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An open architecture control system for multi-axis wood CNC machining center

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Abstract *This paper presents an open architecture control system for multi-axis wood computer numerical control (CNC) milling machining centre, based on LinuxCNC. The wood CNC machining system is supported by an equivalent virtual machine in a CAD/CAM environment, as well as in the control system. Simulation within virtual environment is essential for multi-axis machining, and the developed virtual machines are used for program verification and monitoring of the machining process. The virtual machine in the programming system allows the verification of the program before it's sent to the actual machine, while the virtual machine in the control system represents the final verification of the program, as well as the process monitoring system. Configuration of the control system and implementation of virtual machines will be shown, along with the conducted machining experiments that ensued after the successful simulation on developed virtual machines.*

Keywords *virtual machine, programming, wood CNC machine tool, CAD/CAM*

1. INTRODUCTION

Modern CNC systems are developed with the end-user in mind, where implemented designs emphasize the ease of use, customizability and extensibility. However, CNC machine tools' expensive hardware (base structure, linear and rotary guides, servo drives, servos, hydraulics, etc.) frequently outlives the provided software that is essential for the proper machine utilization. The end result leads to machines that are physically in working condition, but are rendered useless by the outdated software. New, commercially available CNC units end up costing more than the actual machine tool's worth and/or do not facilitate the necessary functions that are specific for the machine tool at hand. To overcome these issues, a solution may be found in the open-architecture domain, where one of the most commonly applied ones is LinuxCNC [1].

As the authors have plenty of experience in configuring, modifying, and implementing LinuxCNC on various machine tools and robots [2-8], the development and implementation of a control system for a multi-axis wood machining centre was just a sequel.

This paper presents sequences in the development and configuration of a control system for a multi-axis wood machine tool, utilizing virtual commissioning. In order to cover all aspects of using open-architecture software tools, the paper is organised into six sections, including the Introduction. Section 2 shows the details of the multi-axis wood CNC machining centre, with an emphasis on machine structure and its kinematic complexity as the main drivers behind our open-architecture

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approach. As the most important part of control system development by virtual commissioning methodology, section 3 covers the development of the virtual multi-axis wood CNC machining centre. Configuration of virtual machines in the CAD/CAM system is shown together with corresponding control and programming systems. Structure of LinuxCNC as a software tool for control system development is briefly presented in section 4. Necessary steps in development and configuration of control systems based on LinuxCNC are given in the same chapter. Proof of machine tool functionalities with the newly developed control system is presented in section 5. Concluding remarks are given in section 6.

2. MULTI AXIS WOOD CNC MACHINING CENTER

The multi-axis wood CNC machining centre considered in this paper is a vertical milling machine tool with complex kinematics in Y'(V')OXZBA spindle-tilting arrangement, Fig. 1a.

