# Hybrid Hexapods Resolve Inherent Weaknesses of Conventional Hexapods

## The hybrid hexapod enables applications that can benefit from six-degrees-of-freedom motion.

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Technology advancements ranging from the design and manufacturing of next-generation consumer electronics to more efficient and reliable manufacturing processes, to improved metrology sensors, continually drive the need for motion control systems with higher accuracy, improved repeatability, and better geometric (i.e. 3D) performance. In complex applications where high-precision, six-degrees-of-freedom of motion is required (X, Y, Z, pitch, yaw, roll), a hexapod is commonly used, as it offers compact size and reduced errors relative to serial stacked stages. However, hexapods are not without their limitations that themselves can limit the level of precision that can be attained.

A hybrid hexapod® system is an innovative motion system that improves on existing hexapod technology, while eliminating inherent weaknesses of traditional hexapods. As a result, the hybrid hexapod achieves nanometer level performance with respect to accuracy, repeatability, and geometric 3D performance.

Also known as Stewart platforms or parallel kinematic manipulators (PKM), hexapods are devices where six links or actuators (that extend and retract) join a stationary bottom plate with a top plate that performs coordinated motion in six degrees of freedom (see figure 1). A sample, fixture, sensor, or any device can be mounted to the top plate and be manipulated to be in any location and orientation in the available range of travel.

Hexapods are commonly used because, compared to stacking six individual single-axis stages and the associated stack-up of errors, alignment difficulties, and cable management issues, the hexapod will have less error and higher precision

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in a clean, compact form. Additionally, hexapods have high Z stiffness due to six links/actuators oriented in near vertical orientations.

While hexapod manufacturers are always developing advancements in their products, such as new complex ways to calibrate or creative alternative position feedback systems, those advancements won't truly be able to overcome the hexapod's inherent limitations. Hexapods are characterized with vague specifications. They present hazy situations for engineers, who often aren't told the full picture of the actual hexapod precision. These weaknesses are not inadequacies of one manufacturer or design compared to another, but are weaknesses and limitations of the hexapod concept in general, and present micrometer order limitations on the performance that can be achieved with a hexapod.

**THE HYBRID HEXAPOD LINKS WERE DESIGNED FROM THE GROUND UP WITH OPTIMUM PRECISION AS THE PRIMARY FOCUS.**

The hybrid hexapod addresses the critical weaknesses and limitations of conventional hexapods. The goal of this device is to achieve nanometer order accuracy, nanometer order bidirectional repeatability, and high-integrity flatness and straightness of motion in a six-degrees-of-freedom motion system.

The name hybrid hexapod is indicative that the system supplies all the known six-degrees-of-freedom motion and existing functionality of a hexapod, but is a hybrid serial kinematic and parallel kinematic structure. It includes a parallel kinematic tripod constructed of three links/actuators generating the Z, pitch, and roll motion. The tripod is integrated with a monolithic serial kinematic XY motion stage and a rotary (yaw) axis mounted into the top of the tripod (or underneath, depending on the application). With this design, individual axes can be customized to provide flexible configurations and travel ranges from millimeters to more than a meter, while maintaining nanometer precision levels. In addition, the links and structure of the tripod parallel kinematic system were redesigned relative to existing hexapod links to enable nanometer order performance of the system.

## LINK DESIGN

This hybrid concept remains a simple solution that draws on the best features of serial and parallel kinematic systems to enable a significant performance improvement over hexapods. Traditional hexapod links or actuators are generally designed to support the load against gravity, with precision of the link motion a secondary priority. The motors are driven by mechanical contact mechanisms, such as a micrometer lead screw paired with a rotary motor or a friction drive motor (typically piezoelectric motor), which aren't considered high-precision motor solutions and introduce heat gradients and vibration

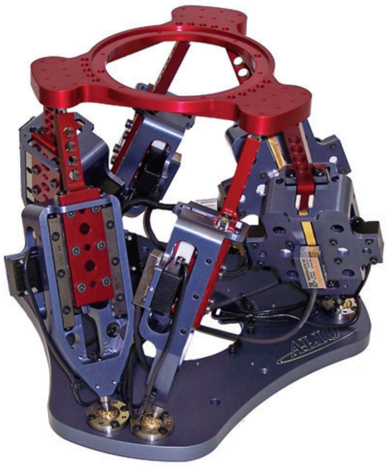
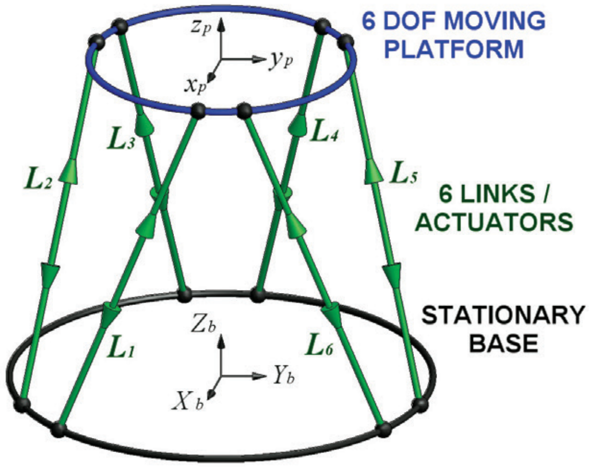


