Beyond Nanopositioning

Recent Advances in Nano-Precision Motion Technologies Address the Resolution/Speed Tradeoff

Illustration: LightConnect.com

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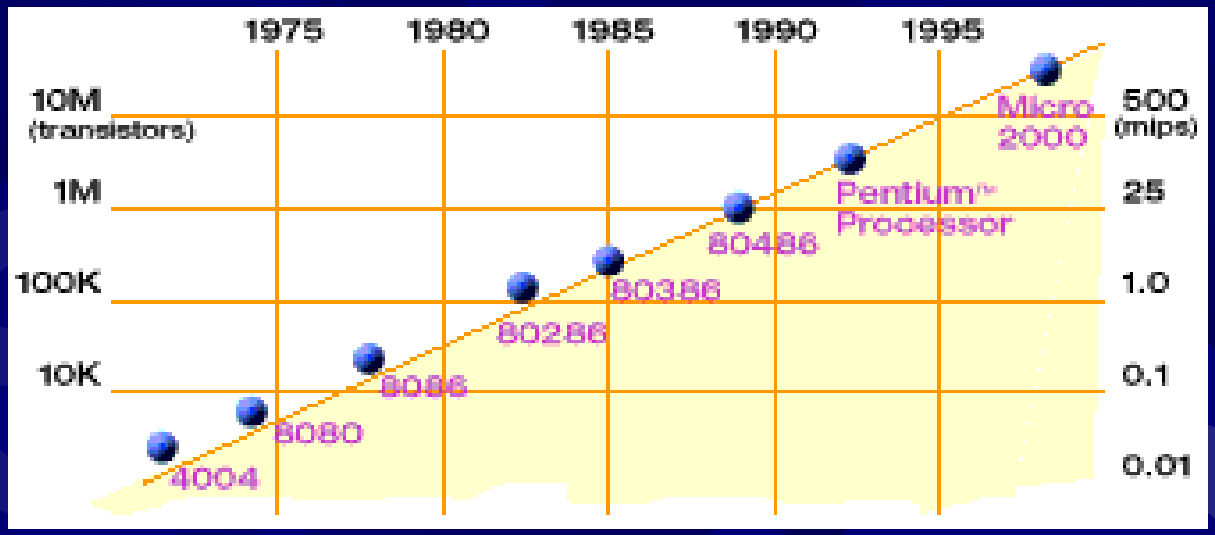
Agenda

- A Look at Several Industries
  - Trends in common
  - The economic squeeze
  - Parallels in research
- NanoAutomation®
  - Definition
  - Overview of technologies
  - What it portends for research and manufacturing

