THEORETICAL AND EXPERIMENTAL INVESTIGATION OF AN ORTHOGLIDE MECHANISM USED IN CNC MILLING MACHINE

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Abstract: This paper presents some performances of a modified orthoglide parallel mechanism build for integration in a CNC milling machine. The parallel mechanism is driven and controlled by a vertical CNC milling machine. The designed mechanism is modeled with the finite elements method (FEM) in order to analyze the static behavior inside the workspace. The FEM model is validated by comparing the theoretical values of the natural frequencies with the experimental ones of the prototype mechanism. Furthermore various tests are performed in order to investigate the position precision of the designed mechanism.

Key words: orthoglide, genetic algorithm, milling machine, FEM, modal analysis

1. INTRODUCTION

Parallel kinematic machines (PKM) are commonly used for machining processes because of their advantages such as high stiffness, low inertia, high accuracy and also the ability to have increased number of degrees of freedom compared to classic machine tools (Tsai, 2009). The construction of such a machine tool into a university laboratory for experimental and educational purposes requires high cost. In order to construct and demonstrate a PKM with low cost, the facilities (actuation, control, hardware, software) of a CNC milling machine existing into the laboratory can be used (Glavonjic et al., 2005, Glavonjic et al., 2009). For that purpose an orthoglide parallel mechanism with three degrees of freedom (dof) is used (Wenger & Chablat, 2000, Pashkevich et al., 2005). The geometry and kinematics of this mechanism makes it ideal to be placed in the milling machine existing into the laboratory with minimum modifications and low cost.
Various methods have been proposed in the literature for the analysis and optimization of the 3 dof mechanisms. Gosselin presents in (Gosselin et al., 2002, Gosselin & Zhang, 2002) a new method to analyze the effect of the link flexibility on a parallel mechanism's stiffness named lumped kinetostatic modeling. Majou presents at (Majou et al.,2007) a parametric stiffness analysis of the orthoglide that allows a simple systematic analysis of the influence of the geometric design parameters and to quickly identify the critical link parameters. Pashkevich presents a new stiffness analysis method of over constrained parallel manipulators with flexible links and compliant actuating joints (Pashkevich et al., 2009). In references (Wenger & Chablat, 2003, Pashkevic et al., 2005) are presented an architecture optimization of the orthoglide and design strategies for the geometric synthesis of the ortholgide type mechanism respectively. In our previous research (Mitsi et al., 2007), using a genetic algorithm, the optimal design of a symmetrical orthoglide mechanism was performed so as to maximize the workspace, the conditioning index and the stiffness of the mechanism, considering the limits imposed by the CNC milling machine geometry.
In the present paper the performance of the designed and constructed orthoglide mechanism is evaluated. In section 2 the workspace and the conditioning index of the proposed mechanism are estimated. Stiffness evaluation can be obtained from results of a compliant analysis of the mechanism. In section 3 the evaluation of compliant displacements of the end-effector (TCP - tool center point), under given load at different mechanism configurations is performed using a FEM simulation. Furthermore, the natural frequencies of the mechanism configuration corresponding to the center of the workspace are obtained from the model analysis of a FEM simulation. The experimental values of the natural frequencies of the same mechanism configuration are compared with the theoretical ones to validate the FEM model. Finally, in section 4, other characteristics of the mechanism such as the accuracy and repeatability are evaluated..

2. KINEMATIC MODELLING OF THE ORTHOGLIDE MECHANISM

The parallel kinematic device integrated into a vertical CNC milling machine is a modified orthoglide parallel mechanism (Fig. 1). The mechanism consists from the base, a moving platform and three fixed-length links, connected to the base by prismatic joints. Each of the three links contains one parallelogram. The three parallelograms are connected

to the moving platform and the sliders by revolute and universal joints respectively. A serial 2-dof passive mechanism (arm in Fig. 1) is attached for decoupling of the CNC machine x and y axes.

