ORIENTATION MECHANISMS BASED ON PARALLEL KINEMATIC STRUCTURE

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Abstract:

In technical praxis there are many situations, when it is necessary to positioning or orienting of some objects. In this paper we deal with mechanisms which are used for orienting of different objects in the defined space and which are frequently called like spherical mechanisms. Their usage is very wide and heterogeneous, for example the rotational head for spindle orientation or mechanisms for workpieces orientation in 5-axis machining, flight and car simulators, mount of antennas and telescopes, etc. The most of spherical mechanisms are based on Cardan jamb, which contains two rotational axes in series (serial kinematic structure). The alternative to this type of orientation devices are the mechanisms with parallel kinematics, which are also the main subject of this paper.

Keywords: parallel kinematic structure, orientation mechanisms, spherical mechanisms

1. INTRODUCTION

Mechanical systems that allow a rigid body (here called end-effector) to move with respect to a fixed base play a very important role in numerous applications. A rigid body in space can move in various ways, in translation or rotary motion. These are called degrees of freedom (DOF). The total number of degrees of freedom of a rigid body in space cannot exceed 6 (for example three translation motions along mutually orthogonal axes and three rotary motions around these axes). The position and the orientation of the end-effector (its pose) can be described by its generalized coordinates; these are usually the coordinates of a specific point of the end-effector and the angles that define its orientation. As soon as it is possible to control several degrees of freedom of the end-effector via mechanical system, this system can be called a robot [2].

1.1 Parallel robots

Parallel kinematics structure (PKS) is mechanism with closed kinematical chain that consists of the base, platform and at least two reciprocally independent leading legs. Leading chains are also ordered parallel towards base and platform. Kinematical chains arrangement of parallel kinematic machines is more varied compared to serial kinematics [10]. For that reason parallel kinematics are usually presented in the specialized literature through typical construction with six degree of freedom, which is called hexapod (Fig. 1).

Generally, we can divide the mechanisms with parallel kinematic structure by the type of realized motion into the three basic groups:

- mechanisms for positioning and orientation (2, 3, 4, 5 or 6 DOF),
- mechanisms for positioning (1, 2 or 3 DOF),
- mechanisms for orientation (1, 2 or 3 DOF).

We are going to deal with mechanisms which make it possible the orientation or orientation together with positioning of different objects.

2. THE BASIC KINEMATIC STRUCTURE OF PARALLEL MECHANISMS

The DOF number and the realized motion type of all parallel mechanisms depend on the type and architecture of kinematic structure which consists from apportionable parts connected together. We must know from which type of each part it is possible to choose.

2.1 The basic structural elements used for PKS

Type of connections (joints)

Joints and actuators are the basic structural elements of each parallel mechanism. Generally, it is possible to choose from these types of joints (ordered by increasing DOF) [2]:

- revolute (R) – 1 rotational DOF,
- prismatic (P) – 1 translational DOF,
- universal (U) – 2 rotational DOF,
- ball-and-socket (S) – 3 rotational DOF.

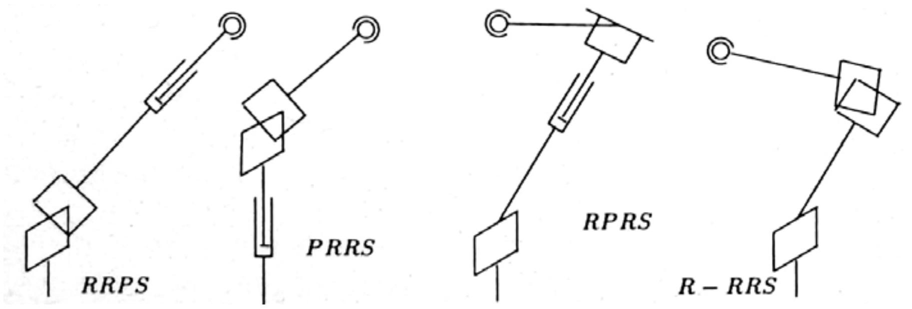
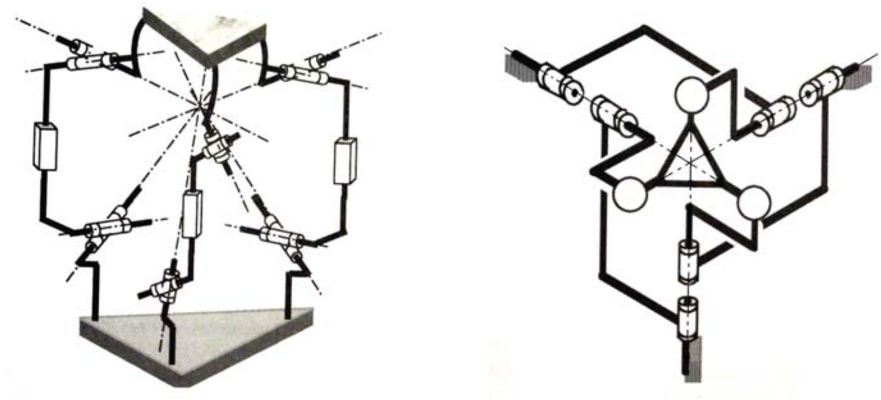


