Teaching Analog New Tricks

Integrating real-time optical metrology with high-throughput piezo motions

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Many scanning, alignment and spectroscopy applications require optical power metrology coordinated with motion, with positioning precisions that often necessitate piezo-class motion devices. Unfortunately, traditional optical power meters show their "bench-top heritage" in their slow performance and pokey communications. Their communications speeds accommodate only a few dozen readings per second, and though many meters offer analog outputs which can in theory be sampled at many kilosamples per second, their analog bandwidths are on generally on the order of a few dozen Hz or less, and auto-ranging must be disabled for the results to make sense.

These limitations have made optical metrology a perennial bottleneck in applications as diverse as scanned-probe microscopy, fiber alignment, device characterization, laser cavity optimization, fluorescence studies and laser spectroscopy.

However, a new optical power meter architecture has recently come to market to address such applications, utilizing fresh design principles that dovetail nicely with such throughput-driven piezo-motion applications. These unique, patent-pending meters are built for PI-USA by Small Planet Photonics.
Alignment video at: www.youtube.com/v/c7uF6OKyEj4
provided with PI LabVIEW libraries which facilitate easy integration into high-throughput NanoAutomation® applications.
The combination of:

- Accurate,
- Low-latency,
- Broad-dynamic-range,
- Linear-response,
- Fully-autoranged,
- High-bandwidth optical power metrology,
- *Synchronous* with high-throughput piezo motion for scanning, tuning or aligning…

…represents an enabling technology for improving the throughput of target applications (Figure 1). Paradoxically, at the heart of this breakthrough is not an exotic communications protocol or an arcane digital-signal-processing methodology. Instead, the new approach leverages the most tried-and-true interfacing methodology of all: analog I/O.

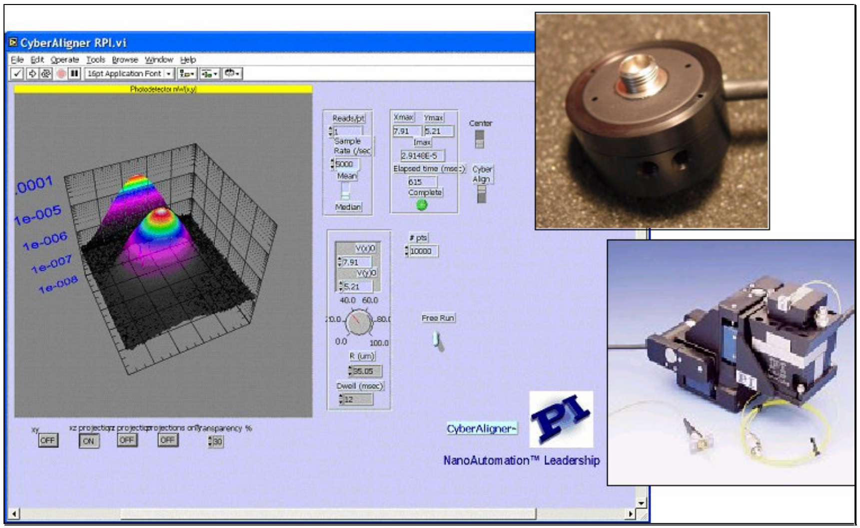


Figure 1. The SPP Series optical power meter (upper right—yes, that's the meter, not just the optical head; shown with optional FC connector) offers industry-leading 10kHz bandwidth and a patent-pending interface technique that supports fully-autoranged, fully-timestamped sampling at rates exceeding 100kHz—for synchronous data acquisition during high-throughput motions.

Background: Analog Interfacing

Analog interfacing is the original, still-popular, and often the fastest way of commanding piezoelectrically-driven motion. Its functionality is even greater today with the popularity of highly functional analog I/O cards for PCs plus powerful programming environments such as National Instruments' LabVIEW®, which allows rapid construction of automated applications that can include arbitrary waveform generation and "virtual oscilloscope" data acquisition.

The speed of even the most affordable analog I/O cards is phenomenal, allowing input and/or output of hundreds of thousands of data-points per second. Using LabVIEW®, an immense volume of data may be acquired directly into the PC's memory or may even be spooled to disk or across a network. And importantly, the data acquisition processes can be synchronized with waveform output processes with sub-µsecond indeterminacies. Most analog I/O cards have onboard clocks which are independent from the PC's, so I/O operations are never interrupted or delayed by system processes such as network events or background calculations.

