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THE IMPLEMENTATION OF A MODULAR OPEN ARCHITECTURE PC-BASED CNC SYSTEM USED AS A RESEARCH AND EDUCATION EQUIPMENT

Radu-Eugen BREAZ[1,*], Sever-Gabriel RACZ[2], Melania TERA[3], Mihai CRENGANIȘ[3]

[1)] Prof., PhD, Department of Industrial Machines and Equipment, "Lucian Blaga" University of Sibiu, Sibiu, Romania
[2)] Prof., PhD, Head of Department, Department of Industrial Machines and Equipment, "Lucian Blaga" University of Sibiu, Sibiu, Romania
[3)] Ass. Prof., PhD, Department of Industrial Machines and Equipment, "Lucian Blaga" University of Sibiu, Sibiu, Romania
[3)] Ass. Prof., PhD, Department of Industrial Machines and Equipment, "Lucian Blaga" University of Sibiu, Sibiu, Romania

Abstract: *Open-architecture CNC technological equipment are used nowadays both for industrial and educational purposes. Using a modular structure and a PC-based CNC controller, these devices allow the users to develop and test new control and machining strategies, to train in the field of CNC programming and CAD/CAM techniques, while keeping the costs as low as possible, in comparison with the industrial, closed architecture, CNC machine-tools. However, the modular, reconfigurable, structure and consequently the modular assembly method, comes with some drawbacks, most of them related the accuracy of the system. Also, PC-based open architecture controllers lacks some important features linked with 4&5-axis indexed machining and 4&5-axis continuous machining, which normally are present in industrial CNC controllers. Among these features, the ability to use local coordinate systems and the ability of using tool center point management are the most important, and their absence makes the use of CNC machines with PC-based open architecture for multi-axis machining quite difficult. This paper present the implementation of a 5-axis modular CNC machining center, built in a modular way and using LinuxCNC as PC-based CNC controller. Some methods for improving the accuracy of the equipment and strategies to overcome the difficulties related to 4&5 axis machining are presented.*

Key words: *CNC open architecture, modular structure, 4&5-axis machining, contouring accuracy, kinematic model.*

1. INTRODUCTION

CNC machine-tools are nowadays the backbone of machining processes throughout all industries. While most of them are manufactured by specialized companies in a closed architecture manner, some researches are reported in the literature regarding open architecture solutions.

The CNC controller, seen mostly as a software environment which controls al the machine functions is considered as the core of the open architecture approach [1]. The most important requirements for an open architecture CNC system are modularity, reconfigurability and maintainability, according to [2]. The development of a software kernel which could be used as the software core for an open CNC controller was presented in [3]. Other approaches of developing open architecture CNC systems are reported in [4] and [5]. Open architecture controllers are also used when intelligent functions are added to the machine tool, such as auto-diagnosis modules or cutting tool monitoring by means of multi-sensor fusion [6].

Other approaches were oriented to develop open architecture CNC machine-tools and industrial robots by using the software solution provided as open source software kernel LinuxCNC [7]. Linux CNC is a highly configurable software solution, based upon real-time Linux operating system, which allow the users to build control modular CNC equipment by integrating structural modules, servo-systems, tools and/or tool changing systems. After building the CNC system, LinuxCNC can be easily used as a PC-based CNC controller. Both CNC machine-tools and robots were successfully developed using LinuxCNC [8, 9].

However, from a practical point of view, building a CNC machine-tool in a modular, reconfigurable way, may be subject to some accuracy related problems. Also, when multi-axis machining comes into attention, PC-based CNC controllers, such as LinuxCNC are not always as good as their industrial, closed-architecture CNC controllers.

2. THE MODULAR 5-AXIS CNC MACHINE-TOOL

A 5-axis modular CNC machine-tool was developed and has been subject of this research program. The main idea was to provide an experimental testbed for 5-axis machining and control strategies, which can be also used for teaching activities. The overall view of the machine is presented in Fig. 1,*a*, while Fig. 1,*b* shows the rotational axes (swivel axis *A* and rotary axis *C*).

