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Experimental evaluation of static stiffness of a spatial translational parallel manipulator.

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Abstract: - In this work a methodology for the experimental determination of the static stiffness of a manipulator of parallel kinematics is presented. On the basis of a systematic strategy, maps of stiffness in the space of work of a robot of three translational degrees of freedom are represented. These maps provide to the designer quantitative information of special importance for the type of application considered.

Key-Words: - parallel manipulator, translational motion pattern, stiffness, experimentation.

1 Introduction

The main objective of the companies is to send to the market every time more competitive products. For it they resort to more specialized and automated processes in which the development of its manipulators is greater. In order to compete in the sector they need more accurate robots which execute the tasks at greater speed and that they are more flexible and adaptable to the processes in which they are used. This will allow the provider a faster answer for the changing necessities of the client.

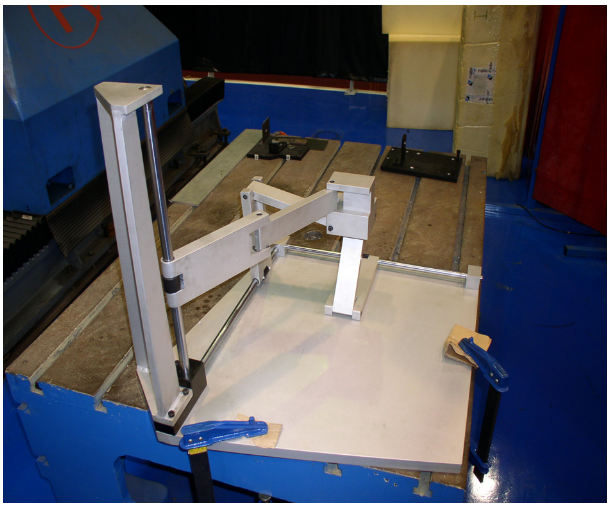

Fig.1 TPM prototype.

Parallel kinematics manipulators conform perfectly to these necessities since they fit in with some of their main advantages as they are the precision, the high stiffness and good dynamic behaviour [1].

In the scope of the parallel manipulators the precision with they are able to execute the objective depends directly on the stiffness of the manipulator. For all the manipulators, stiffness is a function that depends, among other factors, of the configuration and the location of the manipulator as well as of its orientation [2].

Therefore it is necessary to know how the parameter varies throughout the workspace [3]. In order to obtain this objective a work of determination of the manipulator's stiffness by means of an experimental method has been made which has resulted in stiffness maps for this parallel kinematics platform.

2 Problem Formulation

In order to develop this study it turns out necessary to know the geometric characteristics of the prototype and the resolution of the inverse kinematics problem that will serve to know the values of the input data for a theoretical position for the manipulator's experimentation points.

2.1 Robot kinematics description

Translational Parallel Manipulator (TPM) is parallel kinematics mechanism consisting on two platforms, one fixed and the other movable, connected by means of three identical legs [4].

Each one of the legs is formed by two articulated beams linked to each other by means of a rotational joint. The connection of the legs to the platforms is made by means of a cylindrical joint, for the connection to the fixed platform, and a rotational joint with the moving platform (figure 1).

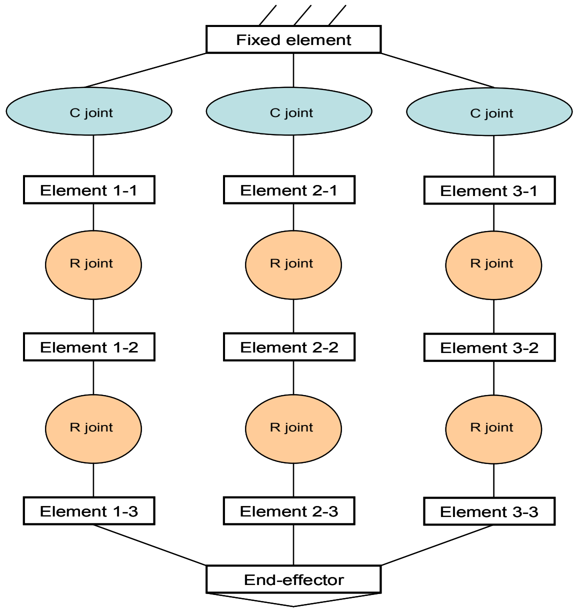

Fig.2 TPM's joints and legs sequences.

In figure 2, the sequential representation of pairs and loops of the mechanism is shown. The elements are into square boxes and the kinematical pairs surrounded by a circle.

