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Hybrid Hexapods® Resolve Inherent Weaknesses of Conventional Hexapods, Enabling Applications that Require Two Orders of Magnitude Better Positional Repeatability

The patent pending Hybrid Hexapod®, a newly developed motion solution combining best-in-class, hybrid parallel and serial kinematic systems, from ALIO Industries, takes advantage of True Nano® precision Z, pitch and roll capabilities in the parallel kinematic tripod, while utilizing serial stages to provide a 6-DOF motion system. For the first time, this motion system meets the nanometer-level precision, ultra-smooth motion and platform stiffness needs of applications that require the best in 6-D path motion resolution, as well as unparalleled positional repeatability. Mission critical applications include laser processing, optical inspection, photonics, semiconductor metrology and medical device or other micro-machining applications.

by Nathan Brown (BSME),
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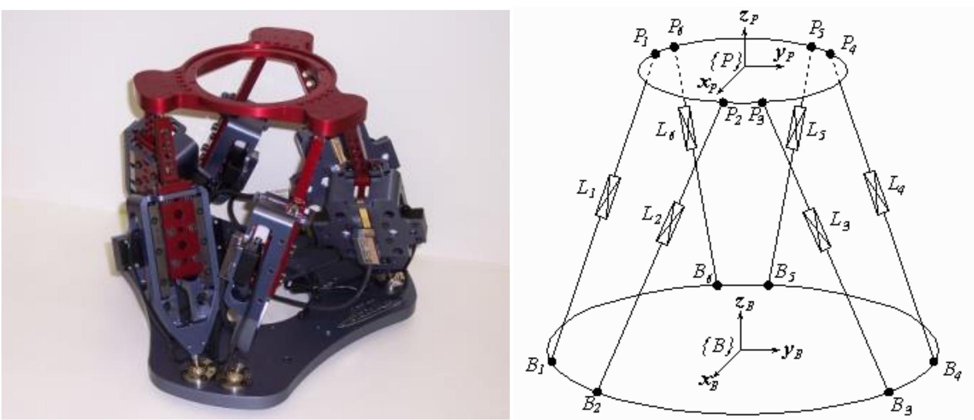
As technology products steadily move toward sub-micron level miniaturization, the need for process application motion systems migrates from micro to True Nano® precision. True Nano is defined as true positioning performance at the bi-directional, nanometer level, as opposed to conventional unidirectional planar numbers which are typically several microns in true stage performance. Advancements in manufacturing processes and metrology sensors, along with the continuing demand for more advanced manufacturing technologies and products, has driven the need for motion control systems that provide both higher accuracy and repeatability.

For many years, in order to achieve such precision at the micron-level or higher, hexapods have commonly been used where six degrees of freedom (6-DOF or 6-D) was needed. Thus effectively reducing the footprint of serial kinematic stacked stage positioning systems, and most times reducing stacked stage error quotients.

Hexapods, by definition, are six-legged parallel-kinematic mechanism (PKM) motion systems. In their most common form consisting of two platforms, a fixed base platform and a second movable platform, which are connected and supported by six independent legs (struts or links) that expand and contract in parallel (see Figure 1). Coordinated motion of these six struts enables the movable platform, and devices mounted to it, to move in any direction, operating in 6-D relative to the base platform. With 6-DOF, the secondary platform is capable of moving in three linear directions, lateral (X) and longitudinal (Y), vertically (Z), and the three angular directions (pitch, roll and yaw), by the six legs. Because hexapods have all six degrees of freedom, they can perform manipulations that encompass total freedom of motion in three-dimensional space in a relatively compact space.



(a) *(b)*

Figure 1. Example of (a) the ALIO HR2 hexapod model, and (b) the six link parallel kinematic layout common to hexapod motion systems.

The hexapod has proved sufficient for precision at micron-level tolerances when a position in space is desired. As motion requirements have increased from micrometers to nanometers, so has the demand for bi-directional path motions such as straightness of path, smooth contours or spherical motion profiles. In the past, other existing hexapod platforms in the current market could not meet these new nanometer-level motion requirements. This is due to performance limitations inherent in the conventional hexapod designs that require the task of accurately coordinating the movement all six axes to accomplish a motion profile, even when the need was a simple single-axis motion.

