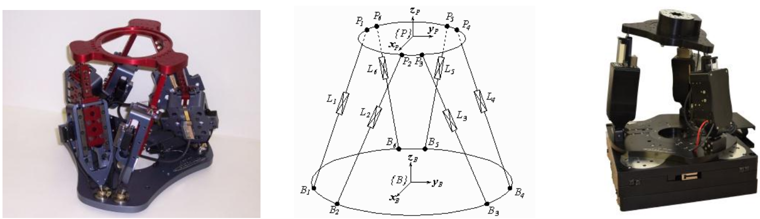
Design and Performance of a 6 DOF Hybrid Hexapod

N.L. Brown[1], C.W. Hennessey[1]
[1]*ALIO Industries, USA*
nathan@alioindustries.com

Abstract

Hexapods, also known as parallel kinematic machines or Stewart platforms (see Figure 1a and 1b), have no moving cables, increased dynamic response, smaller moving mass, better Z stiffness, and smaller size compared to serial kinematic systems making them the accepted six axis motion system for precision applications [1,2,3,4]. As precision motion requirements increase from the 10's of micrometers to the nanometer level, existing hexapods cannot meet motion system requirements due to performance limitations inherent in existing designs. A new six degrees of freedom hybrid parallel and serial kinematic design (see Figure 1c) is presented that addresses the performance limitations of hexapods and achieves sub-micron accuracy, repeatability and straightness as required for advancements in optical, semiconductor, manufacturing, metrology, and micro-machining industries.



(a) *(b)* *(c)*

Figure 1: 6 DOF motion systems: a) ALIO HR2 hexapod, b) example of a six axis parallel kinematic layout, and c) hybrid parallel and serial XY- Tripod-Theta system.

1 Hexapod Limitations

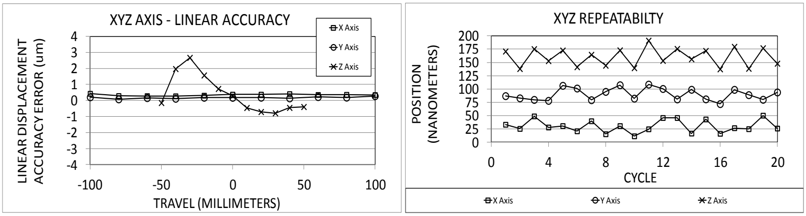
Hexapods have six links joined together moving a common platform and thus the motion error of the platform will be a function of the errors of all links and joints. Hexapods are known to have optimum accuracy, repeatability, and path integrity when performing Z axis moves because all links perform the same motion at the same link angle. When any other X, Y, pitch, yaw, or roll motion is commanded, accuracy and geometric path performance of the hexapod degrades because all links are performing different motions [5]. Additionally, hexapods are marketed as having good stiffness compared to serial stacked multi-axis systems [2,3,4,5]. However it is only the Z (vertical) stiffness that is acceptable. Stiffness has a large impact on platform repeatability and rigidity and thus the relatively weak XY stiffness, which is 10-30 times less than Z stiffness (Table 1), negatively affects XY axis performance. Lastly while there are documented compensation methods to reduce error sources, they do not improve performance to the sub-micron level.

2 Design Summary: Hybrid 6 DOF System

The presented hybrid parallel and serial kinematic system is designed to address and minimize link and system error sources to achieve nanometer order performance. The system is a serial stack of an XY stage, a redesigned parallel kinematic tripod (Z, pitch, and roll), and a rotation (yaw) stage, see Figure 1c. The tripod includes a new link design with precision linear crossed-roller bearings, non-contact optical linear encoders, and brushless linear servo motors oriented along the link axis. This design eliminates backlash, micrometer screw pitch errors, and error sources from rotary encoders. Near frictionless pneumatic or magnetic counterbalances in each link maintain high payload capabilities. This redesigned tripod is joined with XY and rotary stages that provide optimized performance for XY and yaw motions. In this hybrid concept, individual axes can be customized to provide travel ranges ranging from millimeters to over one meter and still maintain nanometer levels of precision. The following sections describe the improvements of this hybrid structure in reference to the specific performance capabilities.