This is a mechanism of three translational degrees of freedom (DOF), that is to say, once the platform base is fixed, the actuator has a relative parallel movement of translation to the first [5]. Its drive can be carried out by means of three translations or three rotations and for the actuator's movement we obtain a purely translational movement according to the directions of the three Cartesian axes. The translational drives can be implemented through a small spindle mechanism which would transform an auxiliary rotatory input action to the corresponding translation, or directly a rotatory input (e.g. with an electrical step by step motor).

Finally, there is another important characteristic: this manipulator is fully parallel or totally parallel, that is to say, that it has as many DOF in its movable platform as kinematical chains between itself and the fixed platform, being each kinematical chain composed by a single active or acted pair.

2.1.1 Inverse kinematics position problem resolution

From the illustration observed in figure 3 the closing equations for the obtaining of the position of the of the platform's actuator are deduced. The closed-loop equation would be:

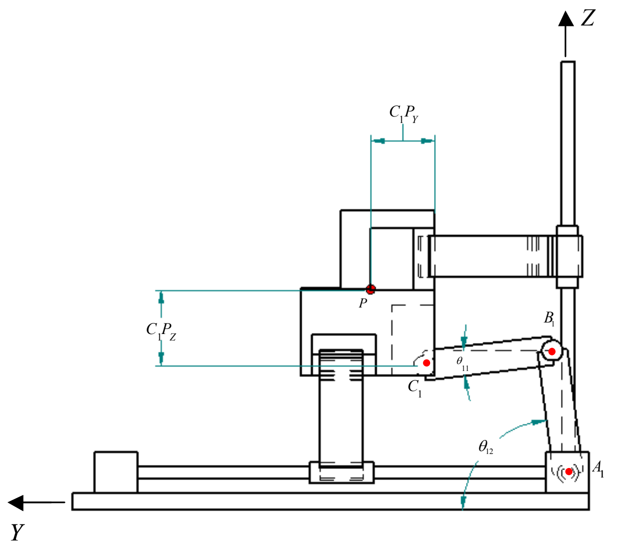

Fig.3 Y-Z plane view.

$$\overrightarrow{A_1P} = \overrightarrow{A_1B_1} + \overrightarrow{B_1C_1} + \overrightarrow{C_1P} \qquad (1)$$

After some suitable operation and rearranging this equation we can obtain the value of the input angles based on the position of the actuator:

$$\theta_{11} = \frac{1}{2}\cdot Arc\cos\left[\frac{(Y-\overline{C_1P_Y})^2-(Z-\overline{C_1P_Z})^2}{(Y-\overline{C_1P_Y})^2+(Z-\overline{C_1P_Z})^2}\right] + \frac{1}{2}\cdot Arc\cos\left[\frac{(Y-\overline{C_1P_Y})^2+(Z-\overline{C_1P_Z})^2}{2\cdot \overline{A_1B_1}^2}-1\right] \qquad (2)$$

$$\theta_{12} = \frac{1}{2}\cdot Arc\cos\left[\frac{(Y-\overline{C_1P_Y})^2-(Z-\overline{C_1P_Z})^2}{(Y-\overline{C_1P_Y})^2+(Z-\overline{C_1P_Z})^2}\right] - \frac{1}{2}\cdot Arc\cos\left[\frac{(Y-\overline{C_1P_Y})^2+(Z-\overline{C_1P_Z})^2}{2\cdot \overline{A_1B_1}^2}-1\right] \qquad (3)$$

For a given position of the terminal element it is possible to know the values of the angles θ_{11} and θ_{12}. In the same the other planes with their corresponding variables are solved: θ_{21}, θ_{22}, θ_{31} and θ_{32}.

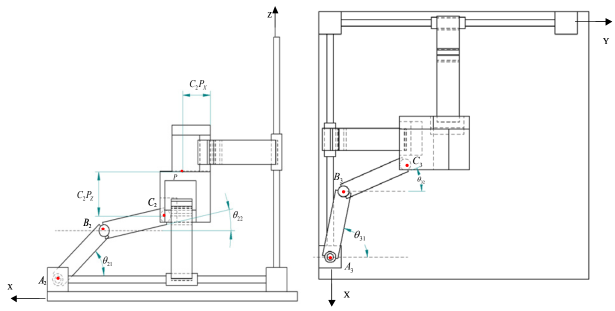

Fig.4 Front and top views.

