PI

Fundamentals & Recent Advances in Nanopositioning for Fast Photonics Process Automation

Mechanisms, Controls & Algorithms
… and a brief update on The National Photonics Initiative

Lunch & Learn @ UC Irvine Photonics
Thurs. Nov. 6, 2014

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QUALITY

PRECISION

INNOVATION

PI

Agenda

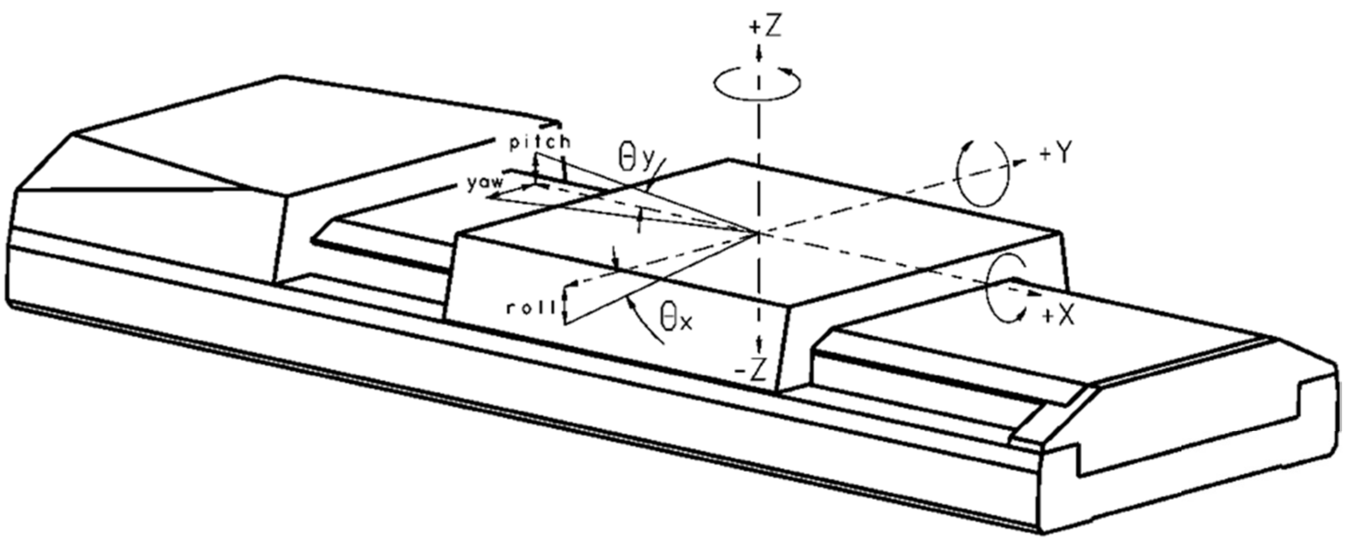
- **Fundamentals – Micro & Nano Positioning**
  - Micropositioning definitions – microscopy examples
  - Nanopositioning definitions – more microscopy examples
    - **<u>Short Q&A</u>**

- **Photonics Process Automation Architectural overview**
- **Novel algorithms and capabilities**
  - Fast alignments of multiple DOFs
  - New optimizations provide real-time drift compensation
- Intriguing applications
  - Silicon Photonics planar device test

- **Integrated industrial systems**
  - **<u>Short Q&A</u>**

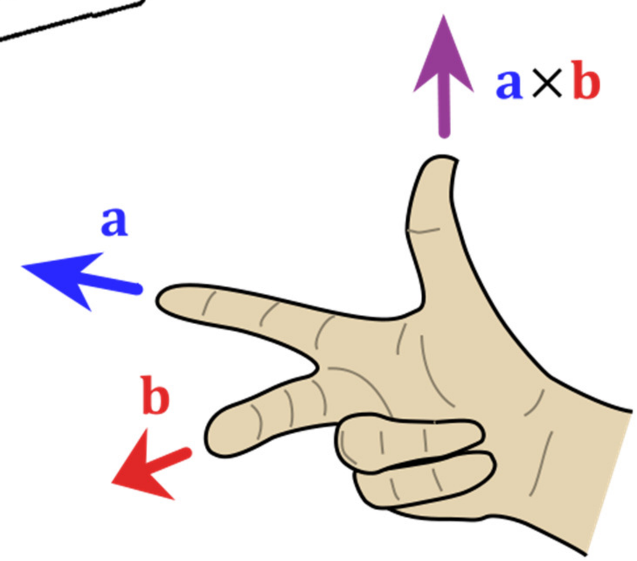
- **National Photonics Initiative – a brief update**
  - **<u>Short Q&A</u>**

Fundamentals – Micro Positioning



Definition of axes and angles

X: Linear motion in (first) positioning direction
Y: Linear motion perpendicular to X in basic plane (usually horizontal)
Z: Linear motion perpendicular to X and Y (usually vertical)
θ_X: Angular motion around X (roll)
θ_Y: Angular motion around Y (pitch)
θ_Z: Angular motion around Z (yaw)

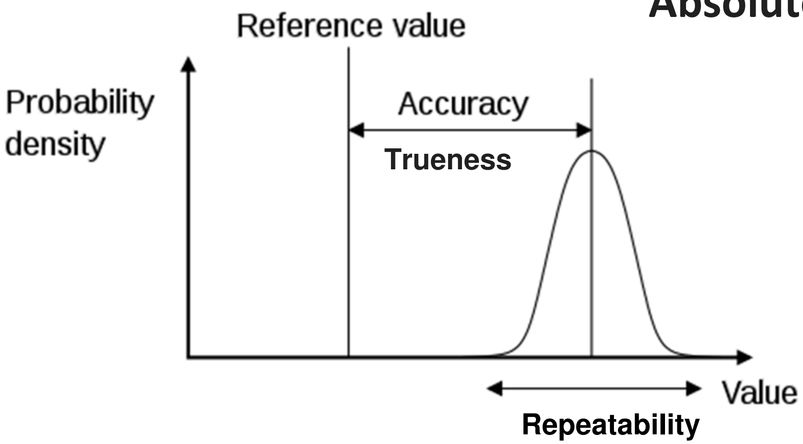


Right Hand Rule

Watch out for + / -

Fundamentals – Micro & Nano Positioning

Absolute Accuracy

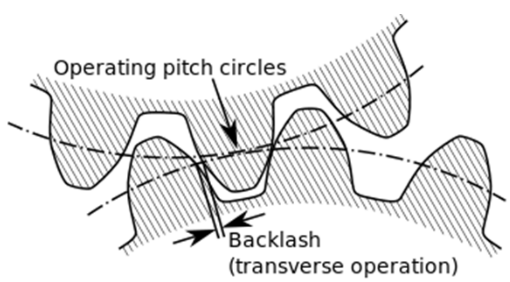


Low accuracy, good trueness, poor repeatability

Low accuracy, poor trueness, good repeatability

http://en.wikipedia.org/wiki/Accuracy_and_precision and **ASME B5.57 and ISO-230.**

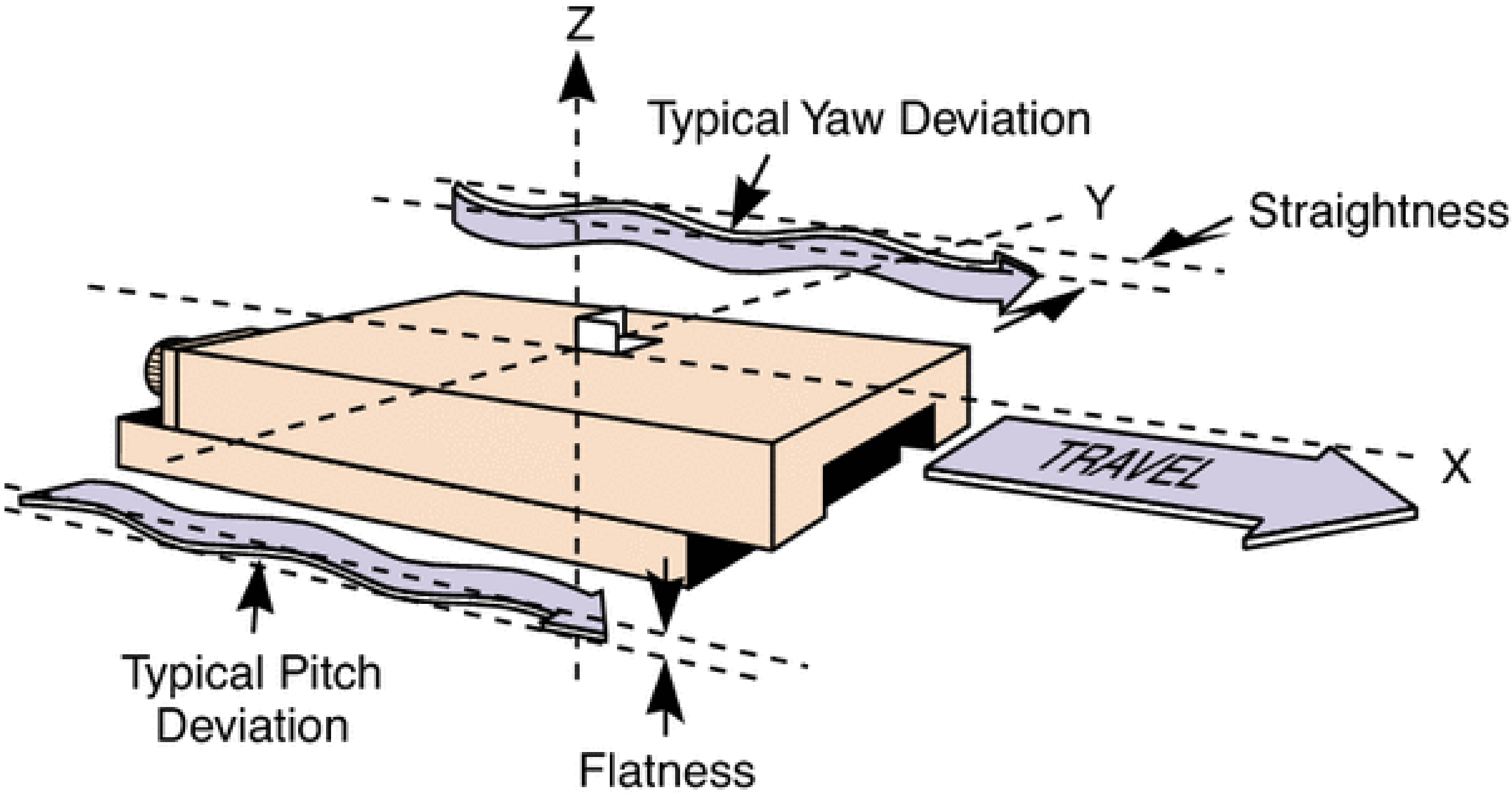
Backlash



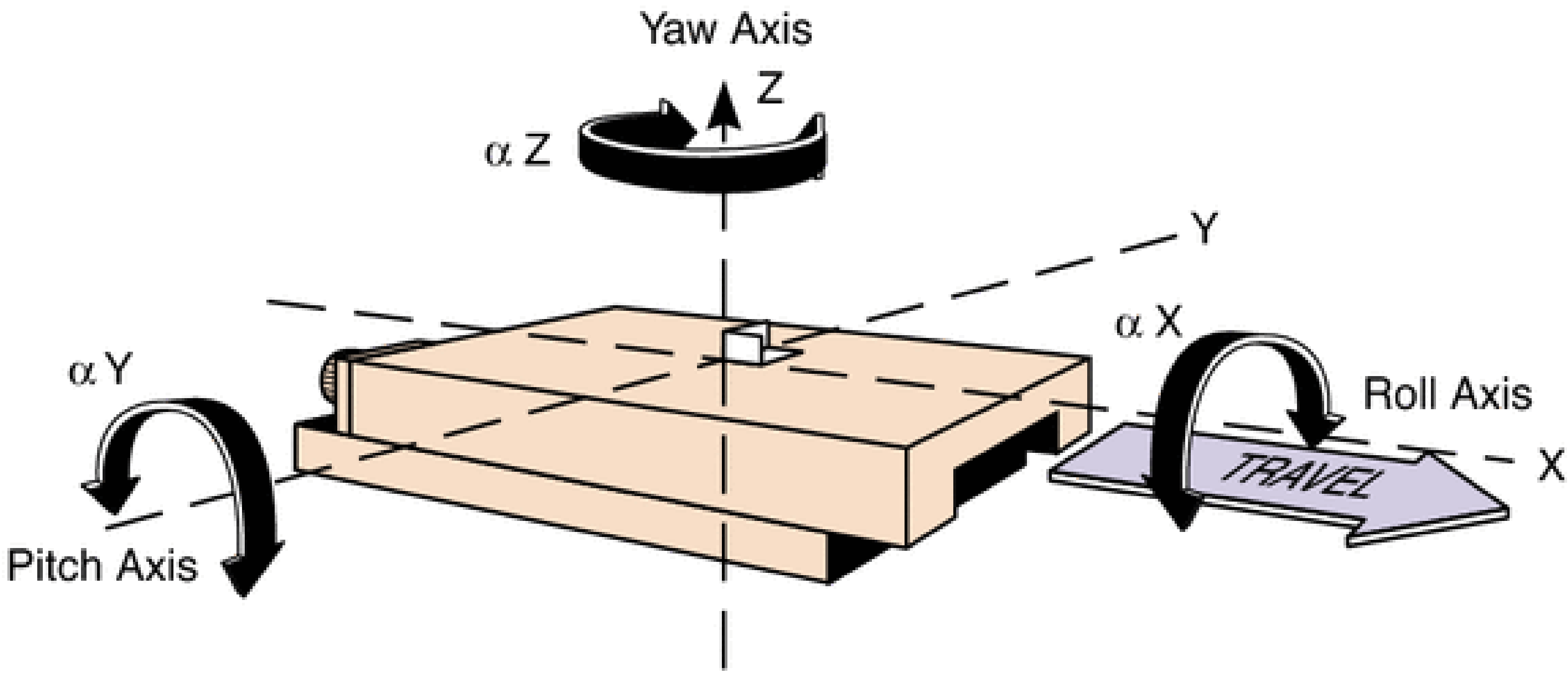
http://en.wikipedia.org/wiki/Backlash_(engineering)

Unidirectional Repeatability

Runout of a Linear Stage



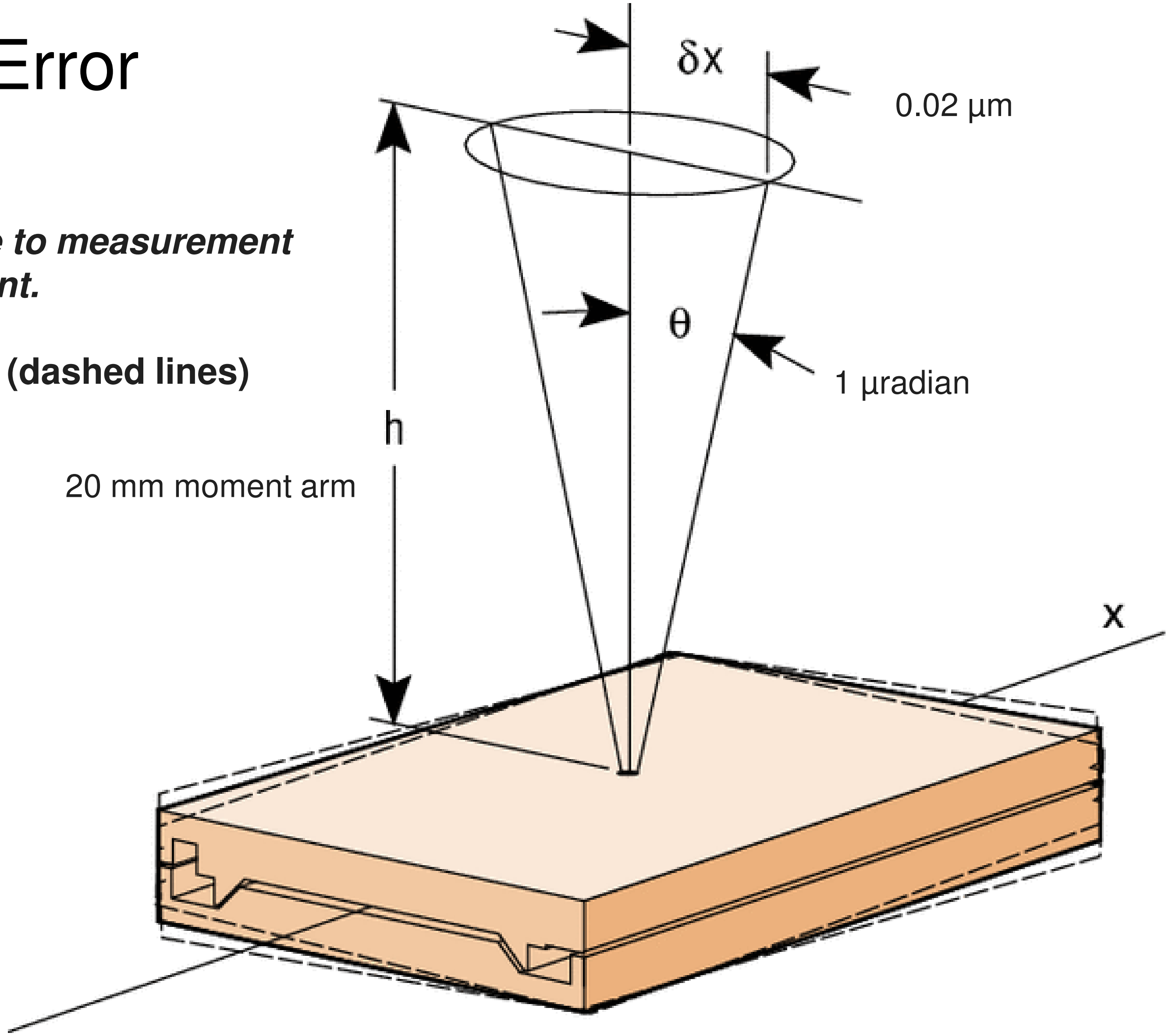
Angular Runout



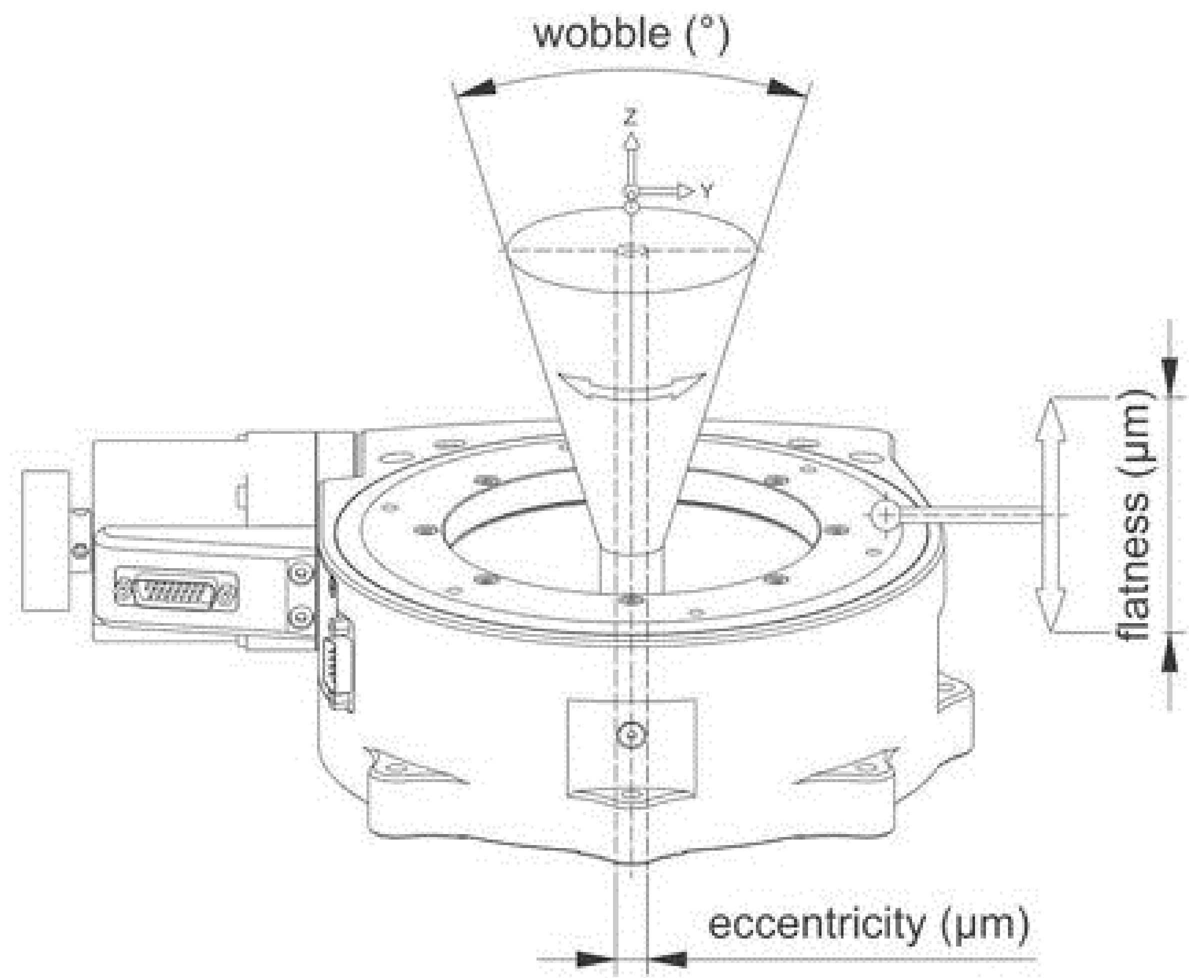
Abbe Error

Abbe Error due to measurement at an offset point.

