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Parallel positioning technology for a high-energy synchrotron beam-line system

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Abstract
Several newly developed positioning devices working inside of a high energy beam-line (HEX) from 3rd generation synchrotron facility (NSLS-II) are presented. Developed for a new complex multiaxis and multipurpose positioning system (MPS), some of the devices are based on parallel positioning technology (PPT), providing the necessary power, stability and accuracy of motion, in relative small-allocated spaces, to manipulate samples (and instruments) towards an X-ray beam. The proposed devices are helping several scattering techniques to investigate advanced engineering materials. Their innovative design and capabilities to quicky, stably and precisely pose heavy loads/large sizes or dynamic behaviour of the objects in the right necessary experimental position are revealed. Parallel Positioning Tables Devices (P-PTD) have been developed, as combinations of different sets of actuators (and guides), moving the related experimental surfaces (interfaces) inside of the required tolerances (planeity/straightness). Parallel Alignment Table (P-AT) based on TRIPOD PKM structure was developed to manipulate samples, weighing several hundred kilograms with high precision. Alignment capabilities has been provided. Parallel Lifting Table (P-LT1), manipulating a collimator instrument has been developed on BIPOD principle having a precision elongated table. Parallel Lifting Table (P-LT2), manipulating a heavy imaging detector instrument was developed using a QUATROPOD structure. The paper presents several important aspects of precision (challenges and solutions), related with mechanic and design concepts and manufacturing processes for the first finalized products (protoypes).

Synchrotron positioning, conceptual design, parallel technology, kinematics, motion, precision

1. Introduction

Synchrotron Radiation (SR) proved to be a powerful tool to investigate the micro/nanoscopic structure of matter. Produced by very complex sources, called synchrotrons [1], the actual generation (3rd) are producing very brilliant radiation comparing with the first one (1st)[2]. Having a continuous spectrum over a broad range of frequencies, from microwave to X-ray, SR has a great advantage of being non-destructive. The demands for research investigations of materials are coming from a large areas of sciences as biology, geology, etc up to engineering.

Synchrotron X-ray diffraction (XRD) has been developed as a fundamental experimental technique, being successfully applied for a broad range of materials from crystalline to amourphous ones [3]. The actual modern techniques [4] are investigating the structure of materials for micro/nano engineering purposes, as necessary in photonics, electronics, defence, etc.

Today challenging issues (e.g., electric vehicles) directed the research community to be strongly focused on sustainable energy. The intention is to discover new advanced materials, able to improve the actual existent supports (batteries) and savings (storage) and the ways of conversion (fuel cells), for a long-term sustainability [5]. Interesting results are expected to be obtained in the future, by the development of new techniques and adequate instruments [6].

Till now, most of the basic diffractive research have been performed on traditional (standard) machines called diffractometers. There are existing several wellk-nown such multiaxis machines mainly, based on corelated rotational motions (circles) where, the basic X-ray technique (XRD) applied.

Today tendency is to use basic and modern X-ray techniques combined in one place. This has the advantage of obtaining a large spectrum of results in a short time within the same allocated space, by reducing the total costs and increasing the profitability of investigations, see for example [7].

However, from the design point of view, by taken in consideration all the cumulative aspects related with the increased number of samples, techniques, together with precision have proved to be challenging for the whole machine (system). The structures are becoming complex with some of the specifications contradictory and special technological solutions necessary to be applied, e.g. air bearing and the results often are standing as a nonconventional product [8].

At one of the most important national research institution in the world [9], including a 3rd generation synchrotron facilities [10], an upgradation process started few years ago. Inside of a Hard X-ray Scattering and Spectroscopy (HSS) science program, a new beam line [11] is expected to be built and open soon to the users (2022). By benefiting from the use of a high energy radiation power of the beam and future versatile machines, it will combine several techniques to study various material engineering structures and processes in one place, from batteries to functional ceramics under induced (in-situ) and real (in-operando) conditions [12].

