Precision Motion Control for Photonics: Five Keys to Success

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INTRODUCTION

The misalignment of optical components in photonic devices is detrimental to quality, and results in unacceptable power losses. Photonics applications such as optical wafer probing (as shown in Figure 1) require high-performance solutions that offer the best possible balance of precision and speed. However, these metrics are difficult to achieve simultaneously, especially where nanometer-level tolerances are involved. Motion control system selection therefore requires careful consideration to facilitate successful optical alignments.

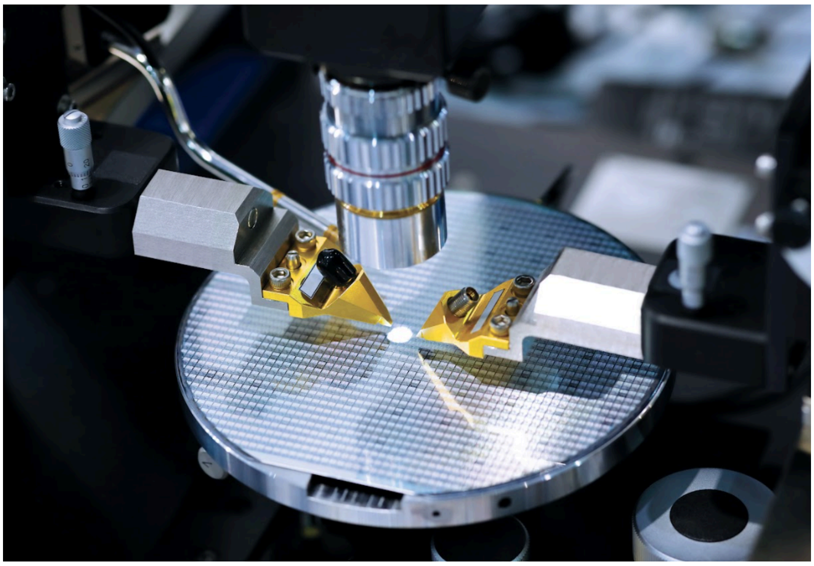

Figure 1. *Optical wafer probing requires extremely high precision and speed.*

Active optical alignments are needed to manufacture and test:

- Photonic integrated circuits
- Co-packaged optics
- Quantum computing systems
- Consumer electronics, including generative AI smartphones
- Automotive sensors for advanced driver assistance
- Augmented reality/virtual reality devices

Understandably, many of the photonics industry's most talented engineers are not necessarily motion control experts. And while this white paper will not turn readers into motion authorities, it will provide valuable insights into five keys to success:

1. Precision motion fundamentals
2. Error budgeting
3. Stage technology
4. Controller technology
5. Working with motion suppliers

1. PRECISION MOTION FUNDAMENTALS

Accuracy and Repeatability

Fundamentally, accuracy describes the maximum deviation between a commanded position and the actual position achieved by a motion system. Repeatability characterizes the ability of the motion system to return to a given position consistently over multiple attempts. There are many ways to quantify the accuracy and repeatability specifications of a motion control system like a positioning stage. A good starting point is to consult industrial metrology standards, such as:

- ISO 230-2
- ASME B5.64
- ASME B5.54
- VDI 3441
- JIS B 6201

It is worth noting that some motion suppliers have developed their own methods of reporting, typically involving statistically treated numbers. This adds complexity and confusion, especially when such a supplier does not clearly specify how they are defining or reporting these specifications. The advice? Be wary.

Key takeaway: Comparing specification tables from multiple suppliers can be risky, if they are reported using different methods. Instead, inquire how each supplier being considered reports these specifications, and convert them to a common format for comparison across multiple suppliers. To minimize risk, choose a motion control supplier that reports transparent and easy to understand peak-to-peak values for the actual equipment over the full motion of travel, not statistically treated numbers.

Off-Axis Error Motions

On-axis errors such as accuracy (errors in the direction of motion) form only part of the equation. There are five additional degrees of freedom to consider, and some amount of off-axis error motions will also be present. In a linear stage, these include horizontal and vertical straightness (linear motion perpendicular to the axis direction), as well as three angular errors corresponding to rotation about the X, Y and Z axes: roll, pitch and yaw. All five errors are shown in Figure 2.