Conventional Hexapod Limitations

With increasing demands for sub-nanometer levels of performance, and in order to achieve such high confidence levels of performance, motion control systems must be correctly characterized for operation within 6-DOF. This six degrees of freedom refers to the freedom of movement of a rigid body in three-dimensional space. Design considerations of cumulative error must be considered as part of any multi-axis stage design. Specific to the hexapod, the body is free to move forward and backward, up and down, left and right, combined with rotation about three perpendicular axes – pitch, yaw and roll.

All hexapod motion systems operate within three-dimensional space, and have errors in all six degrees of freedom. However, hexapod motion systems have typically only been characterized by performance data of a single degree of freedom. This practice leaves error sources unaccounted for in several degrees of freedom, especially with flatness and straightness which are critical precision needs in the nano-age. The hexapod's best flatness and straightness of travel is still no more precise than in the order of magnitude of tens of microns per axis.

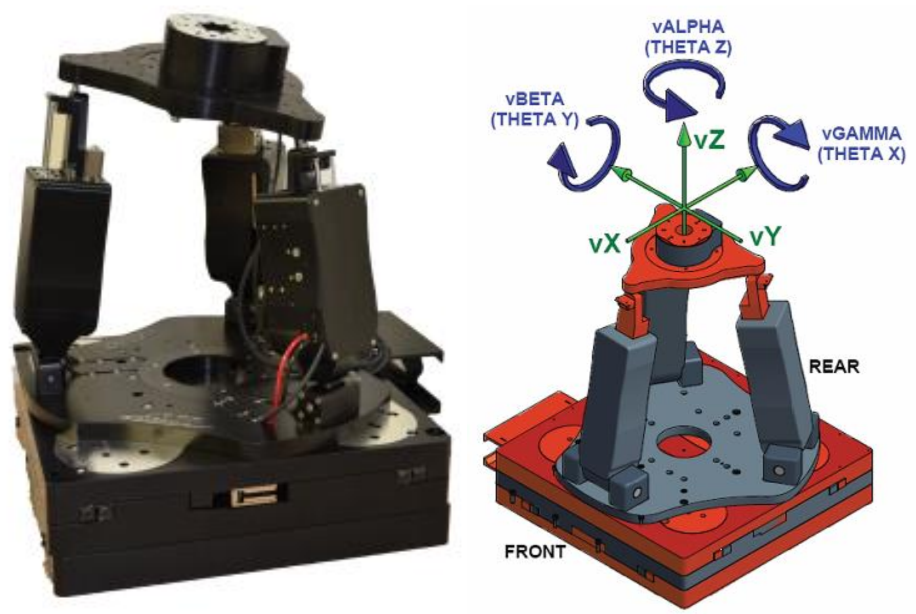
Because hexapods have six independently controlled links joined together moving a common platform, the motion error of the platform will be a function of the errors of all links and joints. Hexapods are known to have optimum accuracy and repeatability when performing Z axis moves, because all links perform the same motion at the same relative link angle. However, when any other X, Y, pitch, yaw or roll motion is commanded, accuracy and geometric path performance of the hexapod degrades substantially because all links are performing different motions. In the case of legacy hexapods built with non-precision joints and motion controllers that are not capable of forward and inverse kinematics equations, the source of error is even more pronounced. With current controller technologies along with higher resolution feedback position sensors, the new controller platforms are able to monitor all the links at nanometer resolution relative to the tool center point precision.

Furthermore, it is a common belief that hexapods have relatively good stiffness compared to serial stacked multi-axis systems. However, it is often only the hexapod's Z (vertical) stiffness that is considered. Geometric design stiffness has a critical impact on hexapods' platform repeatability and rigidity. A lack of design stiffness relates directly to a weak XY plane stiffness with the conventional hexapod working platform. Moreover, this inherent design flaw of the conventional hexapod negatively affects XY axis performance, especially with thermal bonding or machining applications that require more force to be performed accurately within the XY plane.

While there are compensation methods to reduce error sources in conventional 6-link hexapods, they do not improve performance at the single-digit micron or nanometer level. Motion systems' straightness and repeatability performance must be analyzed and specified using a point precision methodology that accounts for all 6-D spatial errors in order to provide a true representation of nanometer precision, or True Nano precision.

