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Parallel Kinematic Machines

Saša Živanović,
Production Engineerring Department
Mechanical Engineering Faculty
University of Belgrade / YU

Abstract: - The subject of this paper is the machining system with machine tool, designed by the parallel mechanism necessary motors, transmission and corresponding control. Such processing system has got, by the rule, six axes and it is kinematic redundant in relation to most methods of cutting which is carried out by traditional machine tools. Incorporated parallel mechanism has got parallel axes, so these machine tools are said to have virtual axes. This virtuality is the consequence of parallel mechanism working principle. This is the first time it appears on such machine tools. Its characteristic is difference between machine axes and necessary tool movements in relation to workpiece in programming. Until present times the unit mapping from necessary movement coordinates in Decart coordinate system on available machine movements was possible, because in traditional machine tools serial ortogonal mechanisms were incorporated. On the basis of insight into already existing accomplishment in realizing machine tools with parallel kinematics and my own researches this paper plan to carry out real knowledge by the method of unfinished concept, which it is better to make self concepts and develop further this conception instead of buying somebody else's unfinished product. That is why designing of certain manufacturing module with parallel mechanism was planned. The idea is to use available resources of traditional manufacturing equipment in an untraditional an educational system without getting into development and building of typical components for communication, programming motors, and control.

1. INTRODUCTION

Traditional machine tools with serial mechanism already existed two centuries of its existing. They brought out the burden of industrial revolution in the past century; they contributed to the rapid development and production of goods in present century and provided systematic approach to building and using of manufacturing systems. Now, they serve also for building of the first prototypes of promising machines with parallel mechanism. Such new type of machines carried out larger requirements for control subsystem because they are not able to accomplish not even the most simplified coordinate movement by positioning without superposition of its movement, typically of all its available axes.

It is clear now that there is need for peoples with new knowledge for design, building and application of such machine tools. Also there is need for new components for building, new systems for programming, new users for support of the further development and new manufacturing systems for presentation of the performances of such modules. It is assumed that products with such requirements should be known, and also that these products should be needed for someone, now or in the future. It is possible that the leading manufacturers of machine tools have such modules in their production programs, to acquire necessary experiences, before other companies, and to start with true development after fulfilling any of mentioned conditions. For the moment such machines exist as a prototypes only, with rare specimens installed at avant-garde users.

There is dilemma if such machines are more suitable as industrial robots for assembly purposes and manipulation or for machining operations, because built prototypes have the both purposes.

Thus the term parallel kinematics machine(PKM) is related to the machine tools and also for the robots. The dilemma is larger because of suspicions about high rigidity of such machines (thanks to parallel mechanism) which is stated as higher than rigidity of robust traditional machine tools with serial configuration.
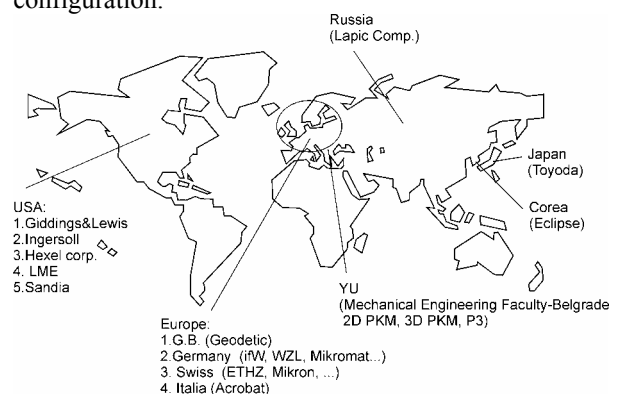

Figure 1.1. Distribution of industrial and research centers for machine tools with parallel kinematics

Looking at these modules from aspect of the potential manufacturer or from the position of potential planner of long-term research and/or development program of modern manufacturing systems, that it would be necessary to explain, much precisely, reasons for unexpected fall of big swing, which originally

characterized research and building. The culmination of this rising interest was before round five years on the IMTS Fair in Chicago (1995.), when the first specimens of such machine tools were presented. In following years this trend was affirm also in Europe, where the consortium for machine tools with parallel mechanism was established. European scope in the research of these machines was shown at The Hanover Fair in 1997. Figure 1.1. shows distribution of famous companies or research centers in domain of design and/or manufacturing of machines with parallel kinematics.

