euspen's 23rd International Conference & Exhibition, Copenhagen, DK, June 2023
www.euspen.eu

Air bearing hexapod for motion and positioning in six degrees of freedom with sub-micrometer precision

Jens Matitschka[1], Brad Engel[2], Christian Rudolf[1]

[1]*Physik Instrumente (PI) GmbH & Co. KG, Germany*
[2]*PI (Physik Instrumente) L.P., United States*

j.matitschka@pi.de

Abstract
A new compact hexapod positioner is being developed that utilizes frictionless air bearing guides, direct drive motors, and parallel kinematics. This enables precise and fast motion, while minimizing wear and allowing for high lifetime at high duty cycles. Hexapod positioners with sub-micrometer precision are used in laboratory and industrial settings to move objects in six degrees of freedom over a workspace of several tens of millimeters and degrees. As part of the development process a functional model has been built for testing and optimization. In this paper, the system design and measurement results of its precision and dynamic performance are presented. Crosstalk between axes of motion and parasitic forces are identified as the focus for further development.

Hexapod, air bearing, direct drive, high precision, parallel kinematics

1. Introduction

Large-scale production of high-resolution optical components [1] like smartphone cameras or automated testing in the growing field of silicon photonics [2] are two examples where high precision positioning of an object in up to six degrees of freedom is essential. Both examples have in common the need for continuous operation at high throughput, high dynamic motion profiles, and low downtime.

Hexapods, six-axis parallel kinematic positioning systems also known as Stewart or Gough-Stewart platforms, have been used in various fields of research and industry for many years for aligning and displacing objects in six degrees of freedom [3]. However, while hexapods are well suited for said applications because of attainable sub-micrometer precision over a millimeter workspace and high load capacity, it is a challenge to maintain the demanding precision specifications over an extended period at high duty cycles.

A new hexapod is being developed to overcome these challenges. By using air bearings in conjunction with electromagnetic direct drives, friction and wear are significantly reduced in the hexapod actuators compared to more common concepts employing screw drives or piezoelectric actuators. However, these advantages come at the expense of a lower system stiffness and a more challenging controllability. Early in the development process a functional model is built to test the entire system including electronic and pneumatic components. Another possibility would be to model all subsystems and kinematic connections in a multiphysics simulation with the additional freedom to test different variants but also the risk of modeling errors and inaccurate estimates of model variables.

In the first part of this contribution the system design of the air bearing hexapod is introduced. The pneumatics, the electromechanical subsystems and their interactions are reviewed to subsequently describe opportunities for tuning of the system's performance and control. In the second part of the paper, measurement results are presented that focus on positioning accuracy, position stability, and dynamic behavior. Finally, the knowledge gained from building and testing of the functional model are summarized and possible next steps to optimize the current design are described.

2. System design

The hexapod kinematics comprises six identical actuators with variable length, each connected by joints to a baseplate and a moving platform, see Fig. 1. The actuators themselves must provide one linear and one rotational degree of freedom to achieve a fully constrained kinematic system. The target length of each actuator is calculated by inverse kinematics given the desired position of the platform. An incremental linear encoder is used to measure length variation in the actuators' axes of motion. The linear and rotational motion along these axes is guided by air bearings. Voice coils, a type of electromagnetic direct drive, are used to adjust the actuators' length. An additional predominantly static force is created by regulating pneumatic pressure in a cavity in each actuator. This additional force is adjusted to partially compensate for largely static, external loads to minimize static voice coil currents, thereby reducing heat generated in the actuators that might result in a diminishing positioning stability due to thermal expansion.

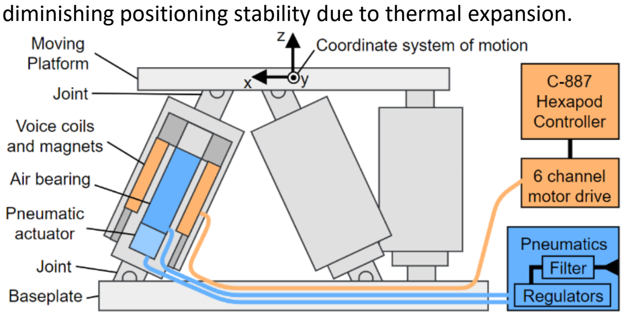

Figure 1. Schematic of the air bearing hexapod detailing the subsystems of the actuators, control devices and connections in between

Baseplate, platform, and cardanic joints with axes offset used in the functional model are identical to the parts used in the H-811.I2 hexapod (by Physik Instrumente (PI) GmbH & Co. KG) due to their proven precision for this kind of application. Electrical and pneumatic connections run from each actuator to a digital controller with motor drives (motion control, power supply, communication interface), adjustable air pressure regulators, air filters and an input air pressure regulator. It is expected that the friction caused by moving cables and air hoses and by the preloaded bearings in the joints is very small. Fig. 2 shows the functional model with connected control devices.

