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HEXAPODS AT THE ESRF: MECHANICAL ASPECTS, RESULTS OBTAINED

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Abstract

Hexapods (also called Gough / Stewart platforms) enable to position a mobile platform with six degrees of freedom. This is achieved by a parallel robot architecture: the mobile platform is linked to the base via six struts of variable lengths, articulated at both ends. Varying the lengths of the six struts enables to move the mobile platform with six degrees of freedom (d.o.f.). At the ESRF, in 1993, efforts were started in order to design an hexapod with a resolution in the micrometer/microradian range and a high stability, to be used as a motorised positioner for X ray mirrors or X ray monochromators. Since then, 17 hexapods of this type have been built and are used on various ESRF Beamlines. This paper gathers some information concerning the ESRF hexapods: Advantages of hexapods compared to classical serial positioning devices; Dimensions, strokes, load capacity; Influence of the hexapod geometry on the accuracy and stiffness, based on two examples; Characteristics of the stepper motor driven jacks (telescopic struts): Design, stiffness, measured resolution and backlash; Characteristics of the articulation joints (two models): Stiffness, measured friction torque; Influence of applied external forces; Measurements taken on complete hexapods: linear/angular resolution, accuracy, reproducibility, natural frequency.

1 Introduction

An example of hexapod is shown in fig.1. It is composed of a fixed platform and a mobile platform, linked together by six struts. Each strut is connected via ball joints at each of its ends to the fixed/mobile platform. This forms an isostatic mechanical assembly, and enables to move the mobile platform with 6 degrees of freedom, by changing the lengths of the six struts to adequate values. In the practical implementation, the six struts are telescopic jacks, powered by electrical motors, or hydraulic or pneumatic control.

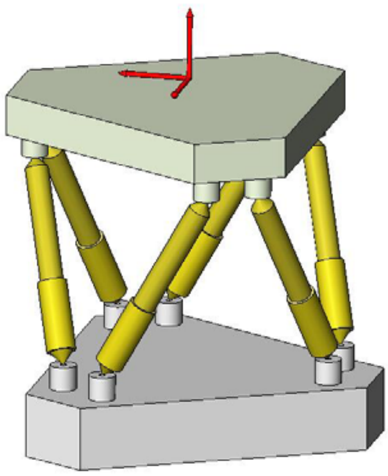


Fig.1: Schematic description of an hexapod of octahedral geometry

Several geometries of hexapods have been proposed. For instance, the orthogonal geometry (three struts parallel to Z axis, two struts parallel to Y axis, one strut parallel to X axis), is extensively used in some synchrotron radiation laboratories, as manually adjustable supports. This paper will concentrate on the octahedral geometry (fig 1), which has been chosen for the ESRF hexapods.

The first hexapod of octahedral geometry [1] was built by Dr Eric Gough [2] in 1954, for a tyre test machine at Dunlop Rubber Co., Birmingham, England (see fig. 2).

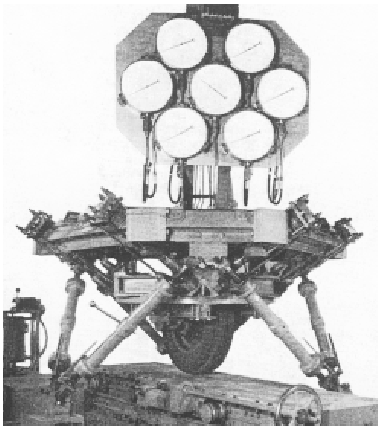


Fig.2: The tyre test machine of Dr Eric Gough

In 1965, a paper [3] was published by D. Stewart in the proceedings of the (British) ImechE, describing a 6 d.o.f. motion platform for use as a flight simulator. The quality of this paper was strongly acknowledged, and this is why octahedral hexapods are since then commonly called Stewart platforms. Since these early times a lot of hexapod based machines have been developed for various applications, like Flight simulators, Telescopes, Machine tools, and, more recently, for precision positioning devices by PI (www.pi.ws), Micos (www.micos.ws), and down to nanometric resolution by Alio (alioindustries.com).