For sake of specificity of parallel mechanisms and complexity of the modeling, control, design and utilization of machine tools and robots based on them, research and development of such systems is based on the high level of cooperation of university, research institutes and the industry.
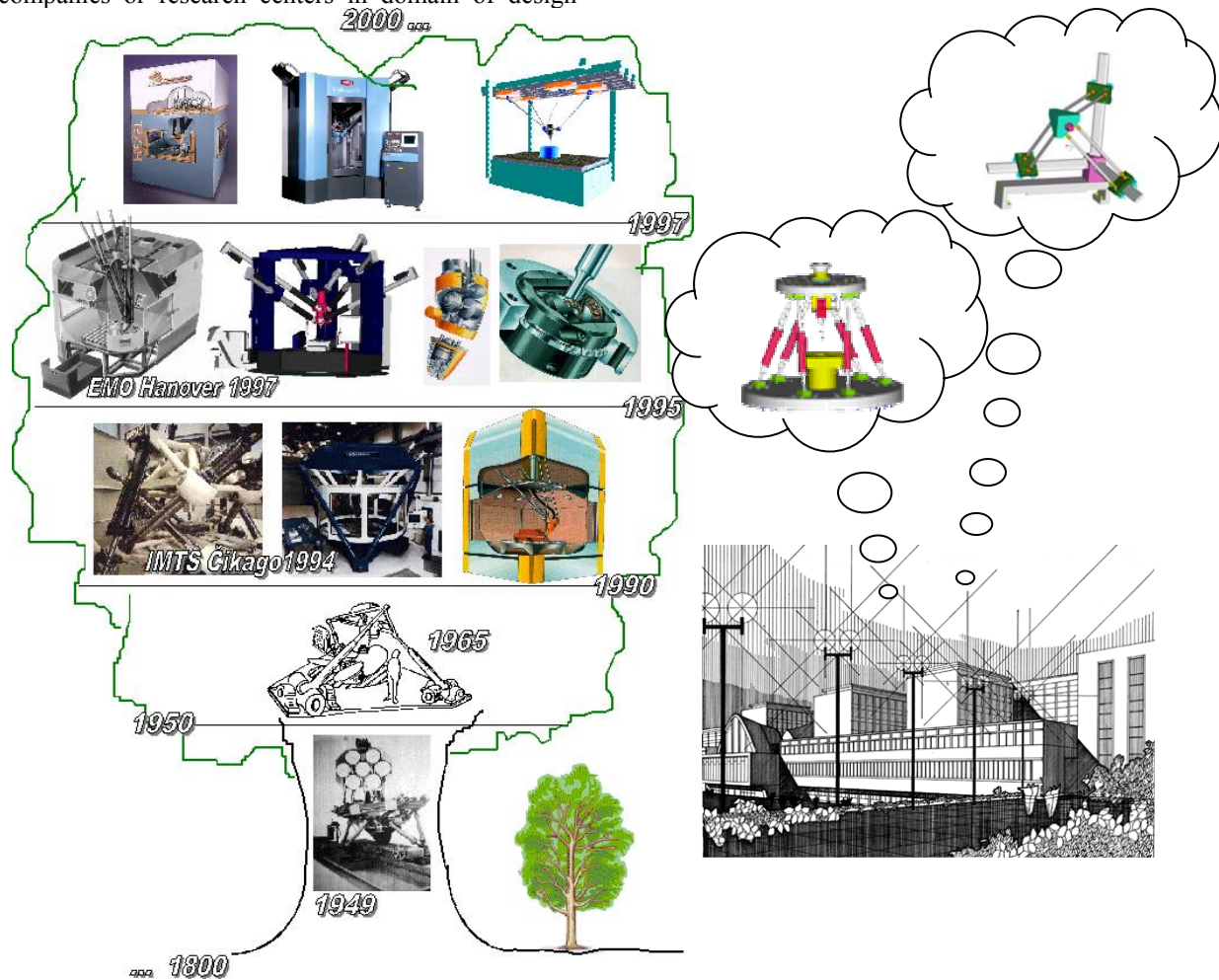

Figure 1.2 The tree of machine tools with parallel mechanism through history

On the figure 1.2 there is symbolically presented tree of PKMs through history with marked important years in their development. This tree which was sowed at the beginning of last century is grown-up and it begins to give the fruits – parallel kinematics machines (PKM) at the beginning of the XXI century. After looking on exhibited machines of this type, after mentioned Chicago fair, there were started with the first steps in this field also in our country. The first results were: general physical model with variable length of legs and with six degrees of freedom, and the last one was the building of the two- and three-axis machines with parallel kinematics which are explained, more detailed in following text.