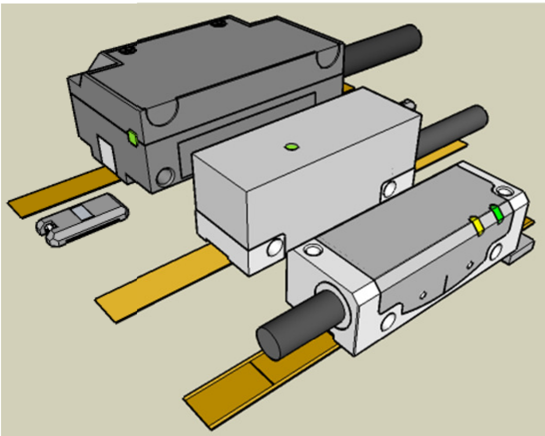
Note stage tilt. **(dashed lines)**

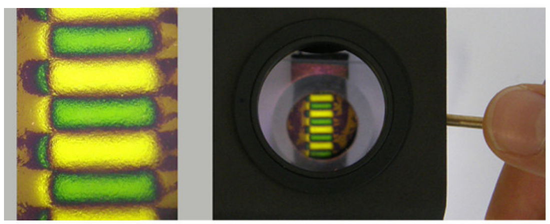


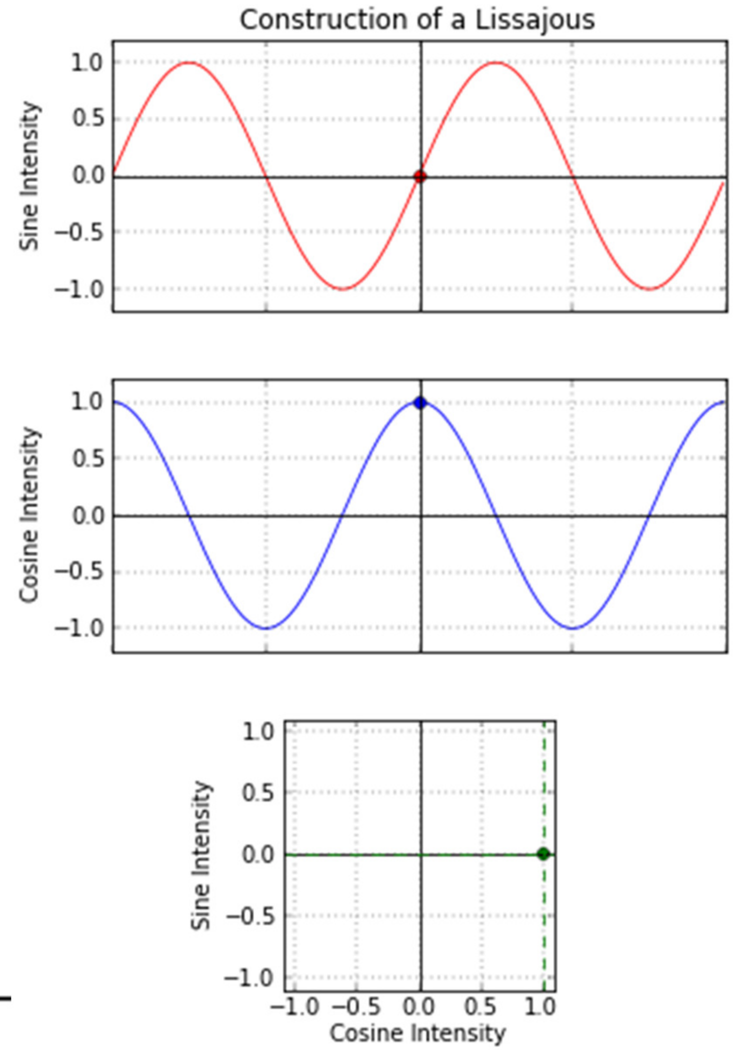
Rotation Stages

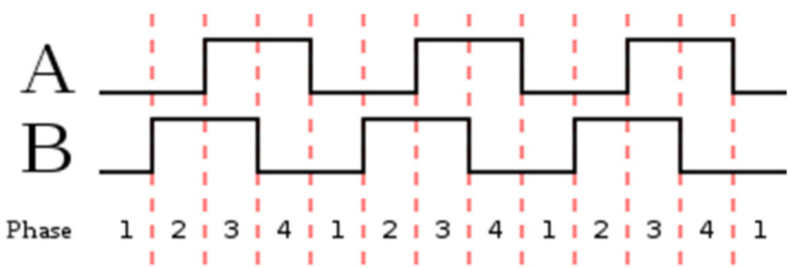


Encoders – Feedback to know position

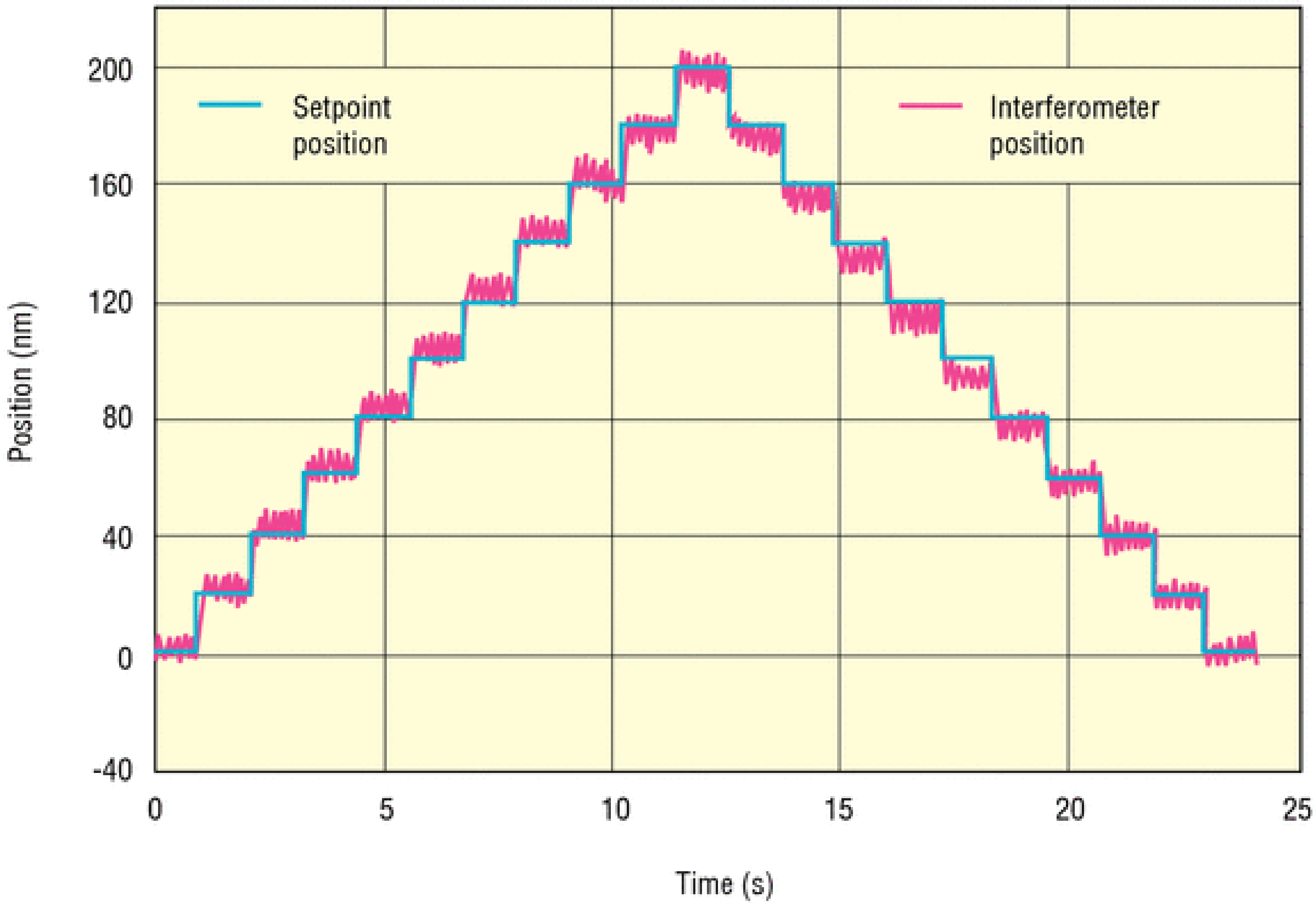




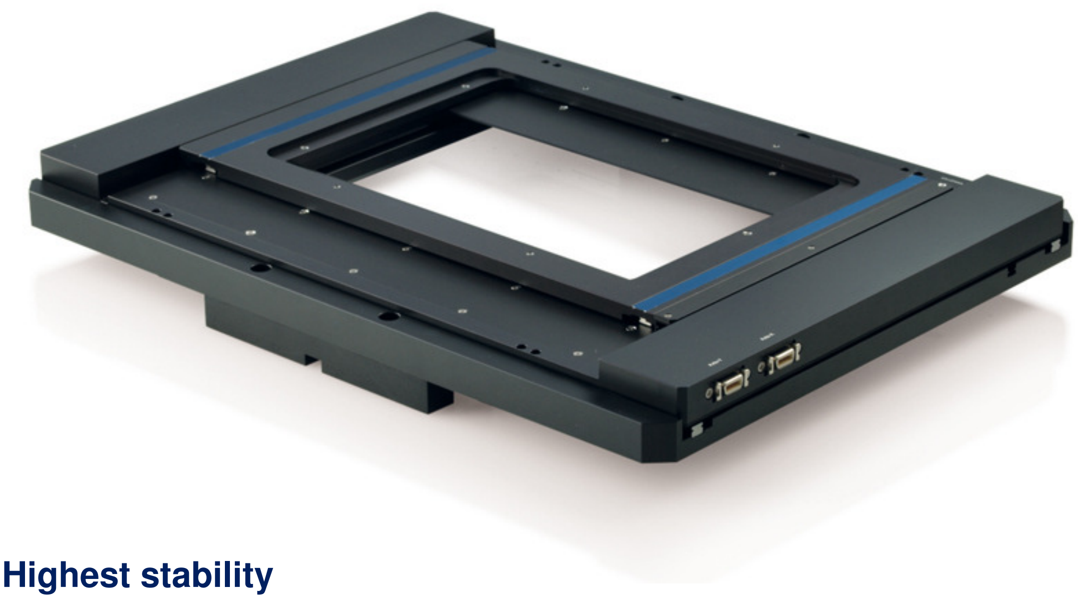


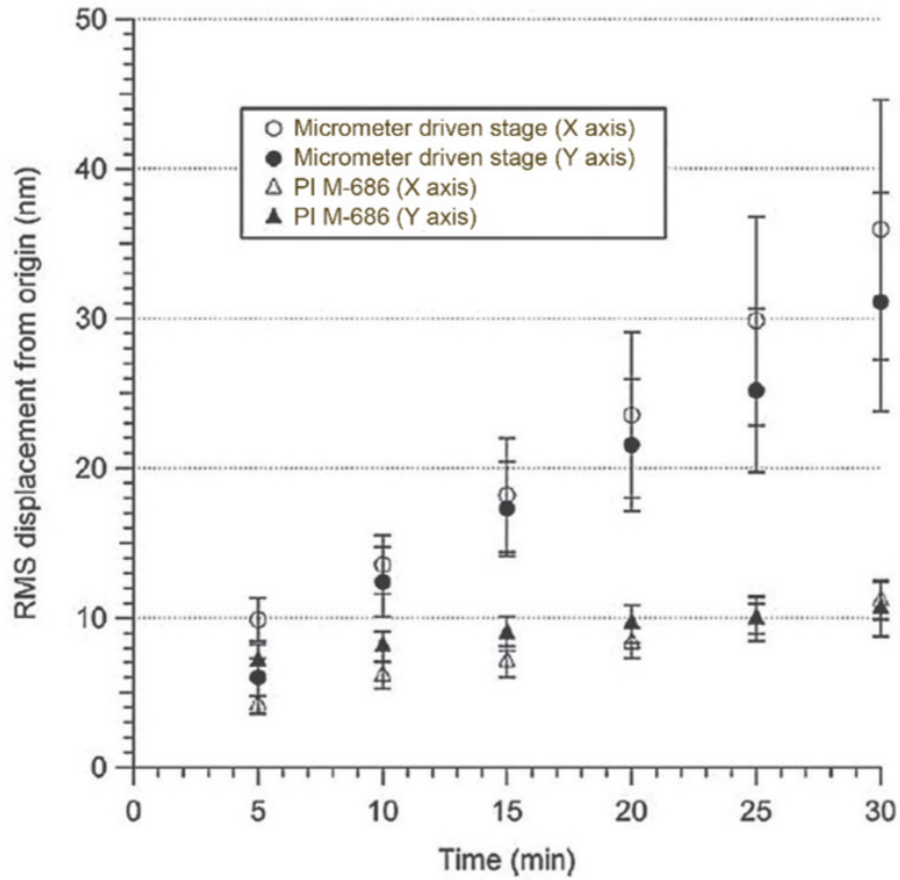


Minimum Incremental Motion



PI - M-687 XY Microscope Stage with PILine® Motor, Controller and Joystick

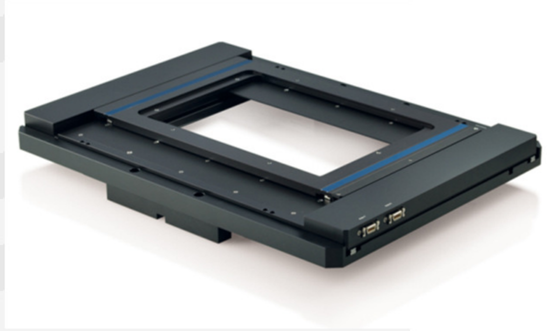




- **Highest stability**
- **0.1 µm resolution**
- **Travel range up to 135 mm × 85 mm**
- **For inverted microscopes, free rotation of turret**
- **Suitable Z sample scanner available**
- **Velocity up to 120 mm/s**
- **High velocity constancy at 10 µm/s**
- **Direct-metrology linear encoder**
- **Compact design with low profile allows free access to the sample**
- **For the inverse microscopes Olympus IX2 and Nikon Eclipse Ti**

S.C. Jordan/P.C. Anthony: Design Considerations for Micro- and Nanopositioning: Leveraging the Latest for Biophysical Applications, Current Pharmaceutical Biotechnology, 2009, 10, 515-521

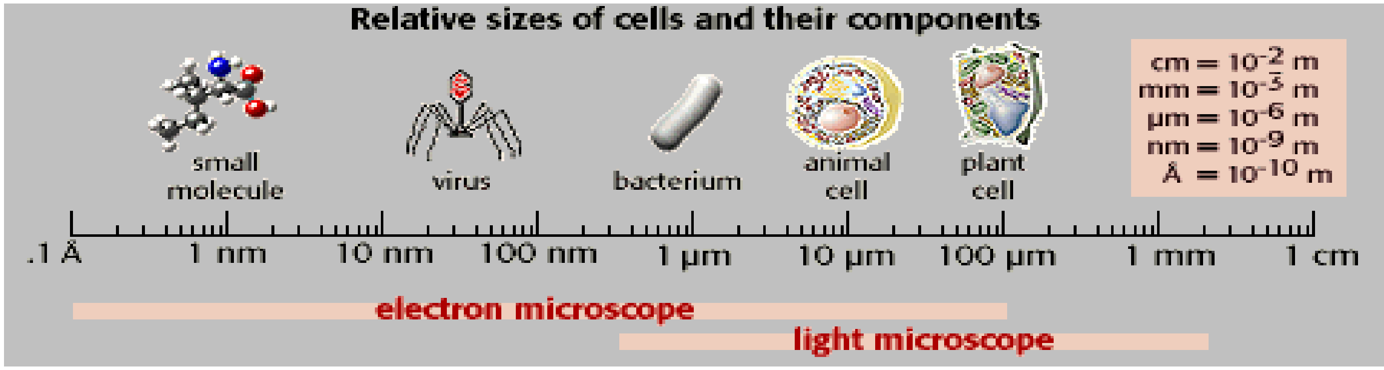
	M26821LNJ	M26821LOJ	Units	Tolerance
	System with M-687.UN for Nikon microscopes	System with M-687.UO for Olympus microscopes		
Active axes	X, Y	X, Y		
Motion and positioning				
Travel range	135 x 85	100 x 75	mm	
Integrated sensor	Linear encoder	Linear encoder		
Sensor resolution	0.1	0.1	µm	
Bidirectional repeatability	0.4	0.4	µm	
Pitch / Yaw	±300	±300	µrad	typ.
Max. velocity	120	120	mm/s	
Reference point switches	Optical, 1 µm repeatability	Optical, 1 µm repeatability		
Limit Switches	Hall-effect	Hall-effect		
Mechanical properties				
Max. load	50	50	N	
Max. push / pull force	7	7	N	
Miscellaneous				
Operating temperature range	20 to 40	20 to 40	°C	
Material	Al (black anodized)	Al (black anodized)		
Mass	3.2	3.8	kg	±5 %
Piezomotor controller	C-867.262 with USB joystick (included in delivery)			
Communication interfaces	USB, RS-232, Ethernet			
I/O Connector	4 analog/digital in, 4 digital out (Mini-DIN, 9-pin) digital: TTL; analog: 0 to 5 V, USB joystick			
Command set	PI General Command Set (GCS)			
User software	PIMikroMove			
Software drivers	LabVIEW drivers, GCS-DLL, dynamic link libraries for Windows (DLL) and Linux			
Supported functionality	Start-up macro, macro, data recorder / trace memory, MetaMorph, µManager, MATLAB			
Controller dimensions	320 x 150 x 80.5 mm (including mounting rails)			



Nanopositioning Overview

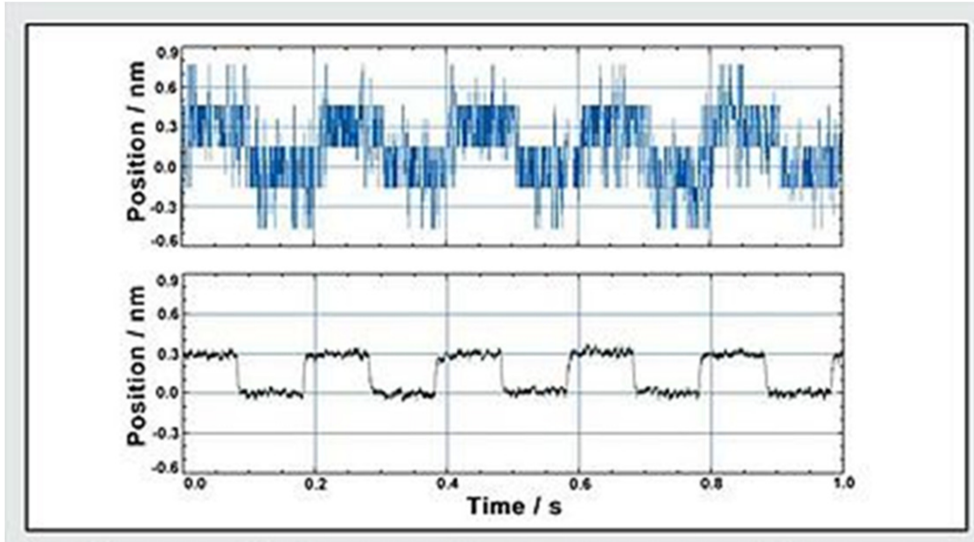
Figure 2

microscope basics



The size of things down to the nanometer scale. Focusing is key.

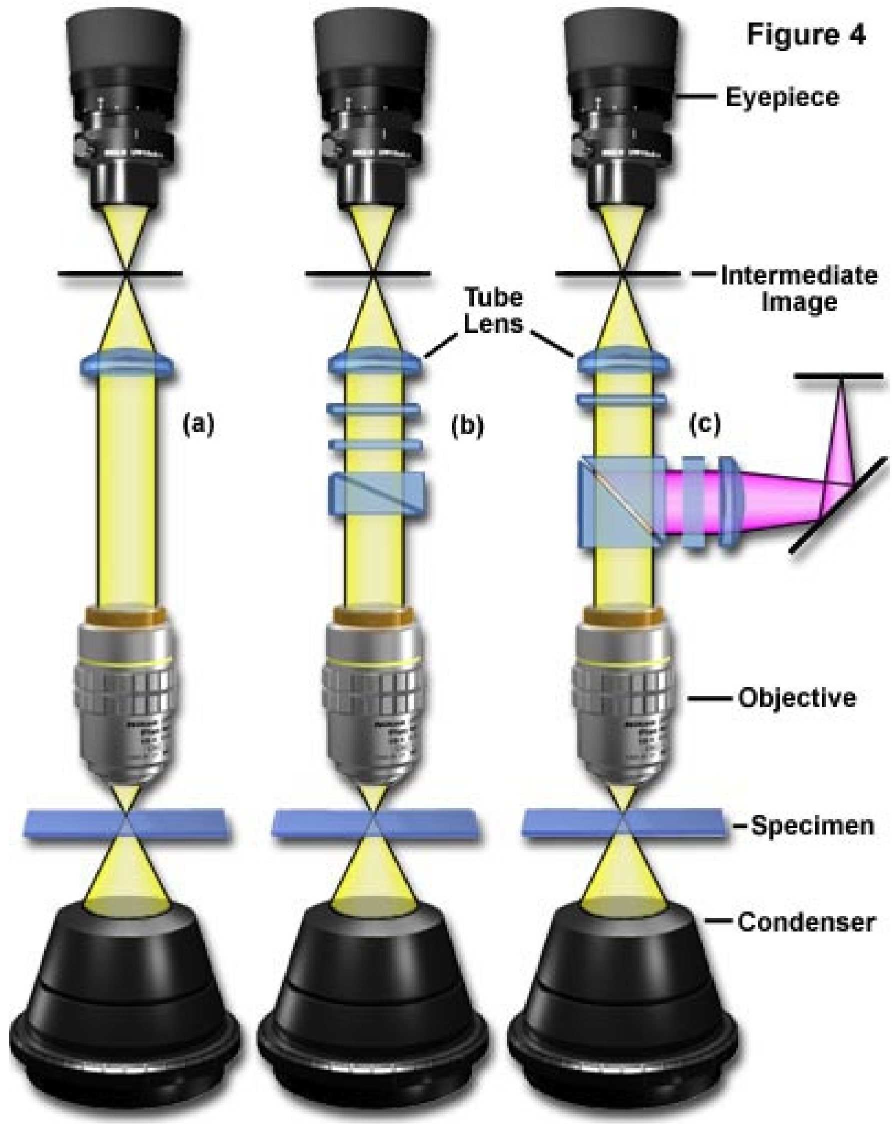
Moving a lens at the nanometer scale

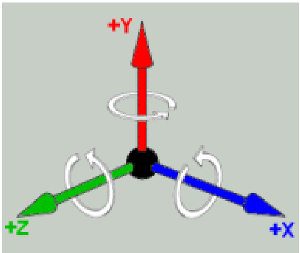


Measuring nanometer motion and position

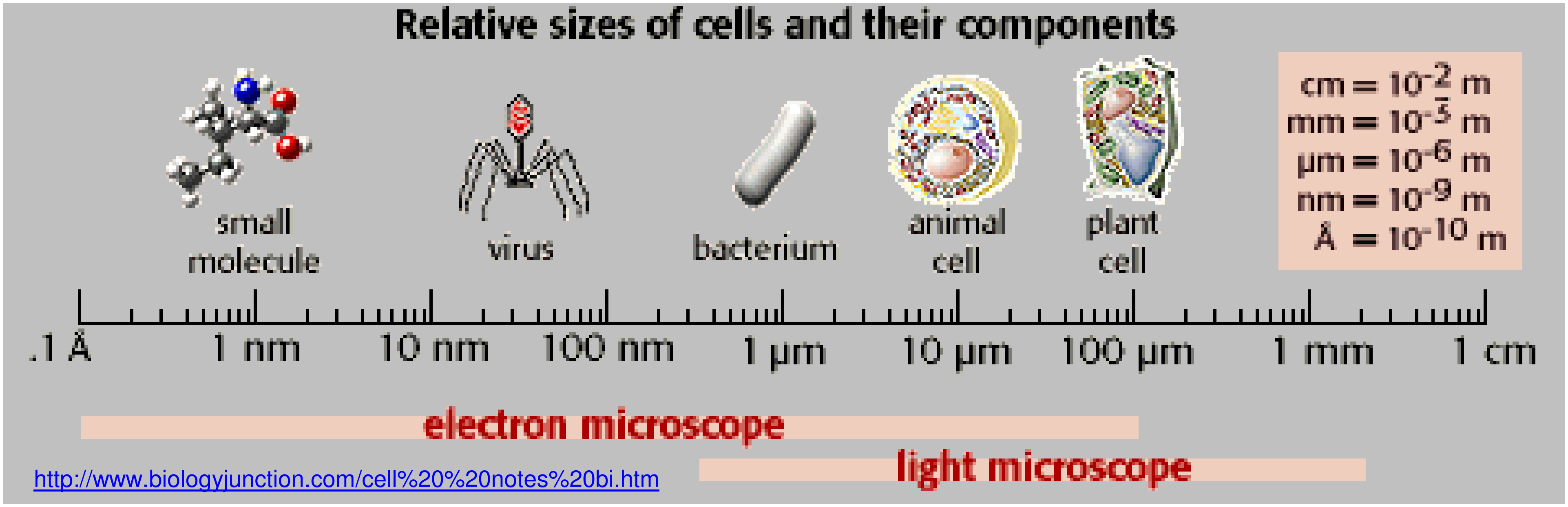
PI

Adding components to infinity corrected lenses





Why automate the focus mechanism to the nanometer level?



