Dynamic alignment, tolerances and metrology fundamentals at the nano and micro scales

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ABSTRACT

Although the terms "micropositioning" and "nanopositioning" refer to different classes of positioning systems, "nanopositioning" is often used mistakenly to describe micropositioning systems. Micropositioning systems are typically motor-driven stages with travel ranges of a few millimeters up to a few hundred millimeters. Because the guiding systems in such stages — usually bearings of some kind — generate frictional forces, their resolution and repeatability are typically limited to 0.1 µm. The guiding system working principle also adds errors that are typically in the micrometer range. Nanopositioning systems are typically based on frictionless drives and guiding systems such as piezo actuators and flexures. These systems can achieve resolutions and guiding accuracies down to the sub-nanometer level.

Both of these classes of precision positioning and motion systems are used extensively in precision optical and photonic systems to achieve desired performance specifications of instruments and experimental research projects. Currently, many precision positioning and motion systems have been design and implemented to cross over from the micro to the nano ranges with excellent results. This paper will describe some of the fundamental performance parameters and tolerances typical of these systems, some of the metrology used to confirm specifications and a few high end applications of general interest.

Keywords: Micropositioning, Nanopositioning, Piezoelectric Drives, Electromagnetic Drives, Parallel Kinematics, Sensor Technologies, Electronic Controllers, Guiding Systems, Force Transmission, Dynamic Alignment, Tolerances, Vacuum Environments

1. INTRODUCTION

While both nano and micro positioning systems have been around for many years, even decades, the widespread adoption of systems spanning both ranges simultaneously are only now being implemented successfully in many applications worldwide. Before getting into the details of the new technologies that are enabling systems to span both the nano and micro ranges, this paper will review the standard state of the art micro and nanopositioning systems, their fundamental performance capabilities and specifications and metrology details. To begin, we will start by identifying the micro and nano scales as they relate to precision positioning and motion control for optical systems; including typical positioning and tolerance ranges. Then we will cover some fundamental concepts orienting us in 3D space with concepts like accuracy and backlash. Following that we will review a couple fundamental applications, one in each range, like moving a single lens and then some control with feedback concepts, including calibration basics and performance test results.

Moving to some more advanced systems, we will review multi-axis systems such as stacking multiple stages and hexapods to gain multiple degrees of freedom for critical optical alignment projects. These will include hexapods and metrology processes for verifying their performance. Finally, we will explore an advanced Silicon Photonics alignment application where multiple optical fibers in an array are simultaneously positioned at both the entry and exit of an array waveguide to optimize the optical throughput of the system. By combining nano with micro positioning systems with advance digital electronic controls, we demonstrate a current popular application example in Silicon Photonics Fab-Focused implementation. This could be used in a test and measurement situation or a final production process. Since there are so many technologies available to accomplish these and many more practical requirements, we will briefly review a Motion Technology Roadmap that mentions some more technologies and give a few examples.

Optical System Alignment, Tolerancing, and Verification IX, edited by José Sasián, Richard N. Youngworth
Proc. of SPIE Vol. 9582, 95820B · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2191844

2. MICRO & NANO POSITIONING

Beginning at the macro scale which humans are very familiar, we start with the simple concept that 1 meter equals 1000 mm and go smaller. The poster in Figure 1, Macro Micro Nano, The Scale of Things, offers a quick reference to orient us with some natural and some man-made objects, many that are commonly used in optics and photonics related research. We can easily take steps that are 3 orders of magnitude each to quickly get to the single nanometer range; where 1 nm equals 1000 picometers. So for Micro and Nano Positioning, we ask, what is the difference?

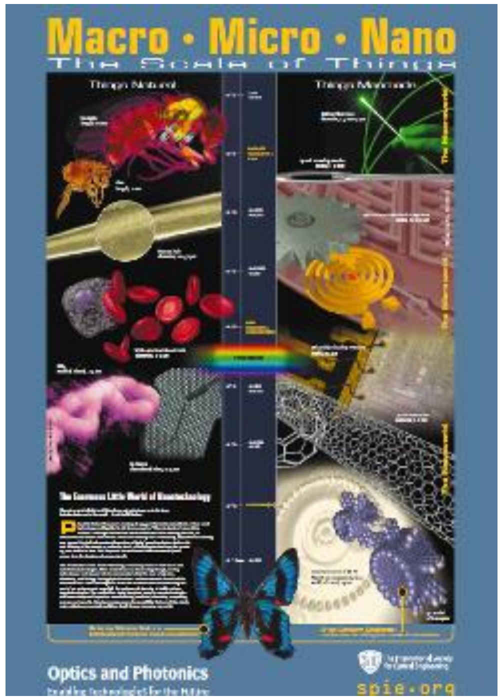

Figure 1. Macro Micro Nano – The Scale of Things – SPIE Poster.

A typical micropositioning system, a precision long travel vacuum compatible linear stage in this example, has 350 mm of travel and can have resolution of 10s of nanometers. A system like this, as shown in Figure 2, is usually classified as a micropositioning system, although some may describe it as a nanopositioning system.

Figure 2. Precision long travel vacuum compatible linear stage.

Looking at the graph in Figure 3, it shows the measurement results taken as this stage is commanded to move in 10 nm steps every second. While this is very impressive for a micropositioning stage, it may still be referred to as micropositioning.

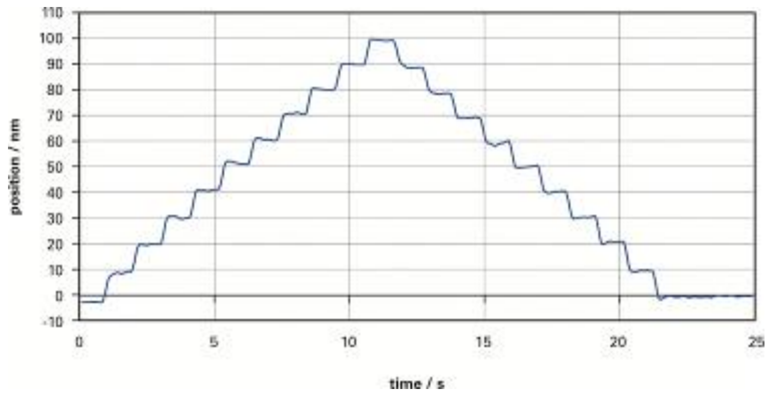

Figure 3. Graphical results of a micropositioning stage moving 10 nm every second.

3. TOLERANCES & FUNDAMENTALS

Discussing positioning tolerances and fundamentals like orientation and accuracy requires just a bit of common sense. A ‘rule of thumb’ could be that when positioning range is 1 mm to 1 meter, the micropositioning tolerance range will be 1 to 1000 micrometers. For the nanopositioning range of 1 to 1000 micrometers, the tolerance range maybe from 1 to 100 nanometers and to go even smaller, for positioning in the 1 to 1000 nanometer range, the tolerances might be 20 to 500 picometers. These may all be a bit subjective with the naming ranges, but numerically, these are good starting points. When dealing with specific real systems, as we shall review in later sections of this paper, the details will dictate the actual positioning and tolerance ranges for each system and application.