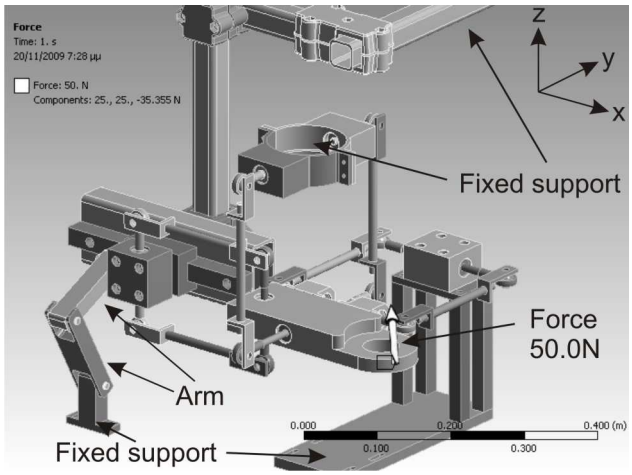

Fig. 1. 3D model of the mechanism showing supports, the point of the applied force and the serial mechanism (arm).

The drive and the control of the prismatic joints in x, y and z directions are performed by CNC milling machine actuators. The moving platform of the mechanism has three translational dof with respect to the base, so that it retains a constant orientation during the motion.

Kinematic analysis of the mechanism (Mitsi et al., 2007) is based on its geometric model (Fig. 2), where each parallelogram is illustrated as a unique rod.

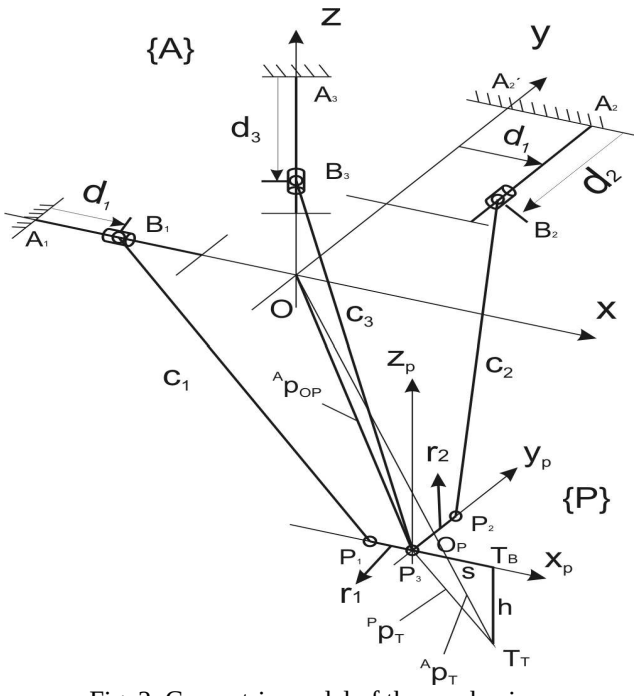

Fig. 2. Geometric model of the mechanism.

All mechanism parameters are defined as shown in Fig. 2 where the A_iB_i are the scalar variables of the actuated prismatic joints with length d_i (i=1, 2, 3), R_i are the distances OA_i (i=1, 2, 3) of the base, r_i the distances O_pP_i (i=1, 2, 3) of the moving platform and c_i are the links length B_iP_i (i=1, 2, 3). T_B and T_T are the tool base and the tool tip respectively.

Due to the geometry of the CNC milling machine, a semi symmetrical parallel machine is designed. The design parameters of the mechanism have been adjusted in order to gain volume for the workspace. The design parameters of the mechanism are inserted in Table 1.

Table 1. Main dimensions of the modified orthoglide mechanism.

Lengths (mm)		
Base	Moving platform	Link
R_1=392	r_1=75	c_1=218
R_2=312	r_2=75	c_2=218
R_3=255	r_3=0	c_3=248

The workspace of the mechanism is $9{,}46 \times 10^6$ mm^3 and its shape is presented in Fig. 3.

