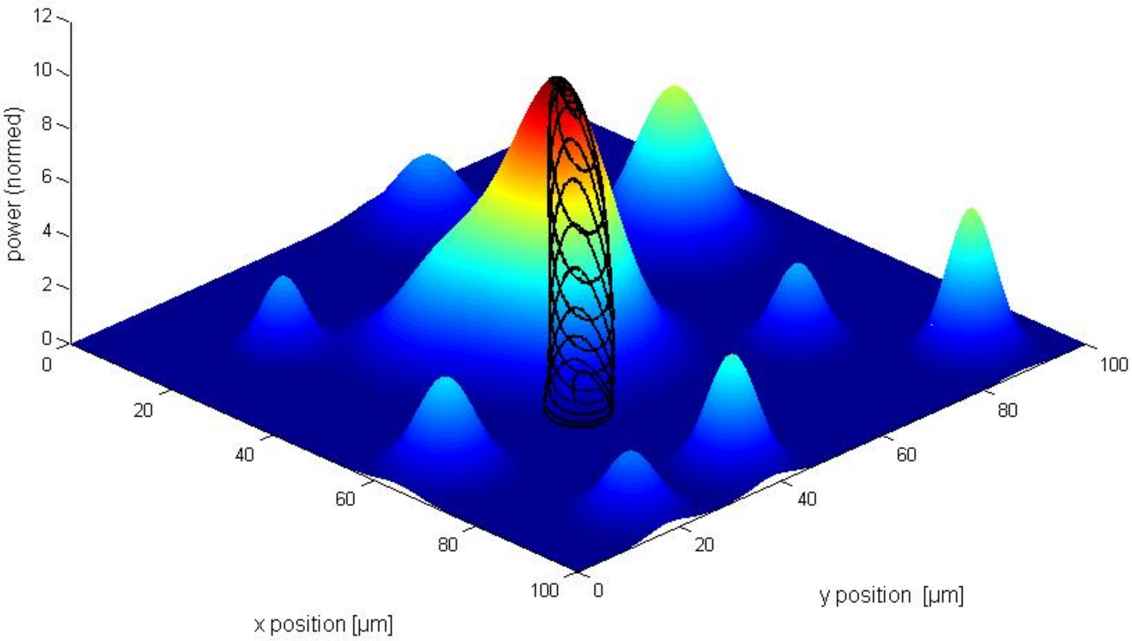
Practical Examples of Parallel Alignment Automation



PI's Fast, Multi-Channel Photonics Alignment (FMPA) technology is a set of firmware-level commands built into its highest-performance digital nanopositioning and hexapod controllers. These commands allow fast coupling optimization between photonic and other optical devices and assemblies, including optimization across multiple degrees-of-freedom, inputs and outputs, elements and channels. Importantly, these optimizations can often be performed in parallel, even if the individual optimizations interact. Examples where significant process savings can be achieved span the spectrum from multichannel Silicon Photonics devices to LIDAR sensors to smartphone camera assemblies.

1 Serial versus parallel alignments

For example, in the short waveguides increasingly utilized in Silicon Photonics (SiP) devices, the input and output couplings can steer each other. As one side is optimized, the other shifts slightly and needs re-optimization. Formerly, this necessitated a time-consuming, serial sequence of back-and-forth adjustments of the input, then the output, repeating until a global consensus alignment was eventually achieved. Similarly, when optimizing an angle, the transverse alignment would be impacted and would conventionally need to be re-optimized, again in a time-consuming serial loop.

But with FMPA, these interacting alignments can often be optimized simultaneously, in parallel. This allows a global consensus alignment to be achieved in one go. Tracking and continuous optimization of all the alignments is also possible in many circumstances, allowing compensation of drift, curing stresses, and so on.

The results are much higher production throughput and often dramatically lower costs. As devices become more complex and precise, and as their production and test requirements grow more demanding, this parallelism is increasingly critical to process economics.