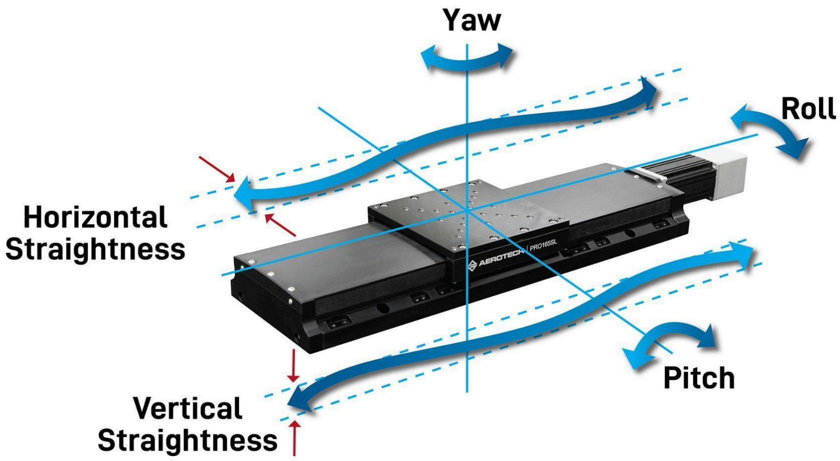

Figure 2. *A depiction of the five off-axis errors of a linear stage.*

Rotary stages also exhibit off-axis error motion:

- Axial error motion: motion in the direction of the rotation axis
- Radial error motion: motion in X and Y perpendicular to the axis of rotation
- Tilt error motion: rotation about the two axes perpendicular to the axis of rotation

Key takeaway: All off-axis geometric error motions can be measured, quantified and sometimes even mapped out. However, correcting these errors often involves compensating using additional stages.

What Causes Stage Positioning Errors?

Many factors can contribute to stage positioning errors, including:

- Component tolerances and form-errors
- Temperature and environmental variations or instability
- Motor/amplifier heating
- Friction
- Forces from cable management
- Non-uniformities in bearing lubrication
- Sensor and electrical noise
- Imperfect bearing behavior

- Poor vibration isolation
- Contamination and particulates
- Encoder scale errors
- Angular errors (e.g. Abbe error)
- Off-axis and parasitic motor forces (especially common with iron-core motors)

This is not an exhaustive list — many other factors can result in error motions that affect a motion system's precision. A pragmatic approach to understanding and addressing these challenges is to recognize that nothing is infinitely stiff, most physical objects tend to vary as a function of temperature, and everything has one or more tolerances associated with it. The implication here is that mechatronic systems behave like springs and thermometers. Never assume that stiffness and thermal effects are negligible.

Key takeaway: Failing to consider these factors in the design of precision machinery and capital equipment will result in imprecise, unrepeatable, non-optimal motion.

Angular Errors and Abbe Error

Angular error motions impart negative effects on a motion system. The work point at which a photonic process such as active alignment takes place – perhaps a fiber coupling or wafer probing process – will be located at a workpoint some distance from the stage tabletop. Angular errors magnify over the distance of that point from the location of the stage feedback device. In the specific case of angular error in the pitch direction – known as Abbe error (shown in Figure 3) – these error motions can make it seem like the workpoint has travelled farther or shorter than the position reported by the stage's position feedback device.