Most cards also have triggering and clocking capabilities which facilitate synchronization between processes in an application. By comparison, even the fastest instrumentation peripherals using RS-232 or IEEE-488 interfaces can only accommodate a few hundred commands per second, with indeterminacies that can range from a few milliseconds to many hundreds of milliseconds in some cases, such as when a poorly-behaved instrument monopolizes an IEEE-488 bus. Some instruments can sample more quickly internally, spooling data internally to send to the PC later in a block; unfortunately this usually isn't an answer to real-time applications as it greatly complicates synchronization. Similarly, some instruments can accept a macro string of commands for autonomous execution, but synchronization with external processes can be difficult or impossible.

Cards such as National Instruments' popular E-Series offer either 12 or 16 bits of resolution. This means the voltage I/O range of the card (typically 0-to-10V or -5-to-+5V) is divided into 2^{12} or 2^{16} steps. A 12-bit card with a range of 0-to-10V would then differentiate between voltage input or output differences as little as 2.4mV, while a similar 16-bit card can command or resolve voltage differences as little as 0.15mV.

Meanwhile, the "resolution" figure quoted for piezo nanopositioning mechanisms generally represents their drive amplifier's noise floor and can be much less than 1nm. In theory, the ultimate positional resolution of piezo technology is unknown, as it surpasses all available position metrology techniques. Piezo motion devices are consequently used for subatomic controlled motions in atomic-force-microscopy, nanolithography, optical tweezers and other leading-edge applications. For a 25µm-travel piezo stage using analog interfacing to command its controller, the 12-bit card mentioned above would provide a positional resolution of 6.1nm, while a 16 bit card would provide a positional resolution of 0.4nm.

High speed is another key attribute of piezo devices. An off-the-shelf piezo actuator driven by a sufficiently powerful amplifier can achieve 10-kilogee accelerations. Packaged into stages that can incorporate closed-loop position metrology, piezo actuators provide sub-millisecond responsiveness with sub-nm accuracies and repeatabilities. This has made piezo stages critical for throughput-driven applications as diverse as active optics; semiconductor fabrication, inspection and packaging; photonics alignment automation; scanned fluorescence microscopy; sub-pixel image enhancement; autofocusing and tuning applications.

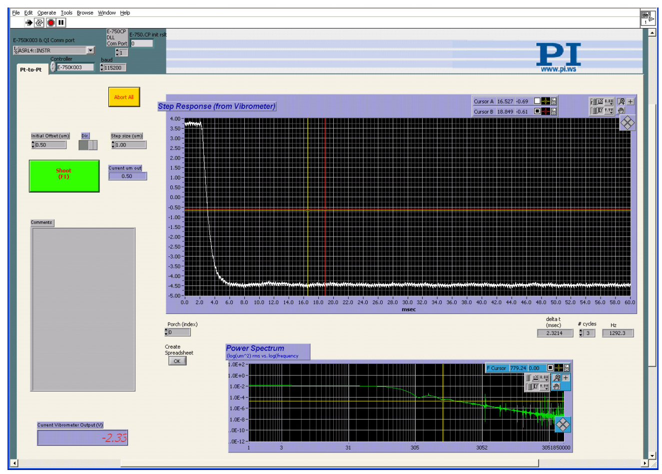


Figure 2. Piezo stages provide extraordinarily fast motions, and shown in this test of a 15um travel closed-loop stage using independent non-contact metrology.

The Throughput Logjam

Many piezo-motion applications involve optical signals which vary with position and which must be measured for power as position changes, either to elucidate power as a dependent variable, or to normalize the application against variations of source power, or both. For these applications, the slow communications and limited bandwidth of available optical metrology instrumentation has served as the familiar logjam to throughput, and the potential of the high speed piezo motion goes unutilized.

The "throughput logjam" has manifested itself in various ways. Conventionally, either:

- Processes must be performed in a pointwise, step-by-step fashion, allowing time for the optical power meter to autorange and settle, and for communications to complete, or

- Alternatively, such processes might need to be performed in continuous but slow scans whose speed is limited by the long latencies, slow sampling, limited bandwidth and poor communications speeds of typical optical power meters.

Obviously, meshing the immense capability of today's DAQ cards together with the high throughput capabilities of piezo motion devices would form an extraordinarily powerful combination… if only the optical power meter could keep up. But even if a conventional optical power meter's analog output is sampled by a DAQ card, the meter's analog front end will lack the bandwidth to make high sampling rates worthwhile. Also, either autoranging must be turned off—effectively limiting the instrumentation to a single decade of dynamic range—or a logarithmic-response mode must be chosen, coarsening resolution by spreading the finite number of DAQ bits over several decades of range.

None of these is acceptable in demanding applications.