Perspective: Moore's Law



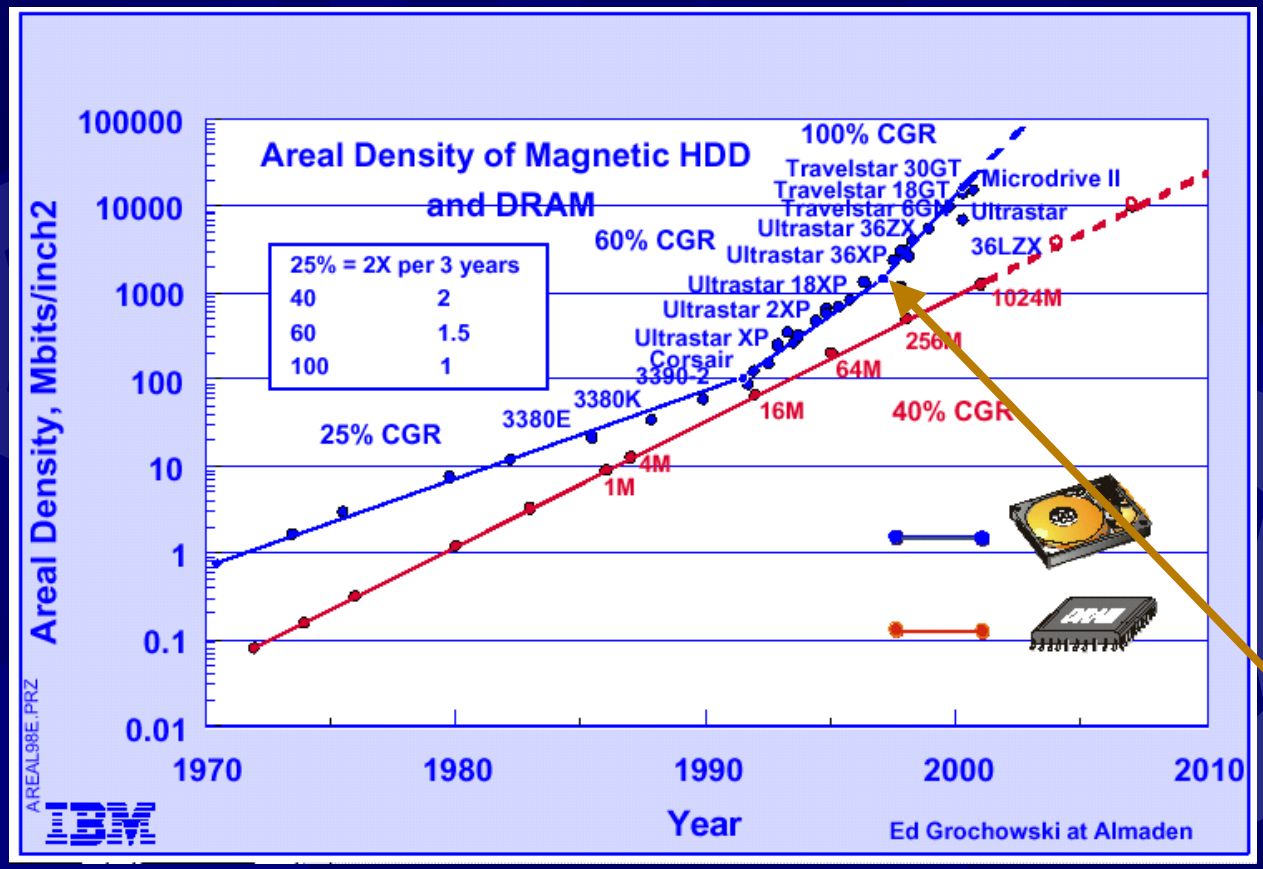
Source: http://www.intel.com/intel/museum/25anniv/hof/moore.htm

$$(\text{logic bits/cm}^2) \sim 2^{(\text{year} - 1962)/1.5}$$

"In 1959, a single transistor sold for about $5. Today that same $5 will buy you *sixteen million* transistors."