A dedicated system [13] using several X-ray techniques is expected to work here, which will be installed soon in the allocated experimental hutch (EH). Inside, several manipulation devices have to adequately work, related with loads, speed and precision. The solutions have been proposed based on in-house parallel positioning technology (PPT) [14]. Precision challenging issues and solutions from conceptual kinematic and design pov, together with manufacturing aspects are shortly presented below.

2. Multipurpose Positioning System

The mission of the High Energy (250keV) Engineering X-ray Scattering beam line 27-ID (HEX) is to advance the developments of clean solutions and creative technologies for the future of energy. In this respect, a positioning system role(s) is to give the possibility for the investigations to be performed, using different types of: a) samples – small/medium/heavy (0.5kg/50kg/500kg) and b) techniques–diffraction/imaging/tomography (XRD/CCD/CT) on engineering materials(thick) and related processes (chemical, mechanical, etc). However, due to the time-constrain beam-line issue, these should be done, as fast as possible and in an easy way, in the allocated EH space (L=10m).

A dedicated multiaxis/multipurpose positioning system (MPS-HEX) has been proposed. From *mechanical* pov, it consists of several positioning modules (Pm) linearly disposed in-parallel and along the beamline, relating the main components - sample(S), detectors(D), shield(s), collimator (C), and optics (O) with the beam line and reciprocally, Fig.1. Some of Pm being moved/removed from working area.

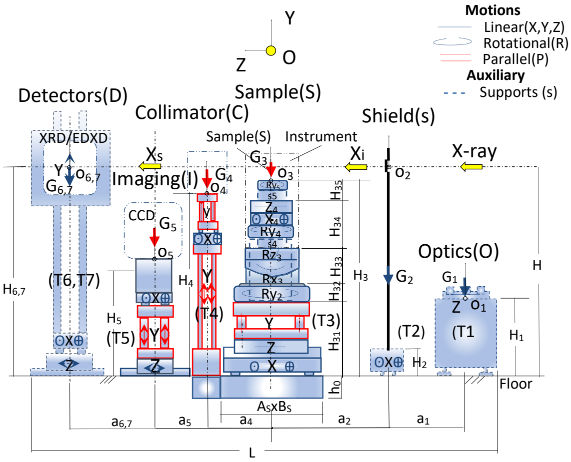

Figure 1. MPS-HEX (Mechanical structure)

Pm are generally built on classical(stacked) combinations of positioning units (Pu), with simple linear (X,Y,Z) or rotational (Rx,Ry,Rz) motions(stages), supported by positioning tables (T1-T7). However, from the considerations explained further on (c.3), some of them (T3-T5) are using in-parallel (P) motions.

Optics(O) Pm is using (T1) for supporting beam conditioning optical components before the beam is goes to the sample. *Shield(s)* Pm is protecting the devices agains X-ray through a panel (lead), coming perpendicular to the beam through (T2*).*

Sample tower(S) Pm is using (T3) to manipulate the samples (and additional instruments) toward the incoming Xi(i-incident) beam. It should provide an adequate means to support (and move) all the samples (m3=0.5-500kg) and related instruments, in a stable and highly precise way, along/around every direction in space (XYZ), approaching the beam from above. In order to quickly be adapted at necessary samples/techniques, a modular concept has been chosen. Five modules(M1….M5) are consisting from a combination of positioning devices (precision stages) stacked one after the another, starting from the basic one (M1), based on (T3). Two gonio stages (M4, M5) are performing high speed rotations-a) Ry4=10rev/s(m3=1kg, SoC< 1 µm) and b) Ry5= 50 rev/s(m3=-0.5kg, SoC<1 µm), SoC-Sphere of confusion.

Colimator (C) Pm based on *(T4)* is carrying the collimating instruments (m4=50kg) up and down(Y), performing long/short (YX) precision motions.