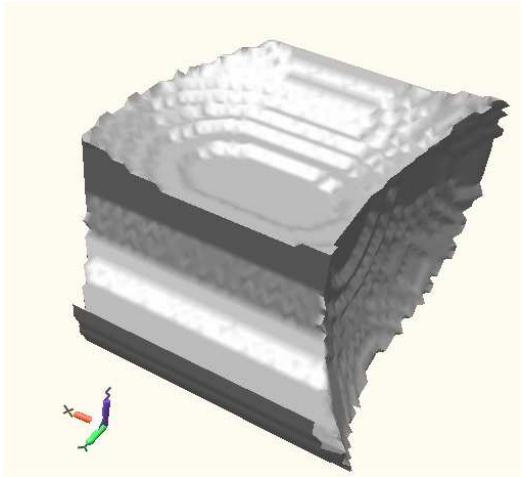

Fig. 3. Workspace of the modified orthoglide mechanism.

The manipulability of the mechanism is estimated through the local and global conditioning index (Mitsi et al., 2007). The global conditioning index is 0,366. The local conditioning index (LCI) depends on the position of the mechanism within its workspace.

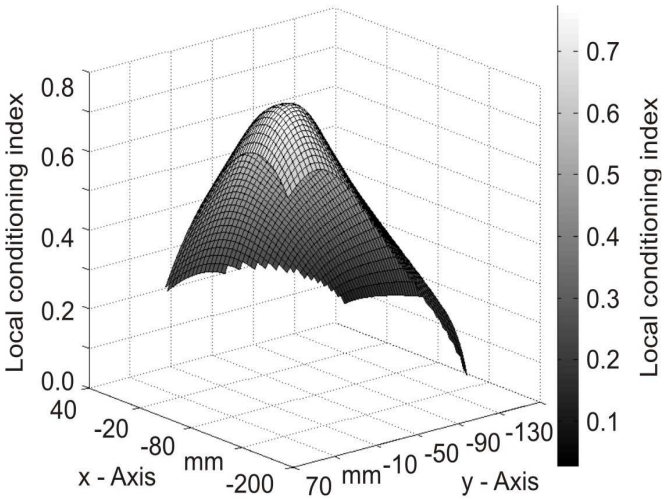

Fig. 4. Local conditioning index of the modified orthoglide mechanism for z-axis level -80mm.

The minimum value of the LCI is 0.0 and appears at boundaries of the workspace and the maximum value of LCI 0.94 appears at the center of the workspace. Singularity poses, where LCI equals 0.0, appear only near the boundaries of the workspace (Mitsi et al., 2007). These poses are excluded from the workspace.
For example the distribution of the conditioning index for a specific z-axis level – 80 mm is presented in Fig. 4. The local conditioning index has high values near the center of the workspace, i.e. manipulability of the mechanism increases towards the center of the workspace and so the mechanism becomes more controllable.

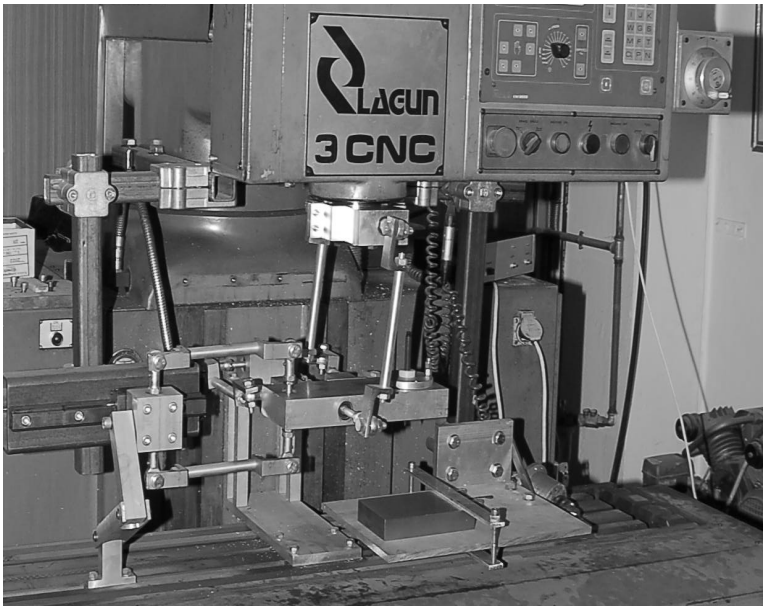

Fig. 5. Modified orthoglide mechanism integrated into a CNC milling machine.