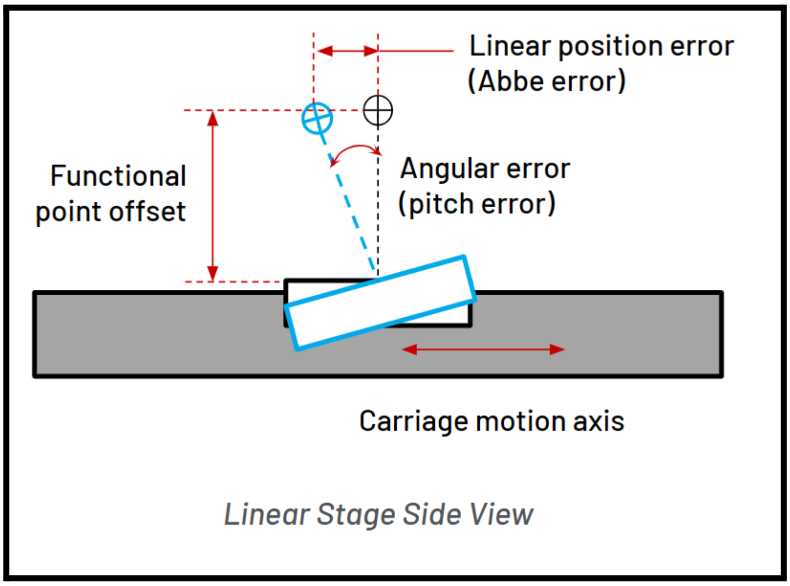

Figure 3. *Illustration of the Abbe error principle.*

Although it is impossible to eliminate these errors, they can be managed and minimized by doing the following:

- Measuring and error-mapping the stage position at the work point to compensate
- Optimizing the system architecture, stiffness, and axis alignments
- Carefully selecting the stage and its mechanical configuration to minimize errors
- Minimizing the distance from the stage to the functional point
- Using additional motion axes to compensate for error motions

Key takeaway: Before undertaking any of these activities, it is prudent to develop an error budget; in other words, calculate the maximum allowable error in the process and compare it to the estimated error at the motion system's functional point.

2. ERROR BUDGETING

In a six degree-of-freedom (DOF) motion system there are 36 sources of error (six DOF multiplied by six axes). By defining all errors in terms of their maximum allowable deviation, it is possible to develop an error budget for the motion system.

High-Level Error Budgeting Process
First, gather the following information:

- The positioning accuracy of all axes, typically by reviewing supplier datasheets
- The horizontal straightness, vertical straightness, pitch, roll and yaw errors of all linear axes
- The axial, radial and tilt errors of all rotary axes
- The distances from the work point to the tabletop of each stage
- The travel range of interest for each axis
- The allowable angular misalignment of each axis relative to the others
- The allowable axis intersection deviation of each rotary axis relative to the others

With this information in place, the process can continue as follows. First, determine the on- and off-axis error contributions for each stage in the multi-axis stage assembly in each of the X, Y and Z directions, converting angular errors into linear errors for the given workpoint offset distance. This makes it possible to determine how each error motion of every stage in the assembly contributes to errors at the workpoint. At this point, it is crucial to understand if the process is fixed-sensitive or moving-sensitive, as offsets can vary depending on both the working area of interest and what is moving (e.g. the workpiece, tool or sensor).

Next, factor in any additional error contributions resulting from misalignments in the stage-stack assembly. Combine all of the resultant errors in the global X, Y and Z directions, using a root sum of squares (RSS) technique. The RSS technique is valid because it's very unlikely for all of the error motions in a direction to occur at maximum deviation simultaneously; in practice, the RSS estimation coincides reasonably well with actual measurements.

At this point, this process has generated an estimate of the deviations in each global direction (X, Y and Z). Finally, these results can be combined as vectors in two or three dimensions to provide a meaningful estimate of the XY and XYZ vector RSS errors, respectively.

These error-budgeting calculations and estimates can become rather complex, especially when a system has many axes of motion. Understanding the specific application details and process architecture is where an experienced motion supplier can be of tremendous assistance in making and validating the estimated system performance at the workpoint.

Key takeaway: Gathering the information and executing the process for error budgeting becomes vastly easier with the input of an experienced motion supplier.

