, material removal simulation for different materials, and finally postprocessing the toolpath into G-code.

An example of the application of specialized CAM software that works based on the STL file is shown in Figure 4. Fig. 4 shows an example of the generated paths for roughing and finishing, as well as the corresponding verification of material removal in the software itself. Postprocessing was then performed to obtain the G code. The post processed G code was additionally verified by a material removal simulation in another program such as the CIMCO editor.

Based on this example, machining had performed. The results of that verification were presented in section 4.

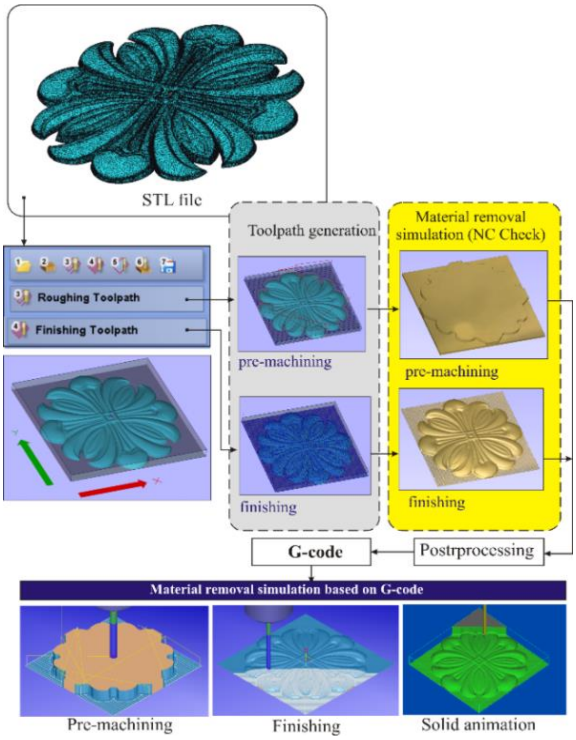


Fig. 4. Rapid prototyping using subtractive technology based on STL files in CUT3D [7]

D. *Programming additive process based on STL files*

The most common CNC machine tools for additive processes have serial kinematics and three translatory axes [9]. In this case, we present the machine that combined parallel and serial kinematics as the 3 axes hybrid kinematic CNC machine for rapid prototyping. In this chapter, we consider its programming.

A typical process for additive technologies includes the following stages: (1) Obtain model in STL format, (2) Load model into software, (3) Setting parameters for 3D printing, (4) Export to G-code (5) Simulate of 3D printing, (7) Build prototype on the machine, Fig.5.

There are various specialized software for 3D printing, such as

Slic3r, Replicator G, Catalyst EX, Repetier-Host, and others. These programs represent an interface for communication with additive manufacturing machines. The input into these programs is an STL file based on which we prepared additive layers and the required paths for adding materials obtained. Such programs usually allow [10]: (i) 3D display of the model; (ii) scaling the model to the desired size; (iii) control of model orientation in the workspace; (iv) Automatic or manual basing of the model in the case of making several parts in one production process; (v) slicing and forming additive layers; (vi) Simulation of the addition of layers and display of each layer; (vii) generating G code for the machine.

The Slic3r software was tested as software for programming of the considered 3-axis hybrid kinematics CNC machine for additive processes. Basic steps for obtaining G-code were shown in Fig.5.

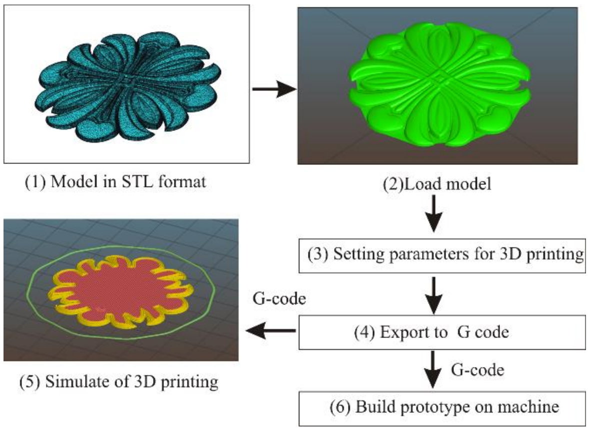


Fig. 5. Programming additive processes based on STL files

An example for programming additive processes was tested on the example of the Rosetta model in STL format. Examples of some characteristic single layers obtained using Slic3r software are shown in Fig.6.

