MINI EDUCATIONAL 3-AXIS PARALLEL KINEMATIC MILLING MACHINE

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ABSTRACT

Parallel kinematic machines (PKM) are still R&D topic in many laboratories although many of them unfortunately, have no PKM at all. Therefore the use of a low cost mini educational 3-axis parallel kinematic milling machine is suggested as a help in the process of acquiring basic experiences in the field of PKM. The developed mini educational 3-axis parallel kinematic milling machine is based on a newly developed 3-DOF spatial parallel mechanism. This paper describes the structure of machine, modelling approach, and control and programming system based on PC Linux platform.

KEYWORDS: Parallel mechanism, Modelling, Milling Machine

1. INTRODUCTION

Compared with conventional machine tools, PKM have many advantages, e.g. higher stiffness and higher ratio of force – to – weight. This is regarded as a revolutionary concept for machine tools. Many research works about diverse aspects of PKM have been published but they are still R&D topic in many laboratories. Today, unfortunately, the great majority of research institutes, university laboratories and companies have no PKM. The reason, obviously, is the high cost of education and training for a new technology, such as PKM.

In order to contribute to acquiring practical experiences in modelling, design, control, programming and the use of PKM, functional simulator of parallel kinematic milling machine has been first developed /1/ and then a low-cost mini educational 3-axis parallel kinematic milling machine is suggested. The developed mini educational 3-axis parallel kinematic milling machine is based on a newly developed 3-DOF spatial parallel mechanism. This mechanism was first used for successful development of experimental vertical milling machine prototype described in detail in /2,3/. On the basis of several-years' experience in developing vertical milling machine prototype, we arrived at the conclusion that based on the same mechanism a low-cost mini educational 3-axis parallel kinematic milling machine can be developed as a help in the process of acquiring basic experiences in the field of PKM.

The paper describes the structure of mechanism, modelling approach, developed experimental prototype of mini educational 3-axis parallel kinematic milling machine, and control and programming system based on PC Linux platform.

2. MECHANISM STRUCTURE END CHARACTERISTICS

It is well known that the shape and volume of the workspace are one of the greatest weaknesses of parallel kinematic machine tools. Hexaglide and Triaglide mechanisms are examples where workspace extension is achieved by elongating one axis as a principal motion axis that is a common feature of all Cartesian machines. With the idea of principal axis of motion in mind, a new 3-DOF spatial parallel mechanism for horizontal and vertical milling machines has been developed, Figure 1. As shown in Figure 1, the mechanism consists of the mobile platform,

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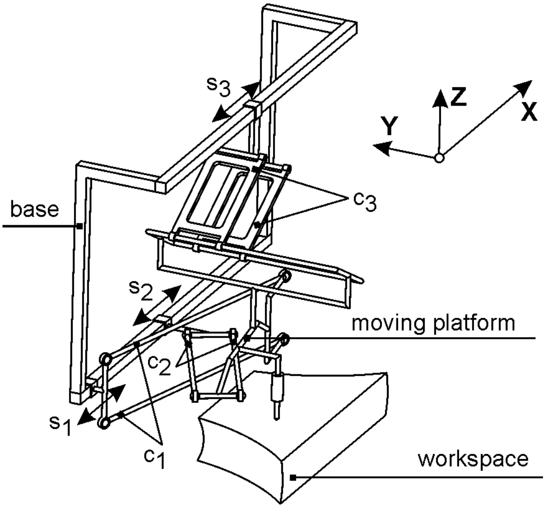

Figure 1: Mechanism's model

three joint parallelograms c_1, c_2 and c_3, and a stationary base with two parallel guideways. Two crossed parallelograms c_1 and c_2, with spherical and/or universal, i.e., cardan joints, are connected with one of their ends to the mobile platform, and with their other ends to the independent sliders s_1 and s_2 which, with a common guideway, make two powered and controlled translatory joints.

The third joint parallelogram c_3 is connected with one of its ends, through passive translatory-rotating joints with 2- DOF, to the mobile platform. Its other end is connected with rotating joints to the slider s_3, which makes, with the second guideway, the third powered and controlled translatory joint. The actuation of sliders s_1, s_2 and s_3 offers three degrees of freedom to the mobile latform, i.e., the tool, so that the platform in its motion through the space retains constant orientation.

