DEVELOPMENT OF A PARALLEL KINEMATIC DEVICE INTEGRATED INTO A 3-AXIS MILLING CENTRE

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ABSTRACT
Parallel kinematic machines (PKM) are R&D topic in many laboratories but many of them, unfortunately, have no PKM. To gain practical experience, especially in programming and the use of PKM, the parallel kinematic device integrated into 3-axis milling machine has been developed. The device is considered as the low cost but functional simulator of 3D parallel kinematic machine. The device is based on several developed mechanisms with constant strut lengths and linear joints and is driven and controlled by a conventional 3D CNC machine tool. The paper describes device design, modelling approach, algorithms and software for the control and programming in the same way as in serial machine tools.

KEYWORDS: Parallel mechanism, Modelling, Milling machine

1. INTRODUCTION

The strategic importance of education and training, especially in technology and scientific subjects, is growing throughout the world. This also applies to the parallel kinematic machines (PKM) which are today a worldwide topic in R&D and education. Unfortunately, the great majority of research institutes, university laboratories and companies, today do not have any PKM at all. The reason for this is obviously high costs of education and training for new technology, such as PKM.
In order to gain practical experience in modeling, design, control and especially in programming and use of PKM the Eureka project E!3239 PAKICUT for development of parallel kinematic device integrated into 3-axis milling centre has been launched /1/. The device is a low cost but functional simulator of 3D parallel kinematic machine. Basic part of the device is parallel kinematic mechanism with constant strut lengths and three orthogonal linear joints similar to DELTA mechanism /2/. The device is driven and controlled by conventional 3D CNC machine tool and integrates the existing technological equipment (CNC machine tool, CAD/CAM hardware and software) and parallel kinematic mechanism into a comprehensive and sophisticated didactic facility. In order to install device on different serial horizontal and vertical 3-axis CNC milling machines several different variants of mechanisms have been developed /1,3/.
This paper describes some results achieved in project relating to the device design, modeling approach, calibration, algorithms and software for control and programming. To evaluate the prototypes of developed devices under full operational conditions some standardized test pieces have been successfully made of foam.

2. INITIAL DEVICE CONCEPT AND MECHANISM STRUCTURE

The research and education in the PKM field quickly shifts from the field of theory and simulation to PKMs as a necessary experimental basis. With the analysis of this problem

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and having in mind the example of our laboratories, as well as in principle, the following constraints may be summarized:

- Economic constraints: big investment, the need to deal with big PKM manufacturers and full engagement of the entire laboratory.
- Technical constraints: dominant presence of serial kinematic machines and CAD/CAM systems for their programming, existing postprocessor generators are non-adjustable to PKM, the existence of solutions specific to PKM control units only, and incomplete unification of PKM concepts and components.
- Exploitation constraints: insufficient adjustment of PKMs for education and research purposes.

Based on previous knowledge about the serial kinematic machines and available resources for their programming an idea to make the device as a hybrid structure of driving serial and driven operating parallel mechanism has been born. The first obtained result has been the system of a functional simulator for 3D milling of softer materials, Figure 1, consisting of:

- Fully parallel 3 DOF mechanism with constant strut lengths and linear joints actuated and controlled by the conventional 3D CNC machine. The mechanism is based on linear DELTA mechanism but with orthogonal linear actuated joints to facilitate its connection with X_S, Y_S and Z_S axes of horizontal or vertical serial kinematic machines. The universal platform, that always remains parallel with the base, enables the placement of spindle in different directions (T_x, T_y, T_z). Out of several possible mechanism configurations, the one with the platform inside the trihedron (X_B, Y_B, $-Z_B$) has been selected since it enables easy mounting of the parallel mechanism on the serial machine X_S axis guideways.
- Serial 2 DOF passive mechanism for decoupling of serial machines Y_S and Z_S axes.

In addition to the development of the device mechanisms, the following procedures, models, algorithms and software have also been defined and developed:

- The procedure and accessories for adjustment of referent parallel mechanism points to simplify the programming.
- The procedure for device testing under working conditions by machining of various test pieces.