Figure 1 *The basic types of motion generators (kinematic chains) used for parallel mechanisms [2]*

Type of used actuators

For manipulators using revolute actuators the consensus is that electric motors should be used whilst for manipulators using linear actuators several options are possible: pneumatic, hydraulic, electrical, magnetic, piezoelectric, shape memory alloy, or even magnetostrictive.

2.2 The basic kinematic principles of orientation mechanisms



a) b)

Figure 2 *The difference between the Wrist 3-UPU and Spatial Mechanisms 3-RRS [15]*
a – mechanism Wrist 3-UPU, b – Spatial Mechanism 3-RRS (Agile Eye – classic form)

Spatial Mechanism 3-RRR (Figure 2, b and Figure 3, d)
This mechanism is also known as Agile Eye by Gosselin. The 3-RRR spatial mechanism is composed of three legs of kinematic chain RRR, where R represents a rotational joint, and the underline indicates that the joint is actuated. The centers of all the joints coincide in the same point **P**, which is the rotation center. This mechanism is over-actuated.

Wrist 3-UPU (Di Gregorio) (Figure 2, a)
The 3-UPU wrist platform is composed of three legs, where each leg has three joints: a universal joint that links the lower platform with the leg, a prismatic joint that is used by the actuator, and a universal joint that links the upper platform with the leg. The 3-UPU wrist robot has some manufacturing and mounting characteristics that become this robot in a spherical robot, different from the **3-UPU translational** robot. In this case one of the axes of all the universal joints intersects in a common point **P** and the other two axes are parallel. This is cause that the platform has the behavior as a spherical joint with three DOF's.

The manipulators allowing three rotations about one point represent an interesting alternative to the wrist with three revolute joints having convergent axes classically used for serial robots.