Although from these solutions up to eight different configurations can be obtained, with the fixed element placed and defined the quadrant by the elements of union to the fixed one we restricted the number of viable configurations to the one of the described solution and it is represented in figure 5:

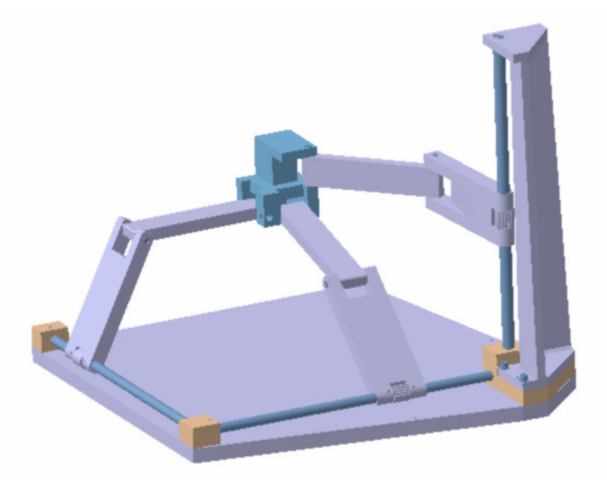

Fig.5 TPM's assembled CAD.

3 Experimental stiffness calculation

Once the inverse kinematics problem is solved, the following step consists on the obtaining of the values of stiffness within the whole workspace [6], [7]. In order to obtain it different stages must be completed and they are described next.

3.1 Stiffness matrix analysis

As the manipulator is purely translational and the given characteristics of the input / output movement, we will have guidelines and/or limitations at the time of establishing the procedure to make the different experimental measures throughout the workspace.

In the first place, the static problem of the stiffness is being described. The equation for the calculation of the static problem indicates that:

$$\mathbf{f}=[K]\cdot\delta \qquad (4)$$

where,

$$[K]=\begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix} \qquad (5)$$

Where **f** is applied force's vector and δ resultant displacement's one.

3.2 Experimental setting

For the execution of the tests in the trustworthy form it needs, it's necessary to mount and fit the fixed frame and the instrumentation well so that the errors in the measures are as small as possible.

3.2.1 Measuring components

Next, all the elements of measurement that have been used in the execution of the tests for the determination of the stiffness in the different points are shown in figure 6 and figure 7.

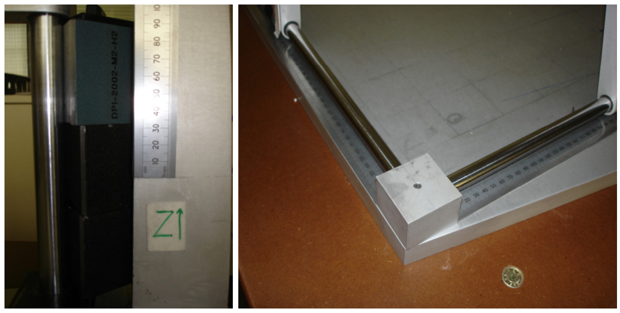

Fig.6 Reference system (X,Y,Z).

Fig.7 Devices of measurement.

In this case the preparation of the bank of tests is a relatively simple stage. Next the measurers of angles (inclinometers) on the arms and the movable platform are installed. For measurement of the position variations and also of the corresponding loads that cause the displacements in the vertical direction the dial indicators are used.

On the fixed platform, scales for the position of the movable platform measurement have been installed. This way the origin of our system of reference on the fixed platform is defined as illustrated in figures 6, 7 and 8. In addition a plate has been added to facilitate the application of the load on the movable platform.

Fig.8 Experimental setting.

3.2.2 Procedure of the measures

Since the manipulator in its output is purely translational and that to the input the selected drives are the linear ones this leads us to a systematization of measures consisting on the division of the working space in planes of constant coordinate Z. In each plane thirty measures will be made following next protocol:

First step:

-It is used as border limit in the measures the defined one by the workspace of the manipulator.

-It is placed Z arm totally stretched to a constant level of height.

-They are placed X and Y arms as close as possible to the frame of reference for the measurements origin.

-The coordinate is increased and until arm X is totally stretched.

Second step:

-In the following stage arm Z is no longer totally stretched.

-Now the Y arm is totally stretched and X arm increases its position by intervals of 50 mm.

-The last point is with arms X and Y totally stretched.

Third step:

-Now the process is followed until folding the arms next to the origin. In this case the coordinate Y is reduced by 50 in 50 mm until x-axis makes top and the actuator is as close as possible of the vertical axis that contains Z arm.

Forth step:

-Reduce x coordinate by 50 in 50 mm until x-axis and Y are as close as possible to the origin. In this situation Z axis is completely stretched.

