DIDACTIC PROTOTYPE OF A MACHINE TOOL BASED ON A PARALLEL KINEMATIC MECHANISM

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Abstract. *In the past recent years Parallel Kinematic Mechanisms (PKM) have attracted a lot of attention from academic and industrial communities due to their potential applications not only as robot manipulators but also as machine tools. Traditionally, these systems are employed as flight simulators for pilot training or even people entertaining. From the analysis of their typical topologies, it can be observed that they are composed by two or more closed kinematic chain mechanisms. In general, they demonstrate a higher performance than serial kinematic mechanisms, once the last ones present deficiencies related to structural stiffness, load capacity and positioning accuracy. On the other hand, parallel kinematic mechanisms are much more rigid, accurate and have higher load capacity and, therefore, can be lighter. Besides, when these mechanisms are used as machine tools, they are able to produce workpieces with very complex geometries, giving shapes and surfaces which would be difficult to obtain from conventional or even NC machine tools. This article deals with a type of parallel kinematic mechanism with four degrees of mobility that allows positioning and orientation of the platform (table) that supports a piece to be machined. This article also presents the mechanism mathematical model, describes the prototype built, shows technical specifications of its subsystems and comments its future applications.*

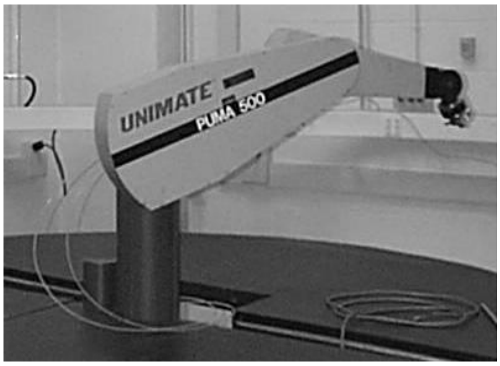
Keywords: *Mechanisms, Machining centers, Robotics*

1. INTRODUCTION

A Parallel Kinematic Mechanism (PKM) is a mechanical system in which the end-effector (mobile platform) is connected to the base by at least two independent closed-loop kinematic chains (Merlet, 2000). In general, it demonstrates a higher performance than a serial kinematic mechanism, once the last one presents deficiencies related to structural stiffness, load/weight ratio and positioning-orientation accuracy. On the other hand, parallel kinematic mechanisms are much more rigid, accurate and have higher load capacity and, therefore, can be lighter. Furthermore, eventual actuators errors are not additive which also contributes for its overall accuracy. The disadvantages are smaller workspace and more complexity of direct kinematic analysis (Souza, 1997).

In the past recent years, PKMs have attracted a lot of attention from academic and industrial communities due to their potential applications not only as robot manipulators but also as machine tools (Khol, 1994; Weck, 1997). While a conventional machine tool depends heavily on its supporting structure, the "Variax", manufactured by Gidding & Lewis, does not need one. The actuators form a rigid truss with five times the structural rigidity of conventional way-and-column machines. There are also no cantilevered beams as in conventional machines (Khol, 1994). Warnecke et al. (1998) also presented the development of an hexapod based machine tool. In their article, the authors compared different design variants of parallel mechanisms with regard to the load of the structures and singularity. Abbasi et al. (2000) have built a prototype of a mechanism for contour milling. The major accomplishments of their research were performance specifications for the milling task and a geometric design based on dynamic modeling results.

(a)



(b)

Figure 1 - (a) Parallel kinematic mechanism, (b) serial kinematic mechanism.

Dasgupta & Mruthyunjaya (2000) have enumerated some open problems related to PKMs. Much less research has been developed on dynamic modeling and control of different configurations of parallel mechanisms with 4, 5 and 6 degrees of mobility. Apart from this, there are very few works on the systematic design of platform manipulator and study in that direction is important for the enhancement and realization of its potential. Besides, it is needed to investigate the establishment of existence criteria for singularity-free paths with given end-postures.

