euspen's 26th International Conference & Exhibition, Krakow, PL, June 2026
www.euspen.eu

A compact cube-shaped parallel kinematic machine for dynamic and high-precision positioning in six degrees of freedom

Tillmann Volz [1], Stefan Schulz[1], Stephanie Streit[1]

[1]*Physik Instrumente (PI) SE & Co. KG*

T.Volz@PI.de

Abstract

This paper introduces a compact, direct-driven, cube-shaped parallel kinematic machine (PKM) that employs electromagnetic voice coil motors with linear cross-roller bearings. The motion of the motors is directly transferred to the end effector via passive struts, and adjustable magnetic counterbalances are paired with the motors to compensate for the lack of self-locking. Unlike typical PKM configurations with parallel top and base plates, this cube-shaped PKM uses three pairs of actuators, where these pairs of motors, bearings, and passive struts are aligned along Cartesian axes, forming a cubic structure. Each pair of struts is attached to a planar top plate, which is then interconnected to form a corner-cube-shaped top plate, offering three faces for payload attachment and versatile integration into systems. The design ensures consistent stiffness, resolution, and dynamic capabilities in all Cartesian directions, even when oriented with one surface of the top plate facing downward. Additionally, the absence of ball- or roller-screws, commonly used in standard PKMs for high-precision positioning, enhances the system's lifetime, while also providing significantly higher dynamics (velocity and acceleration).

Hexapod, Positioning, Dynamic

1. Introduction

PKMs with ball- or roller-screws, combined with electromagnetic motors saw a large growth over the last years and are today the go to and turn-key solution in a vast number of applications whenever motion in six degrees of freedom, very high precision down to the nanometre range and high stiffness is demanded. By their nature however, such systems are limited, mainly in two regimes. One being dynamic capabilities, namely velocity and acceleration. The other being lifetime, especially due to dynamic motion with small step sizes or amplitudes that may cause accelerated wear and tear of raceways and rolling elements used in driving components. To expand the application range of PKMs and enable a wide application in an industrial environment where high reliability, high lifetime and high throughput are necessary, an approach with a direct transfer of the electromagnetic motor motion to the PKMs platform is promising. The development of the cube-shaped PKM, that is presented in this paper, is a natural progression from a series of direct-driven PKMs that Physik Instrumente (PI) SE & Co. KG has developed over recent years, such as an air-bearing hexapod presented by Matitschka et al. [1] and the lever-actuated direct-driven PKM presented by Volz et al. [2]. Further advancements in fully flexure-based direct-driven PKMs have been made by Naves et al. [3, 4, 5]. Unlike the aforementioned direct-driven PKM configurations, where the top and base plates are typically arranged in parallel in the initial position and exhibit exceptional stiffness and resolution, especially in the direction normal to the baseplate (usually the Z direction), the cube-shaped hexapod presented in this paper features a unique design. In this, three pairs of actuators and passive struts (see figure 1) are aligned parallel to the Cartesian axes. Each pair of actuators is housed in a separate unit, which is then assembled to form the cube-shaped PKM. The top plate forms the corner of the cube, providing three faces available for payload attachment, and is connected to the actuators via six passive struts with two universal and one rotational joint (URU). In this configuration, there is no preferred orientation but stiffness, resolution and dynamics are the same in all three Cartesian directions. The cube-shaped design allows flexible positioning of the payload on the three surfaces of the top plate without reorienting the PKM. Even in a rotated configuration, where one face of the top plate faces downward, dynamic behavior and stiffness remain largely unchanged, unlike in conventional Stewart platforms.

2. Mechanical Design and Specifications

As mentioned, the PKM is designed to provide isotropic stiffness along the Cartesian axes by using three pairs of passive struts aligned parallel to these axes (see figure 1 on the right). This setup provides mechanical decoupling of the struts, simplifying the control of the PKM. Each passive strut connects the corner-cube-shaped top plate to a linear voice coil motor integrated with linear crossroller guides, enhancing stiffness and ensuring precise positioning.

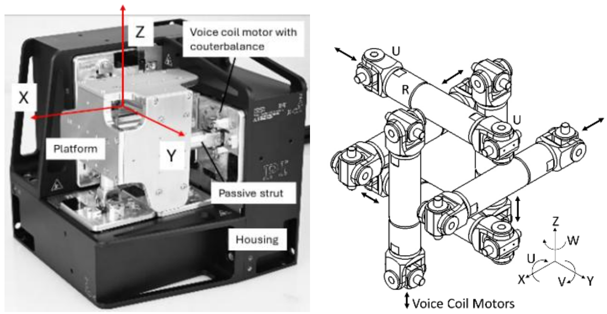

Figure 1. Cube-shaped PKM in an upright orientation (left) and schematic arrangement of passive struts connecting platform and actuators (right)

Additionally, each actuator features an adjustable magnetic counterbalance that compensates for the payload, thereby increasing dynamics and reducing power consumption and with that, thermal drift. The setup allows for a lateral workspace of ±5 mm and a rotational range of ±5 degrees. A summary of the mechanical specifications of the PKM is shown in the following table 1.