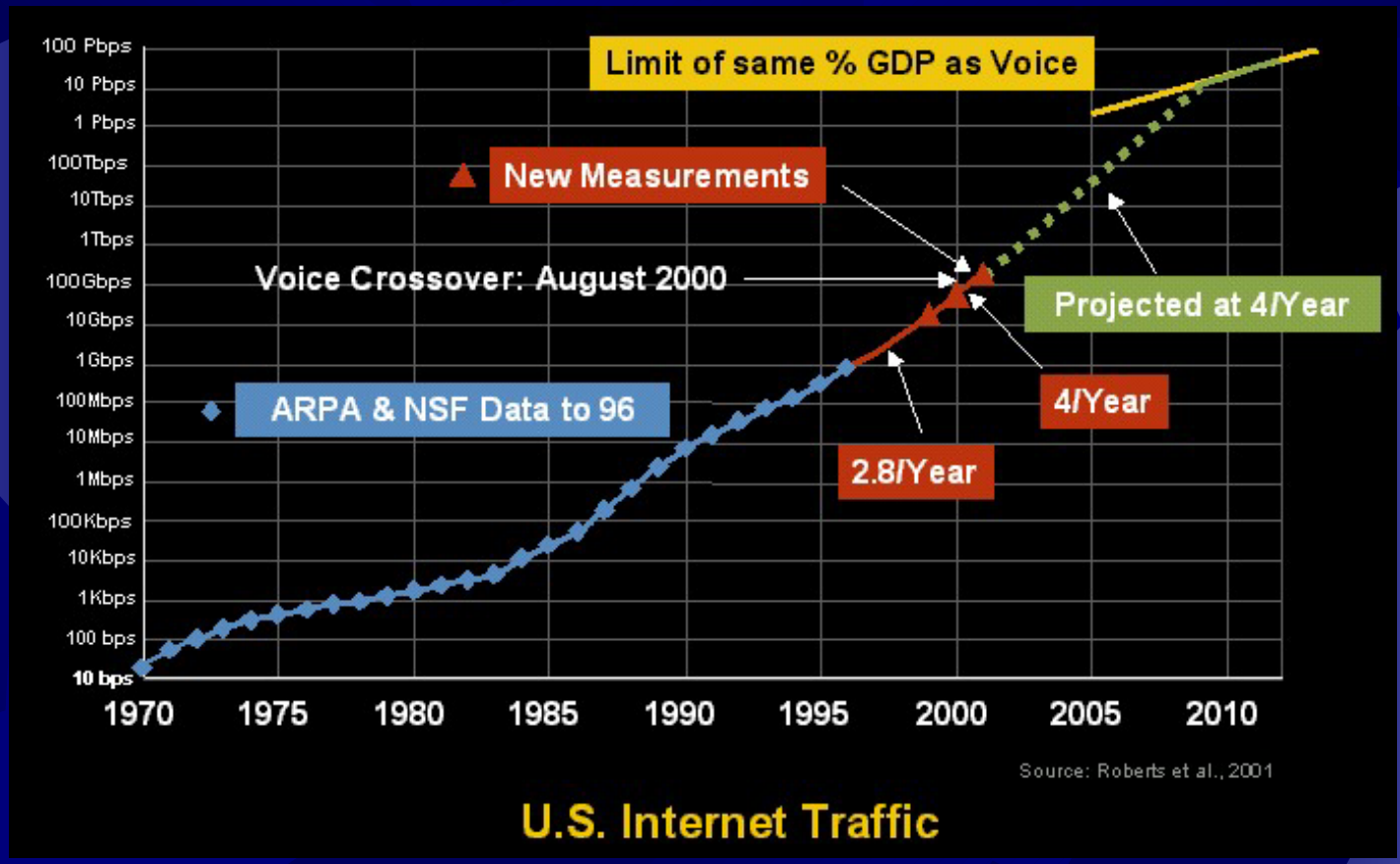
--Gordon Moore, 1997

Perspective: Areal Density



Yet another Inflection Point!