[*] Corresponding author: Victoriei 10, 550024 Sibiu,
Tel.: +40-(269) 21.60.62/1453;
Fax: +40-(269) 21.27.16
E-mail addresses: *radu.breaz@ulbsibiu.ro* (R.E. Breaz), *gabriel.racz@ulbsibiu.ro* (S.G..Racz), *melania.tera@ulbsibiu.ro* (M. Tera), *mihai.crenganis@ulbsibiu.ro* (M. Crenganiș)

a

b

Fig. 1. The 5-axis modular machine-tool: *a* – overall view; *b* – rotational axes.

The machine was designed and built by General Numeric, a specialized company from Brașov, Romania, which have also implemented the PC-based open architecture LinuxCNC controller on it. The mechanical structure of the machine was assembled from custom-built modules manufactured by General Numeric company, which were combined with ISEL guiding and transmission systems.

It is here noticeable the fact that the machine is a prototype, designed specifically for the needs of the final customer, "Lucian Blaga" University of Sibiu.

The main design requirements for this machine were:

- modular structure (it can be used either as 3-axis or as 5-axis CNC machine);
- PC-based open architecture controller (LinuxCNC);
- open workspace with the strokes on X and Y axes much bigger with the stroke on Z axis (router type);
- three translational axes (X, Y and Z) and two rotational axes (A and C);
- all feed drives, on all five axes are realized as closed-loop motion control systems, using d.c. servomotors as actuation devices and rotational encoders as feedback devices.

The machine is also equipped with an automatic tool measuring system. The tool has to be changed manually, there is neither automatic tool changer, nor tool magazine available.

The main kinematic chain uses an a.c. 1.5 KW ISEL asynchronous motor, controlled by a voltage/frequency inverter, which can rotate the tool up to 24 000 rev/min.

The machine table is made from special aluminum profiles with T-slots, which facilitate the rapid and easy fixture of large workpieces.

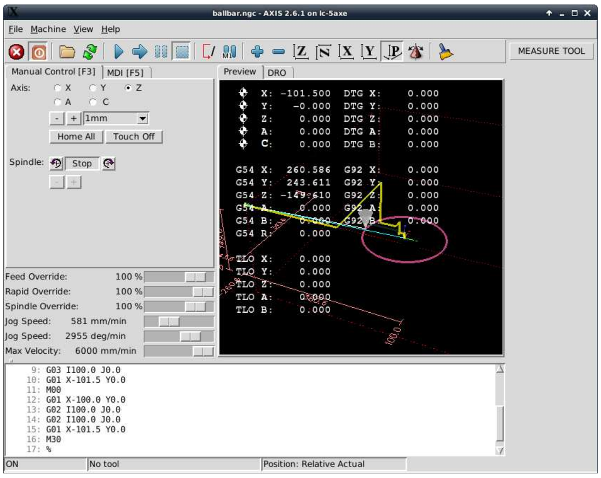


Fig. 2. The control interface for LinuxCNC.

For small workpieces, the machine is also fitted with a manually driven vice. Also, the rotary axis C is fitted with a universal clamping system with three self-centering jaws (Fig. 1,*b*), which can be used either for 3-axis machining of cylindrical workpieces or for 5-axis machining.

LinuxCNC, v. 2.6, under Debian Linux is used as PC-based open architecture CNC controller. The interface of the CNC controller, available by means of a PC is presented in Fig. 2.

3. IMPROVING THE CONTOURING ACCURACY

In order to test the contouring accuracy of the 5-axis machine tool, a Renishaw QC-10 ballbar system was used. The experimental layout for running the contouring accuracy in dry-run regime is presented in Fig. 3,*a* and *b*.

The results of the tests (before and after unfolding the corrections) are presented in Fig. 4,*a* and *b*. while a synthesis of the results (before and after) are presented in Table 1.

a

b

Fig. 3. Running the contouring accuracy test: *a* – overall view; *b* – the ballbar device.