Hybrid Hexapod Advantages Explained

The Hybrid Hexapod® was developed by ALIO Industries to address the critical weaknesses of conventional legacy hexapod designs as outlined above, as well as the weaknesses of stacked serial stages, and to achieve nanometer accuracy, repeatability, and high-integrity flatness and straightness during motion. The name Hybrid Hexapod is indicative of a 6-DOF function motion positioning system constructed of a hybrid serial and parallel kinematic structure, rather than a six-link pure parallel kinematic design structure (see Figure 2). It utilizes a tripod parallel kinematics structure to deliver Z plane and tip/tilt motion, integrated with a monolithic serial kinematic structure for XY motion. A rotary stage integrated into the top of the tripod (or underneath it depending on application needs) provides 360 degree continuous yaw rotation. In this hybrid design, individual axes can be customized to provide travel ranges from millimeters to over one meter, while maintaining nanometer levels of precision.



(a) *(b)*

Figure 2. Example of (a) the ALIO Hybrid Hexapod, and (b) the six degrees of freedom of motion capable with the Hybrid Hexapod.

This hybrid structure is designed for unprecedented precision performance at the nano-scale level, with significant improvements over conventional hexapods in the following critical aspects:

***Link Design* –** Each link of a common hexapod works in coordination with the other links to position the top platform or user mounting surface. The precision of the top platform is a direct consequence of the precision of the individual links. While link designs for hexapods come in many forms and technologies, the fact that they are oriented vertically and work against gravity has led to design decisions and restrictions that prohibit achieving True Nano precision performance.

Specifically, some manufacturers simply use an off-the-shelf linear actuator as the link in a hexapod. As the hexapod moves, the forces on each joint end of the actuator will vary in magnitude and direction, and often the actuators were not originally designed to handle such varying loads and still maintain the cantilevered joint location in space with high precision. From a motor perspective, the consensus has been to use either rotational motors attached to a ball screw (or micrometer lead screw) or use a friction motor (typically piezoelectric) to drive the link linearly. This is because the mechanical advantage or friction of the motor helps the motor support the load against gravity. That capability is the motor's inherent weakness, such that it is the motor that supports the payload against gravity and thus the load on the motor varies with the angle of the link and whether the link is moving upward (against gravity) or downward (with gravity). Any precision engineer will tell you thermal gradients or heat sources are the enemy of precision. Varying motor loads directly corresponds to varying heat generation. Finally, many actuators have rotary encoders on the back of the rotary motors, or linear encoders on coupled linear directions, such that they measure one position and convert it, via calculations, to a link position. These designs introduce backlash and accuracy errors due to lead screw pitch errors and assumptions in the position conversion.

While it is possible to do advanced level calibration of hexapods and add in external sensors to the platform, this is costly and time consuming, and still generally will not get performance below the 10s of microns level.

The Hybrid Hexapod, however, has been designed to counteract the liabilities presented above, and enable optimum performance in several ways:

a) Its design utilizes a vertical brushless, linear servo-motor oriented along the link axis. Since linear motors are non-contact, there is no friction or wear, hence, very little heat is generated. Additionally the force axis of the motor is aligned with the linear axis of the link, so there is no mechanical coupling (as required with ball screws) that can introduce other error sources. Typically, designers have stayed away from this concept due to heat generation.

b) A near frictionless pneumatic or non-contact magnetic spring is employed on each strut, which zeros-out the strut load against gravity, allowing for high payload capabilities. Aside from the slight inertia of the payload, there is very little force that the motor needs to overcome to move the system, because the counterbalance supports the mass. The counterbalancing effect also ensures that whatever heat is generated by the motor stays relatively consistent.

