

## HEXAPODS FOR PRECISION MOTION AND VIBRATION CONTROL

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### Introduction

Parallel kinematic manipulators offer several advantages over their serial counterparts for certain applications. Among the advantages are greater load carrying capacity, higher stiffness, reduced sensitivity to certain errors, and built-in redundancy. The hexapod is one form of parallel manipulator that is used increasingly in manufacturing, inspection and research. This paper highlights features of several hexapods developed for different applications.

The ultimate hexapod would provide large motions for massive payloads in up to six degrees of freedom with high accuracy, resolution and repeatability. In practice, a range-to-resolution specification much greater than 60 dB is difficult to achieve, and most likely can be realized only at the expense of substantially reduced bandwidth and slew rates. High load carrying capacity restricts options in design of strut ends, also compromising precision. The current paper explores the limits of practical hexapods, through an overview of several existing systems and a discussion of important design issues.

Hexapods provide advantages over other architectures, but indiscriminate application of hexapods can be inappropriate. In particular, systems needing fewer than three axes of control are unlikely to require a hexapod. Further, position and angle specifications that vary significantly between axes may point to a serial motion control system.

### Survey of Hexapods

The hexapods built by the authors over the last ten years are distinguished by their size, shape, actuation (Figure 1), sensing, control systems, and performance metrics. Vibration isolation and precision positioning are the two primary metrics that drive designs. The hexapods considered here range in size from 130 mm to 3 m, with load capacities between 0.5 and 1500 kg.

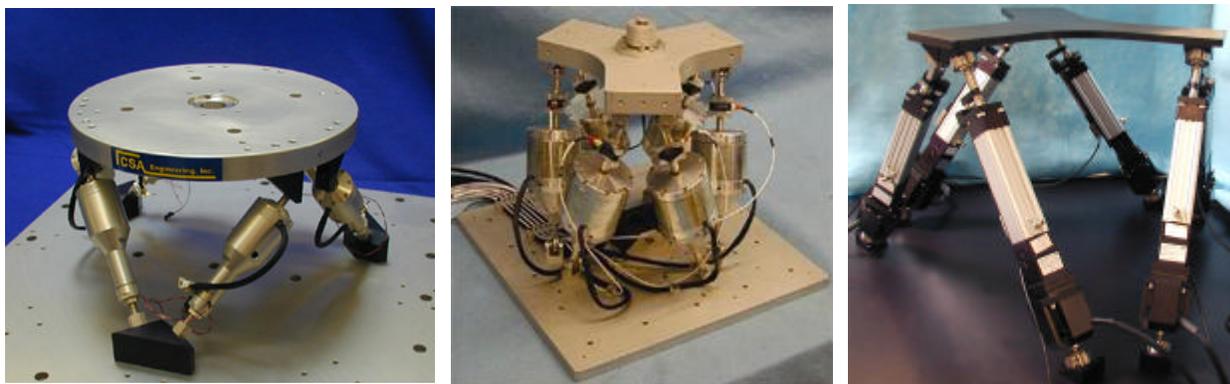


Figure 1: Hexapods using piezoelectric, electromagnetic and motor-driven screw actuators

The features of a particular hexapod are closely tied to its intended use. The generic diagram of Figure 2 describes a basic architecture that is common to most systems.

