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THE CONCEPT OF HSC MILLING MACHINE WITH HYBRID KINEMATIC STRUCTURE APPLICATION

ABSTRACT:
This paper describes the concept of high speed cutting (HSC) milling machine based on hybrid kinematic structure. 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. For the application for HSC milling operation we select the mechanism called trivariant. This mechanism is similar to the well known and top-selling concept represented by various realization of tricept. At our department were designed few alternatives and selected the best one, there was built the first small-scale mechanism prototype used for testing, functional verification but also for education and training. Designed was also the simulation software and control system based on standard PC for this prototype. Our prototype is designed like small CNC milling machine but it is possible to modify it also for the manipulation with objects like robot device. According to the application (milling machine or robot) mechanism can work with 5 or 6 degrees of freedom.

KEYWORDS:
machine tools, parallel kinematic structure, hybrid structure, milling, high speed cutting

INTRODUCTION

For the past few years extensive research activities have been conducted in the area of machines with parallel kinematic structure for application as machine tools. Many of these new machines are intended for high speed milling.

Serial milling machines may one day find their limits in high-speed milling due to their limited dynamic characteristics. Indeed, the major drawback of a serial structure is that it consists of a pile of actuated joints; hence the mass on board for the axis underneath can be huge. This is mainly the reason why parallel structures are of interest in milling: in order to go faster.

Such structures have been developed since 1980 for robotic tasks, while the first parallel kinematics machine tool appeared only 14 years later. Since then, a lot of papers have been published that deal with the potential of these structures in milling. The objective of this study is to show the potentialities of parallel structures in milling and especially in high-speed milling of free form surfaces, in comparison to serial structures.

Parallel kinematics structures have been used with success for robotic tasks since the early 1980s. Since the first presentation of parallel kinematics machines (PKM) in 1994, very few are used nowadays in industry, and when it is the case, they mainly achieve drilling operations. However, the dynamics of these structures could be of great interest for high-speed milling as their acceleration potential is much higher than that of serial structures.

PARALLEL KINEMATICS STRUCTURES AND MACHINES

A parallel mechanism is a closed-loop mechanism in which the end-effector is connected to the base by at least two independent kinematics chains [1, 2].

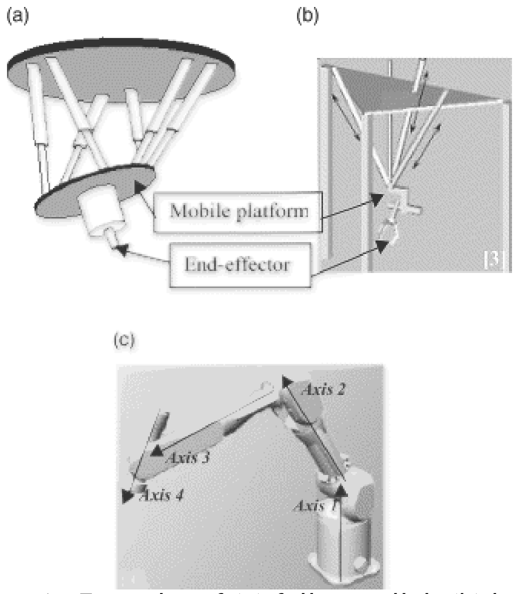

Figure 1 - Examples of (a) fully parallel, (b) hybrid parallel and (c) serial (anthropomorphic) mechanisms

One can classify these parallel mechanisms into two main families:

- *Fully parallel mechanism: a mechanism with an n-degrees-of-freedom (DOF) end-effector connected to the base by n independent kinematics chains, each having a single actuated joint (Fig. 1(a)).*
- *Hybrid parallel mechanism: a mechanism with an n-DOF end-effector connected to the base by m (m<n) independent kinematics chains, each having one or more actuated joints (Fig. 1(b)).*

Parallel manipulators are in "contrast with" serial manipulators, which are just a pile of actuated joints.

The story of parallel structures is not simple; however, here are the main dates:

1813: Cauchy works on the first parallel mechanism called the Octahedral.

1947: McGough builds a mechanism similar to the Octahedral that he uses to test tires in different positions.

1965: Stewart develops this mechanism for flight simulators; here arises a well-known structure: the Stewart platform or Gough-Stewart platform (hexapod family). At this time, he imagines the possibility to develop this structure for machine tools or platform drilling.

1979: MacCallion designs the first mechanism that allows fine positioning, of interest in assembly tasks. It marks the beginning of the use of parallel structures for robotic tasks like pick and place [3].

Late 1980s, early 1990s: Numerous papers try to solve the different problems caused by these new architectures (calibration, accuracy, etc.]).