The modified orthoglide mechanism integrated into the CNC milling machine is presented in Fig. 5.

3. FEM SIMULATION OF THE ORTHOGLIDE MECHANISM

The stiffness of the orthoglide mechanism integrated into CNC milling machine is an important performance because higher stiffness allows higher machining speeds with higher accuracy of the end-effector.
The stiffness changes with the variation of the mechanism configurations within its workspace as well as the direction of the applied wrenches. Stiffness evaluation of the orthoglide mechanism can be obtained from results of a compliant analysis of the system. The main sources of compliance are considered the links, joints and the moving platform (end-effector) of the mechanism.
The evaluation of compliant displacements of the moving platform under given load exerted against it at different mechanism configurations is performed with the finite element method (FEM). Using a CAD model of the orthoglide mechanism implemented in the finite element software ANSYS, the FE model is obtained. As seen in Fig. 1 the mechanism is fix supported onto the CNC milling machine at four points. The materials of the parts and the contacts of the model are defined properly. In the FE model of the mechanism the screws, bolts and ball bearings are replaced with the proper contact conditions. The meshing process is performed by the program automatically creating roughly 305812 nodes and 155193 tetrahedral elements. The meshed FE model of the mechanism is presented in Fig. 6 and can be seen that the size of the created elements depends on the geometry curvature and proximity of the parts.

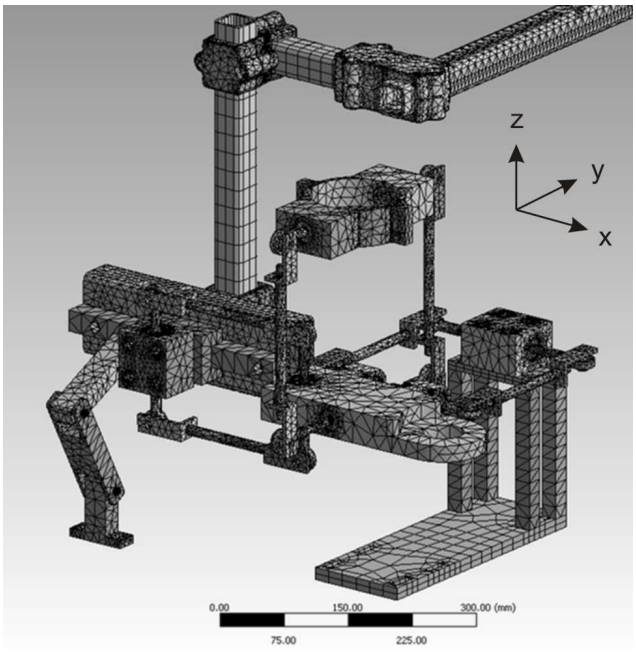

Fig. 6. 3D FE model of the modified orthoglide parallel mechanism.

To simulate the moving platform compliant displacement under simulated cutting forces F_x=25 N,

F_y= 25 N and F_z= 35.355 N applied in the tool within workspace of the mechanism, the compliance analysis is performed in four different xy levels of z axis. Sixteen points-positions are chosen in each xy level uniformly distributed inside workspace and so static analysis is performed for 4 x 16 = 64 different configurations of the mechanism. Thus, the global compliance behavior is taken into account.

The deformation of TCP of the moving platform is presented in Fig. 7 - Fig. 10. In each figure the deformation for 16 positions of the mechanism is presented for a specific z – axis level.

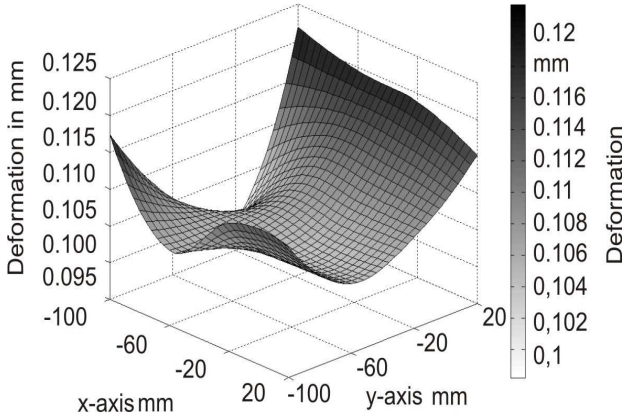

Fig. 7. TCP deformation of the mechanism with FEM simulation for z-axis level -120mm.

