HYBRID HEXAPODS RESOLVE INHERENT WEAKNESSES OF CONVENTIONAL HEXAPODS,

Enabling Applications that Require Two Orders of Magnitude Better Positional Repeatability

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The patent-pending Hybrid Hexapod, from ALIO Industries, is a parallel kinematic tripod providing Z, pitch and roll motion combined with serial XY and rotary stages to provide a complete six degree of freedom motion system. This motion system meets the nanometer-level precision and repeatability, ultra-smooth motion, and platform stiffness needs of the most demanding six degree of freedom motion applications. The Hybrid Hexapod is the ideal motion system for laser processing, optical inspection, photonics, semiconductor metrology and medical device or other micro machining applications.

Advancement in technology ranging from the design and manufacturing of next generation consumer electronics to more efficient and reliable manufacturing processes to improved metrology sensors continually drives the need for motion control systems that provide higher accuracy, improved repeatability, and better geometric (i.e. three-dimensional) performance. In complex applications where high precision six degree of freedom of motion is required (i.e X, Y, Z, pitch, yaw, roll) the hexapod is commonly used for its known benefits of compact size and reduced error relative to serial stacked stages. While commonly used for their publicised benefits, hexapods are not without their weaknesses that can directly limit the level of precision that can be attained.

The presented Hybrid Hexapod system is an innovative motion system that does not just improve on existing hexapod technology, but completely eliminates inherent weaknesses of the traditional hexapod concept. As a result, the Hybrid Hexapod achieves nanometer level performance with respect to accuracy, repeatability and geometric three-dimensional performance. Currently, there is a void in industry where hexapods have reached their performance limitations, but complex motion system needs have not stopped advancing — the Hybrid Hexapod fills this void.

Traditional Hexapod Background

Hexapods, also known as Stewart platforms or parallel kinematic manipulators (PKM), 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). The six degrees of freedom (6-DOF or 6D) are the three linear directions, lateral (X), longitudinal (Y), vertical (Z), and the three angular rotations about the three linear axes (pitch, roll and yaw). A sample, fixture, sensor or any device can

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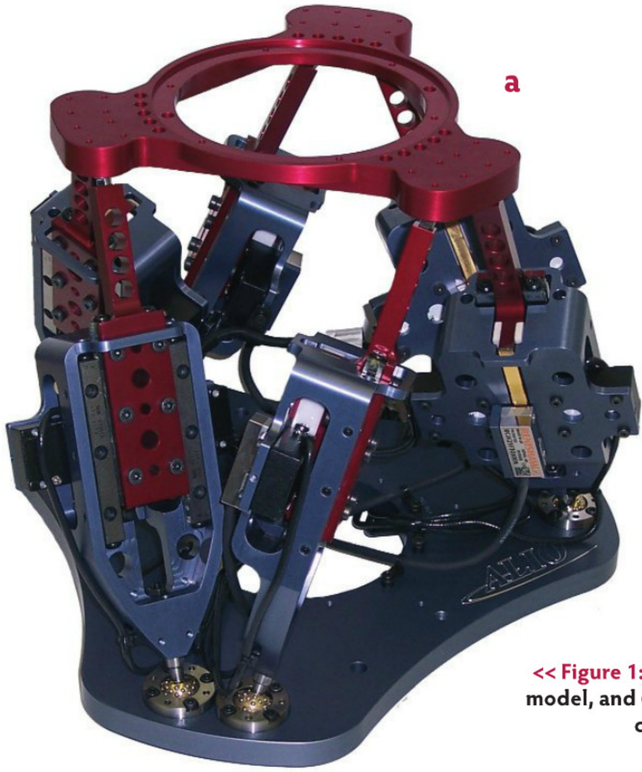

