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Research paper

CONFIGURING A MACHINE TOOL BASED ON HYBRID O-X GLIDE MECHANISM

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Abstract: *The application of computer technologies based on enhanced geometric interpretation of the product in terms of virtual prototype is considered as the basis for product development in the XXI century. This enables integrated development of products that includes the conception, design, optimization, production planning and the manufacture of machine tool as a product of complex mechatronic structure. This paper describes the configuration of the new machine tool with a hybrid kinematic structure based on the original O-X glide mechanism, which includes analyses of kinematics, workspace, virtual prototype simulation and planning of the control system for the management and programming.*

Key words: *O-X glide mechanism, virtual prototype, CAD/CAM, EMC2*

1. INTRODUCTION

In order to increase the competitiveness of products on the market as well as the rationalization of production, all areas of industry have gone through significant changes in recent years. Production technologies, and especially machine tools that are actualizing industrial production, are thus exposed to significant improvements. This primarily includes development through the introduction of virtual prototype technology, perfecting the mechanical structures of machine tools and increasing the flexibility in service. These directions are aimed at faster and more productive development of primarily machine tools, by enhancing their efficiency and flexibility, necessary to meet the demands of the modern market.

Functional computer models and, in recent years, virtual prototypes are the foundation for increasing the development efficiency of the machine tools [1, 2, 3]. This enables faster and more efficient conception of complex mechatronic systems, simulation of their work in different conditions, as well as more efficient optimization that includes the search for a compromise between the structure, selection of components and the desired exploitation characteristics.

Application of new conceptual solutions for machine tools includes the application of mechanical structures with parallel and hybrid kinematics that may be considered optimal solutions in some machine tools application areas [4].

This paper presents part of the research related to the development and production of desktop machine tools with hybrid kinematics. Presented research phases include the evaluation process of machine tool conceptual design based on the original O-X glide hybrid mechanism. This includes analyses of kinematics and workspace, machine tool modeling for selected components and the design of the control structures based on PC-CNC control. The entire design process as well as workspace and kinematics analyses are realized by application of machine tool virtual prototype in the CAD/CAM system environment *PTC Creo 2*. As a basis for the further control development of the considered machine tool, software EMC2 (*Enhanced Machine Controller*) was selected, which presents a real- time management software for machine tools and robots control, running on PC Linux platform.

2. INITIAL CONCEPT AND STRUCTURE OF O-X MECHANISM

Machine tool with hybrid kinematics, which is discussed in this paper, is based on a hybrid O-X glide mechanism that is obtained by combining planar parallel mechanism, serial axis and support structure [3-6]. Planar parallel mechanism is designed in a way so that the tool on the mobile platform can reach the largest part of the workspace in two configuration mechanisms - extended (O) and crossed (X), enabling it to act as a dual two parallel mechanism with different characteristics in terms of: workspace dimensions, stiffness, speed and the like. This concept increases the machine flexibility providing the basis for the development of a family of reconfigurable machine tools, where it is possible to use one or both of the configuration mechanisms during exploitation.

Figure 1 shows the conceptual design of the machine with hybrid kinematics in an extended (O), Figure 1a, and crossed (X) position, Figure 1b [4, 5]. Further analyzes describe kinematic characteristics and show the virtual prototype, using to some extent modified conceptual design which was adopted as a basis for further phases of research implementation.

Coordinate system of the machine is adopted according to the standard for vertical numerically controlled machine

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tools. Planar parallel mechanism consists of a mobile platform P, which is attached to the rods of constant length via spherical joints. At the other end, by utilizing rotating joints (with one degree of freedom), rods are attached to the respective sliders s_1 and s_2, both of which moving on its own guide. In order to increase the autonomy of the slides 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 mechanism movement in an extended (O) and crossed (X) position. A parallel mechanism enables movements in the (XZ) plane, while the translatory movement of the entire parallel mechanism is realized by a parallel serial axis s_3, on the support structure.