Reducing The Functional Point Error Estimate

If the error budget estimate does not align with process needs, then it makes sense to reexamine the system architecture and candidate stage selection. First, determine if the functional point can be lowered closer to the stages, because this reduces the linear error contributions from the angular errors. Also consider reducing the lateral workpoint offset to bring it nearer to the center of the stage assembly. This may involve changing the system architecture. Some processes may not be able to accommodate changing the functional point, in which case there are additional error reduction methods. Additionally, consider the axis alignment of the stages in the multi-axis assembly. Increasing the alignment precision not only helps to prevent crosstalk but also can reduce systematic, multi-axis error motion contributions.

Another approach to reducing the functional point error is to choose different stages that comprise the multi-axis stage assembly. Determine which stages in the stack are contributing the most error, and consider replacing them with products that exhibit higher stiffness and lower error motions. This can be a balancing act, because higher-performing stages tend to be more expensive. Therefore, it's crucial to understand the tradeoffs in terms of performance and cost.

Even with the world's highest-performing stages, there will still be error motions to manage. An effective way of doing this involves performing error mapping and calibration at the functional workpoint, as illustrated in Figure 4.

Figure 4. *A technician performs metrology and calibration on a linear stage.*

With a capable motion controller, it's possible to correct a portion of the errors of one stage by using the other stages to compensate. By measuring the position at the workpoint, the repeatable errors can be mapped and corrected through techniques such as straightness compensation, orthogonality correction, and 2D or 3D calibrations.

3. STAGE TECHNOLOGIES

Bearing Technologies

Regardless of bearing quality and grade, some amount of off-axis motion error will remain. The following bearing types are common in stages for photonics applications:

- Recirculating-element bearings, such as linear motion guides with truck-and-rail architecture, are a cost-effective choice for quick point-to-point motion in linear and rotary stages. They offer long travel ranges and high load capacities, but the bearing elements' recirculating nature can introduce noise and vibration that may be problematic in highly sensitive applications (e.g. where velocity stability at extremely low speeds is critical).
- Crossed-roller bearings offer exceptionally high stiffness; unlike ball bearings with point contact, crossed-roller bearings have line contact. And because there

are no recirculating elements, crossed-roller bearings offer incredibly smooth motion with minimal disturbances. However, drawbacks include shorter travel ranges and higher costs.

- Air bearings offer the most precision and smoothness of motion. They operate by maintaining a precise cushion of air between precision-ground surfaces to offer virtually frictionless motion and minimal geometric error. Compared to the mechanical bearings discussed above, air bearings tend to be more compliant (because air is a compressible fluid) – especially in compact air-bearing designs with relatively small bearing surfaces – and tend to have limited load capacities compared to similarly sized mechanical bearings. Additionally, air bearings tend to be more expensive and need a clean, dry air supply.
- Flexure bearings rely on the controlled deflection and spring rate of a material featuring a specific geometry. Although the travel range is limited to a handful of millimeters (or degrees, in the case of rotational flexure bearings) at most, flexure bearings are precise and smooth. Plus, they are easily customized to achieve specific travel, stiffness and form-factor requirements. Load capacity is also a limitation compared to the other bearing types.

Key takeaway: Bearing selection is a trade-off between price and performance. In multi-axis motion systems, consider the bearing type of each stage relative to the axis performance requirements.

Drive Mechanisms

Drive mechanism choice plays an important role in stage selection, positioning performance and reliability. Two fundamental drive types are prevalent in photonics applications: indirect and direct.

- Indirect-drive mechanisms include ballscrews, lead screws, belt drives, worm gears and similar. Indirect means the motor does not act directly on the moving carriage, instead using a coupling to connect to a drive train such as a ball screw, belt drive or worm gear mechanism.
- Direct-drive mechanisms include technologies such as linear motors and torque motors, where the motor couples directly to the moving carriage, thereby eliminating any coupling components that could introduce position errors or act as a point of failure.

Indirect-drive stages typically offer some mechanical advantage and are usually lower in cost than direct-drive stages, prompting selection in many mid-precision applications. Backlash can be a concern, however, contributing to positioning errors. Indirect drives also tend to be slower in operation due to ball screw and gear reduction ratios. Further, the couplings can introduce wind-up and a potential failure point. On the plus side, indirect-drive stages tend to be stable and robust, because their servo gains are relatively insensitive to payload variations.