Imaging(I) Pm is using a positioning table (T5) for precisely posing the related instrument (CCD cameras), having an appreciable mass (m5=200kg), in the right position (XY) and then moved/removed (Z).

Detectors(D) Pm role is to catch the scatered Xs-ray beam (X_s, s-scattered) after it comes from the sample. They are specific to: a) EDXD and b) XRD/powder, techniques. (T6,T7) must adequately manipulate them to correctly collect the spot.

Note: 1) A general coordinate system of reference (OXYZ) has origin (O) in the center of the sample/beam line and the partial ones (oxyz)i, i=1,7 with origin (o) in the center of the functional (experimental) surfaces. 2) As the nominal value of the beam height(H) is set-up at 1.4 m, two Pm have underfloor base (S,C).

The positional motion ranges and precision of components is affecting the design solutions. For the parallel actuated tables (T3-T5) they are given in Table 1, including the repeatability and resolution parameter values, respectively.

Table 1 Motion specifications(tables)

Table (T)	Axis (XYZ)	Range (mm)	Rep. (µm)	Res. (µm)
T3	XZY	1500*/100/100	5/1/1	1
T4	YXy	620*/150/90	10/1/1	10/1/1
T5	ZYX	2760*/200/100	200/10/10	10

*Long stroke

As seen from above, the positioning tables (T3-T5) should perform precision or high precision motions, performing both, long and short strokes. In addition, the subsequently (experimental) surfaces (Σi, i=3,5), see Fig.2 with horizontal orientations must fulfil some geometric errors specifications. For (Σ3) it must be not tilted more than 250 µrad over the complete travel range. With other words, straightness/flatness values have are to be limited at maximum: ε(X3)=25µm, ε(Y3)=20µm, ε(Z3)=10µm. XY stage (M4), must not tilt the sample more than 100µrad, or errors to be less than: ε(X34)= ε(Y34)=10µm values.

Due to the high number of positioning devices involved, the space around the sample became very crowded. Especially, the relatively small existent space between the floor and beam.

As such, compact and powerful solutions was necessary to be investigated, and prevailed. The results were that in the final *design* review (FDR) step, for short stroke the positioning table devices (T3-T5) have been built, using parallel positioning technology (PPT) principle, Fig.2. In addition, for some standard components (stages) the size and power were also modified.

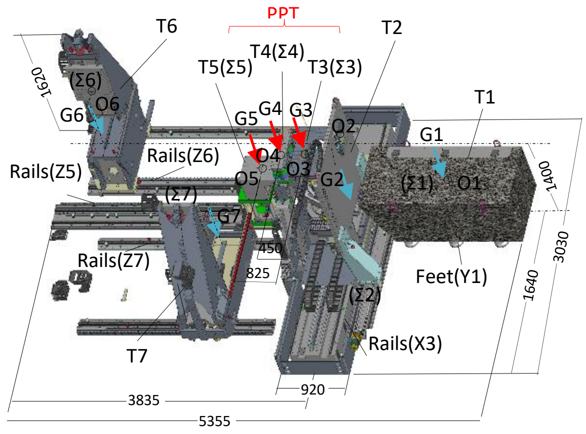

Figure 2. MPS-HEX (Design)

3. Parallel Positioning Technology

Parallel positioning technology (PPT) is not a new technological concept. It was already applied for relative long time in various applications, especially those related with synchrotron positioning. More specific, where heavy loads and high precision manipulations tasks have had to be successfully accomplished [14]. It includes actuation, guides and sensors as the first components.

Devices conceived on parallel kinematic mechanisms (PKM) principle are all using PPT in a way or another. The Hexapods are the best examples, being increasingly used, as positioning table devices inside of various systems. However, when some constraints must be taken into consideration, as small(particular) available spaces or reduced degrees of freedom (dof<6) to be used, the existent solution not satisfied the design expectations. Then, the designers have look for another solutions.