Hexapods are parallel mechanisms (several actuators acting in parallel on a mobile platform), as opposed to serial mechanisms, composed of several motions stacked on each other (examples: robot arms, or diffractometers used for Synchrotron radiation experiments). Some advantages and drawbacks of the hexapods, as compared to classical serial positioning devices are listed below:

Advantages:

- Easy way to get 6 degrees of freedom (modular mechanical construction)
- Inherently stiff architecture: the struts are submitted to quasi purely axial forces; no bending occurs, which guarantees low deflections
- In the case of serial mechanisms, the motion and guiding located at the bottom of the stack must support all the other motions. This bottom motion is located far away from the object to be displaced and its angular errors (yaw, pitch, roll) result in important positioning errors (Abbe errors).
- With an adequate software, an hexapod enables to generate any trajectory of motion. For instance, when the hexapod is used as a mirror positioner, it is possible and convenient to generate a rotation about an axis which is in the plane of the optical surface.

Drawbacks:

- No manual mode is possible. An adequate software is required to control the hexapod motions.
- Travel ranges are limited.

2 The Hexapods developed at the ESRF

In third generation Synchrotron radiation sources, very small and stable X-ray beams are reflected by mirrors and mononochromators, before reaching the sample to be analysed. A high level of precision, stability and stiffness is required for the motorized supports positioning these optics and the sample in order to achieve a micrometric (submicrometric in some cases) resolution and stability of the beam on the sample. In the case of X-ray mirrors, four degrees of freedom are often required, with limited travel ranges, which fits well within the capabilities of a Hexapod based positioning device.

In 1993, under the impulsion of Fabio Comin [4], efforts were started at the ESRF to develop hexapods with adequate specifications to be used as SR mirror supports and potentially, monochromators and samples supports. Several types of hexapods have then been developed, including air pressure jacks hexapods, and motorised orthogonal hexapods. This paper describes the octahedral hexapods based on stepper motor driven jacks, which are the most commonly used at the ESRF.

The complete assembly is shown on pictures 1 and 2. The mirror and the vacuum vessel housing it are rigidly linked to the top mobile platform of the hexapod. The Beam entrance and Beam exit flange of the vessel are connected to the downstream and upstream components via bellows providing flexibility for the X, Y, Z, Rotation/X, Rotation/Y and Rotation/X (limited) motions.

Picture 1: ID16 Vertical focusing mirror assembly

Picture 2: ID8 vertical focusing mirror assembly

Dimensions

Depending on the precision and stiffness required and on the available space, several different dimensions have been used. The range of dimensions is indicated on fig.3. Note that the ball joints at the ends of the jacks are located on circles and that the diameter of the top circle (mobile platform)and bottom circle (fixed platform) are similar. The influence of the hexapod dimensions will be discussed in section 3.

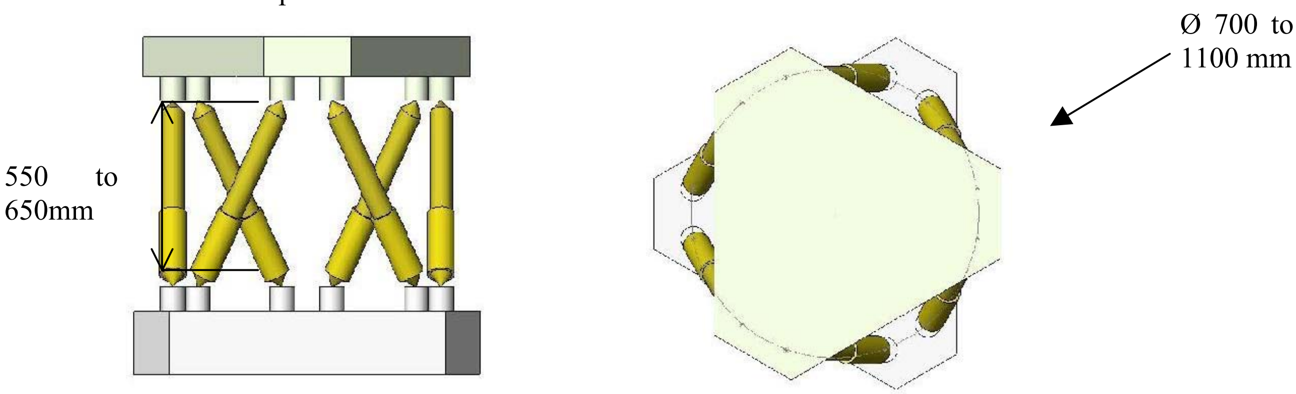


Fig.3: Dimensions of the ESRF hexapods

Load capacity

Vertical load capacity of the hexapod: 20000N
(corresponds to 4000N axial load on each jack)

Typical strokes

With our standard jacks (jack stroke = +/- 40mm), the following typical strokes can be achieved:

Typical travel range in the vertical direction (vertical motion only): +/- 45mm (surprising at first glance, but a geometrical sketch demonstrates that for a pure vertical motion, the vertical travel is larger than the jacks travel)
Typical travel range in the horizontal direction (Y motion only): +/- 80mm

Example of combined travels:
Translation Z: +/-20mm; Translation Y: +/-30mm; Rotation/Z : +/-10 mradian ; Rotation/Y : +/-10 mradian. (see the X, Y, Z axes on fig.1)

In order to check that a desired combination of travel ranges can be achieved, one possible method is to draw the hexapod using a 3D CAD software and to measure the corresponding lengths variations of the 6 jacks.

