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A HYBRID SERIAL-PARALLEL MECHANISM FOR MILLING APPLICATIONS

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Abstract. *Parallel mechanism have some potential advantages in a comparison with serial structures, namely, high load capacity, high rigidity, low inertia, fast dynamic response and precision. Because of these features, it has been employed in flight simulators, robotic manipulators and machine tools. This work presents a 4 DOF serial-parallel mechanism to be applied in milling applications. The methodology applied in this work involves: the choice of the robotic structure, the development of the direct and inverse kinematic models and available workspace evaluation. A prototype was built, which is formed by the following subsystems: mechanical, actuator and control. This prototype was tested under the machining operations. The predicted workspace was approximately reached by the built prototype. Moreover, based on the kinematic behavior obtained by the built prototype, we conclude that there is a potential for this hybrid serial-parallel mechanism as a machine tool.*

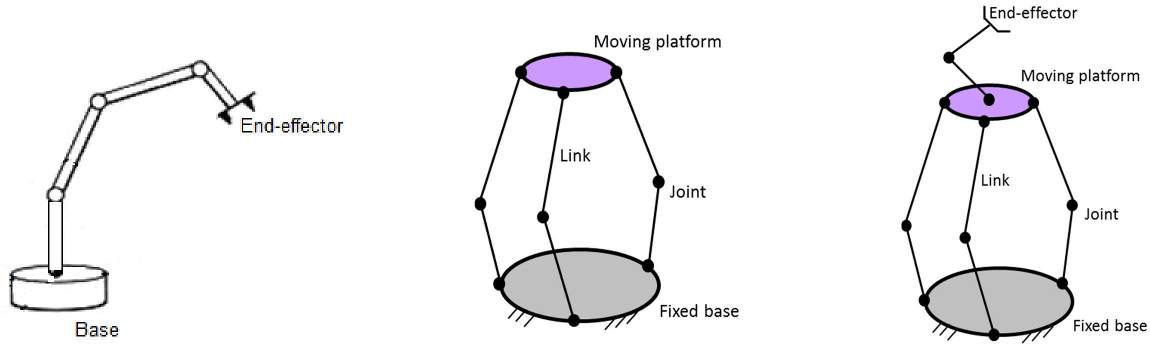
Keywords: *Machine tools, Parallel mechanism, Kinematic analysis, Workspace.*

1. INTRODUCTION

Parallel mechanism is a mechanical system with a n-DOF end-effector connected to the base by *n* independent kinematics chains, each having a single actuated joints (Bonev, 2015). Parallel Kinematic Machines (PKM) have gained attention in machine tool research area due to the fact that they present some potential advantages in comparison to Serial Kinematic Machines (SKM), such as high load capacity, high rigidity, low inertia, fast dynamic response and precision.

A hybrid parallel mechanism is a mechanism with a n-DOF end-effector connected to the base by m (m<n) independent kinematics chains. Each of them has got one or more actuated joints (Bonev, 2015). Figure 1 shows a serial mechanism, a full parallel mechanism and a hybrid parallel mechanism.

The first parallel milling machine, named Variax, was presented in 1994. It had six degrees of freedom. However, this machine presents some disadvantages, such as the small workspace volume for the machine size, as well it needs to control six axes to position the cutting tool. On the other hand, the main commercialized parallel kinematics machine tool is the Tricept (Neumann, 2004). It presents a hybrid architecture, where the parallel portion is a tetrapod with one central passive limb to constrain the motion of the moving platform. Differently to its formers ones, the Tricept has been applied for automotive and aerospace industry. Currently, many works have presented the potential of full parallel and hybrid serial-parallel mechanism to be applied in milling machines (Xie *et al*., 2014; Darvekar *et al*., 2013; Son *et al*., 2009; Glavonjic and Milutinovic, 2008; Terrier *et al*., 2004; Raszl, 2003).



(a) (b) (c)

Figure 1. a) Serial mechanism; b) Full parallel mechanism; c) Hybrid parallel mechanism

Terrier *et. al*. (2004) showed that the PKMs were able to provide the same range of quality as SKMs structure. It has the potential for milling free form surfaces and hence for high-speed milling. The tests have been conducted on four different SKMs machines and four different PKMs.