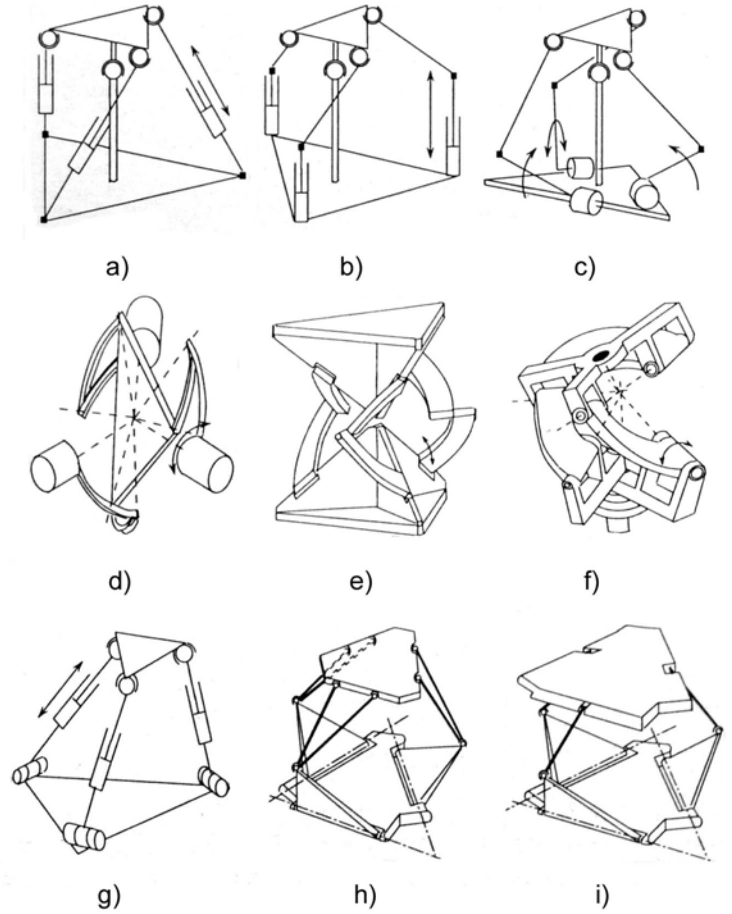


Figure 3 *The basic kinematic principles of orientation mechanisms with PKS [2]*
a, b, c – the mechanical principles of mechanism with central mast and final number 3 DOF,
d, e, f – three different realizations of Agile Eye with 3 DOF,
g, h, i – three different concepts of Wrist with 2 DOF

2.3 Hexapod - general mechanism with 6 DOF for positioning and orientation

Hexapod can be considered as the general parallel mechanism with complex DOF because it produces 6 DOF of the general rigid body motion. Hexapod is mechanism, which is compound by the six parallel arrangement legs with variable length, whose are connecting base with platform. All connections between base, legs and platform are realized by universal joints but often we can see the design with universal joints used for connection of legs to the base and between legs and platform are ball-and-socket joints.

Considering to this arrangement platform has six degree of freedom, what allows her sliding in axis: x, y, z and rotation around those axes φ_x, φ_y, φ_z. Final motion of platform is set up by contemporary change of lengths of all legs. It follows that, motion of one leg evocate spatial and angle position of platform in all axes. Those behaviors are modal for all parallel kinematics. Machines with parallel kinematics structures are characterized as nonlinear three-dimensional system not respecting superposition principle of fractional movements [10, 11].

At Department of Automation and Production Systems at University of Žilina were developed school hexapod and its control system in last few years. The general scheme, virtual model and real construction are presented on Figure 4. Now we work on the project of TriVariant, which represent hybrid kinematic structure.

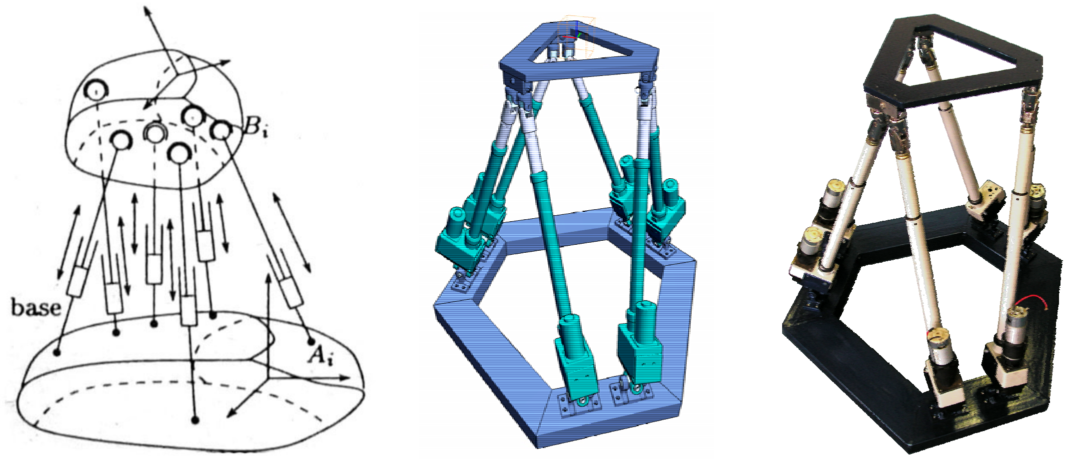


Figure 4 *The general 6 DOF parallel mechanism (Hexapod) developed at University of Žilina - physical model, 3D model and real construction [10, 11]*

3. APPLICATIONS OF ORIENTATION MECHANISMS WITH PKS

3.1 Parallel mechanisms for high speed camera orientation

The Agile Eye is a 3 DOF (or 2 DOF) 3-<u>R</u>RR spherical parallel manipulator developed in the first place for the rapid orientation of a camera system or other light objects. Its mechanical architecture leads to high velocities and accelerations.

