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High-precision table positioning device

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Abstract

A new parallel positioning table device able to work with increased load and precision, especially inside of diffraction machines (Diffractometers) for manipulating the sample (and, instruments) is presented. The Table Positioning Device (TPD) consists from a symmetrical redundant parallel mechanical structure having four (4) **PP**PS legs and eight orthogonally arranged prismatic actuated joints (8**P**), each of two forming a planar gliding actuation module (2**P**). The OCTOGLIDE (OG) TPD is belonging to Quadropod (Qp) family, and by the kinematics of the mechanism, the motions along (around) the main axis (XYZ) can easy be predicted. By using a pairs of wedges in its design, a compact, stiff and powerful manipulator for the heavy load manipulations in all 6 DoF has resulted, fitting well inside of Difractometers (Dm) workspaces for doing various experimental investigations, especially under specific environmental conditions (ex. vacuum). The concept and design, together with the first experimental prototype are revealed.

Keywords: Positioning, Parallel Kinematics, Redundancy, Mechanisms, Design, Accuracy

1. Introduction

Diffraction machines (Diffractometers) are still the workhorses of synchrotron beam lines [1]. By using the light (X-ray) as tool for materials' atomic structure investigations and based on different diffraction techniques (XRD, etc), the sample and related instruments are manipulated inside of a dedicated space towards the incoming X-ray beam [2]. This must be done with high precision and for various defined positions (especially, orientations) following the physics' diffraction principles and rules and maintained as long as the experiment is needed. The actual available positioning devices provide the above capabilities by materializing each motion axes through stages (linear and/or rotation) by simply stacking each one on another. However, in the case of several dof (>3) the accuracy, carried load and the remaining available working space is sometimes not enough for the additional instruments (ex. vacuum chambers). Moreover, the rotation distance around the centre point (C) cannot be changed [3].

Parallel Kinematics (PK) is another solution, as for ex. precision hexapods [4]. In this case, a pivot point (P) can be relatively free chosen to coincide with CoR. However, by their mechanical structure, including the actuators arranged along the legs, they have an appreciable height, too. A more desired structure is to have flat actuators. There are existing several proposals in literature and products (ex. SpaceFAB/MICOS), but for other purposes. The stiffness is not enough and motion along/around each axis not easy predictable (workshop desire).

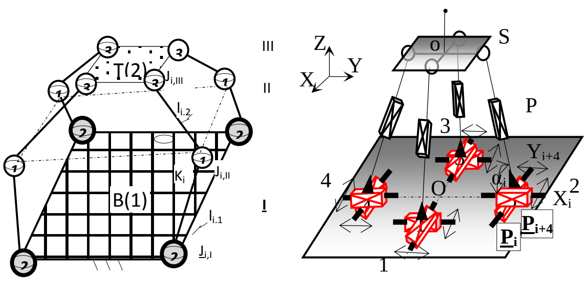
A former R&D project aiming to conceive new PKM for high precision positioning tasks to work inside synchrotron facilities has resulted in several new and interesting PKM structures / architectures (2011). Especially, one has exhibited useful features to comply with above Dm working specificity, as a Table Positioning Device (TPD) [5]. A prototype has been then accomplished (2013). An overview of its kinematics and design features is presented here.

2. Kinematics

2.1. Topology

From the structural point of view (pov) the TPD is belonging to parallel kinematics general class of QUADROPODS [6]. The 6-[4(**2**13)] family, Fig. 1 (left) is a fully symmetric four legs/chains (K_i) Parallel Kinematic Structure (PKS) having - actuation joints on the base (I) with 2dof (f_a=2) and (f=1) and (f=3) - passive joints on the last two levels (II-III), respectively. Following these it is a PKS with actuation redundancy (Ra=2).

Figure 1. Kinematics - structure (left) and mechanism (right).