Son *et. al*. (2009) demonstrated that hybrid mechanisms are potentially attractive candidates for small 5-axis machine tool applications. Darvekar *et. al*. (2013) presented a 2-DOF PKM machine tool that can successfully perform the machining operation upon metals like high strength Aluminium alloy.

This work deals with a hybrid serial-parallel mechanism purposely conceived as a machine tool for milling operations. Initially, the mechanism topology is briefly described in section 2. Then, the position kinematics analysis and workspace are presented in section 3. Section 4 focuses in details on the built prototype. The results obtained by the prototype in machining operations are shown in section 5. Finally, the conclusions are presented in section 6.

2. MECHANISM SYNTHESIS

Topologically, it is a hybrid serial-parallel mechanism with 4 DOF. The proposed structure is based on a 3PRR planar parallel architecture, assembled on a serial base, which is able to translate in one direction. The piece to be machined is fixed on the moving platform, which is capable to execute 3 translations and 1 rotation.

In order to obtain a planar parallel architecture, a Method for Enumeration of Kinematic Structures was applied (Hunt, 1983; Tsai, 2001). In this method, the number of limbs (m) is equal to the mechanism mobility (M). Besides, the connectivity of limbs can be obtained by the equation (1).

$$(\lambda + 1)M - \lambda = \sum_{k=1}^{m} C_K \tag{1}$$

Where λ represents the degrees of freedom of the space in which the mechanism is intended to function. For planar mechanism λ = 3.

According to Tsai (2001), the connectivity of each limb (defined as the number of degrees of freedom associated with all the joints, including the terminal joints, in that limb) can be obtained using equation (2).

$$\lambda \geq C_k \geq M \tag{2}$$

For a planar 3-DOF parallel mechanisms $\lambda = 3$, M = 3 and $m = 3$. Substituting these values into equations (1) and (2) we obtain $\sum_{k=1}^{m} C_K = 9$ and $C_K = 3$, respectively. Using revolute and prismatic joints as the allowable kinematic pairs, we obtain seven possible limb configurations: *RRR, RRP, RPR, PRR, RPP, PRP,* and *PPR*, where the first symbol denotes a base-connected joint and the last symbol represents a platform-connected joint. Focusing in manufacturing facilities, we chose to assembly the actuators on the prismatic joints at the base. Then, the limb configurations could be *PRR, PRP,* and *PPR.* As prismatic joints usually are heavier than revolute joints we selected the limb PRR. Figure 2 shows skeleton kinematic diagram with six possible lay-outs for the 3PRR mechanism. An underlined letter represents an active joint, which states the presence of a prismatic actuator.

Focusing on manufacturing facilities the lay-out showed in Fig. 2f was chosen because all actuators on the prismatic joints are on the same plane. Therefore, it makes easier the final adjustment and assembly. The CAD model and the kinematic scheme of parallel mechanism 3PRR are presented in Fig. 3a and in Fig. 3b, respectively.