Concerning to the design of control system for PKM machines, Huang et al. (2000) adopted the principle of axiomatic design of PKM control system because it gives an explicit relationship between functional requirements and design parameters of control modules.

Two problems can be distinguished for the kinematic aspects: *inverse* and *direct* kinematics (Merlet, 2000). The inverse kinematics problem deals with finding the link lengths for a given posture of the end-effector. On the other hand, direct kinematics treats on the opposite problem i.e. finding the posture of the mobile platform for given link lengths. In general, this problem has more than one possible solution. In the case of Stewart platform mechanism, there will be up to 40 different solutions which means 40 possible postures of the platform. Many authors investigate closed-form solutions for many types of PKMs (Innocenti & Parenti-Castelli, 1990; Sreenivasan et al., 1994). Another practical way to solve the direct kinematics problem is to add appropriate orientation sensors in the links enabling to compute the posture of the mobile platform (Parenti-Castelli & Di Gregorio, 1999).

Another important issue is singularity prediction. The singularities of serial mechanisms are associated with a loss in degrees of mobility and partial locking while the preponderant type of singularities of parallel mechanisms is associated with a gain in degrees of mobility and uncontrollability (Dasgupta & Mruthyunjaya, 2000). An open problem is to determine if there are singular configurations inside the workspace of the parallel mechanism (Wang & Gosselin, 1998; Merlet, 2000).

A new method for autonomous calibration of hexapod machine tool has been proposed by Zhuang et allii (2000). One of the advantages of their method is that the calibration task can be performed without interrupting the normal operation of the machine.

This article deals with a type of parallel kinematic mechanism with four degrees of mobility that allows positioning and orientation of the platform (table) that supports a piece to be machined. This work also presents the mechanism mathematical model, describes the prototype built, shows technical specifications of its subsystems and comments its future applications.