2. THE INCUBATION OF ONE EDUCATIONAL PKM

In order to establish of experimental work on this subject, it was thought that existing equipment in The Laboratory for machine tools at The Mechanical faculty could be used in nontradional manner. Actually, this equipment was expected to be basis for conception and building of experimental and educational prototype of the three-axis machine tool as a manufacturing module, based on the parallel mechanism. Basic idea was using of the serial mechanism of horizontal machining center (ILR HBG80) with required modifications. Incubation of such machine was started with 2D parallel mechanism for acquiring basic experiences and knowledge, in order to realize aimed 3D conception et the end. It was intention of using available equipment on nontradional way to build own experimental and educational, without engagement in development and

building of typical components for communication, programming, drive and control.

2.1 Two-axis PKM

There is question if the base machine HBG80 contains some parallel machine. The answer is positive; it has three parallel machines with (XY), (YZ) and (XZ) axis, where both axes simultaneously drive the tool. Two axes (Xhbg and Zhbg) were considered in this paper (Fig. 2.2).

For control purposes of such machines it was necessary to solve inverse (IKP) and direct (DKP) kinematic problem. Calculation for IKP and DKP are shown on figure 2.1. Their solutions are given in following text and they are elementary for this case and also suitable for analysis and conclusions.
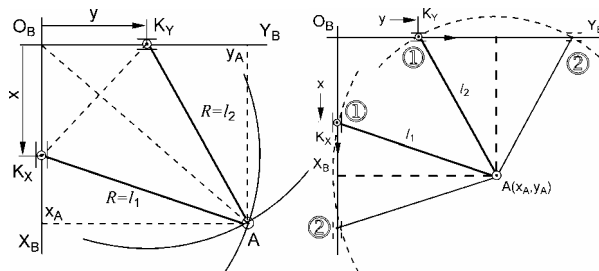

Figure 2.1 Direct and inverse kinematic problem for two-axis PKM

Solution for IKP is obtained as cross point of circles with centers in given position of the tool (X_A, Y_A), with radius l_1 and l_2 and lines y=0 and x=0, respectively. Equation system based on previous assumption is given as (1):

$$(x - x_A)^2 + (y - y_A)^2 = l_1^2 \quad , \quad y = 0$$
$$(x - x_A)^2 + (y - y_A)^2 = l_2^2 \quad , \quad x = 0 \tag{1}$$

$$x = x_A \pm \sqrt{l_1^2 - y_A^2} \rightarrow x = x_A - \sqrt{l_1^2 - y_A^2}$$
$$y = y_A \pm \sqrt{l_2^2 - x_A^2} \quad y = y_A - \sqrt{l_2^2 - x_A^2} \tag{2}$$

Equation (2) is solution of IKP and it can be concluded the existence of two solutions, which present two positions of the sliders on axes for achieving the same position. Solution implies that there is not allowed value for Xa which is larger than link length (l_2) of y-axis and y1 could not be larger than link length (l_1) of x-axis. As there exist two solutions for same position of the tool, there will be considered, in following, solutions which are closer to origin Ob. The solution is the corner of the triangle which is given by positions K_x, K_y and which is with known link-length l_1 and l_2. Solution of the DKP can be obtained as cross of two circles with centers in slider positions K_x and K_y, with radius l_1 and l_2, respectively (3).

$$(x_A - x)^2 + y_A^2 = l_1^2$$
$$x_A^2 + (y_A - y)^2 = l_2^2 \tag{3}$$

After substitution and rearranging, the general form of quadratic equation is obtain, from which is simple to obtain solutions for xa.