Regarding fundamental nomenclature for axes and angles there are standards that should be at least mentioned once. So the diagram and labels in Figure 4 document the typical designations and names for these parameters.

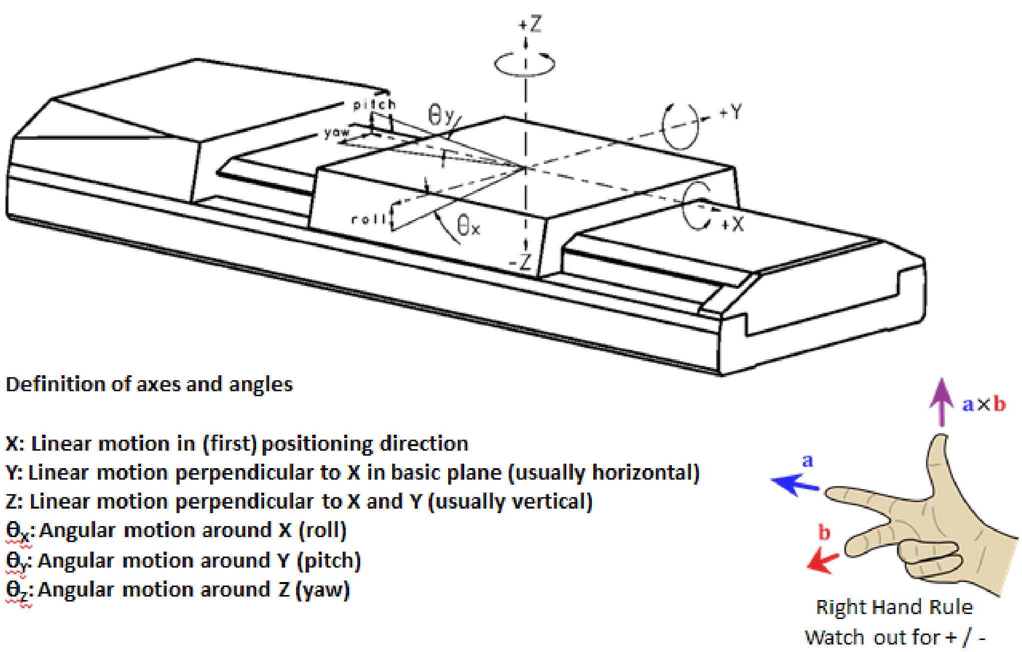

Figure 4. Fundamental definitions of axes and angles of a motorized linear stage and the Right-Hand Rule which is shown for an easy comparison.

For any given input, absolute accuracy is the maximum difference between the commanded (ideal) position and the actual position. For real systems, resolution is usually a great deal higher than absolute accuracy, which is limited by backlash, hysteresis, drift, drive or sensor nonlinearity and cosine error. The best absolute accuracy is achieved with direct metrology sensor systems. In such systems, the position of the platform itself is measured, with, for example, an interferometer or linear glass scale. Indirect metrology systems (e.g. rotary encoders), or open-loop stepper-motor-driven stages, have significantly lower absolute accuracies. Independent of this fact, they can still offer high resolutions and repeatability.

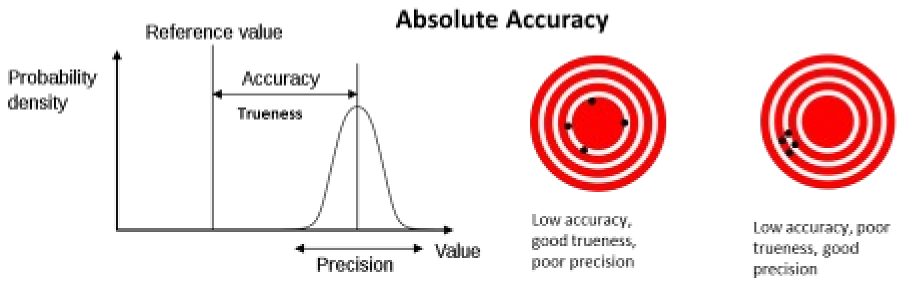

Figure 5. Absolute accuracy diagrams showing the relationship to precision and a reference value. Wikipedia.

Backlash is position error that appears upon reversing direction. Backlash is caused by play in the drive train components such as gearheads or bearings, or by friction in the guiding system. Unlike hysteresis, it can lead to instability in closed-loop setups because it causes a dead band in the servo-loop. Some manufacturers promote controllers with automatic backlash compensation that add the estimated amount of lost motion upon each reversal. This solution is very limited in practice, as backlash is not constant but varies with temperature, deceleration, acceleration, load, leadscrew position, direction, wear, etc.

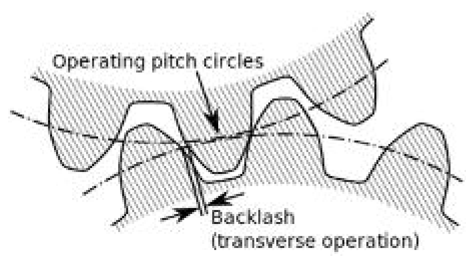

Figure 6. Backlash diagram showing how gears have some space between the teeth. Wikipedia.

Bidirectional repeatability is the accuracy of returning to a position from any position, regardless of direction. Effects such as hysteresis and backlash affect bidirectional repeatability.

Bidirectional repeatability is a measure of the ability of a system to achieve a commanded position over many attempts when approached from either direction. Each position must be approached from a distance greater than the reversal value to achieve an accurate representation of repeatability. Figure 7 graphically represents bi-directional performance data. Vertical separation of the forward and reverse data is caused by the reversal value. Ten values are presented at each position: Five in the forward and 5 in the reverse directions. The dots represent the spread of the values at each position. All positions are approached from a distance that is greater than the reversal value.

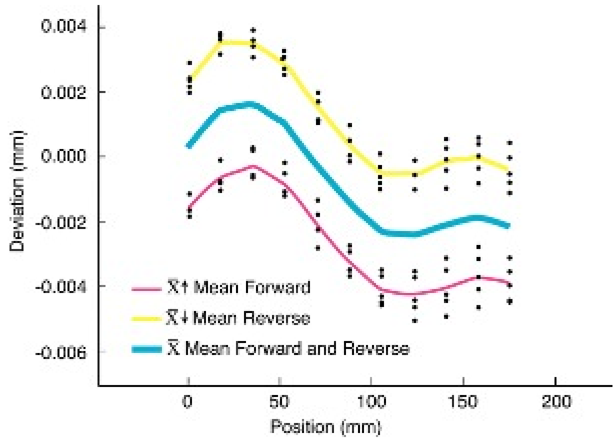

Figure 7. Bidirectional repeatability graph showing mean forward, mean reverse and their sum. Newport Corporation.

4. FUNDAMENTAL APPLICATION – MOVING A SINGLE LENS

The fundamental application example of moving a single lens is shown in this section for both the micro and nano scale regions. An automated optical measurement bench (Trioptics) measures key fundamental functional lens parameters such as effective, back and flange focal lengths, modulation transfer function and lens radius of curvature. The single most important precision positioning and motion control function of this system is accomplished by using a long travel linear stage like the one shown earlier in Figure 2. This optical measurement bench, shown in Figure 8, includes a light source, resolution target (as the object), a place for a lens under test, a collimating lens, a CCD camera and the precision motorized linear stage; as well as the mechanical housings, base and associated electronics. The system performance of this optical measurement bench is dependent on a number of parameters and tolerances, including to a large extent, but not limited to, the motorized linear stage.