Therefore, by using a larger parallel actuation (PA) concept, for a limited number of dof (or, even single one), several proposed positioning devices solved de problem. *Note:* In the actual context, PA concept is used to provide the necessary power (motion) to a final component, involving any dof, including the minimum one (1dof). The solution is often coming, as a divided (differential) action from a central one, see for example [16].

More details of the PA/PPT applied in the MPS-HEX context are given below.

3.1. Parallel Positioning Table Devices

The proposed positioning devices for (T3-T5), using PA/PPT are shown in Fig. 3. Their new and innovative design *concepts* are described taken in to account their specific requirements.

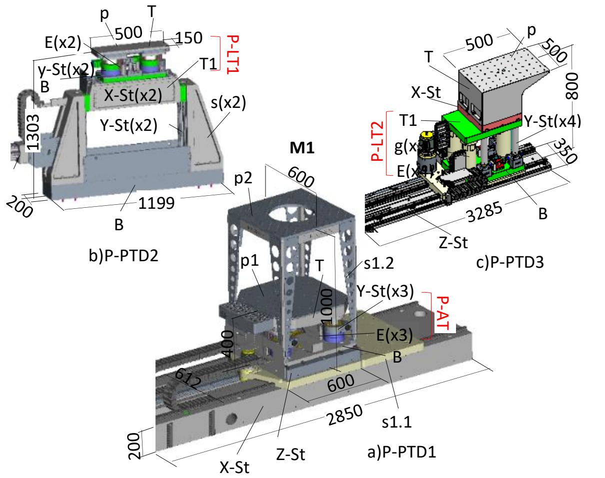

Figure 3. P-PTD (Concepts): a)Sample tower, b)Collimator), c)Imaging

The P-PTD1 corresponding to (T3) have to manipulate various samples and instruments under a modular approach applied to sample tower(S) positioning module. M1 basic module is dedicated to heavy/large samples to precisely manipulate its Σ3 (alignment) surface. M2 module should provide heavy load/ large size samples precision position capability in rotation around vertical axis through a precision rotation stage (G440XE, Ry2=±180°, e<1μm, e-eccentricity). M3 module is able to manipulate the same type of samples as (M2). In addition, the sample can also be rotated in two perpendicular directions using a modified gonio stage (G5203.80XE, Rx,Rz=±5°, eccentricity<10 μm). M4 module dedicated to tomography is using small samples, rotating continuously around a vertical axis with high speed and precision for which an air-bearing stage (EZ0570, Ry4=±360°, eccentricity ≤1μm) has been included. Both, being supported on a strong hollow spacer (s4). Horizontal adjustment (alignment) of motion axis can be possible through a modified translational XZ stage (T5102.20XE), diminishing the inertial effect (imbalance). M5 module is similar with last one but using a smaller size sample rotation stage (EZ310, Ry5=±360°, eccentricity≤1μm) on a higher spacer (s5). P-PTD1 should be strong enough to manipulate all samples, stages and supports, coming from all modules built up on it. An overview of the involved masses (mi, i=2,5) are given in Tab.2.

Table 2. Design specifications (T3)

M	Type	m (kg)
M2	s1/G440*	16/77
M3	s1/G440*/G5203.80*	16/77/94
M4	s4/G3/T5102.20*	55/12/9
M5	s5/G4	90/5

* XE-Extreme precision

Shortly, as P-PTD1 is an integrated part of all modules (M1-M5) it has to support/move a mass in the worst case (M3) of at least m3=700kg, including m(sample)=500kg, m(stages)=171kg and m (supports)=16kg and m(plates, etc)=13kg, in addition, to high precision parameters related with the geometry of motion (straightness/planarity) mentioned before.

As such, P-PTD1 concept was developed around a Parallel Alignment Table (P-AT) with PKM structure for vertical motion (Y). In addition, two translational stages (X-St, Z-St) stacked one under another.