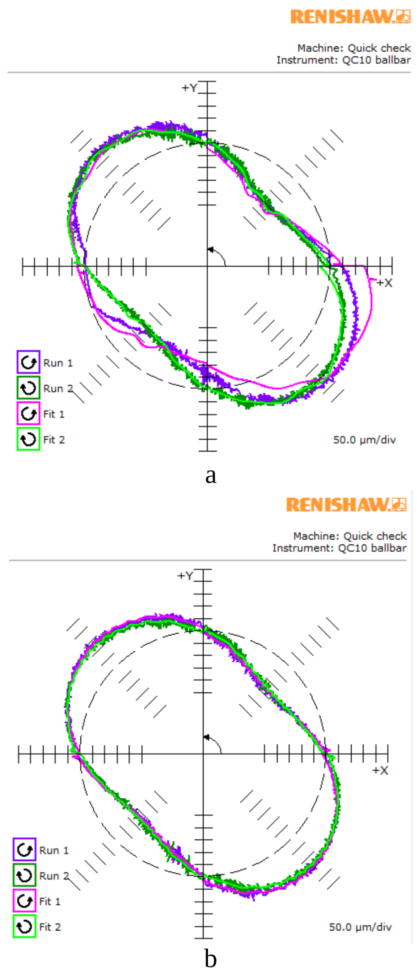


Fig. 4. Test result: *a* – before; *b* – after corrections.

Table 1

Contouring accuracy -Tests results

Output	**Test 1 (before)**		**Test 2 (after)**	
	Value	[%]	Value	[%]
Squareness	2760 µm/m	32%	2614 µm/m	62%
Lateral play *X*	►144.5 µm ◄–21.5 µm	10%	-	-
Lateral play *Y*	▲23.6 µm ▼128.2 µm	10%	-	-
Backlash *X*	►–62.4 µm ◄8.4 µm	7%	►16 µm ◄14 µm	4%
Backlash *Y*	-	-	▲18.7 µm ▼18 µm	4%
Reversal spikes *X*	►–32.9 µm ◄24.7 µm	7%	► 25.5 µm ◄25.2 µm	6%
Straightness *Y*	-	-	24.2 µm	3%
	Circularity 396.6 µm		Circularity 310.7 µm	

The symbols ►, ◄, ▲, ▼ from Table 1 are used for depicting the direction of motion on axes *X* and *Y*. The percentages within Table 1 indicates the contribution of each output to the overall balance of the circularity error.

From Table 1, it can be noticed that the main influence upon the circularity error is due to the mechanical errors.

The test can identify the contribution of the mismatched control parameters of the servosystems for each axis (*X* and *Y*), but their contribution is negligible, according to Table 1.

The most important contribution is due the squareness error, which indicates the fact that the axes *X* and *Y* are not perfectly perpendicular to each other [10]. The second biggest influence is due to the lateral play on *X* and *Y* axes, which may be caused by looseness in the guideways.

Taken into consideration that all the above-mentioned errors are influenced by mechanical misalignments, the corrections actions were targeted accordingly. The builder of the machine has equipped it with capabilities of adjusting these mechanical errors.

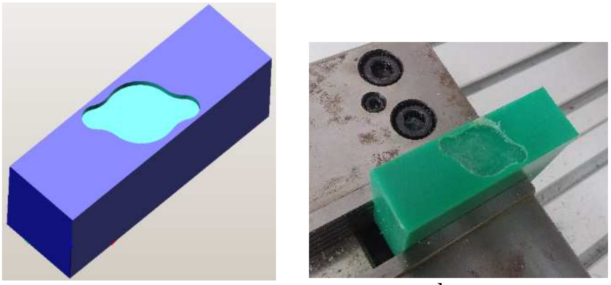
To adjust the angle between *X* and *Y* axes, eight adjusting screws were provided on each side of the machine Fig 5. The position of these screws can be slightly adjusted by moving them along their holes (which are shaped as slots), allowing the user to modify the above-mentioned angle. The degree of control of these movements is small, but after a trial and error process, the test results have shown the values presented in Table 1 under "Test 2" column.