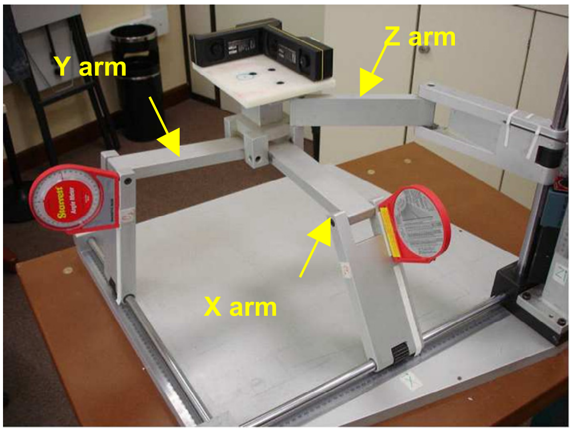

Fig.9 X, Y, Z legs.

Known the variation stages of the arms' position the methodology for the taking of data throughout the workspace can be defined. In order to cover all this space divides each XY plane in a grid of 50x50 mm which defines the measured points.

The platform in the point of corresponding measurement is positioned. Its position it scored and the pairs of entrance are fixed by means of the screw system of fixation. Arm Z is also immobilized by means of wedges that restrain it in vertical direction. Once everything is fixed, the position of the actuator and the values of the angles are written down θ_{11} and θ_{21}.

Next we introduce a load of 2 kg. This preload is used to remove gaps of the structure. With the preload we turn on the inclinometers located on the actuator and store the initial angles and the new initial coordinates of the platform.

The dial indicators are restarted and is placed the load of 2 kg. then we again store all the positions and the displacements indicated by the clocks.

Between all the measures taken some of them, as the variations of the platform's rotations, θ_x, θ_y and θ_z in addition to the displacements according to X and Y are of the same order of magnitude that the error of precision of the dial indicators so it has no sense to consider these measures.

Finally and after the analysis of the first experimental measures the study of stiffness is restricted to the component k_{zz} of the stiffness matrix. This is because of the order of magnitude of the deformations corresponding to the other four components initially proposed in the work was of the same order that the precision of the measuring instruments.

4 Results representation

Through the previous methodology, values in discrete points of the workspace are obtained. In order to complete the objective of the stiffness maps, the stiffness like a continuous function of the point throughout the workspace must be represented. For it the tool of interpolation of Matlab software will be used which provides interpolated values for the rest of the points of the workspace.

Of course, the error that introduces the interpolation (difference between the real values and the approximated ones) must be smaller than the one of the own experimental process (difference between the real values and the measured values).

Like parameter to evaluate the quality of our interpolation the standard deviation of procedures, the interpolation and the experimentation will be used.

4.1 Experimental standard deviation

In order to evaluate the error committed in the experimental stage the measurement of an only point in twenty times will be carried out and calculated the standard deviation of this experimentation (figure 10).

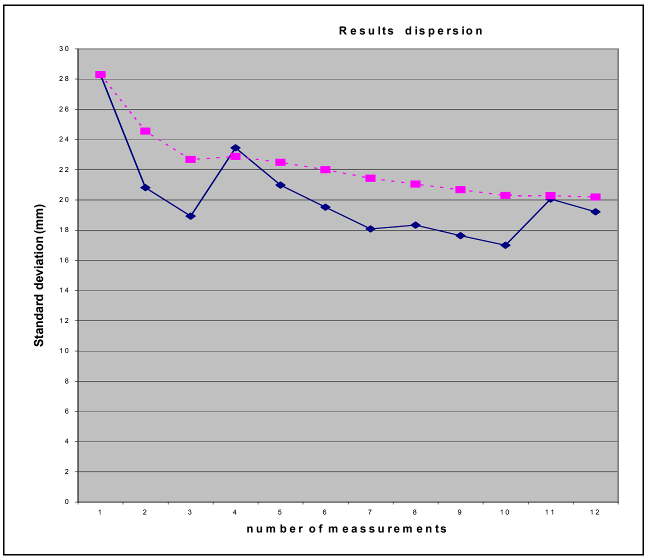

Fig.10 Experimental error's standard deviation.

In order to obtain a continuous representation of the stiffness throughout the workspace, different types from interpolation [8] until determining as it is the approach that less error introduces were made.

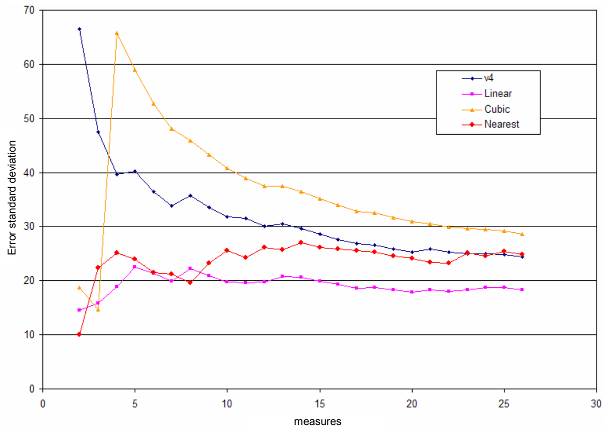

Fig.11 Standard deviation of interpolations.