Direct-drive stages are capable of much higher speeds and accelerations. These inherently non-contact drive mechanisms also exhibit virtually no wear or performance degradation over time. Smoothness of motion is a further advantage. Although direct-drive mechanisms tend to cost more upfront, they lead to a lower total cost of ownership in the long term because high speeds, ultra-smooth motion and long device lifetime contribute to increased throughput and enhanced process capability.

As with bearings, there is the potential to combine direct- and indirect-drive stages in the same motion system.

Key takeaway: Understanding the specific requirements and functions of each axis will point to the optimal drive mechanism.

Serial Vs Parallel Kinematics

There are two prevailing mechanical approaches to six-DOF alignments: serial- or parallel-kinematic architecture. Each has its unique advantages.

- In serial-kinematic architecture, single-axis positioning stages mount on top of one another. The orientation of each stage corresponds to a direction of motion: for instance, providing an input to the Y stage results in motion only in the Y direction and so forth.
- In parallel-kinematic architecture, such as a hexapod or Stewart platform, multiple actuators or struts operate in parallel to position a single moving platform.

Serial-kinematic architectures – like the example in Figure 5 – are deterministic and more intuitive to understand.

Figure 5. *An example of serial-kinematic architecture, which typically delivers superior accuracy and repeatability at the work point.*

They allow for mixing and matching different stage technologies and precision grades. With direct-drive, serial-kinematic architectures, high-dynamic performance with excellent precision is a distinct advantage, especially in high-throughput processes. Additionally, serial-kinematic stage assemblies can be limited to the number of degrees of freedom that the process actually needs. For instance, if a process only requires motion in X, Y, Z and B (rotation about Y), this can be achieved with only four stages. However, serial-kinematic stage assemblies are prone to tolerance and error stackups, and they are often more limited in terms of stiffness and load capacity. Plus, managing the cables for each stage can add complexity to the system design.

Parallel-kinematic architectures like the hexapod in Figure 6 can provide increased stiffness and payload-carrying capacity due to the struts acting in parallel.

Figure 6. *A hexapod's parallel-kinematic architecture typically increases stiffness and can save space.*

Plus, it can be more compact – especially in the vertical direction – which leads to shorter offset distances to the workpoint. Hexapods offer ample load capacity and better access to the payload or workpiece, with minimal obstructions from cables or support brackets. However, most hexapods are screw-driven, meaning that they tend to be slower than direct-drive, serial-kinematic solutions.

Key takeaway: Both architectures are common in photonics applications. The best choice for the application depends on the prioritization of requirements.

4. CONTROLLER TECHNOLOGIES

For the nanometer-level performance required in photonics applications, critical controller selection criteria include:

- Noise

- Bandwidth
- Trajectory rate
- Latency
- Multi-axis capabilities
- Automated search algorithms

True next-generation system performance comes from a combination of precise mechanics, powerful controls, advanced metrology and application expertise. It's extremely difficult to make up for poor mechanics (even with a powerful controller) when trying to squeeze every nanometer of performance out of the motion system. When considering controller selection, look for the following features and functionality to bolster system performance:

- An architecture that supports multiple axis types, including servo stages, stepper motors, hexapods, voice coils and more
- The ability to coordinate at least six axes of motion in real time
- Advanced tuning capabilities that are easy to use
- Automated search algorithms for applications like fiber alignment and wafer probing

Among the first decisions is whether to use a pulse-width modulation (PWM) drive, or a linear amplifier. While PWM drives tend to be more economical in terms of size and cost, they are prone to switching noise, which can disturb processes operating at nanometer precision levels.

