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parallel kinematic structures
hybrid kinematic structures
parallel kinematic machines
parallel kinematic robots

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THE DEVELOPMENT OF MECHANISM WITH HYBRID KINEMATIC STRUCTURE PROTOTYPE

This paper deals with the development of mechanism with hybrid kinematic structure called trivariant and its subsystems. Hybrid machines are characterized by connecting advantages of both type mechanisms together – high dynamics of parallel mechanisms for positioning and high flexibility and high mobility range of serial mechanisms for orientation. At our department was built the small-scale mechanism prototype used for testing, functional verification, for education and training. There was created the simulation software and control system based on standard PC for this prototype. Our prototype can be applied like small CNC milling machine but it is possible to modify it also for the manipulation with objects like robot device.

1. INTRODUCTION

Numerically controlled (NC) machine tools can be considered as a backbone and hard core of flexible automation of modern manufacturing processes. Started just after 1950, it has brought a real revolution to all phases of metalworking production [10]. The requirements posed on NC machine tools conception since the beginning till now has been continually changed. The start of HSC (High Speed Cutting) application into the practice had the most significant influence on machine tools design. With respect to the mechanical limits of machines with conventional serial kinematics, it appears as better to use for HSC just the machines with parallel or hybrid kinematic structure. Similar trends have started also in field of industrial robots.

Parallel kinematic structure represents a closed-loop mechanism in which the end-effector is connected to the base by at least two independent kinematic chains.

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Hexapod represents the best-known fully parallel manipulator. It has been investigated in many industrial applications such as machining or positioning. However, despite intensive efforts by research and industry, the commercial success of hexapod and parallel mechanisms with similar kinematic structure, has still been limited. Compared to other parallel manipulators, the primary drawbacks of the traditional 6 degree of freedom (DOF) structures are well known: their workspace-to-machine volume is small and the moving platform’s tilt angle is limited to about ±30° as a consequence of singularities.

2. THE MECHANISMS WITH HYBRID KINEMATIC STRUCTURE

When the serial and also the parallel mechanisms go to their limits we can use the mechanisms based on hybrid kinematics structure, which combine together the advantages both types of kinematics – high dynamics of parallel mechanisms for positioning and high flexibility and high mobility range of serial mechanisms for orientation. During the last decade, the mechanism with hybrid kinematic structure called tricept, has found various commercial applications, such as high-speed milling, welding and component assembling in aeronautical and automotive industry. One of these concepts is also the mechanism called trivariant, which is the main topic of this paper.

a) b)

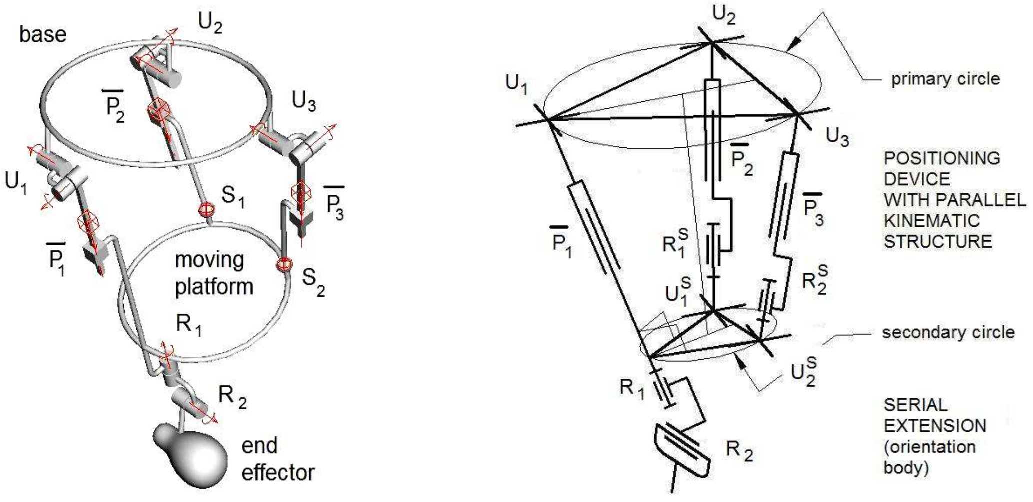
Fig. 1. Machine tool based on hybrid kinematic structure (PKM - Spain) [7]
a – configuration of horizontal milling centre Tricept 9000, b – design concept of Tricept 1005

Specialists at universities and research institute in the whole world deal with research and development in the field of parallel or hybrid mechanisms. Few years ago also the Department of Automation and Production Systems at University of Žilina began with research in this field. During this period there were designed some construction concepts of parallel mechanism, for example school hexapod and also the design project of hybrid kinematic structure trivariant which is still in progress (Fig. 5). There were also designed some different kinds of simulation software for these types of mechanism.