http://www.biologyjunction.com/cell%20%20notes%20bi.htm

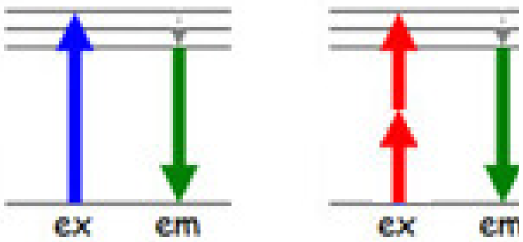
Confocal

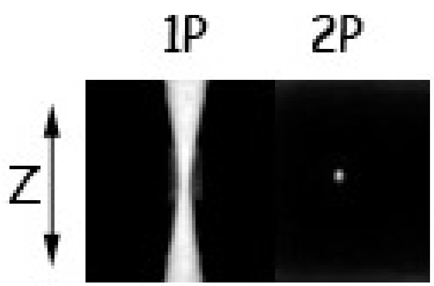
STED

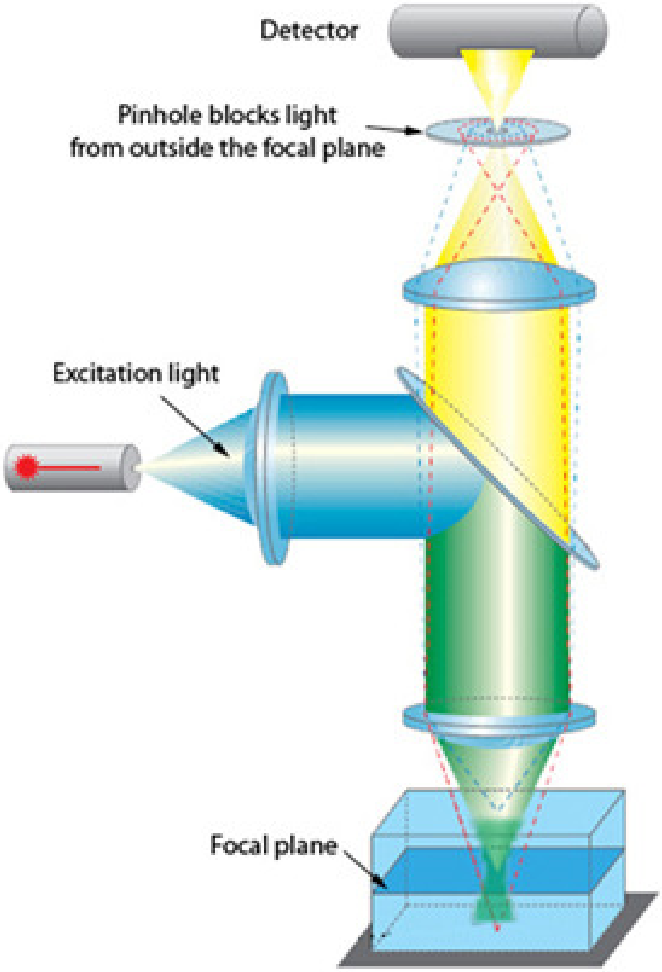
Stimulated emission Depletion

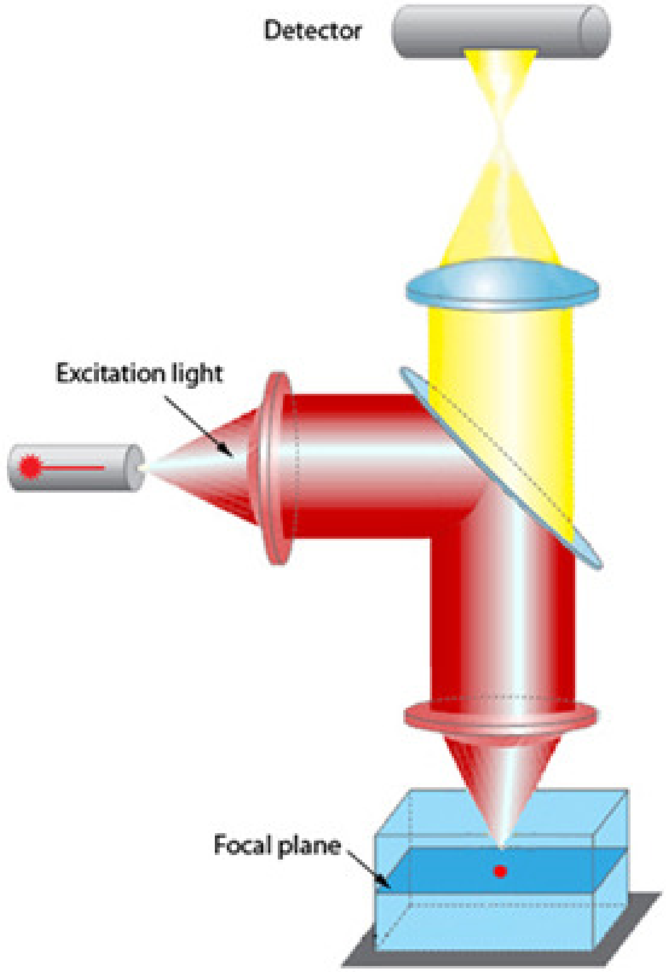
1-Photon

2-Photon





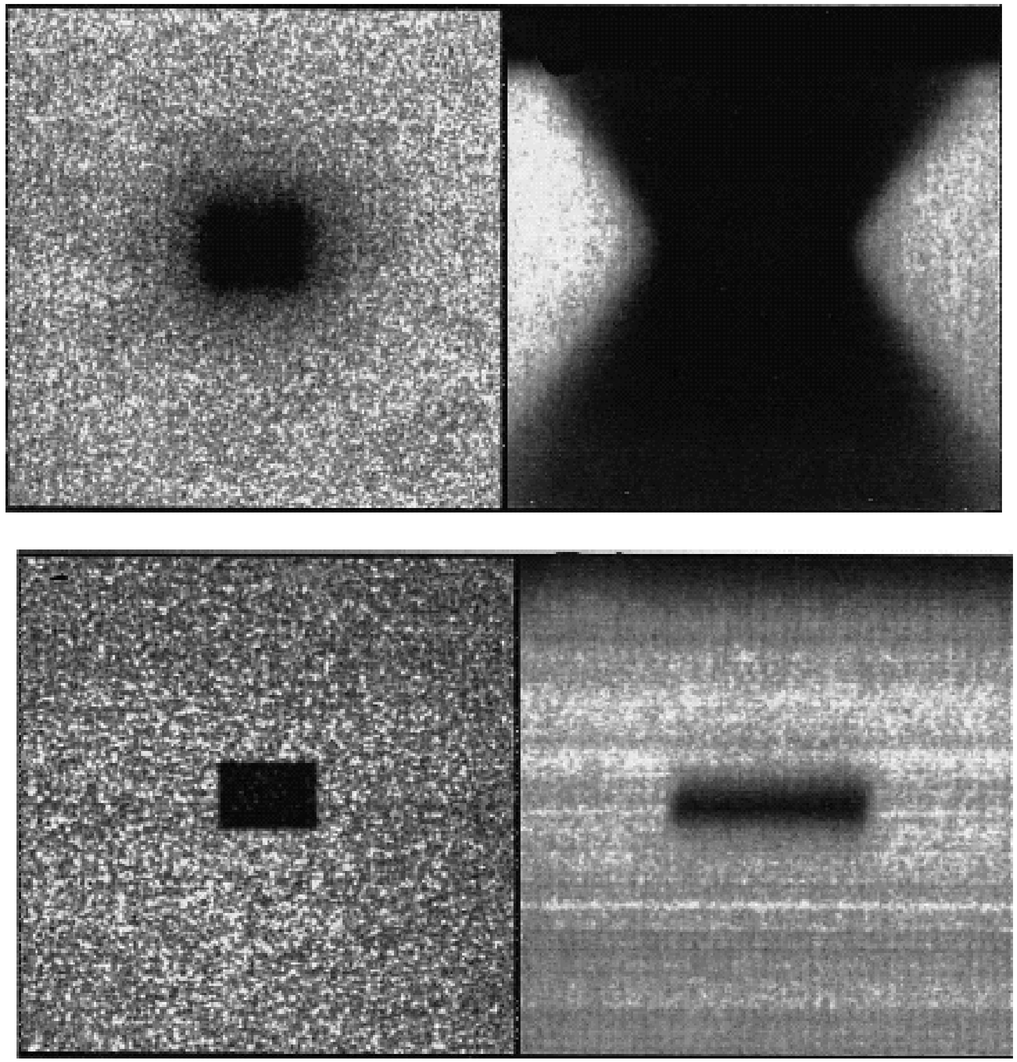




http://microscopy.duke.edu/introtomicroscopy/twophotonex.html

(3D-FITC-dextran gel; irradiated area ~ 10 x 20 µm)

single-photon absorbtion (488 nm; Ar)



focal plane

y
x

x
z

two-photon absorbtion (760 nm; Ti:Sa)

focal plane

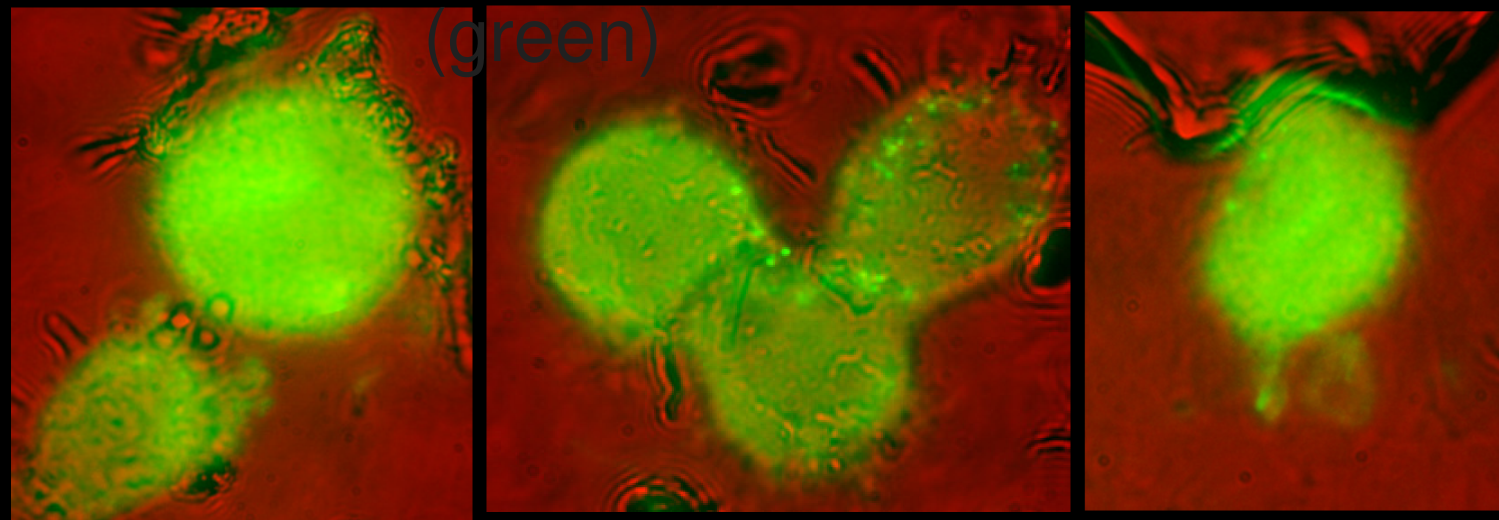
20 µm

10 µm

(with modification Kubitscheck et al., 1996)

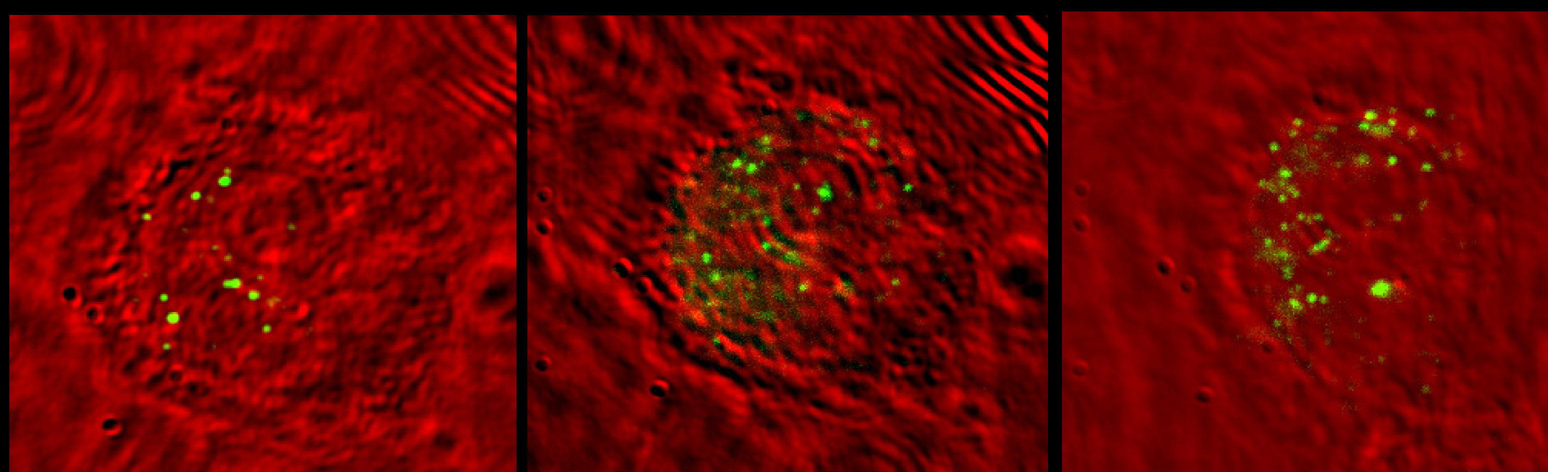
Overlay of cells' brightfield images (red) and fluorescence (green)

REGULAR FLUORESCENCE MICROSCOPY
A lot of autofluorescence



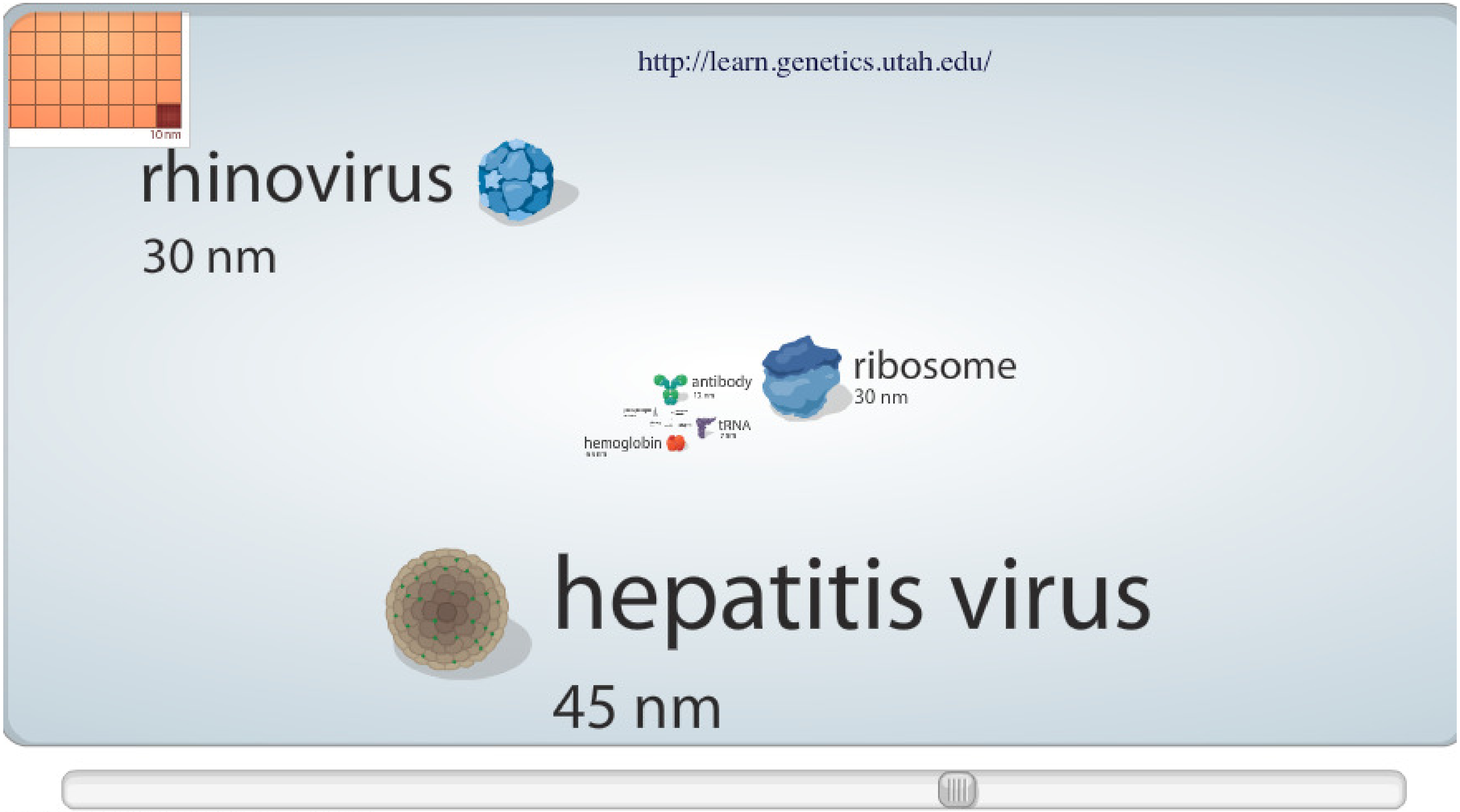
MDA-MB-468 Cells. 1nM QD (EB:SQ=1:1)

TWO-PHOTON Q-DOT EXCITED FLUORESCENC E MICROSCOPY



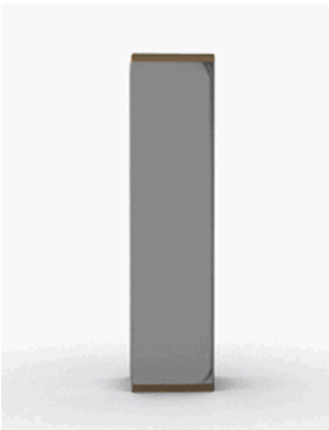
Eli Rothenberg at UIUC; Tony Ng and Gilbert Fruhwirth @ King's College School of Medicine & Dentistry, London

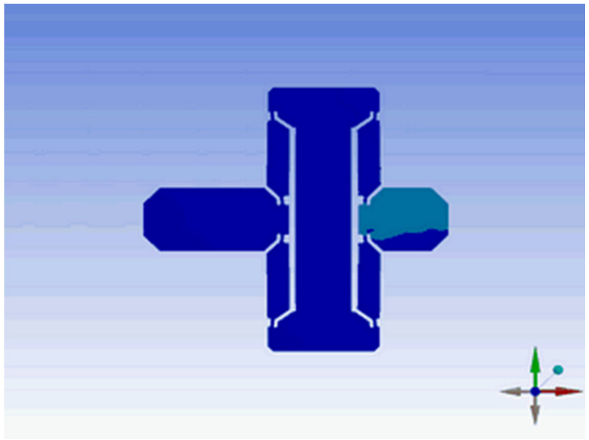
What are the requirements?