Breaking the Logjam

Enter Small Planet Photonics' patent-pending Parallel Analog™ interface. The interface capitalizes on the accurate timing of the analog inputs and outputs of DAQ cards like the National Instruments E-Series. There are two analog outputs: normalized value, and decade range (e.g., 1mW, 0.1mW…). This interface allows many decades of sensor measurement to be accurately digitized by the DAQ card without resorting to resolution-coarsening logarithmic scaling. The crucial point for throughput-intensive applications is that the power reading thus retrieved with a simple calculation from the value and range lines is very tightly timed by the card to other inputs and outputs of the card, and in fact is fully time-stamped in LabVIEW®. This opens a new world of opportunity for fast optical scanning.

Figure 3. The SPP meter shown with adaptor ring and FC connector adaptor. The unit is compatible with popular adaptors from many industry sources. Coin not included!

The super-fast Parallel Analog™ interface of the SPP-Series Power Meter is complemented by a blank-sheet-of-paper design approach. For example, a novel amplifier design provides 10 kHz analog bandwidth and 70 µsec autoranging time between six decades of range. One of the patent-pending features of the Parallel Analog interface is that it automatically indicates when the very brief, 70µsec autoranging switching interval is underway, eliminating invalid data points in the acquired data. There is a wide range of configuration possibilities accessible by the included LabVIEW® drivers through an RS-232 utility connection, including wavelength selection and 256 analog bandwidth settings from 10 kHz down to 120 Hz. All of this together with NIST traceable accuracy (there is a cost-effective, nominally-calibrated autoranging SmartDetector™ version as well) is provided in a total package size for the whole meter which is less than that of most conventional power meter heads alone.

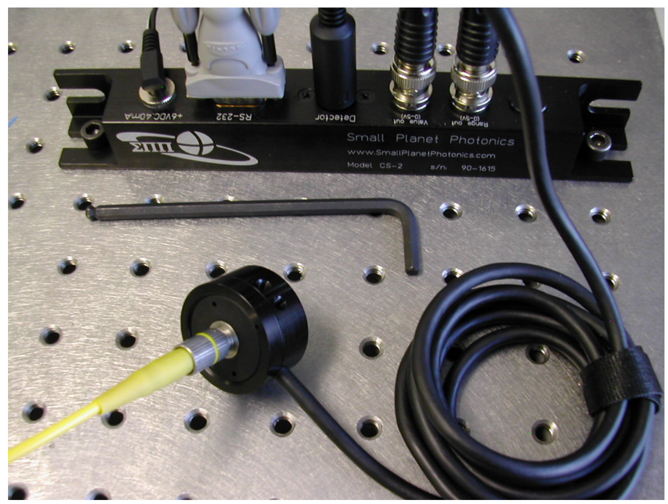


Figure 4. The SPP meter, shown with convenient panel-mount connector strip. The meter connects to the PC via RS-232 for setup, and via its patent-pending Parallel Analog™ interface for high-speed synchronous sampling of autoranged optical power at speeds exceeding 100ksamples/sec.

The Software Toolbox

Combining all the above with its NanoAutomation® positioning technologies, PI has developed modular LabVIEW® subroutines (subVIs) which integrate motion-waveform generation with synchronous, fully-autoranged optical power data acquisition providing NIST-traceable accuracy. By combining fast non-stop piezo motion with the speed of the new meter, these software modules constitute enabling technology for a variety of applications in semiconductor manufacturing, data storage research and production, photonics packaging automation and device characterization, scanned microscopy, and life-sciences applications.

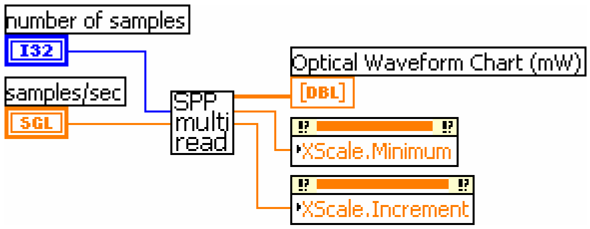


Figure 5. The LabVIEW® driver set supports scalar (single-reading) and array (timed) data formats. Optical power readings are in human-readable units with all values fully time-stamped. Multichannel and motion-synchronized non-stop scans are supported by the extensive library.

For quick time-to-market for OEMs and quick productivity for research users, the LabVIEW® library makes the motion/metrology integration task quick and easy. Sampling rates in excess of 100ksamples/sec are supported, with each data-point tightly correlated to piezo stage position and fully time-stamped. Time-stamping means each data point's occurrence in time is known, allowing ready correlation with other concurrent data. The library includes documented, preconfigured subroutines (subVIs) which integrate real-time, continuous motion pattern generation, synchronous with metrology of one or more channels of optical signal plus precise position feedback from the motion device.

