Nanopositioning: fighting the myths

The need to align optical equipment and samples to within a nanometre is now crucial in many industries. **Stefan Vorndran** describes the technology that makes it possible.

Take your pick: nanopositioning stages and controllers come in a wide range of sizes and specifications.

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Nanopositioning – the means of controlling motion on the nanometre scale – is now a key enabling technology in high-tech fields such as semiconductor test and measurement, photonics alignment, scanning microscopy and microlithography.

However, selecting the most appropriate nanopositioning stage doesn't only involve finding one with the required level of resolution and accuracy. A potential buyer must also consider factors such as stage time response (dynamics), size, cost, and compatibility with the application environment.

Unfortunately, the term nanopositioning is often misused. It is not uncommon to find micropositioning stages, which by definition operate on the micrometre scale, re-labelled as nanopositioning stages in an attempt to make them sound more impressive. For example, the simplest approaches involve bolting a micro-stepped motor and a reduction gearbox to a lead-screw mechanism, while the more sophisticated methods add position feedback in the form of an encoder and interpolator circuit.

Specification sheets for the above examples often quote impressive figures in the nanometre realm and below, but a buyer needs to consider more than just these numbers. A true nanopositioning system that performs well consists of a lot more than a motor, an encoder and interpolator circuit.

A device should only be referred to as a nanopositioning stage if it is capable of repeatedly producing motion in increments as small as 1 nm or below.

Drive technology

The fundamental difference between a nanopositioning stage and a micropositioning stage lies in the way they deal with friction. Common drive mechanisms found in micropositioning equipment (such as leadscrews and ballscrews) rely on mechanical actuation to control motion and this produces friction. When friction is present, it is not possible to achieve repeatable motion at the nanometre level. A true nanopositioning stage should be equipped with frictionless drives.

Appropriate drive technologies include electromagnetic linear motors, voice-coil drives and solid-state piezo actuators (PZTs). The first two are preferred for larger distances. The drawback is that they produce magnetic fields and heat, which some applications cannot tolerate. They provide moderate stiffness, resulting in a relatively low bandwidth (time response).

PZT drive technology is limited to smaller distances, but achieves much higher bandwidths in the kilohertz range, enabling it to respond to commands rapidly. In addition, it does not produce magnetic fields. Other benefits of the latest ceramic-encapsulated actuators are: fast response on a microsecond timescale; maintenance-free, solid-state construction; high efficiency; and vacuum-compatibility with zero outgassing.

For a positioning stage to perform well it is vital that motion is guided in the desired direction. Friction rules out all devices with conventional roller or sliding bearings (which also lack the guiding precision required in nanopositioning), so only two types of bearings have found common use in nanopositioning systems: air bearings and flexures. Air bearings are the only option for long travel ranges, but are larger than flexures and can be expensive to operate as they need a clean air supply. Also, they don't work in a vacuum, where many of today's nanopositioning applications happen.

For these reasons, the highest precision nanopositioning systems are generally guided by flexures (see figure 1). A flexure is a frictionless, stictionless device that relies upon the elastic deformation (flexing) of a solid material. Flexures, if designed properly, are very stiff, lightweight and provide trajectory control with nanometre straightness and flatness. They exhibit no wear and suit multi-axis arrangements, but their travel range is limited to a few millimetres. ▷

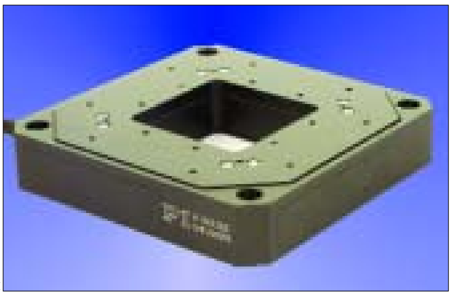

Fig. 1: A flexure-guided nanopositioning stage equipped with capacitive position sensors.

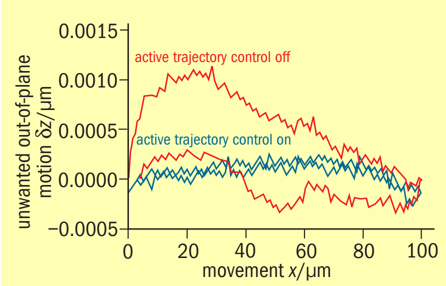

Fig. 2: Run-out of a flexure-guided nanopositioning system with and without active trajectory control.