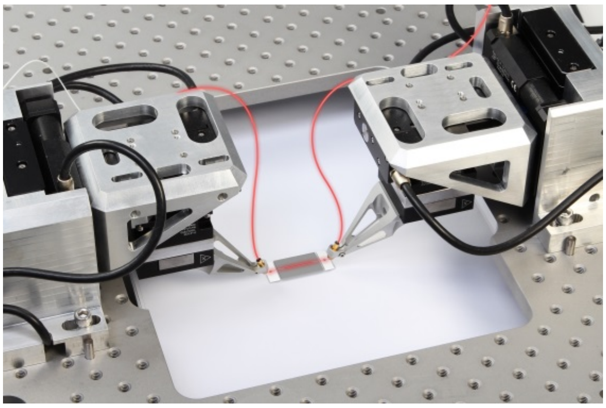


Fig. 1 Aligning the inputs and outputs of waveguide devices at an industrial pace requires parallel optimisation and nanoscale accuracy.

1.1 Look for the loops

Fully exploiting this capability for maximum overall cost savings can require some different thinking than what one might be used-to with classical alignment hardware. In general, one looks for loops of sequential alignments, for which simultaneous optimizations can usually be substituted. This article reviews a few sample applications and discusses implementation issues to illustrate how this remarkable new capability can be utilized to maximize productivity in test and packaging.

2 Background of FMPA operation

The device alignment should be broken down into discrete alignment processes. For example, probing a waveguide with one input and one output using lensed fibers typically involves four alignment processes:

1. transverse optimization routine, input
2. transverse optimization routine, output
3. Z optimization routine, input (beam waist seek)
4. Z optimization routine, output (beam waist seek).

If the device has one or more additional inputs or outputs, add as necessary:

5. theta-Z optimization routine, input
6. theta-Z optimization routine, output.

If the device requires optimization in theta-X and theta-Y, add:

7. gimbaling optimization routine, input
8. gimbaling optimization routine, output.

And so on. Dividing the overall alignment task into these sub-processes is key to identifying which processes can be performed simultaneously.

With FMPA, you take the list of alignment routines and define these directly into the controller. This only needs to be done once (and can be changed or updated any time). Once a routine is defined, it can be executed repeatedly. You can execute more than one routine at a time —this is the parallelism!

Defining a process means instructing the controller which axes are involved in the process, which analog input presents the quantity to be optimized (optical power, MTF…), and various process options. Give each process a name… the numbers in the list we just made are perfect for that.

Routines are executed by calling the Fast Routine Start command, FRS. Referring to the list we just constructed, FRS 1 would commence the transverse optimization on the input. FRS 2 would commence the transverse optimization on the output. And FRS 1 2 would do both at once!

3 Types of alignment routines

For each side of the device, independent alignment engine hardware is of course necessary. Any number of alignment engines can be used; most common configurations utilize one or two, but three or more will be increasingly common as SiP technology matures.

Most often, each alignment engine is constructed of a multi-axis long-travel assembly and a shorter-travel, high-speed, high-resolution piezoelectric multi-axis nanopositioning stage. The modularity of the approach is a key benefit. Some applications don't require the long travel mechanism; some applications don't require the speed, resolution or continuous tracking capability of the nanopositioning stage. In any case, all FMPA algorithms and processes are virtually identical regardless of the type of motion system involved; only the capabilities will differ.

Fig. 2 F-712.MA2 high precision fiber alignment system.