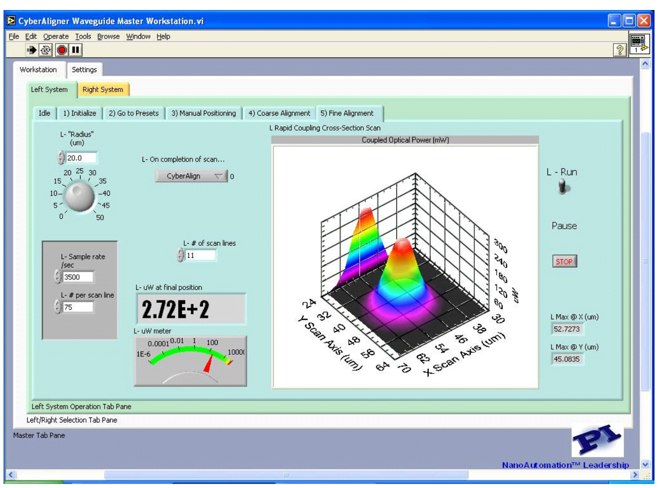


Figure 6. The SPP Series software tools synchronously integrate high-speed nanopositioning and optical power metrology, allowing quick construction of sophisticated software such as this custom multichannel waveguide input-output XYZ-XYZ alignment workstation.

With these tools, plus the high data rate of the SPP meter and the power of LabVIEW®, the user can easily implement advanced sampling strategies such as pretrigger analyses, synchronous or pseudosynchronous sampling, stream-to-disk sampling and even web-enabled or distributed deterministic metrology together with synchronous motion—using standard PCs or NI's PXI chassis workstations and FieldPoint™ distributed intelligent metrology devices.

Integration with digital piezo controls

So far we have discussed the integration of optical metrology with high-performance, cost-effective analog piezo motion controls. For some applications, however, the benefits of digital nanopositioning controls are compelling. Depending on model, these may include:

- Automatic plug-and-play calibration of motion devices, facilitating swapping and reconfigurations in the field
- 4th Order (or higher) compensation of linearity errors, resulting in higher accuracy
- Improved stability and accuracy resulting from the motion-commanding DAC being within the feedback/servo loop rather than external to it
- Waveform generation capability
- Importantly, high-speed digital communications interfaces including galvanically-isolated fiber interfaces; specialized parallel interfaces, and trigger and strobe lines.

In these cases the communications speed can match that of the fastest analog I/O. PI's E-711 Series controllers, for example, offer a patent-pending parallel I/O interface offering command rates to 2µsec for feedforward and status commands, plus real-time synchronization utility lines. Intended for advanced process-control and metrology applications requiring real-time tracking and position-compensation (such as certain active-optic, photonic and disk-drive production uses), these controllers are a natural counterpart to the fast Parallel Analog™ I/O methodology of the SPP meter for the most throughput-intensive usage.

Conclusion

For the first time, NIST-traceable, fully-autoranged optical metrology with linear responsiveness is available to improve the throughput of motion-intensive applications. By leveraging popular interface hardware and software, the throughput logjam presented by conventional optical power meters is eliminated. Systems can easily be constructed which collect optical data synchronously, without the time-wasting pointwise approach formerly necessitated by conventional architectures. The result is a multifold improvement of system throughput, together with cost and size reduction.

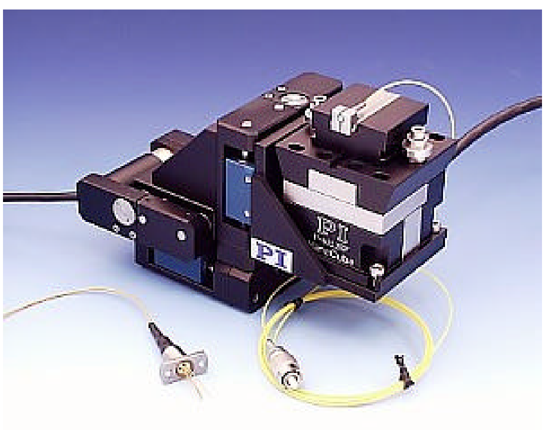
Industrial Alignment Innovation:
CyberAligner™ Modular OEM Alignment Workstation
Ideal for cost-effective photonics production and test

Automated alignment applications are among the most challenging in motion control. For example, single-mode fiber pigtailing requires 10-50nm accuracies plus real-time compensation of drift forces. Increasingly high throughput is demanded due to cost-of-ownership and yield pressures.

Currently-available systems fall into a few categories:

- Laboratory-duty instruments with alignment automation capability. Automation is via analog phase demodulation or hill-climbing decision-path methodologies. These mechanisms are usually open-loop.
- Purpose-built industrial process tools configured to perform specific pigtailing, bonding or other narrowly-defined procedures. These tend to be costly and require custom application.
- Integrated multi-axis microrobotic systems specifically designed for photonic packaging automation.
- Stacks of long-travel stages providing many mm of travel with high resolution. These tend to be bulky and costly since the high resolution is provided by long-travel encoders of exceptional capability.