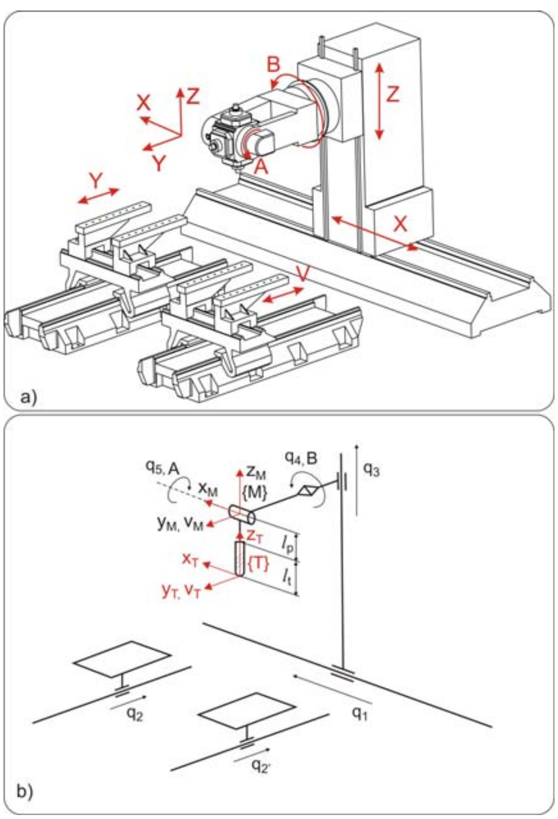

Fig. 1. Multi-axis wood CNC machining center Bacci MX6

The machine is equipped with two work tables which enable setting up the workpiece on one, while the other is used in operation. Alternatively, the two tables can be connected kinematically in order to better utilize the available workspace. Aforementioned table strategies are implemented as user-switchable through the open-architecture software extension. The existence of two work tables is "omitted" in order to solve the kinematic equations for machine tool from the previous figure [2].

The kinematic model of the machine's mechanism is shown in Fig. 1b. Coordinate reference frame (M) and the coordinate tool frame (T) are attached to the pivot, and the tooltip, as well as joint coordinates = [1 2 2′ 3 4 5] and the world coordinates = [ ]. The inverse kinematic solutions for both worktables are:

$$
\begin{aligned}
x_T &= q_1 - (l_p + l_t)\sin q_4 \cos q_5 \\
y_T &= q_2 + (l_p + l_t)\sin q_5 \\
y_T &= q_2' + (l_p + l_t)\sin q_5 \\
z_T &= q_3 - (l_p + l_t)\cos q_4 \cos q_5 \\
A_T &= q_5 \\
B_T &= q_4
\end{aligned}
\tag{1}
$$

where coordinates x_T, y_T, z_T and angles A_T, B_T determine tool position and orientation in the Cartesian coordinate system. Pivot length and tool length are designated as l_p and l_t, respectively.

The direct kinematic solutions were derived as shown in the next equations:

$$
\begin{aligned}
q_1 &= x_T - (l_p + l_t)\sin B_T \cos A_T \\
q_2 &= y_T + (l_p + l_t)\sin A_T \\
q_2' &= v_T + (l_p + l_t)\sin A_T \\
q_3 &= z_T - (l_p + l_t)\cos B_T \cos A_T \\
q_4 &= B_T \\
q_5 &= A_T
\end{aligned}
\tag{2}
$$

where q_i, $i=1,2,\ldots,5$ and q_2' are scalar joint variables controlled by the actuators.

3. VIRTUAL MACHINE CONFIGURATION

Programming of wood CNC machining is conventional, similar to any other milling or drilling CNC operation. Originally, specialized CAD/CAM software PITAGORA [1] was used for programming of the considered Bacci machine tool. This approach required the adoption of non-standard axes directions and kinematics. Implementation of a new control system enabled the adoption of a standard kinematic model, making it possible to utilize widely available CAD/CAM systems.

One of the established systems for programming and verification of NC programs for wood CNC machining centre is shown in section 4. The CAD model of a workpiece is the basis for tool path generation, stored in CLF (Cutter Location File) format. The CAD/CAM system PTC Creo is used as a programming system.

Generated tool path can be checked in three ways:

- tool path simulation,
- material removal simulation (NC Check),
- machine simulation, according to CLF.

After successful verification of the tool path, the program is postprocessed and the resulting G code is sent to the machine for the execution.

3.1 Virtual machine in programming system

The configured virtual wood CNC machining centre is used to simulate the tool path generated in the CAD/CAM system.

Virtual machine simulation is crucial for the following reasons [1]: (i) programming environment configuration, including virtual machine; (ii) NC program verification prior to machining, and (iii) collision detection, essential for 5 axis machining.

CLF-based machine simulation is enabled through specifying kinematics that are utilized on the virtual model of the machine within the CAD/CAM environment. This allows a virtual machine model to function like a system of rigid bodies [4,5,7,8].

The kinematic model generation required applying slider type links for all translational axes (X, Y, and Z) and cylinder links for two rotational axes (B and A). The corresponding movement limits are defined for each axis [1].