3. KINEMATIC SCHEME OF TRIVARIANT

Generally for the design of parallel and hybrid mechanisms can be used several base type of joints – rotational (R), prismatic (P), universal (U) and spherical (S). They can be optional connected together (different type and different number of each joint) by links and actuated by linear or rotational actuators. By designing the architecture of realized mechanism is the most important viewpoint the required shape and dimensions of the mechanism’s workspace and its stiffness [3]. In our case, we need to achieve 5 DOF and good ratio between the dimensions of mechanism itself and dimensions of its workspace. The real workspace you can see in Fig. 4.

From the viewpoint of mechanisms, the trivariant may be decomposed into the one spherical-coordinate parallel mechanism (PM) and the serial extension (SE; or also serial module) based on two rotational joints with orthogonal axes. The subsystem with parallel kinematics represents the positioning of tool center point (TCP) in mechanism’s workspace whilst the serial extension covers the orientation of end-effector. The mechanism architecture is very similar to the classical tricept. The difference lies in PM, where is one active leg aligned with one passive leg.



a) b)

Fig. 2. Designed trivariant kinematic scheme
a – original kinematic scheme, b – modified kinematic scheme (S joints replaced by RU joints)

In more detailed view, the PM consists of a fixed base, a moving platform and three active legs. Two of them are identical and based on architecture UP□S (Fig. 2 – a). The last one is different and based on architecture UP□ which means that the moving platform is direct connected to this leg (rigid connection). This leg allows only two rotational and one translational movement of the moving platform. It means that one platform’s rotation around the P joint axis and two translations perpendicular to the P joint are disabled. There U, P and S represent the universal, prismatic and spherical joint. Additionally, P□ denotes an active prismatic joint usually powered by a servomotor. The S joint at the end of each two identical legs UP□S can be replaced by one R and one U joint – it means the architecture of legs were changed on UP□(RU) but the number of DOF is still 3 (Fig. 2 - b).

4. TRIVARIANT MATHEMATICAL MODEL AND INVERSE KINEMATICS

The mathematical model of trivariant represents a description of real mechanism by system of mathematical equations. It is the basic problem of each mechanism’s control system solving. For a tool (effector) movement control by the programmed trajectory is necessary to know the functional relations between a tool centre point (TCP) and active variable of each drive. Therefore was created an inverse kinematics of machine. Inverse kinematics was solved by homogenous matrix transformation.

4.1. TRIVARIANT MATHEMATICAL MODEL

In the next section we describe the way how to get the mathematical model of trivariant prototype. All calculations are performed in the Cartesian coordinate system. One or more coordinate systems are rigid connected to each part of mechanism. Coordinate system of the frame is considered as the global coordinate system (GSS). To determine the relative position and orientation between the separate parts of kinematic structure we are used homogeneous coordinates and homogeneous transformations.

At the beginning the kinematic scheme of trivariant is decomposed into the three separate loops (Fig. 3), which can be used for calculating of whole mechanism. These loops we describe by three basic matrixes (each matrix for one loop) [2]. The solving of main loop (black arrows and the red one) transformation matrix gives us the inverse kinematics of main loop. By analogous way we obtain the inverse task of kinematics for two remaining loops.

First loop description:

$$\begin{aligned}\mathrm{Trivariant}_6^1 = {} & Trans(x,0,0)\cdot RotY(ay)\cdot RotX(ax)\cdot Trans(0,0,-z_1)\cdot RotZ(az)\cdot \\ & \cdot Trans(0,0,-z_2)\cdot RotY(ayy)\cdot Trans(0,0,-z_3,-z_4)\cdot RotZ(azz)\end{aligned} \tag{1}$$

Second loop description – actuator Nr. 1:

$$\begin{aligned}RotY(ay)\cdot RotX(ax)\cdot Trans(0,0,-z_1) = {} & M_{JOINT11}\cdot RotX(ax11)\cdot RotY(ay11)\cdot \\ & \cdot Trans(0,0,-z)\cdot RotZ(az11)\cdot RotY(ay12)\cdot RotX(ax12)\cdot M_{JOINT12}\end{aligned} \tag{2}$$

Second loop description – actuator Nr. 2:

$$\begin{aligned} RotY(ay)\cdot RotX(ax)\cdot Trans(0,0,-z_1) = M_{JOINT\,21}\cdot RotX(ax21)\cdot RotY(ay21)\cdot \\ \cdot Trans(0,0,-z)\cdot RotZ(az21)\cdot RotY(ay22)\cdot RotX(ax22)\cdot M_{JOINT\,22} \end{aligned} \tag{3}$$