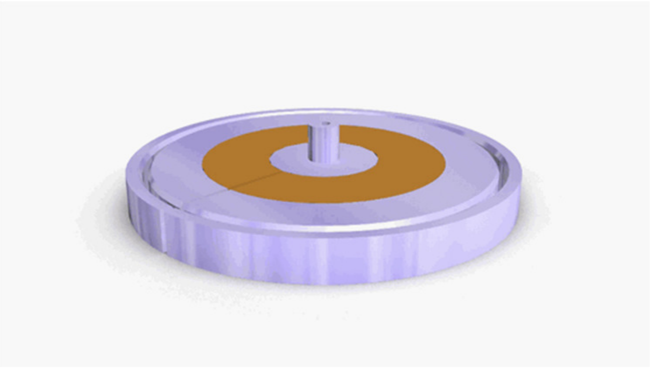


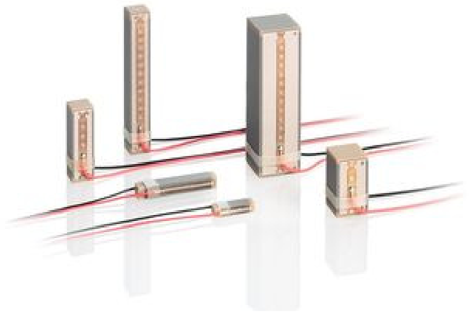
Meter (m)	Centimeter (cm)	Millimeter (mm)	Micrometer (µm) (aka micron)	Nanometer (nm)	Angstrom (Å)	Picometer (pm)
10^{0} m	10^{-2} m	10^{-3} m	10^{-6} m	10^{-9} m	10^{-10} m	10^{-12} m
1 m	0.01 m	0.001 m	0.000001 m	0.000000001 m	0.0000000001 m	0.000000000001 m
	1/100 m	1/1,000 m	1/1,000,000 m	1/1,000,000,000 m	1/10,000,000,000 m	1/1,000,000,000,000 m
	hundredth of a meter	thousandth of a meter	millionth of a meter	billionth of a meter	ten billionth of a meter	trillionth of a meter

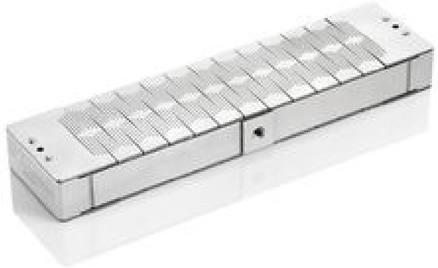
Different Types of Piezo Actuators



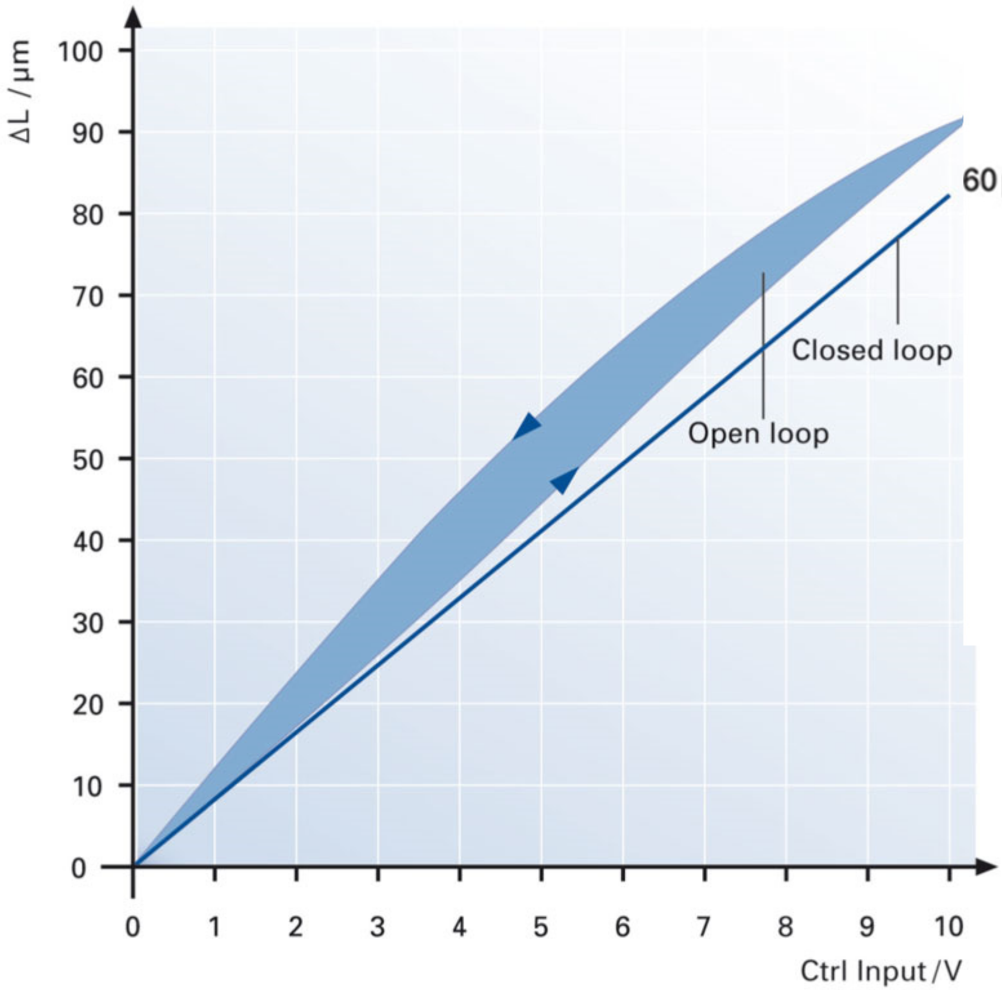




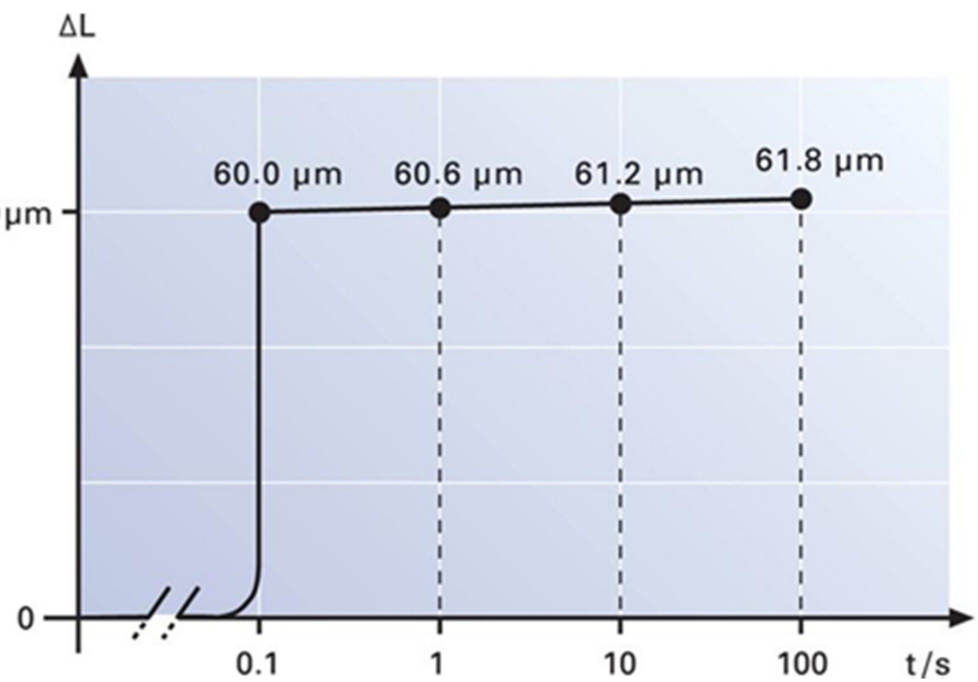




Open-Loop Piezo Operation - Hysteresis & Creep {drift}

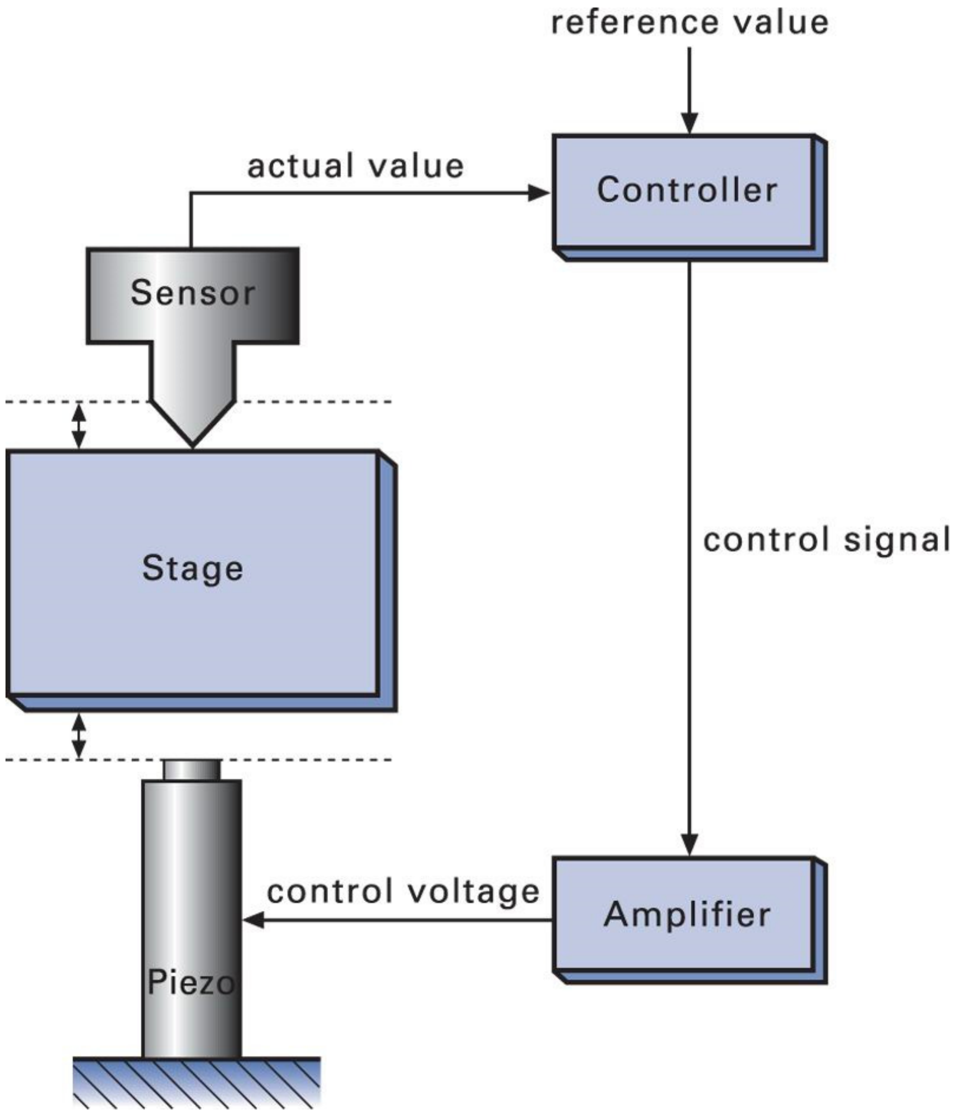


Open-loop vs. closed-loop performance graph of a typical PI piezo actuator.



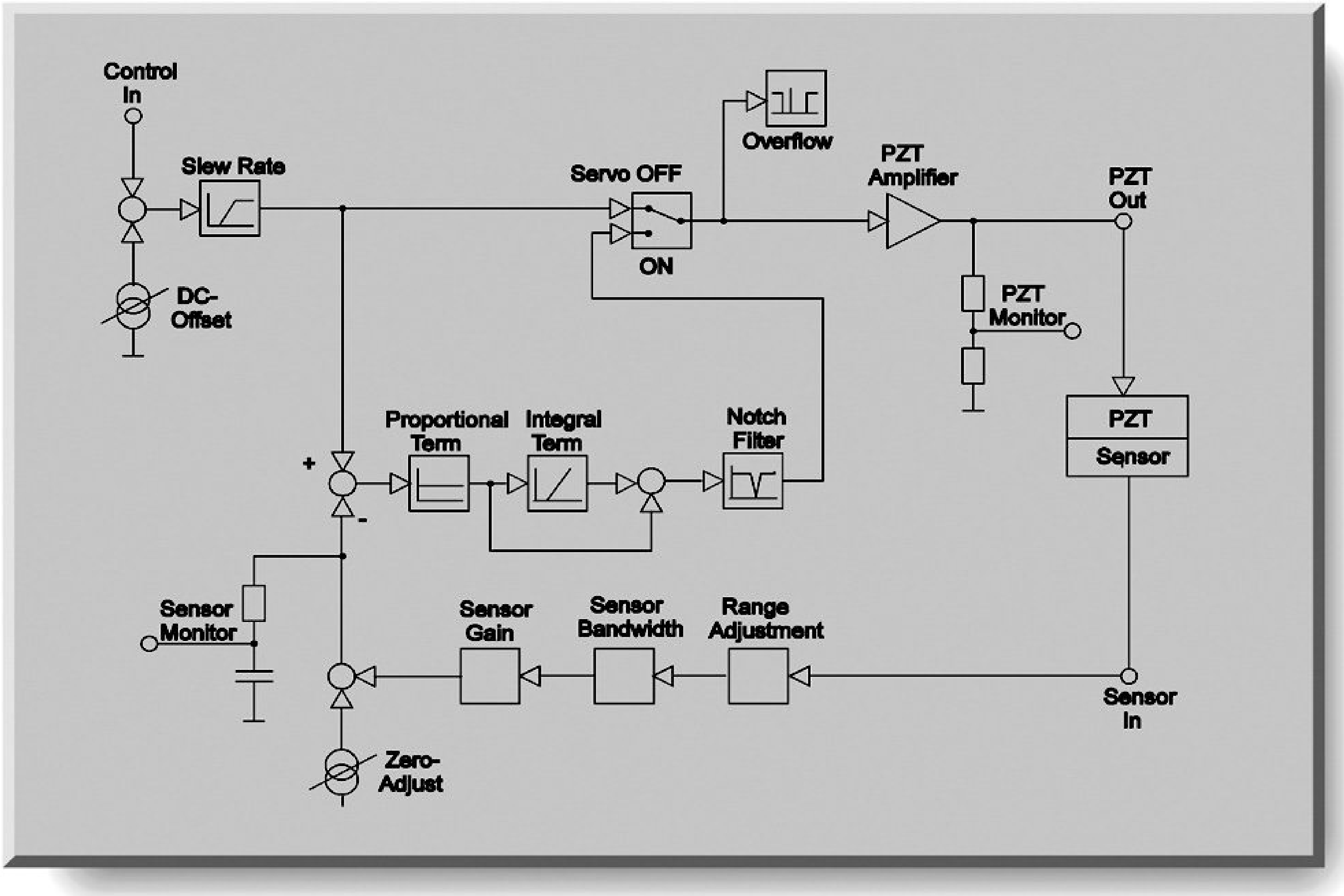
$$\Delta L(t) \approx \Delta L_{t=0.1}\left[1+\gamma \cdot \lg\left(\frac{t}{0.1}\right)\right]$$

Creep of open-loop PZT motion after a 60 µm change in length as a function of time. Creep is on the order of 1 % of the last commanded motion per time decade.

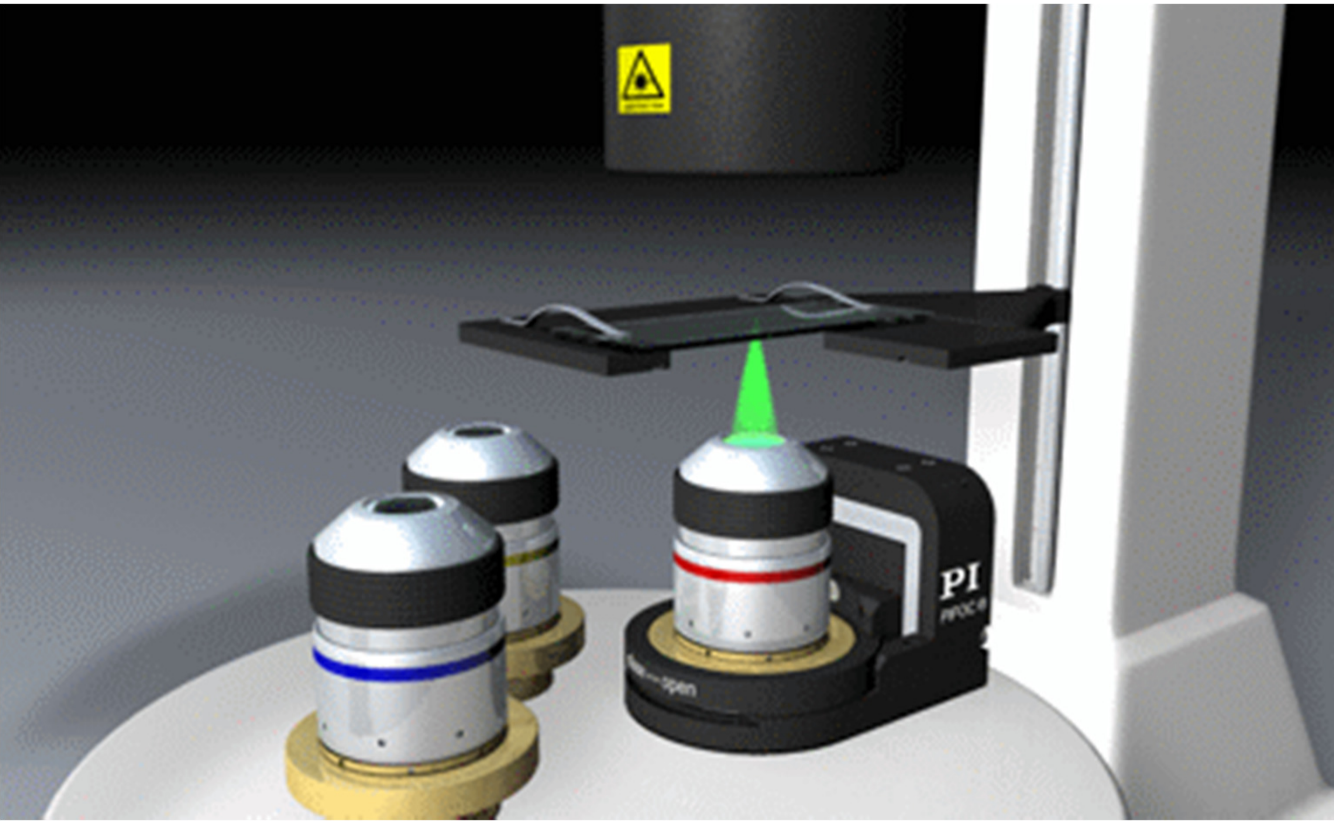


For optimum performance, the sensor is mounted directly on the object to be positioned (direct metrology).

Closed loop Piezo positioning system block diagram



Block diagram of a typical PI closed-loop piezo positioning system.

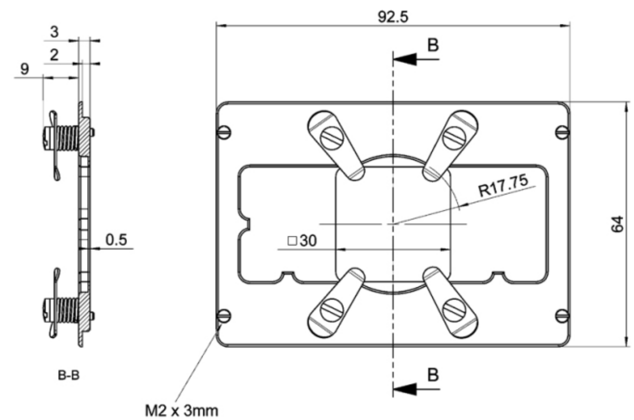


With Quick Lock Adapters
Work with all objective threads

Nanopositioning XYZ Super Resolution Microscopy Stage

P-545.xC7 PInano® Cap XY(Z) Piezo System

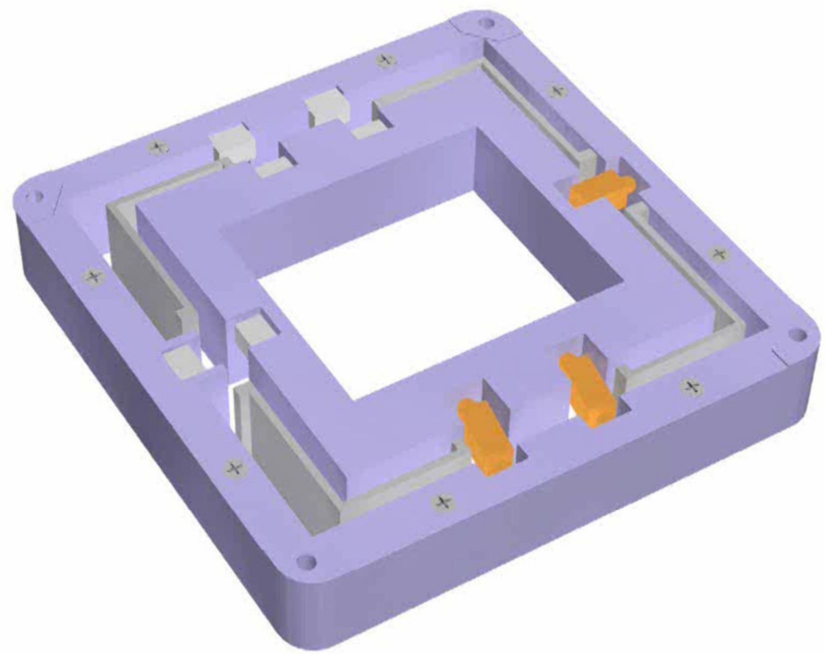
Capacitive positioning measurement for super-resolution microscopy



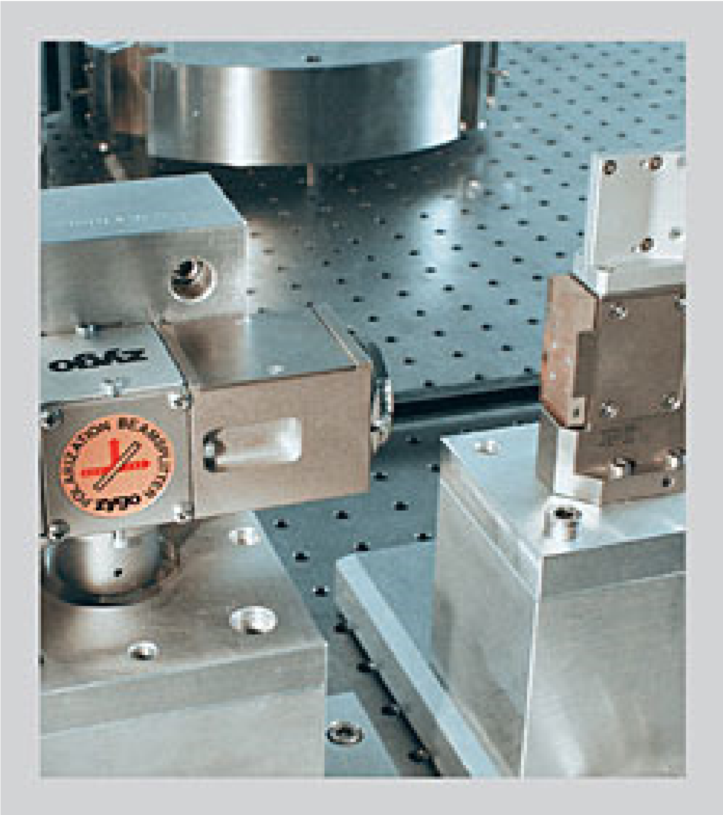
Accessories: sample & petri dish holders dimensions in mm

