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Invited paper

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THE APPLICATION OF VIRTUAL PROTOTYPE IN DESIGN OF A HYBRID MECHANISM BASED MACHINE TOOLS

Abstract: *Designing of products by using of virtual prototypes in modern conditions allows much faster and cheaper selection of elements and optimisation of construction.*
The paper presents the application of virtual prototype of manufacturing capabilities verification process in case of machine tools with kinematic structure which is based on O-X hybrid mechanism.
Key words: *Virtual prototype, hybrid mechanism, CNC*

1. INTRODUCTION

Development of a product with a large number of moving elements, before building of physical prototype, involves various types of analysis of exploitation conditions in the goal of verification and optimisation of conceptual design.

Machine tools with a large number moving components and exploitation in different conditions is a typical representative of this group of products. A key role in the choice of components, in process of its development, has an analysis of the working of machine tools in the operating conditions.

Developing of a virtual prototype using DMU (Digital Mock Up) concept is more often replacing physical prototype and allows the combination of CAD and CAE technology to optimize product [1]. Usage of DMU technology in optimization allows analysis of kinematic parameters through collision detection and singularities in mechanism work and analysis of the workpiece machining borders before making a physical prototype.

This paper describes a part of the research of patented O-X mechanism usage possibilities [2], [3] as a base for machine tools through the analysis of machining characteristic capabilities forms on the workpiece by using DMU technology.

2. CHARACTERISTICS OF THE O-X MECHANISM

The base of virtual prototype is hybrid O-X glide mechanism composed of planar parallel kinematic mechanism and support structure that enables translational movement (Fig. 1). [3]

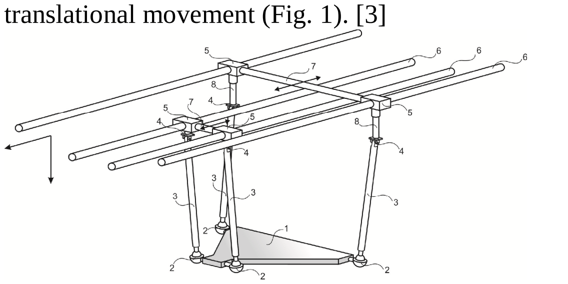

Fig. 1. Planar parallel mechanism

Figure presents planar parallel mechanism whose base is movable platform (1), connected with four struts (3) using spherical joints. Struts are at the other end attached to the sliders (5) over the joints with one rotary degree of freedom (4). Each of sliders can move at own guide (6). Sliders are grouped into pairs that are connected with rigid connection (7) thus providing their same speed and acceleration. In order to increase the autonomy movement of the slider, they are positioned at different distances in the direction of the vertical axis, which allows their passing in the plane, and the duality of movement of the mechanism. That are the movement in the extended (O) and the crossed (X) position. Compensation of differences in the distances between the slider and moving platforms is performed by introducing vertical compensating elements (8), at higher sliders.

Primary specificity of O-X glide mechanism makes the duality of its structure in a plane element. This enables it to work in extended and crossed form. Except this, dimensions of the workspace are larger than similar mechanisms, because of hybrid structure.

The geometric model of parallel mechanism (Fig. 2), which is base of a hybrid O-X glide mechanism, can be presented in a simpler form using of a parallelogram A’B’C’D, which is connected with constant length struts. At the other end the struts are connected with sliders AB and CD, moving on horizontal guides (D’’D, A’’A, B’’B, C’’C).

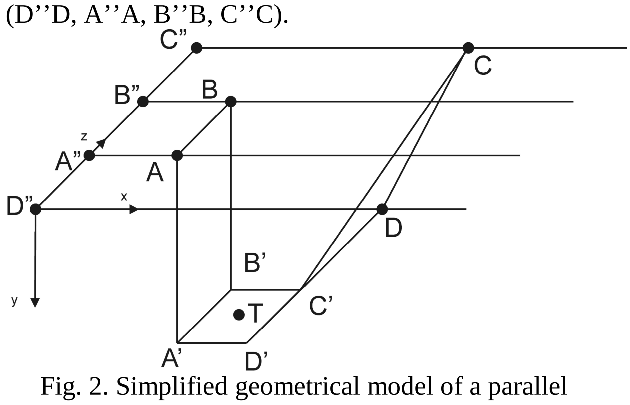

Fig. 2. Simplified geometrical model of a parallel mechanism

Based on the this, we can write vector equations of parallel mechanism

$$\overrightarrow{OD} + \overrightarrow{DD'} = \overrightarrow{TD'} + \overrightarrow{OT'}$$
$$\overrightarrow{OA''} + \overrightarrow{A''A} + \overrightarrow{AA'} = \overrightarrow{OT} + \overrightarrow{TA'}$$
$$\overrightarrow{OB''} + \overrightarrow{B''B} + \overrightarrow{BB'} = \overrightarrow{OT} + \overrightarrow{TB'}$$
$$\overrightarrow{OC''} + \overrightarrow{C''C} + \overrightarrow{CC'} = \overrightarrow{OT} + \overrightarrow{TC'}$$

