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CONFIGURING OF 3 AXIS MINI CNC MACHINE TOOL WITH CONTROL SYSTEM BASED ON LINUXCNC

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Abstract: In this paper, a mini CNC machine tool with three translational axis and open–architecture control system is being considered. Existing CAD/CAM software environment was used in order to create adequate corresponding virtual machine and to enable CNC program development and testing for the specific platform. Prototype of the machine was made utilizing parts salvaged from multiple CD/DVD drives. Control system hardware is realized in two ways: based on PC platform and based on Raspberry Pi 3B+, while the software part uses open–architecture LinuxCNC. Experiments were performed in order to verify proper functioning of the entire system.
Keywords: mini CNC, CAD/CAM, virtual prototype, simulation, control, LinuxCNC, open architecture control

1. INTRODUCTION

Modern production is based on CNC machine tools and such production demands highly skilled workforce. Skills needed for proper CNC utilization are taught in various courses at secondary schools, faculties and specialized organizations [1,2]. Additionally, further development of small and medium–sized enterprises relies heavily on the use of CNC machine tools. Since procurement of CNC machine tools can be seen as a form of capital investment, in order to bridge the economic gap, many small enterprises opt for modernization or revitalization of their existing machines by using low–cost variants of CNC controllers, among which the most notable one is LinuxCNC – obtainable free of charge, fully customizable for target hardware and open–source [3]. This paper takes into consideration problems related to proper CNC operator education and demonstrates specific implementation of the open–architecture control system on self–constructed 3–axis mini CNC machine.

The CNC machine tool presented in this paper is primarily an educational machine and can be made with readily available, low–cost components and single compatible computer, acting as a host for CNC software. Proposed machine is controlled using open–architecture LinuxCNC software which has proven itself in numerous occasions as an acceptable alternative to available industrial–grade solutions. Programming of machining operations is done through utilization of G code and it does not differ from usual practice that is already established in the field. As a consequence, proposed mini CNC machine can be a fully functional part of an educational system [1] and eliminates the problems which potential equipment procurement incurs. Significant investments are circumvented since the machine can be easily replicated, enabling every candidate enrolled in a course to work with a personal, dedicated machine. Educational machines are in high demand and a large number of secondary schools and faculties face troubles obtaining such specialized equipment. Institutions in Serbia most frequently procure educational CNC machines through EMCO Education Ltd, while other big bidders of such systems are Roland DG Corporation, The Cool Tool, Renishaw etc.

Currently, CNC training is usually performed in groups on a single CNC machine, which oftentimes lowers the overall quality of the training due to the availability issues.

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If the CNC machine is not available, training is reduced to program verification using the CNC simulator, leaving the trainee with no experience in using a real CNC machine. The machine proposed in this work can be easily replicated in large quantities with very low price per unit, thus enabling the concept of a single trainee per CNC machine.
Further development of open architecture control systems should provide appropriate level of flexibility, modularity and adaptability of interfaces that is required by new machine tools.
In chapter 2 of this paper, existing mini CNC machines based on CD/DVD drive hardware are presented and analyzed. Proposed mini CNC machine tool is presented in chapter 3, which includes the development of a virtual prototype in CAD/CAM environment, simulation of working virtual prototype according to the given program (G code) and physical realization of the machine. Chapter 4 describes the implemented machine control system, while chapter 5 shows the experimental trial of the machine and tests the control system by drawing a large number of programmed contours.
The expected efficiency and quality of human work correlated with modern CNC machine tools can be achieved by applying a high quality educational system. The system must provide adequate learning environment and output individuals with levels of knowledge and skill that are satisfactory in order to correctly utilize the potential of CNC machines. Proposed mini CNC represents a utility that could usher in the future high–quality educational system for CNC operators.

2. MINI CNC MACHINE TOOLS

Mini CNC machine tools based on CD/DVD drive hardware are usually self–constructed machines, but there are also commercial solutions on the market. These machines are commonly used as mini CNC plotters that draw programmed contours, or as laser engraving machines and mini 3D printers. Figure 1 gives an overview of the selected solutions for such machines, presented in several categories:

- 2 axis mini CNC machine tools for laser engraving (Figure 1.a,b,c),
- 2 ½ axis mini CNC machine tools for draw programmed contours (Figure 1.d,e),
- mini CNC 3D printer (Figure 1.f)
- 3–axis mini CNC machine tools to draw programmed contours (Figure 1.g–l).