Parallel positioning table device (P-PTD2), Fig. 3b has to have not only good supporting (load) and precision (motion) capabilities, but to be very flexible, to quickly performing long/ short stroke vertical motions (Y/y). In addition, it should avoid the existent imaging device in the minimal(nominal) position. The dedicated device developed is a combination of two – coarse(Y)/fine(y) lifting devices, including a small one Parallel Lifting Table (P-LT1).

Parallel positioning table device carrying a heavy/large detector (CCD camera) nearby of the sample and then removed it, Fig. 3c involves a motion performed with precision, in vertical (Y) direction towards the beam. Care has been taken to overcome the collimator table (P-PTD2), being already there in the nominal (lower) position. A dedicated device based on a specific Parallel Lifting Tables (P-LT2) was developed.

More details are given below for the above parallel positioning table devices (P-PTD), from *kinematic* point of view, Fig.4.

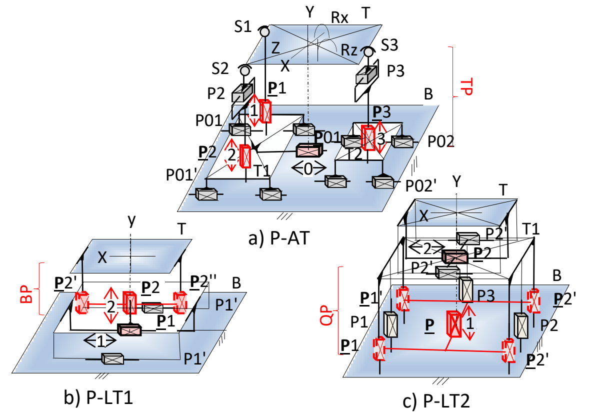

Figure 4. P-PTD (Mechanisms): a)Alignment, b) and c) Lifting

The parallel positioning mechanism conceived to work inside of P-PTD1, as *Parallel alignment table (P-AT)* is based on a new TRIPOD (TP) structure, providing 1T2R (T-trans., R-rot.) capabilities, Fig.4,a.

The corresponding mechanism 3-[2(**P**P)-**P**]S consists of a pairs of identical kinematics chains (**P**PS) in addition to single (**P**S) one. Each chain comprising the same type of joints (P-Prismatic, S-Spherical). From space constrain consideration, on two bases (B1,B2) are vertically arranged a set of three **P** (active), horizontally supporting (passive) P joints, which in turn support the table (T) through (passive) spherical (S) ones. This mechanism will be able to perform short positioning vertical motion (Y=±50 mm) with the possibility of small rotational (Rx,Rz=±5°) for the alignment purposes. In addition, the whole mechanism can be horizontally shortly moved (Z=±50 mm) support base (B), which in turn is moving along long rails in X direction. *Note:* By taken in to account all motions, the whole mechanism can be seen as a hybrid kinematic structure with serial(Z)/parallel(YRxRy) motions.

The parallel lifting table (P-LT1), Fig.4b is consisting from a new serial combination of two BIPOD mechanisms. The first one (BP1), based on a differential parallel actuation (**P**1/**P**1'**P**1'') is providing the coarse motion (not shown). The second one (BP2), providing small (fine) precision motion, through another differential actuation (**P2**/**P2**',**P2**'') is horizontally keeping the final table (T) surface with the desired accuracy. As such, the (pseudo)BP2 mechanism has one (1) dof vertical (y) motion. *Note*: An additional (X) necessary motion in-between the two BPs, is qualifying the whole mechanism, as a hybrid kinematic structure with serial(X)/parallel(y) motions.