1994: The Variax (by Giddings and Lewis) is the first parallel kinematics machine tool, which is presented at the IMTS of Chicago.

Late 1990s, early 2000s: Many prototypes of PKM have been developed, but very few papers have been published dealing with their suitability in milling [1].

PKS APPLICATIONS

Parallel kinematics structures are particularly interesting as they can offer, in theory, great dynamics characteristics (i.e. high accuracy, high rigidity and high speed) while allowing a great load carrying capability. Hence, they are quite interesting to use in different domains like positioning devices, motion generators, and ultra-fast pick and place robots [2].

Depending on the task to be carried out, a structure will be more adequate than another. Indeed, for assembly tasks, the Delta is one of the most common robots encountered, as it is an ultra-light structure allowing great accelerations [3]. This parallel structure is composed of three parallelograms, which entirely constrain the orientation of the mobile platform in order to allow it only to translate (3 DOF) as shown in Fig. 2(a). In the same manner, hexapod structures are often used for flight simulators (Fig. 2(b)).

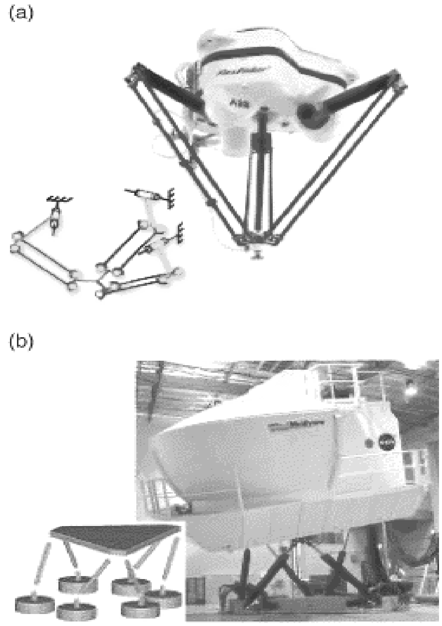

Figure 2 – (a) ABB's FlexPicker (Delta robot); (b) NASA's flight simulator (Hexapod)

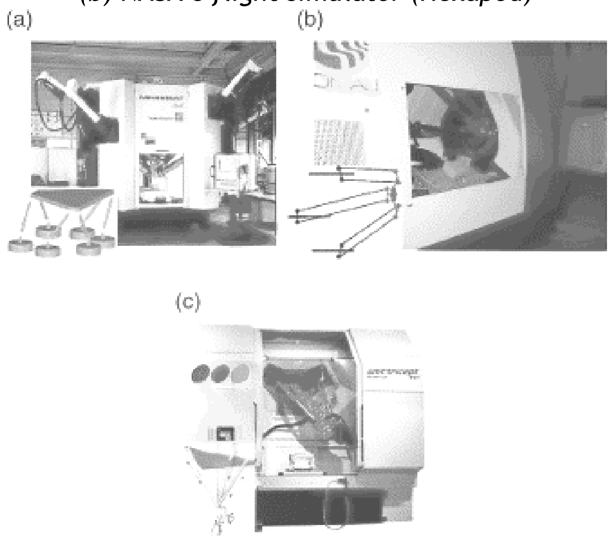

Figure 3 - Examples of PKM: (a) 6X; (b) Urane SX; (c) Tricept

In milling, the development of such structures is of great interest, especially for high-speed milling, as all the axes support the tool. Hence, the mass supported by each axis is less important with a parallel structure than with a serial structure for which the axis underneath supports the mass of the other axes plus that of the tool. Moreover, serial structures find their limits in terms of acceleration; hence, the great dynamics performances of parallel structures (high accelerations) will help in going faster.

PARALLEL KINEMATICS MACHINE TOOLS

Since 1994, many prototypes based on all kinds of structures have been developed (hexapods like the 6X developed by Mikromat, linear Delta robots like the Urane SX developed by Renault Automation), hybrids like the Tricept developed by SMT Tricept and etc. – Fig. 3).

Different studies and point of views, based on theoretical criteria (workspace volume, stiffness, etc.), have been given on the weakness of each parallel structure [4, 5]. However, as Merlet pointed out [2], the major problem encountered with the use of parallel structures in milling is due to the fact that all the advantages are only potentials. Any real parallel robot will present, in practice, impressive performances only if all its components (either hardware or software) present a high level of performance.

Hence, not all the prototypes of PKM developed are nowadays able to mill pieces in materials like aluminum alloy or steel. Among those that can, we can quote mainly Tricept of SMT Tricept (Sweden), Sprint Z3 of DS Technologies and Cincinnati (Germany and USA), 6X of Mikromat (Germany), CMW300 of CMW (France), Hermes of Fatronik (Spain), and P800 of Metrom (Germany).