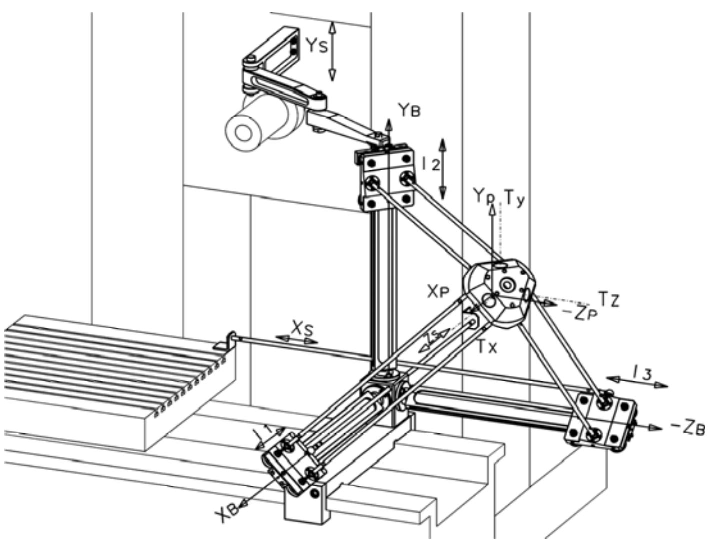


Figure 1: Overall view of the developed device.

- The solutions for inverse and direct kinematics. Based on inverse kinematics the postprocessor has been developed and implemented in one CAD/CAM system.

2.1 Device modelling

Detailed kinematic analysis of the device is based on its geometric model, figure 2. As the platform, by mechanism's nature, remains parallel with the base, each spatial parallelogram, Figure 1, has been represented by one strut. Due to the fact that the coordinate frames {B} and {P} connected to the base and the platform are parallel, as well as that they are parallel with the referent serial machine coordinate frame {S}, it is possible to generalize the modelling of the entire device. This means that it is feasible to separate the modelling of the parallel mechanism itself, regardless of its mounting on the horizontal or vertical serial machine as well as of the position of the spindle on its platform. All device parameters are defined as shown in figure 2, where leading superscripts are used to indicate the coordinate frames to which the vectors refer to.

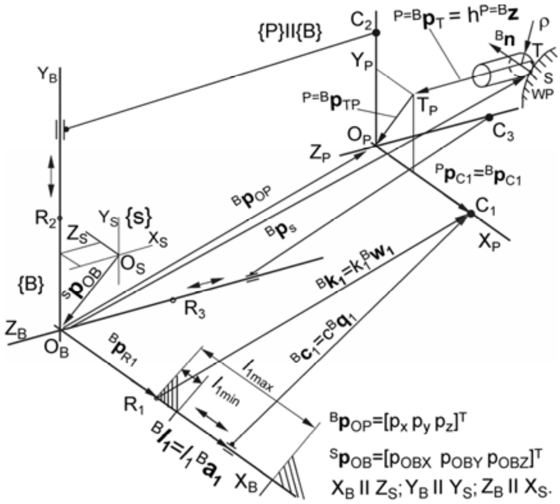


Figure 2: Geometric model of the device.

The parallel mechanism is described by unit vectors ${}^{B}\boldsymbol{a}_i$, ${}^{B}\boldsymbol{q}_i$ and ${}^{B}\boldsymbol{w}_i$, vectors ${}^{B}\boldsymbol{p}_{Ri}$, ${}^{B}\boldsymbol{p}_{Ci}$, scalars l_i, k_i, i=1,2,3 and strut lengths c. Unit vectors ${}^{B}\boldsymbol{a}_i$ describe the orientations of driving device axes while the l_i scalar variables are controlled by serial machine actuators and must be within the following range $l_{i\,min} \le l_i \le l_{i\,max}$, where $l_{i\,min} > 0$.

Possible positions of the spindle with tool on the platform are described by the vectors ${}^{P=B}\boldsymbol{p}_{TP}$ and ${}^{P=B}\boldsymbol{p}_{T}$. Figure 2 shows an example of ball endmill, with radius ρ, parallel to the Z_P axis. The geometry of the workpiece is described by the vector ${}^{B}\boldsymbol{p}_S$ and unit normal vector ${}^{B}\boldsymbol{n}$.