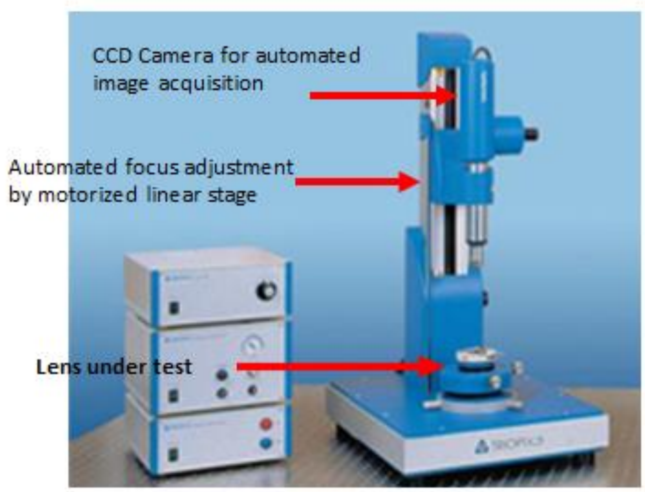

Figure 8. Automated optical measurement with motorized linear stage to measure lens optical properties. Trioptics, GmbH.

As shown in Figure 9 as an example, the capability to accurately measure the Effective Focal Length (EFL) of a lens under test is dependent on the range of the EFL to be determined. For EFLs in the range of 5 to 25 mm, the tolerance might be 25 µm, for the range 25 to 500 mm, 7.5 µm could be the tolerance and for large EFLs up to 1 meter, the tolerance could be as large as 0.25 mm. These values are for educational purposes only and for actual performance ranges and tolerances the manufacturer should be consulted. Referring back again to the stage in Figure 2 and the graph in Figure 3, it should be noted that the stage has a much higher resolution than the optical measurement bench.

This will then be due to a number of other components in the optical measurement bench, including the CCD camera, the collimator lens, the light source and object (resolution target) and how all these work together. This fundamental concept of system specifications and tolerances is the topic of a number of educational courses at various colleges and universities and the reader is provided with one reference to such a course at the end of this paper.

System Performance	EFL		
Resolution:	0.03...0.2%		Tolerance
Measurement Accuracy	5...25 mm:	0.1%.....0.3%	5 µm
	25 500 mm:	0.03%...0.1%	7.5 µm
	500...1000 mm:	0.05%...0.3%	250 µm

Figure 9. Example system performance of the optical measurement bench shown in Figure 8.

Moving to another example, this time moving a single lens at the nano scale, we focus our attention to a microscope objective lens, in this case on a standard inverted research microscope as shown in Figure 10. Here the application is to investigate natural phenomena such as the inner workings of plant and animal cells, viruses and single molecules.

Figure 10. Example of standard inverted microscope. Wikipedia.

As shown in Figure 11, these size regions go from the many 10s of microns to the single nanometer range. Focusing the microscope objective to the single nanometer range reliably and repeatedly requires systems like those shown in Figure 12, piezo based flexure structures with capacitive sensors, as shown in Figure 13, for real time position feedback. In general, these systems are available with travel ranges from a few 10s of microns up to 1 mm or more. Their tolerance levels will also scale as we saw in the micropositioning example; but for different technical reasons. Specifically, while there will be optically related tolerance stack ups as in the optical measurement bench example, the resolution of the capacitive sensors themselves scale with travel range from fundamental principles. The details of these capacitive sensors (and other nanopositioning sensor technologies) needs to be left for another time, the fundamentals of the electronic control systems will be reviewed briefly next.

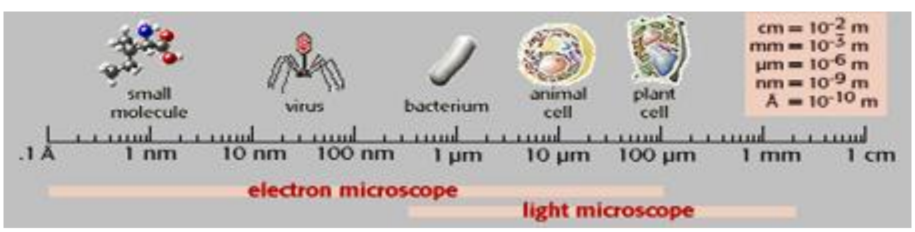

Figure 11. Relative size of cells and their components. Wikipedia.

Figure 12. Example of piezoelectric (PZT) microscope objective scanner (PIFOC)

Figure 13. Example of capacitive sensors for position feedback; used in PZT stages and scanners.

5. POSITION CONTROL ELECTRONICS – OPTIMIZING SYSTEM PROPERTIES

Position servo-control eliminates nonlinear behavior of piezo ceramics such as hysteresis and creep and is the key to highly repeatable nanometric motion. The advantages of position servo-control are: high linearity, stability, repeatability and accuracy, automatic compensation for varying loads or forces, virtually infinite stiffness (within load limits) and elimination of hysteresis and creep effects. Closed-loop piezo actuators and systems are typically equipped with position measuring systems providing sub-nanometer resolution, linearity to 0.01 %, and bandwidths up to 10 kHz. A servo-controller (digital or analog) determines the output voltage to the PZT ceramics by comparing a reference signal (commanded position) to the actual sensor position signal (see Figure 14). For maximum accuracy, it is best if the sensor measures the motion of the part whose position is of interest (direct metrology). There are a large variety of piezo actuators and stages with integrated direct-metrology sensors. Capacitive sensors provide the best accuracy, while simpler, less accurate systems measure things like strain in drive elements.

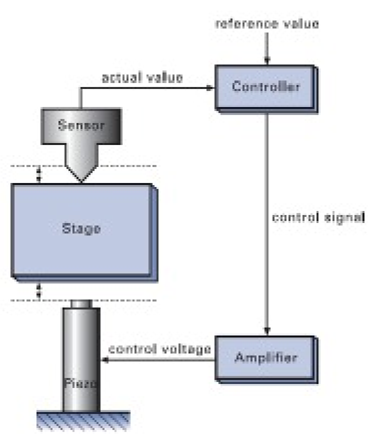

Figure 14. Typical closed loop feedback system representation for PZT driven stage.

Stepping through the diagram in Figure 15 below, it shows a number of the ley concepts involved with controlling position at the Nano scale with PZTs and sensors. The Slew Rate determines how fast the voltage moves into the system regulating the speed in which the piezo might expand. Then, if the Servo is on, changing the Proportional Gain and Integral Time adjusts the amplitude and time of the voltage. The Notch Filter helps block out frequencies that might make the mechanical system oscillate near a natural resonance. The voltage to the PZT gets amplified, typically 10×, but can be much more, depending on the specific amplifier design and the sensor senses the motion and reports back to the sensor monitoring circuit. The sensor range, bandwidth and gain are all adjusted during the factory calibration procedure, which will be the next topic.