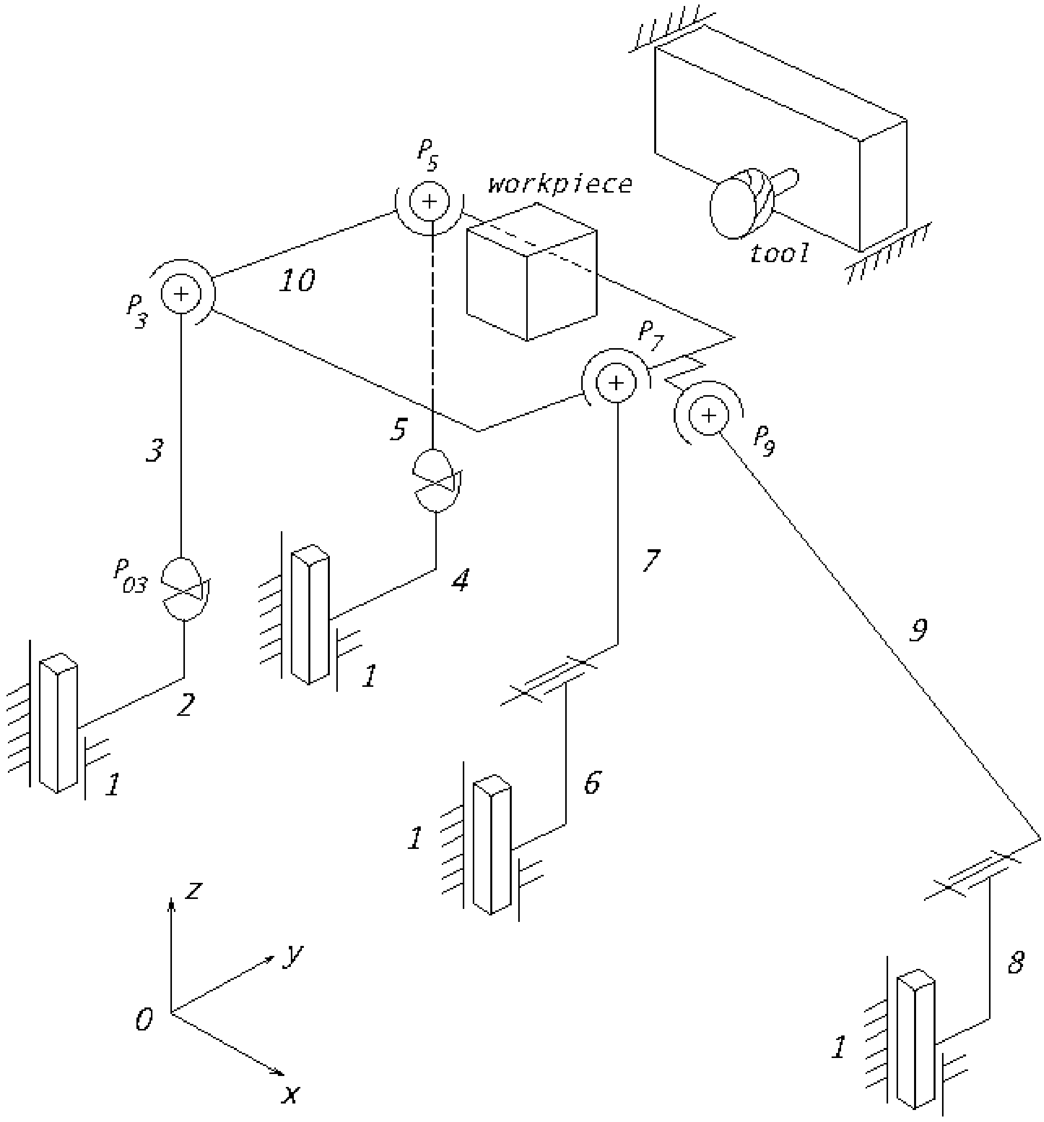


Figure 2 - Kinematic representation of the mechanism.

2. MECHANISM TOPOLOGY AND ITS MATHEMATICAL MODELING

For the task of milling contour, one appropriate configuration of a parallel kinematic mechanism is selected and presented in fig. 2. Its parts consist of a fixed base *(1)*, a mobile platform *(10)* that carries the workpiece, four constant length links *(3, 5, 7, 9)*, with one of their ends connected to the platform by means of spherical kinematic pairs (joints), and the other ends connected to parts *(2)*, *(4)*, *(6)* and *(8)* by means of universal, universal, revolute and revolute pairs, respectively. These parts, in their turn, are constrained to linear translation relative to the base by prismatic pairs. Besides, parts *(2)*, *(4)*, *(6)* and *(8)* are also responsible for the available input motion of the mechanism causing a desired output motion of the platform and, consequently, of the workpiece. Constructively, kinematic prismatic pairs can be represented by pneumatic, hydraulic cylinders, or even, screw actuators rotating by the action of electric motors.

Topics treated on the mathematical modeling of the selected mechanism are verification of available degrees of mobility and its inverse kinematic analysis. To determine the degrees of mobility of a three-dimensional mechanism, Grübler suggests a criterion based on the topology of its kinematic chains (Shigley & Uicker, 1981),

$$G.M. = 6.(n-1) - \sum_{j=1}^{5} (n-j).n_{pj} \tag{1}$$

where n is number of its parts and n_{pj} is the number of pairs that allows j degrees of freedom. According to fig. 2, n equals to 10, n_{p1} values 2, n_{p2} equals to 2 and n_{p3} values 4, resulting *four* degrees of mobility of the mobile platform *(10)*. These four degrees of mobility are represented by two translations on "x" and "z" directions, and two rotations around "x" and "y" axis.