To start the machine simulation, it is necessary to define the coordinate system of the workpiece (MACH_ZERO) and the coordinate system of the tool (TOOL_POINT). These coordinate systems connect the coordinate systems of the workpiece and the tool with corresponding coordinate systems on the virtual machine.

Matching these coordinate systems enables the setting of the workpiece on the configured virtual machine and setting the tool at the head of the main spindle on the virtual machine during simulation.

A single chair machining strategy (Fig. 2a) is given as an example in order to demonstrate the programming and simulation capabilities of our developed system.

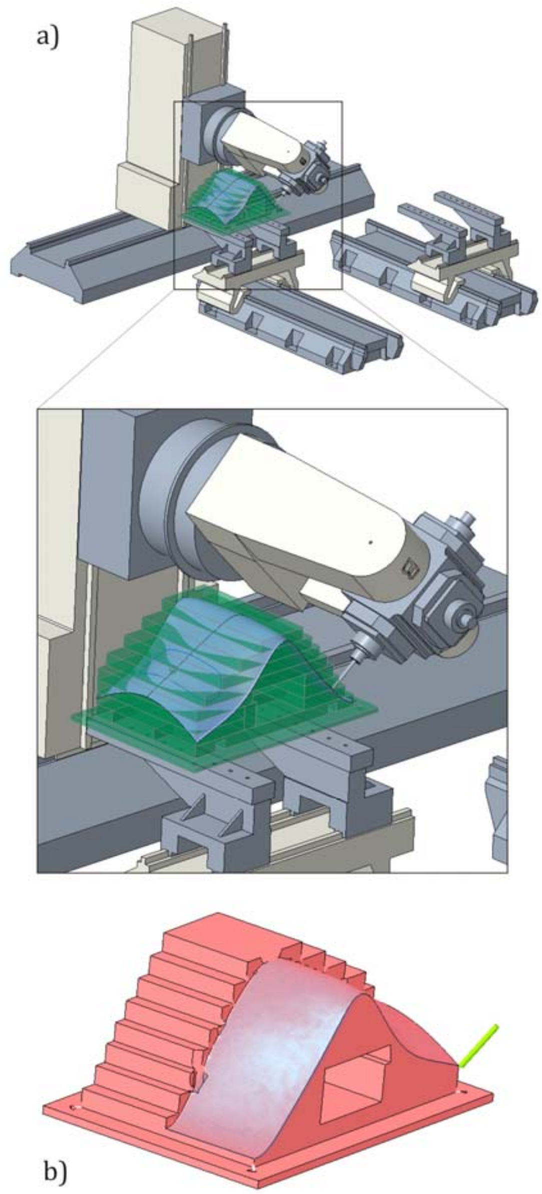

Fig. 2. Programme verification through virtual machining

A surface milling strategy was applied for the machining of the chair's shape. After generating the tool path for five-axis machining, material removal simulation was performed in order to verify the tool path. An example of a material removal simulation is shown in Fig.2b. Result of the simulation (the virtual workpiece) helps determine the accuracy of future machining by comparison with the standard CAD model of the workpiece. The tool path verification was followed by post-processing and obtaining the G code ready for transfer to the control unit. The obtained G code is finally verified on a virtual machine integrated with the real machine control system, shown in Chapter 4.2.

4.2 Virtual machine in the control system

The virtual machine has a significant role when developing a control system for a machine with complex kinematics. Considering all safety precautions necessary for testing of the kinematic functions intended for real machine, virtual commissioning [9,10] proves priceless during development. Our approach implies error-driven development without safety issues. Virtual machines are also significant during machine tool exploitation. Machining program verification by virtual machining is a crucial task on multi-axis machine tools which allows:

- visual detection of collisions between the moving parts of the machine and between the tool, workpieces and fixtures;
- checking if the machine can execute the specified tool path within the limited motions, ranges, and speeds.