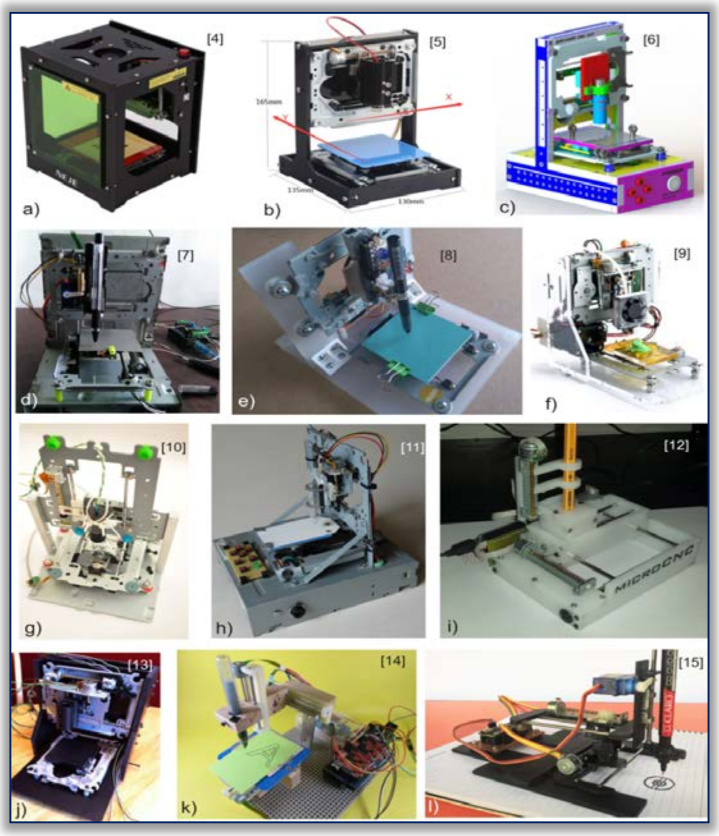

Figure 1. Mini CNC machine tools based on CD/DVD drive hardware [4–15]

The first group of mini CNC machine tools for laser engraving have two numerically controlled axes (Figure1. a,b,c). The first two of them from (Figure1.a,b) are commercial solutions of mini CNC machine tools for laser engraving.
The machine shown on Figure1c was entirely 3D printed with all of its components. The second group of 2 ½ axes mini CNC machine tools has X and Y axis which use CD/DVD drive hardware, but the Z axis uses a simple motor for lowering and raising of the pen (positional axis). Figure1f shows a mini 3D printer. Other machines from the fourth group have 3 axes and CD/DVD drive components were utilized for all of them. Main differences between mentioned solutions occur in their mechanical structure and the axis arrangement. The simplest solutions used metal housings of the CD/DVD drives as the structure that carries the drive axes (Figure 1.d,g,h). Very often, structural parts are made with 3D printer or out of wood or plastic (Figure1. e,f,i,j,k.l).
If you analyze the kinematics of these machines, most of them have one Degree–of–Freedom (DoF)

for the workpiece and two DoF for the tool. Solutions where all three movements (X, Y, Z) are done by the tool are possible, in which case, the workpiece is fixed (Figure 1. i,l).

In this paper, a 3–axis mini CNC machine tool with kinematic structure X'OYZ is selected for realization. Drawing pen is fixed along the Z–axis. Special Z–axis laser module is planned in order to use the machine for engraving. LinuxCNC open–architecture software system is used for machine control.

3. CONFIGURING OF THE 3–AXIS MINI CNC MACHINE TOOL

Development of the machine was led by the idea that the hardware found in obsolete CD/DVD drives is enough for the realization of the 3–axis mini CNC machine. Geometric and kinematic parameters of the machine are dictated by the constraints of the hardware salvaged from the CD/DVD drives, resulting in a relatively small, cube–shaped workspace of 35x35x35 mm. As mentioned, accepted kinematic structure of the machine was X'OYZ. The worktable is moving along the X'–axis and the slider is moving on the Y–axis while carrying the Z–axis.