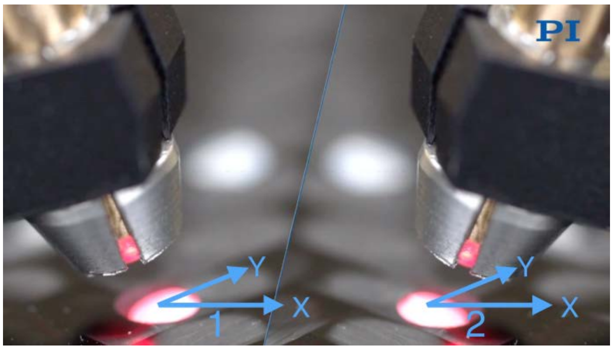


Fig. 3 Dividing a task like waveguide I/O coupling into sub-tasks like "1" and "2" shown will illuminate opportunities for parallel execution. Here, the two processes can proceed in parallel even though they interact, especially in the case of short waveguides where inputs and outputs steer each other. Similarly, processes related geometrically (such as a transverse and Z optimization in situations such as shown, with an angled beam) can be performed in parallel.

Fig. 4 NanoCube®, piezo-based, high dynamic, 3-axis scanner with 100 µm travel range. Besides its nanoscale resolution and blazing speeds, this flexure-based subsystem can perform continuous tracking without wear.

3.1 Long travel options

For situations requiring no angular optimizations or array alignments, a stack of linear stages is sufficient. Otherwise a hexapod is required— not only in situations where full six-degree-of-freedom positioning and optimization is necessary but also in simpler situations, as the hexapod allows the rotational centerpoint of even a single angular optimization to be placed on the optical axis, at the beam waist, etc. This is vital for reducing parasitic geometric errors, another key to improved overall productivity. Sometimes very long travel is necessary in one or two axes for loading operations, and in these cases the hexapod can be mounted on a long-travel motorized stage. (The hexapod controller accommodates two additional DC-servomotor axes. Alternatively, force-sensor elements can be integrated.)

Fig. 5 Single-sided fiber alignment system.

4 The alignment processes

There are two types of processes: areal scans intended to localize a peak within a defined region, and gradient searches intended to efficiently optimize coupling (and optionally track it to mitigate drift processes, disturbances, etc.).

4.1 Gradient searches

Gradient searches perform a small circular dither motion of one device versus the other, which modulates the coupling. The amount of modulation of the figure-of-merit being optimized (for example, optical power or MTF) is a measure of the local gradient of the coupling. The modulation falls to zero at optimum (Fig. 6).

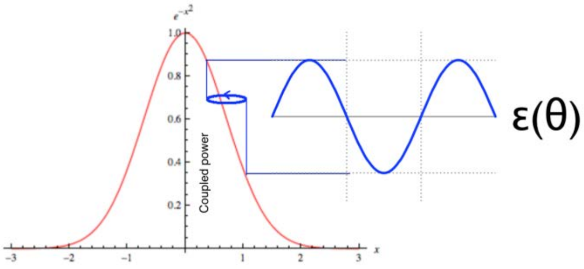


Fig. 6 Graphical depiction of gradient determination via a circular dither, which modulates the coupled power (or other quantity) observed. The phase of the modulation with respect to the dither indicates the direction towards maximum while its amplitude falls to 0 at optimum.

$$|\varepsilon(\theta)|=\nabla I=(I_{min}-I_{max})/I_{min}$$

Equation 1: The observed gradient serves as a measure of alignment error.

From the observed modulation you can mathematically deduce the local gradient via a very simple calculation such as Equation 1. Note that the gradient ∇I falls to zero at optimum.

Any axes in an FMPA system can perform any of these types of alignments (subject to the physical capabilities of the axes, of course). So, areal scans can be performed with motorized-stage axes, which can be very handy for finding first light. Gradient searches are most familiar from transverse optimization but they can also be performed (for example) in a single linear axis, which is ideal for localizing the beam waist in a lensed coupling, or in a gimbaling fashion to optimize an angular orientation. There are many possibilities! These are highly general-purpose algorithms suitable for all kinds of optimizations, including bulk optic, cavity and pinhole alignments.