In the same way, among the prototypes quoted before, only very few are nowadays used in industry. The most commercialized parallel kinematics machine tool is the Tricept from SMT Tricept. This CNC machine tool is used in automotive (e.g. General Motors, Renault, Volkswagen) and aerospace industries (e.g. Boeing) for milling, drilling, laser welding, and assembly. According to SMT Tricept, its strength, stability, and flexibility make it well suited for machining applications, especially in aluminum alloy [6].

In [7], the authors have done a synthesis of the main PKM that can be encountered in industry and research institutes. Thanks to a survey, they have been able to collect information on 46 PKMs; however, very few manufacturers gave the repeatability and accuracy of their machines. All this leads to a certain difficulty in estimating the potential of such machine tools. A recent study has been done in the UK, within the context of the EU CRAFT project RAMOULDIE, in order to compare the machining performance of the Variax (hexapod structure) with conventional 3- and 5-axis machine tools [8]. The authors have shown the difficulty in comparing machine tools which have different structures and different numerical controllers (NC).

So far, their conclusion is that for the test-piece and the criteria chosen, the hexapod has a similar level of accuracy but no better, which is already a great leap forward. However, more studies need to be done on other PKM in order to make a generalization if possible, or at least show the interest, or not, in such structures in milling.

DEVELOPMENT OF HYBRID MECHANISMUS

Hybrid kinematics structure combines 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 [9].

DESIGN OF MECHANICAL PART OF HYBRID MECHANISMS

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 or tree rotational joints with orthogonal axes. The subsystem with parallel kinematics represents the positioning of tool centre 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. Kinematic scheme of trivariant hybrid structure is in figure 4.

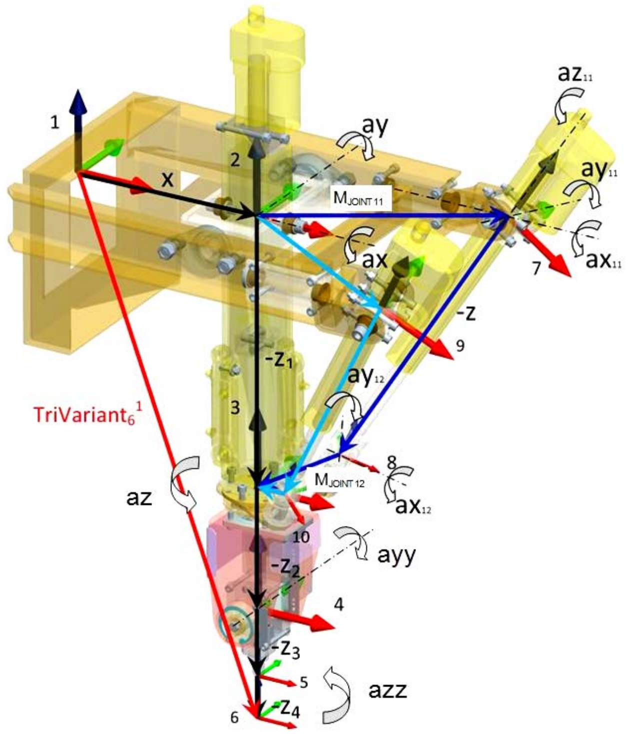

Figure 4 - Kinematic scheme of trivariant hybrid structure with coordinate systems (CS), movements and three kinematic loops: 1 – frame (GCS), 2 – central U joint, 3 – moving platform, 4 – basic part of serial extension, 5 – end-effector, 6 – tool, 7 – top-left U joint, 8 – bottom-left U joint, 9 - top-right 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.

After the end of design phase we have started the building of real mechanism prototype. We would like to apply it for machining operations, concretely milling.

The device has totally 5 degree of freedom (DOF), which is enough for the 5D machining. It is possible also to apply it like robot device for handling operations. But in this case one more rotational axis have to add to the kinematical scheme of SE.

Thereby we obtain mechanism with 6 DOF. In this time building of mechanism is finalized but the testing of all mechanical and also electrical components is still in progress. According to this point and also to the fact, that it is realized like a first prototype for practical verification of designed control system, there is a difference between real and theoretical value of accuracy. In the next period we will try to increase the mechanisms accuracy.

SIMULATION SOFTWARE

Simulation software was created for computer analyses of machine with hybrid kinematic structure. Software allows simulation kinematic properties of Trivariant machine and off-line computer control of tool movements. When the tool is moved from one point to another, software calculates all point of this trajectory and orientation of tool axis which are shown on figure 5.