Now, PI introduces F-130 and F-131, a modular, compact family of coarse/fine OEM solutions for industrial-class, high-throughput nanoscale XYZ alignment and positioning (see Figure 1 and Figure 4). This revolutionary concept integrates proven, space-efficient and cost-effective positioners into a versatile and reliable subassembly suitable for a wide variety of industrial production and test applications. It provides sub-µm resolution over an operating volume up to 15x15x15mm plus nanometer-scale resolution/millisecond responsiveness over a 100µm cube. This new solution offers groundbreaking compactness, speed and cost-effectiveness.



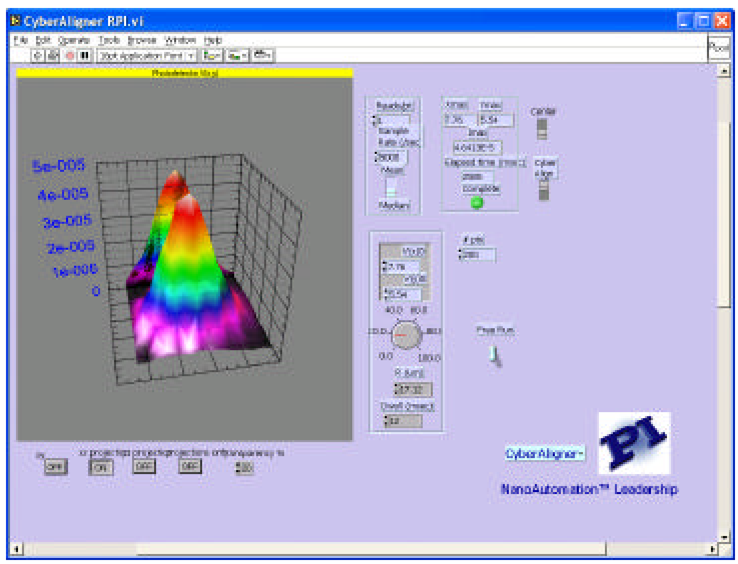


Figure 1. F-130/131 (left) includes a fast, robust XYZ or XY NanoCube™ nanopositioner integrated onto an XYZ stack of high-resolution motorized stages for up to 15mm travel. The combination provides long travel with piezo-class resolution and speed, providing exceptional cost-effectiveness, flexibility and modularity. The CyberAligner™ software (right) is a LabVIEW-based coarse/fine alignment workstation, fully integrable into advanced packaging and characterization applications.

Bridging the Gap: The OEM solution

The F-130/131 open-architecture approach, featured on PI Catalog page 8-18, is based on high-volume, general-purpose nanopositioners from PI's broad line of positioning products:

- A NanoCube XYZ piezo nanopositioning stage is used for fine alignments and tracking.
- In the closed-loop version, strain gauge sensors are integrated for high-bandwidth loop closure, addressing hysteresis and drift.
- An XYZ stack of PI’s popular M-110 stages provides long travel positioning. 5mm and 15mm versions are offered. Generally, the open-loop stepper-motor versions of these stages offer the most cost-effective solution for most alignment applications; closed-loop servo-motor versions are also offered. All are provided with integral Hall-effect limit/home switches for repeatable system initialization.
- The result is a high-speed, high-resolution, long-travel assembly with nanometer-scale resolution over a long travel range, but much more compact and much less costly than a stack of stages of commensurate resolution over their entire travel. The combination is compatible with all analog and digital alignment methodologies.

Conceived for Challenging NanoAutomation® Applications

Recognizing that today's production and test applications require not just nanometers, but nanometers in milliseconds™, the F-130/131 architecture is built for round-the-clock throughput:

- The nanopositioning stage uses *no bearings*. Bearings are susceptible to cage creep and nonreproducible stiction in the sort of rapid, repetitive actuations typical of packaging and alignment applications.
- The stages require *no scheduled maintenance*.
- The *flat-topped actuation platform* is compatible with a variety of fixturing and clamping devices from PI and partner companies, including SD Instruments’ manual and automated tweezers.

Versatile CyberAligner™ Software Automates Alignment, Profiling

While F-130/131 is compatible with any alignment methodology you might wish to use, a valuable tool in Polytec PI's arsenal of OEM NanoAutomation solutions is the CyberAligner™ Modular Alignment Engine, a comprehensive software package with high-throughput alignment automation and exquisite 2D profiling capabilities. CyberAligner is an object-oriented set of software modules which perform rapid nanoscale positioning, synchronized with metrology. CyberAligner is based on LabVIEW 6i for open support of a wide variety of metrology instruments and a wealth of analytical and connectivity options. CyberAligner is compatible with many PI NanoAutomation mechanisms in addition to the NanoCube.

