Small Steps

Nanoscale positioning requires complete system-level design

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Our world is in a constant state of flux. New technologies are constantly being developed and improved, enabling smaller, faster, better and cheaper devices.

Examples are all around us. The 2014 Nobel Prize for Chemistry was awarded to researchers who enabled higher-resolution optical imaging by pushing optical resolution past a barrier believed to be insurmountable for more than 100 years. Data-storage demands have grown nearly 50 percent per year recently due to our constant thirst for more electronic-data storage. Current semiconductor manufacturing processes are working at the 14nm node, which is expected to decrease by at least a factor of two over the next 3 to 4 years, according to a report from the International Technology Roadmap for Semiconductors organization.

Emerging nanotechnologies are key enablers for many of these improvements and advances, and most of these enabling technologies require nanoscale positioning of parts or samples.

Nanoscale positioning, or nanopositioning, can be defined as reliable and accurate positioning performance at the 1nm to 100nm level. To design a system or instrument that requires nanopositioning, a complete system-level design approach is essential. The nanopositioning system requires high-quality components—including bearing and structural elements, drive and feedback technology, and control systems—along with knowledge and control of the operating environment. These elements act as mechanical springs in series, with the weakest spring having the largest adverse effect on performance.

For example, a high-accuracy, low-noise feedback device will hurt positioning-stage performance if it is designed with a poor actuation mechanism or substandard bearing system. Likewise, a nearly perfect nanopositioning stage will not perform as well in an environment where the temperature fluctuates by 5° C hourly

Aerotech's QNP-L piezo nanopositioner positions an optic in an interferometry application.

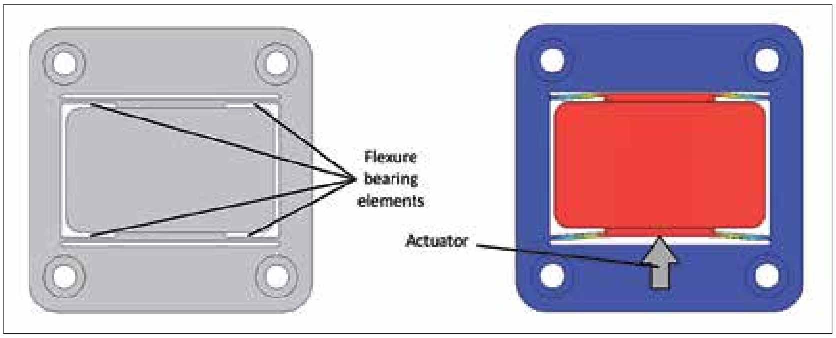


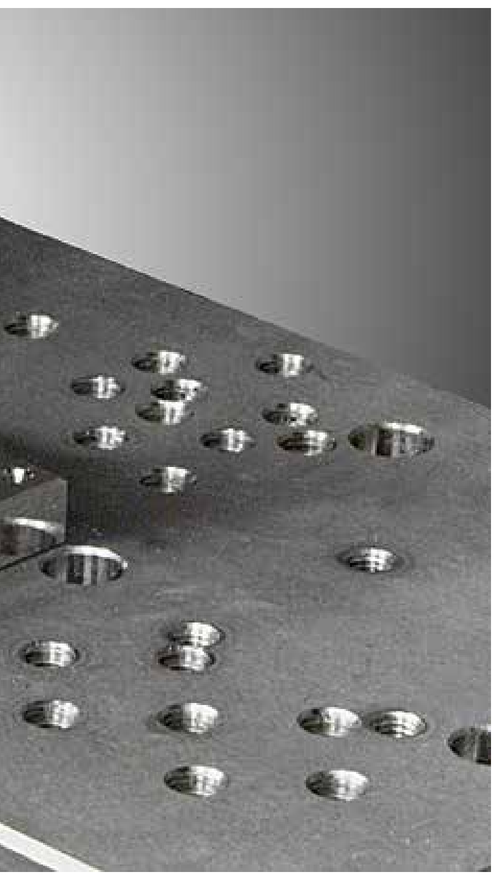
Figure 1: A flexure bearing, when actuated flexes (deforms), causing motion of a positioning system component.