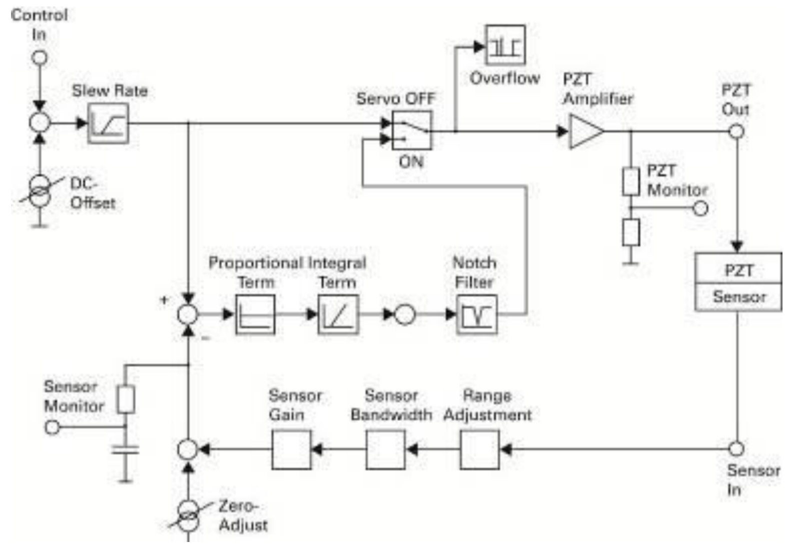

Figure 15. Typical closed and open loop feedback system representation for PZT driven stage.

Typical closed loop PZT control systems often experience a lag time between the commanded signal and the actual sensed motion of the stage. This is shown clearly in Figure 16 as the commanded signal position is shown with the solid black line and the measured position provided by the sensor feedback is shown in the dashed line. Here the adjusted PID parameters described above and the complete system was not able to keep up with the frequency of the commanded signal position and a phase lag is experienced. There is also a solid green line that overlaps the solid black line and this is from an advanced algorithm known as Digital Dynamic Linearization (DDL). This DDL and a number of other advanced software algorithms and programs can be used in addition to standard systems to greatly improve the performance of these precision position and motion control systems. Later in this paper such a system for Silicon Photonics applications will be reviewed briefly.

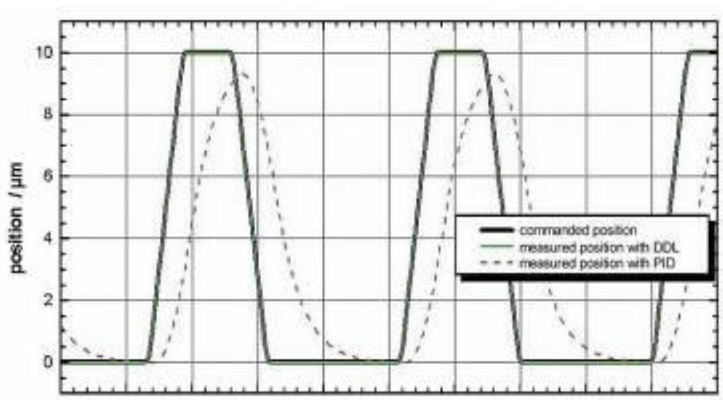

Figure 16. Comparison between commanded signal positions, measured position with standard PID and measured position with advanced DDL.

Piezo nanopositioning systems are significant investments for the user. Optimizing the performance of every system individually should be a requirement and every stage should be optimized for both static and dynamic performance for the user's specific application. The metrology test protocol should be part of the system's delivery package. It should show the user what the performance of the system was at the time of delivery and which system components belong together. Every metrology procedure and its recording should be considered a quality assurance instrument, and only nanopositioning systems which meet their specifications should be provided to the end user. Furthermore, manufacturers should make significant continuing investments to improve quality with higher performance nanometrology equipment so that they can deliver better value to the users. Because a Nano mechanism can only be as accurate as the equipment it was tuned and tested with, closed-loop stages are typically measured with interferometers and other high precision external sensors like those shown in Figure 17.

Figure 17. Typical distance measuring interferometer (DMI) used to measured closed loop position of a PZT system.

Typical nanometrology laboratories are seismically, electromagnetically and thermally isolated, with temperatures controlled to better than 0.25 °C / 24 hrs. The best manufacturers are confident that their metrology capabilities and procedures are at or above the benchmark for the industry. An example nanometrology laboratory is shown in Figure 18.

Figure 18. Typical nanometrology laboratory.

Capacitive position sensors are analog non-contact devices. A two-electrode capacitive position sensor consists of two RF driven plates that are part of a capacitive bridge, as previously shown in Figure 13. The high-frequency AC excitation provides better long term stability than DC excited sensors. One plate (probe) is fixed, the other plate (target) is connected to the object to be positioned. Since the plate size and the dielectric medium (air) remains unchanged, capacitance is directly related to the distance between the plates. Ultra-precise electronics convert the capacitance information into a signal proportional to distance.

Capacitive sensors are the most accurate measuring systems for nanopositioning applications currently available. In contrast to high resolution sensors measuring deformation in the drive train like strain gauge or piezo resistive sensors, capacitive sensors are noncontact, direct-metrology devices – a fact which gives them many advantages: Better phase fidelity, higher bandwidth, no periodic error, non-contacting, ideal for parallel metrology, higher linearity, better reproducibility and higher long-term stability.

Capacitive sensors are especially well-suited for parallel metrology configurations. In multi-axis nanopositioning systems, parallel metrology means that the controller monitors all controlled degrees of freedom relative to “ground” (the fixed frame) and uses each actuator to compensate the undesired off-axis motion of the others automatically (active trajectory control). As a result, it is possible to keep deviations in the sub-nanometer and sub micro-radian range.

Resolution on the order of picometers is achievable with short-range, two-electrode capacitive position sensors (single-electrode capacitive position sensors provide less resolution, linearity and accuracy than two-electrode sensors). Theoretical measurement resolution is limited only by quantum noise. In practical applications, stray radiation, electronics- induced noise and geometric effects are the limiting factors.

For example, with the 100 µm range, a PI (Physik Instrumente) D-100.00 sensor and E-509.C1A electronics, the effective noise factor is $0.02\ \text{nm}/(\text{Hz})^{-2}$. This translates to 0.2 nm at 100 Hz bandwidth. The maximum standard bandwidth for this system is 3 kHz. Figure 19 shows the results of a D-015, 15 µm capacitive position sensor and an interferometer, both measuring nanometer-range actuator cycles. The graphs clearly show the superior resolution of the capacitive position sensing technique.