Design process of mechanism contains (this process is general – for all parallel mechanisms):

- the development of kinematic model of this manipulator,
- the geometric optimization in order to determine the dimensional parameters which would produce the best accuracy for the mechanism,
- design of complete dynamic model,
- design of control system.

Agile Eye with 3DOF

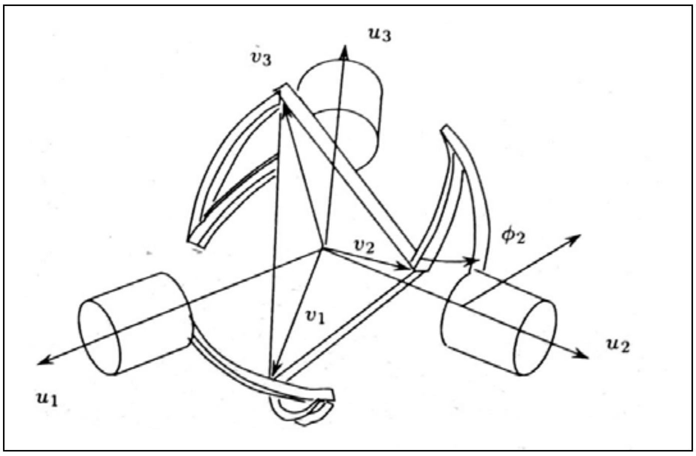


Figure 5 *Scheme and model of 3DOF Agile Eye [6]*

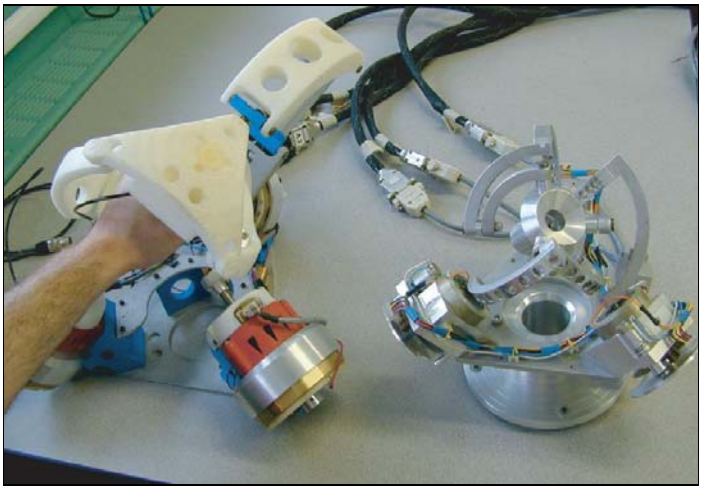


Figure 6 *Agile Eye with 3 DOF (Laval University, Canada) controlled by haptic device [6]*

One of the prototypes of this mechanism was built in 1993 at Laval University in Canada. The workspace of this Agile Eye is superior to that of the human eye. The miniature camera attached to the end-effector can be pointed in a cone of vision of 140° with ±30° in torsion. Moreover, due to its low inertia and its inherent stiffness, the mechanism can achieve angular velocities above 1 000 deg.s^{-1} and angular accelerations greater than 20 000 deg.s^{-2} which are beyond the capabilities of the human eye.

One of the most interesting topics of research related to the Agile Eye is the analysis of its singularities. Surprisingly, the singular positions of the Agile Eye are independent from the chosen branch (there are a total of 8 branches). Note that for general 3-RRR spherical parallel manipulators, the singular positions are strictly dependent on the chosen branch. In addition, in the Agile Eye, there exist four poses for the mobile platform in which arbitrary finite motions of the actuators do not produce any output at the mobile platform. Finally, the direct kinematic problem of the Agile Eye allows 8 assembly modes [6].