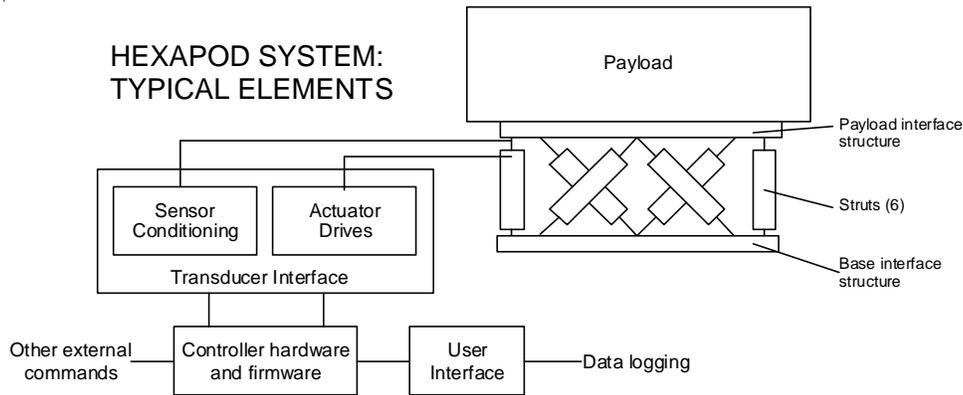


Figure 2: Each active hexapod has certain common elements

The *application* determines everything else, and provides the most fundamental requirements: payload mass properties and geometry, range, accuracy, and resolution requirements in six axes, and bandwidth. The “dynamic range” of the hexapod may be computed by axis, and is usually expressed as a ratio of range-to-resolution. The most capable systems built by the authors have a dynamic range of about 75 dB. Secondary requirements include cross-axis sensitivity, zero power hold, external loading, collision avoidance, load measurement and environmental conditions and compatibility.

Vibration isolation and control is a special case of motion control that requires either a stable platform in the presence of a base vibration environment, or minimization of load transmission from a noisy platform to the base to which it is connected. The system on the left in Figure 3 was designed to provide ultra-stable small platforms on satellites. Base vibrations of more than 30 micrometers will saturate this microprecision system, which has a baseline of feedback control used to actively soften the stiff suspension system. The hexapod on the right in Figure 3 was designed to support a vibration-generating machine, in particular a machine that produces undesirable vibration at a single frequency and its integer multiples. It combines a passive vibration isolation system with electromagnetic actuation and load measurement in each strut.

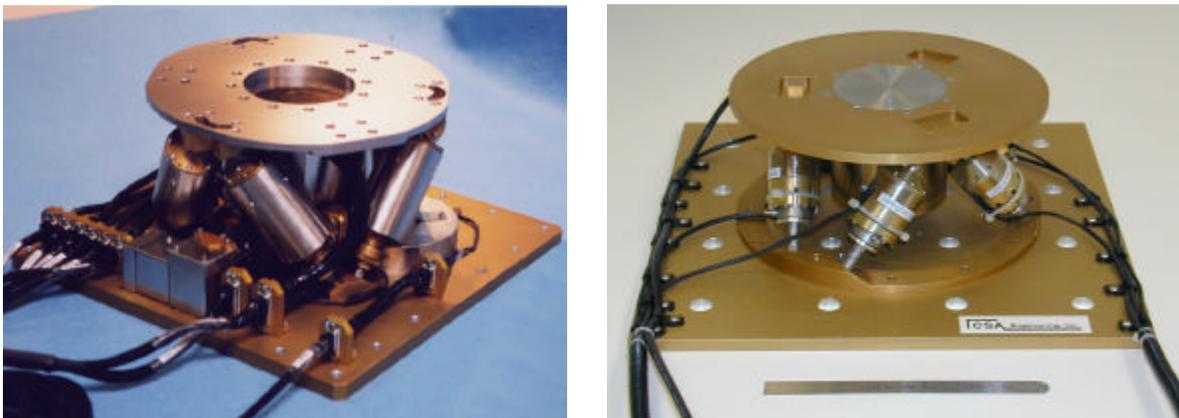


Figure 3: Piezoelectric-based isolated platform (left) and electromagnetic hexapod for isolating noisy component (right)

The appropriate *actuation* is largely determined by the range and geometry that together imply leg length and extension requirements. Larger masses and higher bandwidth increase actuator force requirements. A certain minimum resolution is also required, although this does not usually determine system resolution. The authors have built systems using piezoelectric, voice coil, pneumatic, motor-driven screw, and hybrid actuation schemes. For the largest payload masses that also require zero-power hold, precision screw actuation is likely to be preferred. Both of the motor-driven screw systems in Figure 4 carry payloads greater than 1000 kg and achieve greater than 70 dB dynamic range.