From a precision standpoint, linear amplifiers offer advantages that include an extremely low noise floor for outstanding in-position stability (<1nm, compared with 1-10nm for PWM), minimum incremental motion and reduced sensitivity to electromagnetic interference. On the flip side, linear amplifiers are often physically larger, partly because of less efficient power dissipation. Heat sinks and fans for thermal management are subsequently commonplace, with this added complexity usually leading to higher cost per axis. Further, the heat generation from linear amplifiers, and the associated vibrations from cooling fans, result in mechanical and thermal disturbances to the motion system

It is, however, possible to simultaneously reap the benefits of both PWM and linear amplifiers. Advanced PWM technologies, such as Aerotech's PWM+, use state-of-the-art components and craftsmanship to deliver industry-leading linear amplifier performance in a more accessible, efficient and compact PWM package. With a compact, cost-effective PWM+ drive, users achieve sub-nanometer in-position stability, high-dynamic step-and-settle and superior tracking performance like never before. Figure 7 offers a performance comparison of these three types of amplifiers.

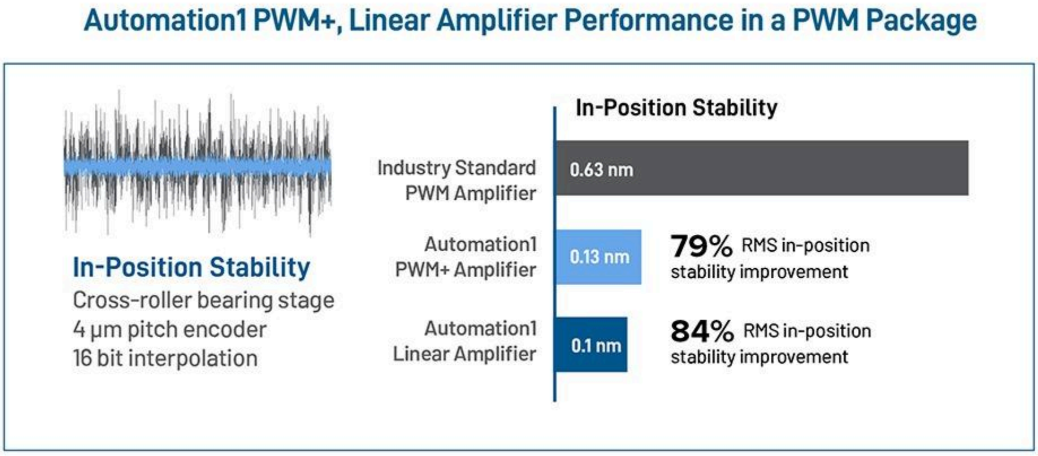

Figure 7. *Aerotech's Automation1 PWM+ technology delivers linear amplifier performance—sub-nanometer in-position stability, high-dynamic step-and-settle and superior tracking performance—in a more accessible, compact, efficient PWM package.*

Key takeaway: The controller and amplifier selection plays a critical role in overall system performance. Achieve the best of both worlds with advanced technologies like PWM+.

Trajectory Rates and Advanced Tuning Features

Trajectory and servo feedback rates are another factor with significant influence on the speed and precision at which a photonics process operates.

The process will almost certainly require some level of quick and precise circular or spiral motion, such as a first-light search or final alignment optimization. Accurate position tracking is paramount, and controller trajectory generation rates play an important role.

Consider defining a circle with a fixed number of points. If the number of points is too small, the controller will end up tracking some type of polygon rather than a circle. Errors and incorrect positioning will result. There are two ways to address the issue:

- Slow down to generate more points on the circle (undesirable in a high-throughput process)
- Use a higher trajectory rate to execute the motion faster with fewer errors

Most drive suppliers use a 1 kHz command interpolated to a 20 kHz trajectory. However, when interpolating different features, such as a corner, the trajectory might not meet exact requirements. In contrast, generating a 20 kHz command for a 20 kHz trajectory will result in the desired outcome, with no interpolation between points. The effects of these scenarios on the trajectory are illustrated in Figure 8.