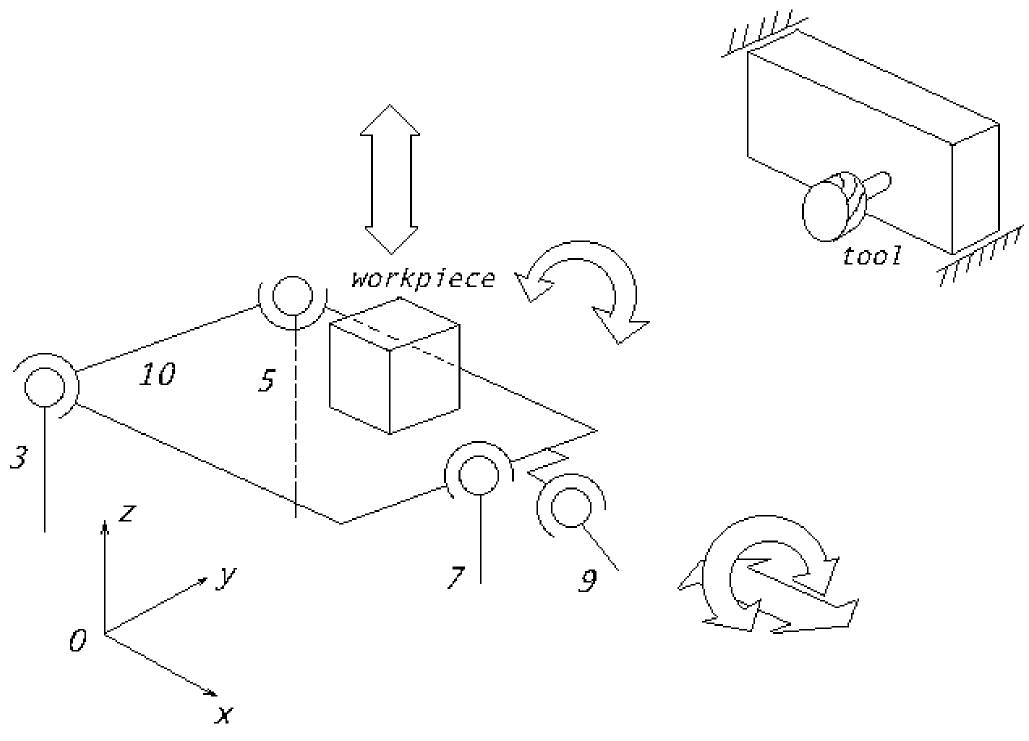


Figure 3 - Degrees of mobility of the workpiece.

In order to control the platform movement, it is necessary to establish a correlation between platform posture and angular displacements of the four actuators. Inverse kinematics analysis deals with this task. Platform posture is characterized by two linear displacements, Δx and Δz , and an angular displacement, θ around an axis defined by a unity vector $\boldsymbol{e}$ with only x and y components. Angular displacements of the actuators are represented by variables $\Delta\varphi_j$, *(j=3,5,7,9)*. These variables depend on helicoidal step of the screw axis, p_r . The relationship between variables involved is indicated in equation (2). Some important geometrical points, P_j *(j=3,5,7,9)* and G (center of mass), belong to the platform, where the subscripts "*in*" and "*fin*" indicate initial and final coordinates, respectively. Equation (2) simultaneously considers the general motion of the platform, including a translation vector [T] and a rotational matrix [R] .

$$P_{j,fin} = P_{j,in} + [T] + ([R]-I).(P_{j,in} - G_{in}) \qquad j=3,5,7,9 \tag{2}$$

where

$$[T]=[\Delta x,\ 0,\ \Delta z]^T \tag{3}$$

and I is the $3x3$ identity matrix.