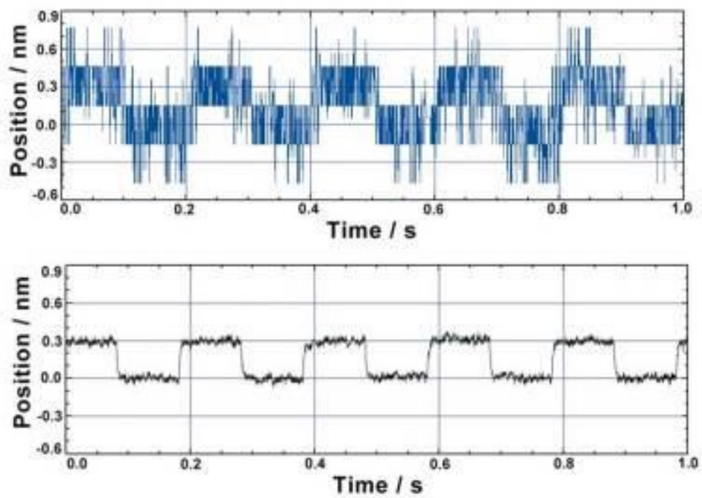

Figure 19. Piezo nanopositioning system making 0.3 nm steps, measured with PI capacitive sensor (lower curve) and with a highly precise laser interferometer. The capacitive sensor provides significantly higher resolution than the interferometer.

Once a piezo nanopositioning system is tested, the results should be clearly documented and provided to the user. An example of this is shown in Figure 20. Here all the details of the system tested are described and the equipment used and environment is specified. The numerical results are tabulated as well as graphed for easy and quick review and comprehension by the user.

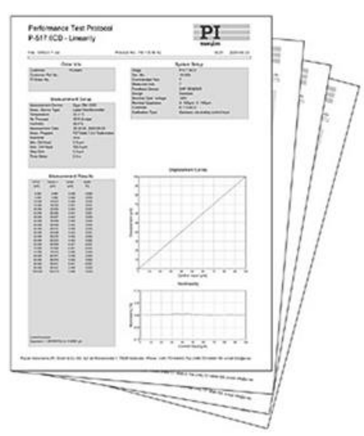

Figure 20. Typical nanopositioning systems come with extensive performance documentation.

6. MULTI-AXIS MOTION – MANY DIFFERENT APPROACHES

There are many different approaches to design and implement precision multi-axis motion solutions at both the nano and micro scales. The three most common are known as; stacked stages, hexapods (also known as Stewart Platforms) and SpaceFabs.

Historically, the stacked stage approach, as shown by example in Figure 21, has been and still is used very successfully across the optics and photonics world. There are as many combinations possible as stage designs and permutations allow within reasonable physical limits for many applications. So this paper will not discuss this solution except as it relates to the reasons hexapods, as shown by example in Figure 22 and SpaceFabs, as shown by example in Figure 23, are chosen as the preferred solution in some applications.

Figure 21. Typical multi-axis set of stacked stages with Z, X, tip, tilt and rotation on top.

Figure 22. Typical hexapod with six linear actuators connecting a top plate that moves with respect to a fixed base. Video 1. This video demonstrates typical motion of this hexapod. http://dx.doi.org/10.1117/12.2191844.1

Figure 23. Typical SpaceFab with three sets of XY linear stages connecting a top plate that moves with respect to a fixed base.

Hexapod platforms are used for moving and precision positioning, aligning and displacing loads in all six degrees of freedom, i.e. three linear and three rotational axes. Hexapods have a parallel-kinematic structure, i.e. the six drives act together on a single moving platform. The length of the single drives can be changed so that the system moves in all six degrees of freedom in space. This special Hexapod design optimizes the overall system stiffness and allows for a large central aperture.

Depending on their design, Hexapods can position loads from several kg up to several tons in any spatial orientation, in other words independently of the mounting orientation and with sub micrometer precision.   Hexapods can be designed considerably more compact than serially stacked multi-axis positioning systems. Since only a single platform, most often provided with a large aperture, is actuated, the moving mass of the Hexapod is significantly smaller. This results in improved dynamics with considerably faster response. Furthermore, cabling is no issue, so that no additional forces and torques reduce the accuracy. In case of stacked systems, the lower axes not only move the mass of the payload but also the mass all other following drives. This reduces the dynamic properties and the total system stiffness. Moreover, the run outs of the individual axes add up to a lower accuracy and repeatability.

The basis for the hexapod’s high precision motion is a zero-backlash structure and carefully selected and matching components. This includes first of all the right material selection, when e.g. thermal effects are to be expected at the place of operation, such as astronomical telescopes. The motor, if necessary with gearhead, an integrated guiding system, the lead screw/nut unit, as well as the joints for the required load range up to high-resolution position detection in every strut, all these elements determine the achievable precision.

Hexapods for use in optics and photonics applications are traditionally based on electromechanical drives and are much more accurate than the hydraulic hexapods known from flight or driving simulators. Precision leadscrew drives, piezo actuators or linear motors can also be used. Most systems are self-locking to some extent. Direct-drive hexapods ensure higher velocities; for industrial use, brushless motors (BLDC) are particularly suitable.

As described in an earlier section of this paper, distance measuring laser interferometers (DMI) are typically used to calibrate and report the precision of positioning systems. Figure 24 shows how a DMI can be set up to measure the motion of a hexapod, with a small retro reflective mirror mounted on the top platform.

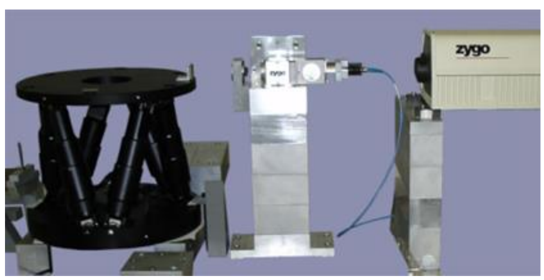

Figure 24. A custom hexapod undergoing performance metrology testing using a Zygo Distance Measuring Interferometer.

Below in Figure 25, the graph shows the positioning accuracy of a few microns in the Z-Axis of a different hexapod over 25 mm of travel and repeatability of less than 0.1 microns.

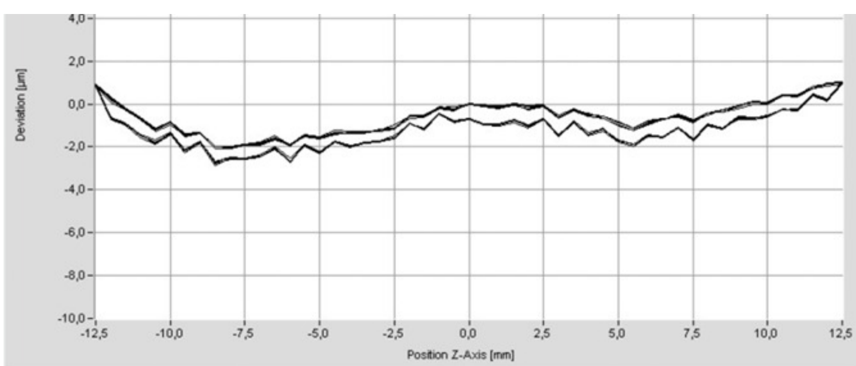

Figure 25. The positioning accuracy of a precision H-824 Hexapod in Z direction over the complete travel range of 25 mm is a few micrometers, and the repeatability is considerably lower than ±0.1 µm

This is then followed by the graph in Figure 26 showing 500 nm steps in the Z direction about every 2 seconds. It is always very important to have actual test data from sample systems and then from the actual systems being implemented into any research or industrial application to ensure proper confidence is built for colleagues and end users.