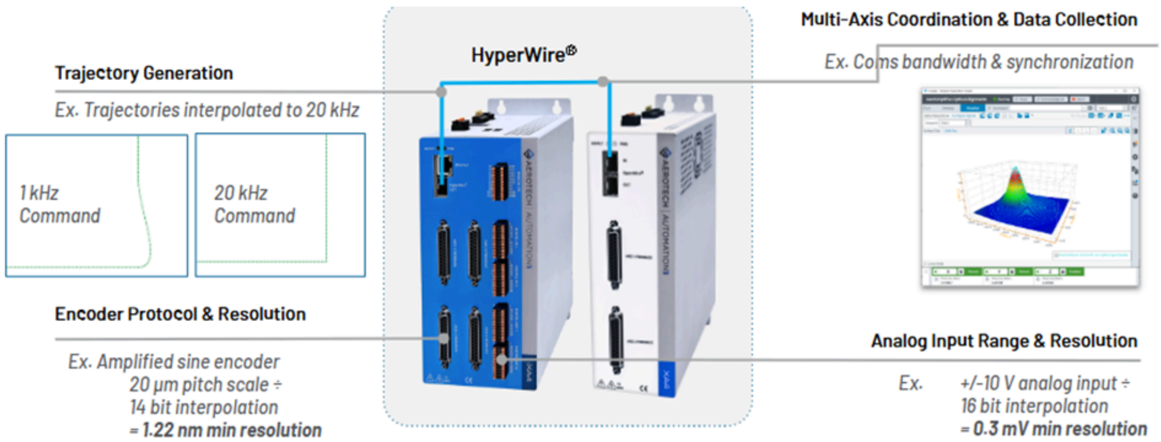

Figure 8. *Trajectory rates, resolution and data collection are as important as bus voltage and current.*

Servo tuning also plays a huge part in system-level performance. Notable differences are evident between standard servo tuning solutions and a controller with embedded intelligence and advanced tuning support. When executing high-speed spiral scans on both systems, the controller with advanced tuning will demonstrate better tracking of the commanded path.

Figure 9 demonstrates the effectiveness of advanced tuning — the plot on the right uses intelligent tuning strategies, while the plot on the left was tuned using traditional PID tuning techniques. The plot on the right with advanced tuning exhibits far fewer occurrences in which the system exceeds the 150 nm dynamic position error threshold.