Parallel lifting table (P-LT2) is based on a typical QUADROPOD structure, as Fig.4c shows. The new proposed mechanism consists of a set of four (4) in pairs (**P**1', **P**2') and (**P**1'', **P**2'') actuation elements driven by a central one (**P**) and a set of three (guiding) pairs (P1-P3) supporting the table(T1). With this type of (differential) actuation, the P-LT2 belongs to the large (PA) family of quadropods. However, as each of the actuation is not independent, the correctly name of the structure should be (pseudo)QP in the strict sense of parallel mechanisms theory. *Note:* As structure has also the possibility to hold and move the instruments in X direction (top), the whole system can be seen as a hybrid-parallel (Y)/serial(X) kinematic structure.

From *design* point of view the corresponding solutions for above mechanisms are presented below, see Fig.3.

P-AT design is using modified vertical standard stages (G5103.A20) to increase the power, acting the legs/pods, located in-between two robust components – base (B) and table (T). On their upper part support, linear guides (LWLF/MLF30/IKO) and spherical plain bearing (GE10AW/INA) were assembled.

P-LT1 design has been implemented with specific components delivering short strokes. Each of the pods of BP2 being actuated by actuators built with vertical gonio stages (G5103.A20) driven by a simple common transmission (coupling) coming from a single stepping motor (PKP266VEXTA/ORIENTAL).

P-LT2 design has a centralized motor, transmiting (splitting) the motion to both pairs of pods (pillars) through specific transmissions (motion axis & couplings). Each of the legs/pillars are based on two screwed parts, one in relative motion to another (fixed), specific to jack devices (T5103.D20) powered by 2-phase high torque motors (PKP266VEXTA/ORIENTAL) through a gear box (HSG1/INKOMA). Strong pillars (g) are using linear precision guides (0672-250-40/BOSCH) for guiding the table.

Note: All motorised axis above are controlled in a closed loop way, through a dedicated control box (SMC9000) and dedicated software for which sensors as absolute encoders(E) RESOLUTE/RENISHAW have been provided, together with electrical limit switches and mechanical stop/end components.

P-PTD devices have been *manufactured* at the end of 2021, waiting now for the installation/commissioning of the whole prototype.

As most of PPT components were commercially available, for which mounting experience already existed in the factory, care has been taken in machining of sensitive functional surfaces. These included not only the supporting surfaces of samples (plates) and instruments (interfaces), but those related with PPT, as for example for actuation (Y-stages) and guides (linear). The procedures were based on quality and tolerances (dimensional/ geometric) control, exceptions being for granite, connectors and cables parts coming from outsourcing, where additional work was not necessary to be done. An overview of the final physical products is shown in Fig. 5.

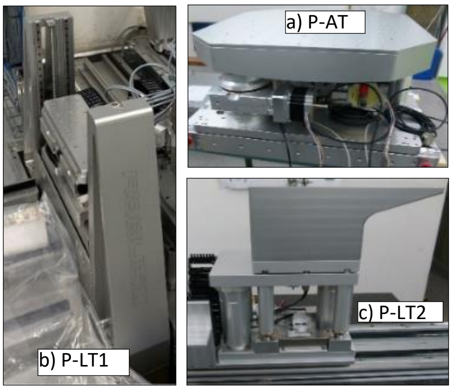

Figure 5. P-PTD (Prototypes): a)Alignment, b) and c) Lifting

Note: All the sample/experimental surfaces, having standard interfaces from Al plates (20/10 mm) with an array of holes (M6/50mm), allowing various configurations of samples/ instruments to be easly fixed, were aligned using metrological devices (levelling) and related procedures.

4. Conclusions

New and innovative parallel positioning table devices (P-PTD) integrated in a new complex multipurpose positioning system (MPS-HEX) have been presented from kinematic and design pov.

The tests included in a factory acceptance test (FAT) report have been performed for components in motion (with payloads). At the end, all have been met the customer expectations. In the P-PTD1(P-AT) case, corresponding to the vertical motion(Y), the obtained measurement values for positioning accuracy (repeatability/resolution) being (0.7/0.5) µm and, for geometric errors (straightness/planarity) as (2.1/3.4) µm. More results will be latter reported, together with their graphical and numerical variation.

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