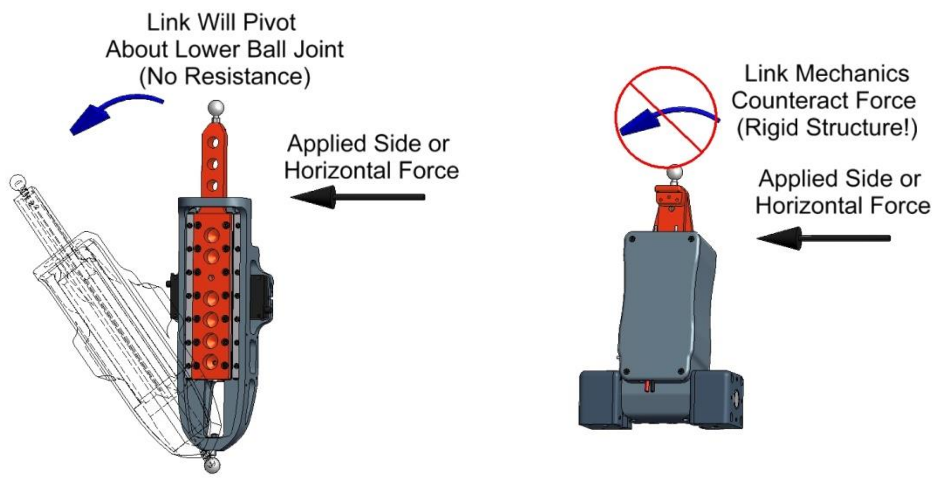
c) A non-contact optical linear encoder that eliminates backlash and error sources common to rotary encoder systems. The link position sensor is positioned vertically, directly in the axis of motion, reflecting the highest precision of link placement coinciding with joint placement, and thus, the least amount of errors.

The Hybrid Hexapod design improvements enable a drastic improvement in positioning accuracy while also increasing velocity, payload, and range of travel capabilities of the system.

***Stiffness* –** Stiffness is a measure of deflection when a load is applied and is a common spec for hexapods. Hexapods are advertised as having better stiffness than serial kinematic (i.e. stacked stage) systems. This is true, but most manufacturers will only tell you what they want you to hear. What they do not publicize is it is only the Z stiffness that is often an improvement and the

X and Y horizontal stiffness remains relatively weak. A review of hexapod manufacturer websites will show XY to Z stiffness ratios ranging from 1:10 to 1:32.

Why is the hexapod so stiff in the Z direction? All six links are typically oriented near vertical and thus the force of all links is near vertical. Why is the hexapod so weak in the XY direction? There are two reasons: 1) the links are near vertical and only the small component of the motor force acting in a horizontal direction defines the XY stiffness; and 2) the hexapod joints to the top and bottom plate are spherical flexures, or universal joints (providing the function of a ball and socket joint) which provide zero mechanical stiffness (see Figure 3a for what happens when you push laterally on a hexapod link). Basically, all you have defining the horizontal stiffness is the small component of the motor/link force that is acting horizontally, and that is only when the motor is engaged/enabled.



(a) *(b)*

Figure 3.

In order to improve the overall stiffness, hence performance, the ALIO Hybrid Hexapod utilizes the tripod parallel kinematic structure which offers both excellent Z stiffness, from motors aligned in each link vertically, and excellent XY stiffness, from mechanical stiffness of the tripod joints. Specifically, the tripod joint between the link and base plate has only one rotational degrees of freedom (i.e. hinge), and thus it allows link rotation in one direction, but provides mechanical stiffness in other rotational loading directions (see Figure 3b for what happens when you push laterally on a Hybrid Hexapod tripod link.). With three mechanically rigid joints positioned at relative angles, the tripod can provide equivalent XY stiffness in any vector direction in the XY plane.

Motion Trajectory/Straightness – With any motion system, if you command motion in a straight line, industry standards define "straightness" as the measure of deviation of the actual motion away from the perfectly straight ideal path. All motion systems will have these "straightness" errors, and the pertinent question to most motion system end users is, how large are those errors and do they negatively impact the application, measurement, or process? Non-straight motion trajectories can also be analyzed to determine how closely a commanded free-form path can be followed. Is a commanded circle actually a circle or is it an oval or a three lobed shape?

Motion trajectory and straightness are not performance metrics often discussed in conjunction with hexapods or parallel kinematic structures. In fact, a quick review of hexapod manufacturer specifications available on the Internet will show that virtually none mention straightness at all in specifications for their hexapods. That is because hexapods are known by the manufacturers and experts in the field to have relatively poor straightness and motion trajectory performance. Specifically, many standard hexapods will have a straightness on the order of 100 micrometers per 100 millimeters of travel. (This is compared to a common single-axis stage that can easily be procured to have 1 – 8 micrometers, or < $1/10^{th}$ of straightness for the same travel.)