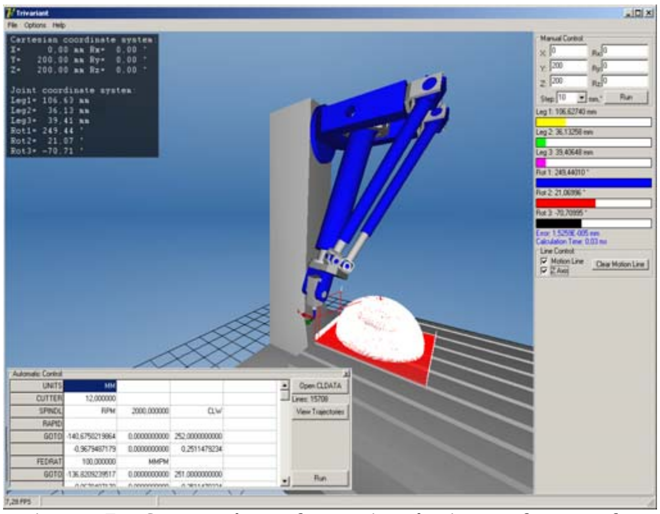

Figure 5 - Screenshots from simulation software for trivariant - main graphic window

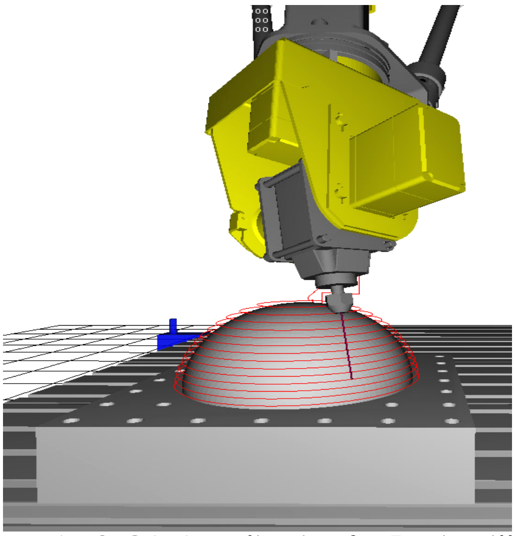

Figure 6 – CL DATA application for 5-axis milling

In each point are calculated important parameters by inversion kinematic of Trivariant machine and computed data are recorded into a graph. Position and orientation of Trivariant base in a simulation space can be changed in dependence on used frame of machine.

In control system is use next parameter: correction of tool length – this parameter is used for tools with a different length with a same control program.

Kinematic visualization is created by importing a STL file of each part of machine to the OpenGL.

CL DATA APPLICATION FOR TRAJECTORY DESCRIPTION

Designed simulation software allows two regimes of work - manual and automatic control of mechanism. Because the manual control is toilsome and time-consuming it seems like more advantage to use the CL DATA generated by appropriate CAM system for trajectory generation.

We can use the CL DATA for describing of the cutting process by application of mechanism like CNC tool machine. If we want to apply the mechanism for manipulation, it is possible to use CL DATA like universal "meta-language" for describing of movement between each position.

CONTROL SYSTEM DESIGN

Control system is built on the base of standard PC with OS Windows and simulation software of Trivariant, which allows off-line programming, simulating activities of this hybrid kinematic structures and consecutive control of machine by data obtained during simulation.

During simulation can by trajectory controlled manually or automatically. In automatic mode are for trajectory planning used CL DATA generated by CAM system (in our case Pro/Engineer).

Trajectory of Trivariant movement is planed with velocity profile which is presented on the figure 5. Classical trapezoidal velocity profile was supplemented by continuous change of velocity for jerk-less movements.

System Architecture - there are two distinctive PC-based control system architectures which are widely being implemented in industries. Firstly, the PC-based control system which the PC itself is the Machine Control Unit (MCU) where is connected to the system. Secondly, a PC-based control system which uses a PC connected a motion controller.