$$s_6 x_A^2 + s_7 x_A + s_8 = 0 \tag{4}$$

and finally, the shape of chosen solution of the DKP has form as:

$$x_{A1,2} = \frac{-s_7 + \sqrt{s_7^2 - 4s_6 s_8}}{2s_6} \tag{5}$$

$$y_A = +\sqrt{s_1 - x_A^2 - s_3 x_A}$$

Parallel mechanism is in the form of moving scissors with two translatory axes and two sticks (sticks1 and sticks2) with equal length (figure 2.2). In general case these sticks can be of different lenghts. This was considered in previous kinematic calculations. Mechanism is constructed for testing with equal length of sticks, but it can be used for more general case when these lengths are not equal.
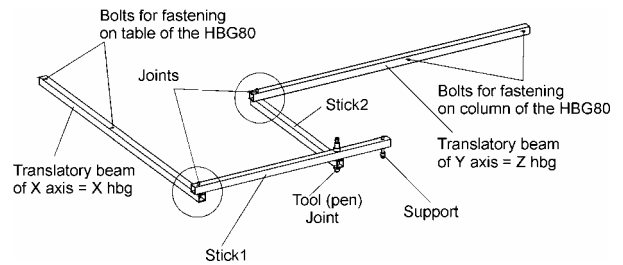

Figure 2.2 Basic ekements of two axis PKM

In considered plane (Xhbg-Zhbg) the mechanism has satisfactory stiffness, what is not a case for vertical direction. To avoid bending of the sticks in vertical plane there was mounted a support on the end of stick 1. This support at it's end has a plastic insert which slides on the plate. Lenghts of supporting pin is adjustable according to the position on the plate. This plate presents working board on which can be placed an etalon (paper with mm-grid for example) for monitoring of the pick (end) of the mechanism. Position of working table can be adjusted on various heights for better contact with etalon.
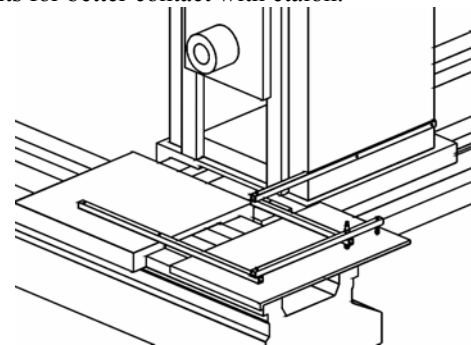

Figure 2.3 Two axis PKM mounted on the base machine HBG80

Mounting of 2D PKM on the base machine HBG80 was realized in Laboratory for machine tools. In this way there was realized necessary part for building of the experimental equipment by own resources. Use of this equipment should support experimental research. Also it is expected that this equipment will have a

significant role as a manufacturing module in laboratory works with students through subjects of Production Engineering Department.

2.2. Three axis PKM

Three-axis PKM (3D PKM) was planned to be realized as manufacturing module with parallel mechanism according to general conception of parallel mechanism with translatory movable joints and legs of equal constant lenght. Such module is designed for mounting on existing axes of machining center HBG80.
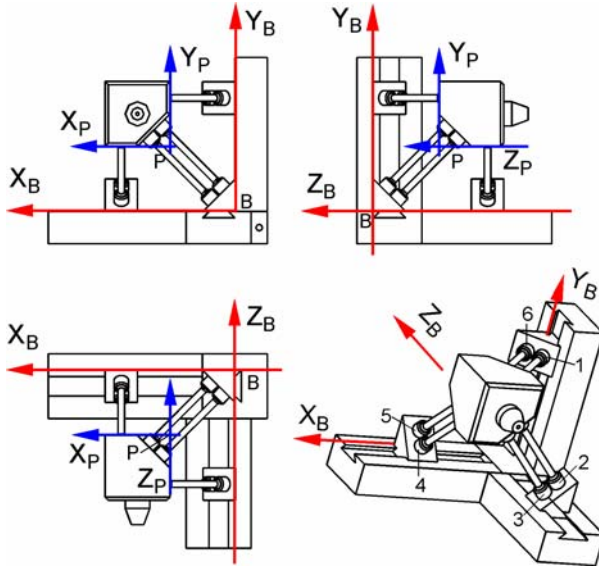

Figure 2.4 Basic structure of the three-axis PKM

Previous works on examination of the existancy of such machines conception were on wooden model. Basic conception assumes parallelity of axes of traditional machine to the axes of moving of PKM's sliders with joints. Every slider is inclined for 45°, and cube of the platform also has cut-off surfaces faced to corresponding sliders. Platform and any slider are connected with pair of legs of same length. There are spherical joints at the both ends of each leg. In this way by straight moving of sliders it is possible to change position of the platform in three axis. Similarly to traditional three-axis machines there is no change of spindle orientation. Spindle axis always remains parallel to Z - axis.