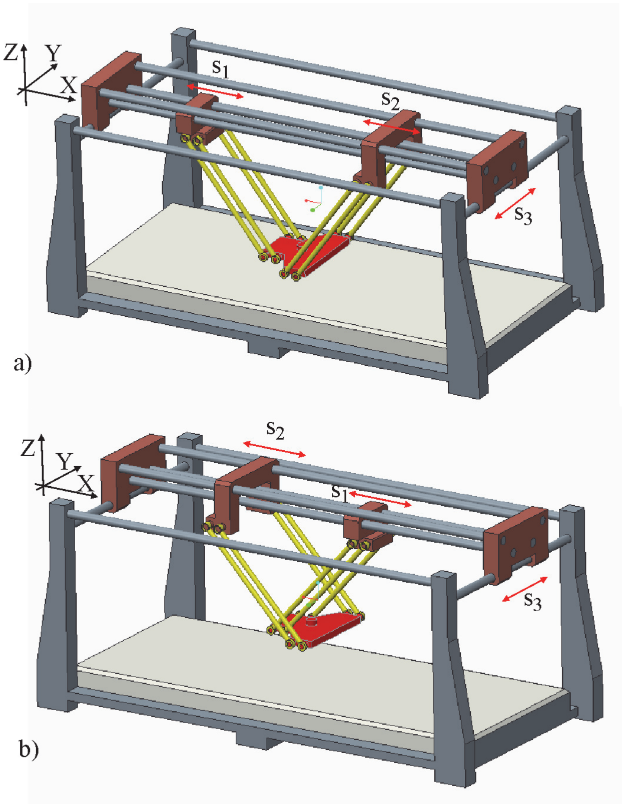

Fig.1. CAD model of the O-X glide mechanism

By starting the sliders s_1, s_2 and s_3, three degrees of freedom of the moving platform (i.e. tool) are provided, so while the platform moves in space it remains parallel to itself, i.e. it maintains a constant orientation of the tool in the working area of the machine. Displacement of the planar parallel mechanism is realized by translational movement of sliders s_1 and s_2, while the third serial degree of freedom is achieved by moving the slider s_3 using its guide on the support structure.

3. KINEMATIC ANALYSIS

In general, the inverse kinematics of parallel mechanisms is pretty simple, while the direct kinematics is often complex. In this case, due to its simple construction, both direct and inverse kinematics of the O-X glide mechanism are simple and analytically solvable. This chapter presents solutions for inverse and direct kinematics for both mechanism forms - extended (O) and crossed (X).

3.1. Inverse Kinematics

The general formula for determining the inverse kinematics of the mechanism is:

$$s_i = f(x_p, y_p, z_p),\ i = 1,2,3 \qquad (1)$$

Hybrid O-X glide mechanism can be considered in two forms, so the analyses for both forms, extended (O), and crossed (X), will be presented next.

CAD model of the machine, presented in Figure 1, can be simplified with a basic wired kinematic model, shown in Figure 2, with the purpose of concrete calculations and obtaining the equivalent kinematic model. Each pair of rods is replaced with one end rod, while platform is replaced with line between selected joints.

Figure 2 shows a planar scheme of the O-X glide mechanism's arbitrary position, the crossed mechanism in this case. Kinematics solving is done in a (X, Z) coordinate system. For a model shown in Figure 2, symbols have the following meanings:

- R1 (0, x_{R1}) and R2 (0, x_{R2}) are reference points of the drive axis,
- P(x_P, z_P) – external coordinates of the mobile platform,
- s_1, s_2 – are the internal coordinates of parallel mechanism's driving axes,
- (X,Z) – is the reference coordinate system of the machine in which all calculations related to the control and programming are performed,
- The parameters of the machine are: the couplings lengths l_1 i l_2, the distance between joints p_1 i p_2.

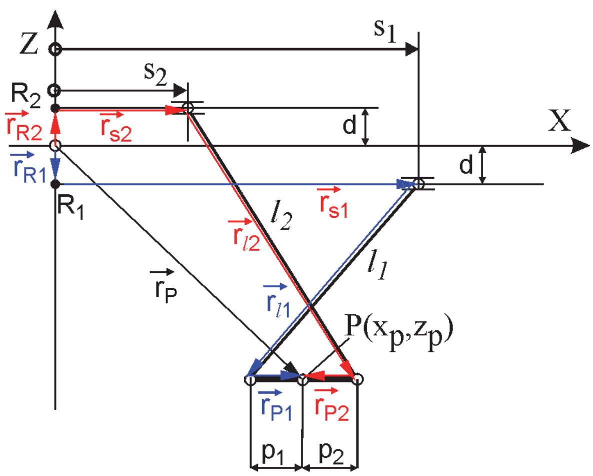

Fig.2. Kinematic model of the O-X glide mechanism

Kinematics mechanism solving can be performed by using vectors, according to Figure 2, after which the inverse, and then direct kinematic problems are solved.