It is observed that the deformation has a minimum value in an area near the center of the workspace and rises towards the edges.

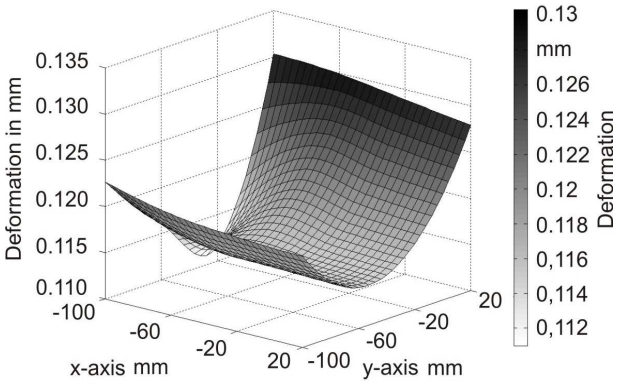

Fig. 8. TCP deformation of the constructed mechanism with FEM simulation for z-axis level -80mm.

The maximum and minimum values of moving platform deformation obtained from the static analysis into the whole workspace are presented in Table 2.

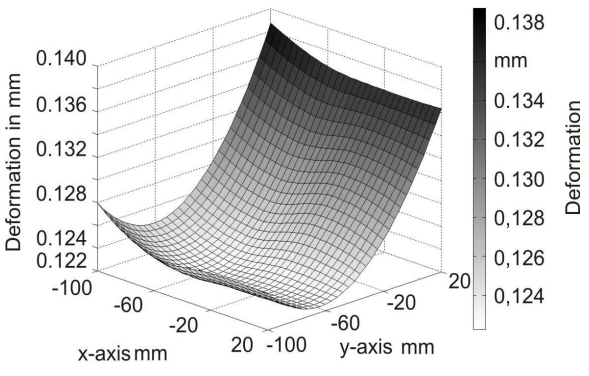

Fig 9. TCP deformation of the constructed mechanism with FEM simulation for z-axis level -40mm.

The results are of great interest for the end-user in order to place manufacturing paths in the workspace achieving the lowest errors due to structural compliance.

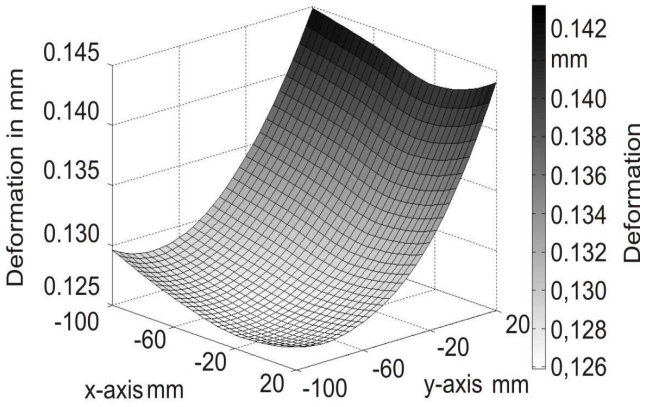

Fig. 10. TCP deformation of the constructed mechanism with FEM simulation for z-axis level 0mm.

In order to verify the validity of the developed FEM simulation, for the mechanism configuration corresponding to (x=0, y=0, z=0) position of the moving platform, the natural frequencies values calculated with the aid of FEM (Table 3 left) will be compared with experimental ones.

Table 2. Maximum and minimum value of moving platform deformation.