Agile Eye with 2DOF - the simplified version

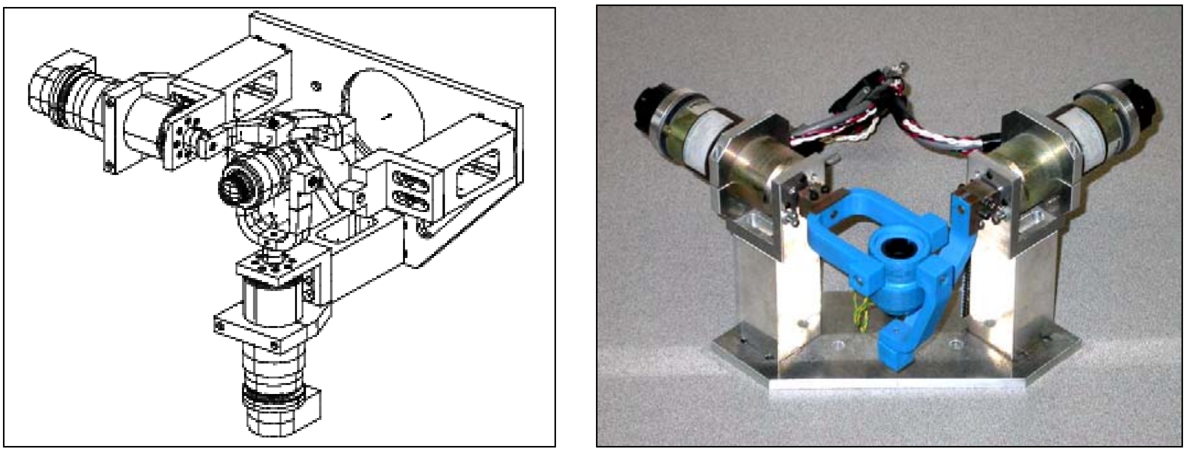


***Figure** 7 Scheme and model of 2 DOF Agile Eye developed at Laval University [6]*

A simplified 2-DOF version of the Agile Eye has been also recently developed at Laval University and patented. Its obvious advantages are very low cost, trivial inverse kinematics, simplified direct kinematics (only four assembly modes), enlarged workspace, and trivial singularity analysis. Another interesting feature is that the orientation of the camera (the mobile platform) is completely specified by an azimuth and an altitude angle, i.e., there is no torsion.

This architecture was also used in collaboration with the Computer Vision and Digital Systems Laboratory (CVDSL) for the development of an agile stereo pair involving two rapid, precise and independent cameras enabling three-dimensional vision [6].

HexaSphere (ČVUT Praha) – redundant parallel mechanism

As was written the singular positions and their removal are one of the more interesting and also more difficulty topics for research in area of parallel mechanisms. Under the term "singularity" is often known a specific position of mechanism in which it is not exactly assigned which direction is preferred for next move. In this position mechanism lost the stability (geometrical singularity). Besides this type of singularity we know also other types – the position in which the velocities go without end or are not defined.

It is obvious that by action of mechanism we must avoid these points. But there exist some ways for solution. One of them is using of the redundant kinematic structure. In this case is mechanism overactuated. It is interesting to have more actuators than necessary because actuator forces can be reduced and singularities avoided. Then we have better possibility of control over the mechanism movement.

Mechanism HexaSphere is also designed as the redundant – it has 6 actuators (like classical Hexapod) but only 3 DOF (3 rotational axis). This mechanism was developed in the last time and its creators present that it can reach angle $\pm 100^{o}$. For example classical Hexapod can reach angle only about $\pm 40^{o}$ [17].

We can see that redundant kinematic structures have better behavior and properties in comparison to the non-redundant mechanisms. The disadvantage of this approach is that we must use the high number of actuators. Then the decision to use redundant kinematic structure must be reasonable.