Device's joint coordinates vector is $\boldsymbol{L} = [l_1 \quad l_2 \quad l_3]^T$ while its world coordinates vector is described by workpiece geometry, tool types, tool position and dimensions as

$$ {}^{B}\mathbf{p}_{OP} = [p_x \quad p_y \quad p_z]^T = {}^{B}\mathbf{p}_S + \rho\,{}^{B}\mathbf{n} + (h-\rho)\,{}^{B}z + {}^{B}\mathbf{p}_{TP} \quad (1) $$

The relations between the device joint coordinates and serial machine joint coordinates $\boldsymbol{Q}=[x_s\ y_s\ z_s]^T$, as shown in Figure 2, are:

$$x_S = l_3 + p_{OBx} \quad y_S = l_2 + p_{OBy} \quad z_S = -l_1 + p_{OBz} \tag{2}$$

Kinematics of the parallel mechanism

The following equations are derived on the basis of the geometric model shown in figure 2 and the approach in /4/:

$$k_i\,{}^B\boldsymbol{w}_i = {}^B\boldsymbol{p}_{OP} + {}^{P=B}\boldsymbol{p}_{Ci} - {}^B\boldsymbol{p}_{Ri} \tag{3}$$

$$k_i\,{}^B\boldsymbol{w}_i = l_i\,{}^B\boldsymbol{a}_i + c\,{}^B\boldsymbol{q}_i \tag{4}$$

By taking the square of both sides in equation (4) the following relation is derived:

$$c^2 = k_i^2 + l_i^2 - 2l_i\left({}^B\boldsymbol{a}_i k_i\,{}^B\boldsymbol{w}_i\right) \tag{5}$$

By adopting that in the equation (3) ${}^{P=B}\boldsymbol{p}_{Ci} - {}^B\boldsymbol{p}_{Ri} = 0$ kinematic modelling can be simplified /1/. In order to fulfill this requirement specific calibration method for this device has been developed. When the equation (5) is developed the system of three equations is obtained:

$$\begin{aligned} p_x^2 + p_y^2 + p_z^2 + l_1^2 - 2l_1 p_x - c^2 &= 0 \\ p_x^2 + p_y^2 + p_z^2 + l_2^2 - 2l_2 p_y - c^2 &= 0 \\ p_x^2 + p_y^2 + p_z^2 + l_3^2 + 2l_3 p_z - c^2 &= 0 \end{aligned} \tag{6}$$

The solutions of this system of equations for l_i, i=1,2,3 for the given p_x, p_y and p_z represents inverse kinematics and are given as:

$$\begin{aligned} l_1 &= p_x \pm \sqrt{c^2 - p_y^2 - p_z^2} \\ l_2 &= p_y \pm \sqrt{c^2 - p_x^2 - p_z^2} \\ l_3 &= -p_z \pm \sqrt{c^2 - p_x^2 - p_y^2} \end{aligned} \tag{7}$$

When selecting these solutions they should be closer to the origin O_B in the octant ($X_B>0$, $Y_B>0$, $Z_B<0$). This inverse kinematic solution, based on equations (2), is implemented in the postprocessor for device programming, as well as in the specific procedure for shape and dimension analysis of the workspace.

The solution of the system of equations (6) for p_x, p_y and p_z for the given l_1, l_2 and l_3 is a closed form of direct kinematics and it is used to select components and for mechanism sizing. For analysis of the relationship between TCP and driving axes velocities, the singularity and static stiffness of the mechanism, the overall Jacobian matrix $\boldsymbol{J}$ is derived from equations (6), as:

$$\boldsymbol{J} = \boldsymbol{J}_L^{-1}\boldsymbol{J}_P = \begin{bmatrix} 1 & \dfrac{p_y}{p_x - l_1} & \dfrac{p_z}{p_x - l_1} \\ \dfrac{p_x}{p_y - l_2} & 1 & \dfrac{p_z}{p_y - l_2} \\ -\dfrac{p_x}{p_z + l_3} & -\dfrac{p_y}{p_z + l_3} & -1 \end{bmatrix} \tag{8}$$

where the Jacobian matrices $\boldsymbol{J}_L$ and $\boldsymbol{J}_P$ enable the analysis of inverse and direct kinematic singularities. This and other forms of overall Jacobian matrix enable the analysis of combined singularities.