Figure 2. Aerotech's QNP-L piezo nanopositioning stages use flexure bearings for high guidance accuracy.

due to a poorly tuned HVAC system. All elements in the positioning system and the environment where the system will ultimately reside must be closely scrutinized to ensure nanoscale-positioning performance.

Bearing systems

The "perfect" nanopositioning bearing system provides infinite load capacity and stiffness without friction or hysteresis, as well as perfect guidance accuracy (no error motions) when moving. Various bearing elements are available to the instrument designer and, of course, in the real world tradeoffs exist when selecting them.



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Air bearings are an attractive option for nanopositioning because they offer near-zero friction levels and high guidance accuracy. However, to obtain high stiffness and load capacity, the bearing elements must be very large because both the stiffness and load capacity are directly proportional to the size of the bearing land area.

Oil-type hydrostatic bearings are an improvement on air bearings from a stiffness and load-capacity standpoint, but have the disadvantage of requiring pumping and collection systems. Also, the presence of hydrocarbons in oil-based systems is problematic in certain applications due to contamination concerns.

Flexure bearings, which allow motion via flexing of the bearing material, are often used in nanopositioners. They exhibit zero friction and if designed and machined properly, typically with a wire EDM, can provide exceptionally low guidance errors (on the order of single-digit nanometers). This makes them very attractive for both nanopositioner designers and users.

Examples of a flexure bearing element, along with a nanopositioning stage that uses this element, are shown in Figures 1 and 2. One disadvantage of flexures is that they are generally limited to shorter travels—on the order of a few millimeters. The longer the travel, the more compliant the flexure material needs to be in order to keep material stress at a manageable level. As a result, system dynamics suffer due to the compliance in the bearing element.

Flexures can be made extremely stiff and have a high load capacity, but large forces may be required to actuate them. These large forces, in turn, require large and powerful actuators to drive them, which makes the final system much larger in size and more susceptible to thermal errors.

Active magnetic bearings are a promising technology for nanopositioning. They exhibit nearly zero friction, have very high stiffness and load capacity, and have high guidance accuracy. Magnetic bearings operate by sensing the bearing gap and providing closed-loop actuation to maintain the desired gap as the system moves. Because the bearing gap is actively controlled, magnetic bearings can exhibit infinite static stiffness over the bearing's working-load range. Guidance errors—a function of the sensor, gap control loop and target—can approach the single-digit-nanometer range.

However, a key disadvantage of magnetic bearings is their high cost and complexity. Each degree of freedom in a magnetic bearing system requires a sensor, actuator and control system.

For this reason, they have only found widespread commercial use in high-end semiconductor lithography and inspection equipment.

Finally, rolling element bearings, especially crossed-roller bearings, can be good choices for nanopositioning applications. They provide high stiffness and load capacity in a compact package.

However, the rolling nature of the bearings can lead to higher guidance errors and higher friction than other types of bearing elements. Careful attention to bearing tolerances—such as the roundness of rollers, bearing rail straightness and surface finish, and mounting surface tolerances—can help minimize these guidance errors. Also, rolling element bearings require lubrication, which must be chosen carefully to minimize friction and maintain uniform lubricant particulate size, so as to not degrade guidance accuracy.

Figure 3. Section view of a Lorentz force linear motor showing the coils and permanent magnets.

Actuation systems at the ready

Nanopositioning system designers have many actuation options at their disposal. Force density (force output per unit volume), power dissipation, actuation resolution and linearity, and cost and complexity must be considered. Although many actuation devices exist, two of the more commonly used for nanopositioning are piezoelectric and Lorentz force actuators.

Piezoelectric actuators have the advantages of very high force density (100s of Newtons), low power dissipation (< 1W) and high-actuation resolution (<< 1nm). Disadvantages of piezoelectric actuators are the inherent nonlinearity of the actuator, along with limited stroke.