The influence of mechanism's structure on geometrical workspace characteristics is reflected in the following:

- The paralelism of guideways provides:
  - Arbitrary workspace length in X direction, and
  - Regular workspace shape on its boundaries in Y direction i.e., Y_{min}=constant and Y_{max}=constant.
- Passive translatory DOF or joint in Y direction provides:
  - Decoupling of platform motions in Z and Y directions, and
  - Exceptional workspace regularity with Z_{min}=constant and Z_{max}=constant on its borders for each of $Y_{min} \leq Y \leq Y_{max}$.
- The crossing of joint parallelograms c_1 and c_2 provides:
  - Decreasing of guideway lengths for the same X dimension of workspace, and
  - Smaller curvature at X_{min} and X_{max} workspace borders.

In comparison with similar developed mechanisms it has several advantages such as: rather regular shape of the workspace (slightly modified block) similar to serial machines; greater stiffness by nature of struts arrangement; good force and speed ratio through the entire mechanism's workspace.

The variance of mechanism's structure and design solutions enables a wide range of application for vertical and horizontal 3-axis milling machines, as described in /2,3/ where first developed vertical milling machines prototype has been presented.

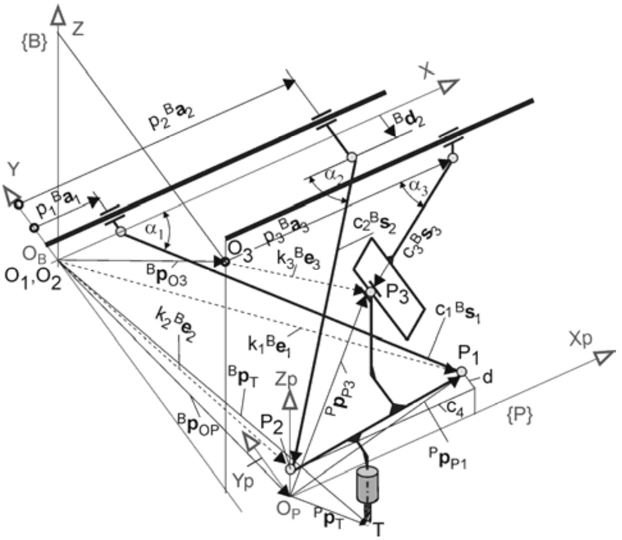

Figure 2: Geometric model of the mechanism.

3. MECHANISM MODELING

Figure 2 represents a geometric model of the mechanism from from Figure 1, where each parallelogram is represented as a unique rod. Coordinate frames $\{B\}$ and $\{P\}$, attached to the base and mobile platform are always mutually parallel due to the mechanism's nature. Vectors **v** referenced in frames $\{B\}$ and $\{P\}$ are denoted by $^B\mathbf{v}$ and $^P\mathbf{v}$.

Vectors defined by the machine's parameters:

- The position vectors of the midpoints P_i, i=1,2,3 between joint centers at the mobile platform are defined in the frame $\{P\}$, as $^P\mathbf{p}_{pi}$, where , $^P\mathbf{p}_{p1} = [c_4\ d\ z_{p2}]^T$, $^P\mathbf{p}_{p2} = [0\ \ 0\ \ z_{p2}]^T$, $^P\mathbf{p}_{p3} = [x_{p3}\ y_{p3}\ z_{p3}]^T$.
- The position vector of the tool tip is defined in the frame $\{P\}$ as $^P\mathbf{p}_T=[x_{TP}\ y_{TP}\ z_{TP}]^T$.
- The position vectors of driving axes reference points O_i and the position vectors of the midpoints of joint centers on the sliders are defined in the coordinate frame $\{B\}$ as $^B\mathbf{p}_{0i}$ and $^B\mathbf{d}_i$ where $^B\mathbf{p}_{01}={}^B\mathbf{p}_{02}=0$, $^B\mathbf{p}_{03} = [0\ \ y_{03}\ z_{03}]^T$, $^B\mathbf{d}_1={}^B\mathbf{d}_3= [0\ \ 0\ 0]^T$ and $^B\mathbf{d}_2 = [0\ \ -d\ \ 0]^T$.

Joint coordinates vector:

- $\mathbf{p}=[p_1\ \ p_2\ \ p_3]^T$, where p_i, i=1,2,3 are scalar variables controlled by actuators while $^B\mathbf{a}_i=[1\ 0\ 0]^T$, are unit vectors.