Virtual machine development under the LinuxCNC software environment relies on OpenGL and several interface classes written in Python programming language [6]. Python is an interpreted programming language, with a gentle learning curve, suitable for scripting tasks, such as development and configuration of virtual environments. The basic concept of a virtual machine configuration is shown in Fig. 3.
Here, models of machine components were imported in ASCII STL format and connected according to the established kinematic model via rotational or translational joints. The ASCII STL files of the machine components were obtained from the CAD environment of the PTC Creo.
After the virtual machine is configured, it is integrated within the control system. During the execution of the machining program, the virtual machine components are moving in real-time, fully synchronized with the moving parts of the real machine [2], which was confirmed by machining experiments.

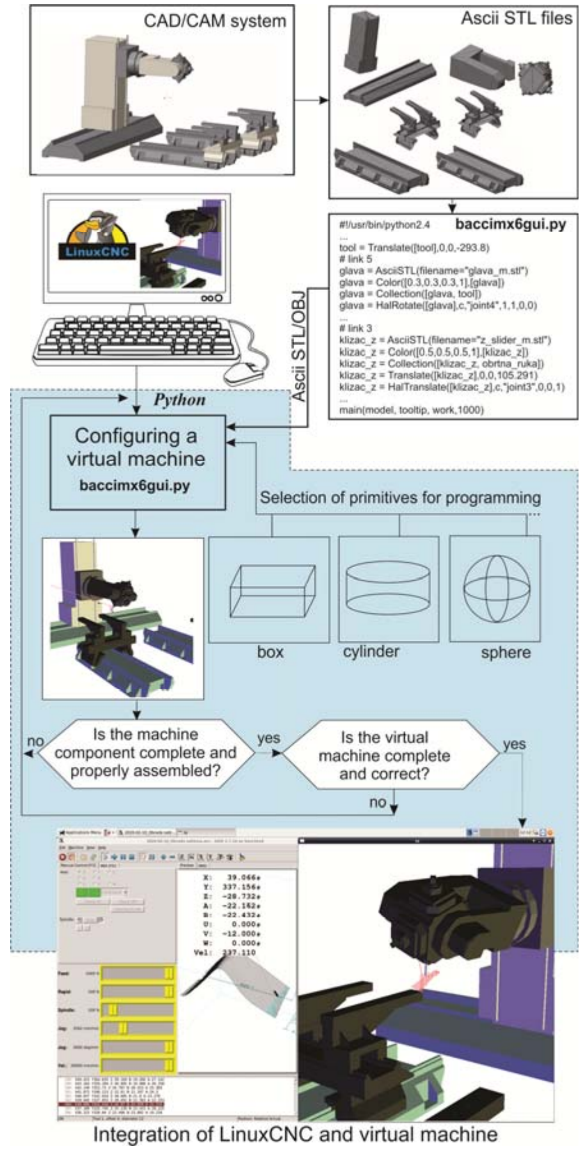

Fig. 3. Configuring virtual machine in control system

4. PROGRAMMING AND CONTROL SYSTEM BASED ON LINUXCNC

During the development of the control and programming system for the multi-axis machining centre, the main objective was to enable the use of standard CAD/CAM systems to generate a machining program.
Using expensive postprocessors for this machine was not an option. Thus, all non-standard and complex functionalities of the machine had to be encapsulated in term of object-oriented programming.

The solution lies in complex switchable kinematic functions, developed machine cycles and intuitive graphical interfaces.
After all development effort, end-user can generate a machining program using standard CAD/CAM system such as PTC Creo, CATIA or similar, choosing one among multiple generic postprocessors, Fig. 4.