**Figure 1. Shown are the Alio HR2 hexapod model (left) and the six link parallel kinematic layout common to hexapod motion systems (right).**

into the links. Additionally, screw-driven actuators are characterized by backlash and employ rotary encoders from which linear position is calculated, not measured. Furthermore, as any hexapod moves, the forces on each joint of the actuator will vary greatly in magnitude and angular direction.

The link designs, some of which are simply off-the-shelf linear actuators, aren't designed to maintain the end-joint location of the cantilevered actuator with high precision under such varied loading. The varying loads can also cause motor forces, and thus motor heat generation to vary drastically, adversely affecting precision. Most hexapod links or actuators wouldn't be used in a precision single axis stage, for the reasons mentioned, but when coupled together in the form of a hexapod, they're billed as a precise six-degrees-of-freedom motion system.

The hybrid hexapod links were designed from the ground up with optimum precision as the primary focus. The links use brushless, non-contact, linear servo-motors oriented along the link axis, eliminating any mechanical coupling. This causes no friction or wear to adversely affect precision or create backlash, while it minimizes vibration and heat generation. Heat variation is minimized by coupling the motor with near frictionless pneumatic cylinders (or non-contact magnetic springs) in each link to counterbalance (zero-out) the strut load against gravity. This allows for high payload capabilities.


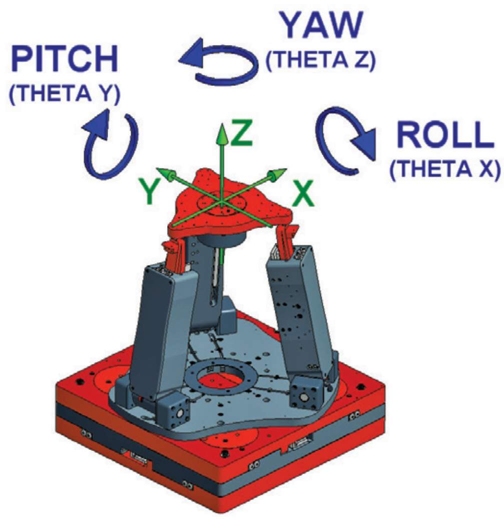


**Figure 2. The figures show the Alio hybrid hexapod (left) and how it is capable of six degrees of freedom (right).**

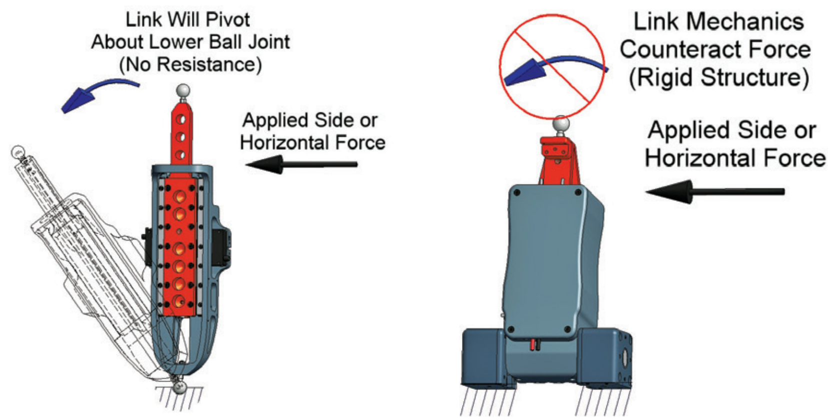


**Figure 3. Force is applied laterally on a conventional hexapod link (left). Then it is applied laterally on a hybrid hexapod tripod link (right).**

Aside from the payload inertia, there's very little force (and thus little heat) the motor needs to generate in order to move the system, because the counterbalance supports the mass. Lastly, all axes of the hybrid hexapod use non-contact optical linear encoders that eliminate backlash and rotary encoder errors. Optimized sensor locations ensure that the position feedback reflects the actual position of each link/axis. The hybrid hexapod link provides less than 50nm repeatability and sub-micron accuracy with higher speed and payload capabilities, making it the ideal link design for a tripod (not hexapod) parallel kinematic structure.