Piezoelectric actuators are made from ferroelectric materials that exhibit hysteresis loops based on the applied electric field and the history of that applied field. Therefore, closed-loop control of these actuators is used to linearize the output. The strain of piezo actuators is typically limited to around 0.1 percent, meaning that 1µm output displacement is possible for every 1mm in length of the piezo-actuator stack.

To achieve long travels with piezo actuators, lever-amplification mechanisms are usually required. However, the stiffness decreases with the square of the lever-amplification ratio. Therefore, longer-travel, piezo-actuated nanopositioning stages generally have lower dynamics than shorter-travel stages.

When a long stroke is required, Lorentz force actuators tend to be used. Examples of these actuators include linear motors and voice coils. Their main advantages are the ability to provide force over very long distances and reasonably high force densities, as well as high resolution and linearity.

However, the main drawback of these devices is power dissipation. With Lorentz actuators, force is proportional to current, and the power dissipation is proportional to the current squared. Therefore, in nanopositioning applications, heat must be managed, either by appropriate motor sizing (making sure the current is sufficiently low) or by active cooling (so that temperature rise in the motor does not cause thermal errors in the process or system). Figure 3 shows a Lorentz force actuator (linear motor).

Choosing the best actuator for the application is critical, but its placement in the nanopositioning system can also have a dramatic impact on performance. The actuator should be placed near the centers-of-action (center-of-mass, center-of-friction and center-of-stiffness). In a properly designed system, all centers-of-action lie very close to the same point in space.

However, it may not be possible to make all of these points completely coincident. For dynamic applications, it is usually advantageous to place the actuator near the center-of-mass. For static positioning applications, it may be better to place the actuator near the center-of-stiffness or center-of-friction. Figure 4 shows a stage design with one actuator placed on the center-of-stiffness/friction, and one placed away from the center-of-stiffness/friction.

Feedback sensors

The ideal feedback sensor provides a direct measurement of the motion—i.e., direct metrology—while offering high resolution, linearity and bandwidth. Direct-metrology sensors commonly used in nanopositioning include capacitive sensors, optical encoders and laser interferometers. Capacitive sensors have the advantage of high resolution and high linearity in a compact package. However, they are typically limited to travel ranges of <1mm because travel and resolution are inversely related. Capacitive sensors can be made to work over longer distances, but the resolution starts to decrease as the travel distance increases. This is where other feedback approaches become more favorable.

Optical encoders can be used over very large distances (meters) with nanometer resolution and nanoscale accuracies. Positioning resolutions better than 1nm and accuracies of 10s of nanometers can be achieved with very high-performance optical encoders. A minor drawback of the encoder is packaging. In small nanopositioning systems, the encoder can be as large as the complete positioning stage, thus increasing overall package size and stage footprint.

Laser-interferometer systems accommodate long travels with nanometer-level resolution and accuracy. However, to achieve these accuracy levels, the environment the positioning system operates in must be highly controlled because the wavelength of light is a function of temperature, pressure, humidity and CO_2 content. Local turbulence and air mixing can lead to additional problems with interferometer accuracy and resolution.

Another drawback of interferometer systems is cost. Some interferometer systems can cost five to 20 times more than capacitive sensors or encoder-feedback devices.

