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Compact lever actuated direct driven 6-DoF parallel kinematic positioning system

Tillmann Volz[1], Paul Binder[1], Philipp Ritter[1], Christian Sander[1]

[1]*Physik Instrumente GmbH & Co.KG.*

T.Volz@PI.de

Abstract

In recent years, parallel kinematic machines (PKM) with sub-micrometer precision and six degrees of freedom, also known as hexapods, have seen a significant increase in demand, attesting to their growing importance in various sectors. Certainly, in the field of photonics alignment and wafer level applications, hexapods have the potential to play a significant role in future production lines. However, in industrial production, reliability, robustness and high dynamics are mandatory in order to reduce downtime and increase throughput, while the machine must maintain its high precision over an extended period of use. Therefore, Physik Instrumente GmbH Co. KG (PI) has developed, built, and qualified a functional model of a direct driven compact 6-DoF PKM that aims at enabling superior performance regarding reliability and dynamics compared to available compact spindle driven hexapods. In the developed system, the rotational motion of a motor shaft is directly translated to a circular foot point motion of six struts with constant length and five degrees of freedom using a lever arm attached to the shaft. This direct coupling of the motor rotation and top platform position enables highly dynamic motion, while the mechanical complexity of the machine and thus costs and wear and tear can be reduced. This paper focuses on a detailed description of the PKM design as well as a qualification regarding precision and dynamics to identify the potentials and challenges of direct driven hexapods based on lever actuators for industrial scale use.

Automation, Hexapod, Positioning, Precision

1. Introduction

Physik Instrumente GmbH & Co.KG. (PI) is a leading supplier of high precision positioning systems, including parallel kinematic machines, that are widely used in research facilities and a variety of industries such as automotive, photonics, semiconductors or astronomy. An ever-growing demand for high-precision 6-DoF PKM is driven especially by alignment and scanning applications that become more and more important in the photonics industry on an industrial scale. This generates a demand for compact, highly dynamic and robust systems for 6-DoF high precision positioning [1]. However, available compact spindle driven 6-DoF PKM are limited in their ability to perform motions at high frequencies and amplitudes as shown by Rudolf et al. [2]. Further, small amplitude trajectories at high frequency cause accelerated wear and tear in spindle driven machines limiting the potential in applications mentioned above. More promising candidates are direct driven PKM that provide not only higher accelerations and velocities but are also superior in terms of wear and tear thank to a simple mechanical design. Systems using flexure hinges like the H-860 from PI [2] or the T-Flex hexapod [3] however, are rather inappropriate for an integration in industrial production lines, mainly due to their size necessary to enable usable workspaces. Motivated by the said, PI has developed a direct driven, compact 6-DoF PKM sized comparable to available compact spindle driven hexapods, aiming at high dynamic and precision applications to enable improved throughput and minimal downtime.

2. Design

The design of the newly developed lever actuated 6-DoF positioning machine (shown in fig. 1) is based on the principle of parallel kinematics. The system exists of six actuators arranged in parallel between a top and base platform. While the base platform is fixed, the top platform can be moved laterally and rotationally (X, Y, Z, pitch, roll, yaw).

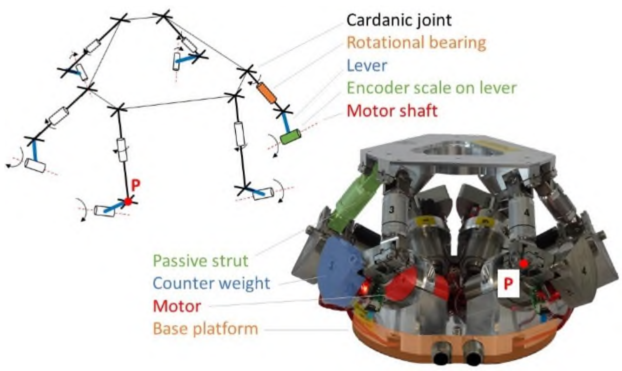

Figure 1. Lever actuated direct driven 6-Dof positioning system (line model on the left and picture on the right)

The actuators of the system are integrated in the base platform and consist of brushless BLDC motors with ceramic bearings and levers attached to the end of the motor shafts. In this setup, no sensor or power cables are moved and thus, no parasitical forces impaire the systems performance. The lever at the end of the motor shaft is connected to the top platform via passive struts with 5 degrees of freedom (two universal joints and one rotational joint). By rotating the levers, the lower strut points (marked *P* in figure 1) are moved along a circular path enabling the motion of the top platform. The position of the levers is determined using a scale opposite to the lever (figure 2). In addition, counterweights are attached to the levers that compensate the weight of the top platform and strut in the initial position. The two universal joints in the passive struts were newly developed for the functional model. While they have to be compact and enable large joint angles for large travel ranges, they have to be light and free of backlash. While ball joints are compact and enable large joint angles, friction and hysteresis effects make them not convenient for high precision positioning. Compact flexure joints however, are hysteresis free but are limited in possible joint angles. Consequently a sub-compact cardanic joint with crossing axes and four ball bearings was developed (figure 2) that is free of backlash and enable the necessary large joint angles. Beside the universal joints, the passive struts contain another high precision rotational bearing to enable the rotation between the upper and lower joint around the struts longitudinal axis.