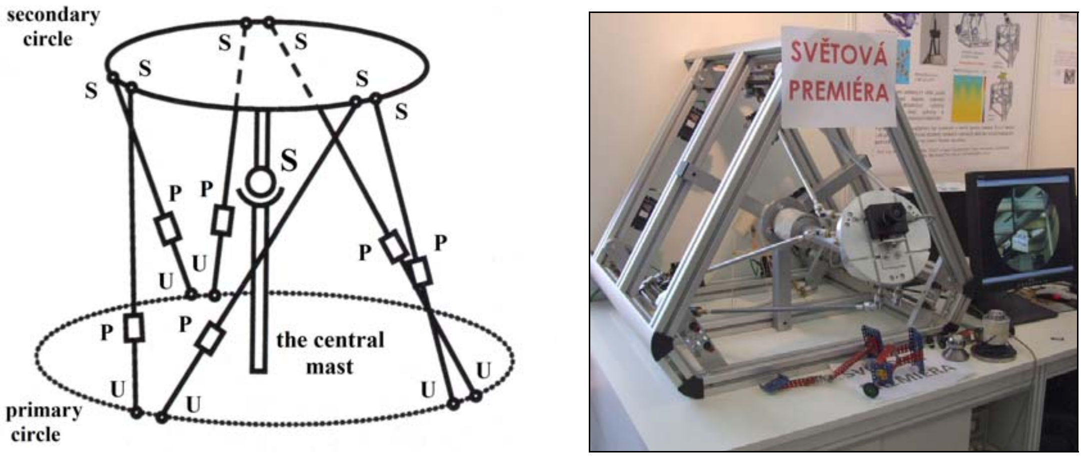


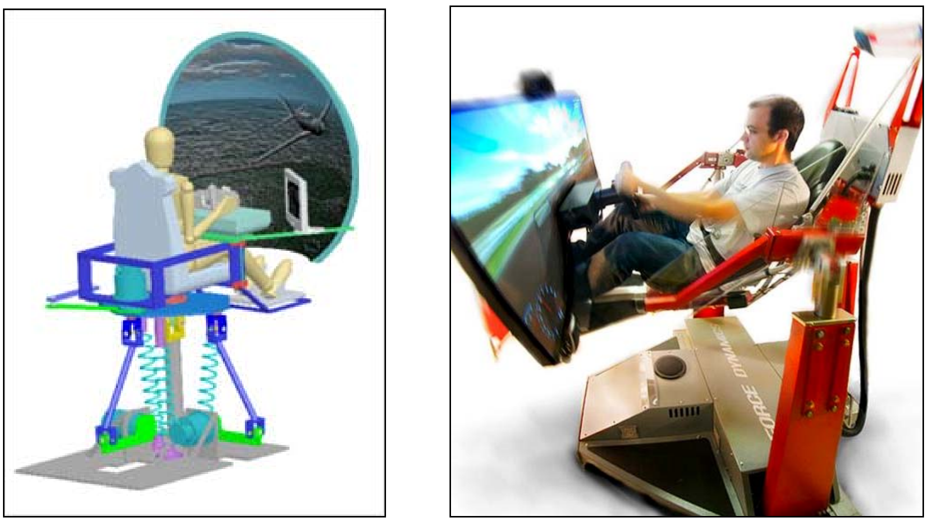
Figure 8 *HexaSphere – scheme and model of redundant PKS for camera orientation [17]*

3.2 Parallel mechanisms used for Flight or Car Simulators

The area of motion simulation especially flight or car simulators (Figure 9) is currently one of the main commercial application of parallel mechanisms (besides of parallel mechanism applied on machine tools). These simulators albeit very popular and providing very realistic cues, have several notable disadvantages including a restricted workspace (mainly with respect to rotation), prohibitive cost, limited operation and they require high maintenance.

To eliminate these disadvantages, the laboratory at Laval University has designed a low-cost flight or car simulator which has a limited number of degrees of freedom and a simple architecture. This simulator is able to create motion cues realistic enough to allow it to be used for the training of pilots (during the first phases of their training).

The laboratory makes also several research studies including a comparison of cues which can be created by various 3-DOF architectures so as to choose the most suitable architecture. Then, a design of a mechanism was achieved incorporating several innovative ideas, such as static balancing and the use of rotoid electric actuators [6].



a) b)

Figure 9 *Flight simulator and car simulator with parallel kinematic structure [6, 7]*
a – flight simulator (Laval University), b – car simulator (ForceDynamics)

The flight simulator developed at Laval University has 2 legs - types RRU and RUS, and one passive Hooke joint on which the seat, controls and screen are mounted. The legs allow rotations to be carried out around a cone, while a motor added to the platform allows the platform to pivot in a plane normal to it. Thus a range of motion of ±60 degrees is possible.