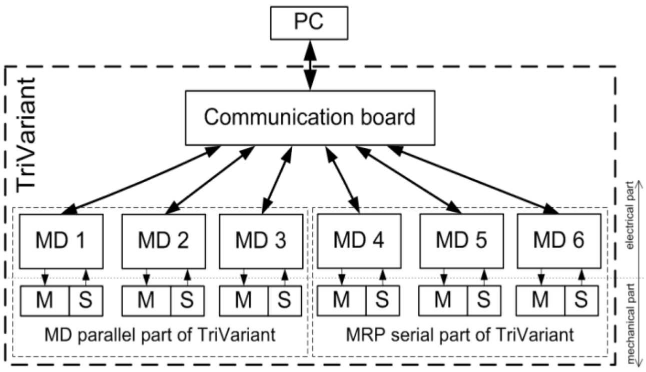

Figure 7 - Block diagram of designed control system

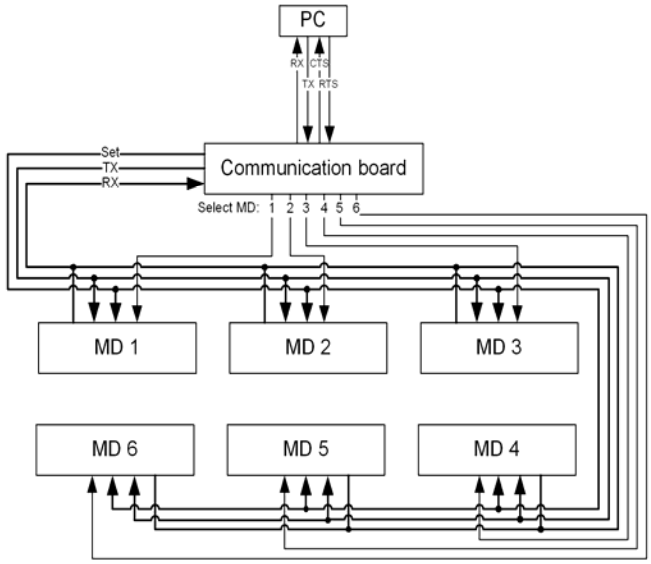

Figure 8 - Communication interfaces in control system

For this kinematic structure we needed design and built a control system. Main request on control system of Trivariant was universality, openness and simplicity of control system.

Base on this request was designed following modular conception of control system (Fig. 7, 8) [9].

CONCLUSION

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.

Software designed for simulation and control of trivariant's prototype allows two working modes - triavariant as a machine tool with 5 DOF as well as a robot with 6 DOF. Designed algorithm interpolates a tool trajectory and in each point of trajectory calculates all necessary values for machine control and for visualization by proposed inversion kinematic of trivariant. Trajectory can by controlled manually or automatically during the simulation. CL DATA generated by CAM system (in our case Pro/ENGINEER) are used for trajectory planning in automatic mode. Functionality of simulation SW and control system was verified on prototype developed in author's workplace.

Developed mechanism prototype can be applied like machine tool (figure 9).

The device has totally 5 degree of freedom, which is enough for the 5D milling.

Figure 9 - Small-scale CNC machine tool builds on trivariant hybrid kinematic structure

It is possible to apply it also like robot device for handling operations. In this case one more rotational axis has to be added into the kinematical scheme of SE, the serial extension must have 3 DOF. Thereby we obtain hybrid mechanism with six degree of freedom.

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REFERENCES

[1] TERRIER, M., DUGAS, A., HASCOËT, J.-Y.: *Qualification of parallel kinematics machines in high-speed milling on free form surfaces. International Journal of Machine Tools and Manufacture, Volume 44, Issues 7-8, June 2004, Pages 865-877*

[2] J.P. MERLET. *Les robots parallèles, Edition Hermès (1990)*

[3] I. BONEV, *Delta parallel robot—the story of success, Parallel MIC, 2001, available form: http://www.parallemic.org/Reviews/Review002.html, accessed October 2003*

[4] F. Xi, D. Zhang, Z. Xu and C.M. Mechefske, *A comparative study on tripod units for machine tools. International Journal of Machine Tools and Manufacture 43 (2003), pp. 721–730*

[5] A. HERRERO, M. ZATARAIN, X. ALMANDOZ, *Development of a five-drive parallel kinematics machine. In: (2000) CD ROM (Ref. B16)*

[6] *http://www.smttricept.com, accessed April 2003*

[7] M. WECK AND D. STAIMER, *Parallel kinematic machine tools—current state and future potentials. Annals of the CIRP 51 2 (2002), pp. 1–13*

[8] M. GELDART, P. WEBB, H. LARSSON, M. BACKSTROM, N. GINDY AND K. RASK, A direct

comparison of the machining performance of a Variax 5 axis parallel kinetic machining centre with conventional 3 and 5 axis machine tools. International Journal of Machine Tools and Manufacture 43 (2003), pp. 1107–1116

[9] *ĎURICA J.: Vývoj riadiaceho systému pre paralelnú kinematickú štruktúru (The Development of Control System for PKS). Disertation thesis, University of Žilina, Slovakia, 2009*

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