3 Optimization of the geometry of the hexapod

The performances strongly depends on the geometry of the hexapod. At the INRIA (Sofia Antipolis – France), powerful softwares have been developed, which enable to determine the workspace (travel ranges), check the absence of singular points in the workspace, the precision and the stiffness of the hexapod in each axis, assuming a given precision and stiffness for each jack. The ESRF hexapods have been designed thanks to a collaboration with Jean Pierre Merlet (INRIA – Sofia Antipolis), who has carried out extensive calculations to optimise their geometry [5].
In order to illustrate this point, the results of some calculations from JP Merlet are given in table 1 (precision), and table 2 (stiffness). In these tables, the calculated precision and stiffness are displayed for two hexapods of the same height and of different diameters (see typical diameters values in Fig.3.- the diameters of the top and bottom platforms are identical). Table 1 indicates the calculated error on the hexapods axes of motion assuming an error of 1µm on each of the 6 jacks. Table 2 indicates the calculated stiffness on the hexapods axes of motion assuming a stiffness of 100 N/µm for each of the 6 jacks (values derived from two private communications from JP Merlet concerning ID26 HDM1 and HFM2 hexapods).

	Error X or error Y (µm)	Error Z (µm)	Error θ_X or θ_Y (µradian)	Error θ_Z (µradian)
Hexapod of “small” diameter	3.8	1.1	3.9	8.4
Hexapod of “large” diameter	2.8	1.1	3	4.2

Table 1: Calculated error on the hexapod Translation (X, Y, Z) and Rotation (θ_X, θ_Y, θ_Z) motions, assuming an error of 1µm on each jack. Values for two hexapods of same height and different diameters (maximum errors over the whole workspace)

	Stiffness K_X or K_Y (N/µm)	Stiffness K_Z (N/µm)	Stiffness $K\theta_X$ or $K\theta_Y$ (N.m/µradian)	Stiffness $K\theta_Z$ (N.m/µradian)
Hexapod of "small" diameter	38	520	3.4	0.9
Hexapod of "large" diameter	70	460	6.3	3.4

Table 2: Calculated linear (KX, KY, KZ) and angular ($K\theta_X$, $K\theta_Y$, $K\theta_Z$) stiffness of the hexapods, assuming a jack stiffness of 100 N/µm. Values for two hexapods of same height and different diameters. (maximum errors over the whole workspace)

These two tables raise the following comments:

- The precision and the stiffness are much better in the vertical direction (Z) compared to the horizontal directions (X, Y)
- By enlarging the diameter of the hexapod, significant improvements are observed for the precision and stiffness in the horizontal direction and also for the angular precision and stiffness. This can be explained by the fact that enlarging the diameter of the hexapod for a constant height has two positive effects: 1/ the angles between the jacks and the vertical axis are increased, which improves the X and Y precision and stiffness. 2/ the distances between the jacks are also increased, which increases the angular precision and stiffness. Note that these rules are only valid for small travels, which do not induce a significant modification of the hexapod geometry.

The price to pay for these improvements is that the larger diameter hexapod will offer reduced travel ranges for horizontal and angular motions compared to the small one. To conclude, in order to improve the precision and the stiffness, provided the required space is available, the recommended strategy is to chose an hexapod of large diameter and small height, as long as its travel ranges are sufficient for the application.