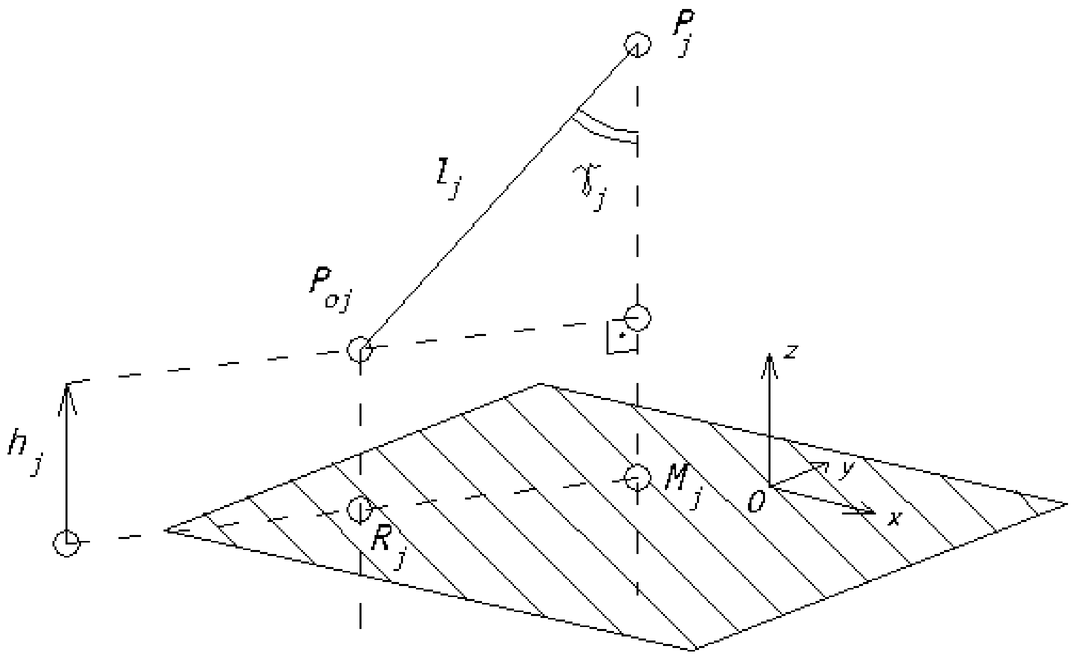


Figure 4 - Determination of linear displacement of the "j" actuator.

$$[R]=\begin{bmatrix} e_x^2(1-\cos(\Theta))+\cos(\Theta) & e_x e_y(1-\cos(\Theta)) & e_y\sin(\Theta) \\ e_x e_y(1-\cos(\Theta)) & e_x^2(1-\cos(\Theta))+\cos(\Theta) & -e_x\sin(\Theta) \\ -e_y\sin(\Theta) & e_x\sin(\Theta) & \cos(\Theta) \end{bmatrix} \tag{4}$$

where

$$\boldsymbol{e} = [\ e_x\ ,\ e_y\ ,\ 0]^T$$

$$h_j=\|P_j-M_j\|-\sqrt{l_j^2-\|R_j-M_j\|^2} \tag{5}$$

$$\varphi_j=\frac{2.\pi\, h_j}{p_r} \qquad j=3,5,7,9 \tag{6}$$

3. MACHINE TOOL PROTOTYPE

This section describes the machine tool prototype and shows technical specifications of its subsystems. The prototype built is formed by the following subsystems: actuator (A), communication (COM), control (C) and mechanical (M) ones.

The actuator subsystem is composed by four electrical AC motors, 1.5 kW power, 380 V three-phase input voltage and four frequency inverters, MOVIDRIVE model, all manufactured by SEW.

The communication subsystem employs field network concept to connect the actuator and control subsystems. It is formed by a network adapter, manufactured by Phoenix Contact, that uses "fieldbus protocol" and a cable that connect a PC computer with the four frequency inverters.

The control subsystem has hardware and software parts. About the hardware parts, they include a PC microcomputer, Pentium II, 64 MB RAM, 300 MHz, 4 GB hard disc; four angular encoders with a resolution of 4096 pulses per revolution for monitoring angular displacements and velocities of motor shafts; four end sensors that work by mechanical contact are needed to initial referencing of the four machine axis. Referring to software parts, it was developed an application written in VisualBASIC language (version 4.0) in order to define command sequence and flux control of information between the subsystems. Besides this application, there is another software, called IPosPlus, recorded in the frequency inverters memories, useful to configure and define parameters associated to the motors control (PID gains).