Assuming that:

$$\overrightarrow{OD''} = \vec{0}; \qquad \overrightarrow{OA''} = \begin{pmatrix} 0 \\ 0 \\ a \end{pmatrix}; \qquad \overrightarrow{OB''} = \begin{pmatrix} 0 \\ 0 \\ 2a \end{pmatrix};$$
$$\overrightarrow{OC''} = \begin{pmatrix} 0 \\ 0 \\ 3a \end{pmatrix}.$$

Where is

a –distance between horizontal sliders

In addition, the structure of the planar mechanism imposes certain restrictions:

$$\overrightarrow{A''A} = \overrightarrow{B''B}$$
$$\overrightarrow{C''C} = \overrightarrow{D''D}$$

3. KINEMATIC ANALYSIS OF THE O-X GLIDE MECHANISM

3.1 Inverse kinematics

The general expression for inverse kinematic chain is:

$$\boldsymbol{P_{A,B,C,D} = f(x_T, y_T, z_T)}$$

Because of the O-X glide mechanism kinematic analysis is carried out in two configurations.

3.1.1 Extended form

Fig. 3 presents planar projection of extended form of the O-X glide mechanism for which is carried out the inverse kinematic analysis

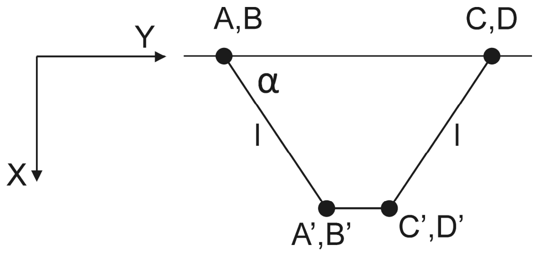

Fig. 3. Planar projection of extended form of O - X glide mechanism

The position of points A and B, can be expressed as follows:

$$x_{A,B} = x_T - \frac{s}{2} - l\cos\alpha = x_T - \frac{s}{2} - l\sqrt{1 - \left(\frac{y_T}{l}\right)^2},$$
$$x_{A,B} = x_T - \frac{s}{2} - \sqrt{l^2 - {y_T}^2}.$$

The position of the points C and D in the same manner can be expressed as:

$$x_{C,D} = l\cos\alpha + \frac{s}{2} + x_T = l\sqrt{1 - \left(\frac{y_T}{l}\right)^2} + \frac{s}{2} + x_T,$$
$$x_{C,D} = \sqrt{l^2 - {y_T}^2} + \frac{s}{2} + x_T.$$

Where are:

l- lenght of struts

s – width of mobile platform

a – distance between horizontal guides

α – angle between the struts and horisontal guides

3.1.2 Crossed form

Fig. 4 presents planar projection of crossed form of the O-X mechanism and his inverse kinematic analysis.

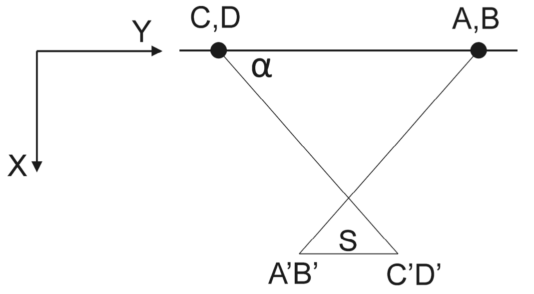

Fig. 4. Planar projection of crossed form of the O-X mechanism

Position of the points A, B, C and D can be expressed as follows:

$$x_{A,B} = x_T - \frac{s}{2} + l\cos\alpha = x_T - \frac{s}{2} + l\sqrt{1 - \left(\frac{y_T}{l}\right)^2},$$
$$x_{A,B} = x_T - \frac{s}{2} + \sqrt{l^2 - {y_T}^2};$$

$$x_{C,D} = \frac{s}{2} + x_T - l\cos\alpha = \frac{s}{2} + x_T - l\sqrt{1 - \left(\frac{y_T}{l}\right)^2},$$
$$x_{C,D} = \frac{s}{2} + x_T - \sqrt{l^2 - {y_T}^2}..$$

3.2 Direct kinematic

Direct kinematic chain can be expressed as follows:

$$\boldsymbol{P_T = f(x_A, x_B, x_C, x_D)}$$

Generally, the inverse kinematics of parallel mechanisms is quite simple, while direct kinematics often very complex. However, because of simple construction in the case of the O-X glide mechanism direct and inverse kinematics are very simple.