According to Figure 2, the following equations can be written:

$$\begin{aligned} \vec{r}_P &= \vec{r}_{R1} + \vec{r}_{s1} + \vec{r}_{l1} + \vec{r}_{P1} \\ \vec{r}_P &= \vec{r}_{R2} + \vec{r}2_{s2} + \vec{r}_{l2} + \vec{r}_{P2} \end{aligned} \qquad (1)$$

If the known coordinates of the vector are introduced in the equation (1), the following equation can be obtained:

$$\begin{Bmatrix} x_p \\ z_p \end{Bmatrix} = \begin{Bmatrix} o \\ -d \end{Bmatrix} + \begin{Bmatrix} s_1 \\ 0 \end{Bmatrix} + \begin{Bmatrix} l_{1x} \\ l_{1z} \end{Bmatrix} + \begin{Bmatrix} p_1 \\ 0 \end{Bmatrix}$$
$$\begin{Bmatrix} x_p \\ z_p \end{Bmatrix} = \begin{Bmatrix} o \\ d \end{Bmatrix} + \begin{Bmatrix} s_2 \\ 0 \end{Bmatrix} + \begin{Bmatrix} l_{2x} \\ l_{2z} \end{Bmatrix} + \begin{Bmatrix} -p_2 \\ 0 \end{Bmatrix} \tag{2}$$

These equations can now be written as:

$$l_{1x} = x_p - s_1 - p_1$$
$$l_{1z} = z_p + d \tag{3}$$

$$l_{2z} = x_p - s_2 + p_2$$
$$l_{2z} = z_p - d \tag{4}$$

Knowing that $l_{1x}^2 + l_{1z}^2 = l_1^2$, both sides of the equation (3) are first squared and then added together. Since $l_{2x}^2 + l_{2z}^2 = l_2^2$, the same principle can be applied to equations (4). After the transformations are complete, the system of equations is obtained:

$$l_1^2 = (x_p - s_1 - p_1)^2 + (z_p + d)^2 \tag{5}$$

$$l_2^2 = (x_p - s_2 + p_2)^2 + (z_p - d)^2 \tag{6}$$

From equations (5) and (6) solutions of the inverse kinematic problem are obtained for both forms of the O-X glide mechanism, as follows:

- for the crossed form of the O-X glide mechanism:

$$s_1 = x_p - p_1 + \sqrt{l_1^2 - (z_p + d)^2} \tag{7}$$

$$s_2 = x_p + p_2 - \sqrt{l_2^2 - (z_p - d)^2} \tag{8}$$

- for the extended form of the O-X glide mechanism:

$$s_1 = x_p - p_1 - \sqrt{l_1^2 - (z_p + d)^2} \tag{9}$$

$$s_2 = x_p + p_2 + \sqrt{l_2^2 - (z_p - d)^2} \tag{10}$$

3.2. Direct Kinematics

The general expression for determining the direct kinematic mechanism can be written as:

$$P(x_p, y_p, z_p) = f(s_1, s_2, s_3) \tag{11}$$

Analytical solutions of the direct kinematics for both forms of the mechanism are determined starting with equations (5) and (6).
Subtracting equation (6) from the equation (5), and after rearrangement, a linear equation solvable by one variable is obtained:

$$2x_p m_1 + 4z_p d + m_2 = 0 \tag{12}$$

where modifications are introduced:

$$m_1 = s_2 - s_1 - p_1 - p_2,$$
$$m_2 = (s_1 + p_1)^2 - (s_2 - p_2)^2 - l_1^2 + l_2^2.$$