The mechanical subsystem is grouped by a base and the components that are fixed to it. Their components include electrical motors, flexible couplings, screw axis, columns, links, universal and spherical joints, and the mobile platform.

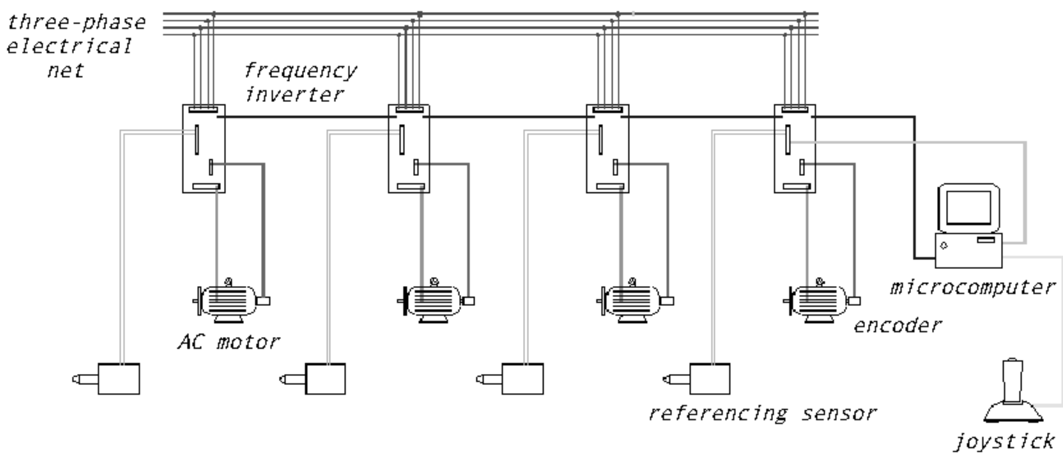


Figure 5 - Actuators and controlling subsystems.

Table 1 - Overall parameters of the prototype

Length (mm)	*1000*
Width (mm)	*600*
Height (mm)	*1500*
Total weight (N)	*900*

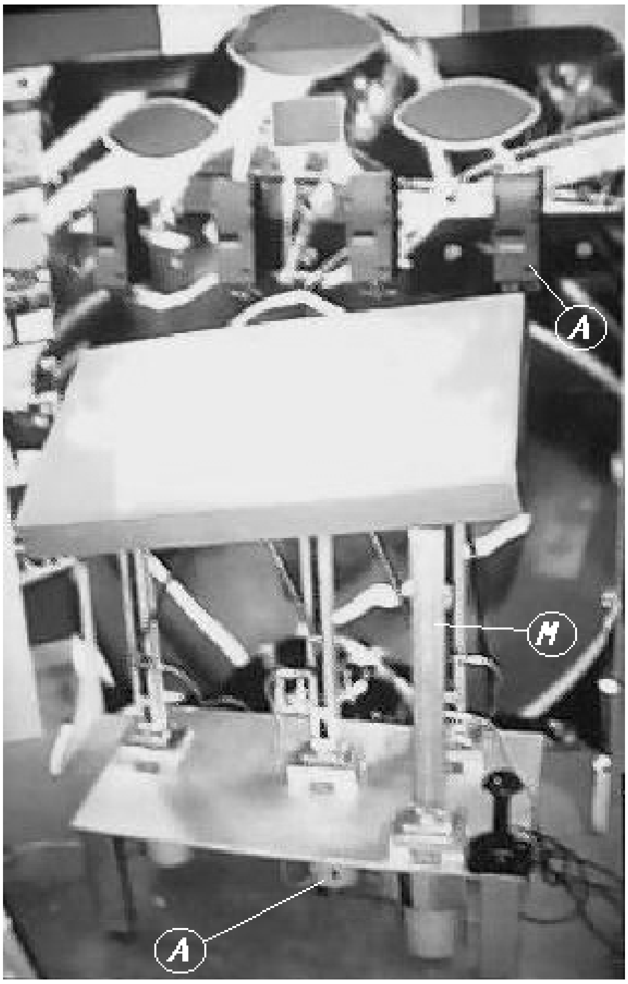


Figure 6 - Prototype built.