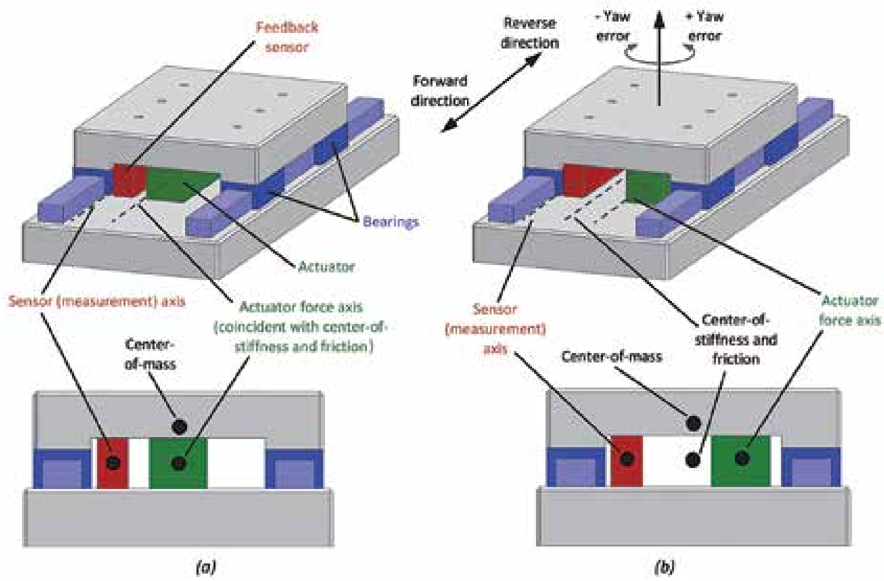

Figure 4. Stage with the actuator placed on the center-of-stiffness and center-of-friction (a) and away from the center-of-stiffness and center-of-friction (b).

As with the actuation system, selection of the feedback sensor is only a part of the process. Sensor placement in the nanopositioning system can have a large impact on overall system performance. If possible, it is best to place the sensor at the process point of interest, due the effect of Abbe error, which describes how angular errors magnify with distance (Figure 5).

In practice, placing the measurement sensor at the work point can be difficult in certain cases—especially when using optical encoders. Capacitive sensors or laser interferometers allow more flexibility, but it can still be difficult for the designer to obey the Abbe principle and minimize sensor-to-process-point offsets. In such cases, minimizing bearing guidance errors and designing a stiff structure between the feedback sensor and process work point, along with implementing error mapping, may be required to achieve nanoscale performance.

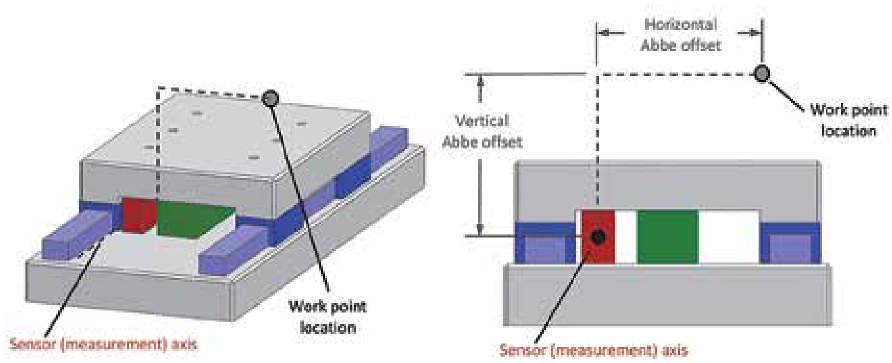

Figure 5. It is best to place the sensor at the process point of interest, due to the effect of Abbe error.

Control systems, drive electronics

Control systems and drive electronics play an equally important role in achieving nanoscale positioning performance. High servo bandwidths and controller data rates are essential to adequately respond to commands and reject external disturbances. Power electronics and amplifiers, which are the source of voltage and/or current to the actuation system, must be designed with low-noise components and with sufficiently high bandwidths (generally on the order of 1 to 10s of kHz). Advanced control algorithms are often necessary to push performance to the nanoscale.

Last, but certainly not least, are the environmental effects that surround the nanopositioning system. Vibration and acoustic isolation are often used to minimize the effects on the process due to ground-floor and airborne-noise vibration.

Thermal effects can be one of the largest sources of errors in precision machinery. It is often necessary to place the nanopositioning system in a temperature-controlled environment and effectively manage internal heat in the system by cooling or isolating the heat sources (e.g., motors).

Designing an effective nanopositioning system requires an in-depth knowledge of fundamental design principles in systems, engineering and mechatronics. All elements must work in unison to extract the highest levels of performance from any stage system and, ultimately, allow that positioning system to be a true nanopositioner. µ

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