The results after corrections have shown that the squareness error was reduced (2760 µm/m before, 2760 µm/m after), while the lateral play was practically eliminated (on both axes). The contribution of the squareness error in the overall error balance has increased, but that can be explained by the fact that most of the other errors have been reduced or eliminated.

Finally, the overall circularity error was reduced from 396.6 µm to 310.6 µm, a decrease of about 22 %. From Fig. 4 it can be also noticed the fact that the oscillations of the system during the movements has been reduced (even this fact can be quantified only in a qualitative (visual) way). The results of the corrections have demonstrated two facts:

- the control system was configurated and tuned properly in the building phase of the machine, and there are no errors in values of controllers' gains to influence the contouring accuracy;
- the contouring accuracy is influenced only by mechanical misalignments, which are acceptable for such system. However, given the proper tools (the ballbar systems) and the adjusting systems, these errors can be kept under control, even the corrections must be made by means of a trial and error process.

Fig. 5. System for adjusting the angle between *X* and *Y* axes.



a b

Fig. 6. Test part for 3-axis machining: *a* –3D model; *b* – machined part.

4. 3-AXIS MACHINING

To demonstrate the capabilities of machining contours, a test part was machined (Fig. 6,*a* and *b*). The machining involved driving the tool on complex trajectories on *XY* plane. The machining could be considered a 2.5*D* one, but movements on *Z*-axis also occur, during the engage phase (involving simultaneous movements on *X*, *Y* and *Z*) and consequently, the machining could be considered a 3-axis one.

5. 5-AXIS MACHINING

For 5 axis machining, which involves movements on both translational and rotational axes, the coordinates on *X*, *Y* and *Z* are the coordinates of the tooling point (tip of the tool) related to the workpiece coordinate system (G54), while the rotary coordinates (*A*, *C*) are related to the machine coordinate system (G53). For different CNC controllers, there are different methods for updating the tooling point and the position of the woorkpiece coordinate system after moving the rotational axes. Modern CNC controllers, such as Sinumerik 840 D and Heidenhain TNC i530 have the so called "Tool Center Point Management (TCPM)" mode available, while LinuxCNC is able to work only in the "3 axis mode".

For the "3 axis mode", the position of the workpiece coordinate system (G54) and the position of the tooling point is not updated after changing the position of rotational axes - the CNC controller behaves as it knows nothing about the machine kinematics – as a regular 3 axis controller. In the TCPM mode, the CNC controller can use local coordinate systems (using the PLANE function at TNC and the ROT function at Sinumerik) and updates the position of the workpiece zero and the position of the tool tip regarding to the actual workpiece-tool orientation.

The situation is explained detail in Fig. 7,*a*, *b*, and *c*. In Fig. 7,*a*, the initial machine configuration ($A = 0°$ C = 0°) is presented. The origin of the workpiece coordinate system (G54, noted with 2) is in the middle of the upper face of the workpiece and the tooling point (noted with 1) is at the tool tip. In figure 7,*b*, the machine configuration after 5 axis positioning without using a local coordinate system is presented ($A = 90°$ and $C = 155°$). The workpiece and the tool are moved, but the origin of the workpiece coordinate system (G54) and the tooling point still stay the same. The generated toolpath will depend on the workpiece setup and the tool length.

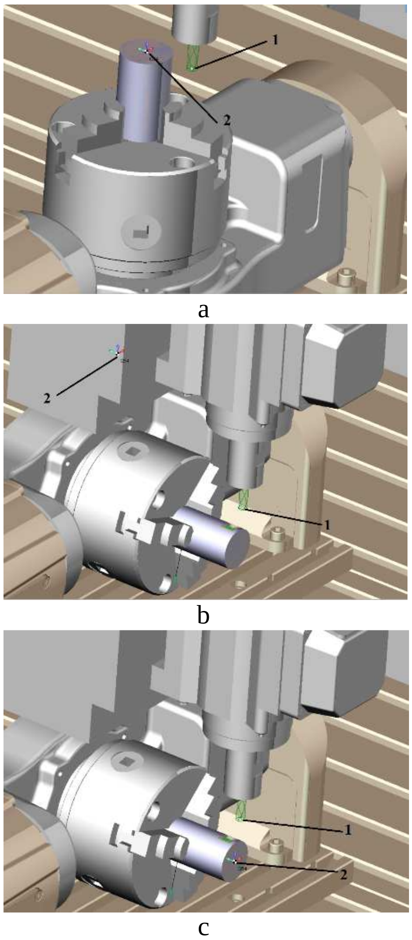


Fig. 7. 5 axis positioning: *a* –initial state; *b* – positioning in "3 axis mode"; *c* – positioning in "TCPM mode".