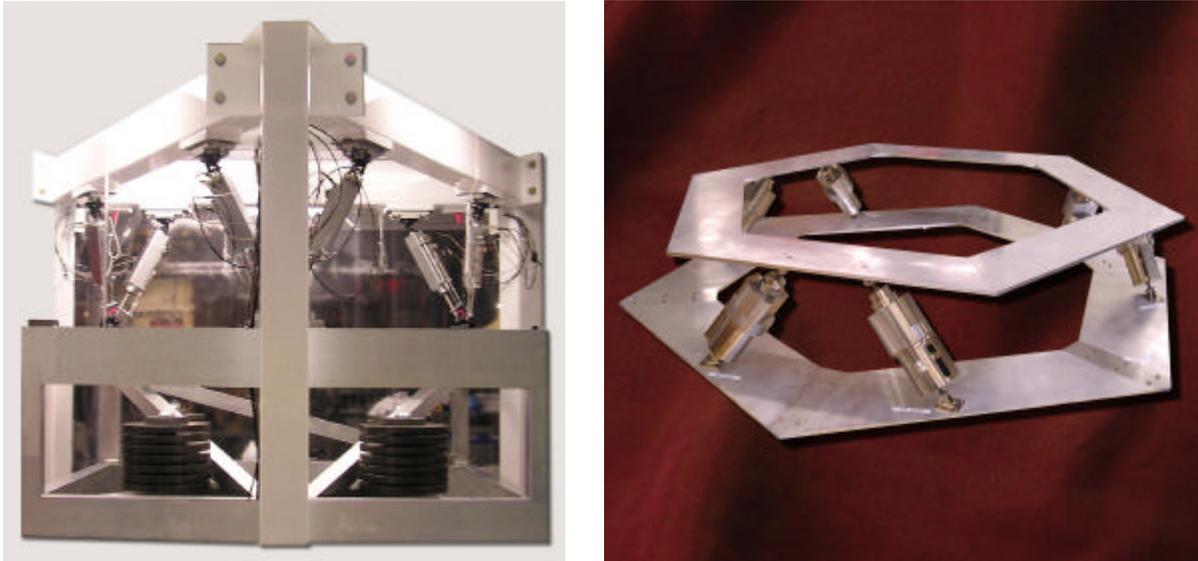


Figure 4: Large hexapod systems used for precision positioning and assembly

*Sensing* is the key to overall resolution and accuracy. In some hexapods, a direct measure of payload position and orientation is available, but in most cases, leg lengths are used to determine payload position. Length sensors should measure all of the leg motion and more than one sensor may be required to provide the needed range with resolution and accuracy. Sensors that provide absolute information are often used when a hexapod is powered up. Higher bandwidth systems may include acceleration or load measurement for basic control or for monitoring of off-nominal performance.

*Control* becomes more challenging when large positions and angles are demanded at high speed. While it is straightforward to determine required leg lengths from desired payload position via the inverse kinematics, changes in hexapod geometry obviously affect the kinematics. Control is complicated some when multiple sensors, or possibly multiple actuators, are used within each strut. Feedback control by leg is commonly used, with gains often set to allow all struts to reach their desired lengths simultaneously. Feedforward control can improve response time when the desired trajectory of the payload is known. A variety of techniques are used in hexapod vibration isolation systems. There are numerous additional requirements for control related to error checking, trajectory verification and collision avoidance.

The control design and implementation for odd hexapod geometries is not necessarily more difficult than that used in standard strut arrangements (Figure 5). While most hexapods take on a standard form (sometimes called 6-6, 3-6, or 3-3), application-specific requirements dictate other geometries that don't appear at least to fit standard forms. For precise, small motion hexapods

like those below, it can sometimes be acceptable to assume the strut end locations are fixed when computing needed leg lengths.