2.2. Mechanism

Even if, at the first view, the use of direct drive (DD) 2dof actuated joints (ex. planar motors) could be an interesting solution, from the stability of motion/positioning pov, the (electro)mechanical actuators (stages) are preferred. A possible mechanism is presented in Fig.1 (right). It is based on four pairs of two (stacked) simple actuated pairs (**P**⊥**P**) each other having motion axes orthogonally arranged followed by symmetrically inclined (α) passive pairs(P) in respect with one of the actuation axes forming a pyramid, with the spherical joint (S) on the last level. By simultaneously motions of a couple of actuated pairs, the simple linear motions along and around the main axes are easy and intuitively performed (decoupled motion) simplifying the control of 6-[4(**PP**PS)], Tab.1.

Table 1. Actuators involvement.

Axes	Displacements (Pi/Pi+4)	Total
X ,Y,Z	(X2=X4)=(X5=X7), (Y1= Y3)=(Y6=Y8) (-X5=X7)=(-Y6=Y8)	4
RX,RY	-Y6≠Y8, -X5≠X7	2

2.3. Modelling & Simulations

In order to fully investigate the kinematic capabilities of the above mechanism, a geometrical model has been established, Fig. 2(left). And, the Invers and Direct Positional Problem (IPP&DPP) analytically and numerically solved (MathCAD).

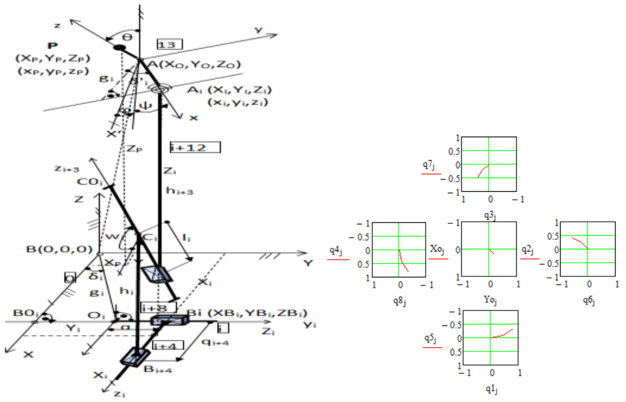


Figure 2. M&S - geometry (left) and motion map (right).

The IPP algorithm consists on a set of four nonlinear equations including the generalized input and output kinematic variables:

$X_P, Y_P, Z_P, \Psi, \phi, \theta$ - Platform coordinates (P = Pivot Point),

q_i, q_{i+4} - Actuators displacement coordinates (i=1,..,4) ;

and designed (fixed) parameters:

a, b - Base/Platform side, g_i, g_i' -Base/Platform Points Radius

δ_i, $\delta`_i$ - Base/Platform Angles, l_i, (h_i, h_{i+4}), w_i - Wedges Displacements (Heights) and Angle,

by expressing the coordinates of guided points $A_i(X_i,Y_i,Z_i)$ in respect with both Cartesian reference systems:

O-XYZ: Fixed Coordinate Systems (O=B / base center)

o-xyz: Mobile Coordinate System(o=A / platform center) :

$$X_i = (R+q_{i+3})c\delta_i - q_i s\delta_i - l_i s w_i\, c\delta_i$$
$$Y_i = (R+q_{i+3})s\delta_i - q_i c\delta_i - l_i s w_i\, s\delta_i \quad (1.1)$$
$$Z_i = h_i - l_i c w_i\,,\ i=1,\dots,4$$

where Cos=c, Sin=s, Tan=tg

$$X_i = X_P + (x_i - x_p)\alpha_1 + (y_i - y_p)\alpha_2 + (z_i - z_p)\alpha_3$$
$$Y_i = Y_P + (x_i - x_p)\beta_1 + (y_i - y_p)\beta_2 + (z_i - z_p)\beta_3 \quad (1.2)$$
$$Z_i = Z_P + (x_i - x_p)\gamma_1 + (y_i - y_p)\gamma_2 + (z_i - z_p)\gamma_3,\ i=1,\dots,4$$

and α_i, β_i, γ_i are the cosine direction (oxyz/OXYZ).