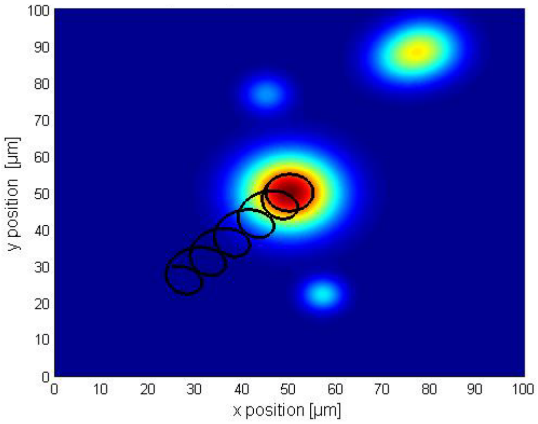


Fig. 7 Optical power distribution

In general, a unique feature of FMPA is that different gradient searches can be performed in parallel. Transverse optimizations tend to be the most sensitive and also the most affected by other alignments. So, transverse routines tend to be relegated to high-speed, high-resolution piezoelectric stages such as PI's P-616 NanoCube. The high speed and continuous tracking capability of the NanoCube allows transverse optimization to be maintained during Z and angular optimizations that would ordinarily require the time-consuming, looping sequential approach.

4.2 Areal scans

Scanning an area to determine the approximate location of the highest coupling peak is useful for a variety of tasks:

- First-light seeking.
- Profiling for dimensional characterization of a coupling. This can be an important process-control step.
- Localizing the main mode of a coupling for subsequent optimization by a gradient search. This hybrid approach helps prevent locking-onto a local maximum and is very powerful.

In addition to reducing the areal scan to a single command, FMPA controllers have automatic curve-fitting capabilities built in, plus a data recorder that can capture the profile on-the-fly for later retrieval, analysis or databasing. FMPA areal scans are very fast, 300msec or so for typical NanoCube applications and loads. The curve-fitting capability can fit a Gaussian to a fairly sparse scan (meaning an especially fast scan), allowing good localization of the optimum coupling point without taking a lot of time to do a really fine scan. Another capability is finding the centroid of a flat-top ("top-hat") coupling, such as seen when probing a deposited photodetector with a single-mode fiber. This allows the scan to terminate with the fiber at the geometric center of a flat or tilted top-hat coupling.

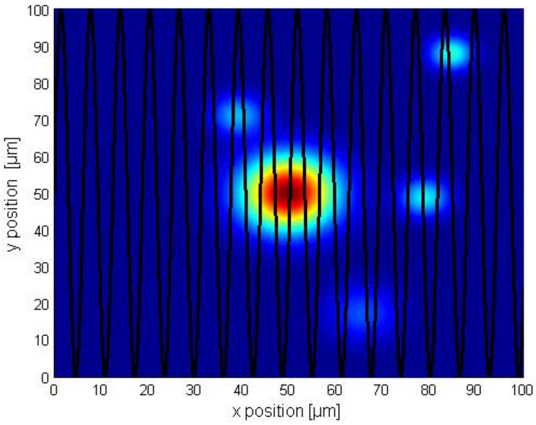


Fig. 8 Optical power distribution

Uniquely, FMPA's areal scan options include single-frequency sinusoid and spiral scans. These are much faster than traditional raster or serpentine scans since they are truly continuous and avoid the settling requirements of the stop-and-start motions used in the traditional scans, and the frequency can be selected to avoid exciting structural resonances. A constant-velocity spiral scan may also be selected, allowing data to be acquired with constant density across the spiral.