There is a fundamental reason for this poor performance metric of hexapods. First, hexapods actually have reasonable Z motion performance, because to perform a Z motion all six links generally are performing the same motion. Each individual link will have its own error sources that vary throughout its individual (link's) travel, and when all links perform the same motion, as in a Z move, the differences in the error sources from link to link are minimized. However, when a hexapod performs any single axis X, Y or XY vector linear move (or any single axis rotational – pitch, roll, or yaw – move), all six individual links are still moving but are moving at different speeds, different directions, and over different distances.

Combine the varying link errors with errors associated with defining the actual link, to platform joint locations, and there are simply too many error sources being introduced into the hexapod system to be able to achieve high performance straightness of motion. Furthermore, many hexapod manufacturers do not include forward kinematic calculations in their controller. Simply said, inverse kinematic equations define where you should end up after the move is complete and they are universally included. Forward kinematic calculations help you determine where you should be during the move. If you are not constantly adjusting the trajectory of the individual links during the move, via forward kinematics, there is literally no control of a trajectory of linear or curved paths.

A Hybrid Hexapod addresses the fundamental issues with gaining high precision trajectory performance with a hexapod. It combines a parallel kinematic tripod (providing known good Z, tip, and tilt performance) with an XY stage designed to provide high performance straightness and trajectory motion in the XY plane. With an ALIO precision XY stage, such as that provided by the Hybrid Hexapod, the link error sources affecting path integrity are reduced to error sources only from the two XY axes, for which the performance can be tightly controlled. In comparison, the Hybrid Hexapod system straightness is less than +/-1 micron per 100mm of linear travel – two orders of magnitude better than typical hexapod performance.

***Linear Displacement and Repeatability* –** In a common hexapod, all six links move to make any motion command. A single linear X axis move in a horizontal plane requires all six links to move. That means for any single axis move, whether it is a single rotation or singular linear move, error sources originate from those six different links. This includes errors generated due to miscalibration of each joint location on the links, joint backlash, or even servo dither.

The Hybrid Hexapod is designed to address these issues and provide True Nano accuracy and repeatability performance. Since 6-DOF systems operate in three dimensional space and have errors in all degrees of freedom, all error sources should be recorded and presented. In order to do that, a new method of analyzing motion in three-dimensional space is briefly presented and explained to help illustrate the improvements of the Hybrid Hexapod. This method focuses on measuring, in three-dimensional space, the Point Precision of a functional point of a motion system.

Briefly, with respect to repeatability, standard test procedures and motion system engineers, define "linear repeatability" as a one-dimensional performance metric on a per-axis basis (see Figure 4). While useful data, this singular representation of repeatability is not a full representation of the performance of the stage in three-dimensional space. While test procedures exist to measure these off-axis repeatability errors (i.e. straightness repeatability) they are often neglected in manufacturer specifications and thus the specifications provide an incomplete picture of the performance in three-dimensional space. The different repeatability distributions shown in Figures 4(a) and 4(b) are often deemed to be equivalent because only linear repeatability is tested, while the straightness repeatability clearly shows the two distributions differ drastically. Conceptually, a spherical tolerance zone around a target point will clearly define the repeatability of a functional point attached to a 6-DOF motion system (see Figure 5). This is a simple example, and figures for a single-axis stage but the same issues apply in the specifications of hexapods and multi-axis systems. Hexapods and Hybrid Hexapods operate in three-dimensional space and thus should be tested and characterized by three-dimensional specifications.