Deformation (mm)	
Maximum	Minimum
0.14484	0.098894

For the same configuration of the prototype mechanism the moving platform is excited by an impulse force along the x, y, z directions

successively. For each of these directions, the acceleration in the x, y, z directions is measured with the aid of an accelerometer attached in the corresponding direction on the moving platform. The measured signals of the acceleration and force are subjected to the FFT analysis and furthermore the natural frequencies of the mechanism are evaluated. In Table 3 right the experimental values of the natural frequencies are inserted. The comparison of the theoretical values with the experimental ones of the natural frequencies shows a good agreement.

Table 3. Natural frequencies from FEM analysis and from actual mechanism with a FFT analyzer

Finite Elements Method		FFT Analyzer	
Mode	Frequency [Hz]	Mode	Frequency [Hz]
1		1	26
2		2	40
3	76	3	76
4	102, 113	4	107
5	121	5	125
6	164	6	144
7		7	181
8	225	8	208
9		9	242
10	298	10	274
11		11	328
12		12	350
13	384	13	372
14		14	382
15	401	15	422

It can be concluded that the FE model of the prototype mechanism is satisfactory and can be used for compliance analysis to different manufacturing tasks.

4. EXPERIMENTAL TEST OF PARALLEL MECHANISM

In order to drive and control the modified orthoglide mechanism with the aid of the CNC milling machine, specialized software is created. This software contains inverse and direct kinematics taking into account the motion ranges of the driving axes and the limits imposed from integration of the orthoglide in CNC milling machine in order to avoid damaging.

To verify the system programming and communication and to evaluate the performances of the orthoglide various tests are performed. A black marker pen with 0.5 mm pin diameter is mounted in the tool center point (TCP) of the moving platform (Fig. 11) and is programmed to go in ten different points. The coordinates x and y of these points are inserted in Table 4 and the coordinate z of all points is -47 mm. The target points are chosen in the stiffness working area in order to decrease the accuracy

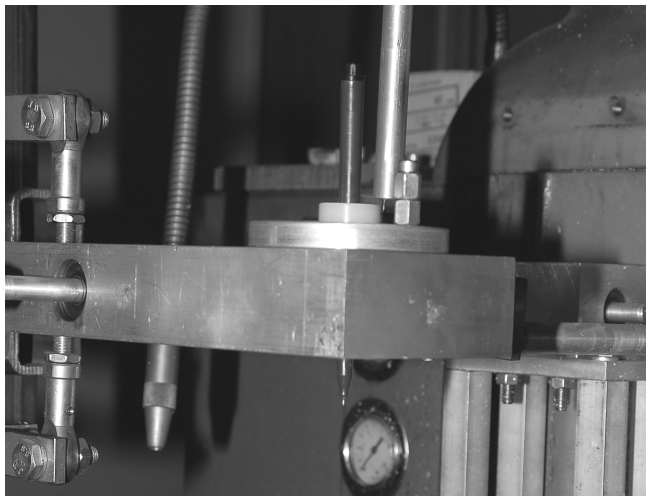

Fig. 11. Close up of the black marker pen fit into the TCP on the moving platform.

and repeatability errors. The ten points and the reference point 0 (x = 0mm, y = 0mm, z = -47mm) are marked by the marker pen onto a fine grinded metal plate. The mark process is repeated ten times. After each test, the plate is removed from the machine table and placed in a measuring device to be photographed.

The measurements of the real coordinates x, y of the marked points are made through high resolution digital photographs (Fig. 12). The target points and the mean measurement points are graphically shown on Fig. 13. The measured and

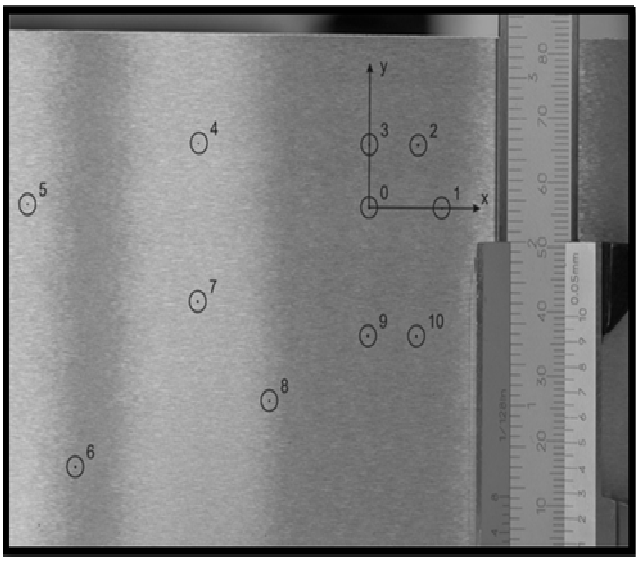

Fig. 12. High resolution photo of the fine grinded plate with the marked points for measurement.