Device calibration and workspace analysis

The calibration method has been developed based on kinematic device analysis and universally designed platform, as shown in figure 3. The dimensions and the shape of the platform are defined according to selected distance between struts, i.e., according to the positions and dimensions of spherical joints and spindle placing holes. Referent struts 200 mm long have been used for calibration. The struts have no joints and are placed into the holes of spherical joints on the base and the platform in the direction of their axes. For the fixed structure assembled in this way the positions of sliders are calculated and points R_i on the driving axes are marked by bushes. In this way, the requirement is met in the equation (3) that ${}^{P=B}\boldsymbol{p}_{Ci} - {}^{B}\boldsymbol{p}_{Ri} = 0$.

After this, other mechanism parameters are selected: l_{imin}=200 mm, l_{imax}=600 mm and $c = 600\sqrt{2}$ mm so that the mechanism is far away from singularities and the angles of spherical joints are in permitted range of ±25°.

Workspace shape and dimensions of the of the tool tip T are determined in two ways:

- By applying direct kinematics solution and machining the half of the workspace cavity on a serial CNC machine before the completion of the device.
- The solution of inverse kinematics is applied to find workspace boundary points starting from a selected point according to specific strategy. The workspace model generated in this way, figure 4, is also suitable for machining on serial CNC machine.

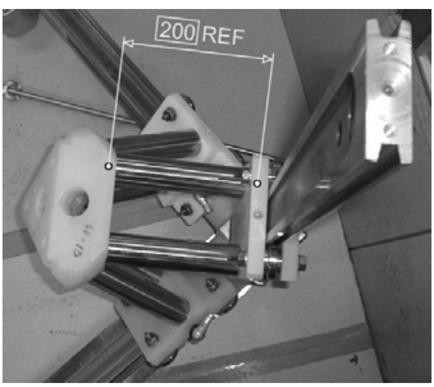


Figure 3: Device calibration.

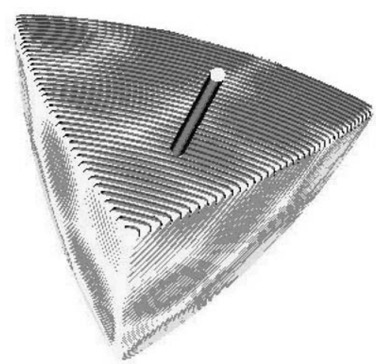


Figure 4: 3D shape of workspace.

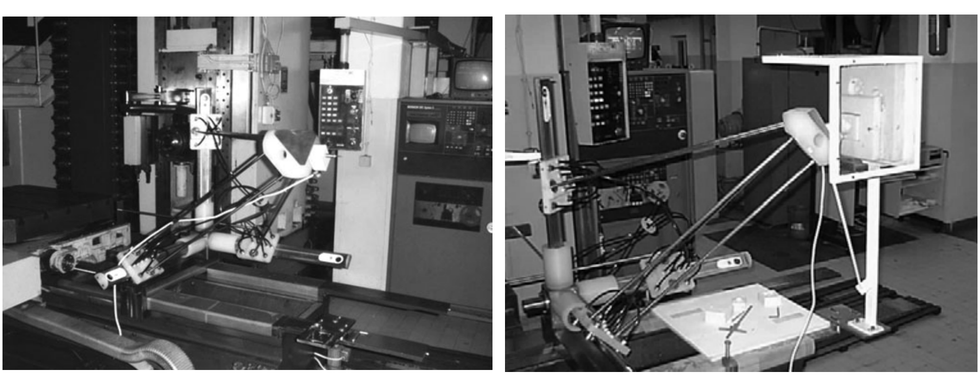


Figure 5: Installed device with horizontal main spindle.

The device is finally installed on serial kinematic machine, figure 5. Its position is thus adjusted according to selected vector ${}^{S}\boldsymbol{p}_{OB}$, figure 2 i.e., equations (2). In such a way the device calibration is completed.