World coordinates vector:

- $^B\mathbf{p}_T = [x_T\ \ y_T\ \ z_T]^T = \mathbf{x}$ represents the position vector of the tool tip, while $^B\mathbf{p}_{OP} = [x_p\ \ y_p\ \ z_p]^T$ represents location of the platform i.e., origin O_P of the coordinate frame $\{P\}$ attached to it. The relationship between these two vectors is obvious since coordinates frames $\{B\}$ and $\{P\}$ are always mutually parallel i.e.

$$^B\mathbf{p}_T={}^B\mathbf{p}_{OP}+{}^P\mathbf{p}_T \tag{1}$$

Other vectors and parameters are defined as shown in Figure 2, where $^B\mathbf{e}_i$ and $^B\mathbf{s}_i$ are unit vectors while c_i, i=1,2,3 are fixed lengths of joint parallelograms /4/.

Based on geometric relations shown in the Figure 2, the following equations are derived:

$$k_i\,{}^B\mathbf{e}_i = {}^B\mathbf{p}_T - {}^P\mathbf{p}_T + {}^P\mathbf{p}_{pi} - {}^B\mathbf{p}_{oi} \tag{2}$$

$$k_i\,{}^B\mathbf{e}_i = p_i\,{}^B\mathbf{a}_i + {}^B\mathbf{d}_i + c_i\,{}^B\mathbf{s}_i \tag{3}$$

As the vectors ${}^B\mathbf{a}_i$ and ${}^B\mathbf{d}_i$ are orthogonal to each other if the square of both sides in equation (3) is taken, the following relation is derived

$$c_i^2 = p_i^2 - 2p_i({}^B\mathbf{a}_i k_i\,{}^B\mathbf{e}_i) + (k_i\,{}^B\mathbf{e}_i - {}^B\mathbf{d}_i)^2 \tag{4}$$

Equation (4) is a second order polynomial in terms of p_i and inverse kinematics can be derived by solving p_i for the given tool tip location ${}^B\mathbf{p}_T$ and machines parameters as

$$p_i = ({}^B\mathbf{a}_i k_i\,{}^B\mathbf{e}_i) \pm \sqrt{({}^B\mathbf{a}_i k_i\,{}^B\mathbf{e}_i)^2 - (k_i\,{}^B\mathbf{e}_i - {}^B\mathbf{d}_i)^2 + c_i^2} \tag{5}$$

Also by substituting the machine's parameters in equation (4) the system of the following three equations is obtained

$$p_1^2 - 2p_1(x_T - x_{TP} + c_4) + (x_T - x_{TP} + c_4)^2 + (y_T - y_{TP} + d)^2 + +(z_T - z_{TP} + z_{p2})^2 - c_1^2 = 0 \tag{6}$$

$$p_2^2 - 2p_2(x_T - x_{TP}) + (x_T - x_{TP})^2 + (y_T - y_{TP} + d)^2 + (z_T - z_{TP} + z_{p2})^2 - c_2^2 = 0 \tag{7}$$

$$p_3^2 - 2p_3(x_T - x_{TP} + x_{p3}) + (x_T - x_{TP} + x_{p3})^2 + (z_T - z_{TP} + z_{p3} - z_{03})^2 - c_3^2 = 0 \tag{8}$$

from which are derived:

- Inverse kinematics equations as

$$p_1 = x_T - x_{TP} + c_4 - \sqrt{c_1^2 - (y_T - y_{TP} + d)^2 - (z_T - z_{TP} + z_{p2})^2} \tag{9}$$

$$p_2 = x_T - x_{TP} + \sqrt{c_2^2 - (y_T - y_{TP} + d)^2 - (z_T - z_{TP} + z_{p2})^2} \tag{10}$$

$$p_3 = x_T - x_{TP} + x_{p3} + \sqrt{c_3^2 - (z_T - z_{TP} + z_{p3} - z_{03})^2} \tag{11}$$

as well as

- Direct kinematics equations as

$$x_T = x_{TP} + \frac{p_2^2 + c_1^2 - c_2^2 - (p_1 - c_4)^2}{2(p_2 - p_1 + c_4)} \tag{12}$$

$$z_T = z_{TP} + z_{03} - z_{p3} - \sqrt{c_3^2 - (p_3 - (x_T - x_{TP} + x_{p3}))^2} \tag{13}$$

$$y_T = y_{TP} - d - \sqrt{c_2^2 - (p_2 - x_T + x_{TP})^2 - (z_T - z_{TP} + z_{p2})^2} \tag{14}$$

4. SINGULARITY ANALYSIS

In view of the significance of singularity of PKM, this problem has been analyzed in detail for the mechanism shown in Figure 2, that has been used for the development of the first vertical milling machine prototype /2,3/. Differentiating equations (9 to 11) with respect to the time Jacobian matrix **J** is obtained.