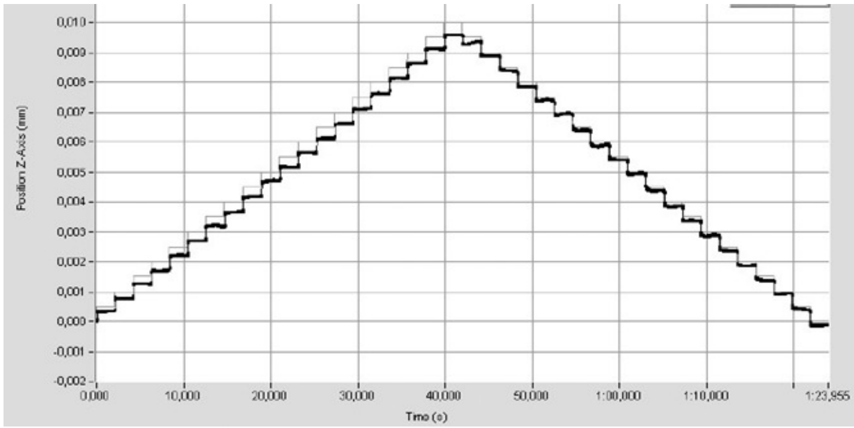

Figure 26. This interferometer test shows high repeatability with 500 nm steps in the +/- Z-direction over more than 1 minute.

7. SILICON PHOTONICS – COMBINING MICRO & NANO

Silicon photonics allows data rates to the magnitude of Tbit/s, is therefore predestined for all computer-supported services which require the highest possible transmission rates. The placement of optical components on silicon semiconductors and the creation of the optical connections can be automated in practice. The advent of silicon photonics has brought new production challenges, including the need for testing of components prior to wafer dicing, analogous to conventional electrical-test wafer probing, but in the optical domain. Similarly, downstream packaging processes are more exacting and complex than ever. Since many classes of components have one or more inputs plus one or more outputs, and each of these needs to be aligned to nanoscale accuracies in order for test or packaging processes to proceed, it quickly becomes uneconomical to use traditional alignment techniques in a sequential fashion. Plus, the multiple couplings often interact, especially in the case of short waveguides. So a global, parallel, simultaneous alignment-optimization solution is needed.

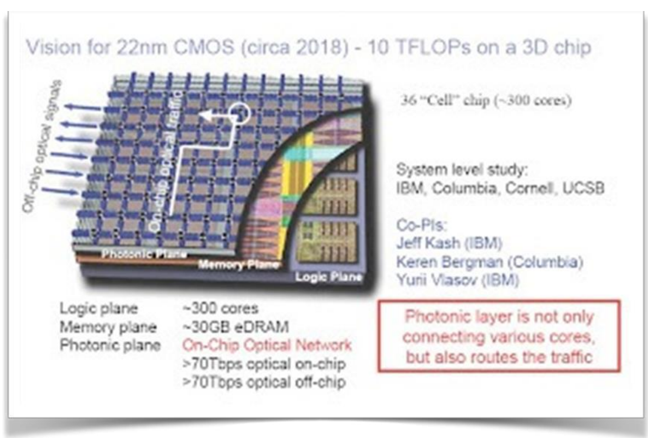

Figure 27. An example of a future 300 core chip with all the cores interconnected via silicon photonic mesh. IBM Corporation.

In order to optically align all the inputs and outputs for systems like those shown in Figure 27, fast micro / nano precision positioning systems with optical feedback is required. In order to understand the physical alignment requirements, a look at the feature sizes of the waveguide channels is needed. The diagrams in Figure 28 show some typical dimensions for the light output distribution of a single mode optical fiber (top left) and the waveguide channel (top right). Here it is shown that these dimensions are of the order of 3.5 μm and that is then the starting point for understanding the alignment specifications and then the tolerances required.

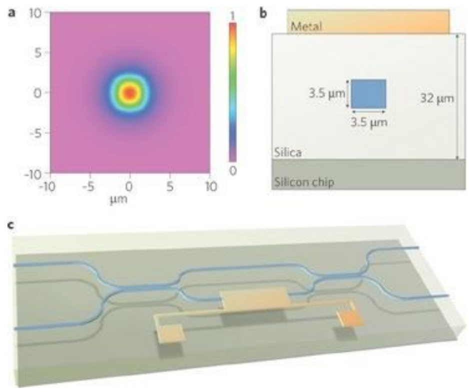

Figure 28. Typical dimensions for the light output distribution of a single mode optical fiber (top left) and the waveguide channel (top right). The bottom diagram shows a typical silicon waveguide interferometer light switch.

To maximize the light throughput from the optical fiber into the waveguide channel and back out, precision of a small fraction of the 3.5 μm dimension is required; and this needs to happen very fast, the faster the better. Ideally, a positioning tolerance of several nanometers to at most several tens of nanometers will be required. For this, a combination of precision micro and nano positioning systems are required, as shown in Figure 29.

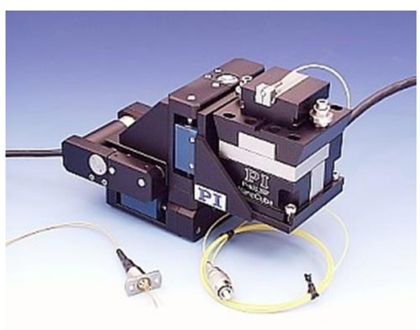

Figure 29. Combination of micro and nano precision positioning systems show the XYZ units on the left with the blue carriers (moving platforms) travel several millimeters with minimal incremental motion (MIM) of 0.2 microns and the NanoCube on the right has XYZ travel of 100 microns and closed loop resolution of 2.0 nm.

Even more aggressive requirements are seen in the current research labs as they propose the path to tera-scale data rates as shown in Figure 30. Here, the semiconductor chip manufacturer Intel describes their path from the current 12.5 Gbps x 4 = 50Gbps to their goal of Terabits per second in the future that will be enabled by silicon photonics.

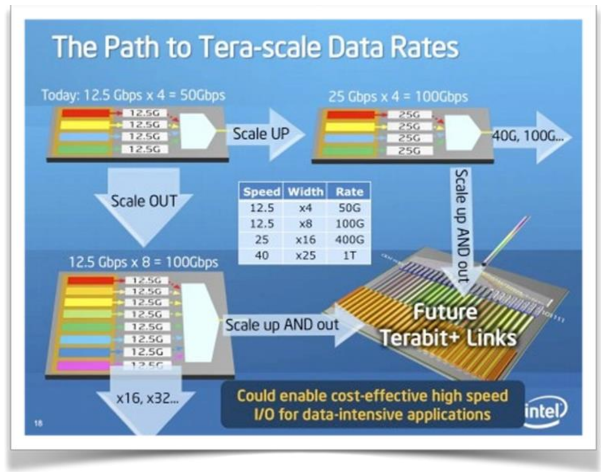

Figure 30. Intel's path to Terabit-scale data rates from their current 50 Gbps systems now being used. Intel Corporation.