The other type of simulator is a car simulator which is made by company Force Dynamics (Figure 9). It was designed with respect to simple mechanical construction, small dimensions and low costs. It is designed as the tripodic kinematic structure, which can make 2 rotational motions and 1 translational motion of seat. Servo system is based on networked 3-axis digital servo drive which controls three Force Dynamics actuators. Actuator motors provide 2,3 kW peak and 2300 N of peak thrust each; actuators are Force Dynamics ball-screw struts with 18° of travel. Maximum driver weight is 110 kg. Raised center of rotation provides superior onset cueing compared to existing motion systems, and reduces parasitic forces that cause motion sickness [7].

3.3 Parallel mechanisms for technological operations

As was written, one of the main applications of these orientation parallel mechanisms is the machine industry, concretely the machining operations. There is possible to take the advantages of parallel mechanisms like high stiffness, high precision, high dynamic behavior (high velocities and accelerations) for 3D HSC (High Speed Cutting) milling operations of shape-complicated parts.

Sprint Z (DS Technologie, GmbH) – Tool orientation

One of the best examples of these machines is the milling centre called Sprint Z (DS Technologie, GmbH) which is used in aeronautic industry for 3D HSC milling of aluminum parts. This machine is based on parallel mechanism with 3 linear actuators and it can realize 2 rotational (when each leg goes independently) and 1 translational motion (when all legs go as one rigid part). During this system it is possible to reach conical workspace with angle ± 45^{o} (or 50^{o}) [16].

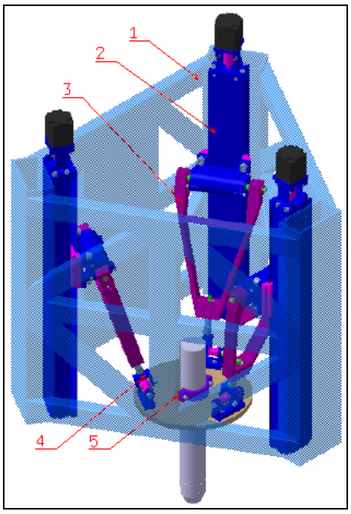


Figure 10 *Orientation mechanism for 3D technological operations*
a – Sprint Z – mechanism for 3D HSC milling operations for aeronautic industry [16],
b – Orientation mechanism for unconventional technologies designed at University of Žilina [12]

Orientation Head with PKS for 3D thermic cutting (University of Žilina)

One year ago on the same principle was the 3D cutting head built at our department. In this case were as the motion units selected the electrical linear actuators with ball screws. Ball screws transform the rotational energy of electromotor to the rectilinear motion of coulisse. From these coulisses the power are transferred to the fixed limbs during revolute joints. The movable platform with fixed tool is connected to the each limb trough one ball-and-socket joint. The great advantage of this construction is fact that there is no torsion of media supply (tubes and cables) by rotation of platform (these parts have only bending stress). In addition we can use the free inside space for media supply placing (guide of electric cables, tube for cooling system and tube for necessary gas media) [12].

9. CONCLUSION

Orientation of objects is beside the object positioning in technical praxis one of very important operations. In the past the Cardam jamb was the most widely used solution for orientation operations.

PKS development is short – run compared with long – run machinery with serial kinematic structure. Whereupon it is possible to expect, that in the future will arise more and more projects supporting PKS research [8, 10].

Due to common interest in obtaining information about development of new technologies in mechanical industry, was realized idea of creation mechanism with parallel kinematics and design simulating program which enables to analyze these mechanisms.

The use of this type of mechanism started, however, only when the first flight simulators were built. During 1960's, the development of the aeronautics industry, the increase in the cost of pilot's training, together with the need to test new equipment while not flying, brought researchers to look into mechanisms with several degrees of freedom that could simulate a heavily loaded platform with high dynamics (for example the whole cockpit of a plane). The manipulator mass is important for dynamics because the disturbing effects (for example the Coriolis force) decrease as the mass of the moving equipment decreases. All those constraints make the use of serial manipulators difficult, because their bandwidth is generally small.

It is necessary to understanding of parallel kinematic structures behavior and also to try using this type of mechanism for the next innovations of devices in praxis - for example HSC tool machines, robots, simulators, etc. [14].

During the last 15 years more than 200 different machines (prototypes, studies) based on parallel kinematic worldwide have been designed and built. In this phase the Hexapod was the dominant design, practical test/ applications and comparisons with state-of-the-art serial kinematic machines (SKM) were often missed or not sufficiently executed [2].

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