- Highest stability and repeatability
- Travel ranges up to 200 x 200 x 200 µm
- Sub-nanometer resolution
- ms-response times
- Low Profile for easy integration: 20 mm
- Recessed slide holder, free rotation of turret

Parellel Kinematics & Metrology



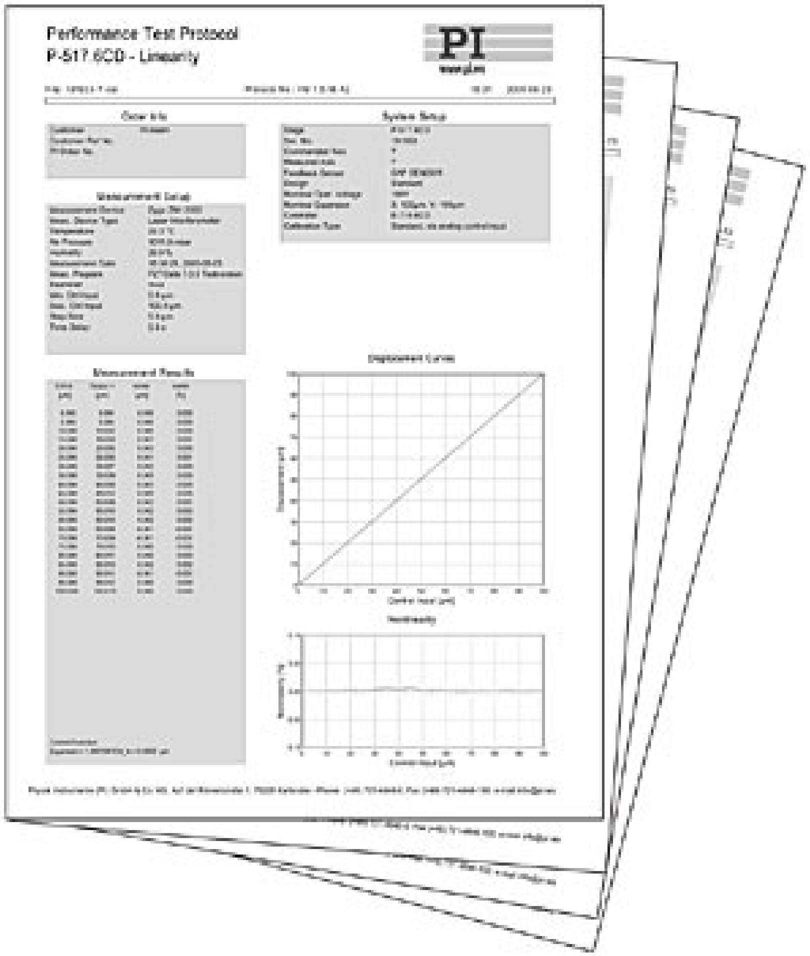
Piezo System Calibration



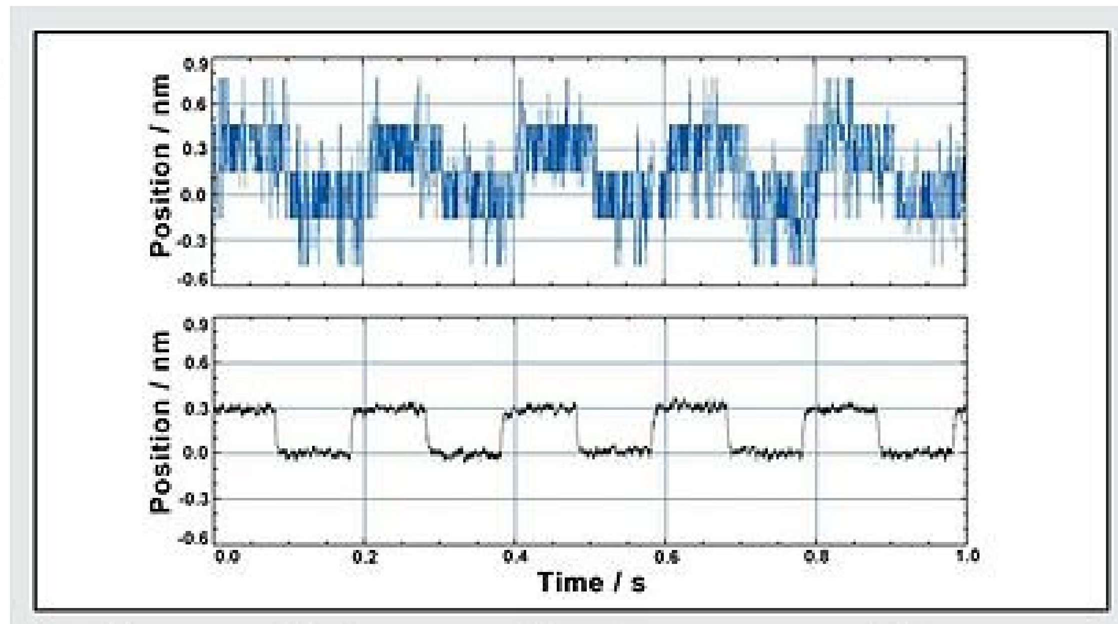
Prestigious Zygo ZMI-2000 and ZMI-1000 interferometers are used in PI´s nanometrology calibration labs. Each stage is individually calibrated and optimized for dynamic response.

State-of-the-art, room-in-room metrology lab with multiple thermal, acoustic and seismic isolation for meaningful sub-nanometer measurements.

Piezo system performance data



All PI nanopositioning systems come with extensive calibration documentation.



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

Not all sensor systems are equal

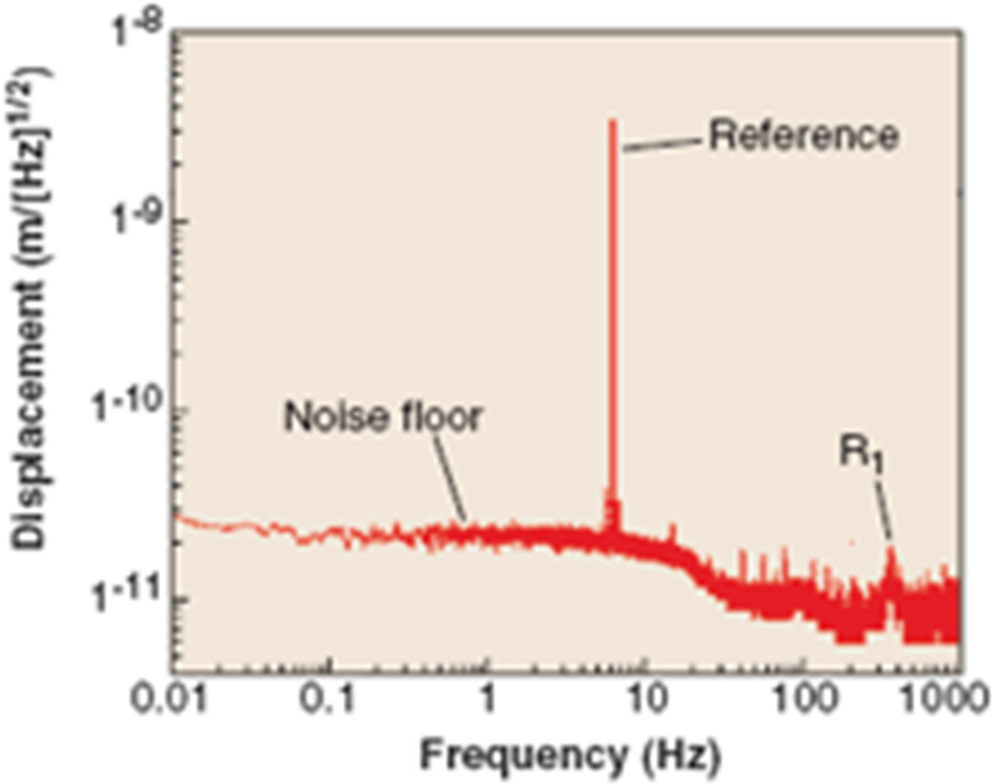
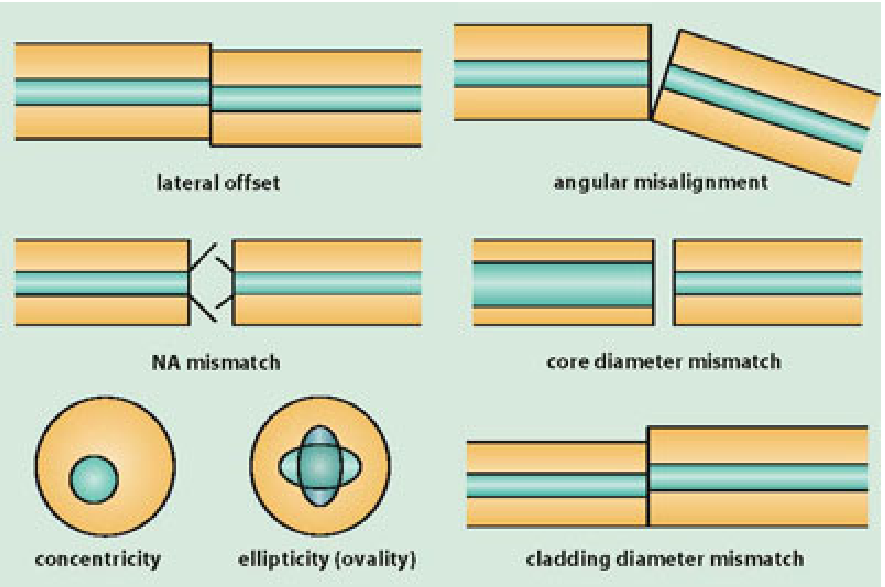


FIGURE 2. In a log-log plot of the peak-to-peak position noise of a 100 µm range-of-motion nanopositioner as a function of frequency, the reference is a 3.5 nm peak-to-peak sine wave at 7 Hz (R_1 is the same mechanical resonance as in Fig. 1). The noise floor for this stage is about 0.03 nm.

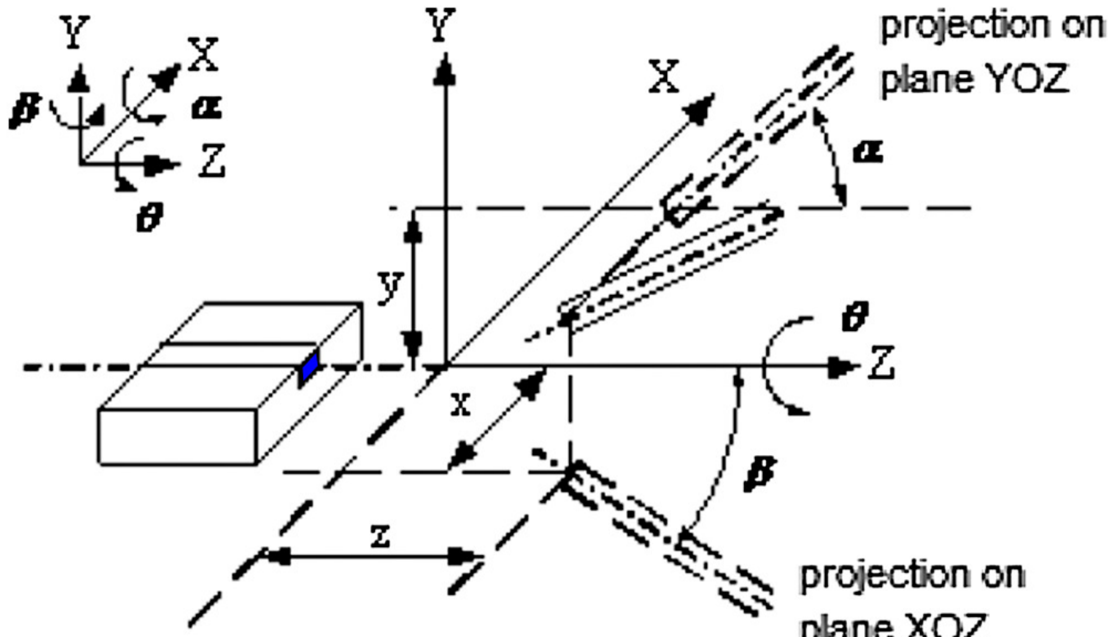
I can take just a few questions now

- And then we will move on quickly to the Photonic Alignment

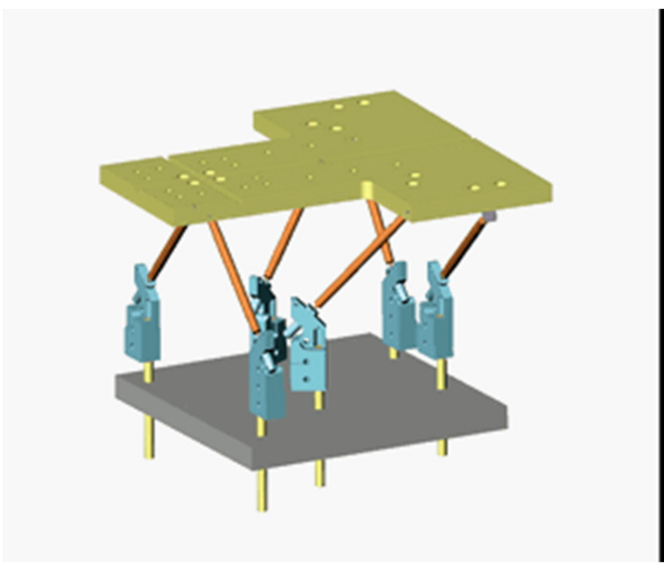
Fiber Optics & Photonics Alignment



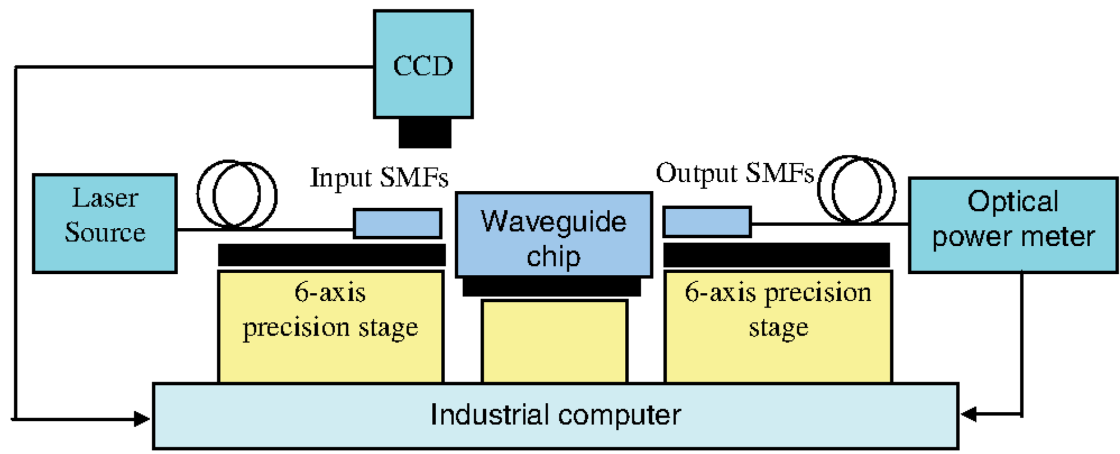
http://www.photonics.com/Article.aspx?AID=25152



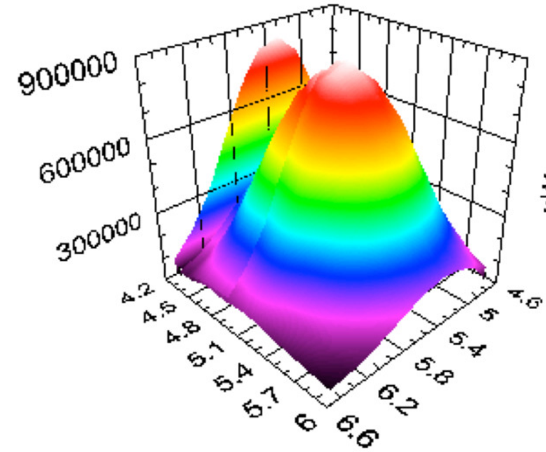
http://opticalengineering.spiedigitallibrary.org/article.aspx?articleid=1372920



http://www.hexapods.net/F206-Hexapod.htm



Photonic Alignment: The Industrial Challenge



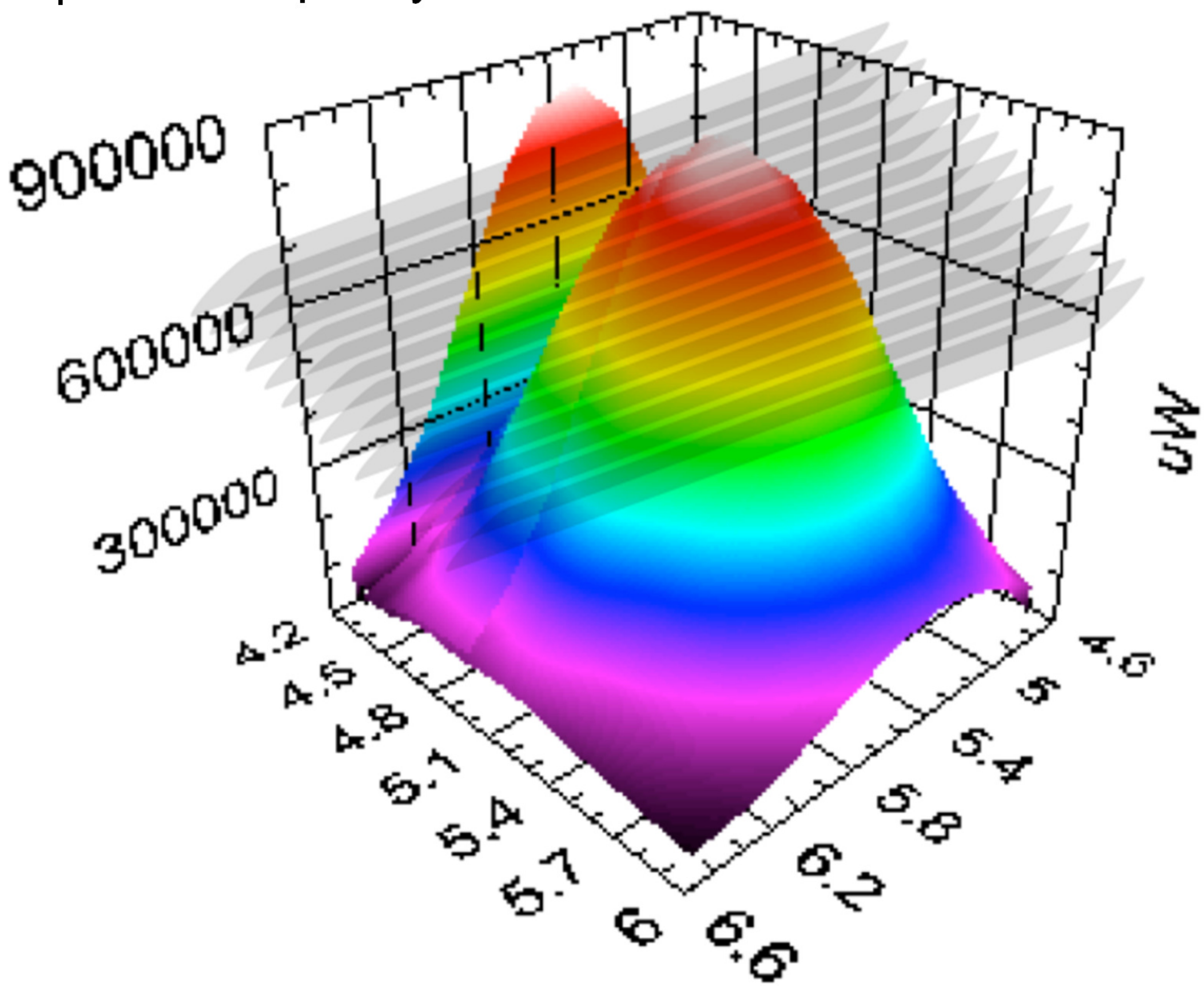
- <u>Problem Statement</u>
  - Alignment needs to be *accurate* on the nanoscale
  - Typical tolerances: 10-50nm
  - Device-device variation must be accommodated
  - Alignment is key to both characterization and packaging
  - Time is money

- Boom years 1997-2001 driven by telecom, dotcom explosion
- Industry overbuilt/overreached; collapsed overnight
- PI kept it key technologies H-206 and CyberAligner alive

- Resurgence driven by datacom and semiconductor manufacturing/ Silicon Photonics/ BioPhotonics/ Energy industries