In Fig. 7,*c* the machine configuration after 5 axis positioning with local coordinate system enabled is presented ($A = 90°$ and $C = 155°$). The origin of the coordinate system (G54) is again in the middle of the upper face of the workpiece, the tooling point is again at the tool tip. The generated toolpath will be independent on the workpiece setup / tool length.

It is here noticeable the fact that the situation presented in Fig. 7,*c* is not available with the Linux CNC controller.

Because LinuxCNC controller only allows the "3 axis mode" for 5-axis machining, to machine parts on the machine, a geometric and kinematic model of the machine is needed [11]. Normally, commercially available CAM software packages can simulate the potential collisions between the tool and the part, while, on the machine, CNC controllers, in TCPM mode can signal the potential collisions between the moving parts of the machine (slides and turntables). For machines whose CNC controllers does not know anything about the machine kinematics (only the "3 axis mode" being available), the potential collisions between the machine slides and turntable can be detected and removed during simulation, but only if a 3D geometric and kinematic model of the machine is available.

In Fig. 8, the 3D geometric and kinematic model of the 5-axis CNC machine-tool is presented. The model was build using the 3D models of the structural modules of the machine.

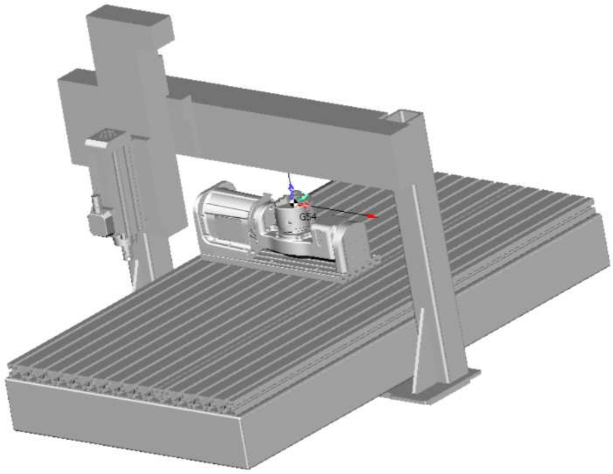


Fig. 8. The 3D geometric and kinematic model of the machine.

Some of the modules were modeled by the authors, while some of them were taken from the manufacturer website (for ISEL modules), as .igs files.

After modeling the assembly of the machine, kinematic dependencies were defined (for example, the *Y*-axis module carries the *X* and *Z*-axis modules, so the movement of *Y*-axis implies also the movement of both *X* and *Z* axes). Finally, the strokes were defined on all axes (linear and circular) and the model was made available in the CAM software package used for generating the NC codes for machining.

From Fig. 8 it can be noticed that the height of the machine was reduced, because it did not influence trajectories of the moving parts of the machine.

To test the 5-axis machining capabilities of the CNC machine-tool, the test part presented in Fig. 9 was machined. The machining process involves two phases:

- a 90° rotation of *A* axes and a 155° rotation of *C* axes for positioning the part (5-axis positioning);
- a 4-axis simultaneous machining phase (with simultaneous movements on *X*, *Y*, *Z* and *B* axes) for machining the cylindrical pocket.

Simultaneous 5-axis continuous milling was not tested at this stage. The tool used for the machining process was a cylindrical mill of 6 mm in diameter, the cutting speed was limited to 40 m/min and the federate 200 mm/min. The cutting depth for each pass during the 4-axis simultaneous machining was 1 mm.