2.1 Linear Displacement Accuracy and Repeatability

Hexapod linear accuracy is limited to micron order performance that varies greatly throughout its range of travel. The hybrid six DOF system pairs the optimized Z axis performance of a parallel kinematic tripod with an XY stage calibrated to have sub-micron accuracy and straightness performance. XY error sources are reduced relative to the hexapod resulting in accuracy error less than +/- 2um in Z and less than +/- 1 um in X and Y. The repeatability of a hexapod depends on the repeatability in three dimensional space of all six links while the hybrid design's improved links combined with high precision serial stages enables repeatability below +/- 50nm.



(a) (b)

Figure 2. The X, Y, and Z linear accuracy (a) and repeatability (b) of the hybrid six DOF system, model AI-6D-300XY-106Z-104R, tested per ASME B5.54:2005. Note: In plot (b) axis repeatability data is offset vertically for clear visualization.

2.2 Motion Trajectory: Straightness

Hexapod straightness of travel is often not quantified by manufacturers because it can be greater than 100um/100mm travel, which is the result of parasitic errors from all six links. With a precision XY stage the link error sources affecting path integrity are reduced to error sources from two XY axes for which the performance can be tightly controlled. Hybrid system straightness is less then +/-2um/100mm of linear travel, which is two orders of magnitude better than typical hexapods, see Figure 3.

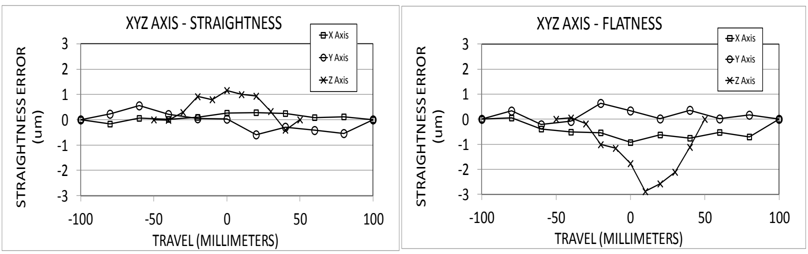


Figure 3. The X, Y, and Z straightness and vertical straightness (flatness) performance of the hybrid six DOF system, model AI-6D-300XY-106Z-104R, tested per ASME B5.54:2005.

2.3 XY Stiffness

In the hybrid system structure the parallel kinematic tripod link lower joint to the base plate has only one degree of freedom and thus the combination of three joints provides mechanical stiffness in the XY directions. Additionally, the XY stage motors are oriented in the XY directions such that the full motor force determines the XY servo stiffness. These changes increase the XY to Z stiffness ratio to 1:1.2, see Table 1. The hybrid six DOF system is ideal for machining, optical, and laser manufacturing applications where electrostatic, bonding, or mechanical forces are applied to the motion system.

Table 1. Published specifications for hexapods and the hybrid 6 DOF motion system showing the differences in XY to Z stiffness.

Published Stiffness Specifications: Hexapods vs ALIO Hybrid 6 DOF			
Manufacturer	**Model**	**Ratio XY : Z Stiffness**	**Type**
Physik Instrumente [3]	M-850	1 : 33	Hexapod
	H-850	1 : 14	
	H-824	1 : 4	
Newport [6]	HXP50-MECA	1 : 11	
	HXP1000-MECA	1 : 10	
ALIO Industries [2]	AI-HEX-HR2-SS	1 : 10	
	AI-HEX-HR4	1 : 14	
ALIO Industries [2]	AI-6D-100XY-24Z-56R	1 : 1.2	Hybrid 6 DOF System
	AI-6D-300XY-55Z-104R	1 : 1.1	

3 Conclusions

There are inherent weaknesses of the hexapod concept that prohibit the use of hexapods in applications requiring sub-nanometer precision. The hybrid parallel and serial kinematic system presented takes advantage of the Z, pitch, and roll capabilities of parallel kinematic tripod and uses serial kinematic stages to provide the X, Y, and yaw axes. The result is a six DOF motion system that can meet increasing motion system needs for sub-micron performance.

References:

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