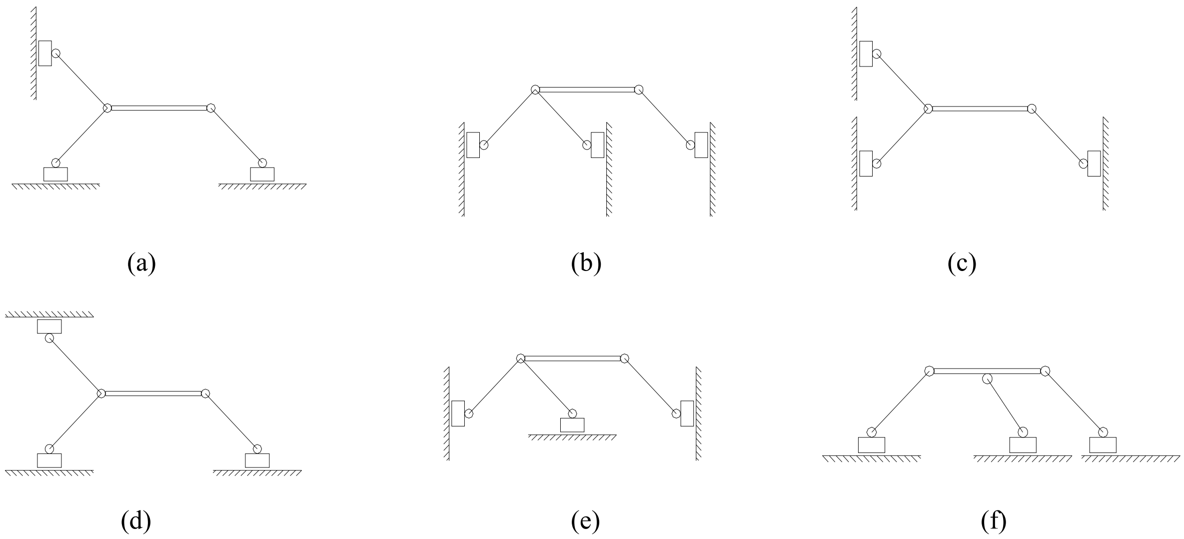


Figure 2. Possible lay-outs for the 3PRR mechanism

In the section 3 the position kinematics and workspace evaluation are analyzed for the parallel mechanism 3-PRR presented in Fig. 3.

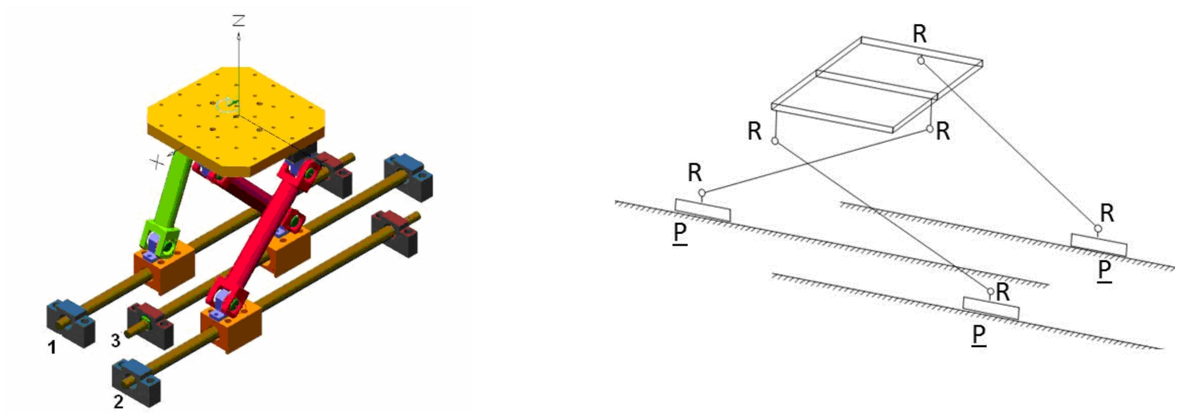


Figure 3. a) CAD model of parallel mechanism b) Kinematic scheme of parallel mechanism

3. KINEMATIC ANALYSIS

In the kinematic analysis the inverse and direct kinematic model are developed. In addition, the reachable workspace was evaluated in order to know the maximum dimensions of the piece that will be milled.

3.1 Position kinematic model

The purpose of the position kinematics model is to determine the mathematical transformation between the actuators displacements L_1, L_2, and L_3, and the moving platform location defined by the variables X, Z and θ (Fig. 4).

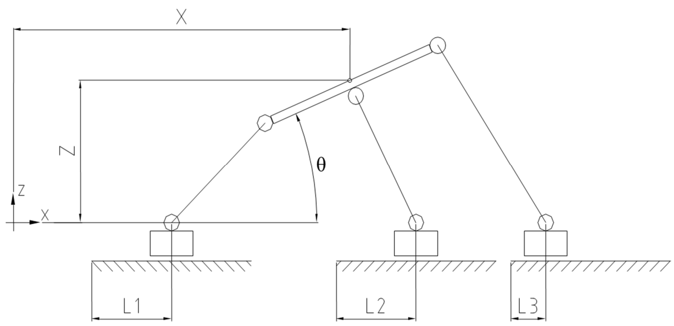


Figure 4. Employed notation for kinematic analysis

The coordinates *X, Z* define the position of a point M that belongs to the moving platform, whose orientation is defined by the angle θ. In the inverse kinematic analysis, the moving platform location is known, while the actuators displacements are unknown.