2.2 Device programming and testing

The system for device programming has been developed in a standard CAD/CAM environment, figure 6. It is possible to exchange geometric workpiece models with other systems and simulate the tool path. Linear interpolated tool path is taken from the standard CL file. The tool path may also be generated in some other way selected by a device user. The basic part of the system consists of developed and implemented postprocessor, without using the postprocessor generator. The postprocessor contains inverse kinematics and device design parameters. Since tool path in the CL file should have sufficiently fine interpolation, the programs are long because the linear interpolation of the serial machine is used as joint interpolation for the device itself. The program is therefore transferred by communication between the PC and CNC machine and can be verified during idle running of the device. The motion range of driving axes has been already checked in the postprocessor. The testing of the device in this phase included:

- Verification of the system for programming and communication.
- Cutting tests by machining various test pieces, figure 7.
- Analysis of the device workspace reconfigured with the new strut lengths and/or new platform, etc.

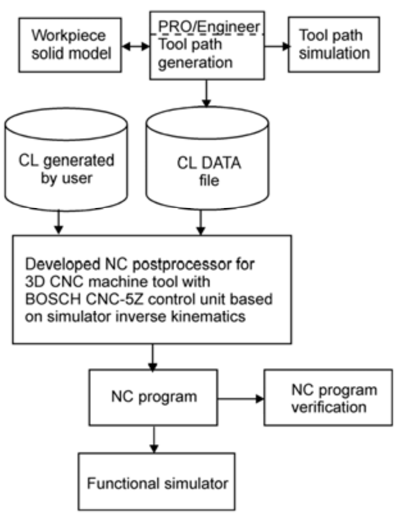


Figure 6: Device programming system.

Figure 7: Test piece made of foam.

3. NEW DEVICE CONCEPTS

After the installation and testing it became clear that the initial version of the device with parallel kinematics has fully justified the expectations. The analysis of possible application of the device on different vertical and horizontal three-axes serial CNC machines has shown, however, that it is not always suitable. These disadvantages become particularly noticable in vertical serial CNC machines, in which Z axis is usually significantly shorter than the others, so that the other two axes have to be used within this range. This even more decreases device's workspace. Other possibiities of configuration of the initial parallel mechanism have therefore been analyzed.

figure 8 shows a variant of parallel mechanism with the platform in opposite octant in relation to the initial device concept shown in figure 1.

The idea of a hybrid mechanism for improving the shape and increasing of device's workspace dimensions has come, with direct copying of the movement of one serial machine axis to the platform axis, figure 9 and figure 10.

Figure 9 shows a variant of parallel mechanism device where direct connection of serial machine Z axis to parallel mechanism movable platform is achieved with the aid of SCARA mechanism. Figure 10 shows a variant of parallel mechanism device where direct connection of serial machine Z axis to movable parallel mechanism platform is achieved with polar mechanism.

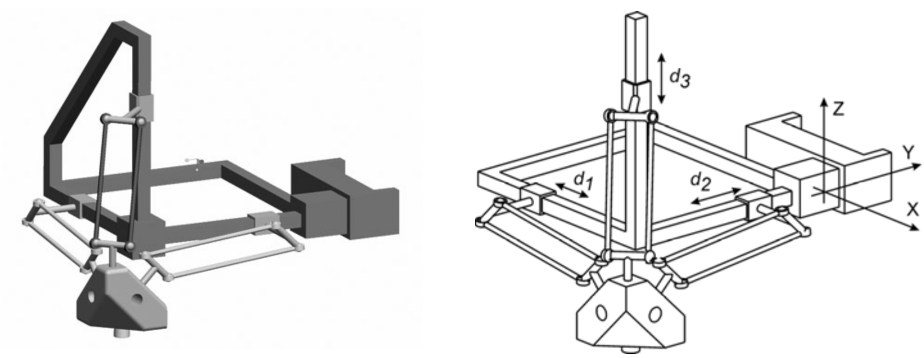


Figure 8: Device with platform on its outer side.

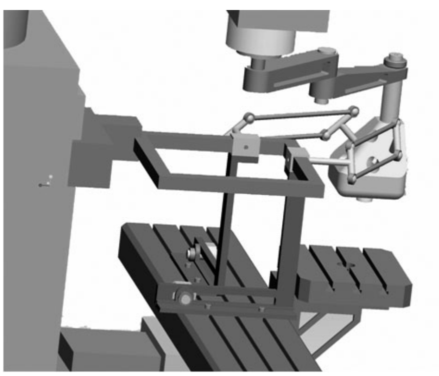


Figure 9: Hybrid device with SCARA mechanism.