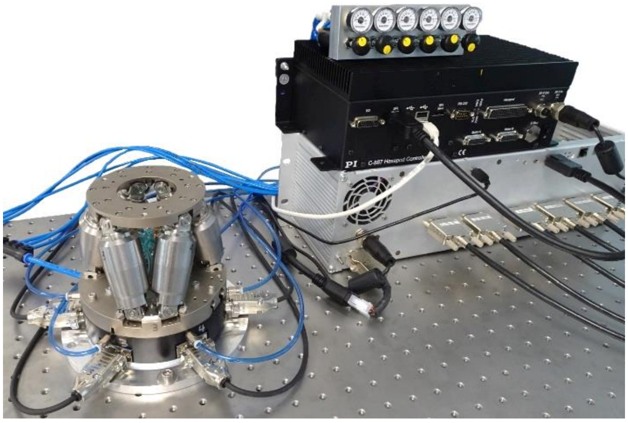

Figure 2. Functional model of the air bearing hexapod connected to a 6 channel motor driver box, C-887.52 Hexapod Motion Controller and air pressure regulators for tuning of the pneumatic force in each actuator

3. Prototype qualification

Positioning of the hexapod is accomplished by decoupled feedback control of the six actuators with PID controllers and a feedforward part to account for different payloads. Crosstalk between the six parallel control loops has been observed. Similar to [4], tuning of this system poses a challenge due to the low friction and direct transfer of the actuation force to the platform. Control settings can still be found for stable operation but must be adapted for different payloads. After activating the control, pneumatic pressure and flow rate are manually adjusted for each actuator to minimize static voice coil currents. This step should be repeated for changing mean positions of planned motions or for different payloads.

Measurements are performed with the functional model fixed to an optical table. The signals from the internal encoders or an external laser interferometer are used, and a linear regression line is subtracted, see [5] for details on the evaluation. The precision partially reaches that of the H-811.I2 hexapod, although many results take on higher values. Selected results are listed in Tab. 1, an exemplary measurement is shown in Fig. 3.

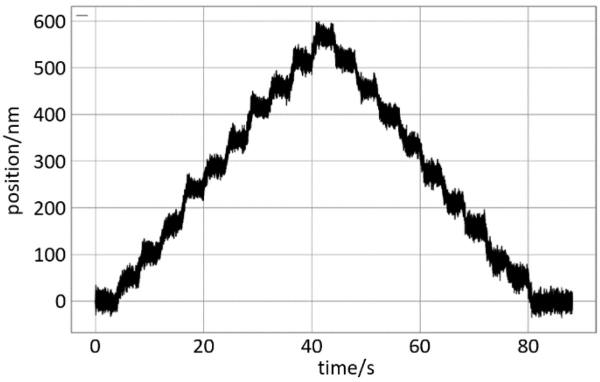

Figure 3. Minimum incremental motion measurement results with step size 50 nm in Z axis without payload; results in X and Y axes are higher (X: 300 nm, Y: 100 nm), which is common with many hexapods

Position stability, which is defined as the position drift in closed loop, is smaller than 70 nm over a duration of 40 minutes (measured in X axis by laser interferometer).

To investigate parasitic forces additional tests are performed. With an optimized routing of the moving cables and air hoses the unidirectional repeatability and backlash in Y and Z axes could be significantly improved, see Tab. 1. The degradation in X axis must be further examined. Other measurement results are not influenced as much.

Table 1 Selected results for initial and optimized system (payload 0 kg)

Measurement	Axis	Initial setup	Optimized setup
Unidirectional	X	0.19	0.22 (+16 %)
repeatability	Y	0.18	0.16 (-11 %)
mean/µm	Z	0.06	0.05 (-17 %)
Backlash	X	0.35	0.86 (+146 %)
mean/µm	Y	0.78	0.18 (-77 %)
	Z	0.17	0.02 (-88 %)

The maximum velocity is set to 100 mm/s for payloads up to 1,5 kg, larger values are possible, but control instabilities arise.

Sine wave excitation is tested up to 80 Hz with an acceleration of 2 m/s². Good control quality is observed in the Z axis up to 30 Hz, while less good results are obtained in X and Y axes, see Fig. 4. This behavior is attributed to the low friction which reveals a strong kinematic coupling between the axes, as well as a low frequency vibrational mode between 8 Hz and 25 Hz.

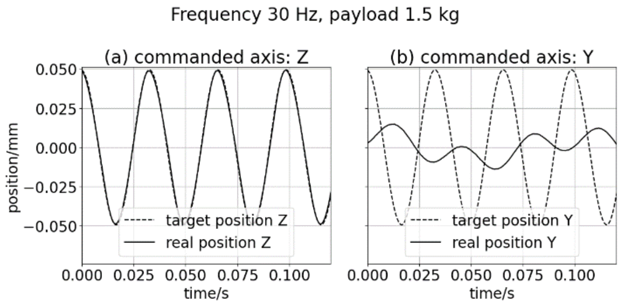

Figure 4. 30 Hz sine motion at payload 1.5 kg with low error in Z axis (a) and large error in Y axis (b)

5. Summary

An air bearing hexapod, its subsystems, and approaches for control tuning and design optimization are presented in this paper. Measurements with a functional model demonstrate sub-micrometer precision with smallest step sizes of 50 nm to 300 nm, depending on the moving axis. Parasitic forces prove to have a significant influence on the precision, especially due to low friction in the actuators. Dynamic motion with low control error is achieved in the Z axis while performance in the X- and Y-axes is to be improved.

In conclusion, stable control and good performance are observed for certain operating points. However, crosstalk between axes of motion and parasitic forces are identified as challenges. Next steps for improvement should focus on the control strategy and optimized routing of cables and air hoses.

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