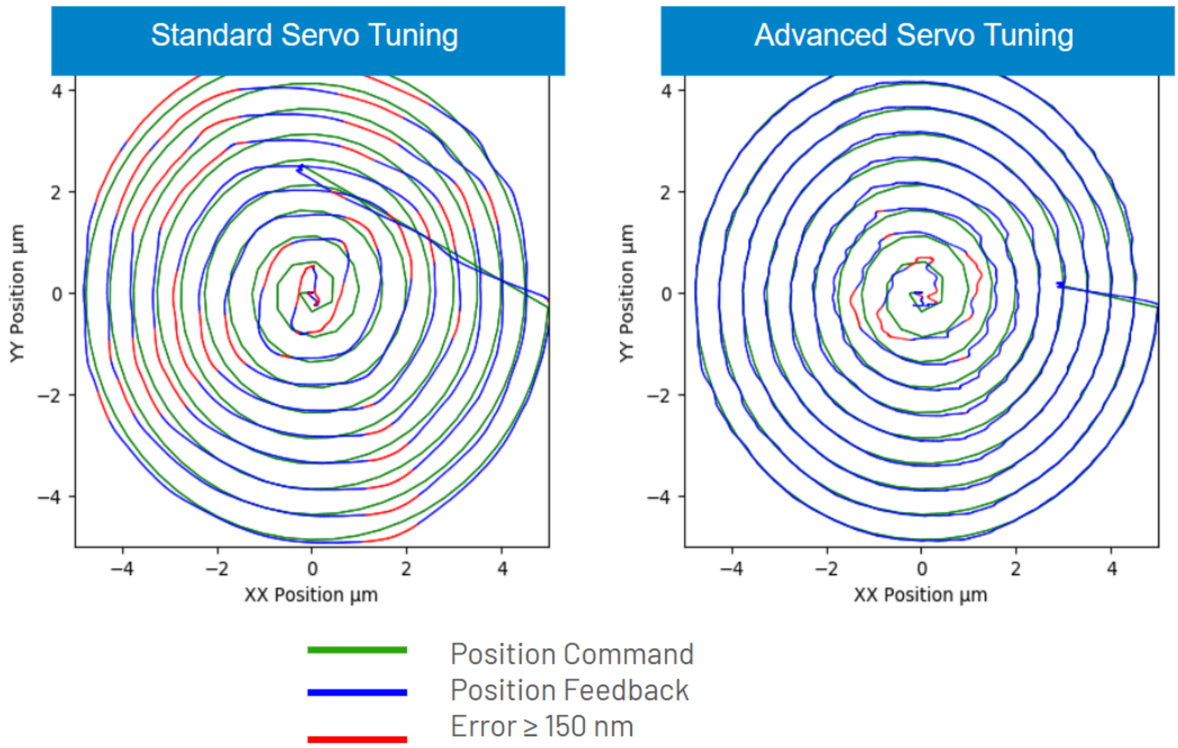

Figure 9. *Error plot of two spiral scans conducted at the same speed. The plot on the right, which involved tuning with advanced techniques, exhibits considerably lower and less frequent errors, compared to traditional servo tuning techniques.*

Key takeaways: It is recommended to have a minimum electrical resolution some 10 times smaller than the desired minimum step size or the desired size of the feature of merit.

While servo tuning cannot fix everything, it can go a long way towards identifying the optimal balance of accuracy, stability, and speed of response.

Advanced Optical Alignment Algorithms

For precision fiber alignments and wafer probing applications, one of the most important and helpful features is the controller's ability to execute defined search and optical alignment algorithms. Not all controllers offer these algorithms, leaving users to write their own, which can compromise time-to-market. Controllers with pre-programmed, parametric alignment algorithms allow users to enable rapid deployment and deliver improved results very quickly. Alignment algorithms can be categorized as follows:

- First-light algorithms, which do not require an initial optical signal to search for optical alignment. An example would be moving two axes in a configurable spiral trajectory until an optical signal is acquired.

- Optimization algorithms, which typically climb the curve of a convex surface to find the peak. They use the existing optical signal to optimize alignments.
- Multi-channel alignments enable the optimization of many optical channels simultaneously.

Algorithms should be fast, but also accurate. For instance, the scan must be thorough enough to prompt certainty in locating the global maximum, rather than a somewhat deceiving local maximum.

Key takeaway: With the rapid evolution of photonic-integrated circuits, it is important to engage with a motion supplier that is able to customize and optimize the algorithms so that users can take control of their specific process.

5. WORKING WITH MOTION CONTROL SYSTEM SUPPLIERS

The optimal motion control system supplier is a partner that understands and appreciates a project's technical and commercial challenges. By exploring a framework of various solutions, some of which may include customization, photonics engineers gain confidence in their decision making process.

Always ask the supplier to describe or demonstrate how similar problems have been solved previously, as it will help to contextualize and quantify technical risks. Most motion suppliers should be able to provide performance plots upon request

Another factor in selecting a motion supplier is the candidate's ability to scale the process from R&D to full production. At the R&D phase of a project, it's often unclear which axes of motion are needed and what the performance criteria should be; as a result, R&D systems tend to be "overdesigned" in order to provide maximum flexibility. However, scaling up to full production demands optimization. Therefore, the R&D solution and the factory production solution may differ from one another. A strong motion control supplier should have the means to provide both types of solutions, with the ability to rapidly achieve volume production.

Finally, an ideal motion control supplier will have a strong global support network. Because R&D processes and volume production processes often take place in different locations, it's crucial that a supplier has a strong global presence – both technically and commercially – to elevate the project's potential for long-term success.

SUMMARY

Precision motion control is only one element of many innovative photonic processes, but it should not be overlooked. Whether manufacturing, inspecting, aligning or bonding, following the five keys to success outlined in this white paper will provide a fundamental understanding of precision motion. They will also help in selecting a motion control partner that can maximize the project's potential for success.

About the Author

Brian Fink, a product manager with Aerotech, has 15+ years of experience in the precision motion control industry. He holds master's degrees in mechanical engineering and business administration from the University of Pittsburgh.