Piezoelectric Hexapods for Ultra-Precise Six-Degree-of-Freedom Positioning in Challenging Environments

Siegmar Klein, Antje Bogner, Christian Sander

Physik Instrumente (PI) SE & Co. KG, Karlsruhe, Germany

c.sander@pi.de

Abstract

Direct drive piezoelectric hexapods for small travel range offer a solution for ultra-precision positioning by combining piezoelectric actuators, high-resolution sensors, and flexure-guided mechanisms. Unlike conventional electric motor-driven systems, they provide frictionless motion transmission without stick-slip effects, enabling positioning accuracy and repeatability in the nanometer range. For larger travel range, piezoelectric motor technologies such as inertia drive and PiezoWalk® systems can achieve comparable resolution, although additional transmission and guiding components may limit overall accuracy and stability. Piezoelectric actuators require neither electromagnetic drive components nor conventional lubricants, resulting in wear-free operation, extremely low outgassing rates, and the absence of particulate contamination. These characteristics make them particularly suitable for ultra-high vacuum, magnetically sensitive, and cryogenic environments. Combined with the non-magnetic properties of their materials and the low-temperature compatibility of selected lead zirconate titanate (PZT) ceramics, piezoelectric hexapods are highly attractive for demanding applications including electron microscopy, extreme ultraviolet (EUV) lithography, synchrotron instrumentation, and quantum computing. Flexure-guided stack-actuator systems offer highest levels of precision, cleanliness, and long-term stability.

Hexapod, Piezo, Precision, Accuracy, Repeatability

1. Introduction

A hexapod is a parallel robot consisting of a base plate, six linear actuators, and an end effector, typically a top plate. The actuators, also named struts, connect the base plate to the end effector and can vary their lengths in a Stewart platform configuration. By synchronized and coordinated length changes, the end effector can be positioned with six degrees of freedom. Figure 1 shows a typical hexapod design in a Stewart platform configuration and illustrates two different poses.

Figure 1. Hexapod in two different poses

The direct connection of each strut to the base plate distinguishes parallel robots from serial robots. This parallel arrangement combines the stiffness of the individual actuators, thereby increasing the overall structural stiffness of the system. Such rigidity is a key advantage of hexapods in precision positioning applications.

Direct drive piezoelectric hexapods, when equipped with high-resolution sensors and appropriately designed flexure joints, can often outperform conventional hexapods based on electromagnetic motor-ball-screw drives in terms of positioning accuracy, repeatability, and long-term stability. In particular, piezoelectric stack actuators, combined with compliant flexure mechanisms, enable frictionless motion transmission without stick-slip effects or other guide-related nonlinearities. As a result, positioning systems can achieve exceptional repeatability and accuracies down to the nanometer range.

For applications requiring larger travel ranges, piezoelectric motors, such as those based on inertia-drive or PiezoWalk® technologies, provide an alternative solution. These drive concepts also enable nanometer-resolution positioning. However, the additional guidance and transmission elements typically required in such systems tend to limit the achievable accuracy and repeatability compared with flexure-guided stack-actuator systems.

Furthermore, piezoelectric actuators offer significant advantages for operation in demanding environments. They do not require electromagnetic drive components, conventional gearboxes, or even conventional lubricants. When combined with flexure-guided mechanisms, they enable virtually wear-free positioning systems exhibiting extremely low outgassing rates under ultra-high vacuum (UHV) conditions and generating no particulate contamination. The non-magnetic nature of the materials used, together with the suitability of selected PZT ceramics for low-temperature operation, also makes these systems ideal for magnetically sensitive and cryogenic applications, including electron microscopes, EUV lithography systems, synchrotron radiation facilities, and quantum computing platforms.

Many of these benefits can also be achieved using piezoelectric motors. However, because their operating principle involves relative motion between drive components, particles may be generated, and depending on the specific drive concept, additional lubrication or surface-conditioning measures may be required. Consequently, flexure-based systems employing piezoelectric stack actuators provide the most favorable solution for applications demanding the highest levels of precision, minimal contamination, and maximum long-term stability.

2. Examples of Hexapods for Challenging Environments

2.1 Hexapod for Cleanroom Environments

In semiconductor companies, cleanrooms are essential for the manufacturing and assembly of high-precision optical and semiconductor components. Even microscopic particles or molecular contamination can degrade the performance of lenses, mirrors, photomasks, and lithography optics. To achieve nanometer level accuracy, highly controlled cleanroom environments with advanced filtration systems, strict gowning procedures, and regulated workflows are mandatory. These measures ensure consistent product quality, reliability, and maximum optical performance. High-precision positioning systems used in such environments must therefore meet stringent cleanliness requirements and minimize particle generation during operation. PI designed a system for cleanroom applications based on NEXLINE® actuators; however, no image is provided herein owing to intellectual property considerations.

The design focuses on high position stability and low overall height. The outer geometry is defined by customer specific requirements. The system provides a translational travel range of ±1.8 mm in all axes and a rotational range of ±0.25°. It is equipped with eroded flexure joints and absolute linear position encoders. During qualification, a minimum incremental motion of 10 nm and 0.25 µrad was achieved at a payload of 60 kg.