Figure 5 shows the fixed frame Bxyz and the moving frame Mxyz, which is attached to the moving platform.

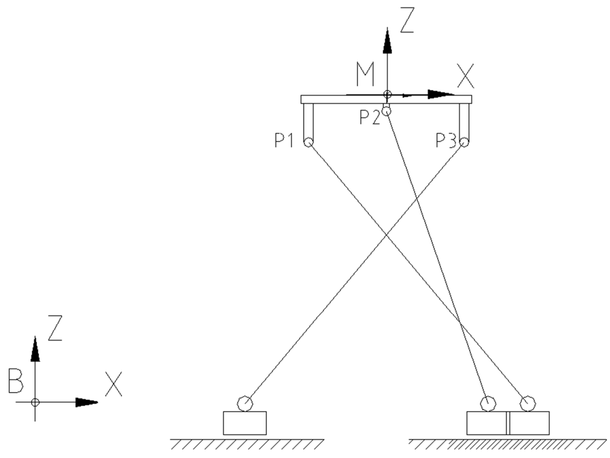


Figure 5. The fixed frame (Bxyz) and the moving frame (Mxyz)

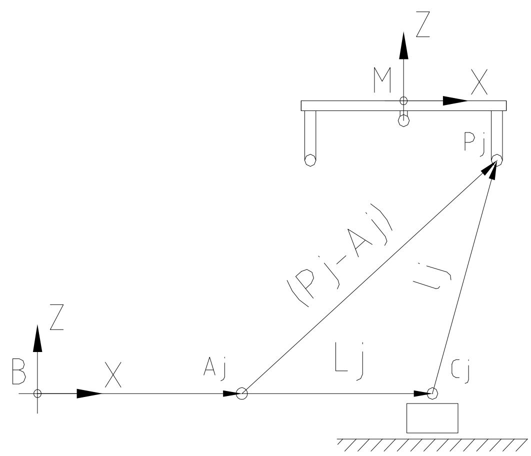


Figure 6. Coordinates of limb j (j=1, 2, 3)

The point P_j is the center of the other revolute joints in each limb j (Fig. 6). The location of this point can be described by the homogeneous transformation (Craig, 1989) of frame M with respect to the fixed frame *B*, ${}^B_M T$.

$$^{B}P_j = {}^B_M T \; {}^M P_j \tag{3}$$

Where

$$^{M}P_j = \begin{bmatrix} {}^M P_{jx} \\ {}^M P_{jz} \\ 1 \end{bmatrix} \qquad {}^B_M T = \begin{bmatrix} c\theta & -s\theta & X \\ s\theta & c\theta & Z \\ 0 & 0 & 1 \end{bmatrix}$$

According to Fig. 6 we obtain,

$$\left({}^B P_j - {}^B A\right) = \left({}^B P_j - {}^B C_j\right) + \left({}^B C_j - {}^B A\right) \tag{4}$$

The point A_j represents the origin of the displacement of each actuator j. The distance between points P_j and C_j is equal to l_j. Therefore,

$$^{B}P_j - {}^B A = \begin{bmatrix} {}^B P_{xj} - {}^B A_{xj} \\ {}^B P_{zj} - {}^B A_{zj} \\ 1 \end{bmatrix} = \begin{bmatrix} {}^B P_{xj} - {}^B C_{xj} \\ {}^B P_{zj} - {}^B C_{zj} \\ 1 \end{bmatrix} + \begin{bmatrix} L_j \\ 0 \\ 1 \end{bmatrix} \tag{5}$$

where

$$^{B}P_{xj} - {}^B C_{xj} = \pm\sqrt{l_j^2 - \left({}^B P_{zj} - {}^B C_{zj}\right)^2} \tag{6}$$