Then, by equalizing (1.1) and (1.2), and doing some calculations the actuators displacements values resulted as,

$$q_i = Y_i c\delta_i - X_i s\delta_i$$
$$q_{i+4} = X_i c\delta_i + Y_i s\delta_i - (Z_i - h)tg(w_i) - R,\ i=1,\dots,4 \quad (1.3)$$

A modelling & simulation process has offered the chance to understand the mechanisms motion behaviour, including even the workspace shape (rectangular) detection. By imposing a desired motion (law) : $X_P = X_P(t)$, $Y_P = Y_P(t)$, $Z_P = Z_P(t)$, $\psi = \psi(t)$, $\phi = \phi(t)$, $\theta = \theta(t)$ and a starting point (P0) and $\Theta(0)$ values, the numerical results have been graphically registered. For P≡o (table center) and t=(j-1)t1 where t1=0.1(increment), j=1,2,3 a motion behaviour map for a=b=1, h=h1=h2=1(w=45°) - unity mechanism case is presented in Fig. 2(right).

3. Design

Inside of the Design for Precision (DfP) concept, the stiffness is primordial when load and accuracy requirements are both involved. In a fully covered(C) modular design: a) two high precision Positioning units (Pu) orthogonally arranged as planar actuator (Ac), b) pair of wedges (w1,w2), as Elevation unit (El) and c) compact precision ball & socket, as spherical/sliding joint (SJ) vertically mounted is forming one of the Positioning modules(Pm), Fig. 3(right) supporting the Table(T). An overview of the design parameters and accuracy can be seen in Tab. 2.

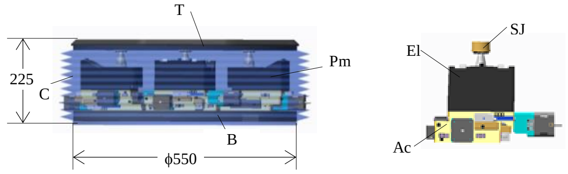


Figure 3. Design - layout (left) and Positioning module (right).

Table 2. Pm Design Components.

Part	Type	Stroke	Accuracy(μm)
SJ	ϕ20	±20°	1
El	α=30°	±15 mm	2
Pu	5102.15(XE)	±25 mm	0.1

In order to move the table (or, pivot point) with the necessary speed and precision in the desired position, an application specific controller has been designed, too. It is a stepping motor unit able to transfer the commands at the 2-phases motors and receive feedback signals from linear encoders by using BISS-C serial protocol, as premises for excellent bi-directional repeatability and stability.

4. Prototype

By using precision standard and customized components and following the general and specific strict rules of the precision assembly, a first Proof of Functionality (PoF) experimental prototype has been accomplished. Basically, it consists from two independent units– Mechanical device (Md) and Controller (C) working together, Fig.3. The first basic tests revealed the capability to perform maximum: translations - X=Y=50mm, Z=29mm and orientations - Rx=Ry=10°, Rz=18° with 3.1μm/ 20mm and 2.6 arcsec/5° accuracy and carrying 100kg load.

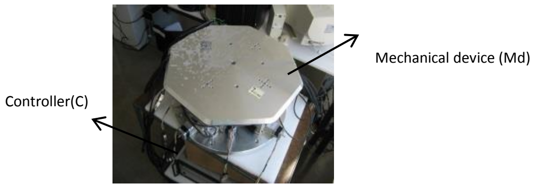


Figure 4. TPD (prototype).

5. Conclusions

A new specific positioning device for high precision and heavy load manipulation able to work inside of Diffractometers machines has been presented. A short kinematic and design analysis of the first prototype has been done. In order to fully be characterised from accuracy point of view, more tests and a graphical control interface are to be done in the next step.

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