Solution for the equation (12) is first generated for external coordinate x_p as:

$$x_p = m_3 + m_4 \cdot z_p \tag{13}$$

where modifications are introduced:

$$m_3 = -\frac{m_2}{2m_1} \text{ i } m_4 = -\frac{2d}{m_1}.$$

Solution for a second external coordinates z_p is performed by replacing the solutions for x_p from the equation (13) to the equation (7) resulting with the quadratic equation solvable by z_p:

$$m_5 z_p^2 + m_6 z_p + m_7 = 0 \tag{14}$$

where modifications are introduced:

$m_5 = 1 + m_4^2$, $m_6 = 2d - 2m_4(s_1 + p_1 - m_3)$ and
$m_7 = (s_1 + p_1 - m_3)^2 + d^2 - l_1^2$

The final solution for the direct kinematic problem can be written as:

$$z_p = \frac{-m_6 - \sqrt{m_6^2 - 4m_5 m_7}}{2m_5}$$
$$x_p = m_3 + m_4 \cdot z_p \tag{15}$$

A demonstration calculation is made for the shown solutions, which confirmed the mutual coincidence of inverse and direct kinematic problem.

4. WORKSPACE ANALYSIS

Workspace of the hybrid O-X glide mechanism represents a certain volume of all the possible positions of point P on the mobile platform. For the workspace analysis, it is sufficient to analyze the workspace of a planar parallel mechanism, because the total workspace which is available to the mobile platform, i.e., the tool of the hybrid mechanism can be obtained by its translation along the Y axis. Workspace of the planar parallel mechanism can be determined geometrically and analytically based on inverse or direct kinematics, for which the analytical expressions are given in Chapter 3.
Figure 3 shows an example of the analytically obtained workspace of a parallel mechanism for crossed form in the plane, using the inverse kinematics solutions and boundary conditions criteria, such as the drive axis strokes and the length of the rods. The parameters of the mechanism in this example are as follows: l_1=302, l_2=432, p=120, p1=55, p2=65, p1+p2=p, d=74, s_{1min}=0, s_{1max}=500, s_{2min}=0 i s_{2max}=500 [mm].
Figure 4 shows a combined display of the workspace and wire model of the mechanism in the position P($x_p = 250,\ z_p = -300$). In the presented workspace, a limited segments of the workspace of rectangular shape can be inscribed, which can be planned for processing

workpieces of different dimensions and heights. Knowing the exact position of these limited workspace segments is very important when setting and basing workpieces during machining.

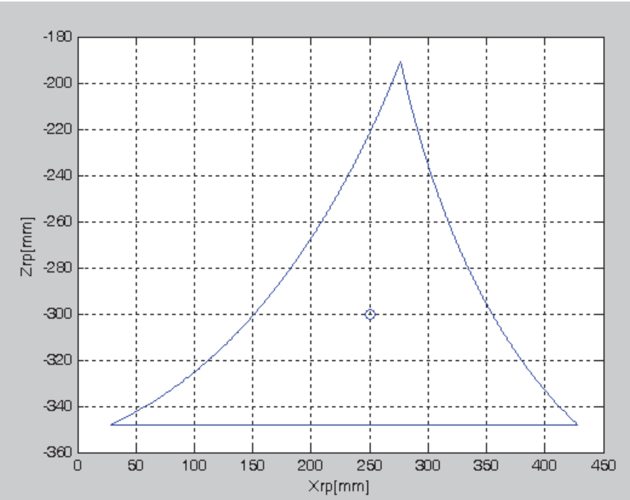

Fig.3. Workspace of the crossed mechanism

The final shape of the workspace is the result of the mechanism concept, and its dimensions can subsequently be customized by using the mechanism parameters. Planning of the mechanism parameters optimization can also be performed in order to increase the dimensions of usable workspace and improve its shape.

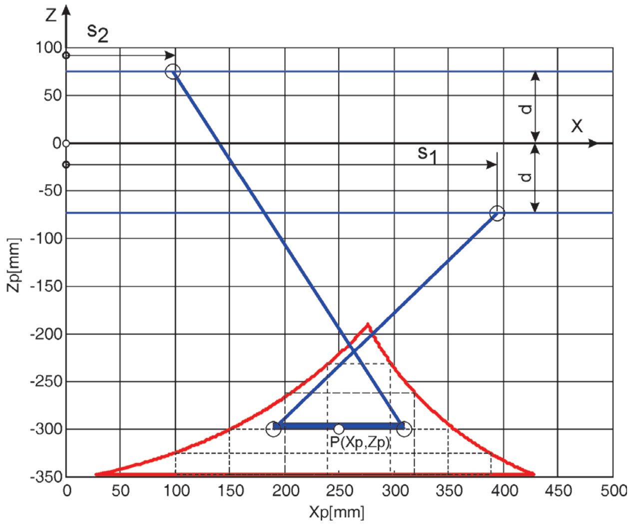

Fig.4. Workspace for the crossed form of the mechanism with marked limitations of the workspace