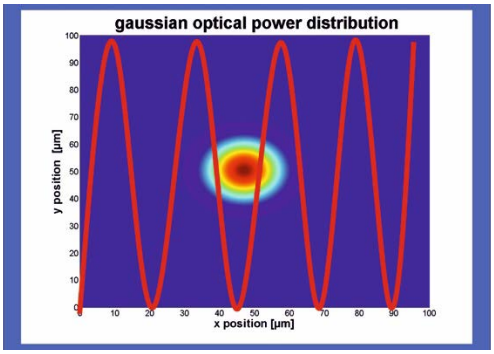


Fig. 9 Sinusoidal area scan

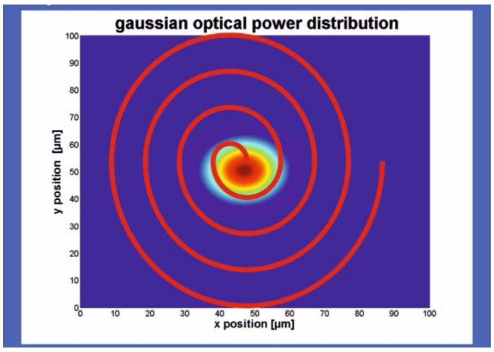


Fig. 10 Spiral area scan

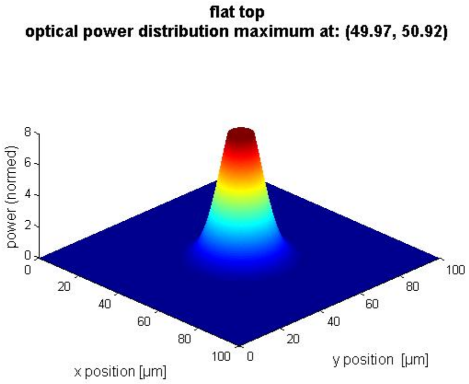


Fig. 11 Uniquely, PI FMPA controllers can perform a fast areal scan and automatically calculate and align robustly to the centroid position of upright and tilted top-hat couplings.

5 Example 1: Wafer probing of angle-insensitive devices

Even in the simplest case of a short waveguide device with just one input and one output, the steering interaction mentioned above can present a frustrating process bottleneck. Add the additional alignments necessary for angle-sensitive couplings and array devices, and the situation would grow complex and time-consuming very quickly. Parallelism mitigates all this and makes short work of the task.

For this example, let us first consider a planar waveguide device with a single input and single output, both accessible for probing via diffractive couplers. Many thousands of such devices are commonly fabricated on large wafers, so throughput is very important. The diffractive couplers typically project the waveguide’s input and output out of the wafer at a typically 10-25° angle from the vertical. Often, lensed probe fibers are used, so there is a fairly distinct optimum separation along the optical axis. Wafer probers of good quality provide wafer placement accuracies much less than the 100µm × 100µm × 100µm field of view of the NanoCube, so first light seeks are generally not needed on a per-device basis in probing applications.

Note that the optical Z axis is at an angle to the mechanical Z axis for normal mounting of the stage stacks:

Z_optical ∦ Z_mechanical

Usually it is not desirable to tilt the motion assembly to accommodate the angled optical beam since the mechanical XY plane should remain parallel to the wafer to avoid collisions. Consequently optimization motions in mechanical Z must be accompanied by compensating motions in X and Y to keep everything aligned.

This is an ideal case for parallelism! From the generic list of alignment routines we compiled above, the first four apply:

1. transverse optimization routine, input
2. transverse optimization routine, output
3. Z optimization routine, input (beam waist seek)
4. Z optimization routine, output (beam waist seek).

Using traditional, non-parallel alignment technology, the conventional approach would be:

1. To accommodate Z_optical ∦ Z_mechanical, loop:
    a. To accommodate steering effects, loop:
        i. Align one side to maximize throughput
        ii. Align the other side to maximize throughput
    b. Move in Z and evaluate if the move direction improved coupling
2. Repeat the above loops until optimized.

Overall time required is often many tens of seconds!

Using FMPA, the process is much simpler and can be two or more orders of magnitude faster. Fundamentally, one defines gradient searches 1-4 from the list (again, this only needs to be done once, though any process can be modified or re-defined freely) and then for each device:

- Issue the Fast Routine Start command: FRS 1 2 3 4

Execution is typically complete in a few hundred msec.