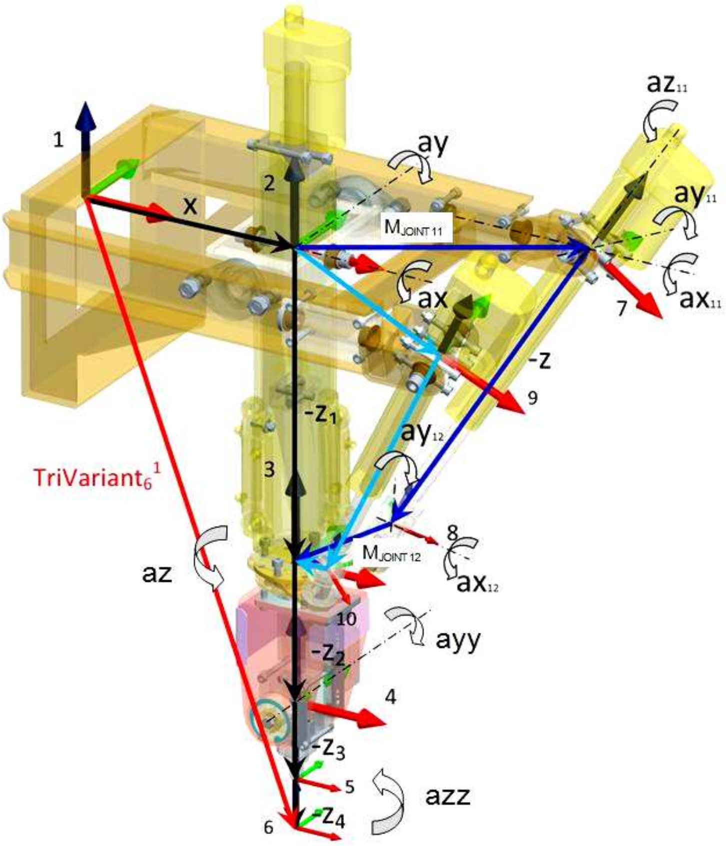


Fig. 3. Kinematic scheme of trivariant with coordinate systems (CS), movements and three kinematic loops [2]
1 – frame (GCS), 2 – central U joint, 3 – moving platform, 4 – basic part of serial extension,
5 – end-effector, 6 – tool, 7 – top-left U joint, 8 – bottom-left U joint, 9 - top-right U joint, 8 – bottom-right U joint,
$M_{JOINT\ 11}$ – linear displacement of top-left U joint, $M_{JOINT\ 12}$ – linear displacement of bottom-left U joint

4.2. TRIVARIANT INVERSE KINEMATICS

Inverse kinematics computes the joint variables corresponding to locations of the machine end-effector. In many applications those locations have got fundamental significance while the motion among them is not required with particular performances but smooth enough for the task. Those locations are usually named ‘precision point’, because they refer both to position and orientation. They are named precision points since it is required that the motion law passes through them precisely or even the motion stops there.

Calculation and control of effector’s trajectory is one of the cardinal functions of CNC control system [2]. By this is providing in machine tool a relative movement between tool and workpiece by trajectories, which are necessary to create a part with required shape, quality and with maximum repeatability. For a machining are using linear and circle interpolation and their composition to get a final tool path.

Different between convention cutting machine with serial kinematic structure and cutting machine with parallel or hybrid kinematic structure is in control of each axis. When we want to move tool from one to another place by linear interpolation we can in a case

of machine tool with serial kinematics, divide a path to particular axis and control each axis so that all axis come to this programmed point in a same time. When we composite movement of each axis, then we get a linear trajectory of tool, whereas in machine tool with a parallel (hybrid) kinematic structures we must calculate a active variable of each joint in all points of interpolated trajectory and we have to change a controlled parameters of each actuators in all this points too. Another difference is in value of feed step which can have got constant value in the case of machine with serial kinematic, whiles in the case of a machine with parallel (hybrid) kinematic must feed step have got same or smaller value then is programmed value, because in some specific tool position must be moving slower or stop and wait for a rotation of some parts of machine.