4 Ball joints and jacks for Hexapods

4.1. Ball joints

Two types of ball joints have been used on the ESRF hexapods:

- commercially available ball joints SMEM 1650 from Unibal
- a sphere-cone ball joint, ESRF designed, shown in fig.4

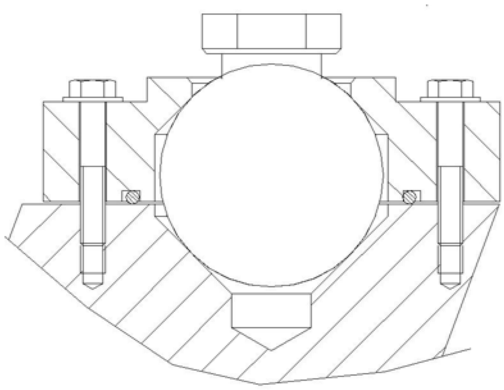


fig. 4

The friction torque and the stiffness of these ball joints when submitted to an axial load has been characterized:

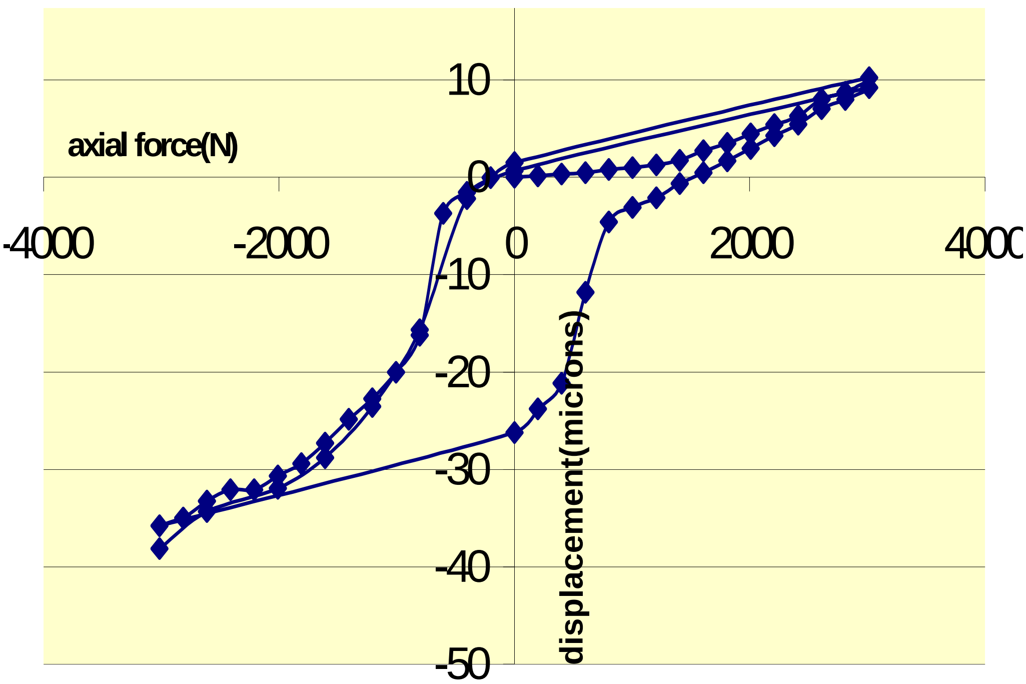
	Friction torque under 3000N load	Axial stiffness
Sphere - cone	8.7 m.N	1200 N/µm
SMEM 1650	3 m.N	180 N/µm

The sphere – cone ball joint is used in the case of high and varying loads. The SMEM 1650 is used in the case of small loads.

4.2. Hexapods jacks:

The hexapod jacks belongs to a large familly of jacks, designed by Gerard Rostaing, extensively used at the ESRF for positioning optical components. These jacks are driven by a stepper motor associated to a low backlash reducer, which a precision nut-screw assembly. The precision of the leadscrew (machined by grinding) and the quality and stiffness of the guiding of the nut (axial bearings) and of the shaft enable to get the required performances at a reasonable cost.
Travel range: 80mm
Load capacity: 5000N
Resolution: 0.3µm (measured)
Bidirectional error: 6µm (measured when changing the direction of the motion)

The graph 1, from which the axial stiffness was derived, shows that the displacement induced by an axial force is limited: Axial stiffness = 130N/µm. However, a displacement of 25 µm is obtained when the direction of the force is reversed (backlash from tension to compression force, mostly due to the slack in the threads).



Graph1: Axial displacement of a jack when applying a positive / negative force

In order not to suffer from this backlash error, adequate precautions must be taken, so that the hexapod jacks are always submitted to compression forces. This implies some conditions on the external forces applied on the hexapod mobile platform. For example, when the hexapod supports a vacuum vessel which is connected to the rest of the Beamline by bellows, horizontal motions will generate forces due to the bellows offsets. It is then necessary to check that the resulting force (horizontal force + vertical force, i.e. weight) applied to the mobile platform does not result in tension forces on the jacks. This often leads to: Horizontal force < 0.2 x Vertical force.