The CyberAligner software offers several modes, all readily accessible from a mouse-driven pushbutton PC interface (see Figure 2):

- Manual positioning, automatic move-to-position and initialization routines are available at the click of the mouse.
- A novel double-spiral scan of the motorized stages finds first light. Unlike most spiral-scan implementation, this performs a second spiral at the first hint of coupling. This greatly speeds up completion of the first-light scan, as one or more entire loops around the initial spiral are eliminated. This also minimizes overall transverse motion— important in blind-hole packaging applications.
- A highly speed-optimized raster scan is available for fine acquisition, characterization and centering of the devices; this is described in more detail below.

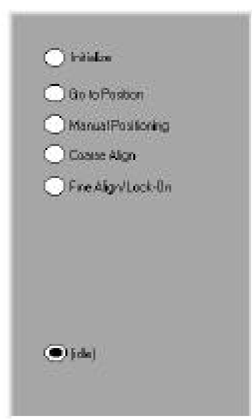


Figure 2. The CyberAligner workstation software is as modular as the hardware. Constructed in LabVIEW 6i, it

includes a variety of alignment and positioning functions which are accessible by a mouse-click.

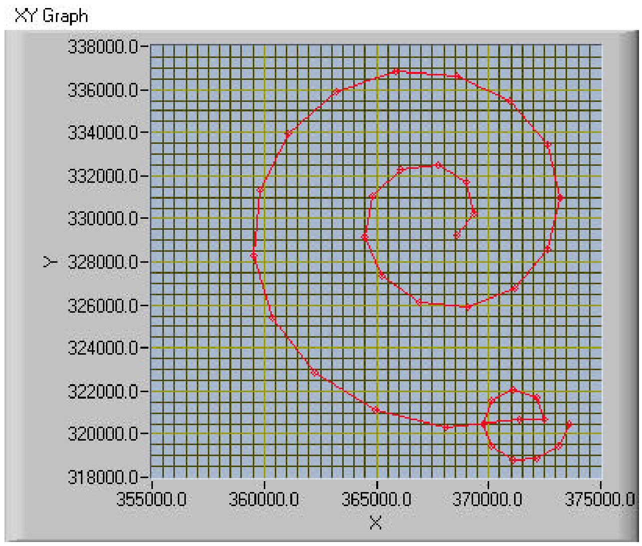


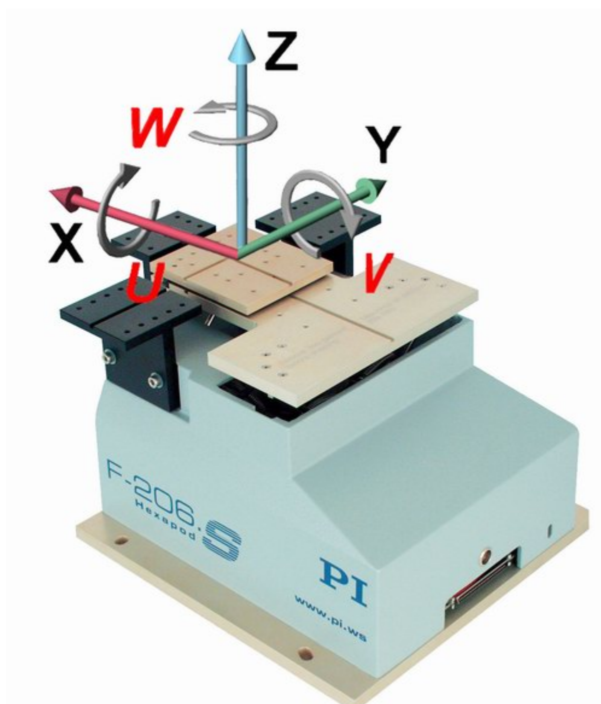
Figure 3. CyberAligner's unique double-spiral first-light scan minimizes both execution time and overall transverse motion. A conventional spiral scan is performed until the first hint of coupling is detected, then a second spiral is automatically performed about that point. This greatly improves alignment speed by eliminating one or more entire loops of the first spiral. The figure shows the path of the coarse-positioning stage from initiation of the first-light search through initial acquisition and final achievement of the user's desired threshold. From here, nanoscale fine-alignment can proceed.