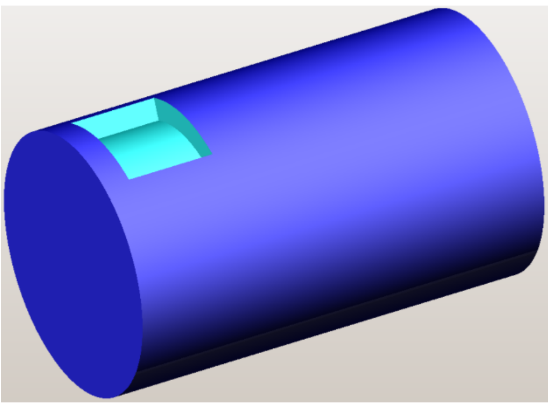
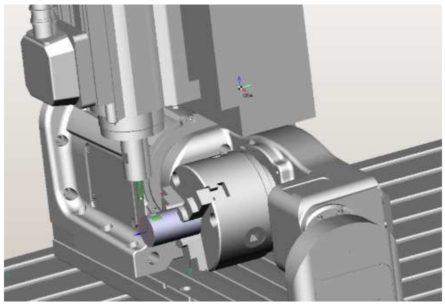
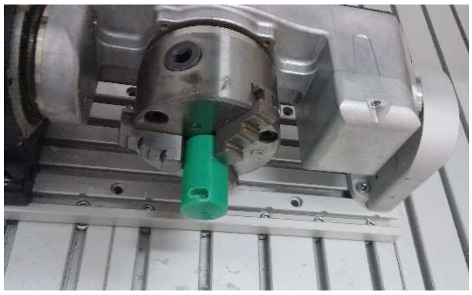


Fig. 9. The test part for 5-axis machining (pocket on a cylinder).



a

b



c

Fig. 10. Cylindrical test part machining: *a* – simulation; *b* – machining; *c* – machining result.

The material chosen for the part was polyamide PA6, to lower the risks linked with tool-workpiece collisions. The NC code was generated in a commercially available software package, but settings were made to post-process it according to "3 axis mode", which is the only one allowed by LinuxCAN controller. Special care should be taken, because the default mode for 4&5 axes machining in CAM software packages is the TCPM one. Post-processing the NC-code with the TCPM mode enable will lead, in this case, to an erroneous code and, possible, to collisions both between the tool and workpiece and between the moving parts of the machine.

6. CONCLUSIONS

The paper presents a research program which aimed to develop and implement an open architecture modular 5-axis CNC machine-tool. The machine-tool is intended to be use for both research and teaching activities.

In the initial stage of the program, the design requirements were established and agreed between "Lucian Blaga" University of Sibiu and General Numeric company, which finally built the machine-tool.

A PC-based open architecture CNC controller, LinuxCNC, was chosen, due to its availability as open-source, its performance and due to its real-time Linux based kernel. The implementation of of LinuxCNC on the machine-tool was also made by General Numeric.

The next step after bringing the CNC machine-tool in the laboratories of "Lucian Blaga" University of Sibiu was to assess its contouring accuracy. A special device (Renishaw QC 10 ballbar) was used for this purpose and the results have proven that only mechanical misalignments are the main source of contouring errors. By means of a trial and error process of mechanical tuning, adjustments were made and the contouring accuracy was improved accordingly. Also, the test had proven the fact that the implementation of LinuxCNC controller was done properly, with regards of the motion control parameters for every kinematic chain.

The machining capabilities of the equipment were tested by machining test parts for 3-axis and 5-axis machining.

Special attention had to be given to 5-axis machining, because LinuxCNC controller lacks the capabilities of modern 5-axis industrial controller, particularly the feature of using local coordinate systems for 5-axis positioning. That means that the controller works as if it does not know any information regarding the machine geometry and kinematics, which can lead to collisions between machine moving parts during machining. To overcome this drawback, a 3D geometric and kinematic model of the machine was developed.

Finally, test parts which involved 5-axis positioning and 4-axis continuous machining were machined.

Further researches will target the capabilities of the machine to perform 5-axis continuous machining.

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