5. VIRTUAL PROTOTYPE DESIGN

The conceptual analysis of the considered O-X glide hybrid mechanism enables selection of the standard components and the establishment of a modular system, in order to complete a parallel mechanism as well as the entire hybrid kinematics machine. Figure 5 shows a modular system of components, which includes the translational drive axes, bearing plates on the sliders for

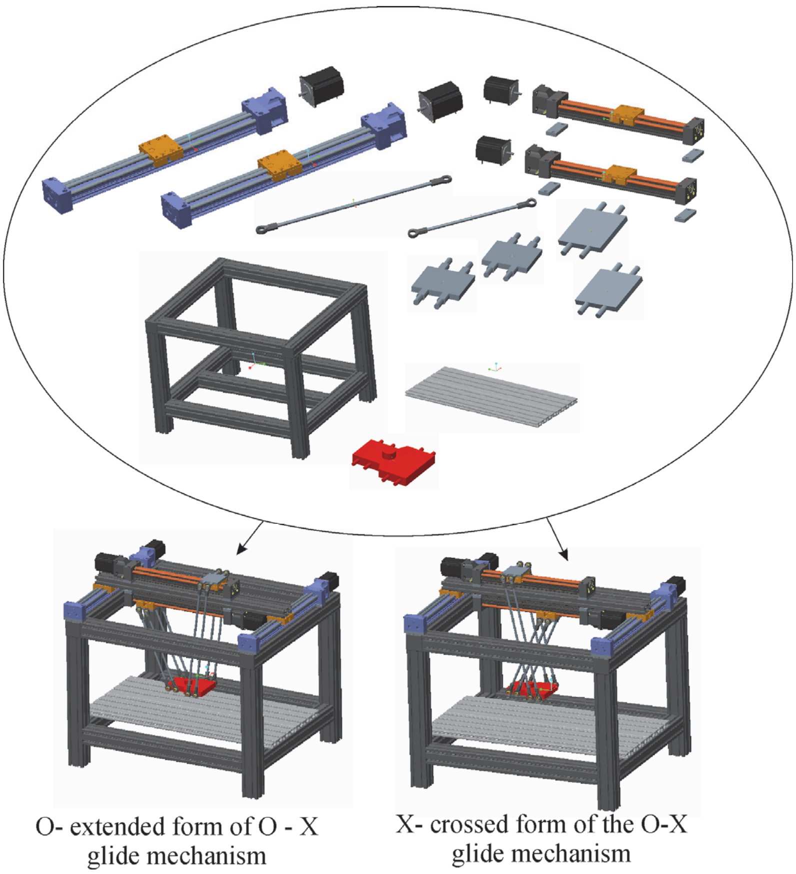

Fig.5. Virtual prototype of extended and crossed form of the O-X glide mechanism

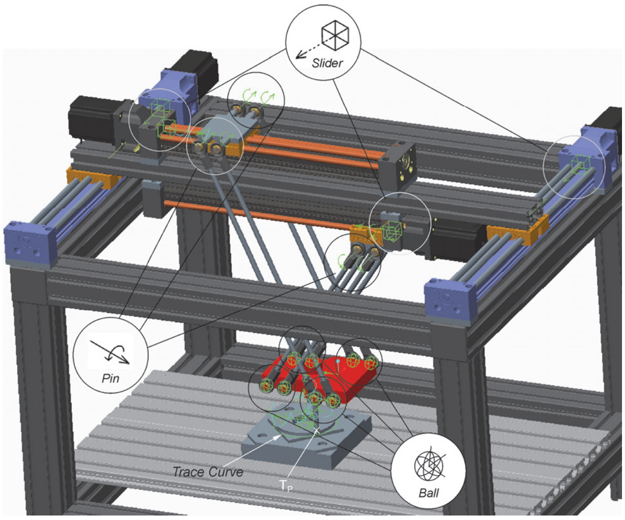

Fig.6. CAD model for the simulation of O-X glide mechanism kinematics [6]

connection with swivel joints, rods, platform, support structure and a work table. By mounting the appropriate module, a virtual prototype can be obtained, which can be, without physical intervention, reconfigured into both considered conceptions of hybrid machine tool based on the O-X glide mechanism, extended and crossed forms.