Basic configuration requirements are as follows: (i) low–cost mini CNC machine tool, (ii) laboratory and education suitable, (iii) performs pen drawing or laser engraving, (iv) implements open–architecture based control, (v) G code programmable.

The following describes the phase prior to the adoption of the final structural design and the ensuing configuration of the virtual prototype in the CAD/CAM environment. Developed virtual prototype later served for the initial manufacturing program verification within a machining simulation.

— Configuring of the virtual prototype

For the configuration of the virtual prototype, CAD/CAM system PTC Creo [16] was selected. All the components, along with the main assembly of the machine, were modelled in PTC Creo. Developed virtual prototype with marked coordinate axes, workspace and the components of the drive are shown in Figure 2.

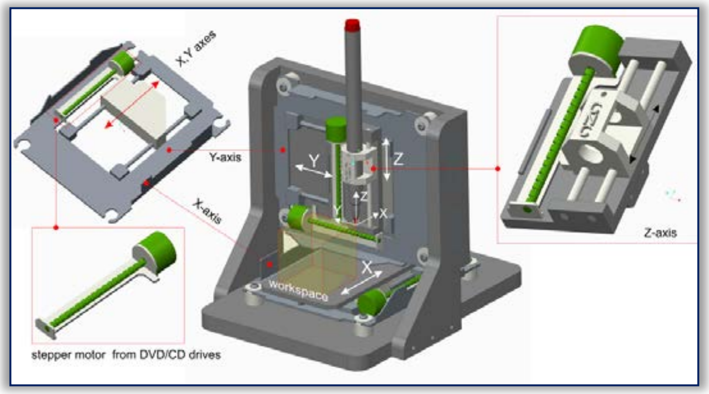

Figure 2. CAD model of the table 3–axis mini CNC machine tool with basic components

For the X–axis and Y–axis the complete drives and guides of CD/DVD hardware were used. For Z–axis, some modifications were necessary, in accordance with the available space. The base structure connects all the drives and forms a complete mechanical system. The example assembly and assembly drawing views of the mini CNC machine tool are shown in Figure 3.

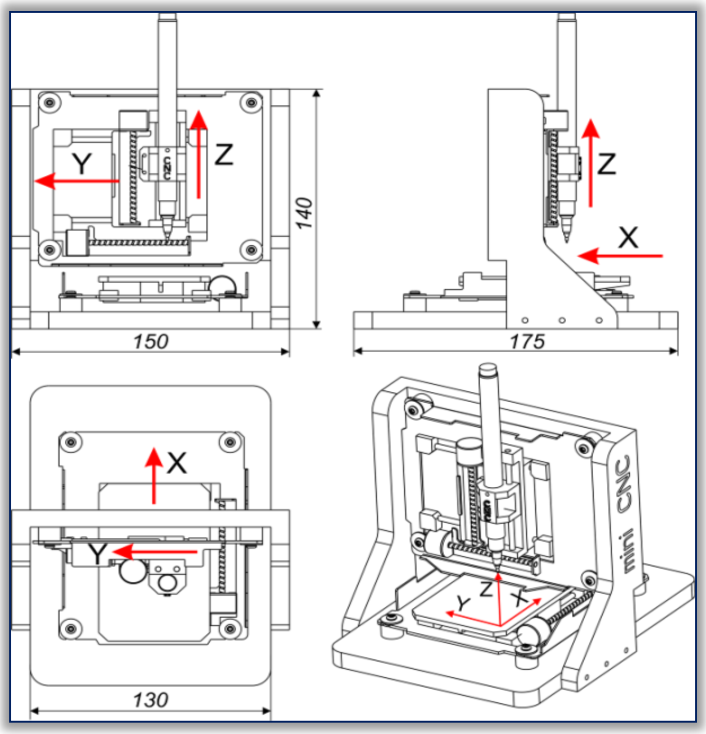

Figure 3. Drawing views of the complete assembly

— Simulation of the virtual prototype in CAD/CAM system

In order to generate virtual model adequate for simulation within designated CAD/CAM system, it was necessary to define corresponding kinematic connections between machine's moving elements. Examples of mentioned simulations can be found in papers [17,18]. PTC Creo software system supports all stages of the modelling and simulation that were needed for the development of our virtual model.