Novel High-Speed Raster Fine-Alignment

Most automated alignment methodologies utilize hill-climbing or gradient-search techniques to fine-tune the optimum orientation of the devices under test. This is necessitated by the comparatively slow speed of typical motion hardware. However, most alignment algorithms can lock-on to local maxima. CyberAligner leverages F-130/131's high-bandwidth nano-actuation to map the entire scan field— practically eliminating the likelihood of lock-on to local maxima. The map itself provides valuable characterization of the coupling cross-section which can provide exquisite spatial and power resolution (Figure 4).

Figure 1shows a CyberAligner profile of butt-coupled single-mode fibers. The Z axis (for the metrology chosen in this particular setup) is in mW. A user-selectable projection of the X-Z plane is shown. CyberAligner's 3D graphics are freely rotatable by the user by clicking and dragging the plot with the mouse; this is highly useful for inspection of features. Statistics for this application example:

Devices:	Butt-coupled 4µm core SM fibers
Data points:	900
Range:	8x8µm
Motion Dwell	1msec (software-settable)
Total Execution Time:	2.6 seconds inc. graphics
PC:	Pentium II, 266MHz, Windows 98, 64Mb, National Instruments analog I/O card



F-206 6-Axis Automatic Fiber Optic Alignment System

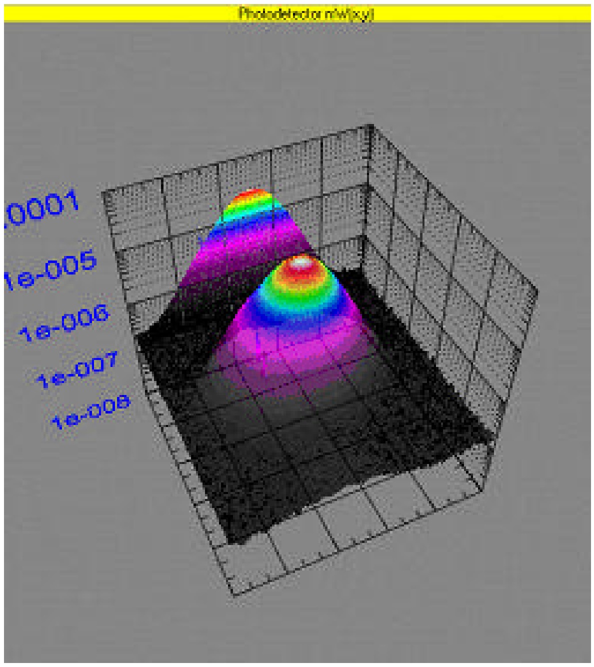


Figure 4. Actual CyberAligner scan data: 30x30mm coupling-cross-section profile of butt-coupled SM fibers @630nm ?. In this implementation, optical power is provided by a Small Planet Photonics optical power meter, providing NIST-traceable accuracy.

If High Throughput Motions Cause Structural Ringing— Mach Stops It!

The Nanocube is an extraordinarily fast positioner, as the sub-3-second execution of the profile shown in Figure 1attests. In applications where even faster actuation of is desired, the rapid motions can sometimes cause recoil-generated ringing of their load, fixturing and adjacent components. Such ringing can take hundreds of milliseconds to damp out.

Conventional wisdom suggests that there is nothing that can be done about these resonant reactions, since they occur outside any servo loop and cannot be observed by the controls. However, PI's optional Mach™ Throughput Coprocessor™ implements the patented Input Shaping™ feedforward algorithm to nullify resonances *before* they start, rather than waiting for them to damp out (turn into heat). The result: the fastest possible motion, with virtually instant settling, as shown in actual vibrometer testing in Figure 5.

Mach is easy to set up for a particular OEM application and robust to dynamical changes in the setup. It requires no change to the system software, application, physical setup or servo parameters. It is available both as an external upgrade to existing PI controllers and as an internal option for our latest generation units. It eliminates unwanted motion-driven resonances and ringing in step-mode and continuous-motion (scanning) applications. In particular, Mach eliminates any resonant reaction of devices mounted on the F-130/131, its platform, and sensitive adjacent optomechanical componentry to improve throughput and resolution in especially high-throughput applications.

For more information, including applications examples, contact Polytec PI for a specific Tech Note on the Mach Throughput Coprocessor.