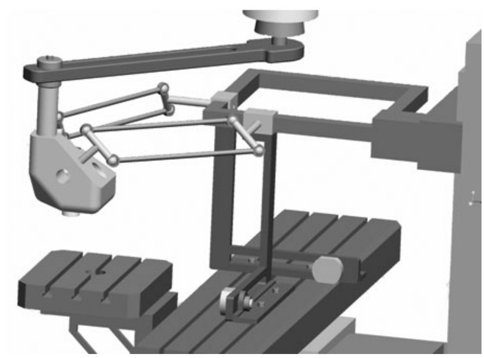


Figure 10: Hybrid device with polar mechanism.

The need that each device should have its own linear joints, as well as difficulties in transfer of movement from serial machine axes to device's joints has imposed consideration of device variants without own linear joints. In this way the complexity of the device will be significantly decreased, as well as its integration with the serial machine. Figure 11 shows the concept of such a device envisaged for implementation on horizontal machining centre. It may be noted that the guideways of X and Z serial machine axes have been used as device's linear joints, while serial machine Y axis is connected with SCARA mechanism to the device's platform. This device is in the stage of construction and testing of the system for its programming.

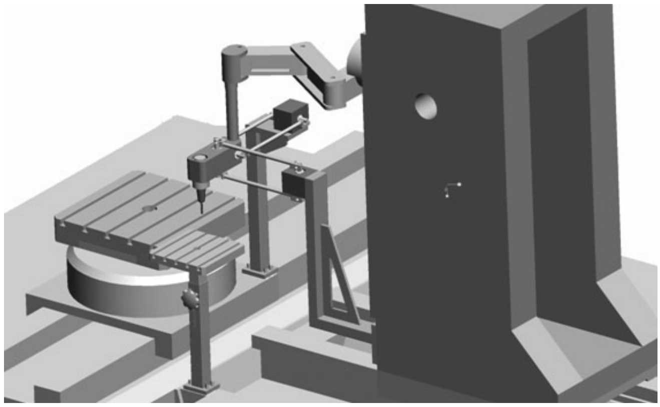


Figure 11: Hybrid device without own linear joints.

3.1 Some modeling and analysis results

Figure 12 shows geometric model with optimized parameters for the devices shown in Figures 9 and 10 if applied on vertical milling machine Lagun FTV-3CNC (X=700mm; Y=320mm; Z=150mm).

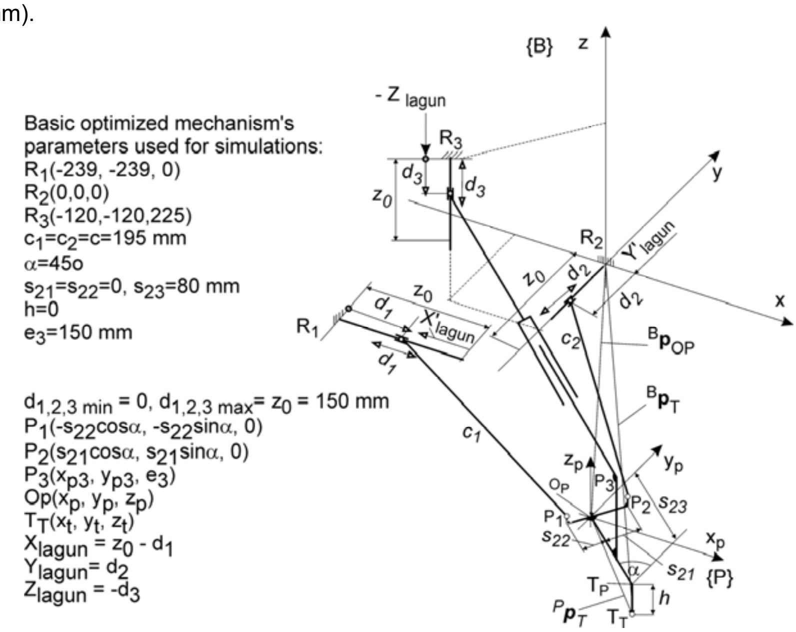


Figure 12: Geometric model of the devices shown in figures 9 and 10.