The stages are as follows: (i) modelling the mechanism with defined kinematic connections, (ii) definition of restrictions in kinematic connections, (iii) manual interactive inspection of defined virtual kinematic connections, (iv) creating a video file of the moving virtual mechanism. Within the used software, kinematic connections of the considered machine were generated by applying a *Slider* connection type for translational movements of all 3 axes and defining corresponding movement limits of each individual axis. Programming of the considered machine is fairly straightforward, since it is a 2D ploting machine. Using the two–axis trajectory milling strategy without compensation of tool radius proved to be a simple and effective solution. Tool radius is unnecessary since, in this case, the tool is a pen and its tip is considered to be a point. Developed virtual machine during simulation of a drawing operation (defined in CLF format) is shown in Figure4. In order to run the simulation, complete virtual model of the machine prototype is loaded. Machining program, defined in CLF format, is supplied and the simulation is run. If the simulated machining program is successfully verified, the CLF program is then postprocessed into adequate G code format. Machining program that was used in the simulation shown in Figure 4 incorporates contours of the coat of arms of the Republic of Serbia. Prepared DXF file containing the target contour is loaded in the PTC Creo environment and through standard CAD/CAM workflow, machining program (designated for drawing) is generated using the 2D trajectory milling strategy.

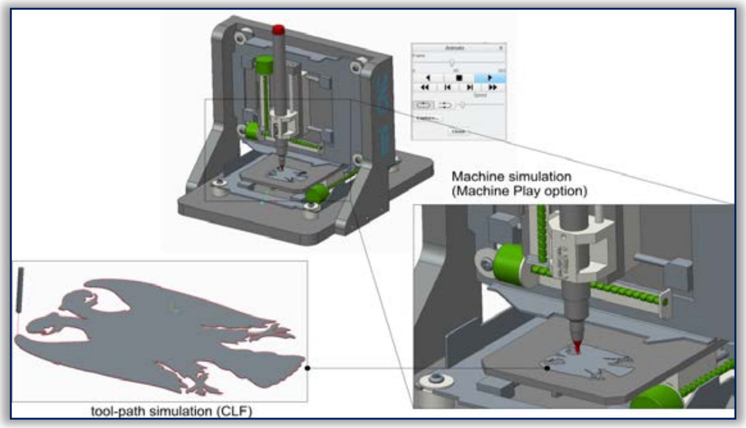

Figure 4. Example of the simulation within the CAD/CAM environment with active virtual machine executing the given machining program (CLF)

— Realization of the prototype

In this chapter, some characteristic details about activities involved in realization of the prototype are given, such as: (i) production of the base structure from MDF(Medium–density fibreboard) board, on which the drives of X–axis and Y–axis are placed; (ii) production of the slider for the X–axis worktable and Y–axis slider by means of 3D printing; (iii) production of the 3D printed Z–axis slider; (iv) preparation of the pen which will be inserted as a tool inside the holder mounted on Z–axis. All components prepared for the machine are shown in Figure5a, while the initial assembly is shown in Figure5b.

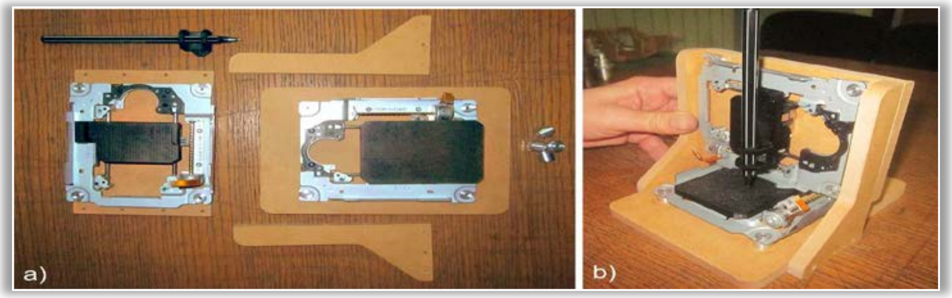

Figure 5. Prepared components before assembly (a) and initial assembly (b)