The resulting virtual prototypes are also used to simulate the kinematics of hybrid O-X glide mechanism [5 - 7]. Simulation of the kinematics of the applied mechanism of the machine tool includes hybrid mechanism modeling with all kinematic connections between components, which enables the possibility of virtual prototype elements movements as a rigid body system, Figure 6. Examples of such simulations can also be found in the literature [4-8].

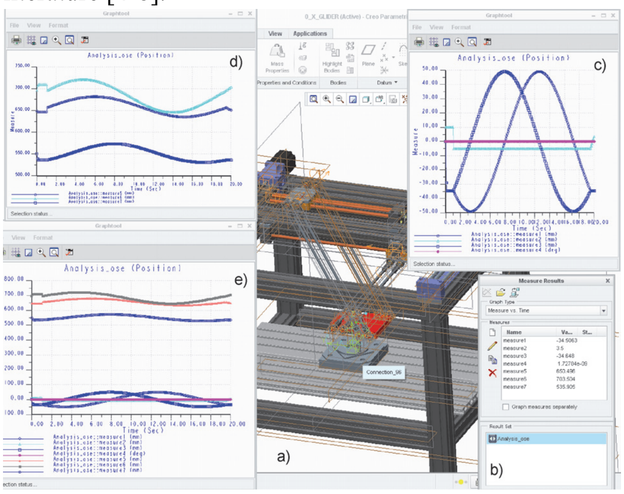

Fig.7. Some results of simulation of O-X glide mechanism kinematics [6]

Simulation of the kinematics mechanism is an option offered by CAD/CAM/CAE systems and for this occasion PTC Creo 2 was selected [10], and its *Mechanism* module. In this way it is possible to realize the movement simulation, by using linear and circular interpolation, as well as create holes and/or openings. In addition to the movement, simulation results can be monitored by using graphics of the desired dependencies. Part of these results for the case of circular interpolation is shown in Figure 7. The mechanism with defined kinematic connections, drives and workpiece is shown in Figure 7a. For the displayed example, tool tip movement drives are defined along circular interpolation for final machining of the cylindrical part of the workpiece. After the simulation is performed, various reports can be created (*Measure Results*) Figure 7b.

Figure 7c shows changes of coordinates X, Y and Z as a function of time for the movement of the programmed tool tip point; dependency of the drive translational axis changes for the realization of circular interpolation is shown in Figure 7d; single diagram presenting a joint view of both previous dependencies as a function of time can be seen in Figure 7e.

Machining simulation plays an important role in a modern production process, both in the development of machines for virtual prototypes testing, as well as during the real machine exploitation for machining program verification.

6. CONTROL AND PROGRAMMING SYSTEM

Configuration management is a separate research task for each machine tool. Small project budget in local conditions implies that such a project can only be carried out using own resources. For control of machine tools with hybrid kinematics, it is suitable to choose available open architecture software, which allows free configuration management, according to the desired kinematics. For machines with parallel and hybrid kinematics, it is necessary to implement inverse and direct kinematics control solutions. As such software, *Enhanced Machine Controller - EMC2* [11] was selected, which is a real-time software for the management of machine tools and robots, whose code can be used, modified and distributed freely (*GNU General Public License*). *EMC2* allows machine programming by functions covered by the ISO 6983 standard. The basis of the program system was developed by the National Institute of Standards and Technology (NIST) [12].

Figure 8 shows the internal software structure of the *EMC* [11, 13], which contains four basic software modules: motion controller (*EMCMOT*), discrete input/output controller (*EMCIO*), processes controller for coordination (*EMCTASK*) and a collection of text or graphic user inerfaces (GUI), Figure 9.