4.2 Results mapping

With the data of the different completed experimental results of the linear interpolation we obtain the representative maps of the stiffness throughout the workspace. By means of the postprocessor we can represent several types of maps. In the first place we have the variation of the stiffness for a constant z plane (figure 12).

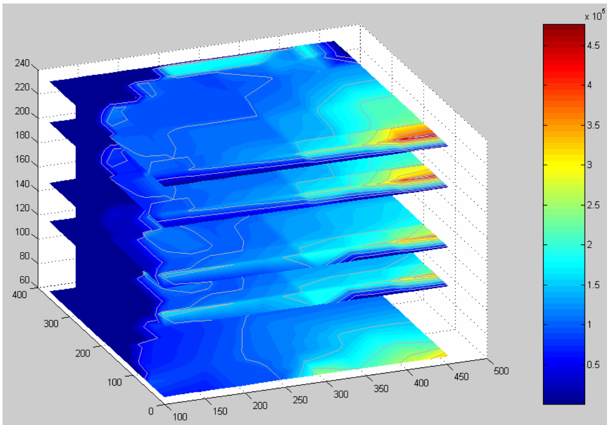

Fig.12 Deformation mapping for various planes.

In the figure 13 we can observe the part of the workspace that fulfils the condition of deformations that don't exceed an indicated value of 200 µm.

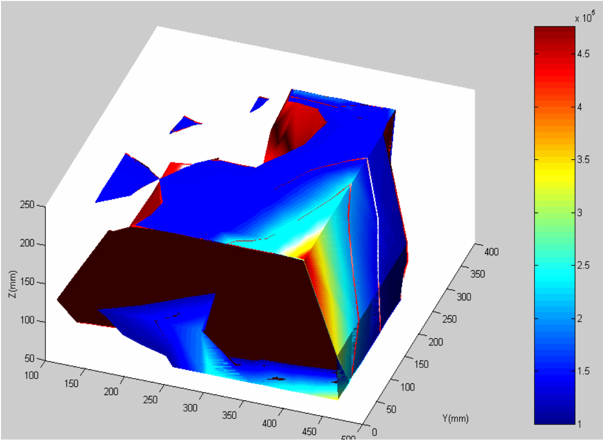

Fig.13 3D mapping of deformations.

Finally, a condition of stiffness rank can also be represented. In figure 14, the boxes represent those zones of the workspace correspond with a considered stiffness range. The smaller geometric forms (boxes) correspond with the highest values of stiffness.

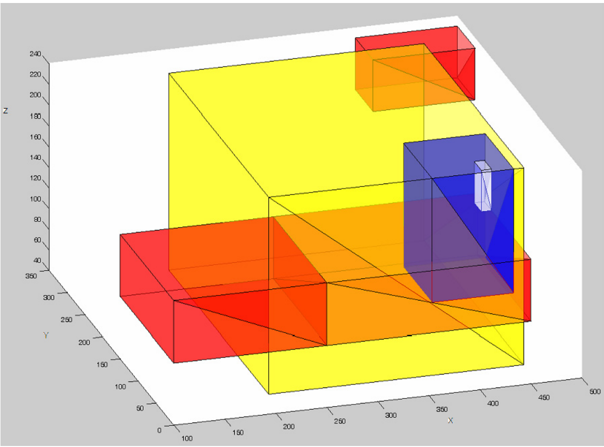

Fig.14 Ranges of stiffness.

The procedure that better comes near to the experimentation is the one of the linear interpolation (discontinuous line in figure 10) since it converges towards the value of 18 µm whereas the deviation of the experimental method was located in a value of 20 µm.

The extreme values are reached in configurations in which the manipulator is more gathered or completely stretched.

5 Conclusion

A methodology for the obtaining of the maps of stiffness of this family of parallel manipulators has been developed who, in principle, will be extrapolable to another type of spatial parallel manipulators of three degrees of freedom.

From a finite number of points (approx 10 points by each plane) and a postprocess based on the interpolation, a continuous map of stiffness with a maximum error of 2 N/µm is obtained.

Three-dimensional maps based on boxes of utility for the user of the machine based on stiffness intervals according to the necessities of each application are obtained.

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