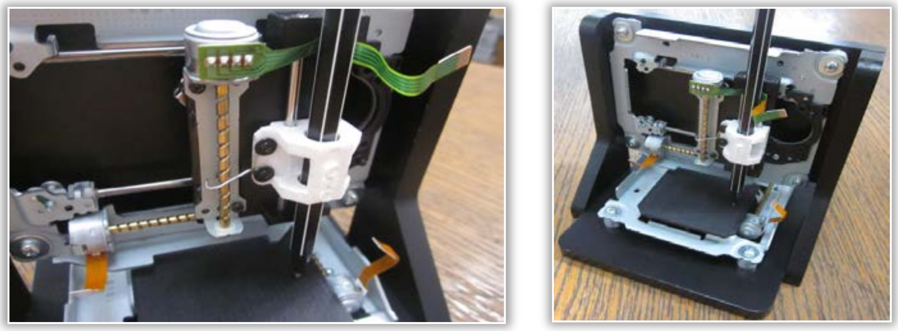
Figure 6. Fully assembled prototype of the machine

Fully assembled, mechanically complete prototype is shown in Figure 6. The next chapter covers the installation of the machine control system.

4. LINUXCNC CONFIGURATION FOR THE MACHINE PROTOTYPE

LinuxCNC was developed by NIST (National Institute of Standards and Technology) from USA [3,20]. LinuxCNC is a real–time control system with open architecture, which can be used control various kinds of machine tools and robots. Years of research went into development of LinuxCNC and it represents solid, time–proven machine control platform. Simplified structure of the control system, including mini CNC machine, is shown in Figure 7. LinuxCNC software system contains four base modules [3]: (i) movement controller EMCMOT; (ii) discrete input/output signals controller EMCIO; (iii) process controller EMCTASK; (iv) GUI (Graphical User Interface).

EMCMOT module performs performs real–time interpolation of the programmed path according to the direct and indirect kinematic models and drives motors of all the axes accordingly. EMCIO module processes all peripheral operations and doesn't have direct connection with motor drivers.

EMCTASK module interprets G–code instructions and coordinates the activities of EMCMOT and EMCIO modules accordingly. As seen in Figure7, communication between real–time EMCMOT module and non–real–time EMCTASK module is done through the shared memory buffer which is a part of RTLinux mechanism. GUI is an external module used for easier machine control, path visualization, code review etc. Different GUIs are available for LinuxCNC: TkLinuxCNC, MiniGUI, AxisGUI, GMOCCAPY GUI, while the one most commonly used is the Axis GUI. In our case, Axis GUI was used during demonstration of the mini CNC machine tool control system.

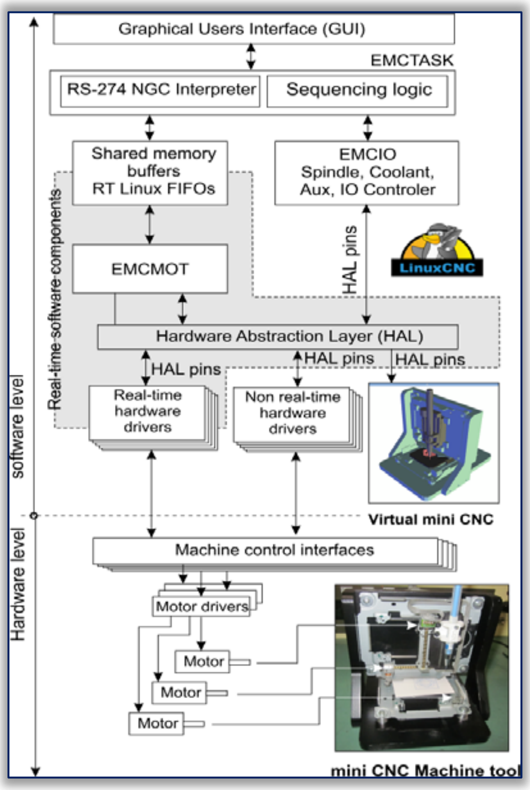

Figure 7. Architecture LinuxCNC–a for mini CNC machine tool

Significant contribution to expansion and popularization of LinuxCNC software was brought through the development of HAL (Hardware Abstraction Layer). HAL enables simple integration of user–defined direct and inverse kinematic models into the control system. Also, it provides a uniform interface for hardware and software modules of the system, thus simplifying connection establishment. In order to use LinuxCNC software to control the mini CNC machine, the following steps were necessary:

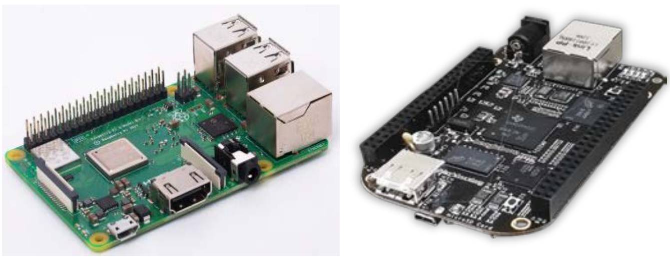

Figure 8. The compact PC platforms Raspberry Pi 3 Model B+ in BeagleBone black

I. Creating a directory which contains all the configuration files of the mini CNC machine tool;
II. Creating configuration (*.ini) files which contain core machine parameters: range of all the axes, maximum velocity and accelerations of all the individual axes, parameres for real–time system operation etc;
III. Creating configuration (*.hal) files which contain information relating to motion control of both real and virtual machine;
IV. Configuring the control system with regard to hardware platform being used as a host. Options here are regular personal computer, or compact (mini) computer, such as Raspberry Pi or Beagle Bone Black (Figure 8).
V. Building and configuration of the interactive virtual mini CNC machine tool within the LinuxCNC system using the tools available in OpenGL–Python 3D environment.

5. CONFIGURING OF THE VIRTUAL MACHINE

Configuring of the interactive virtual machine is done via Python programming language, which simplifies development of GUIs, GUI elements and allows primitive graphics modelling and integration of developed models directly into LinuxCNC control system [27,28]. Graphical model of the virtual machine is connected with the LinuxCNC core through OpenGL–Python hooks, which in turn allows correct movements of the virtual model. Afterwards, virtual model of the mini CNC machine can be used to simulate and verify machining programs directly in Axis GUI, or it can be used to monitor machine activity during machining operations, since the movements of the real and virtual machine are identical.

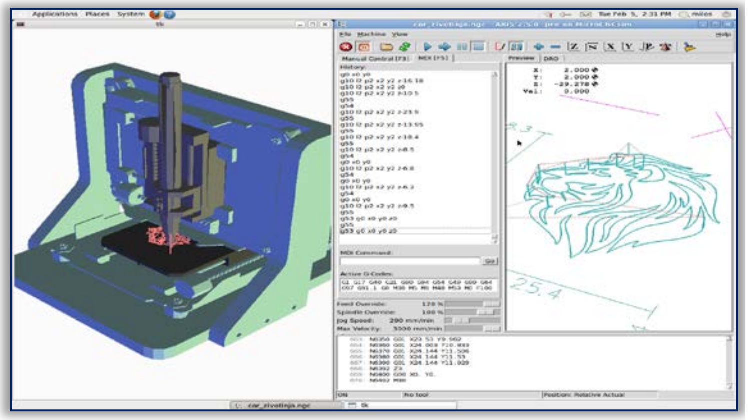

Figure 9. The Virtual machine integrated with the graphic user interface AXIS

Details regarding the virtual machine in OpenGL–Python environment are given in the works [21–23]. In this paper, virtual machine used all models that were developed in PTC Creo. Models were converted from native Creo format into ASCII STL format (OBJ format works as well) and then loaded into Axis GUI through appropriate Python calls. Afterwards, imported components are properly oriented and placed in the virtual environment, resulting in fully functional virtual machine shown in Figure 9.

The virtual machine is placed in a separate window and allows toolpath drawing during movements of the virtual machine elements. During the execution of the machining program written in G code, virtual machine elements are moving in real–time, fully synchronized with moving elements of the real machine, with no visible latency.

6. MACHINE TRIAL RUNS

After successful integration of the control system, trial machining was performed. Prototype of the mini CNC machine features compact design, with fully integrated hardware, shown in Figure10.