For this geometric model inverse kinematic problem has been solved according to the procedure shown in Chapter 2.1:

$$d_1 = x_P + x_{P1} - x_{R1} - \sqrt{c_1^2 - (y_P + y_{P1} - y_{R1})^2 - (z_P + z_{P1})^2} \quad (9)$$

$$d_2 = -y_P - y_{P2} - \sqrt{c_2^2 - (x_P + x_{P2})^2 - (z_P + z_{P2})^2} \tag{10}$$

$$d_3 = z_{R3} - z_P - e_3 \tag{11}$$

where d_1, d_2 and d_3 are joint coordinates of the device powered and controlled by Lagun, while x_P, y_P and z_P are the coordinates of the platform centre O_P.

Direct kinematic problem has been solved according to the same procedure:

$$z_P = z_{R3} - e_3 - d_3; \quad y_P = \frac{-B - \sqrt{B^2 - 4AC}}{2A}; \quad x_P = \frac{D_2 - D_1 - 2y_P(B_1 - B_2)}{2(A_1 - x_{P2})} \tag{12}$$

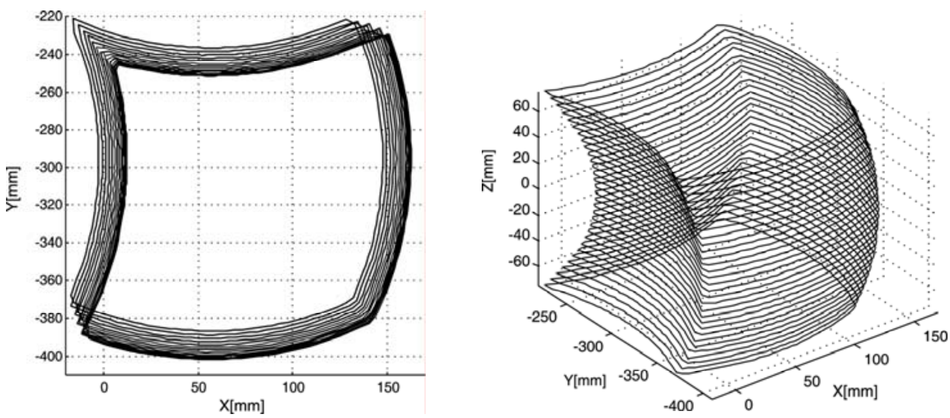
where

$A = 4(B_1 - B_2)^2 + 4(A_1 - x_{P2})^2$, $B = -4(B_1 - B_2)(D_2 - D_1) - 8x_{P2}(B_1 - B_2)(A_1 - x_{P2}) + 8B_2(A_1 - x_{P2})^2$,

$C = (D_2 - D_1)^2 + 4z_P^2(A_1 - x_{P2})^2 + 4x_{P2}(D_2 - D_1)(A_1 - x_{P2}) + 4D_2(A_1 - x_{P2})^2$, $\quad A_1 = x_{P1} - x_{R1} - d_1$,

$B_1 = y_{P1} - y_{R1}$, $D_1 = 2z_P z_{P1} + A_1^2 + B_1^2 + z_{P1}^2 - c_1^2$, $B_2 = y_{P2} + d_2$, $D_2 = 2z_P z_{P2} + B_2^2 + x_{P2}^2 + z_{P2}^2 - c_2^2$.

For optimized parameters of devices shown in Figures 9 and 10 in case of application on Lagun FTV-3CNC vertical milling machine, the shape and workspace dimensions are given in figure 13. (s_{21}=s_{22}=0, s_{23}=80).



(a) Workspace layout. (b) 3D shape and volume of the workspace.

Figure 13: Workspace of the devices shown in figures 9 and 10.

As it may be seen from figure 13 these mechanisms have greater workspace with movement range of driving axes of 150mm (net workspace in the form of a parallelepiped x=115mm, y=115mm and z=150mm), than the initial mechanism with 400mm movement range of driving axesfigure 4.

The structure of the device with optimized parameters from figure 11 is shown in figure 14 for case of application on horizontal milling machine LOLA HMC 500 (X=700mm; Y=500mm; Z=600mm) in the position Tp(0,-100,0).