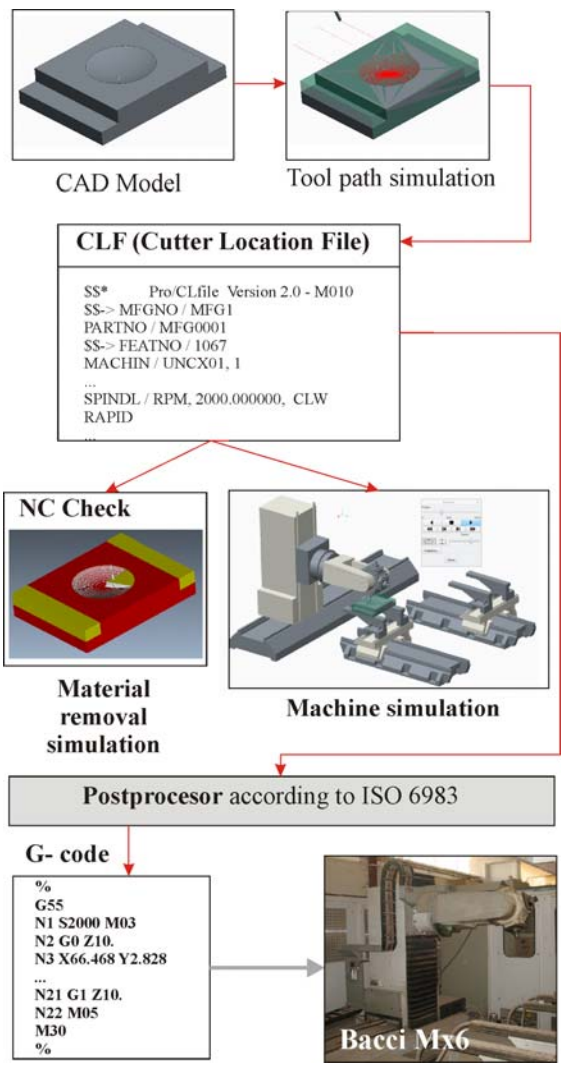

Fig. 4. Programming system

The CAD model of a workpiece is the base for tool path generation. In this study, CAD/CAM system PTC Creo is used to generate a cutter location file (CLF). Generated tool path is tested through the NC Check (material removal simulation) software module, followed by the G-code generation. Postprocessing for the vertical 5-axis milling machines, configured for AB spindle-tilting type, is used to obtain the machining program. The CAD/CAM system PTC Creo can perform a verification of the obtained programs through virtual simulation.
In order to configure LinuxCNC for motion control of the machining centre, as well as control of all the sequential processes that enable axis initialisation, tool change, etc., some development steps had to be made. The key part was coding and testing switchable kinematic functions. Using remappable M functions, M200, M201 and M202, kinematics switchability [2] is achieved as shown in Fig. 5.