As ${}^B C_{zj} = 0$, then

$$L_j = \left({}^B P_{xj} - {}^B A_{xj}\right) \pm \sqrt{l_j^2 - {}^B P_{zj}^2} \qquad j = 1,2,3 \tag{7}$$

In Eq. (7) there are two possible solutions for each limb j. Consequently, this mechanism with 3 limbs can be assembled into eight (2^3) different configurations. These assembly configurations are only theoretical possibilities. In order to attend constructive aspects, one is preferable over the others. The chosen assembly configuration is represented in fig. 3. For this configuration, Eq. (7) reduces to Eq. (8), which represents the inverse kinematic of the parallel mechanism.

$$\begin{aligned} L_1 &= \left({}^B P_{x1} - {}^B A_{x1}\right) + \sqrt{l_1^2 - {}^B P_{z1}^2} \\ L_2 &= \left({}^B P_{x2} - {}^B A_{x2}\right) + \sqrt{l_2^2 - {}^B P_{z2}^2} \\ L_3 &= \left({}^B P_{x3} - {}^B A_{x3}\right) - \sqrt{l_3^2 - {}^B P_{z3}^2} \end{aligned} \tag{8}$$

Where

$${}^B P_{xj} = X + {}^M P_{xj}\cos(\theta) - {}^M P_{zj}\sin(\theta) \tag{9}$$

$${}^B P_{zj} = Z + {}^M P_{xj}\sin(\theta) + {}^M P_{zj}\cos(\theta) \tag{10}$$

Regarding to the direct kinematic, the actuators displacements (L_j, j=1, 2, 3) are known, while the moving platform location (X, Z, θ) is unknown. It can be obtained rearranging Eq. (7) and using Eq. (9) and (10):

$$f(X, Z, \theta, L_j) = -L_j + X + {}^M P_{jx}\, cos(\theta) - {}^M P_{jz}\, sin(\theta) - {}^B A_{jx} \pm \sqrt{l_j^2 - \left(Z + {}^M P_{jx}\, sin(\theta) + {}^M P_{jz}\, cos(\theta)\right)^2} = 0 \quad j = 1,2,3 \tag{11}$$

The Newton-Raphson Method was applied to solve the nonlinear Eq. (11).

3.2 Workspace evaluation

The discretization method was employed to obtain the mechanism workspace. In this method, first, the workspace is considered larger than the feasible workspace, discretized by a regular mesh. Then, a procedure checks whether or not each mesh node violates the physical constraints, which are represented by the bars lengths, actuators stroke and the limits of joints. Consequently, workspace boundaries are composed by a set of nodes that has at least one neighbor node that does not belong to the workspace (Bonev, 2001; Hess-Coelho *et al.*, 2005). In the workspace analysis three values of the angle θ were considered: -45°, 0o and 45°. The angle θ defines the orientation of moving platform. Figure 7 shows the regions achieved by the point M (Fig. 5) when we consider different moving platform orientations. Figure 7a shows the reachable workspace when we consider the angle θ equal to -45°, 0° and 45°. Figure 7b presents the space with blend values of reachable workspace.