3.2.1 Extended form

Direct kinematics analysis of extended form of the O-X mechanism (Figure 4), explains position of the point T depending on the position of points A, B, C and D can be represented as follows:

$$\begin{pmatrix} 0 \\ 0 \\ a \end{pmatrix} + \begin{pmatrix} x_A \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} l\cos\alpha \\ l\sin\alpha \\ 0 \end{pmatrix} = \begin{pmatrix} TA'_x \\ TA'_y \\ TA'_z \end{pmatrix} + \begin{pmatrix} x_T \\ y_T \\ z_T \end{pmatrix}.$$

3.2.2 Crossed form

Similarly as in the previous case, the position of the point T on the movable platform for crossed form of the O-X glide mechanism (Figure 5) can be represented as follows:

$$\begin{pmatrix} 0 \\ 0 \\ a \end{pmatrix} + \begin{pmatrix} x_A \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} -l\cos\alpha \\ l\sin\alpha \\ 0 \end{pmatrix} = \begin{pmatrix} TA'_x \\ TA'_y \\ TA'_z \end{pmatrix} + \begin{pmatrix} x_T \\ y_T \\ z_T \end{pmatrix}.$$

4. STRUCTURE OF THE VIRTUAL PROTOTYPE

The final version of the virtual prototype differs from the concept caused by the physical dimensions of the elements of the prototype. In the final version changes in elements such as the position of the slider, length of the struts and the like are introduced. Figure 5 presents adopted solution of the virtual prototype of the hybrid mechanism.

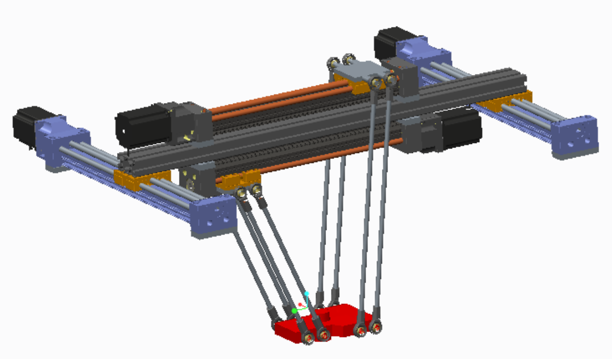

Fig. 5. Virtual prototype of the hybrid mechanism

The virtual prototype which is defined in this way has been subjected to tests that include analysis of capabilities of machining geometric shapes characteristic for the milling. For simulations workpiece with shape based on the NCG recommendations is used.

5. SIMULATION OF MACHINING

Machine simulation by running the program is possible due to the applied modelling of the O-X glide parallel mechanism with all kinematic connections between the components, which allows the motion of a virtual model as a system of rigid bodies.

Fig. 6 shows a detailed virtual prototype of O-X glide parallel mechanism with all kinematic relationships.

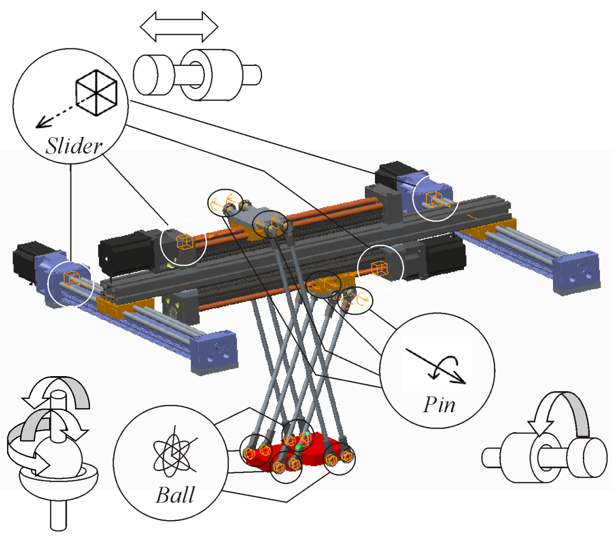

Fig. 6. CAD model for the simulation of parallel mechanism kinematics

This assembly enables the motion of models in the range defined for each connection, which is of particular importance for the identification of possible collisions during the work of the parallel mechanism.

Machining simulation of the virtual prototype allows the motion of movable segments with a tool at the end. The tool path is a result of the execution program obtained by programming using the CAD/CAM system PTC Creo 2.