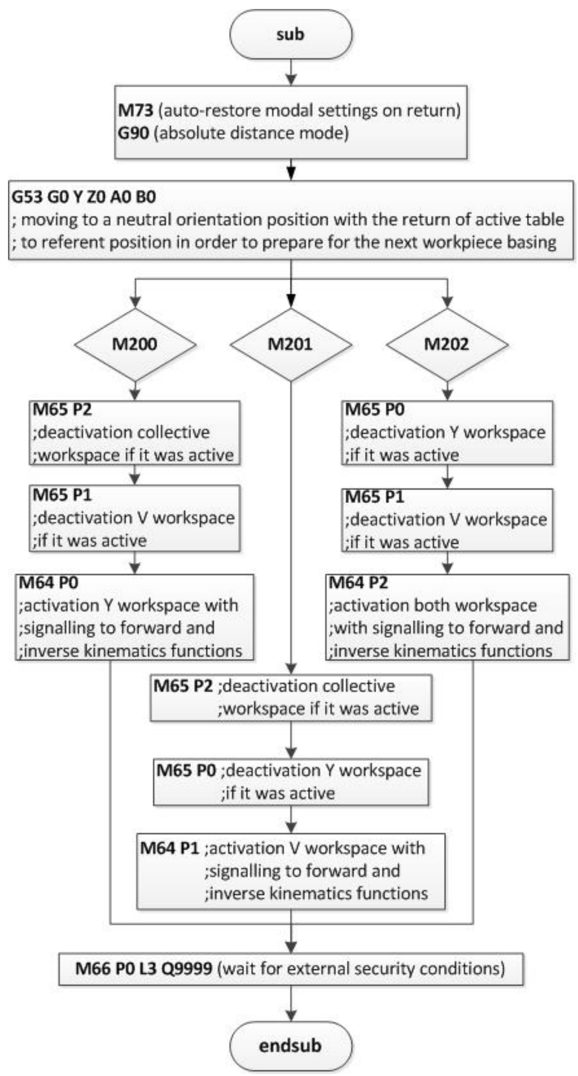

Fig. 5. Customized M functions

After getting a virtual machine environment, which is depicted in the next section in detail, kinematic functions are implemented in the control system. During the test procedure, control signals intended for real machine tool are connected to the virtual machine. That way, test procedures are carried out safely without real machine involvement and the possibility of collisions and damages.

5. MACHINING EXPERIMENTS

Machining experiments were conducted on wood, with respect to production demands of the corresponding industry. Before machining, the programs' tool paths were simulated in LinuxCNC and the virtual machine that's integrated with the control system.

The first test was a 5-axis machining of a concave calotte (Fig. 6), for which an example of programming and simulation in a CAD/CAM environment is shown in Fig. 4.

Fig. 6. 5-axis machining of a concave calotte

The second test was a 5-axis machining of a mould for chair production, with significant immediate finishing-pass surface machining, Fig.7. In this case, virtual machine simulation is essential, providing the collision avoidance mechanism, which detects errors in the workpiece set up and possible collisions of machine parts with the workpiece during machining.

The realized examples have shown that the established kinematic model of the machine and the developed control system, including an adequate environment for programming and program verification, are well-based and ready for industrial applications.

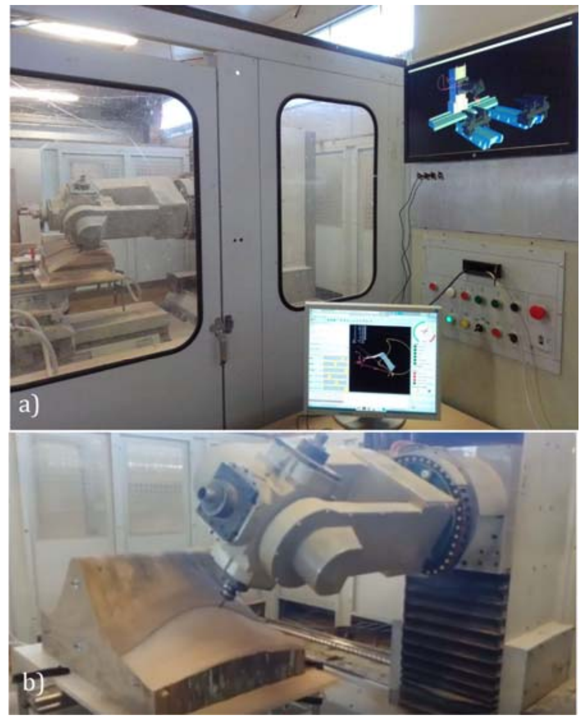

Fig. 7. 5-axis machining a mould for chair production

6. CONCLUSION

This paper presented a methodology for development and configuration of a control system for a multi-axis wood machine tool through virtual commissioning. During the development of the physical machine tool's control system, virtual machines were used for algorithms' testing, an important step for the validation of the new controller's functions.

The developed control system is low-cost and easy to setup, which is especially suitable for retrofit and modernization of older machine tools. The open architecture software is suitable for the development of complex kinematics functions for multi-axis machine tools. Due to the modularity, flexibility, openness, and availability, the proposed system is convenient for machine tools with specific reconfigurable kinematic structures and unique functionalities.

Directions for further research may relate to increasing the functionality of the control system in the field of monitoring and diagnostics, as well as further improving the methods of programming and verification of machining programs.

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