For Intel's goals to be realized, even finer levels of precision will be required. Optical waveguide channels with feature size dimensions under 500 nm per side, as shown in Figure 31 will be commonplace.

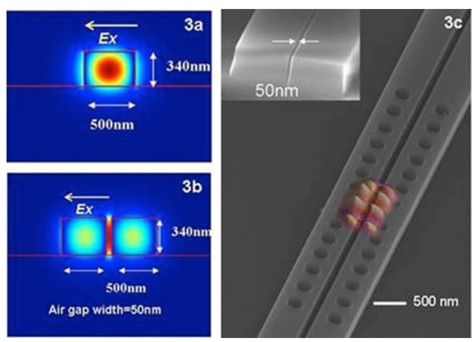

Figure 31. New smaller optical waveguide examples with feature sizes of less than 500 nm challenge the precision positioning instrumentation to make quick work of providing routine alignment capabilities. Intel Corporation.

Again, to meet these critical alignment requirements, the combination of micro and nano positioning systems like those shown in Figure 29 paired with the latest digital electronic controllers with sophisticated software and firmware algorithms provide the path forward for these applications at the leading edge of technology. Specifications of the system shown in Figure 29 are detailed below in Figure 32.

Specifications

	F-131.3SD	Unit
Drive	DC motor, closed-loop PZT drive	
Active axes	X, Y, Z	
Motorized travel range (XYZ)	15	mm
Piezo travel range (XYZ)	100	µm
Design resolution (motor)	0.007	µm
Min. incremental motion (motor)	0.05	µm
Closed-loop / open-loop resolutior (PZT)	2 / 1	nm
Motorized stage	M-111.3DG	
Piezo positioning system	P-611.3SF	
Material	aluminum / steel	

Figure 32. Detailed specifications of a combination micro and nano precision XYZ alignment system meets the requirements of the leading edge systems to bring the next generation of silicon photonics from the research labs to the marketplace.

Here, as briefly described in Figure 29, the three motorized micro positioning stages configured in an XYZ stack provide 15 mm of travel in each axis with a MIM of 50 nm. And the piezo NanoCube provides 100 µm of travel in XYZ with 2 nm of closed loop resolution. These systems are actually very mature technologies that have been available for many years and are now joined with new digital electronic controllers, as shown in Figure 33, implementing new software and firmware algorithms. In a current example, where both optical fiber inputs and outputs are simultaneously aligned on each side of a photonic waveguide array, special fixturing is required, as shown in Figures 34 and 35. A video clip of an animation of the motion of the NanoCube can be seen to better convey the concept of this level of precision motion. The motion in the video clip is greatly magnified in order to see the motion. Since it is only 100 µm in total travel in each direction, that motion cannot typically be seen with the unaided eye.

Figure 33. Photograph of digital electronic controller that has been used to drive the combined micro and nano positioning systems including monitoring the optical signals from the fiber / waveguide outputs used to maximize the precision alignment.

Figure 34. A model of special fixturing that is required to precisely align input and output optical fiber arrays to a waveguide.

Figure 35. A photograph of special fixturing that is required to precisely align input and output optical fiber arrays to a waveguide.

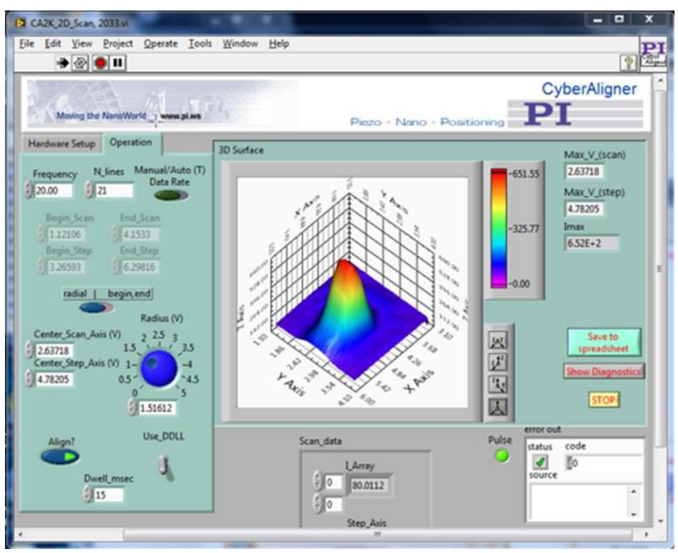

Figure 36. CyberAligner graphical user interface (GUI) developed to control the micro nano precision alignment systems for Silicon Photonics. The center graphics shows the maximized light throughput of a single optical fiber channel. This example shows a device profile captured in a full-field scan in ~400msec.

Video 2. This video demonstrates the Silicon Photonics fast alignment system. http://dx.doi.org/10.1117/12.2191844.2

CyberAligner, as shown in Figure 36, is a comprehensive application that provides a highly time-efficient throughput with a two-step sequence: 1) A unique, space-efficient double-spiral scan, using motorized long-travel stages, for first-light capture and rough optimization, followed by 2) An extremely fast raster scan with the piezoelectric positioners and advanced controls, combined with synchronous data acquisition to compile the transverse coupling cross-section and identify the global maximum.

Recently a new search capability was integrated into the CyberAligner system. CyberTrack, as shown in Figure 37, an efficient implementation of the very latest gradient search algorithm, is based on a patented technique for performing a digital gradient search on-the-fly. This has proven to be an ideal addition and enhancement of the fast CyberAligner double spiral first-light search and fast raster scan: 1) for applications with worse than 100μm fixturing tolerances, motorized stages perform a space and time-efficient double-spiral scan to achieve first-light coupling. 2) A full-field (100x100μm) fast raster scan is performed by the Nanocube, building a detailed optical profile and selecting the global maximum for fine alignment. 3) The CyberTrack digital gradient search is then activated, quickly peaking up the coupling and tracking to accommodate any drift or disturbance.

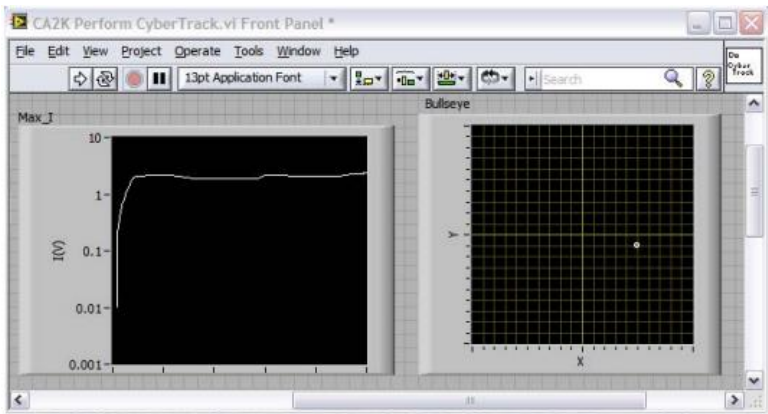

Figure 37. CyberTrack is a new capability for Nanocube and other PZT mechanisms. Based on the latest digital gradient search, it provides high speed optimization and tracking and is easily integrated into production applications.