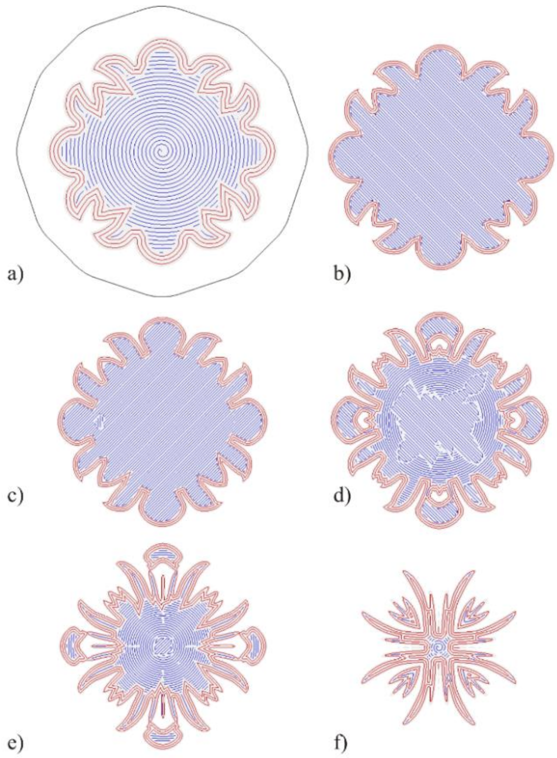


Fig. 6. Examples of paths of adding material for some selected layers obtained using software Slic3r

At this stage of the research, the 3-axis hybrid kinematics CNC machine for additive processes has not been performed yet, so the verification of programming was tested by machine simulation in the CAD / CAM environment of PTC Creo. Machine simulation is performed for the first layer from Fig.6a and shown in Fig.7. Machine tools for additive processes can be modeled as a CAD model that includes appropriate kinematic connections [5,7,10]. To obtain the nozzle path in additive processes, it is necessary to convert the nozzle path into G code. Thus obtained path in G code can be converted to the DXF file using CIMCO software. After that DXF is loaded into the CAM module where this nozzle path was used for generating tool paths. During the simulation, the CAD model of the machine can be loaded. That is important when the machines have hybrid kinematics, as shown in Fig. 7.