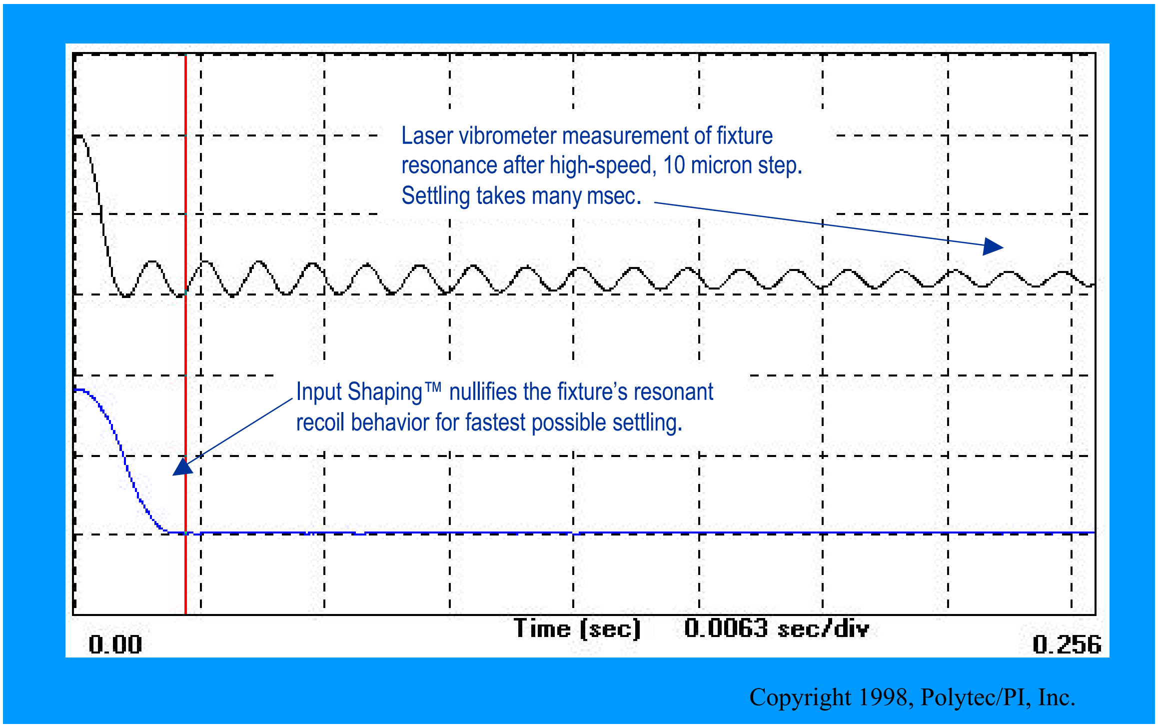


Figure 5. Mach™ Throughput Coprocessor eliminates the recoil-driven resonant reaction of loads and neighboring componentry in applications where the fastest possible nanopositioning is desired. Top: Vibrometer reveals the resonant behavior of a fixture when the stage is stepped. Bottom: Same fixture, same step, with Mach. The structural ringing is eliminated.

Configurations

F-130/131 may be implemented in a variety of configurations to match the broad spectrum of OEM scanning and photonics-packaging application needs and budgets. Open- and closed-loop motorized and nanopositioning stages are offered, with various different travel ranges for the coarse stages, and ball-screw versions for especially intensive 24/7 automation applications.

There is a spectrum of controls options as well. A particularly cost-effective approach includes:

- Open loop F-130/131 stepper motor coarse positioning stages, 5 or 15mm travel, with NanoCube
- Analog PZT controls such as PI's E-5xx series; Mach™ Throughput Coprocessor™ optional
- National Instruments 7344 motion controller card (PCI bus)
- National Instruments 7604 driver/interface (stepper) or PI C-809.40 driver/interface (servo)
- A Small Planet Photonics power meter (recommended for its >10kHz analog bandwidth and NIST-traceable accuracy)

This is a single-card PC solution which leverages the analog utility outputs of the 7344 controller when used with stepper-motor stages. An equivalent PXI-bus configuration is also available with an embedded PC running Windows or a real-time operating system.

Other variations—including systems with longer-travel coarse-positioning stages from PI's catalog, or alternate nanopositioning mechanisms—may be readily configured as well. Consult with your Polytec PI applications engineer.

Conclusion

This Tech Note describes several new products for high-throughput, automated micro-alignment and profiling applications:

- F-130/131 is a unique coarse/fine motion subassembly providing 100µm XYZ nanopositioning range and 5 or 15mm of submicron-precision stepper- or servo-motor coarse positioning. Compact, modular and robust, it is intended for industrial applications in the realm of photonics packaging automation.
- CyberAligner is a versatile software tool for automating profiling and alignment, offering novel, high-throughput first-light and fine-alignment automation capabilities.
- The optional Mach Throughput Coprocessor can improve overall throughput by eliminating settling time: rapid actuation of the nanopositioner can cause ringing of components throughout the assembly in some applications. Mach eliminates this.

Together, these three technologies facilitate a broad array of challenging applications requiring a combination of nanometer-scale precisions, automated alignment and high throughput plus compact size, low cost, and modular flexibility.