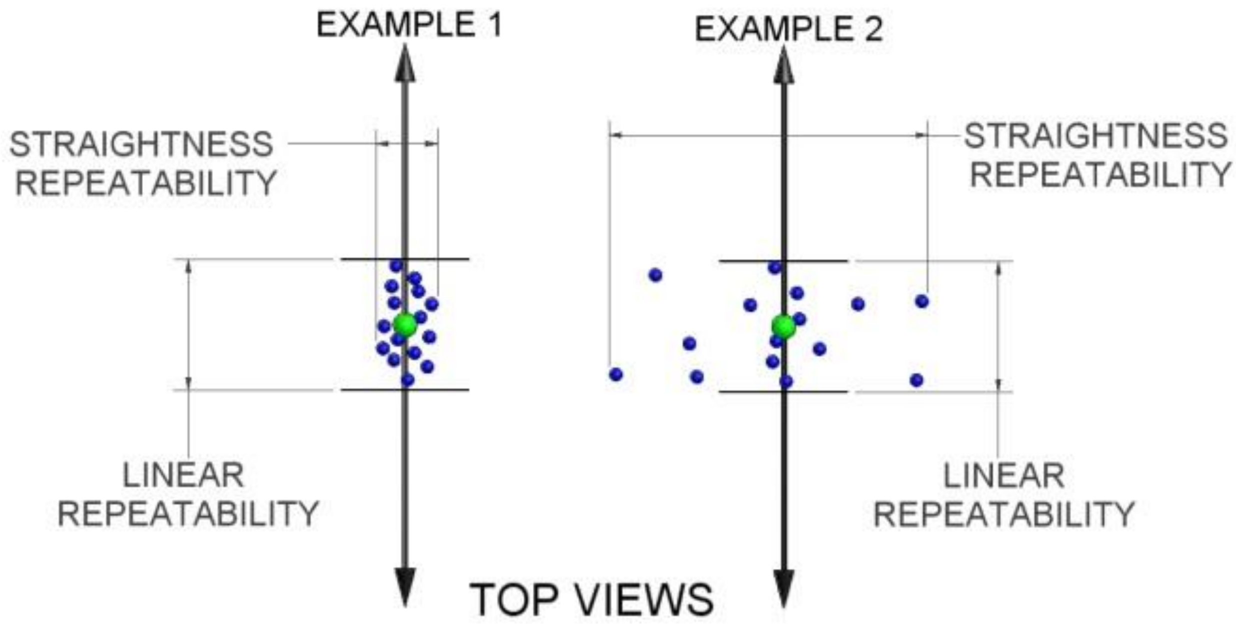


Figure 4. Two examples of repeatability distribution in two dimensions or measurement directions. Clearly the linear repeatability along the axis is equal, but only if the straightness repeatability (perpendicular to the axis of travel) is shown/tested is the difference quantified.

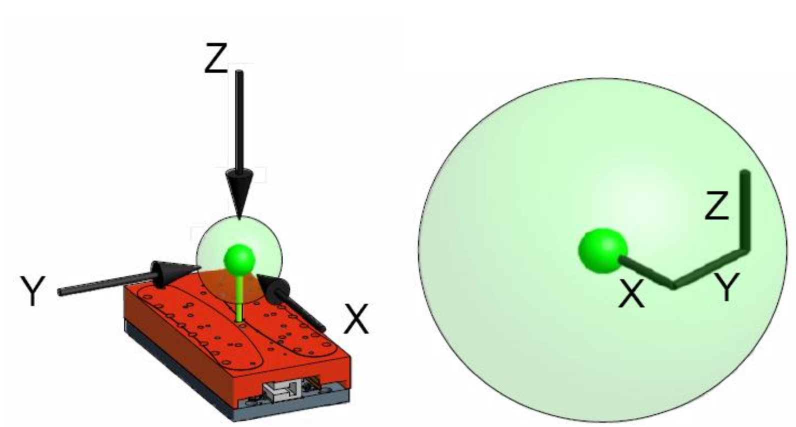


Figure 5. An example of a spherical tolerance zone that represents the X, Y, and Z components of the repeatability distribution in three-dimensional space.

This comprehensive performance viewpoint has been put into practice and reality with the Hybrid Hexapod, which accounts for, and minimizes, all error sources: off axis errors are minimized, linear errors may be compensated, and orthogonality of axes can clearly be defined and compensated. Individual links and axes are designed to provide optimum repeatability and accuracy in three-dimensional space. Hybrid Hexapod XY stages optimize, not just performance in the traditional one-dimensional terms, but also accuracy, repeatability, straightness, and flatness of travel, which cumulatively present a representation of three-dimensional performance. When the Hybrid Hexapod moves, the off-axis error motion can be one to two orders of magnitude smaller than the errors associated with a traditional hexapod. For example, on a 150 millimeter travel XY stage, both the X and Y axis each will display a straightness and flatness of travel of less than one micron, delivering very good planar accuracy.

As an example, in performing a raster scan with the Hybrid Hexapod configuration, the Z motion and the tip/tilt will accurately align a device or substrate, then, a subsequent raster scan does not require any motion of the links of the Hybrid Hexapod, just the high precision XY stages to achieve precision XY motion.