the theoretical values of the x, y coordinates are used to evaluate the accuracy and repeatability errors (Ceccarelli, 2004, Karachaliou, 2007).

The results of the standard deviation errors of the accuracy and repeatability are inserted in Table 4. It can be seen that the maximum error regarding the accuracy and repeatability appears in point number 5. This point is more remote from the center of the workspace.

Table 4. Target and actual points onto metal plate.

Points	Target points (mm)		Standard deviation errors (mm)			
			Accuracy		Repeatability	
	x	y	e_{aS} x	e_{aS} y	e_{rS} x	e_{rS} y
1	15	0	0,125	**0,000**	0,066	**0,000**
2	10	10	0,085	0,102	0,049	0,060
3	0	10	**0,026**	0,100	**0,008**	0,061
4	-35	10	0,281	0,132	0,167	0,072
5	-70	0	**0,590**	0,051	**0,684**	0,034
6	-60	-40	0,503	**0,352**	0,279	**0,232**
7	-35	-15	0,290	0,116	0,168	0,068
8	-20	-30	0,136	0,184	0,098	0,152
9	0	-20	0,052	0,218	0,031	0,217
10	10	-20	0,108	0,093	0,063	0,102

Furthermore the orthoglide is used for cutting a test piece of soft material (Fig. 14).

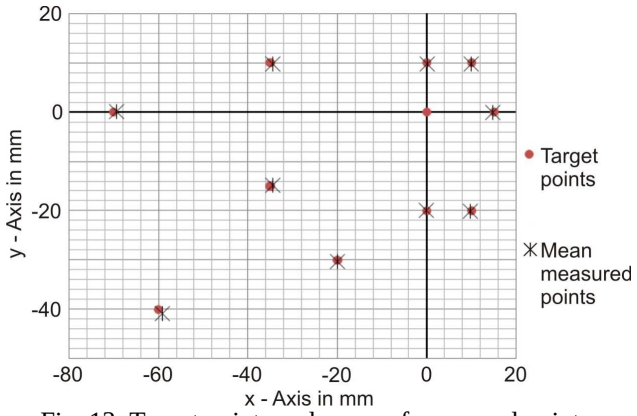

Fig. 13. Target points and mean of measured points.

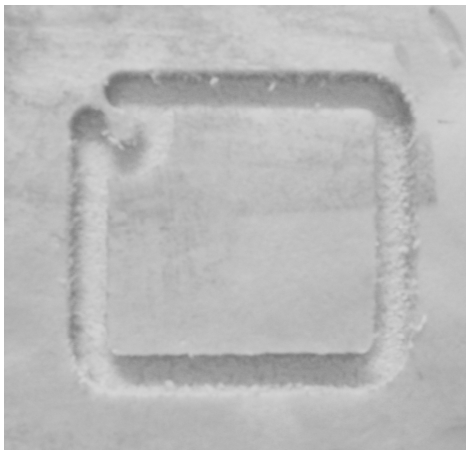

Fig. 14. Test piece machined with the modified orthoglide.

5. CONCLUSIONS

A low cost orthoglide mechanism integrated in a vertical CNC milling machine is investigated. The kinematic parameters such as the workspace volume and the conditioning index of the designed mechanism are evaluated. The compliance analysis of the mechanism with FE method for specific cutting forces and 64 positions of the mechanism is useful to determine the stiffest working zone. The FEM model is validated experimentally. The prototyped orthoglide is tested experimental in order to verify the programming and the position precision.

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