For the test, a scaled ISO test workpiece whose dimensions are 150×150×40mm is used. Because of the particular shape and size of the workspace of parallel kinematics machines, attention should be paid when setting up a workpiece, which must be within the limits of the workspace of the machine. For the test workpiece shown in Fig. 7, the zero point in the middle of the underside of the workpiece has been adopted, with the coordinate axes *x*, *y*, *z* as has been used in the vertical 3-axis milling machine, marked as MACH_ZERO. The identical zero point exists on the machine (on the working table) on which the workpiece is placed, Fig. 7. Matching these two coordinate systems is accomplished by setting the workpiece on the machine during the machining simulation. Fig. 7 also presents the simulated tool path on the scaled ISO test workpiece, based on the generated CL file. The tool coordinate system is defined in the same way as the workpiece coordinate system and marked as a TOOL_POINT.

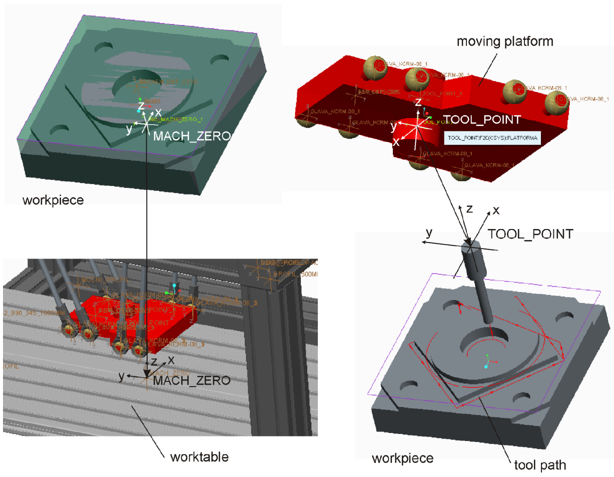

Fig. 7. Coordinate system of the workpiece and tool with tool path simulation

During the simulation of tool paths, a complete prototype of the virtual machine can be included into the simulation, with a machine play option. An example of machine simulation for O-X glide virtual prototype is shown in Fig. 8 for an ISO test workpiece.

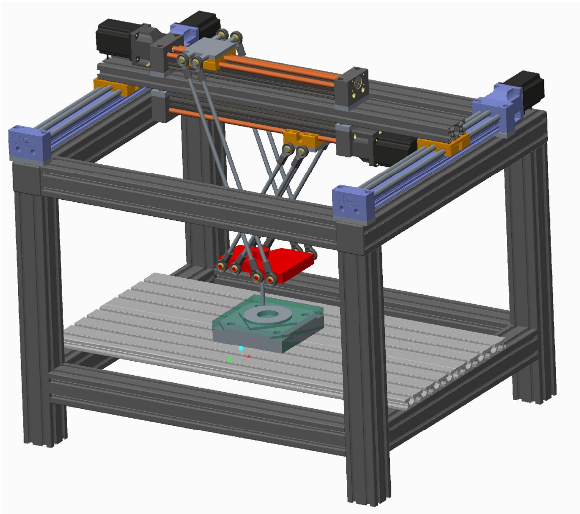

Fig. 8. Machining simulation in the CAD/CAM system

6. RESULTS

Tested workpiece is based on the test workpieces for analyzing of the accuracy of machine tools with numerical control with a three-axis. They could be produced by four characteristic sequence of machining in which had been combined all movements which are expected in the structure of modern machine tools (linear and circular). The dimensions of the workpiece are selected based on the maximum dimensions of the workspace of a parallel mechanism. Results are presented in table 1.

No	Type of moving of the tools/ platform	Successfully completed
1	Face milling, linear movement	■
2	Profile milling, linear movement	■
3	Profile milling, circular movement ϕ50	■
	Profile milling, circular movement ϕ250	■
4	Combined milling, linear movement	■
5	Combined milling, circular movement ϕ50	■
6	Combined milling, circular movement ϕ250	■
7	Hole machining	■

Tab. 1 Successfulness of machining on virtual machine tool

7. DISCUSION AND CONCLUSIONS

Conducted research indicates that the virtual prototypes methods application might decrease machine tools development time especially the time needed for the selection of machine components. In addition, analysis of kinematic and dynamic motion parameters and machining capabilities indicate problems that may occur during the machining of pre-defined shapes. This provides a wide range of possibilities during the design of special type of machines [4] [5].

Present stage of the research identified a number of disadvantages of the initial configuration of machines such as the length and position of the slider struts. All of them were corrected and formed functional virtual prototype. Currently the project is in final stages of building of the physical prototype.

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