Conventional hexapod linear accuracy is limited to 10s or 100s of microns performance that varies greatly throughout its range of travel. The Hybrid Hexapod pairs the optimized Z axis performance of a parallel kinematic tripod with an optimized XY stage calibrated to have nanometer order accuracy and straightness performance.

***Rotary Stage Positioning* –** Standard hexapods provide 6-DOF of motion, including yaw or Theta Z motion. Yaw is generally limited to about +/- 45 degrees of rotation. As discussed previously, for any single rotational move all six links will move, and errors from all six links will affect the motion of the platform. Given this setup, the integrity of the yaw motion, specifically rotational accuracy and axial and radial runout of the yaw rotation, is poor.

Additionally, many hexapods include software tool center point settings that allow the user to set a point in space and perform a rotation around that point. Angular accuracy and runout errors associated with the hexapod can mean that at the completion of a rotation about an offset tool center point (or pivot point or process point) that a fixture, device or optical axis may be pointing many 10s to 100s of micrometers off its originally targeted position. In fact, any of the previously discussed hexapod errors (i.e. straightness) are magnified by the error prone rotations performed in yaw, tip, and tilt.

The Hybrid Hexapod resolves these limitations. Once the Z plane is aligned, the XY planes can still be moved, independent from the Z stage, with very high precision. The rotational stage on top (or below the tripod) is designed to provide precise yaw rotations, with runout error of +/- 1 micrometer and rotational accuracies less than a few arc-seconds, significantly lower than any traditional hexapod can deliver. The inclusion of the precision rotary also allows for 360-degree continuous yaw motion, removing a limitation of the hexapod.

Conventional Hexapods and 6-D Nano Precision®

The performance of traditional hexapod technology is limited based on prior design limitations, design decisions, and the hexapod parallel kinematic concept in general. A new engineering perspective on 6-DOF motion is required in order to move beyond the limitations of the past hexapod designs and recognize the improvements available from the Hybrid Hexapod concept. The Hybrid Hexapod will help advance technology as it enables three-dimensional precision performance not previously capable with prior multi-axis systems. As the technology advances, so must the qualification processes. Hexapods are characterized with vague specifications and present hazy situations for engineers who are told what they want to hear and not the full picture of the actual hexapod performance capabilities. New performance testing metrics are not only better at defining the weaknesses of hexapods, but also clearly characterizing the clear performance benefits of novel innovative designs, such as the Hybrid Hexapod, and communicating those capabilities to industry.

Conventional hexapods had their place, and still do in the micro world, but they do not meet the high precision requirements of 6-D Nano Precision applications in nanotechnology. 6-D Nano Precision means the documented proof of performance over all six degrees of freedom of a body in motion at the nanometer level of precision. As many leading nanotechnology companies in the optical, semiconductor, manufacturing, metrology, laser processing and micro-machining industries will attest, this nanometer level of precision is achieved by the next generation Hybrid Hexapod motion systems. While there is considerable future work to be completed, the Hybrid Hexapod opens up a new realm of possibilities for 6-DOF motion systems.

About the Author
Nathan Brown is Vice President of Engineering for ALIO Industries. Mr. Brown has extensive experience with the design, development, manufacturing and testing of next-generation precision motion systems. He holds a degree in Mechanical Engineering from the University of Texas at Austin, but that was just the start, as he strives to innovate through learning.

About ALIO Industries, Inc.
ALIO Industries, Inc. is the leader in nano-precision motion and robotic systems, providing an extensive line of standard mechanical and air bearing stages and robots. Its motion systems provide unparalleled accuracy and repeatability at the nano-scale enabling next-generation manufacturing in semiconductor, flat panel display, lithography, ink jet deposition, photonics, biomedical and other industries.

The company has set the pace for nano-precision design and systems, exceeding current standards of precision product designs for automation technology. It holds two patents for the Parallel 6 Axis Hexapod and the Parallel 3 Axis Tripod, as well as a patent for NANO Z®, and several patent pending for Hybrid Hexapod® and planar air bearing systems. Its linear and rotary stage lines were designed to be cost-effective and complement the market demand for high quality, nano-precision motion. ALIO's rotary stage designs can be utilized for stand-alone motion or stackable for various serial kinematic structures. These applications can be used in normal atmospheric environments, clean rooms and vacuum chamber environments.

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