A single E-712 controller supports up to four P-616 NanoCubes, which can even be deployed on different workstations— they don’t all need to be processing the same device.

Fig. 12 E-712 digital piezo controller.

5.1 Tracking and the completion criterion

A signature advantage of the gradient search is that it cannot only optimize but also track its optimum. If you have several gradient searches operating on a device, all can track simultaneously. Alternatively, for your application you may wish to align and then stop and hold position at the optimum.

This criterion—whether to align-and-stop or keep tracking—is an example of a parameter you can adjust in the process definition to fine-tune the process’ behavior to meet your application goals; there are many such options. Since the process depends on the instantaneous gradient of the coupling, it is natural to define its stop point in terms of the gradient. We call this the Minimum Level, or ML. Setting the process' ML parameter to 0 means it should never be satisfied and should track until commanded to stop. This is very useful for accommodating drift processes, such as in elevated-temperature testing. Setting ML to a small but non-zero value causes the gradient search to terminate at the observed optimum position. Note that ML=0 tracking should only be performed with flexure-guided mechanisms due to the potential for mechanical wear in mechanical mechanisms.

6 Example 2: Wafer probing of angle-sensitive or array devices

Building on Example 1, you can accommodate angle-sensitive devices and array devices by using a hexapod rather than an XYZ stack of stages for the long travel motion. For many applications a hexapod will provide sufficient resolution and speed, otherwise (or when continuous tracking is needed) a NanoCube can be attached. Again, the modularity of the FMPA architecture yields considerable flexibility.

Alignment hexapods have many advantages over a stack of conventional linear stages and angular positioners such as goniometers. First, hexapods are full six-degree-of-freedom devices, and their rotational centerpoint is freely settable anywhere in space. This means you can rotate about a fiber tip, a beam waist, a waveguide axis or any other optically desirable point in space.

PI hexapods present a sensible Cartesian coordinate system to the user (X, Y, Z, θ_X, θ_Y, θ_Z) and allow you to easily cast and rotate that coordinate system as desired. Among other things, this means you can mount a hexapod on an angle bracket to minimize overall footprint while still having an XY scan plane parallel to a wafer or other important datum surface.

Again the FMPA areal and gradient search capabilities (for linear *and* angular axes), data recorder and profile fitting functionality is built-into the controllers, yet costs are typically less than a stage stack of equivalent resolution and motion performance.

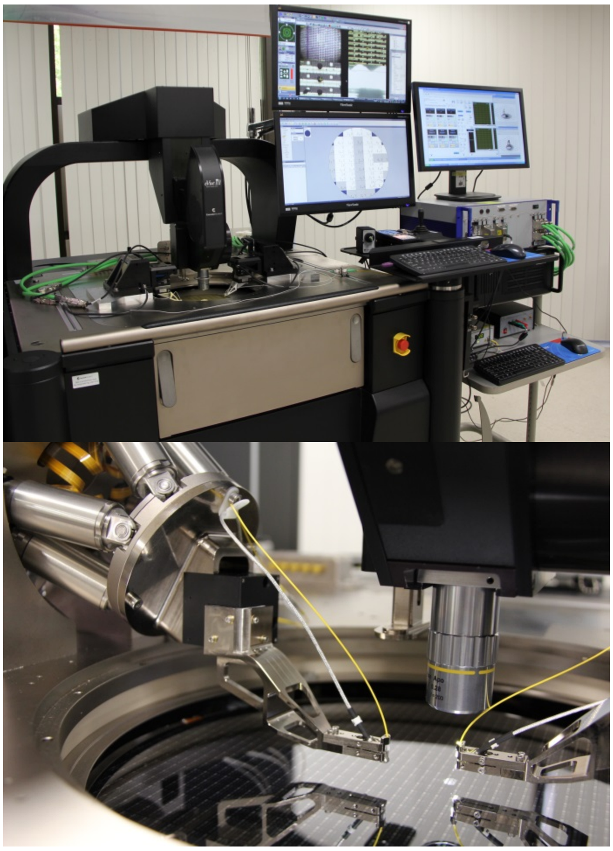


Fig. 13 Cascade Microtech's pioneering CM300 photonics-enabled engineering wafer prober integrates PI's Fast Multichannel Photonics Alignment systems for high throughput, wafer-safe, nano-precision optical probing of on-wafer Silicon Photonics devices. Top: XYZ prober configuration. Bottom: 6-DOF hexapod perober configuration. Courtesy Cascade Microtech div. of Formfactor, Inc.