For programming and control purposes it is necessary to solve inverse kinematics problem (IKP). Solution of the direct kinematics problem (DKP) can be use for determination of the borders of workspace, angles of leg - inclinations and for positions, velocity and acceleration of the platform, by internal interpolation of driving axes. DKP solution can be obtained in algebraic form because the machine is with three-axes. Form this reason, pairs of heighboor legs always form a parallelogram. Then the calculated mean length of legs can be introduced. Their length is also l_o.
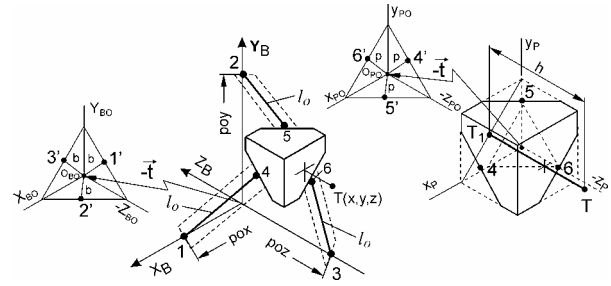

Figure 2.5 The Model of 3D PKM with mean legs

Inverse kinematic calculations are based on obtaining of vector intensity of parallel mechanism. This results in necessary equations with unknown (pox, poy, poz). Substracting of appropriate vectors gives vectors of legs $\vec{L}_1, \vec{L}_2, \vec{L}_3$ with intensity l_o. Intensity of these vectors can be written in form of equation (6).

$$(x_4 - x_1)^2 + (y_4 - y_1)^2 + (z_4 - z_1)^2 = l_0^2$$
$$(x_5 - x_2)^2 + (y_5 - y_2)^2 + (z_5 - z_2)^2 = l_0^2 \quad (6)$$
$$(x_6 - x_3)^2 + (y_6 - y_3)^2 + (z_6 - z_3)^2 = l_0^2$$

After substitution of real values for vector positions of joints which contain pox, poy, poz, and after expressing them as a functions of known parameters we have:

$$pox = x - x_{PT\,1} \mp \sqrt{l_0^2 - (y - y_{PT\,1})^2 - (z + h)^2}$$
$$poy = y - y_{PT\,1} \mp \sqrt{l_0^2 - (x - x_{PT\,1})^2 - (z + h)^2} \quad (7)$$
$$poz = -z - h \mp \sqrt{l_0^2 - (x - x_{PT\,1})^2 - (y - y_{PT\,1})^2}$$

as solution of inverse kinematic problem.

Solving of DKP for three axis PKM assume deteremination of outer coordinates i.e. tool-position (x,y,z), for given values of inner coordinates i.e. translatory movements of the joints of legs (pox, poy, poz). The model for DKP which works together with the previous for IKP is also based on vector calculations and it was explained in [1].
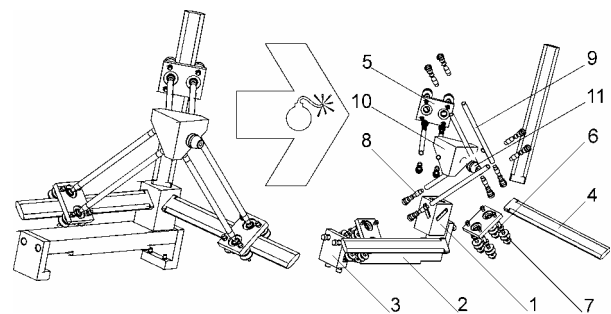

Figure 2.6 Basic conception of one three-axis PKM as a manufacturing module with parallel mechanism which mounted on the HBG80

The 3D PKM uses drives of linear axes of base machine HBG80: Xhbg, Yhbg and Zhbg. 3D PKM's axes are denoted as X_B, Y_B and Z_B. Two axes X_B and Z_B have direct actuation by direct connection with corresponding axes of base machine (see fig.2.7). The