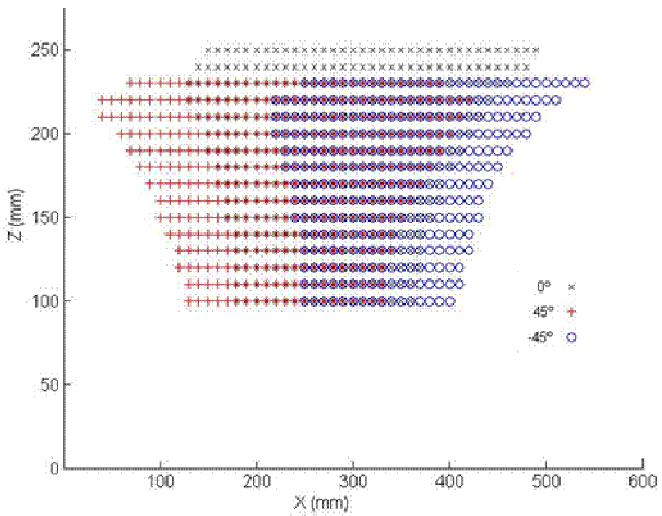
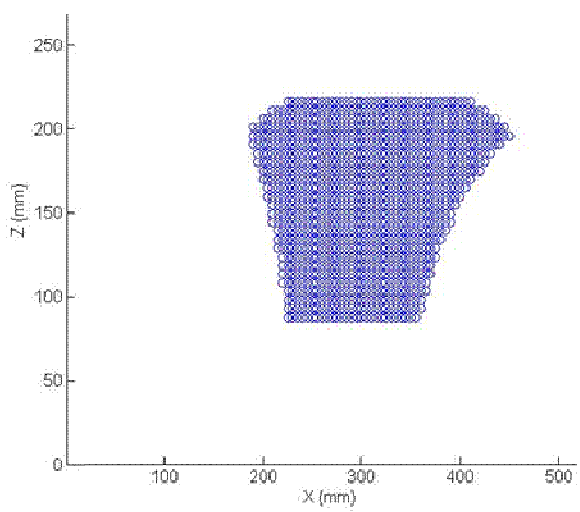


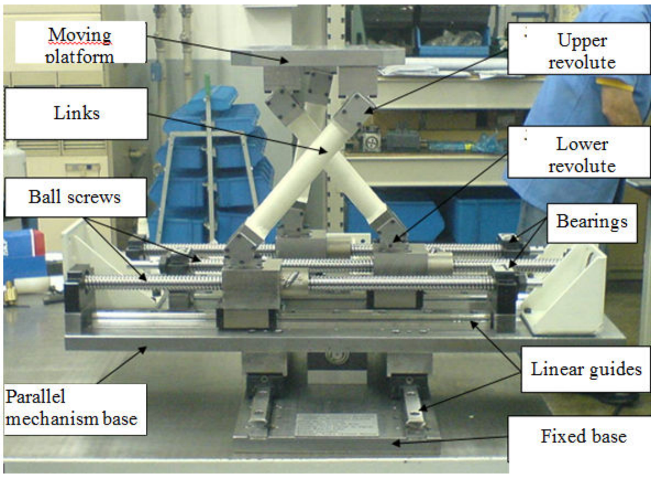
Figure 7. a) Reachable workspace considering angle θ equal to -45°, 0° and 45°



b) Space with blend values of reachable workspace

4. THE BUILT PROTOTYPE

The built prototype is formed by the following subsystems: mechanical, actuator and control. The mechanical subsystem is essentially the serial-parallel mechanism, which contains a serial base and a moving platform, both connected by three active kinematic chains (Fig. 8a). Three electrical DC servomotors and their respective drivers compose the actuator subsystem. Control subsystem includes a Numerical Control, three servomotor controllers, three angular encoders and communication cables (Fig. 8b). In addition, the inverse kinematic model written in MATLAB calculates the actuator displacements from a specified sequence of moving platform positions.



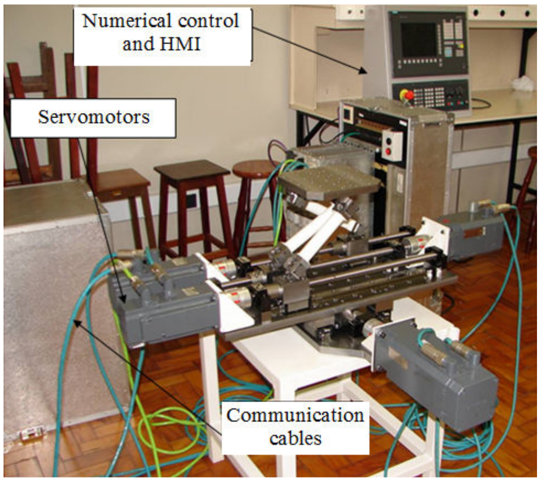


Figure 8. a) Mechanical subsystem of the prototype b) Servomotors and Communication cables

Regarding to the control system, a control drive for each servomotor was used, which transforms the Numerical Control commands into movement for the servomotor. Each servomotor has an encoder to make sure that the actual information of motor position is get back to the driver, what enables the control of position and synchronism between the motors. The encoders are sinusoidal and they work on a base of peak-to-peak reading system, making sure to get a precision of 2048 pulses x 2048 derivations of sinusoidal signal, what results to 4,194,304 pulses per revolution or 0,0000858 degree/pulse. Communication cables connect the servomotors to the control drivers.