Video 3. Fast Alignment CyberTrack http://dx.doi.org/10.1117/12.2191844.3

8. SUMMARY

We began this paper with an introduction to both nano and micro positioning systems used in the optics and photonics industries; indicating that sometimes there has been a blurring for these two regions. We clarified and identified the areas of overlap by specifying the positioning and tolerance ranges at various levels; from the millimeter scale down to and below the nanometer range. We got spatially oriented with some fundamental nomenclature including definitions of axes and angles, absolute accuracy, reference positions, backlash, unidirectional and bidirectional repeatability. Then we reviewed the concept of moving a single lens at the micro scale on an optical measurement bench, understanding how the performance parameters and tolerances stack up from the linear motion stage to the final system specifications. Moving down to the nano range with another single lens example, we looked at moving a microscope objective lens to observe biological cells. Here the piezoelectric nanopositioning systems were reviewed with their standard operating parameters and fundamental tolerances. This was followed by a section on multi-axis motion describing a number of different approaches including the classical method of stacking stages and the more sophisticated systems known as hexapods and SpaceFabs. For all these positioning systems, their fundamental metrology concepts and processes were reviewed to provide the reader with a firm foundation to build more advanced systems as described in the later part of this paper.

In the last section of this paper, we described an advance application of current interest, combining micro and nano positioning systems for aligning optical fiber inputs and outputs with single and multiple channel waveguides for silicon photonics. Here we were able to look at examples of optical fiber light output distributions and waveguide feature size that the light needs to go into; and have an introduction to some advanced processes currently being used to accomplish these dynamic alignments at the micro and nano scales.

Covering this material in this manner is truly only a brief introduction to the title topic. The chart below in Figure 38 summarizes a few of the precision positioning systems we reviewed, including the piezo based short travel / high precision systems like the microscope scanner (top left) and the long travel / lower precision DC Servo linear stage (lower right); and it also describes some systems we have not discussed.

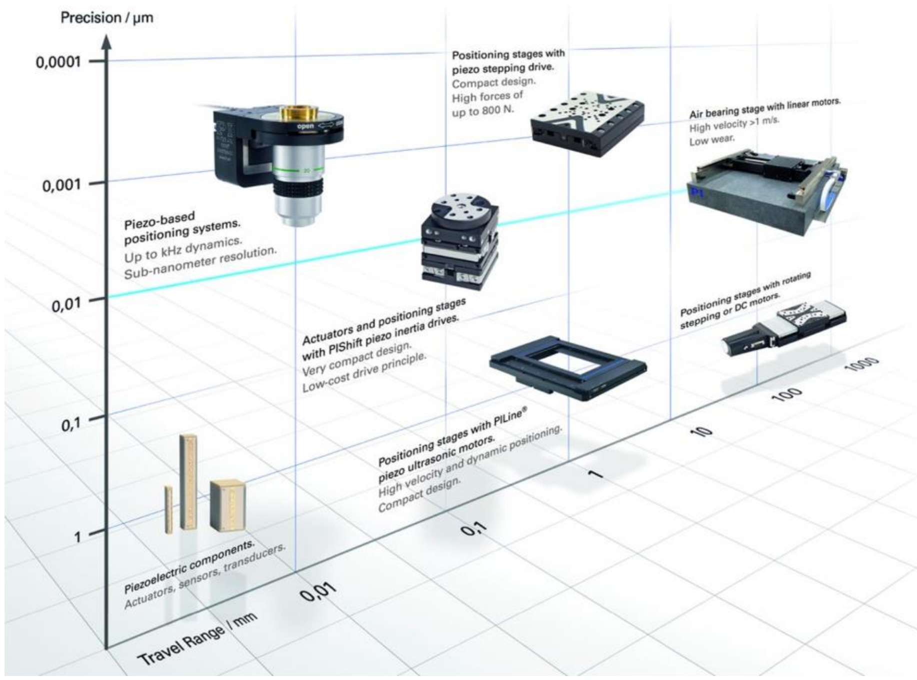

Figure 38. Chart of precision positioning technologies mapped from travel range on the horizontal axis to the precision of each on the vertical axis.

These other systems should have at least a brief mention and they are some air bearing (shown in Figure 39) and piezo motor (shown ion Figure 40) stages that provide both long travel and high precision when paired with special optical encoders like the PIOne described below.

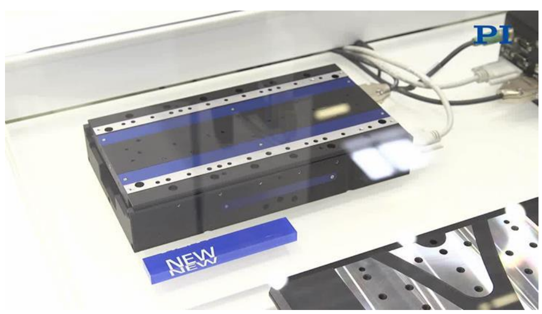

Figure 39. Long travel air bearing stage fitted with high precision PIOne optical encoder to provide high resolution positioning.

Video 4. This video shows the motion on this air bearing stage. http://dx.doi.org/doi.number.goes.here

Figure 40. Medium travel Q-Motion piezo motor based stage with high precision PIOne optical encoder.

Video 5. This video shows the motion of the piezo motor stage and an animation of the drive technology. http://dx.doi.org/10.1117/12.2191844

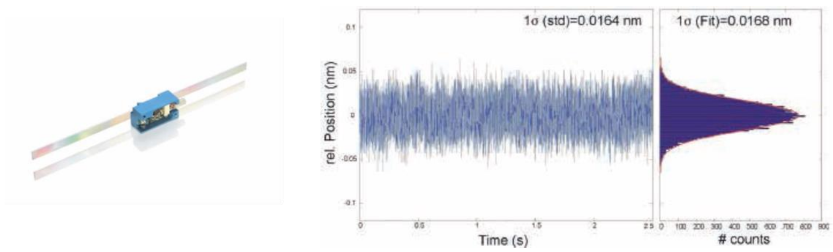

Figure 41. PIOne optical encoder for long travel high precision positioning applications. The graph on the right shows noise measurement of a positioning system with PIOne at approx. 400 kHz bandwidth and 18-bit resolution of the sensor input: 16 picometer RMS and 100 picometer peak-to-peak

The measuring head of the PIOne sensor contains a Mach-Zehnder interferometer which is moved along a linear scale. Sine and cosine signals are generated from the signals of the reflections at the grid. Additional interpolation accounts for the demonstrably small resolution of the system. The sensor head also generates a direction-sensing reference. The sensor head here measures 23 x 12 x 9.5 mm.

In closing, it should be stated that this paper has been written as an introduction to this topic in an educational manner. Extensive additional information is available on the internet from many sources; however, to receive further guided educational instruction, the author teaches an on-line course each Fall quarter through the University of California, Irvine, Extension, titled Precision Positioning and Motion Control for Optical Systems. http://unex.uci.edu/areas/engineering/optics/

REFERENCES

The material in this paper is drawn from PI (Physik Instrumente) L.P., its websites and publications, except where noted in the figure captions. Also, some of this material is from the author's above referenced course.