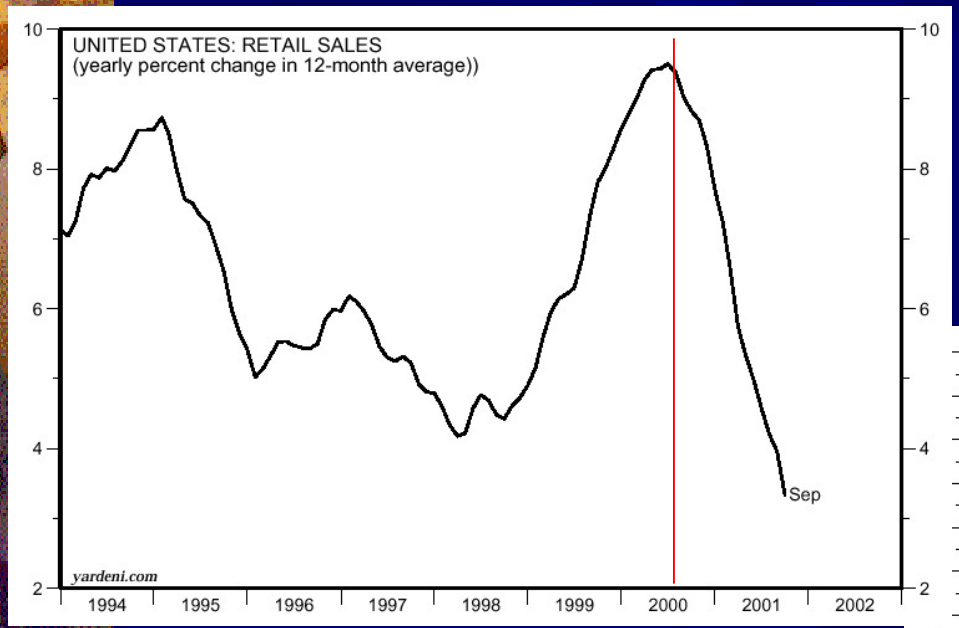
Perspective: Bandwidth Consumption



Parallels

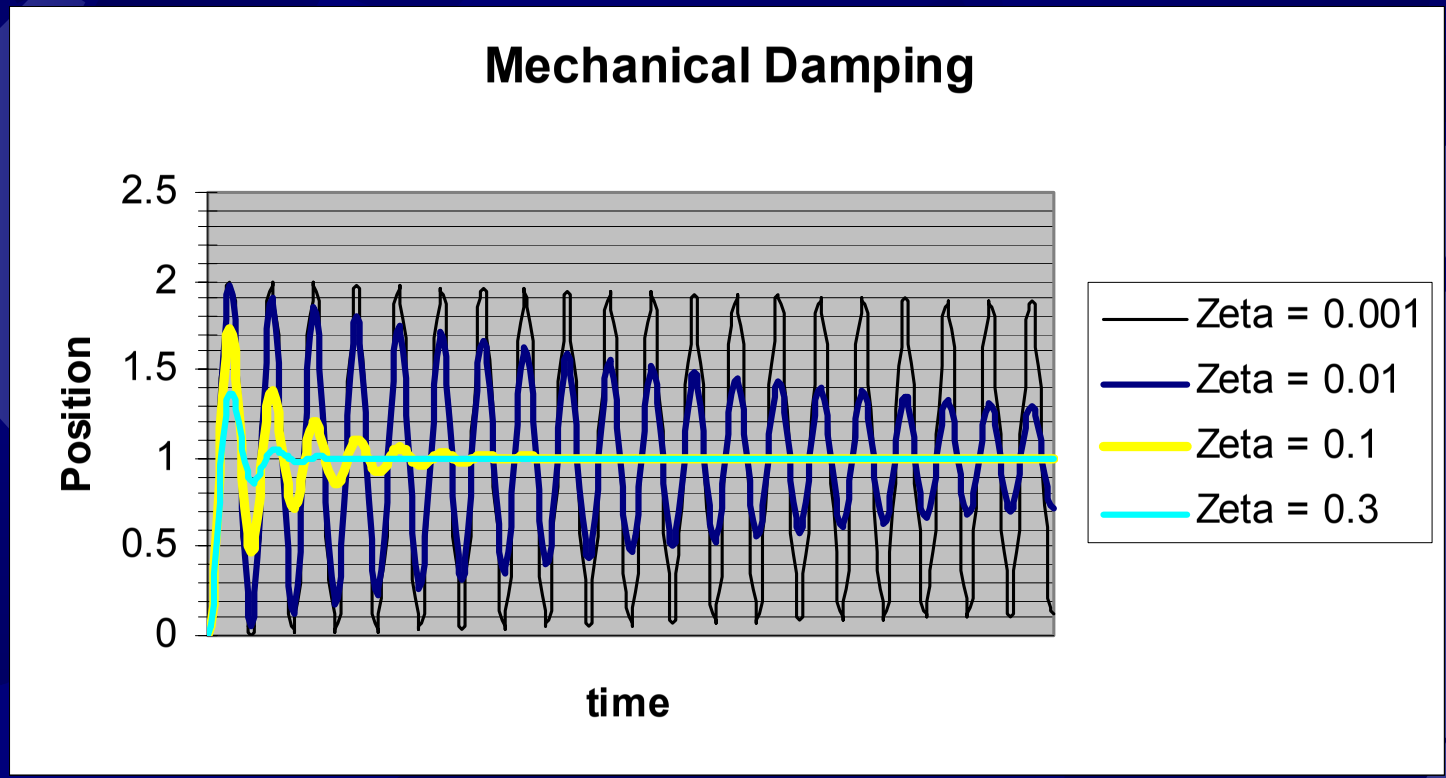
- Rapid innovation
- Compressing dimensions, tolerances
- Exponentiating complexity
- Commoditization
- Opportunity
- High stakes
- Fast pace
- Capital Intensiveness
- Competition
- Globalism
- Niche defenses