The Siemens Sinumerik 840D Numerical Controller was used and the Siemens Sinumerik PCU50 was applied as human-machine interface.

A "Point-to-point" system is used for controlling the mechanism. The desired trajectories for the moving platform were defined. Then, applying the inverse kinematic algorithm, the location of the moving platform for the trajectories was related to the displacement of the actuators. Therefore, the numerical control only follows a list of positions for the motors. "Point-to-point" control system has a disadvantage when creating a program with a large number of command strings. However, it was the method most suitable to the needs of the concerned essay.

This control system is not ideal for applying to machine-tools when it is necessary to generate trajectories extremely complex. For a commercial system, the utilization of kinematic equations directly in the control system must be studied for allowing the trajectories to be converted in real-time.

The human-machine interface was very useful during the tests, allowing to be certified the position of each motor. This interface provides the possibility to control the motors displacements to work on a safe rotation and to not exceed the efforts limits defined in the project. Another important observation regarding to control the motors displacements is the synchronization position that must occur between them in order to obtain the exact trajectory intended at the mechanism.

5. EXPERIMENTAL RESULTS

The objective of the machining tests was to evaluate the potential of this mechanism to be applied as a machine-tool. Trajectories were chosen aiming to analyze the full-range directions of the moving platform (0º, 45º e -45º). The material of the pieces used in the tests was the Cibatool, which has a low-resistance and enables a good surface finish. The machine was a radial drill with 1900 rpm maximum rotation. The cutting tool employed was a high-speed steel top milling cutter with five cuts and 5mm of diameter. Table 1 shows the parameters used during some machining tests on the built prototype.

Table 1. Parameters used in the machining tests. The Machining direction is set up according to the axis showed in Fig. 3a.

Test	Cutting depth [mm]	Rotation [rpm]	Feed rate [mm/min]	Cutting speed [m/min]	Table inclination [degrees]	Machining direction [axis]
1st	1.0	1900	40	14.1	0º	Y
2nd	1.0	1100	40	17.3	45º	X
3rd	2.0	1900	60	29.8	-45º	X
4th	12.0	1900	60	29.8	45º	Y

The first test aimed to assess the rigidity of parallel mechanism in transverse plane. The table (moving platform) was kept at 0º and canals were cut into the work piece in transversal direction according the plane of the parallel mechanism (Fig. 9). It was verified that the moving platform presented vibration.