Sensors and feedback

To ensure that positioning is both precise and repeatable, good nanopositioning systems are equipped with highly accurate feedback sensors. The best systems use direct motion metrology, in which sensors make direct measurements to determine the stage's position. Examples of high-resolution direct metrology sensors are capacitive sensors, laser interferometers and non-contact optical incremental encoders. Laser interferometers are capable of accurately measuring long distances, although bulky optics must be mounted onto the moving parts of the motion system for it to function.

Optical encoders are more compact and rely on diffraction between a moving reticule and a scale composed of finely pitched lines. However, the period of the lines is usually very coarse, ranging from tens of micrometres to just a few. Position is determined by counting fringes and interpolating between individual peaks. While scales with several hundreds of millimetres are available, the signal-to-noise level limits the practical resolution to several nanometres, with cyclic linearity errors of typically 10–100 nm. Interferometers and linear encoders are relative position sensors that must be initialized at a reference position. The stability of this reference position also influences the overall precision.

For travel ranges of less than 1 mm, capacitive sensors have emerged as the default choice. They are compact, high-bandwidth and absolute measuring devices that provide sub-nanometre resolution.

Dynamics

In today's industrial production and testing processes, dynamics and throughput are often paramount. For example, in applications such as disk head testing, sub-nanometre steps need to be executed in a matter of milliseconds. For these applications, PZT-driven, flexure-guided systems provide the only feasible solution. PZT drives can provide acceleration up to 10 000 g and flexure-guided stages can respond to an input signal in less than 0.1 ms.

For nanopositioning applications where a fast response and high-speed scanning or tracking motion are required, the specifications that manufacturers usually quote are of little use. This is because they are typically referring to performance that can be achieved under the best possible conditions, such as a single slow command rather than a series of rapidly executed movements.

At high scanning speeds – as are desirable in scanning microscopy applications – it is inevitable that the scan lines will not be perfectly straight. The deviation is caused by nonlinearities of the components in the scanning system (drive, sensors, amplifier,

servo) and their limited bandwidths. The difference between the desired position and actual position data is called tracking error.

In systems with conventional PID servo controller designs, the tracking error can reach double-digit percentage values for even moderate scanning frequencies. Recent advances in digital controller design have lead to adaptive digital linearization methods that reduce dynamic errors from the micrometre realm to almost indiscernible levels.

Multiaxis designs

In high-speed nanopositioning applications, such as image stabilization or photonic alignment, motion in more than one dimension is required. Conventional multiaxis designs are made by stacking a number of single-axis subassemblies (serial kinematics). In these designs, each axis moves the mass of all the stages (and cables) that are mounted above.

New designs with only one moving platform are known as monolithic parallel-kinematics stages (the six-axis Hexapod is one example). The advantage of these designs is that they significantly reduce inertia and size, and offer improved dynamics. They also allow easy integration of numerous capacitive sensors. This enables simultaneous measurements of a platform's co-ordinates, which a controller can use to automatically compensate for run-out of each axis. This technique is called active trajectory control (figure 2).

When selecting a supplier, it is always worth asking how the product's specifications will be measured. When the specifications sound too good to be true, they usually are. Remember, the laws of physics also apply to nanopositioning. ☐

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The questions to ask

Specs versus real-world performance

The highest-performing system for an application is not necessarily the one with the best spec sheet. The following questions can help to find the right system:

- Is the application static or dynamic?
- What minimum incremental motion is required for the application?
- What linearity must be met?
- What load needs to be moved?
- Will the load on the stage change frequently? If so, a digital controller with optimization tools for the servo parameters is recommended.
- What effect will imperfections in the guiding mechanism have on the application?
- What are the environmental conditions (vacuum, humidity, temperature)?
- Is heat generation a problem?

For dynamic (tracking) applications

- What frequency and waveforms are required?
- What deviation of the actual motion profile from the ideal profile is acceptable? Control algorithms like dynamic digital linearization can reduce tracking errors by several orders of magnitude.
- What is the maximum acceptable settling time after a step?
- How stiff is the payload? In high-speed step and settling applications, the resonant frequency of the payload is a limiting factor that can be addressed by complex control algorithms such as InputShaping®.