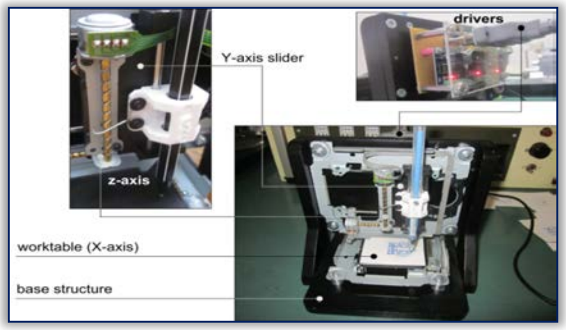

Figure 10. Fully integrated mechanical and control hardware

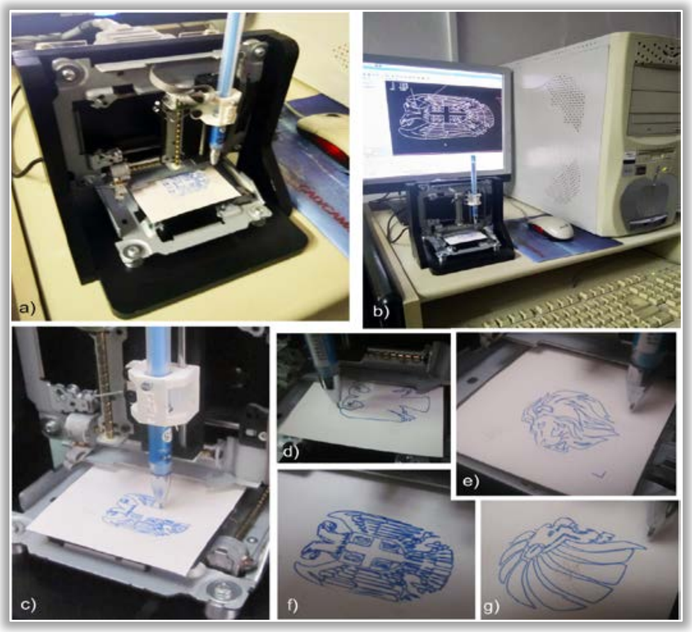

Figure 11. Machine work environment and results of several trials

During trial runs, machine was supposed to draw several complex 2D contours within the available workspace. All the trials were completed successfully, with no detectable defects. Mini CNC machine tool's work environment is shown in Figure 11. a,b, while some of the programmed contours are shown in Figure 11.c,d,e,f,g.

LinuxCNC is suitable for integration of the virtual machine directly within the control system, as shown in section 5. Simultaneous operation of the real machine and the virtual machine has also been successfully tested and shown in Figure 12.

Test runs allow us to conclude the following: (i) no visible differences in the appearance of the drawn and programmed contours confirm that the realized concept is good, (ii) positioning

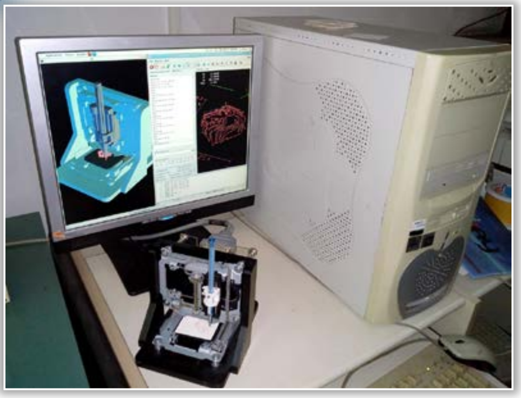
Figure12. Machine work environment with PC control system and integrated virtual machine in the background

accuracy within the boundaries of the machine workspace was good, (iii) the simultaneous work of virtual and real machine was successful.

7. CONCLUSION

3–axis mini CNC machine tool presented in this work was developed to create a suitable and economical environment for laboratory exercises and research in the field of micro and mezo machine tools. Presented machine can also be used for education and configuration of new machine tools, development of systems with open architecture control and CNC machine tool programming practice.

During the configuration of the mini CNC machine tool, following activities were realized: (i) adopting conception, designing and building of the machine tool, (ii) configuration of the machine tool control, (iii) simulation and verification of the virtual prototype, (iv) realization of the virtual prototype, (v) testing and trial runs of the machine tool.

Configuration of the new machine tools, revitalization of existing ones and self–construction of educational machine tools is one of the important factors for raising the level of education quality. At the same time, educational processes rely heavily on software solutions, simulation and virtualization technologies. This can be an economically viable basis for improving the educational system in the field of production engineering.

Further activities include adaptation of the Z–axis of the mini CNC machine tool, so that it can carry a small laser, designated for laser engraving, as well as construction and development of other concepts regarding mini CNC machine tools.

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