EMCTASK (Task coordinating module) distributes commands in the machine. It performs interpretation of the program, G code, all according to ISO6983 standard, as well as RS 274 NGC standard.

EMCIO (Discrete I/O Controller) performs all communications that are not related to motion control. It has subordinate modules for the main spindle, tool change, auxiliary M functions, ALL STOP, lubrication, etc.

EMCMOT (Motion Controller) is a module that runs periodically in real time and performs path planning, calculations related to inverse and direct kinematics and generates control signals for the drives of the machine. It performs feedback loop closure, generates subsequent positions, interpolates path between programmed positions, controls border positions and axes' reference positions etc.

The modular structure of the EMC2 has contributed to its flexibility in the applications on machines with complex kinematics, as well as in its connection with various hardware and software add-ons. This is possible primarily due to HAL (Hardware Abstraction Layer). HAL was conceived as a flexible interface between the movement controllers on one side and as an interface for connection between the user and the machine on the other side. This also implies the multitude of hardware machines interfaces which provide motion controller interface with actuators and measuring systems.

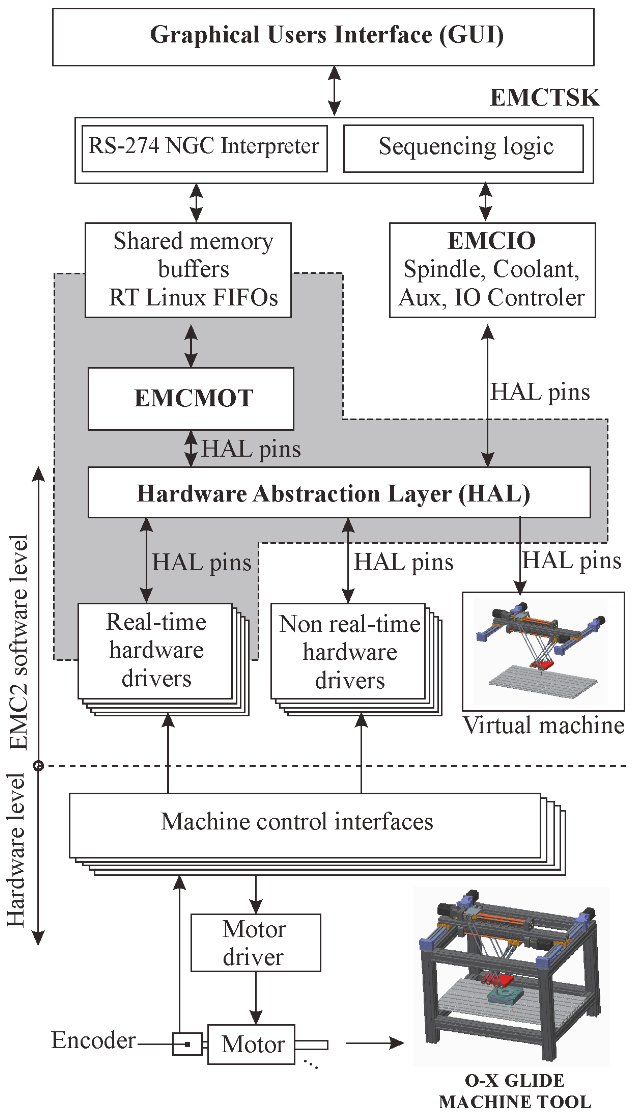

Fig.8. Control system based on EMC2

GUI (Graphical user interface) is an external program which communicates with EMC by sending commands such as: machine turn on, switch to automatic mode, start the program, machine shut down. GUI can also send manual messages, initiated by the operator, such as: moving machines axes in manual mode (JOG) or sending all axes in a reference position. Different GUI can be used, while Axis is the most commonly used user interface, shown in Figure 9 with the loaded program for finishing of test workpiece, which was analyzed during the simulation. This environment is very intuitive with recognizable icons that facilitate the operator's work. In addition, the convenience of the Axis environment is the possibility of integration with the virtual machine.