Table 2 -Maximum allowable kinematic variables

Maximum x-displacement (mm)	*350*
Maximum z-displacement (mm)	*500*
Maximum x-rotation (°)	*-40 to 40*
Maximum y-rotation (°)	*-50 to 30*
Maximum x,z-velocity (mm/s)	*100*
Maximum x,y- angular velocity (rd/s)	*0,2*

As it is shown in fig. 5, two operating modes were implemented. An automatic mode that allows up to four degrees of mobility and a manual mode, that uses a joystick as an input device, which allows two degrees of mobility.

4. CONCLUSION AND FUTURE WORKS

This paper presented a type of parallel kinematic mechanism with four degrees of mobility that allows positioning and orientation of the platform (table) that supports a piece to be machined. The mathematical model treats on inverse kinematic, which is an important analysis that determines the angular displacement of each one of the four actuators for a specified posture of the workpiece relative to the tool. This work also described the prototype built, showed technical specifications of its subsystems. Future works will deal with a great number of machining tests in order to analyze the prototype behavior under different operational conditions. Accuracy, rigidity, machining quality are some of the characteristics that will be evaluated.

5. REFERENCES

Abbasi, W. A., Ridgeway, S. C., Adsit, P. D., Crane, C. D., Duffy, J., 2000, "Investigation of a special 6-6 parallel platform for contour milling", ASME Journal of Manufacturing Science and Engineering, vol. 122, February, pp. 132-139.

Dasgupta, B., & Mruthyunjaya, T. S., 2000, "The Stewart platform manipulator: a review", Mechanism and machine theory, vol. 35, pp. 15-40.

Huang, Q., Hådeby, H., and Sohlenius, G., 2000, "Design of control system for PKM (Parallel Kinematic Mechanism) Machines", Third World Congress on Intelligent Manufacturing Processes & Systems, Cambridge, MA, June 28-30, pp. 322-330.

Innocenti, C., & Parenti-Castelli, V., 1990, "Direct position analysis of the Stewart platform mechanism", Mechanism and machine theory, vol. 25, No. 6, pp. 611-621.

Khol, R., 1994, "A machine tool built from mathematics", American Machinist, October, pp 53-55.

Merlet, J. P., 2000, "Parallel robots", Kluwer Academic Pub.

Parenti-Castelli, V. & Di Gregorio, R., 1999, "Determination of the actual configuration of the general Stewart platform using only one additional sensor", ASME Journal of Mechanical Design, vol. 121, March, pp. 21-25.

Shigley J. E., & Uicker, J. J., 1981, "Theory of Machines and Mechanisms", International Student Edition, Mc Graw Hill, Singapore.

Souza, C. H. J., 1997, "Análise da Posição e orientação da Plataforma de Stewart tipo 3-3 em função de erros nos atuadores", Dissertação de Mestrado, Universidade Federal de Uberlândia.

Sreenivasan, S. V., Waldron, K. J., and, Nanua, P., 1994, "Closed-form direct displacement analysis of a 6-6 Stewart platform", Mechanism and machine theory, vol. 29, No. 6, pp. 855-864.

Wang, J., & Gosselin, C. M., 1998, "Kinematic analysis and singularity loci of spatial four-degree-of-freedom parallel manipulators using a vector formulation", ASME Journal of Mechanical Design, vol. 120, December, pp. 555-558.

Warnecke, H-J., Neugebauer, R., Wieland, F., 1998, "Development of hexapod based machine tool", Annals of CIRP, vol. 47, pp. 337-340.

Weck, E. H. M., 1997, "The hexapod principle", Laboratory for Machine tools and production engineering at AAchen University of Technology.

Zhuang, H., Liu, Lixin, and Masory, O., 2000, "Autonomous calibration of hexapod machine tools", ASME Journal of Manufacturing Science and Engineering, vol. 122, February, pp. 140-148.