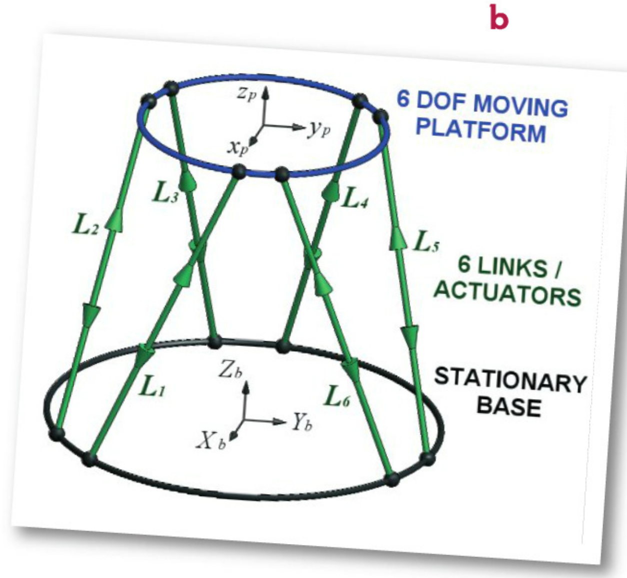

<< Figure 1: **Example of (a) the ALIO HR2 hexapod model, and (b) the six link parallel kinematic layout common to hexapod motion systems.** >>

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 stackup of errors, alignment difficulties, and cable management issues, the hexapod will have less error and a higher level of precision 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 hexapods or creative alternative position feedback systems, none of those advancements will be able to truly overcome inherent limitations of the hexapod design. Additionally, hexapods are characterised 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 precision. These weaknesses, discussed and compared fully below, are not inadequacies of one manufacturer or design compared to another, but are weaknesses and limitations of the hexapod concept in general, and truly present micrometer order limitations on the performance that can be achieved with a hexapod.

Introducing the Hybrid Hexapod and its Advantages

The Hybrid Hexapod was developed by ALIO Industries to address the critical weaknesses and limitations of conventional hexapods. The goal was to achieve nanometer order accuracy, nanometer order bidirectional repeatability, and high-integrity flatness and straightness of motion in a six degree of freedom motion system. The Hybrid Hexapod concept overview is presented, and then its advantages are discussed in detail.

The name Hybrid Hexapod is indicative that the system supplies all the known six degree 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 it depending on application needs). In this hybrid design, individual axes can be customised to provide flexible configurations and travel ranges from millimeters to over one meter, while maintaining nanometer levels of precision. The changes did not stop there, however, as the links and structure of the tripod parallel kinematic system were completely redesigned relative to existing hexapod links to enable nanometer order performance of the system.

This hybrid concept remains a simple and elegant solution that draws on the best features of serial and parallel kinematic systems to enable a significant performance improvement over hexapods. The following sections break down some of the specific differences and how they help improve the overall system performance relative to traditional hexapods.

Link Design

First, traditional hexapod link or actuator designs are generally designed primarily 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 leadscrew paired with a rotary motor or a friction drive motor (typically piezoelectric motor), which are not considered high precision motor solutions and introduce heat gradients and vibration into the links. Additionally, screw driven actuators are characterised 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, are not designed to maintain the location of the end joint 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 would not be used in a precision single axis stage, for the reasons mentioned, but when coupled together in the form of a hexapod they are billed as a precise six degree of freedom motion system.

The new Hybrid Hexapod links were designed from the ground up with optimum precision as the primary focus. The links utilise brushless, non-contact, linear servo-motors oriented along the link axis eliminating any mechanical coupling. There is no friction or wear to adversely affect precision or create backlash, while minimising vibration and heat generation. Heat variation is minimised by coupling the motor with near frictionless pneumatic cylinders (or non-contact magnetic springs) in each link to counter balance (i.e. zero-out) the strut load against gravity. This allows for high payload capabilities. Aside from the inertia of the payload, there is very little force (and thus little heat) that the motor needs to generate 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. Optimised sensor locations ensure the position feedback reflects the actual position of each link/axis. The Hybrid Hexapod link design provides <50 nm 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. Traditional hexapod's high Z stiffness is well publicised, and is a result of all six links being oriented in the 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.