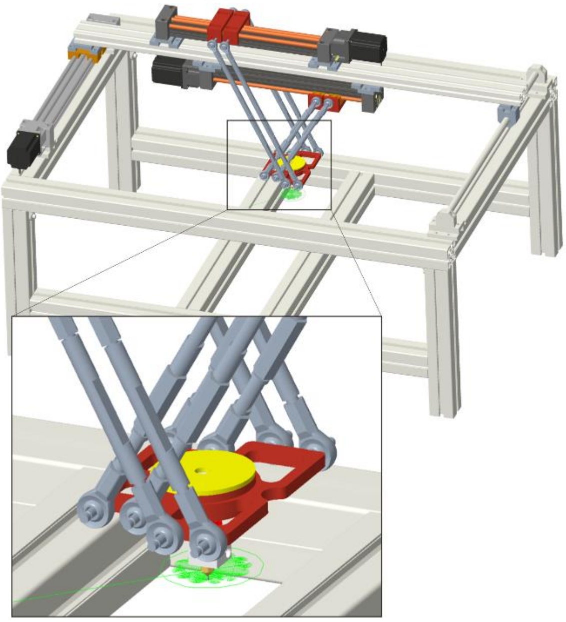


Fig. 7. An example of 3D printing machine simulation in PTC Creo environment

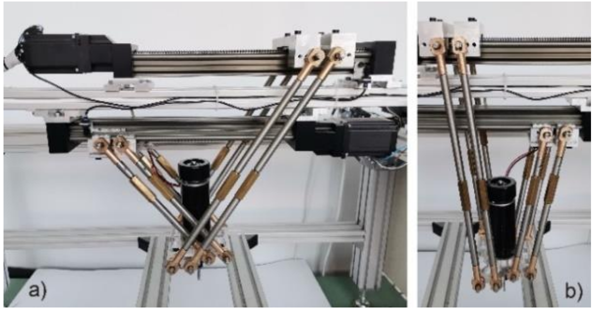
Based on the performed simulation, it is possible to check the set-up of parts within the workspace, as well as the realization of the obtained nozzle path for additive processes.

IV. Machining test

First prototype of the machine tool with hybrid kinematics based on the O-X glide mechanism has been built in the Laboratory on the basis of a customized concept and mechanical characteristics analysis. Linear axes are composed of step motors NEMA 23 and Igus linear axes. Figure 8 shows the realization of both machine variants i.e. with the extended (O) and crossed (X) glide mechanism [6].

The first tests were performed for rapid prototyping using subtractive processes, i.e. desktop milling on a crossed form X configuration the machine by machining the test part. Verification of the machine prototype is realized through machining of several workpieces, whereas a material Styrofoam was used. A custom test workpiece was used for the test of the CNC machines work accuracy in process of verification of the machine's performance during the test work of the machine, Fig 9a.

This test was performed by machining the part similar to the ISO test workpiece. In this case, a flat endmill (diameter 5 mm) was used. The finished test workpiece is presented in Fig. 9b.



a) crossed (X) glide mechanism b) extended (O) glide mechanism

Fig. 8. Configured prototype of the machine with O-X glide hybrid mechanism [6]

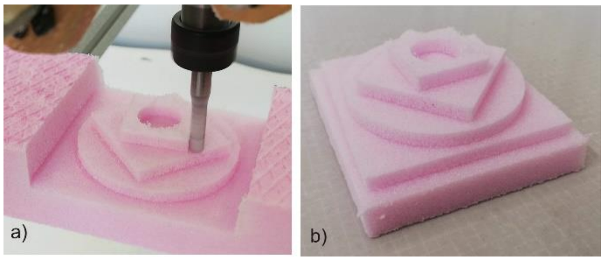


Fig. 9. Machining a custom test workpiece [6]

The second test was performed by machining model of the Rosette, based on STL file, Fig.10.

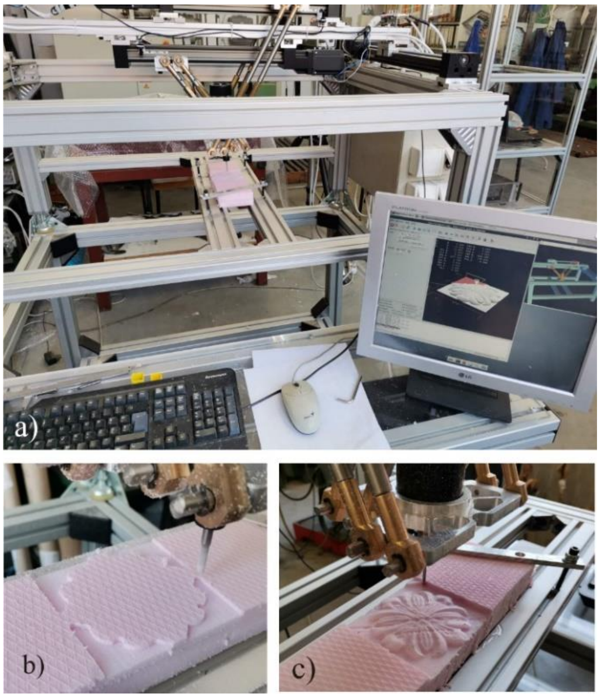


Fig. 10. Desktop milling of the rosette sculpture

The procedure of programming and verification, for this example, is shown in Fig 4. That is an illustration of machining using the subtractive rapid prototyping technique. In that case, a flat-endmill (diameter 5mm) and ball-endmill (diameter 3mm) were used. Figure 10a displays 3-axis machining where is first executed pre-machining (Fig.10b), and after that finishing (Fig.9c).