## STIFFNESS

The tripod structure was selected for its stiffness benefits compared to traditional hexapods. The traditional hexapod's high Z stiffness is well publicized, and results from all six links being oriented in a near vertical angle. However, the XY (horizontal) stiffness is relatively weak. A review of hexapod manufacturers' websites will show XY-to-Z stiffness ratios ranging from 1:10 to 1:32. Poor horizontal stiffness, combined with links that carry varying loads at varying angles, correlates to poor repeatability and positioning performance of the common hexapod top ring. A motion system in three-dimensional space needs to have high and equivalent stiffness in all directions to be able to supply precise motion in all directions.

The tripod parallel kinematic structure offers both excellent Z stiffness from motors aligned in each link vertically, and excellent XY stiffness from mechanical stiffness of the tripod link joints. Specifically, the tripod joint between the link and base plate has only one rotational degree of freedom (like a hinge). This design lets the link rotate in just one direction, but provides mechanical stiffness in other rotational loading directions. Figure (3-right) illustrates the link's ability to withstand lateral loading on the hybrid hexapod tripod link. With three mechanically rigid joints positioned 120 degrees apart, the tripod can provide equivalent XY stiffness in any vector direction in the XY plane, even without servo-power.

## ACCURACY AND REPEATABILITY

In a traditional hexapod, all six links move for any motion command. Therefore, for any single axis move, whether it's a rotation or linear move, the top ring error is a summation of the error sources from all six links. This includes errors due to miscalibration of each joint location, backlash, link translation errors, and even servo dither. Furthermore, the complex kinematic hexapod structure makes these errors hard to isolate or calibrate, and thus, a hexapod's accuracy is limited to the 10s of micrometers and repeatability limited to several micrometers.

While the new hybrid hexapod link can improve accuracy and repeatability, the hybrid serial and parallel kinematic concept enables motion in each degree of freedom to be performed with the minimal amount of error sources affecting its precision. The three-link tripod kinematic structure is simpler and symmetric, and therefore provides simple methods of calibration and compensation to ensure that the Z, pitch, and roll motion degrees of freedom can be performed with sub-micron accuracy.

The hybrid concept, joining the tripod with monolithic XY and rotary stages, decouples error sources of other axes from affecting the XY and yaw motions. Furthermore, with this simplified hybrid approach, all axes, both linear and rotational, can be easily calibrated for accuracy and orthogonality to optimize performance in three-dimensional space. As a result, multi-axis motion will also be more precise, because the error sources from each axis, orthogonality, will have all been minimized.

## MOTION TRAJECTORY, STRAIGHTNESS, & FLATNESS

Motion trajectory, or straightness and flatness of motion performance, is relatively poor for hexapods, due to the multitude of error sources and difficulty of calibration. In fact, a quick review of hexapod manufacturer specs shows that virtually none mention straightness or flatness at all in specifications for their hexapods. Specifically, many standard precision hexapods will have straightness on the order of 100 µm per 100 mm of travel.

Again, the hybrid hexapod's hybrid serial and kinematic approach enables optimized geometric (flatness and straightness) motion errors for all axes. In many applications, the Z, pitch, and roll are used to align a device or substrate, and a process (such as a raster scan) is performed in the XY plane. The precision XY stage, which is designed specifically for accurate and straight planar motion, can perform the raster scan with straightness error of less than +/-1 micron per 100 mm of linear travel. This is two orders of magnitude better than typical hexapod performance. Non-linear or multi-axis motion trajectories (circles) are also performed with single-digit or sub-micrometer precision.

## SYSTEM FLEXIBILITY & RANGES OF TRAVEL

Lastly, standard traditional hexapods provide a limited range of travel for all six degrees of freedom for any given design. If an end user requires any more travel in any one axis, an entire new hexapod model or design is required. In addition, yaw rotation is typically limited to +/-45 degrees maximum.

With the hybrid hexapod, axes can be optimized for range of travel and cost. For example, XY travels of over 1 m can be paired with any tripod sub-assembly. The yaw rotary stage can have limited travel or 360-degree continuous rotation. The yaw rotary stage can be optimized to have less than 1 µm run out. The concept's overall flexibility allows for myriad efficiently configured assemblies to fit any and all six-degrees-of-freedom motion system applications.

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