Table 1 Mechanical specifications overview

Specification	Value
Cube edge length	195 mm
Translation (X, Y, Z)	± 5 mm
Rotation (U, V, W)	± 5°
Payload	~ 1 kg
Maximum speed	> 200 mm /s
Theoretical resolution	< 2,5 nm

3. Motion Performance

For an evaluation of the motion performance, as well as comparison to high precision spindle-driven PKMs in comparable size, the smallest possible step size or minimal incremental motion (MIM), bidirectional repeatability, crosstalk, linearity and position noise were measured externally using an interferometer that tracks the position of the top plate via an attached mirror. The used setup is shown in figure 2 below.

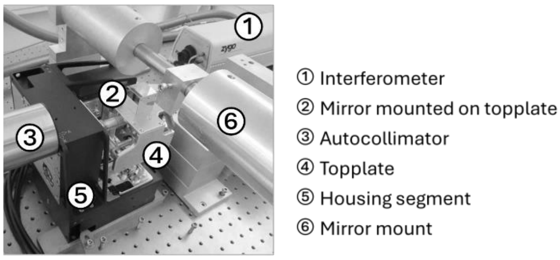

Figure 2. Measurement setup for evaluating the motion performance

The evaluation results are shown in table 2. Compared to compact spindle-driven PKMs, such as the H-811 from PI, the motion performance measurements are comparable and even superior in terms of unidirectional repeatability. Due to the high-resolution sensor and cross-roller bearings, the smallest possible steps, around 20 nm, are very good, even despite the lack of any transmission mechanism. The results also demonstrate that the performance regarding the smallest steps in the X, Y, and Z directions is very consistent, whereas, in classical Stewart platform configurations, the smallest possible steps in the Z direction are usually better than those in the X and Y directions.

Table 2 Mechanical specification overview

Specification	Value
Smallest step size X, Y, Z	20 nm / 20 nm / 20 nm
Position noise 1-sigma X, Y, Z (10s)	4,7 nm / 4,7 nm / 5,8 nm
Crosstalk (X motion, Y error, 8 mm)	314 nm
Linearity X, Y, Z over 8 mm stroke	182 nm / 430 nm / 281 nm
Unidir. repeatability mean X, Y, Z (8 mm)	±22 nm / ±9 nm / ±13 nm

4. Lifetime investigations and alignment tests

One key advantage of the direct-driven and cube-shaped PKMs with cross-roller bearings over spindle-driven PKMs is their extended lifespan, particularly in applications involving dynamic motion trajectories like photonics testing. These applications typically require small, high-frequency movements in the micrometer range, which can accelerate wear in ball screw spindles significantly. To assess the durability of the cross-roller guides used in the cube-shaped PKM, a lifetime test was conducted with a setup featuring a voice coil motor and the cross-roller guides with a short stroke lubricant, but without the magnetic counterbalance or passive strut. The test involved sinusoidal motions with amplitudes decreasing from 10 µm to 1 µm at a constant frequency of 50 Hz, mimicking a planar circular scan for fiber alignment. The starting point was within a 10 µm window, akin to real scan applications where starting points are variable. The condition of the guides was evaluated externally using an interferometer to measure position error and bidirectional repeatability. After over 1.5 billion motions, no significant increase in motion error or deterioration was observed, indicating excellent durability of the cross-roller guides and superiority regarding lifetime compared to spindle-driven PKMs.

Additionally, a single fiber alignment test was conducted using 100 random starting points (see blue dots in Figure 3) within a 10 µm x 10 µm window around the position with maximum signal intensity. The PKM executed a gradient scan to achieve optimal alignment (see orange dots in Figure 3). Results were compared to the H-811 hexapod based on the standard deviation of final positions. The comparison shows a similar performance that demonstrates a significant advantage of the cube-shaped PKM, as its extended lifetime can enable industrial-scale applications.

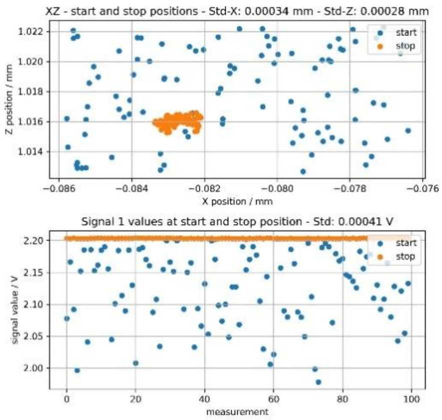

Figure 3. Start- and endpoints of the performed gradient scan

5. Summary and conclusion

A cube-shaped PKM was designed, assembled, and qualified in terms of motion performance and lifetime. Without mechanical transmission, its smallest steps match the precision of spindle-driven PKMs, while achieving significantly higher maximum velocity. Additionally, the cube-shaped PKM demonstrated an impressive lifetime indicating suitability for industrial-scale applications, including those requiring short stroke motions.

References

[1] Volz T et al. 2024 C*ompact lever actuated direct driven 6-dof parallel kinematic positioning system, Proc. of the 24th Int. Conf. of the EUSPEN*
[2] Matitschka J et al. 2023 Air bearing hexapod fr motion and positioning in six degrees of freedom with sub-micrometer precision*, Proc. of the 23th Int. Conf. of the EUSPEN*
[3] M. Naves 2021 Design and optimization of large stroke flexure mechanisms, PhD thesis
[4] M. Naves et al. 2021 T-Flex: A fully flexure-based large range of motion precision hexapod, Precision Engineering 72, pp. 912-928
[5] M. Naves et al. 2020 Flexure-based 60 degrees stroke actuator suspension for a high torque iron core motor, Precision Engineering, Volume 63, pp. 105-114