V. Conclusions

The paper presents a prototype of a 3 - axis machine tool with a hybrid kinematic structure based on the O - X glide mechanism. The presented configuration of the machine tool has been developed in the needs of scientific researches in the field of analysis of the suitability of the application of different methods of manufacturing in the production systems of the future. Part of this research is the improvement of methods for their programming and verification of tool paths using virtual and physical prototype machine tools.

During the realization of the prototype of 3-axis hybrid kinematics CNC machine for rapid prototyping following activities were realized: (i) testing X variant of the mechanism, (ii) configuration of the machine tool control, (iii) configuring of the virtual prototype, (iv) simulation of the virtual prototype for desktop milling and additive processes, (v) preparing and testing programming environment, (vi) verification of generated toolpath and (vii) testing and trial runs of the machine tool for subtractive processes.

Future research in the field of improvements of the presented concept includes an adaptation of a 3-axis hybrid kinematics CNC machine for additive technology and laser engraving.

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References

[1] S. Živanovic, S. Tabaković, M. Zeljković, C. Mladjenovic, “Machining simulation and verification of tool path for CNC machine tools with serial and hybrid kinematics”, Proceedings of VIII International Conference Heavy Machinery-HM 2014, pp.B.63-B.68, Zlatibor, 2014.

[2] S. Tabakovic, M. Zeljkovic, R. Gatalo, C. Mladjenovic, “Device for manipulating workpieces or tools in machine tools and industrial manipulators” in: S. Intellectual Property Office (Ed.), Republic of Serbia, No. 2/2012.

[3] S. Tabakovic, S. Zivanovic, M. Zeljkovic, “The application of virtual prototype in design of a hybrid mechanism based machine tools”, Journal of Production Engineering Vol.18, pp.77-80, 2015.

[4] S. Zivanovic, S. Tabakovic, M. Zeljkovic, Z. Milojevic, “Configuring a machine tool based on hybrid O-X glide mechanism”, Machine Design, Vol.8, pp.141-148, 2016.

[5] S. Tabaković, S. Živanović, “Simulation of kinematic of virtual prototype of a machine tool based on hybrid O-X mechanism”, Proceedings of 3rd International Scientific Conference Conference on Mechanical Engineering Technologies and Applications COMETa 2016, pp.199-206, University of East Sarajevo, Faculty of Mechanical Engineering, Jahorina, B&H, Republic of Srpska, 2016.

[6] S. Tabakovic, S. Zivanovic, Z. Dimic, M. Zeljkovic, “Programming and program verification of 3-axis hybrid kinematics CNC machine for rapid prototyping”, Proceedings of 14th International Scientific Conference mma 2021 – Flexible Technologies, pp. 71-74, University of Novi Sad, Faculty of Technical Scienes, Department for Production Engineering, Novi Sad, 2021.

[7] S. Zivanovic, S. Tabakovic, M. Zeljkovic, Z. Dimic, “Modelling and analysis of machine tool with parallel–serial kinematics based on O-X glide mechanism”, Journal of the Brazilian Society of Mechanical Sciences and Engineering, Vol. 43, No.456, 2021.

[8] S. Zivanovic, M. Popovic, N. Vorkapic, M. Pjevic, N. Slavkovic, “An Overview of Rapid Prototyping Technologies using Subtractive, Additive and Formative Processes”, FME Transactions Vol.48, No. 1, pp. 246-253, 2020.

[9] A. Osmanović, T. Duspara, E.Trakić, S. Čosić, “Mechatronic Approach to Design and Construction of a Low-Budget 3D Printer”, Journal of Mechatronics, Automation and Identification Technology, Vol. 5, No. 1, pp. 11 - 15, 2019.

[10] S. Zivanović, “Rapid prototyping and manufacturing for model of human head”, Proceedings of the 8th International Scientific Conference IRMES 2017- Machine elements and systems in energy sector Development of power production systems, pp. 271-276, Trebinje, Bosnia and Herzegovina, 2017.