Two Key Approaches

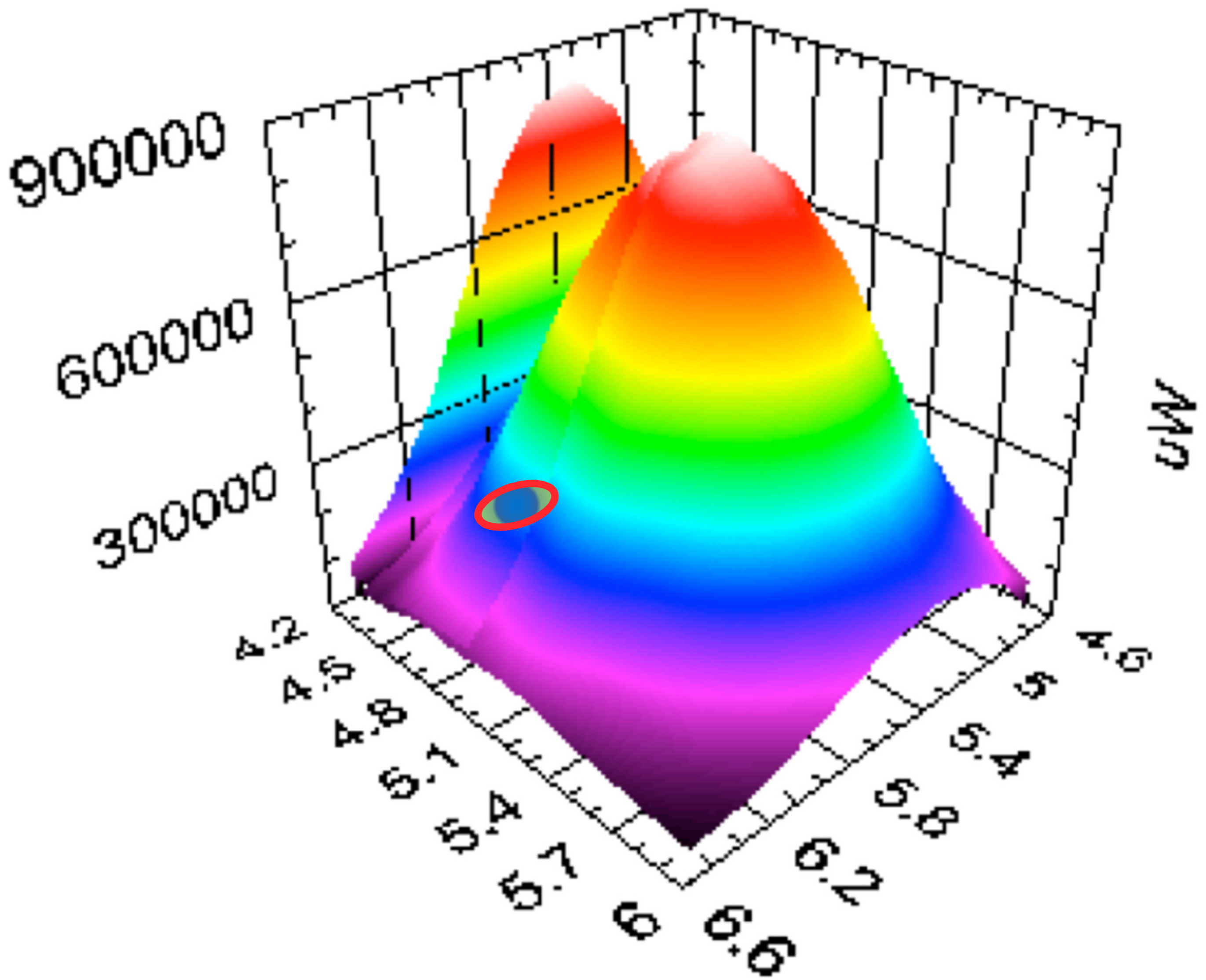
- Fast Raster
  - Piezo can make multiple slices quickly
  - Always finds the global max
  - Suitable for any coupling including messy multimode couplings
  - CyberAligner

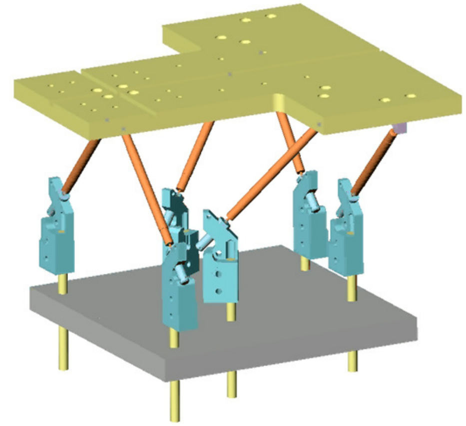


Two Key Approaches

- Gradient Search
  - Small circular dither
  - Algorithm determines “which way is uphill”
  - Suitable for clean single-mode couplings
  - Can track drift

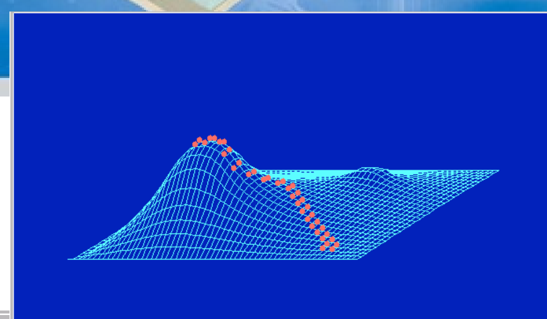
  - CyberTrack

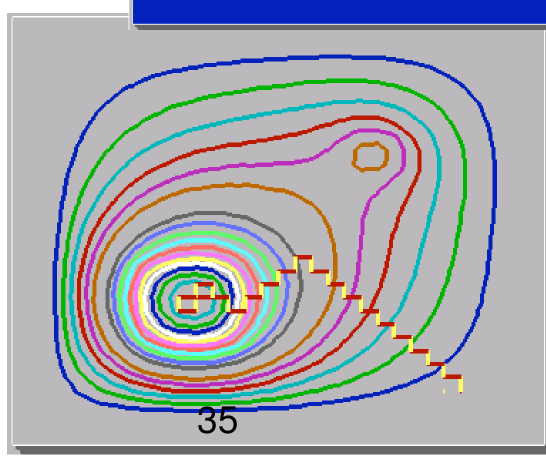


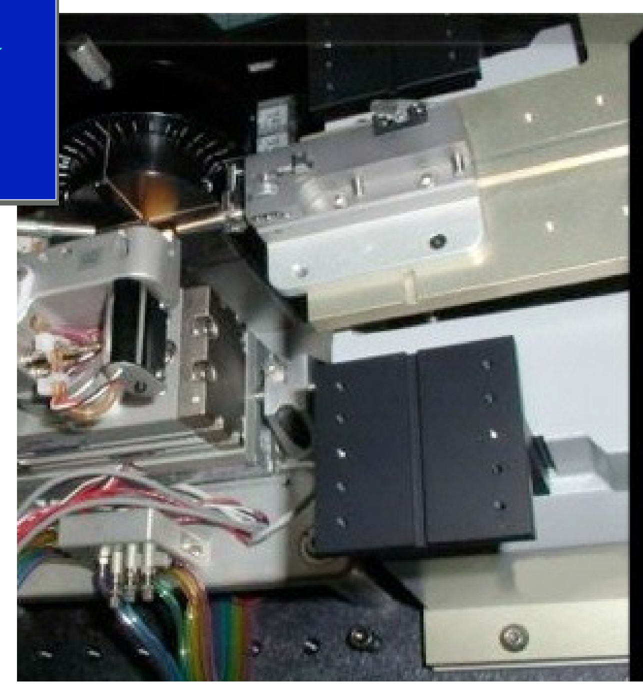


Hexapod Photonic Microrobots

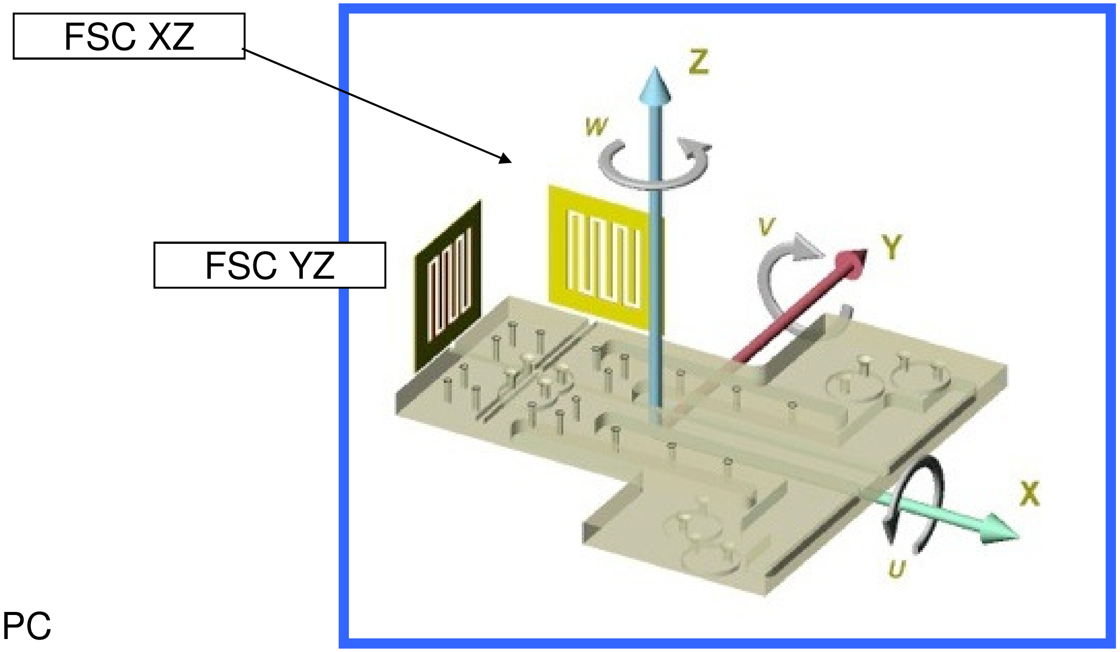
- Only product with:
  flexible angular
  alignment capability
  - Freely settable pivot point
- Built-in autoalignment and scanning capability
- Built-in metrology
- Many alignment options
  - Scans
  - Stepwise gradient search
  - Hybrid/mixed approaches
  - Angle alignment
- Broad architecture
- New higher-load hexapods



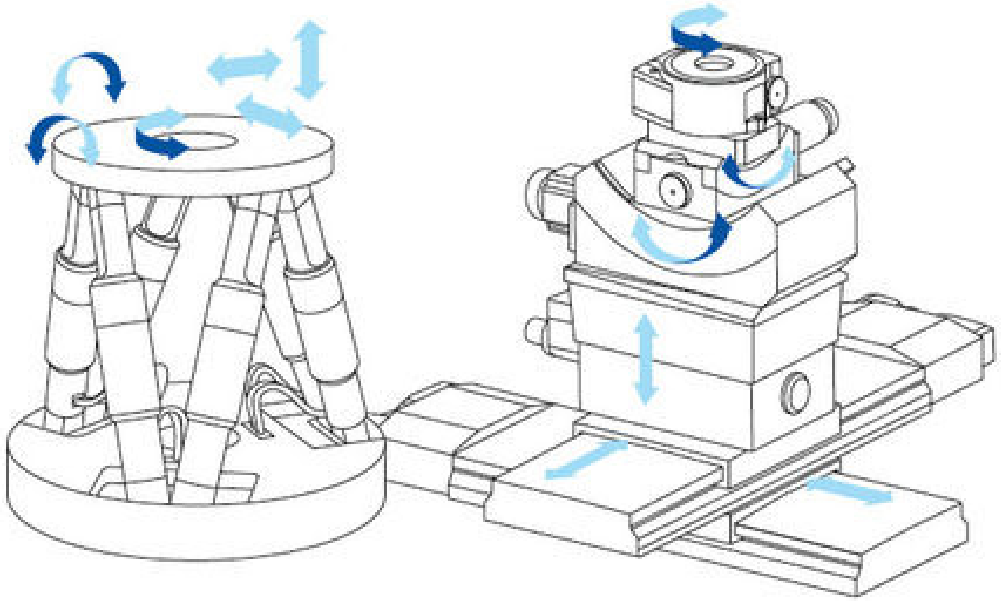




Hexapod advantages

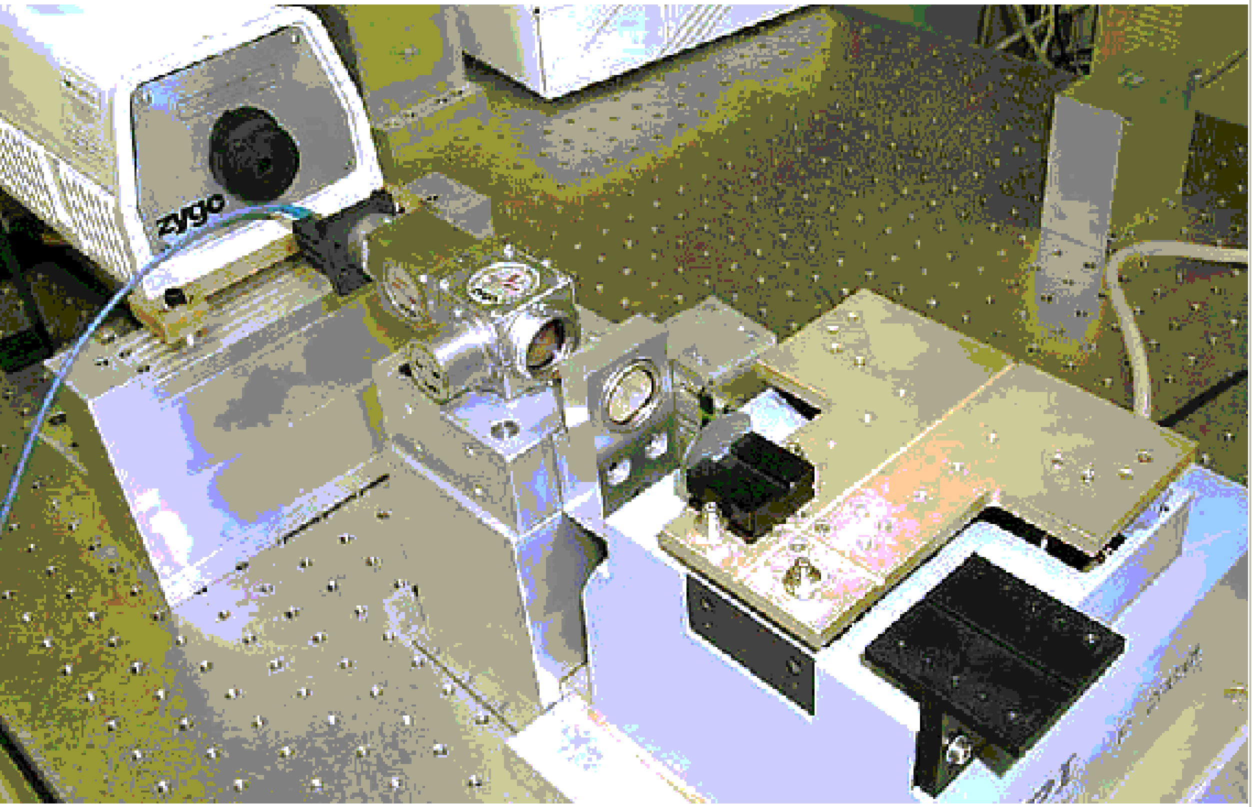


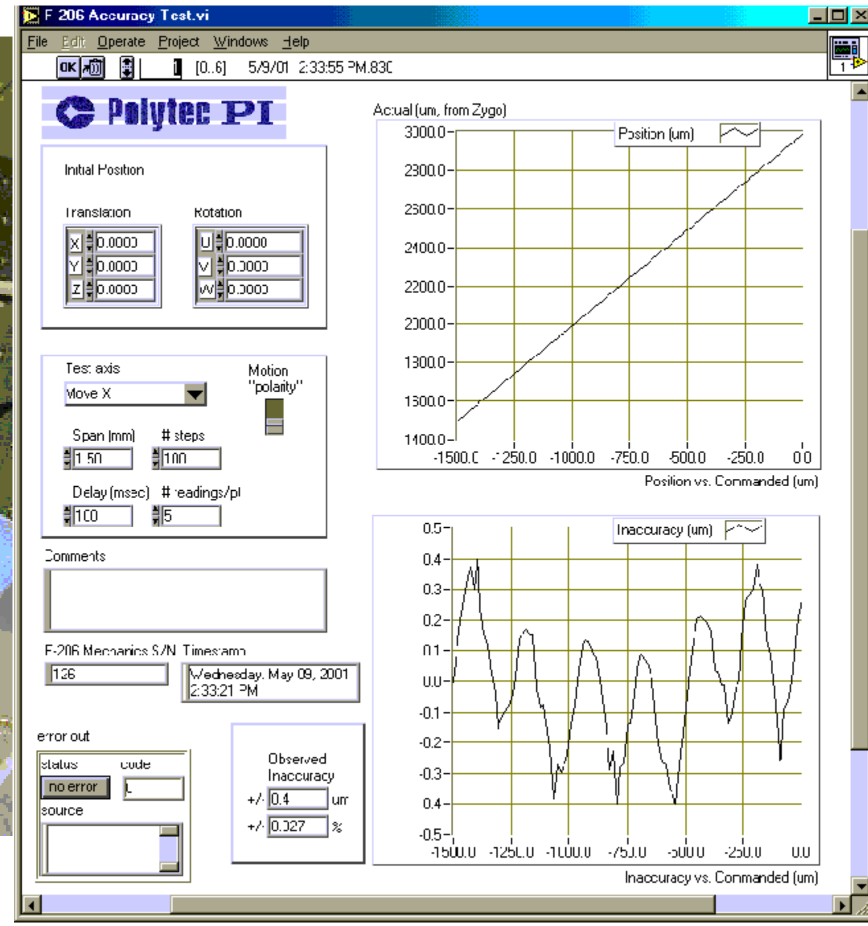
- Trajectory is not defined by bearings
- More compact than stacked stages
- 6 degrees of freedom
- High rigidity (>500Hz w/10kg load, H-850)
- High resolution (0.1µm, H-206)
- Leverages proven technologies
  - DC Servomotors
  - Catalog motor controllers in diskless industrial PC
  - Simple RS-232 & TCP/IP communications
  - Fully automatic 6-space transform



PI

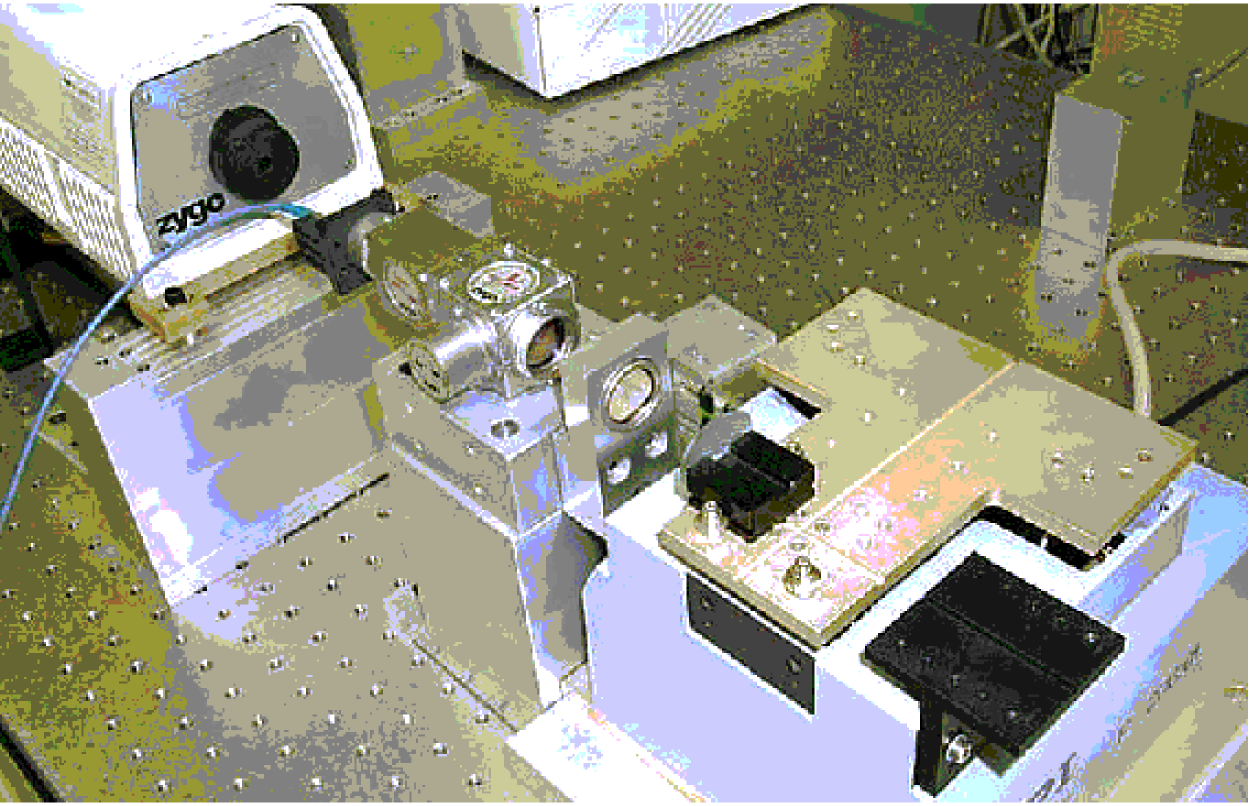
Hexapod performance

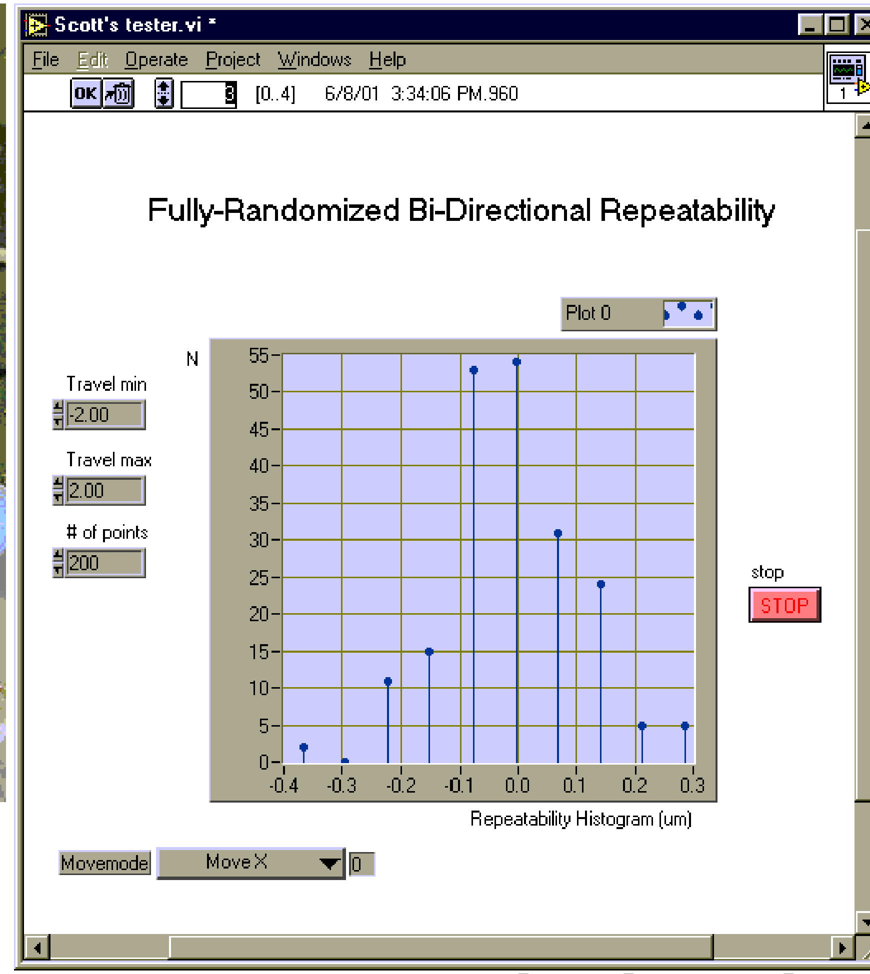




6-DOF performance surpasses *single-axis* capabilities of the world's best stages