third axis Y_B is driven by Yhbg axis, but this connection is realized by serial mechanism (with two cylindrical joints) which was used for decoupling of two coupled axes of base machine.
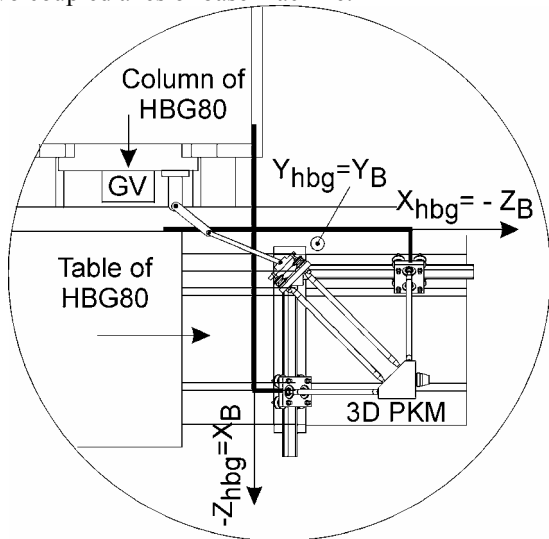

Figure 2.7 Transmission from base machine to three-axis manufacturing module

The 3D PKM is installed in Laboratory for machine tools of Mechanical Engineering faculty in Belgrade and it is in use for experimental research and for education of students.

3. WORKSPACE OF PKM

Workspace of PKM is considerably smaller comparing to workspace of traditional machine tool with similar overall dimensions. There is need to obtain size and shape of workspace can significantly influence on sizes of key components and on the conception of the machine. Borders of this workspace should be known also by setting of workpiece for machining on such machine.

Three exists various approaches of determination of the workspace. In this paper two ways of estimation of workspace were used: geometrical using of some CAD software and as the second, by using of solutions of the direct kinematic problem by computing of achievable positions for all possible positions of actuating axes.

Here are presented, in following, results of workspace shape for 2D and 3D PKM, using DKP and using calculation of achievable positions for all posible positions of actuating axes, according to some chosen strategy. Figure 3.1 shows the mapping between moving of driving axes and the toolpath, based on calculations of the DKP. This approach gives only countures of workspace according to chosen strategy of moving, including repeated parts of counture on ends. This repeating is consequence of double solution of IKP. However this is not a full picture of workspace, and searching of workspace surface was realized, based on different strategies. Necessary calculations were realized by using of DKP, by apropriate programm and matrixes which define strategy of lookup of the workspace.
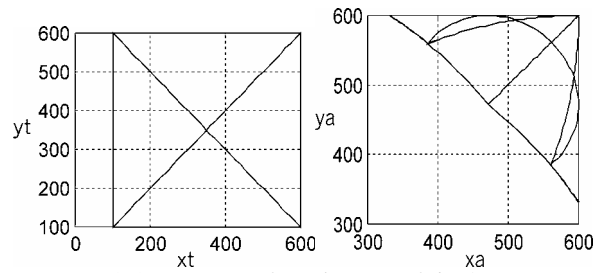

Figure 3.1 Countureof workspace of the 2D PKM on workspace borders

Based on previous considerations there was completed knowledge about true workspace. Workspace shape net obtained by combining of different startegies of lookup of the workspace is shown on figure 3.2 [1].
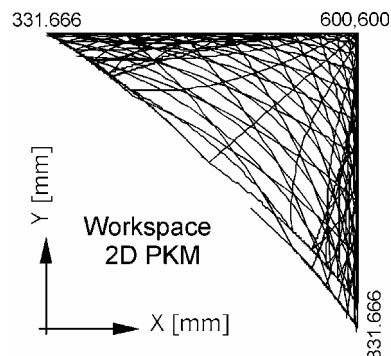

Figure 3.2 Workspace of 2-axis PKM

The same principle was used for workspace of 3D PKM. In order to obtain the workspace model in form of shell, there was created an algorithm and programm for calculations based on specific combining of moving of all driving axes [1,7].

Applying the solution of DKP on this, it is possible to obtain the shell or enclosure of workspace in form of net which is ilustrated on figure 3.4. Coordinates obtained through this procedure were also used for machining of workspace in design phase of 3D PKM.
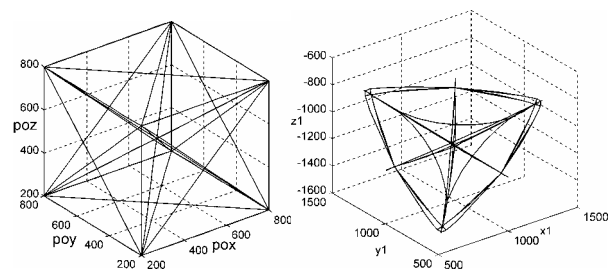