Consider the case of an on-wafer device with an array input, output or both. On the sides with the arrays or other angle-sensitive elements, the hexapod-based alignment engine is mounted.

Using traditional, non-parallel alignment technology, the conventional approach to optimizing this would utilize an even more complex looping sequence:

- For the first channel:
  - To accommodate $Z_{optical} \nparallel Z_{mechanical}$, loop:
    - To accommodate steering effects, loop:
      - Align one side to maximize throughput
      - Align the other side to maximize throughput
  - Move in Z and evaluate if the move direction improved coupling
  - Repeat the above loops until optimized.

- Increment in θ_Z. It is unavoidable that the transverse alignment will be degraded by this.
- Repeat (A). Evaluate if the increment improved coupling in the Nth channel.
- Repeat (A)-(C) until the both the first and Nth channels are optimized. For most applications this will mean the entire array is optimized.

Overall time required is typically multiple minutes.

Using FMPA, the process is again much simpler and vastly faster. As in Example 1, one defines gradient searches 1-4 from the list, and then defines either a single-axis sinusoidal ("areal") scan or a gradient search in θ_Z. Let's call this process 5. (The gradient search requires some initial coupling, but the areal scan does not, so the choice of one or the other depends on the application, fixturing, device consistency, etc. Also, setting soft limits to prevent a gradient search from walking away if optical power is cut is both prudent and easy.)

Then for each device:

- Set the NanoCube to track continuously (*ML*=0 for processes (1)-(4)) for the first channel. Issue the *Fast Routine Start* command: *FRS 1 2 3 4*
- With the NanoCube tracking the transverse and Z couplings on both sides of the waveguide, issue the *Fast Routine Start* command for the θ_Z process 5.

Execution is typically complete in less than a second.

Addressing gimbaling (θ_X/θ_Y) alignment is similarly simple and fast with FMPA.

7 Summary

This is intended to be an illustrative but not exhaustive description. Similar sequences can be quickly devised for packaging, chip-test and other applications. There are other ways of performing each of the examples we have presented, and application considerations may recommend different approaches or modifications. There are additional options and parameters that should be considered in an actual application. PI Applications Engineers can guide you, and we offer effective on-site training and consultation services to speed your implementation. But meanwhile we hope that this overview provides confidence that the productivity of parallelism is accessible in your application.

8 Author

Scott Jordan is head of the photonics market segment in the globally active PI Group, and a PI Fellow. He lives in Silicon Valley and has been with PI for around 20 years; he was active as director of NanoAutomation technologies and made a decisive contribution to continued technological development of the company.

A physicist with an MBA in Finance/New Ventures, Scott is well known in the community for his passion and engagement.

9 About PI

Well known for the high quality of its products, PI (Physik Instrumente) has been one of the leading players in the global market for precision positioning technology for many years. PI has been developing and manufacturing standard and OEM products with piezo or motor drives for 40 years. All key technologies are developed in-house. This allows the company to control every step of the process, from design to shipment: The precision mechanics and electronics as well as position sensors.

By acquiring the majority shares in ACS Motion Control, a worldwide leading developer and manufacturer of modular motion controllers for multi-axis and high-precision drive systems, PI has made a major step forward in providing complete systems for industrial applications with the highest demand on precision and dynamics. In addition to four locations in Germany, the PI Group is represented internationally by fifteen sales and service subsidiaries.