4.3. SINGULAR POSITIONS IN TRIVARIANT'S WORKSPACE

During the solution of mathematical model for trivariant was also necessary to treat encountered singular positions, it means the positions where the mechanism loses one or more DOF. We were limited only to deal with singular points lying within the workspace of mechanism. There is one singular position, which may be located at any point within the workspace. This singular position occurs by the specific configuration of the mechanism, especially when the axis of end-effector (for example axis of milling spindle) is collinear with the first rotational axis of serial extension SE. In this case, it is possible to reach the position independently of the angular displacement of first rotational joint of SE. For this situation we add a special condition into the mathematical model of mechanism which determines its behavior for this case.

5. DESIGN OF TRIVARIANT PROTOTYPE AND ITS WORKSPACE

One of the very important properties of all devices for machining or manipulation is shape and size of their workspace. Forward kinematics can be used for its determination and evaluation. The workspace was designed with using boundary positions of each parts of trivariant kinematic structure. In Fig. 4 you can see the result of trivariant workspace visualization. Since trivariant has a slightly different kinematic structure in comparison to tricept the resulting workspace is different too. By trivariant it can be possible to reach a bit higher mobility range, which can be considered as one of the advantages of this kinematic structure.

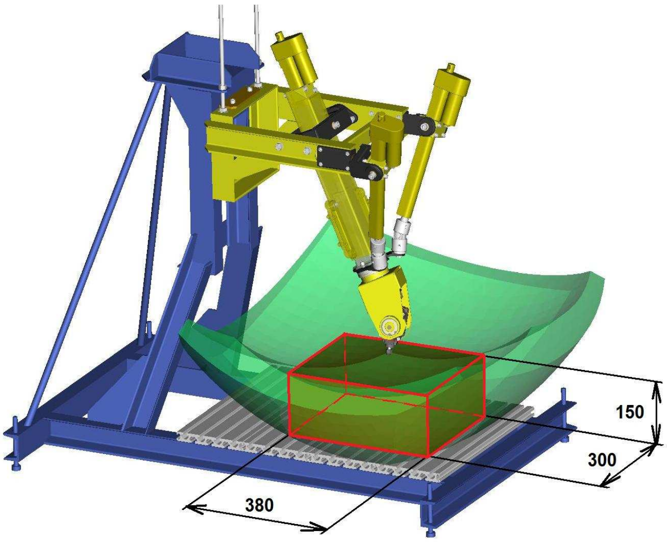


Fig. 4. Workspace of trivariant prototype

Developed mechanism prototype can be applied like machine tool (Fig. 5). The device has totally 5 degree of freedom (DOF), which is enough for the 5D milling. It is possible to apply it also like robot device for handling operations. But in this case one more rotational axis have to be added into the kinematical scheme of SE. Thereby we obtain mechanism with 6 DOF.

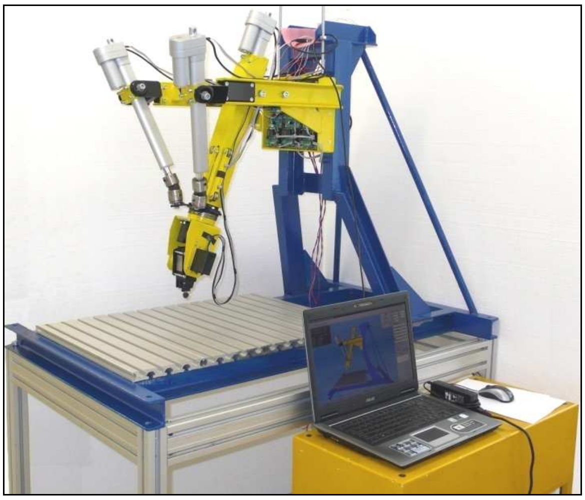


Fig. 5. Small-scale prototype of trivariant (University of Žilina)

6. CONCLUSION

The applying of mechanisms with parallel and hybrid kinematic structure in design of machine tools allows the idea of HSC machining to implement. However the progress in field of parallel and hybrid mechanisms was very markedly during last few years there are still many open problems like friction in joints, singularities, calibration etc. On the one side there are many experts which hope in great potential of parallel mechanisms, on the second side stay the other expert groups – the defenders of classical serial kinematics. Just the machines based on hybrid kinematic structure show like the best solution and alternative for the machines with serial kinematics in machining and also robotics. One of these mechanisms is also trivariant.

At the authors workplace was during the last year designed a small-scale prototype of trivariant which can work as a machine tool with 5 DOF as well as a robot with 6 DOF. One of the main purposes for development of it was the possibility to make some functional analysis of simulation software and control system designed for this type of mechanisms. In this time the building of mechanism go to the final phase. Now we would like to start the testing phase. We have to do detailed analysis of trivariant stiffness and accuracy. After the final improvement trivariant can be apply for machining and for object manipulation.

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