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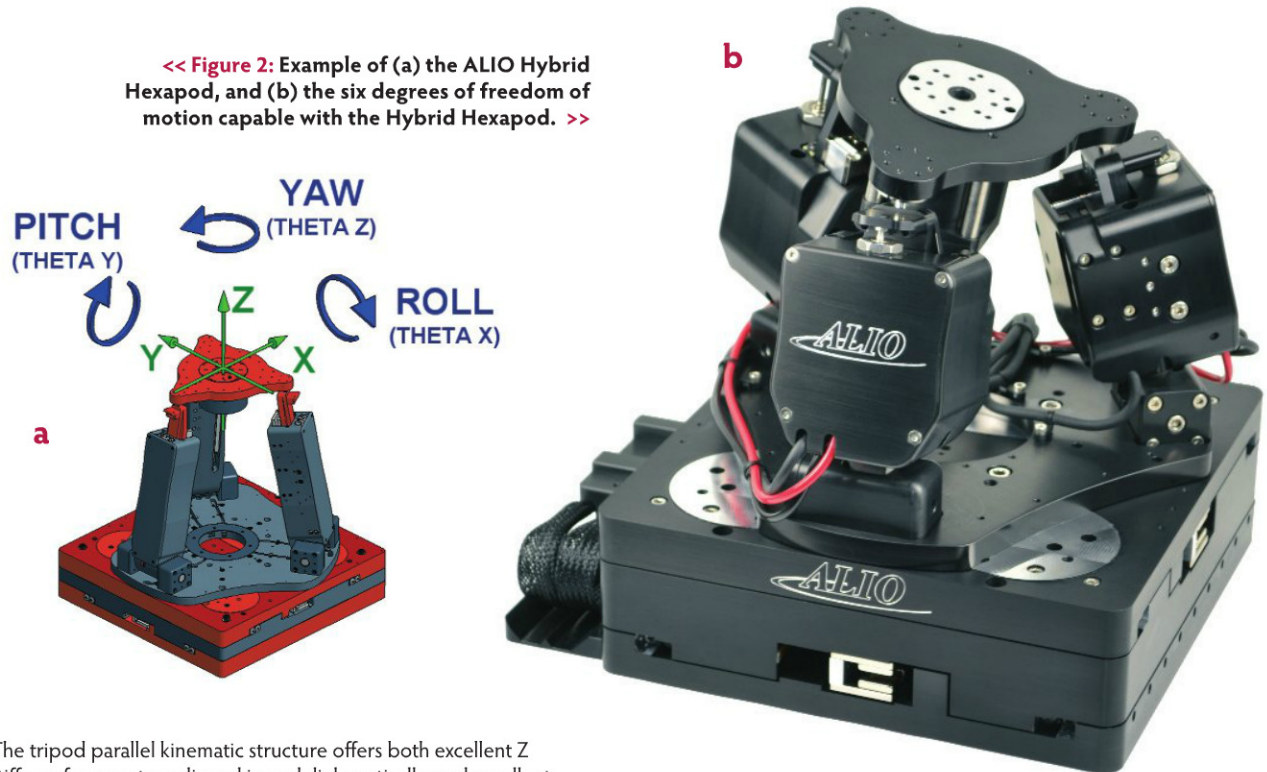
<< Figure 2: Example of (a) the ALIO Hybrid Hexapod, and (b) the six degrees of freedom of motion capable with the Hybrid Hexapod. >>



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 (i.e. hinge). This design allows the link rotation in one direction only, but provides mechanical stiffness in other rotational loading directions. Figure 3b illustrates the links' ability to withstand lateral loading on a 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 is a rotation or linear move, the error of the top ring 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 structure of the hexapod 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 design presented above improves accuracy and repeatability significantly, 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 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 optimise 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 minimised.