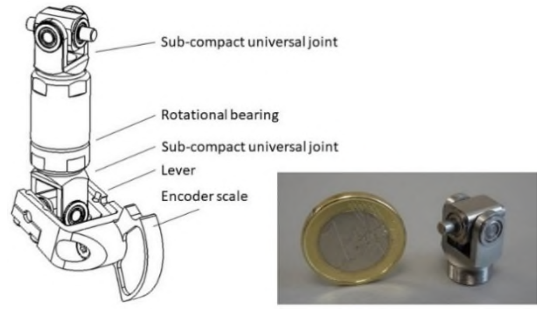

Figure 2. Passive strut with universal joints without axis offset

3. Specifications

The length of the passive struts and levers were choosen to achieve a workspace comparable to the spindle driven 6-DoF PKM H-811 from PI. The exact travel range is listed in table 1. While possible travel in X- and Y-direction is smaller for the functional model, the travel range in Z-direction is larger. Rotations around the X- and Y- axis are the same compared to the H-811 whereas the possible rotation around the Z-axis is about half. The maximum speed of the functional model was measured at about 65 mm/s with counterweights which is about six times faster than a H-811. Due to the lack of the spindle, the payload is significantly smaller compared to the H-811, however, sufficient for most alignment tasks. A summary of the systems specifications is listed in the following table 1.

Table 1. Specifications of the compact lever actuated PKM

Specification	*Value*
Height	104 mm
Diameter	188 mm
Translation (X, Y, Z)	±9.5 mm
Rotation (U, V, W)	± 10 mm
Payload	200 g
Maximum speed	65 mm/s
Theoretical z-resolution @ Z= -9.5 mm	27.8 nm
Theoretical z-resolution @ Z = 9.5 mm	13.6 nm
Bidirectionale Repeatability (X, Y, Z)	< 1 µm

It is to mention, that the theoretical resolution of the hexapod depends on the lever position (maximum and minimum values for pure Z motion in table 1). Along the sensor scale, it is constantly about 20 nm.

4. Technological Performance

To determine the resolution (minimal incremental motion or MIM) the system can perform consistently and reliable steps in closed loop. In this qualification the hexapod executed ten steps with different step widths around the initial position. The resolution is at its worst around initial position. Figure 3 shows the result of 50 nm steps in Z-direction determined with an interferometer. The same measurements were performed for motions in the X- and Y-direction. While the steps are clearly visible in figure 3, noise is present when the hexapod is not moving which is expected to be caused either by the position sensors or the single axis controls. Similar results were determined for the X- and Y- axis. Summed up, in all directions, a MIM of < 100 nm is possible with the system which is comparable to the performance of the H-811.

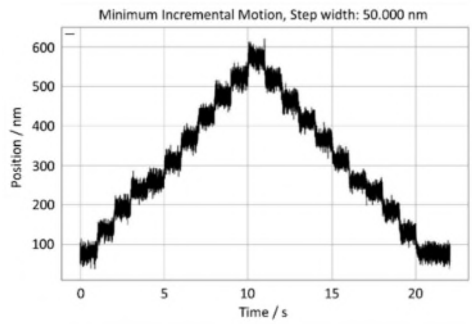

Figure 3. 50 nm steps in Z-direction around the initial position

Further, a frequency analysis was performed for a comparison to a H-811. The following figure 4 shows the amplitude error and the phase offset for different amplitudes (20 µm, 10 µm, 5 µm, 2 µm and 1 µm) and frequencies (10 Hz, 15 Hz, 20 Hz, 25 Hz and 30 Hz). The comparison (direct driven hexapod on the left and H-811 on the right) shows that the direct driven hexapod is superior in both, the phase offset and amplitude error, compared to the H-811 hexapod.

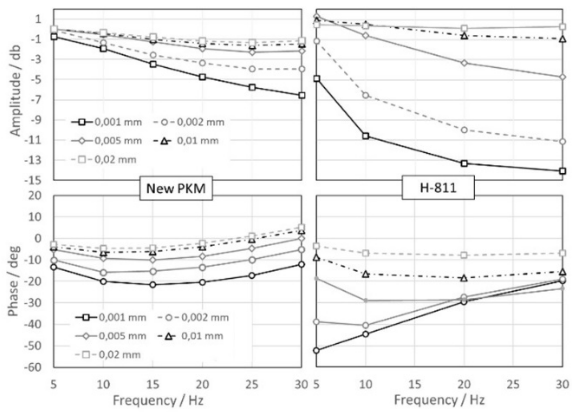

Figure 4. Comparison of frequency analysis (amplitude error and phase offset; left: direct driven hexapod; right: H-811)

5. Conclusion and Outlook

The newly developed functional model of a 6-Dof parallel kinematic lever actuated system shows very promising results regarding fast motion with small amplitudes as required in many alignment applications. However, beside first good results, lifetime tests have to prove robustness and a MIMO control is necessary to use the full potential of the system.

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