As the equations (6 to 8) are implicit functions of joint and world coordinates by their differentiation Jacobian matrix **J** may be also obtained as

$$\mathbf{J} = \mathbf{J}_p^{-1} \cdot \mathbf{J}_x \tag{15}$$

where $\mathbf{J}_p$ and $\mathbf{J}_x$ are Jacobian matrices of inverse and direct kinematics /5/.

In this way three different types of singularities can be identified, e.g., singularities of inverse and direct kinematics as well as combined singularities.
With careful analysis of Jacobian matrices determinants

$$\det(\mathbf{J}) = \frac{(p_2 - p_1 + c_4)(y_T - y_{TP} + d)(z_T - z_{TP} + z_{p3} - z_{03})}{(x_T - x_{TP} + c_4 - p_1)(x_T - x_{TP} - p_2)(x_T - x_{TP} + x_{p3} - p_3)} \tag{16}$$

$$\det(\mathbf{J}_p) = 8(x_T - x_{TP} + c_4 - p_1)(x_T - x_{TP} - p_2)(x_T - x_{TP} + x_{p3} - p_3) \tag{17}$$

$$\det(\mathbf{J}_x) = 8(p_2 - p_1 + c_4)(y_T - y_{TP} + d)(z_T - z_{TP} + z_{p3} - z_{03}) \tag{18}$$

the singularities of inverse and direct kinematics as well as combined singularity may be noticed. As the sliders s_1 and s_2 cannot pass each other, Figure 1 and Figure 2, three singularities of direct kinematics, one singularity of inverse kinematics and one combined singularity, Figure 3, are of some significance.

Figure 3 shows these possible mechanism's singular configurations with corresponding descriptions and equations. As it may be seen from Figure 3, all singularities are on the borders of theoretically achievable workspace, so that it would be possible to avoid them easily with adequate design solutions and/or mechanical constrains, or control algorithms. This means that the effective workspace is smaller than theoretically achievable workspace, i.e., that the borders of the effective workspace are sufficiently removed from the borders of the theoretically achievable workspace.

5. EXPERIENCES IN THE FIRST MILLING MACHINE PROTOTYPE DEVELOPMENT

As it is known in addition to selecting appropriate kinematic topology, the selection of the right geometric dimensions is very important since the performance is highly influenced by PKM geometric dimensions [6,7].

To select the right dimensions with respect to a given application is a difficult task and the development of design tools for PKM is still open research. However, the structure of the mechanism and its decoupled motions in X, Y and Z directions, geometrically enables a relatively easy determination of the basic design parameters for a given workspace dimensions X, Y and Z. The procedure is essentially iterative because in determination of the basic design parameters the attention is paid to the possible interferences of structural elements and the values of det(**J**) and $\det((\mathbf{J}^{-1})^T)$ determinants.

In the simplified geometric model of the mechanism, Figure 4, it may be seen that the Y dimension of the workspace will be primarily affected by the parallelogram lengths c_1 and c_2 and platform dimension c_4. In determination of these parameters for a given Y dimension of the workspace, the attention should be paid to the possible interference between s_1 and s_2 sliders, the sliders and joint parallelograms c_1 and c_2, the joint parallelograms and the mobile platform, as well as to the adequacy of the distance of the mechanism from the direct kinematics singularities, Figure 3. These influences may be covered by the distances ΔX_{min} and ΔX_{max} between the sliders, i.e. by the α_1 and α_2 angles. These parameters, together with the adopted arbitrary workspace X dimension, will influence the length determination of the common guideway of s_1 and s_2 sliders.

It is also easy to see from Figure 4 that the workspace Z dimension and the workspace position in Z direction are primarily under the influence of the length of joint parallelogram c_3 and the position of slider's s_3 guideway, i.e., its coordinate z_{03}. In determination of these parameters for a given Z workspace dimension the attention should be paid to the possible interferences, to the value of angle α_3, as well as to the adequacy of the distance of the mechanism from all possible singularities shown in Figure 3.