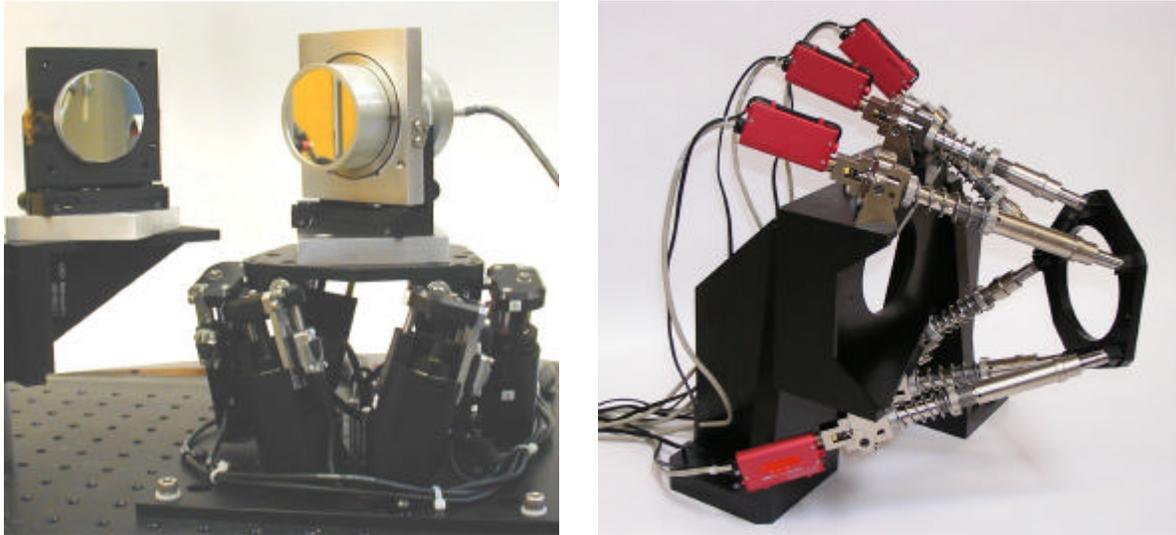


Figure 5: Small precise positioning systems for optics

*Mechanical design* of the strut assemblies is critical to achieve precision and also to allow extended bandwidth operation. Mounting of sensors, side loads on actuators, friction, stiction and backlash within struts require careful consideration. Bandwidth is directly affected by internal strut resonances, and vibration control can be compromised by strut bending modes that allow energy to be transferred without observation by sensors or uncontrollable by actuators. Sometimes the mechanical design of the complete system, and the particular geometry and loading environment, dictate that an octopod rather than a hexapod be used for an application.



Figure 6: Three of many possible kinds of strut ends

The mechanical interface at the strut ends, between the struts and the payload and base, is a critical element of the design. Among the considerations are load carrying capacity, linearity, durability, accommodated angle, and stiffness. Figure 6 shows three common types of end structures, including a high-load uni-ball, a large angle, ball with ball bearings, and a small angle flexure. Nonlinearities including backlash must be minimized because they generally set hexapod-level precision, and in most architectures based on leg length control, the end fitting motion is unobservable.

## Open Research Areas

This section identifies several open research areas in hexapod control and assesses their importance and prospects for progress. It is biased towards several areas that are currently receiving attention from the authors.

- High speed hexapods are needed to compete with serial systems for some manufacturing applications. The processing power is available. Increasingly, mechanical design and unwanted compliance will drive or limit high speed performance.
- Stabilized controlled motion platforms, in which the payload follows a specified trajectory with extremely low vibration or jitter, are needed.
- Improved sensing of leg lengths or other compact methods of direct payload motion measurement is desired. Combinations of multiple sensors and blending of information are useful.
- Actuators that can deliver large motion precisely will find several uses. Actuator heat generation becomes a concern in high speed uses or extreme environments.
- Strut ends usually govern precision of any hexapod. The demanding requirements are for ends that can carry large loads, traverse large angles, and behave linearly, with minimal stiffness in their rotation axes.
- Blending of feedforward and feedback control algorithms can be useful, while fault detection and accommodation, collision avoidance and measurement, control of overdetermined systems, and control of payloads with inherent flexibility will become increasingly important.
- Finally, hexapods for extreme environments are required for specialized applications. The authors are familiar with needs for vacuum operation and operation in extremely low and high temperatures.