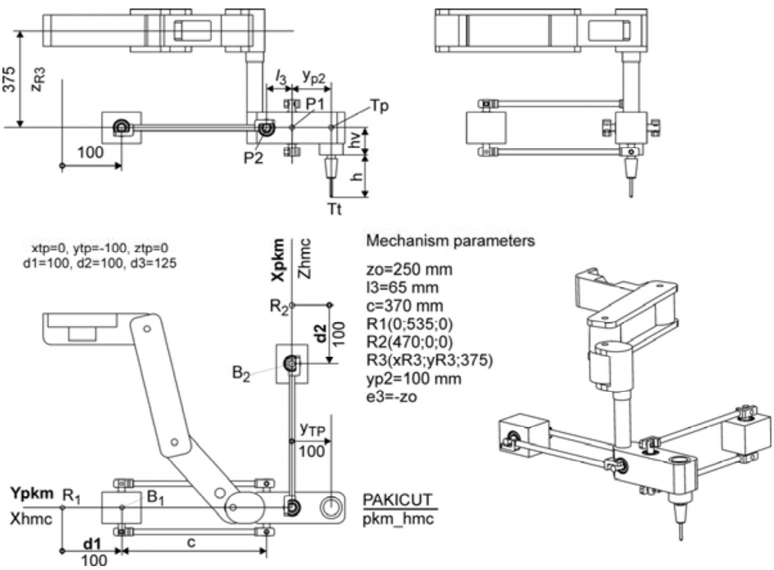
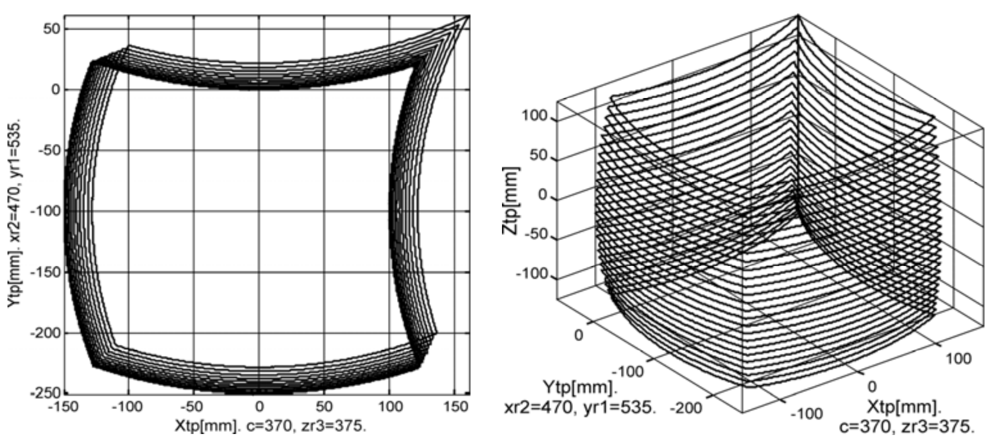


Figure 14: Structure of the hybrid device without own linear joints.

The shape and workspace volume of the point Tp are shown in <u>figure 15</u> for optimized parameters of devices illustrated in figures 11 and 14. As it may be seen this mechanism has greater workspace with movement range of driving axes of 250 mm (net workspace in the form of a parallelepiped x=215mm, y=215mm and z=250mm), than the initial mechanism with movement range of driving axes of 400mm, figure 4.



(a) Workspace layout. (b) 3D shape and volume of the workspace.

Figure 15: Workspace of the devices shown in figure 11.

4. CONCLUSIONS

The developed parallel kinematic devices integrated into 3-axis milling machine, integrate, as hybrid systems, the existing technological equipment (CNC machine tools, CAD/CAM hardware and software) and parallel kinematic mechanisms into a comprehensive and sophisticated didactic facility. Their capabilities and characteristics have shown that such devices have been an interesting and valuable R&D topic considered in Eureka project E!3239 PAKICUT. The laboratories, universities and schools may find planned commercial versions of these devices with corresponding multimedial knowledge base useful and interesting. Some of the versions could be also used for an initial familiarization of factories with the PKM, and used as training devices on which all differences between the serial and parallel kinematic machines can be identified. Details relating to these devices are also available on the web site www.cent.mas.bg.ac.yu.

5. ACKNOWLEDGMENTS

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