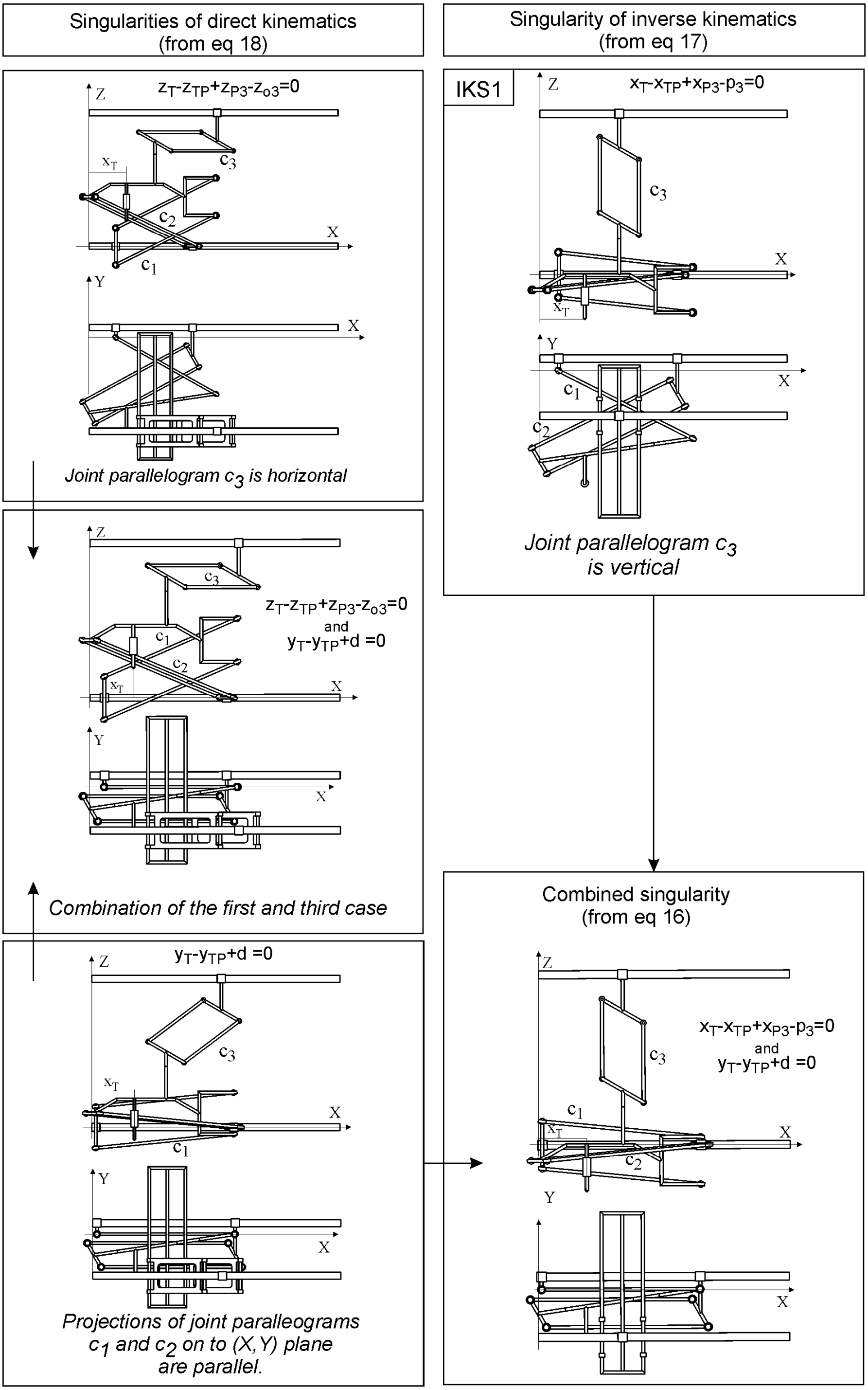

Figure 3: Significant singularity types

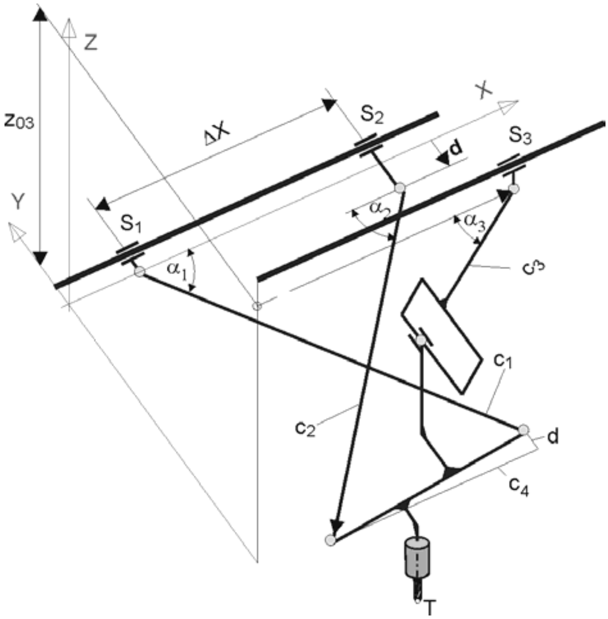

Figure 4: Simlifield geometric model of the mechanism.

The initial point in conceiving the first vertical milling machine prototype has been the relationship between the travel of the main spindle, i.e., workspace dimensions in X, Y and Z directions. The ratio 5:2.5:1 has been approximately adopted, which is a frequent case for vertical serial kinematics milling machines.

Figure 5: Experimental vertical milling machine prototype

For adopted workspace dimensions Y=500mm and Z=200mm the lengths of joint parallelograms c_1, c_2, the length of the platform c_4, the length of the joint parallelogram c_3 and the coordinate z_{03} were analyzed in iterative procedure /2,3/ and adopted as: c_1=1003mm, c_2=1026mm, c_3=500mm, c_4=1019mm, z_{03}=843mm.

On the basis of the adopted concept and design parameters the first vertical milling machine experimental prototype has been built in cooperation with the LOLA System factory, Figure 5.

Figure 6 shows the workspace shape and dimensions of developed prototype from Figure 5.

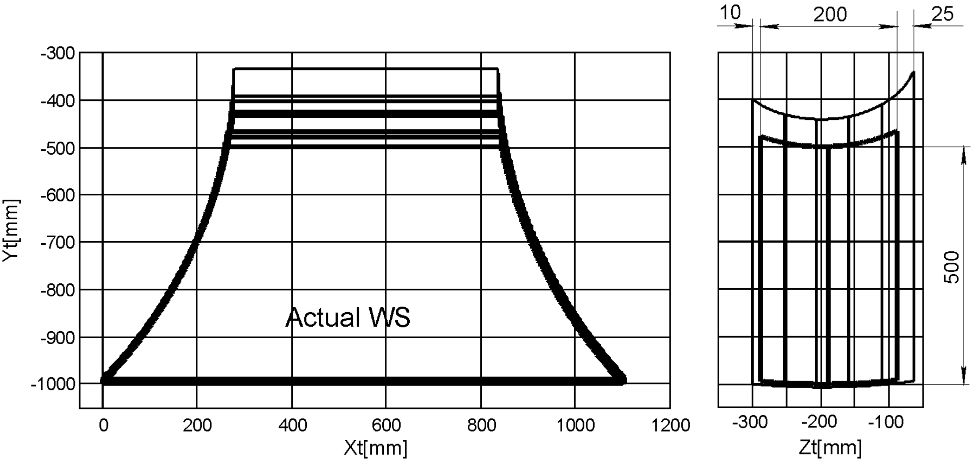

Figure 6: Workspace of developed prototype from Figure 5

6. DEVELOPMENT OF MINI EDUCATIONAL MILLING MACHINE

Research in the field of PKM at the Department for Production Engineering, Mechanical Engineering Faculty, Belgrade University, started in 1995 and initially it was related to the analysis of the existing and synthesis of the new parallel kinematic mechanisms and kinematics modelling. To include this topic into the process of teaching the subjects, such as Machine tools and Industrial robots, a number of physical models of typical parallel kinematics mechanisms and Functional simulator of 3-axis parallel kinematic milling machine /1/ were first developed.

Using previous experience in the field of PKM and successfully developed first experimental prototype of vertical milling machine based on newly developed mechanism, there emerged an idea about developing a low-cost mini educational 3-axis parallel kinematic milling machine. Initially, it was concluded that the developed mechanism is suitable in both design and technological respect. Along with the fact that a complete mechanism modelling and singularity analisys were done during prototype developing, that contol and programming system exist, as well as experience in design, building and assembly, the conception of the system was approached.