Motion Trajectory/Straightness/Flatness

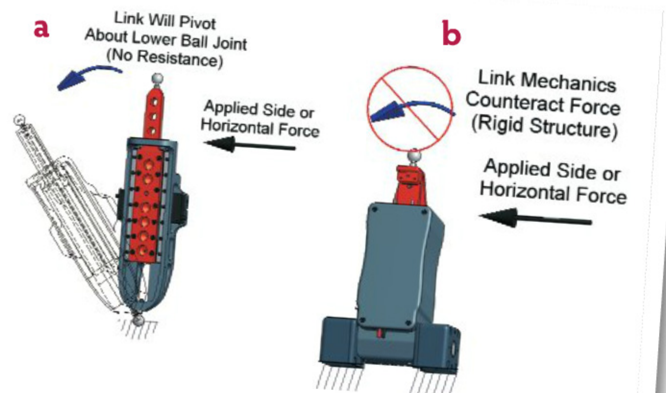
Continuing the discussion above, motion trajectory, or straightness and flatness of motion performance, is relatively poor for hexapods due to the multitude of error sources and difficulty of calibration. In fact, a quick review of hexapod manufacturer specifications will show that virtually none mention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

Again, the hybrid serial and kinematic approach of the Hybrid Hexapod enables optimised geometric (flatness and straightness) motion errors for all axes. In many applications, the Z, pitch and roll are utilised for alignment of 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 — two orders of magnitude better than typical hexapod performance. Non-linear or multi-axis motion trajectories (i.e. circles) are also performed with single-digit or sub-micrometer precision.

System Flexibility and 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. Additionally, yaw rotation is typically limited to ±45 degrees maximum.

With the Hybrid Hexapod, axes can be optimised for range of travel and cost. For example, XY travels of over one meter 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 optimised to have less than one micrometer runout. The overall flexibility of the concept allows for a myriad of efficiently configured assemblies to fit any and all six degree of freedom motion system applications.



<< **Figure 3:** (a) Force applied laterally on a hexapod link. (b) Force applied laterally on a Hybrid Hexapod tripod link. >>

Summarising the Hybrid Hexapod Advantages

Conventional hexapods are commonly used, and have their place in applications requiring 10s of microns of precision, but they do not meet the high-precision motion requirements of 6-D Nano Precision applications. 6-D Nano Precision is a term used to describe motion systems with verifiable nanometer order motion performance for all six degrees of freedom of a body in motion. The patent-pending Hybrid Hexapod was developed with the 6-D Nano Precision concept at the forefront of every decision. It combines precise serial XY and rotary (i.e. yaw) stages with a novel parallel kinematic tripod design to provide six degrees of freedom of motion at performance levels two orders of magnitude beyond current traditional hexapods. The accuracy, repeatability, stiffness and geometric accuracy performance makes the Hybrid Hexapod the ideal motion solution for many leading nanotechnology companies in the optical, semiconductor, manufacturing, metrology, laser processing and micro machining industries. The Hybrid Hexapod continues to open up a new realm of possibilities for 6-DOF motion systems.

Nathan Brown is Vice President of Engineering for ALIO Industries. He has extensive experience with the design, development, manufacturing and testing of next-generation precision motion systems. He continually strives to innovate by finding creative solutions to complex problems. He holds a degree in Mechanical Engineering from the University of Texas at Austin, US.

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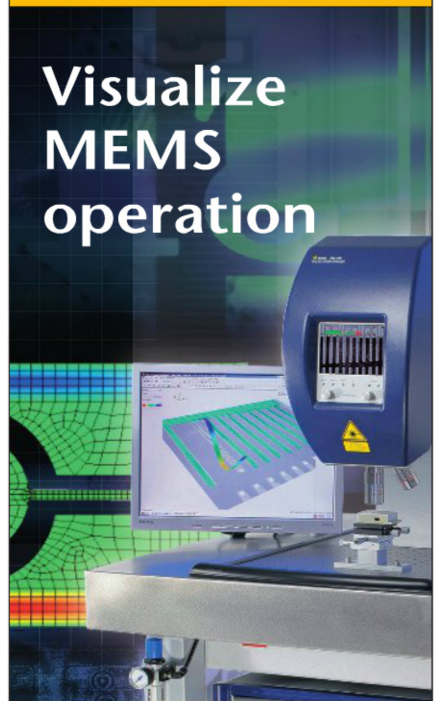

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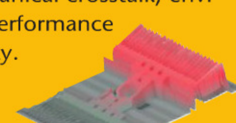

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