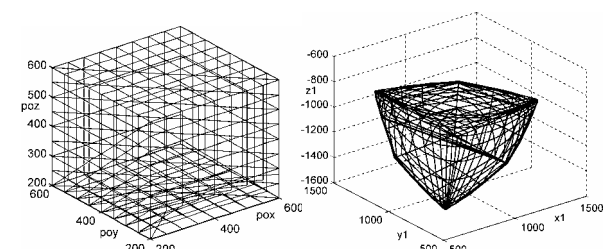*Figure 3.3 Countures of workspace of 3D PKM obtained by DKP*

Figure 3.4 Shell of workspace of 3D PKM obtained by DKP

4. CONCLUSION

Based on the analysis of existing constructions of realized machine tools with parallel kinematics as well as of own research it is planned through this paper that real knowledge would be achieved through the method of nonfinished conception. This method could be explain as an approach which favourize individual conception and building based on such conception instead of buying foreign nonfinished product.
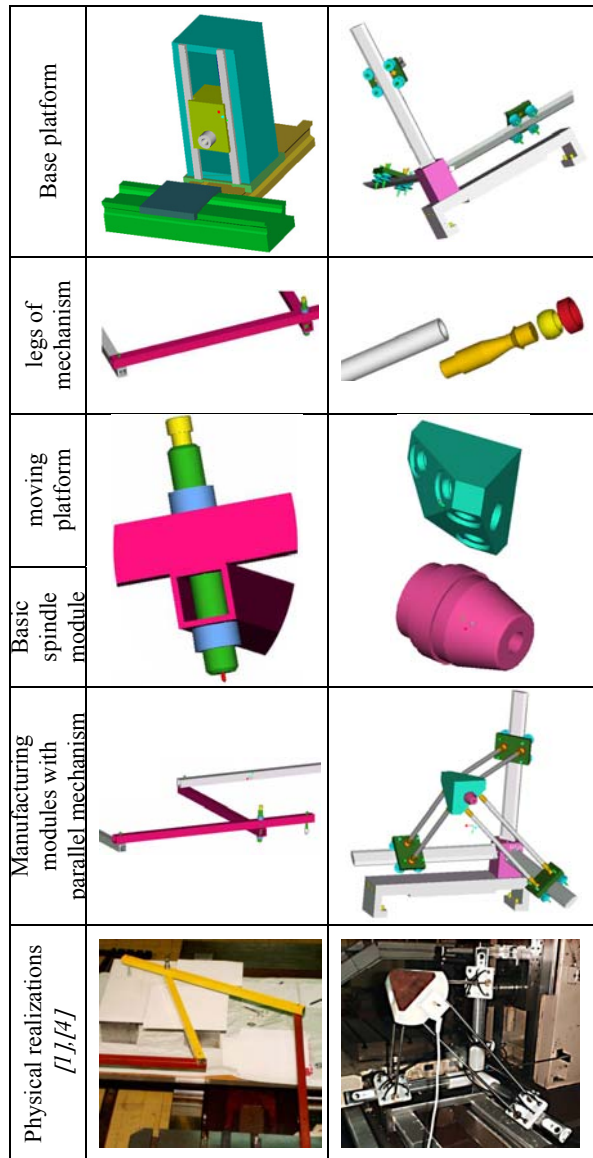
There was idea to use available resources of traditional manufacturing equipment on nontraditional way, in order to build own experimental and educational system. There was not intention for development and building of typical components for communication, programming, drive and control.

Building of such experimental and educational PKM as manufacturing module has following importance:

- Examinations of possibility of application of traditional equipment on nontraditional way i.e. building of parallel machine on the basis of the traditional one.
- Examinations of function of 2D and 3D machine with parallel kinematics, built into horizontal machining center including drives, CNC, NC-programs, PC-CNC communication of such machining center.
- testing of programming possibilities of PKM,
- Education of students through laboratory exercises on production engineering department and further research, which should be continuity of initialized direction of research.

Base platform		
legs of mechanism		
moving platform		
Basic spindle module		
Manufacturing modules with parallel mechanism		
Physical realizations [1],[4]		

Figure 4.Incubation of educational 2D and 3D PKM as manufacturing module with parallel mechanism

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