The first step was to set the goals that can be summed up as follows:

- It is a low-cost mini desktop machine,
- it can machine soft materials,
- it is programmable in a common way,
- it is fully safe for user-beginners.

Using the thus determined goals, elaboration of the concept involved:

- dimensional analysis of the machine and workspace,
- conception of basic units with the choice of possible solutions.

Those two steps are strongly synergetic, because care had to be taken of the previously set goals and constraints, such as: that it is a desktop machine, that components can be procured from a hobby shop (step motors, leadscrews, sliding guideways, joints, etc), that all other components can be built in a laboratory, that control and programming system is based on the EMC software /8,9/ and PC Linux platform.

The analysis evidenced that scale factor 5 compared to the first experimental milling machine prototype from Figure 5 would be an optimal solution because the machine would be desktop and would have 5 times smaller overall sizes and 5 times smaller workspace overall sizes, retaining all advantages of the mechanism used. Those dimensions also provide for applying the existing low-cost components as well as building of other components in our laboratory.

Figure 7 shows CAD model of developed mini educational 3-axis parallel kinematic milling machine that all necessary technical documentation has been generated from. Since geometric model of educational milling machine is identical to the model of developed verttical milling machine prototype from Figure 2 and Figure 4, basic parameters c_1=200mm, c_2=205mm, c_3=100mm, c_4=204mm, z_{03}=169mm provide the same shape of workspace as in Figure 6, however, overall sizes being 5 times smaller, as shown in Figure 8.

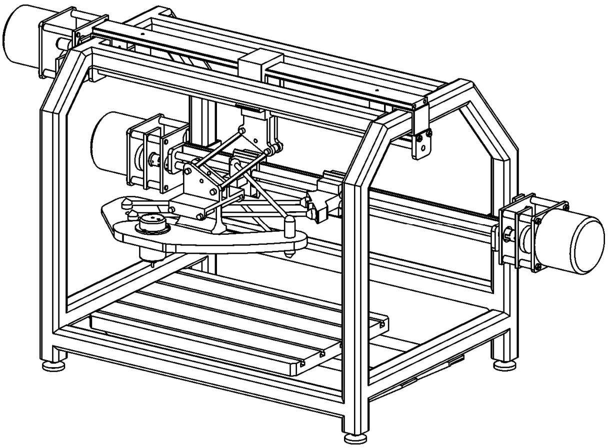

Figure 7: Prototype CAD mode.

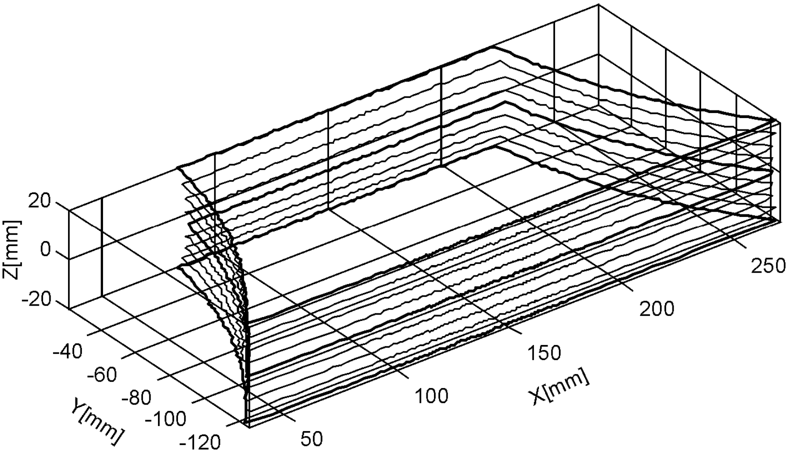

Figure 8: Workspace of developed prototype.

7. EDUCATIONAL MILLING MACHINE PROTOTYPE

On the basis of the adopted concept and design parameters, the first low-cost mini educational 3-axis parallel kinematic milling machine has been built in our Laboratory, Figure 9.

The actuators are composed of step motors, leadscrews and linear sliding guides. These are still widely used and superior in cost, reliability and maintainability.

Figure 9: Mini educational miling machine prototype

The control system is based on PC Linux platform with real time extension and EMC (the **E**nhanced **M**achine **C**ontroller) software system for computer control of machine tools, such as milling machines, cutting machines, robots, hexapods, etc. EMC was created by NIST (the National Institute of Standards and Technology) and is free software released under the terms of the GPL (General Public License).