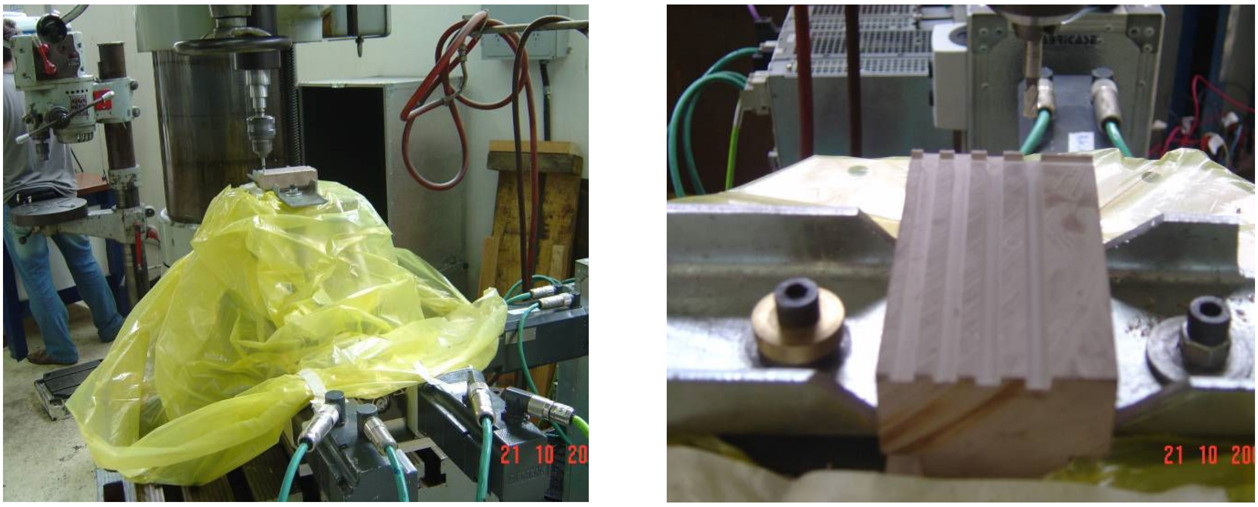


Figure 9. (a) Parallel mechanism at transverse machining plane (b) Work piece after parallel traverse machining

At the second test the table was inclined at 45º and the tool rotation was 1100 rpm, when machining in the longitudinal direction according the plane of the parallel mechanism (Fig. 10). The cutting depth and feed rate were maintained. In comparison to the first test, the second test presented a reduction of vibration in the moving platform and the surface finish of work piece was more uniform. Furthermore, it was verified that increasing the feed rate to 60 mm/min got to improve the overall stability of the assembly. This feed rate was adopted to the later tests.

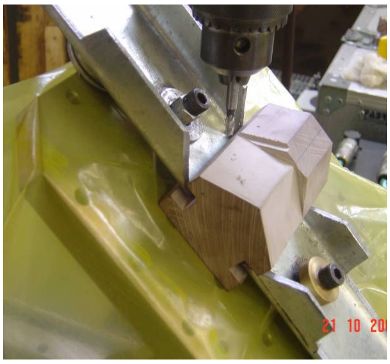


Figure 10. Machining in parallel direction, with table at 45º

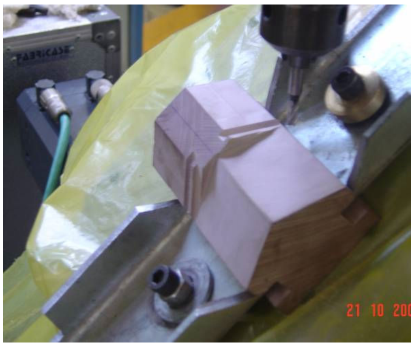


Figure 11. Machining in parallel direction, with table at -45º

Figure 12. Fourth test with 12 mm cutting depth

At the third test the table was inclined at -45º as well the feed rate was 60 mm/min, when machining in the longitudinal direction of the parallel mechanism (Fig. 11). The canal depth was 2 mm and maximum tool rotation was 1900rpm.

In such condition the moving platform did not show any vibration, as well the cutting was smooth. The surface finish in the work piece was excellent as well the chip formation was good.

In the fourth test the cutting depth of the milling cutter was 12 mm. The machining direction was transversal to the plane of the parallel mechanism, with the table at 45º (Fig. 12).

Throughout this test, there was vibration only during the time of the penetration of the milling cutter through the work piece. After the penetration of the tool into the work piece has been completed, the vibration ceased, the cutting was smooth with good chip formation and successful surface finish.

6. CONCLUSIONS

In this paper a 4 DOF serial-parallel mechanism to be applied in milling applications was presented. Appling a systematic methodology for enumeration of kinematic structures, a parallel mechanism was generated. The moving platform of this parallel mechanism is capable to execute 2 translations and 1 rotation. The parallel mechanism was assembled on a serial base, which is able to translate in one direction. As a consequence, the moving platform is capable to execute 3 translations and 1 rotation.

Moreover, the direct and inverse kinematic models were developed and the discretization method was employed to evaluate the available workspace. A prototype was built and tested under the machining operations. Although kinematic behavior obtained by the prototype shows potential for this mechanism as a machine tool, a stiffness analysis will be conducted in order to improve the rigidity of the parallel mechanism when machining in the transverse plane.

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