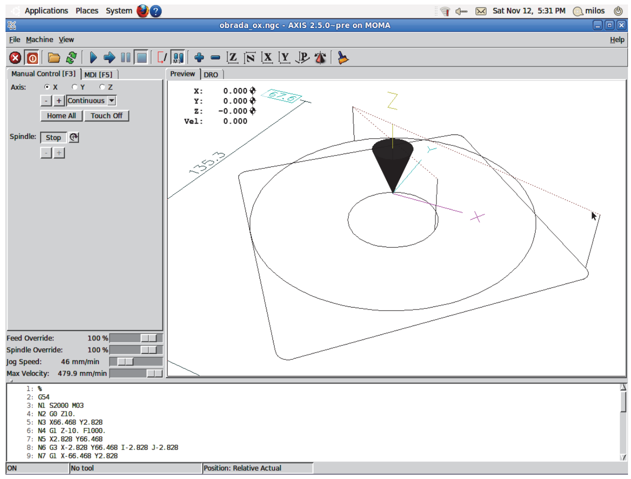

Fig.9. Display of Axis GUI control system based on EMC2

To control the machine with hybrid kinematics, it is necessary to make changes to the core of the EMC2 program system. These changes relate to the replacement of the usual standard trivial functions of inverse and direct kinematics by corresponding inverse and direct kinematics functions for, in this case, a hybrid kinematics machine based on O-X glide mechanism. This includes programming of inverse and direct kinematics functions using C programming language utilizing the appropriate user file for kinematics and the inclusion of this file into EMC2, in the module EMCMOT. While integrating the control model, machine parameters are also defined as well as reference positions of all axes, and then the compiling and software linking are realized.

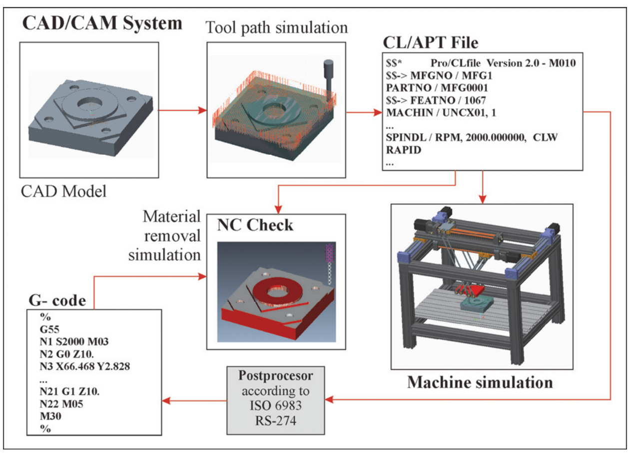

Fig.10. The structure of programming system based on CAD/CAM system

Resources that are utilized for machine tools with serial kinematics programming are selected. Post-processing is performed as for a single vertical three-axes milling machine. An illustration of the programming system by using CAD/CAM system PTC Creo 2.0 [10] is shown in Figure 10. This figure shows the programming environment for the particular case of the machine simulation according to the running program for processing of the test workpiece in order to test the working accuracy of machine tool [14]. Programming environment can represent arbitrary CAD/CAM system or any software that enables manual programming. For program verification, tool path simulation is used, as well as simulation of material removal (NC Check) and operation simulation of the complete virtual prototype of the machine tool which is realized in the machine regime according to the running program.

7. DISCUSSION AND CONCLUSION

The results of the research described in this paper can be viewed from several perspectives: the feasibility of the virtual prototype technology, possibility of application of the machine tool O-X-glide mechanism and the feasibility of low cost control structures which include EMC2 in machine tools having such mechanical structures.

The virtual prototype is developed on the basis of functional, kinematicaly movable model of machine tool with physical characteristics interepretation of all components. This included the machine tool design as a product from the initial sketch to definition of all static and kinematicaly active components (Top-Down Design). Based on this, detailed workspace analyzes and kinematic characteristics of all moving elements based on direct and inverse kinematics mechanism were carried out. Before the realization of physical prototypes, optimization of some of the key parameters of the machine tool mechanism is planned.

Research results showed that the hybrid mechanism, which presents the base of machine tool, proved to be a viable alternative to the serial-designed mechanical structures in the workpieces processing of prismatic forms of less height.

The adopted concept of control structure, which is based on PC-CNC control and real time operating system, has a significant potential in the development of machine tools of complex kinematic structures in systems that require increased flexibility and reconfigurability [15, 16].

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