Part programming is very conventional, with the use of a postprocessor to convert CL file into G code. Figure 10 shows the structure of the control and programming system of developed mini educational milling machine.

8. CONCLUSION

In order to contribute to acquiring experience in modelling, design, control, programming and use of PKM, a low-cost educational 3-axis parallel kinematic milling machine is proposed. The developed mini educational parallel kinematic milling machine is based on newly developed 3-DOF spatial parallel mechanism with specific advantages in comparison with similar mechanisms. The developed low-cost mini educational parallel kinematic milling machine could be comprehensive and sophisticated didactic facility. The laboratories, universities and schools may find a planned commercial version of this machine.

9. ACKNOWLEDGMENTS

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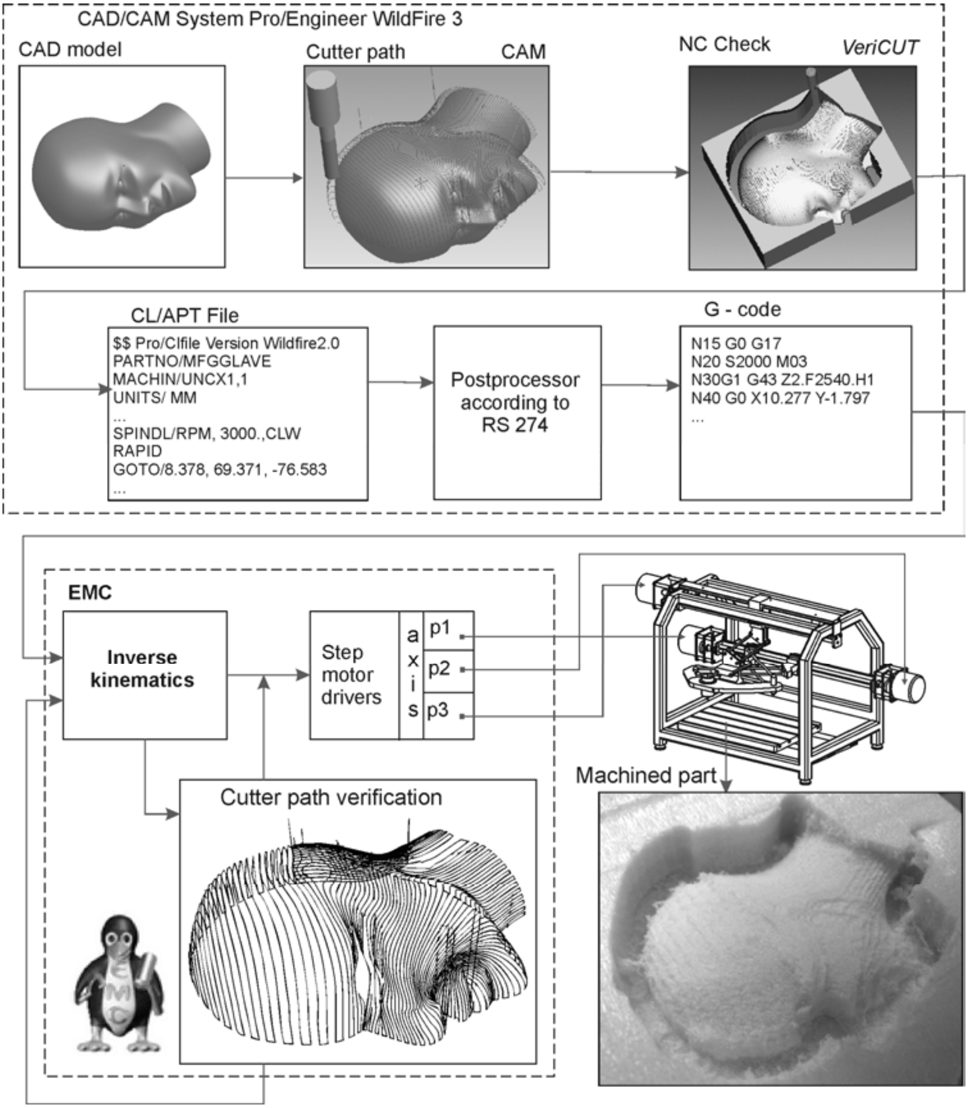

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Figure 10: The structure of control and programming system.

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