2.2. Hexapod for UHV and non-magnetic Environments

Ultra-high vacuum (UHV) and non-magnetic environments are essential for many advanced nanopositioning applications in fields such as semiconductor manufacturing, electron microscopy, synchrotron research, and quantum technologies. In UHV systems, positioning stages must operate without conventional lubricants or materials that could outgas and contaminate the vacuum chamber and customer equipment within the chamber. Non-magnetic designs are equally critical, as even small magnetic disturbances can compromise sensitive measurements, beam alignment, or quantum experiments. Piezo-based nanopositioning systems are particularly well suited for these environments because they provide frictionless motion, nanometer-scale resolution, and can be designed from vacuum-compatible and non-magnetic materials. This combination enables highly stable and precise positioning under conditions where conventional electromagnetic drive technologies reach their limits. The hexapod shown in Figure 2 is based on NEXLINE® actuators and is designed for UHV and non-magnetic applications. It was developed with a strong focus on positioning accuracy, long-term stability, and a compact overall design. Its customer-specific geometry provides a translational travel range of ±0.5 mm in all three axes and a rotational range of ±0.6° about three rotational axes.

The mechanism is based on eroded flexure joints and capacitive position sensing, enabling highly repeatable motion. Furthermore, the system is compatible with

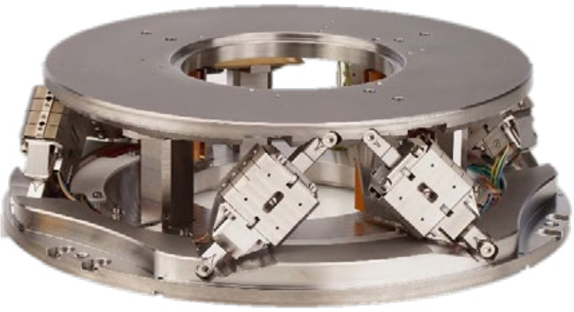

Figure 2. NEXLINE® Hexapod

ultra-high vacuum environments down to 10^{-7} hPa and is designed for payloads of up to 1.5 kg, making it particularly suitable for demanding scientific and industrial nanopositioning applications.

2.3. Hexapod for UHV, Low Magnetic Field and Cryogenic Environments

UHV, cryogenic, and non-magnetic environments are key enabling technologies for many quantum applications, including quantum computing, quantum sensing, trapped-ion systems, and superconducting qubits. Nanopositioning systems used in these experiments must operate reliably under extreme conditions while maintaining nanometer precision. Cryogenic temperatures (e.g., 4 K) reduce thermal noise and enable quantum effects, whereas ultra-high vacuum minimizes contamination and unwanted interactions with the environment. Non-magnetic designs are essential to prevent disturbances of highly sensitive magnetic fields and quantum states, which could degrade measurement accuracy or qubit performance. Piezo-based nanopositioning systems are particularly well suited for these applications, providing motion, high resolution, and compatibility with UHV, cryogenic, and non-magnetic requirements. A huge challenge besides the motor design is a suitable sensor design, working under 4 K or even below. The hexapod shown in Figure 3 uses an inertia drive for actuation in each strut and is equipped with an interferometer in each strut. A detailed description of the hexapod can be found in [1]. The hexapod was developed for operation under extreme environmental conditions while maintaining a compact overall size of Ø 70 mm × 65 mm. It provides a translational travel range of ±3 mm in all three axes. Rotational travel ranges reach ±4° about the three rotational axes.

Position feedback is provided by a PIRRI interferometer [2], while spring-preloaded spherical joints ensure smooth and highly repeatable motion.

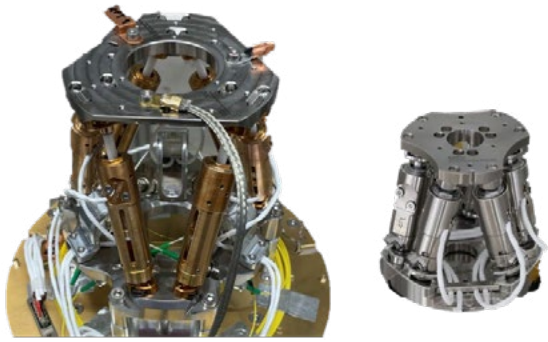

Figure 3. Inertia Drive Cryo Hexapod

The system is designed for cryogenic operation down to 4 K and supports payloads of up to 0.5 kg. These characteristics make it particularly suitable for demanding scientific applications that require high precision nanopositioning under extreme environmental conditions.

3. Conclusion

Piezoelectric driven hexapods provide a highly effective solution for ultra-precise six-degree-of-freedom positioning in demanding environments. Flexure guided systems with piezoelectric stack actuators combine high stiffness, frictionless motion transmission, nanometer-level repeatability, and excellent long-term stability. In comparison with conventional electromagnetic drive concepts, they offer clear advantages in applications requiring high cleanliness, low outgassing, non-magnetic behavior, and compatibility with cryogenic operation.

Different piezoelectric hexapod concepts developed at PI for UHV, non-magnetic, cleanroom, and cryogenic environments were presented. These examples demonstrate how actuator type, joint design, sensor concept, and system geometry can be adapted to meet application-specific requirements while maintaining high precision and reliability.

References

[1] Binder P, Hübner R, and Volz Z: Parallel Kinematic Machines for High Precision Positioning in Cryogenic Applications. *Proc. of PI's 1st Symposium on Mechatronics System Design*, 2026.

[2] Grabowski A, Mittag S, Walenda C, and Kissinger T: PIRRI – Current Development, Possible Applications and Outlook. *Proc. of PI's 1st Symposium on Mechatronics System Design*, 2026.