Hexapod performance

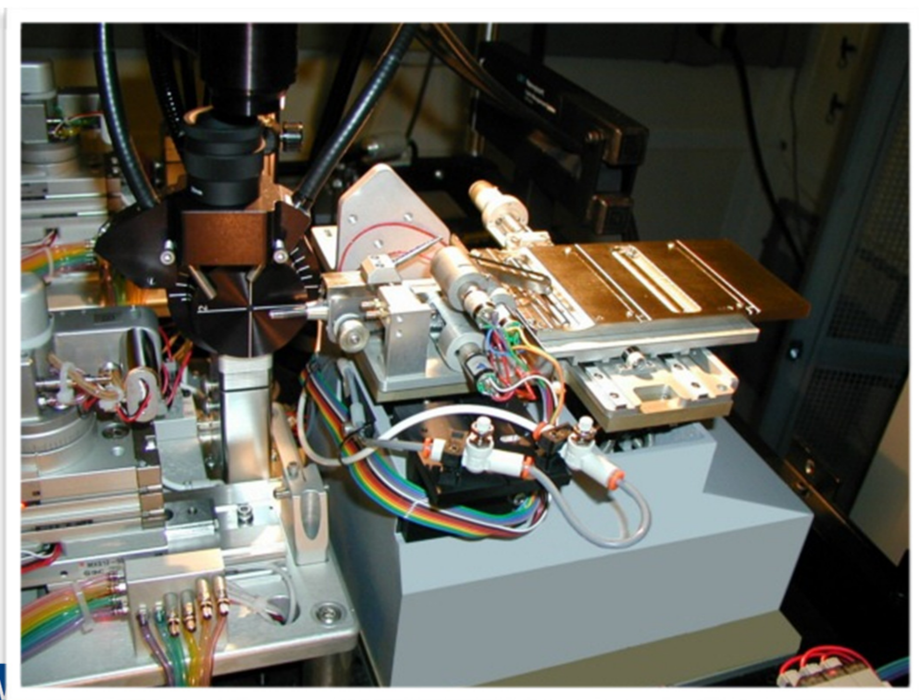


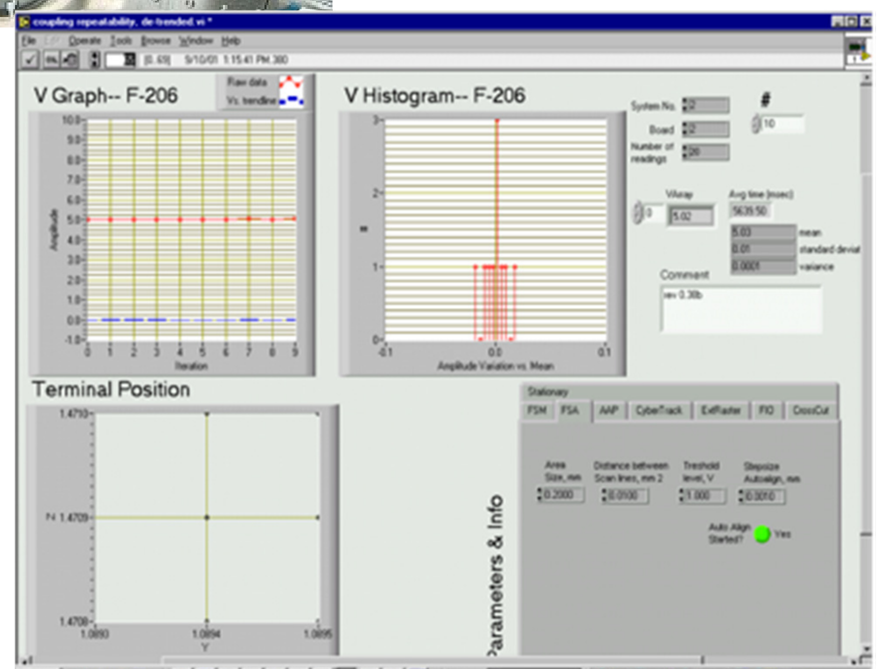


6-DOF performance surpasses *single-axis* capabilities of the world’s best stages

Example applications

- MEMS packaging & test
- Laser diode pigtailing
- COT alignment
- DWDM assembly
- AWG packaging
- Hybrid & Integrated Interconnects
- Silicon photonics

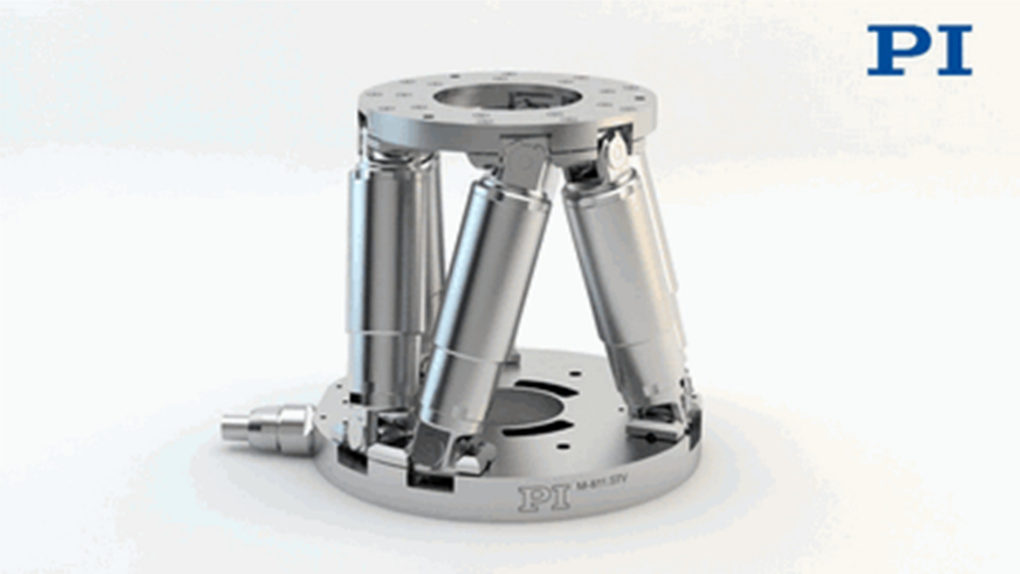


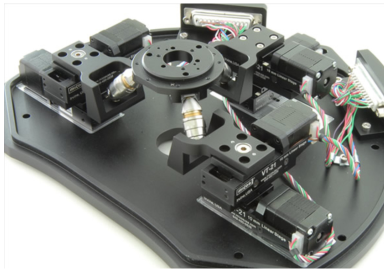


Many different types of solutions

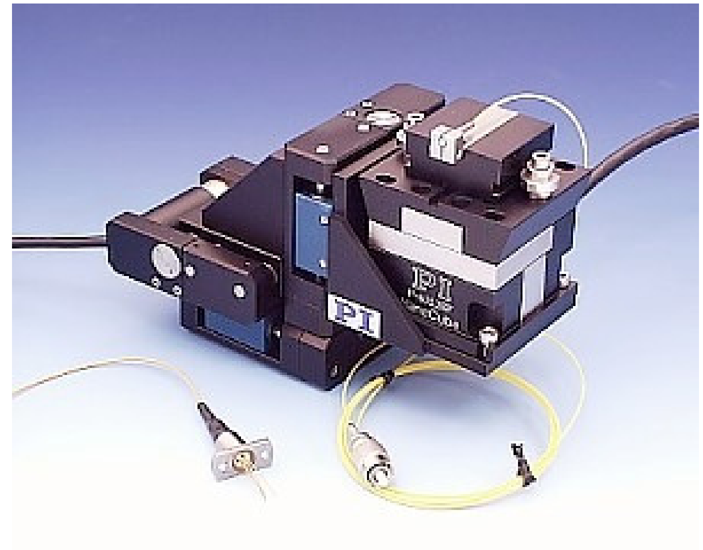
- Hexapods like H-811 & other models
  - Higher loads, alternative orientations
  - Same controller & integrated capabilities as H-206
  - 50nm resolution version

- SpaceFab
  - Broad family of 6-DOF systems
  - Basis for many integrated systems
  - Variety of stepper, servo & piezomotor drive options
  - Design optimized for horizontal travel

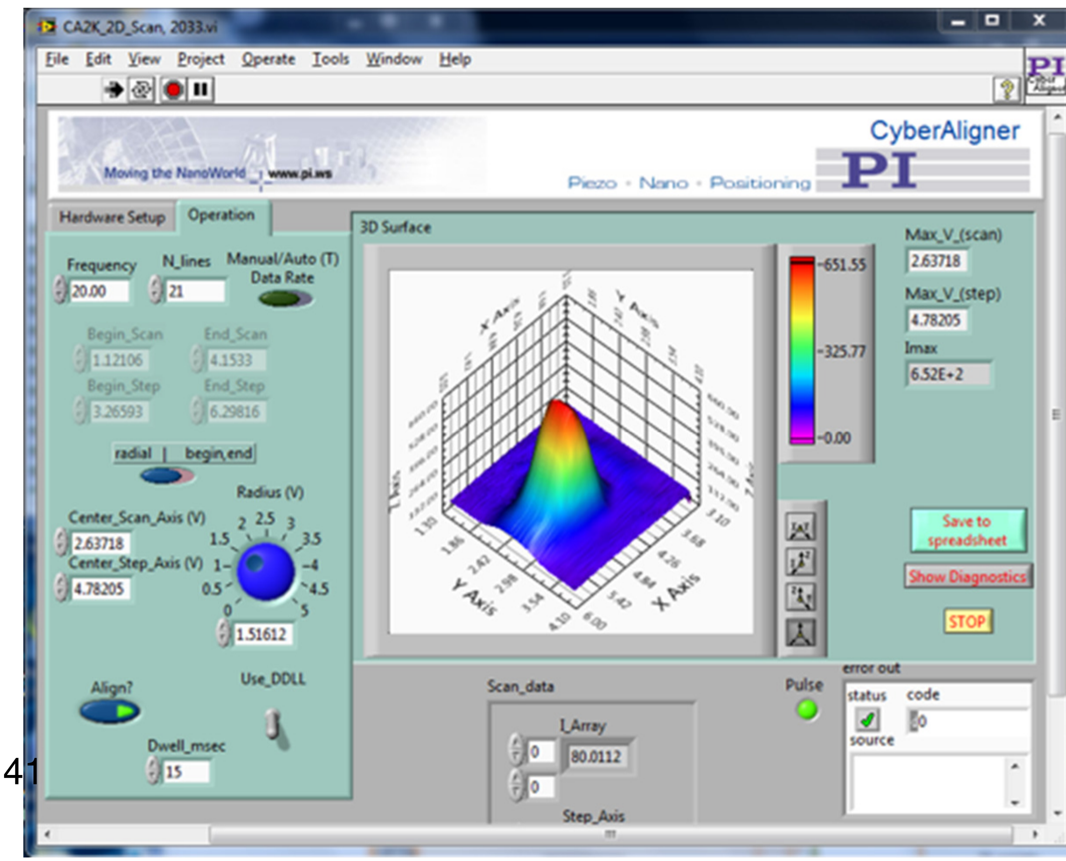




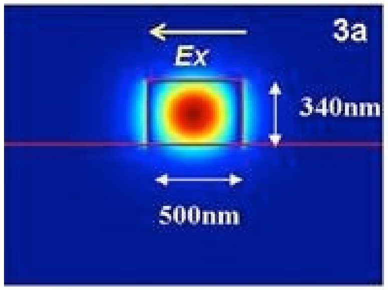
Digital Gradient Search, Ch. 2: CyberAligner & CyberTrack

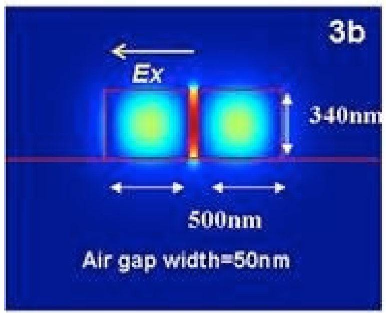


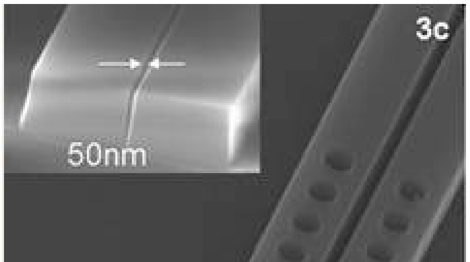
- **CyberAligner**: Highly efficient (~400msec) full-field alignment, 100x100um
  - Profiling as integral step yields valuable process info
  - Aligns anything
- **CyberTrack**:
  - Patented new digital gradient search (U.S. pat. #7,236,680)
  - On-the-fly alignment approach tracks in real time
  - Fast and flexible
- **Hybrid** approach avoids local lock-on
- Software-based GUI workstation
- Automation integration
- NxM implementation