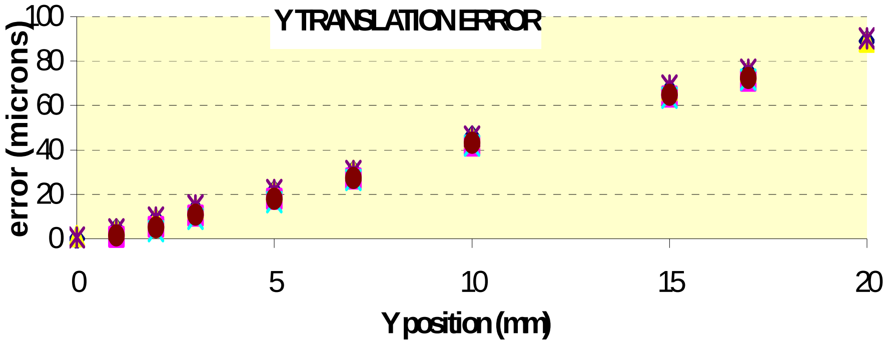
5 Precision measured on ESRF hexapods

A full characterisation of the precision of a hexapod requires to measure the position error in the six degrees of freedom for each translation and translation. Such a thorough analysis has not been done on an ESRF hexapod. However, measurements have been taken on several hexapods, in particular on ID10 Hexapod (by M. Nicola, H.P. Van Der Kleij) on ID13 Hexapod (by L. Eybert) and on ID8 RVFM (by P. Bencok and P. Marion) and the typical results obtained are given in Table 3.

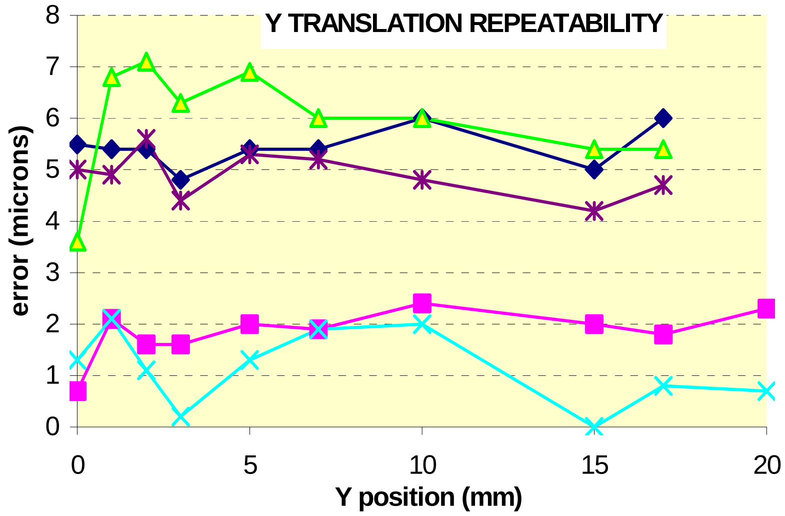
	Y horizontal translation over 20mm	Z vertical translation over 20mm	Rotation / Y over 10mrad
Absolute accuracy	80 µm	15 µm	40 µrad
Unidirectional repeability	2 µm	1 µm	1 µrad
Biderectional repeatability	6 µm	6 µm	7 µrad
Resolution (min. increment)	1 µm	1 µm	1 µrad
Yaw, Pitch, Roll during travel	10 to 20 µrad		-

Table 3: Typical accuracy of the ESRF Hexapods

The absolute accuracy and the repeatability records are shown on graphs 2 and 3, which were taken during 5 horizontal translation runs (3 forwards runs, 2 backwards runs), over a travel range of 20mm,.



Graph 2: Absolute accuracy for an horizontal translation over 20mm



Graph 3: Repeatability for 3 forwards and 2 backwards horizontal runs

6 Conclusion

Seventeen hexapods are now in operation on the ESRF Beamlines, most of them for X-Ray mirrors positioning. After several years of experience, these positioning devices give full satisfaction, thanks to a well adapted and reliable control software [6], and also thanks to a sound mechanical design, which enables to get the required resolution and stability at a reasonable cost. Linear / angular resolution and repeatability in the µm / µrad range have been measured; the absolute accuracy (0.4%) could possibly be improved by a calibration and correction process, but is already sufficient for the present application. The ESRF hexapods are now commercially available from the company Peyronnard (74, Le Pavillon – 38560 – Champ sur Drac – France).

7 Acknowledgements

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