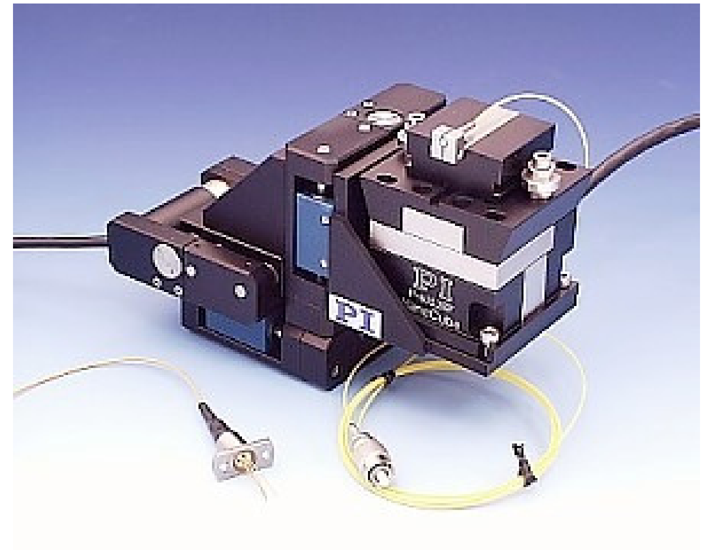


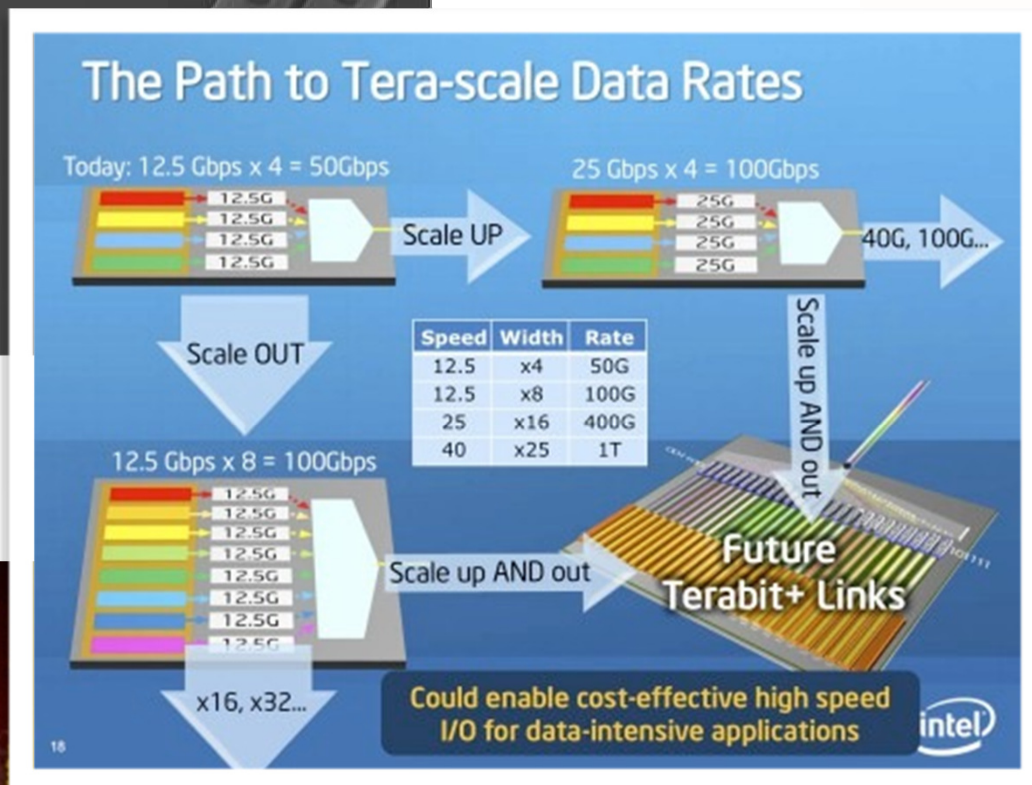
Silicon Photonics

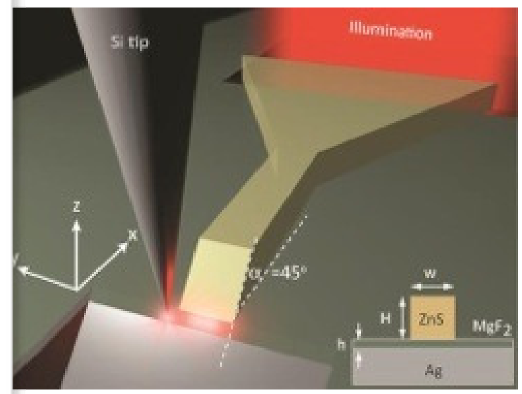


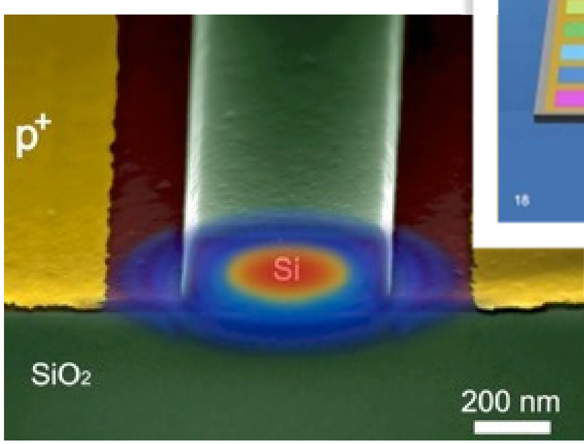




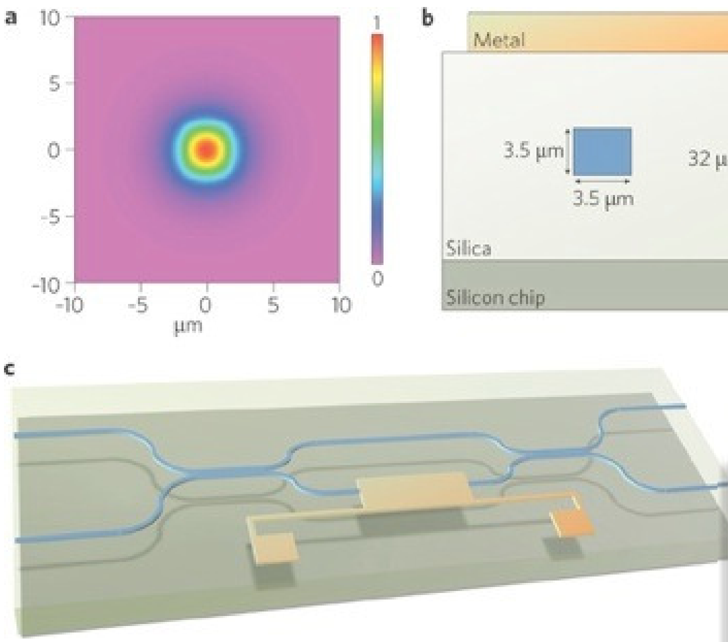


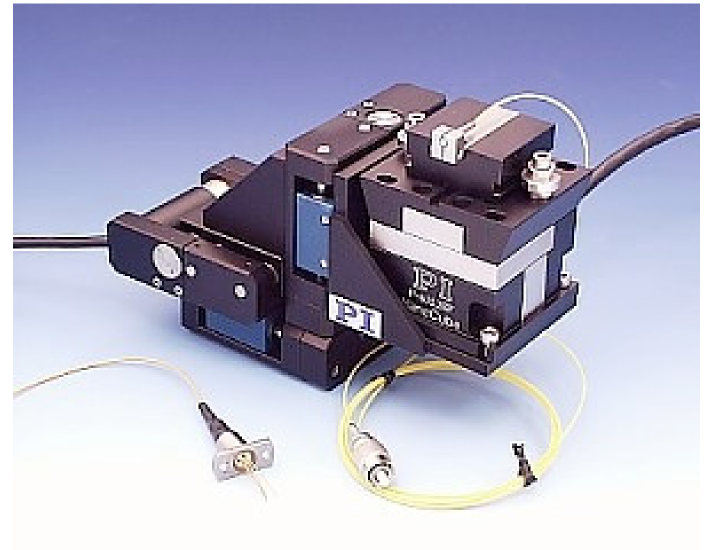


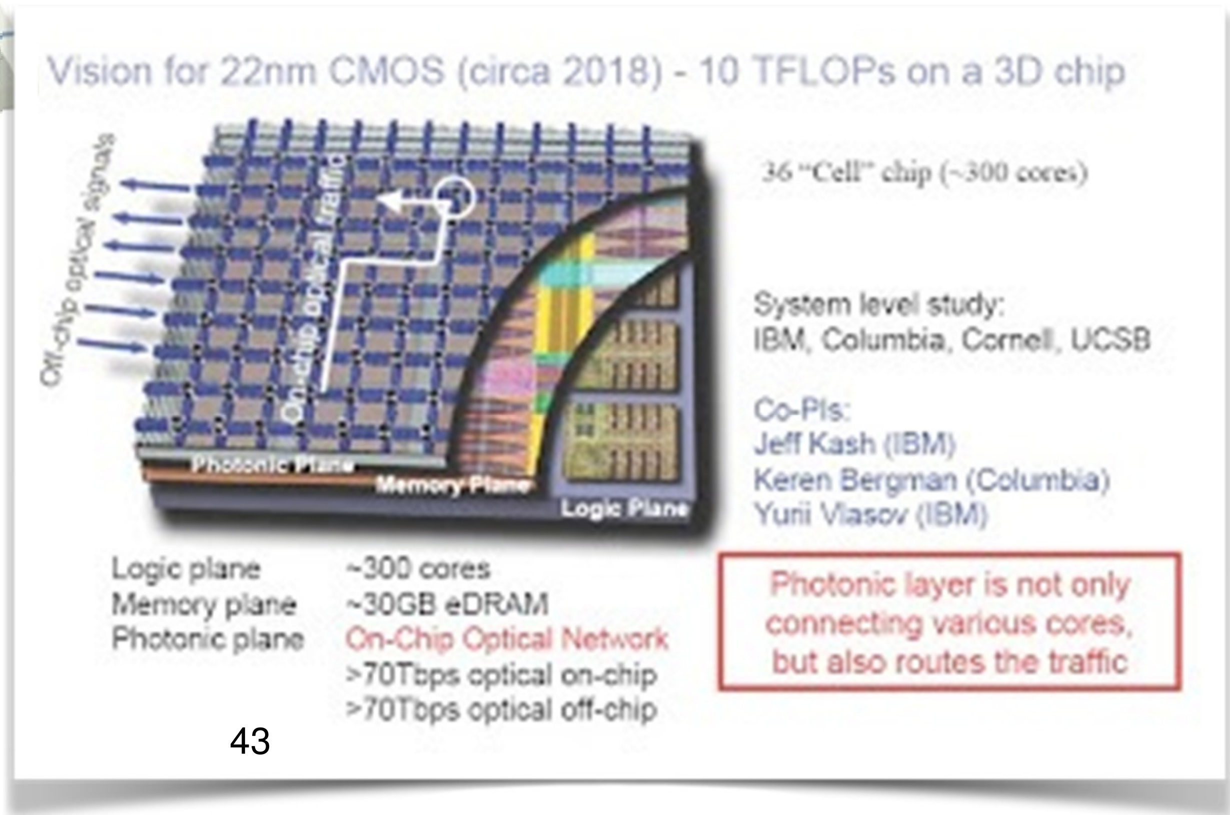


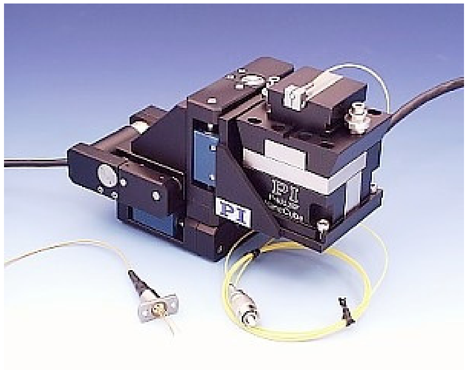


Silicon Photonics





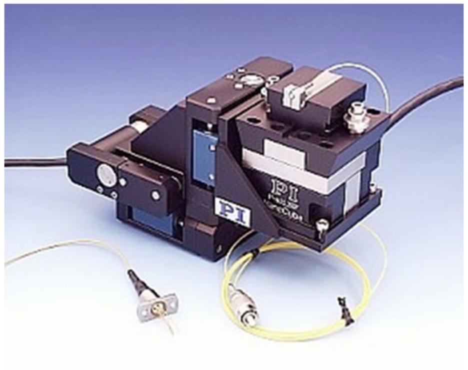




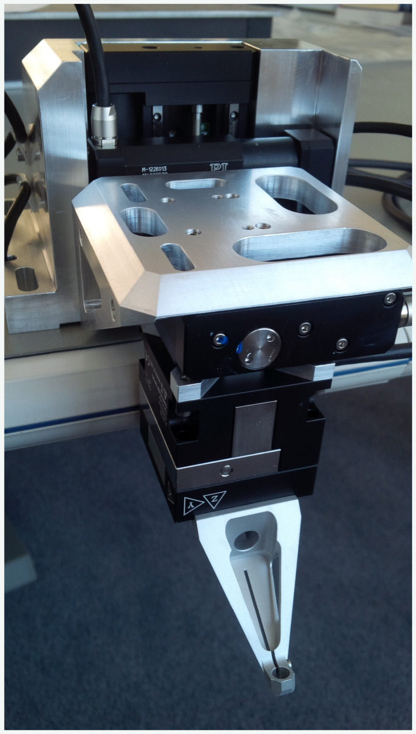
The NxM algorithm

- Aligns multiple inputs and outputs to an optical channel simultaneously
- Example: SiP waveguide alignment:

The Fab-Focused E-712 Implementation



- 4X faster
- Rack mounted, all-digital, integrated coarse-fine solution
- Initial application: planar device test

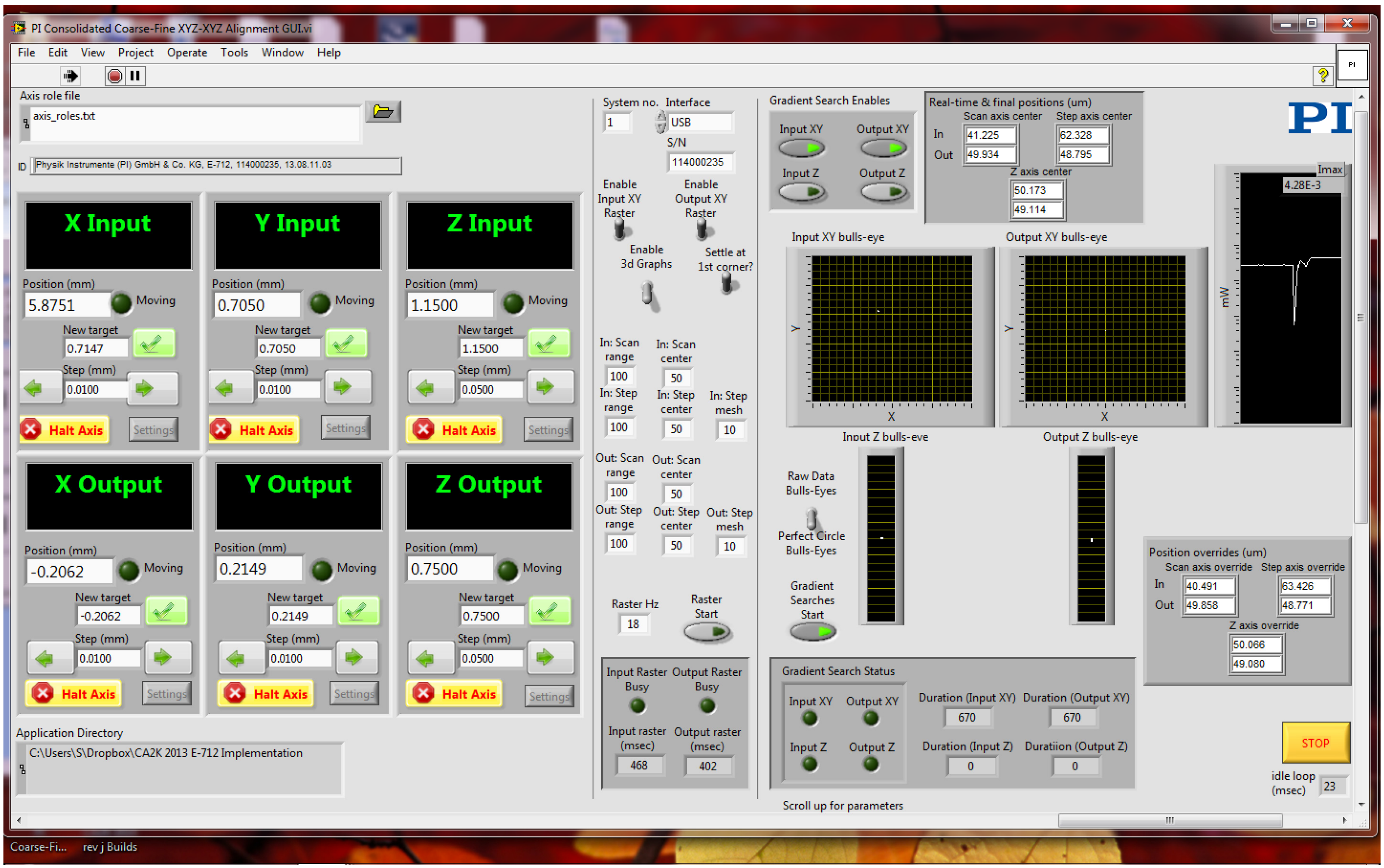


The Fab-Focused E-712 Implementation

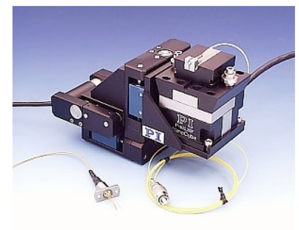
[redacted]

The Fab-Focused E-712 Implementation

- Comprehensive, integrated, fully scriptable coarse/fine GUI interface



Summary: Four unique platforms



	Hexapods	SpaceFab	CyberAligner/ CyberTrack	E-712
Transverse automation	✓ built-in	✓	✓ built-in	✓ built-in
Z automation	✓	✓	✓ built-in (waisted)	✓ built-in (waisted)
Angle automation	✓	✓		
Fully integrated, single-command format	✓		(VI based)	✓
Alignment Speed	High		Higher	Highest
Resolution	High	High	Higher	Highest
NxM capability			✓	✓
Real-Time Tracking			✓	✓

Automated Silicon Photonics Processes

We have time for a few questions now before heading into the NPI discussion.

Optics & Photonics:
Lighting a Path for the Future

Some slides used with permission from Thomas Baer, Executive Director, Stanford Photonics Research Center, NPI Steering Committee Chair.

What is the NPI?

A collaborative alliance seeking to unite industry, academia and government to identify and advance areas of photonics critical to maintaining US competitiveness and national security.

Organizations Involved

Founding Sponsors:

OSA®
The Optical Society

SPIE.

Sponsors:

APS physics™

IEEE photonics® SOCIETY
Transforming science into technology™

LIA
Laser Institute of America
Laser Applications and Safety

NATIONAL PHOTONICS INITIATIVE

Collaborators

SPRC The Stanford Photonics Research Center

NEW YORK PHOTONICS PHOTONICS

CREOL UCF

The Institute of OPTICS

THORLA

Florida Photonics Cluster

OPTICAL SOCIETY OF SOUTHERN CALIFORNIA

DIRECTED LIGHT IN
Focusing on Innovative Solutions

istry for Life®

LASER MECH

infinera

College of Optical Sciences
THE UNIVERSITY OF ARIZONA

Advanced Photonic Crystals, LLC

JENOPTIK

NATIONAL ACADEMY OF SCIENCES
1863–2013 • Celebrating 150 Years of Service to the Nation

Supporters

UNIVERSITY of DAYTON

Raydiance
Precision Like No Other

Mi-Light
Michigan Photonics Cluster

NATIONAL PHOTONICS INITIATIVE

National Photonics Initiative

Focus on 5 areas of highest economic impact

- Information Technology & Telecom 
- Energy and Environment 
- Advanced Manufacturing 
- Defense and Homeland Security 
- Biomedicine 

NATIONAL PHOTONICS INITIATIVE

NPI Timeline

• Convene NPI Steering Committee	09/2013	**NPI Organizing**
• Congressional Testimony on Adv. Manufacturing	09/2013	**Government Outreach**
• Congressional Visit Day	09/2013	
» NPI/Photonics General Education		
» Information gathering		
» Visited over 40 members		
• Approve NPI Strategic Plan	10/2013	
– Circulate to OSA/SPIE Boards for Comment		
• Review and approve GR Plan	12/2013	
• Form Working Groups	12/2013	**Industry Outreach**
– White paper preparation	02/2014	**Report preparation and publication**
– White paper publication	03/2014	
• Congressional Visits Day	03/2014	
• Supply 2015 & 2016 Budget Input	2014-15	
• RFI solicitation	6/2014	
• NSF Dear colleague letter	6/2014	
• BRAIN/PING NPI Collaboration announcement	10/2014	
• IMI Photonics selection announcement	10/2104	

NATIONAL PHOTONICS INITIATIVE

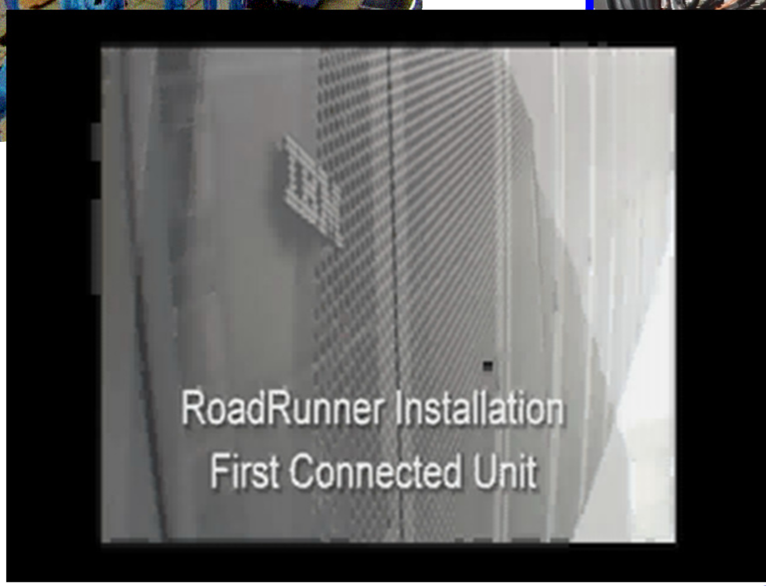
Information Technology & Telecom

- Fund an opto-electronic IC (OEIC) prototyping facility/open-foundry
  - University/government lab/industry collaboration
- Develop domestic sources for OEICs for next-generation data centers and high performance computing
- Expand broad-band connectivity
- Develop materials and devices for next generation opto-magnetic data storage systems
  - Heat assisted magnetic recording (HAMR)

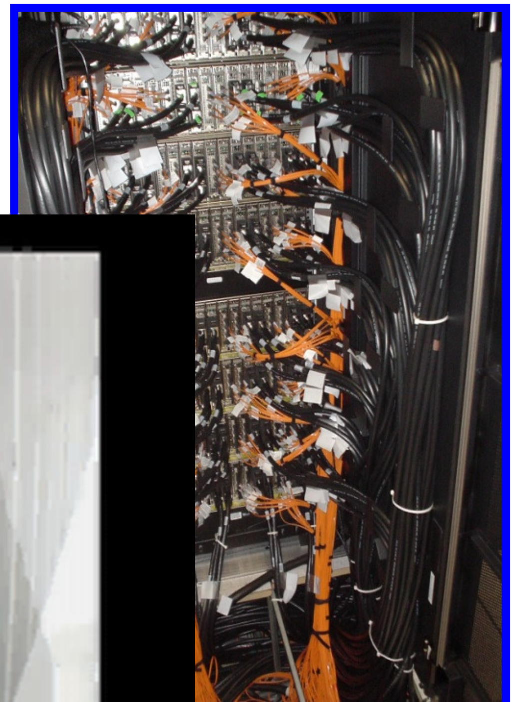
NATIONAL PHOTONICS INITIATIVE

Optical Interconnects for High Speed and Low Power

2002
(30 TeraFlop/s)

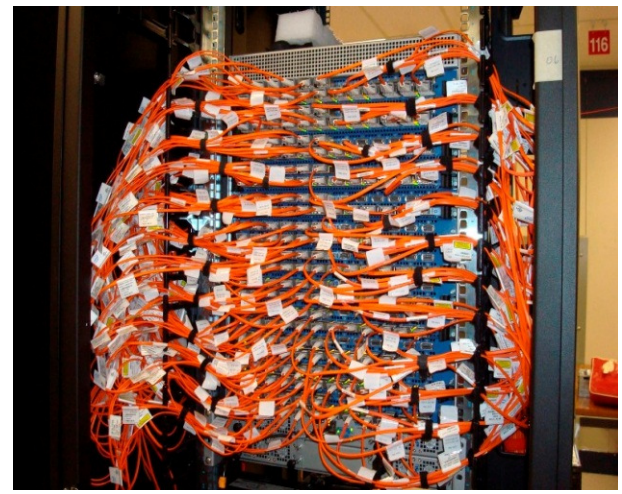


2005
(100 TeraFlop/s)



…ation of Electrical
& Optical Cabling

2008
(1 PetaFlop/s)
(300 Racks)
(130,464 cores)



Los Alamos National Laboratory

Over 40,000 Lasers!

(Courtesy Dr. Jeffrey Kash, IBM Research)

Energy and Environment

- Create an industry led collaboration to develop new sensors for energy exploration and climate monitoring
- Create a permanent DOE advisory committee to document US industry needs and aid in developing a national strategy
- Encourage industry/academic collaboration in longer term photo-voltaic research
- Increase federal funding for developing new solid-state lighting materials and manufacturing processes

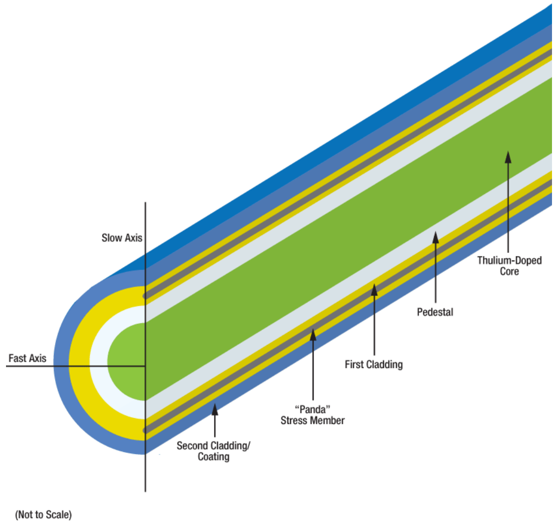
NATIONAL PHOTONICS INITIATIVE

Advanced Manufacturing

- Invest in high power laser technology
    - New laser materials
    - New high power nonlinear optical materials
    - New laser pump sources
    - New laser architectures
        - Ultra-fast, high average power sources
- Support research to improve understanding of laser/material interaction
- Develop higher resolution additive manufacturing systems
    - Closed loop error correction using machine vision
- Train US work force in advanced manufacturing systems and technologies

NATIONAL PHOTONICS INITIATIVE

Industrial Fiber Lasers



http://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=5390

(http://www.ipgphotonics.com/glpm_10.htm)

(http://www.gizmag.com/twi-yb-fiber-laser-demolition/29544/)

NATIONAL PHOTONICS INITIATIVE

Defense and Homeland Security

- Develop directed optical energy systems
  - High energy laser (HEL) systems
  - Coherent and incoherent beam combining
  - Optical materials
  - High Speed beam steering systems
- Imaging systems
  - Ultra-high resolution imaging
  - Night vision/SWIR cameras
- Explore defense applications of opto-electronic integrated circuits
  - US based prototyping facility

NATIONAL PHOTONICS INITIATIVE

Photonics Systems for Defense

http://www.sensorsinc.com/image_forestfireSWIR.html

NATIONAL PHOTONICS INITIATIVE

Biomedicine

- Support research exploring early disease detection using photonic
  - Cost-effective, point-of-care capabilities
  - Lab on a chip
- Build IT Infrastructure to support sharing of large medical image data sets
  - File sharing
  - Feature extraction software
- Support research in genetic engineering of optical properties in model systems
  - Optogenetics

Genetic Engineering of Optical Properties: Imaging Neural Circuitry in vitro

(Carl Deisseroth lab, Stanford)

NATIONAL PHOTONICS INITIATIVE

Precision Optical Hosted NPI Event on Oct. 8th with OSSC, OSA, and SPIE.

Live music, social hour, facility tours, buffet dinner

OSA, SPIE, NPI Leaders, Guest Panelists

Sold out event – standing room only!!

First OSSC Lifetime Achievement Award Presented to Dr. Murty Mantravadi

OSSC Members can view all the photos on the OSSC.org website.

PI

Forming "SCOPE"

The Southern California Optics & Photonics Enterprise

- The Southern California Optics & Photonics Enterprise (SCOPE) will be a **nonprofit trade association** in the optics and photonics industry that enables many other industries in Southern California, the United States and globally. **Based in Orange County**, California, it is located at the epicenter of many industries supported; being close to both San Diego and Los Angeles counties (and other counties in Southern California). SCOPE works in conjunction with other nonprofits, colleges and universities, national and global professional societies, local for profit companies and local departments of educations.
- A main goal of SCOPE is to **serve as a central coordinating entity on behalf of the Southern California Optics & Photonics communities** to further develop and implement cohesive funding for building a stronger infrastructure within these communities. This infrastructure can be described from the potential end result of having a more vibrant and branded optics & photonics community in Southern California, down through the various channels, pipelines and pathways that begin with the K-12 and public education up through our community colleges, universities, research centers and industrial for profit partners.

"SCOPE" Services

1. Act as a focal point for consortium
2. Assemble input from SCOPE members
3. Help prepare proposals for funding
4. Assist members' business marketing efforts

Obama Administration Announces $200 million in Public-Private Investment to Create an Integrated Photonics Manufacturing Institute.

Advanced Manufacturing Portal

... changing the face of manufacturing

About | AMNPO | Agency Partners | Other Organizations | Publications & Resources | Contact

Advanced Manufacturing Portal > NNMI

http://manufacturing.gov/nnmi.html

Quick Links

- National Network for Manufacturing Innovation
- America Makes: National Additive Manufacturing Innovation Institute
- Digital Manufacturing & Design Innovation Institute
- Lightweight & Modern Metals Manufacturing Innovation Institute
- Next Generation Power Electronics Manufacturing Innovation Institute
- Advanced Manufacturing Partnership 2.0

Funding Opportunities

- President Obama Announces Launch of New Integrated Photonics Manufacturing Innovation Institute Competition — October 3, 2014

Snapshot:

National Network for Manufacturing Innovation (NNMI)

Snapshot | Overview | Design | FAQ's | Manufacturing in Context | What is Adv Manufacturing?

President Obama has proposed building the National Network for Manufacturing Innovation (NNMI), consisting of regional hubs that will accelerate development and adoption of cutting-edge manufacturing technologies for making new, globally competitive products. Over the last two years, he has acted to jumpstart the network by launching four innovation hubs and initiating the establishment of four more, all by executive order while awaiting congressional action.

Individually and together, these regional hubs—public-private partnerships called Institutes for Manufacturing Innovation (IMIs)—will help to strengthen the global competitiveness of existing U.S. manufacturers, spur new ventures, and boost local and state economies. (See NNMI at a Glance.)

In his 2013 and 2014 State of the Union Addresses, the President called for creating a full-fledged nationwide network devoted to innovating and scaling up advanced manufacturing technologies and processes. He has asked Congress to authorize a one-time $1 billion investment—to be matched by private and other non-federal funds-to create an initial network of up to 15 IMIs. Over the span of 10 years, he has proposed building out NNMI to encompass 45 IMIs.

While legislation pends, the Administration has made significant progress toward building a manufacturing innovation network with nationwide reach and impact.

NATIONAL PHOTONICS INITIATIVE

Optics & Photonics: Lighting a Path for the Future

http://www.lightourfuture.org/

NATIONAL PHOTONICS INITIATIVE

Discussion