Adding to the pressure: Spring 2000 Downturn

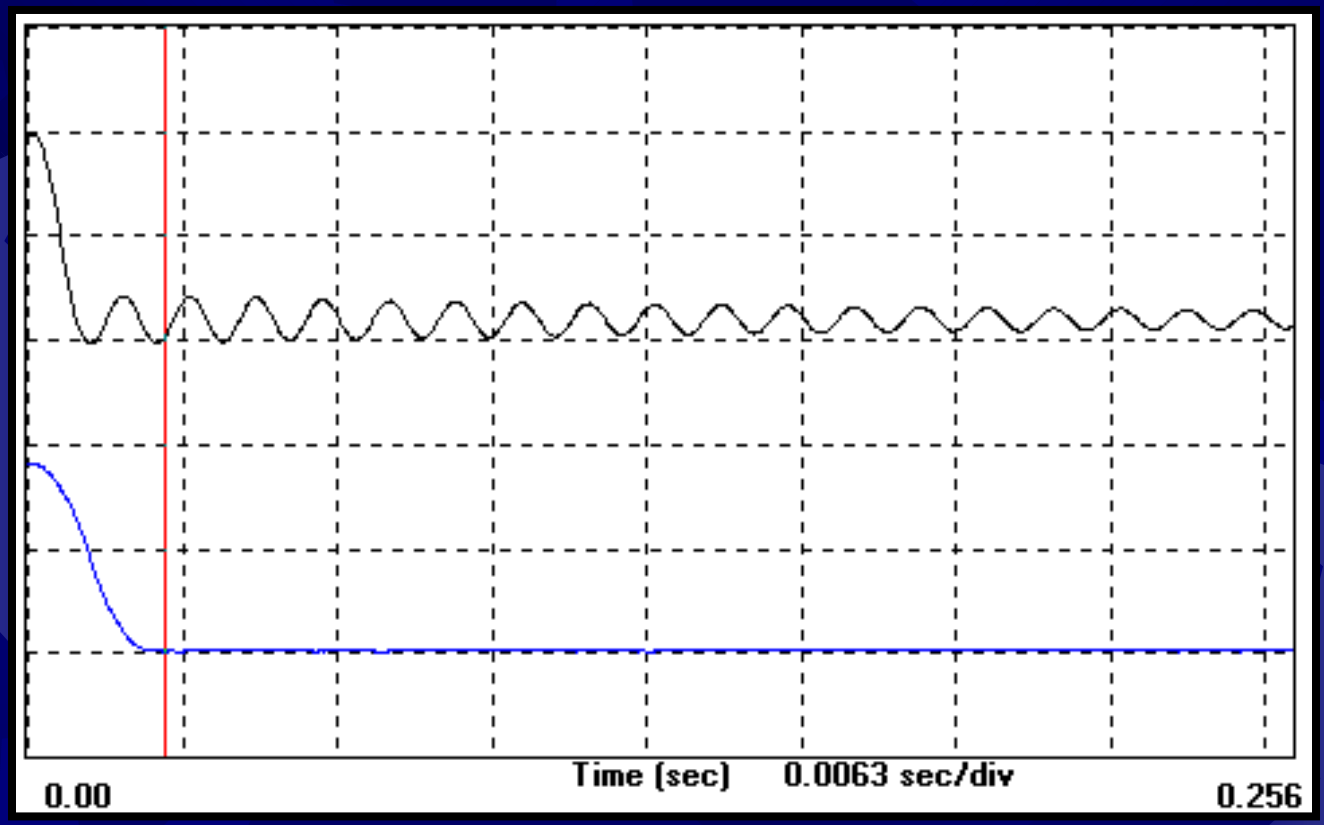


Meanwhile…

Process economics are now often dominated by settling physics



Wouldn’t it be nice…



…Address both resolution and throughput needs simultaneously

Why It Matters: Semiconductors

Today's settling time (sec)	zeta	In 12 months of 60% areal density growth	X change	w/Mach, 2msec risetime	% of time otherwise req'd	Process Cycle-Time Savings
0.400	0.0001	6.238	15.60	0.006	0.1%	99.9%
	0.0005	1.572	3.93		0.4%	99.6%
	0.001	**0.988**	**2.47**		**0.6%**	**99.4%**
	0.005	0.522	1.30		1.2%	98.8%
	0.01	0.463	1.16		1.3%	98.7%
	0.05	0.417	1.04		1.4%	98.6%
	0.1	0.411	1.03		1.5%	98.5%

Table 2. Change in settling time of a track-profiling fixture after 12 months of areal density growth, for a fixture (f_{res} ~250Hz) which settles in 400msec today. A 2msec piezo risetime is assumed. Examples highlighted in the text are boldfaced.

Source: "Zinging the Ringing", Machine Design

Why it Matters: Photonomics

	Cycle time (minutes)	Burdened labor cost/hr	Parts/hr /workstation	Workstations /worker	Yield	Labor cost to assemble (per interconnect)
Manual	15	$50	4	1	30%	$41.67
Automated	1	$50	60	3	80%	$0.35

Source: http://wdm.pennnet.com/Articles/Article_Display.cfm?Section=Archives&Subsection=Display&ARTICLE_ID=93791&KEYWORD=Jordan

Beyond Nanopositioning: PI's NanoAutomation® Initiative

$$\text{NanoAutomation}^{®} \equiv \lim_{t \to \$} \frac{d(nm)}{dt}$$

Specifically…

- Novel Controls Features
  - Mach™ Input Shaping®
    - Eliminates settling time
  - Input Pre-Shaping
    - Eliminates following error in repetitive actuation
  - New Communications Interfaces
  - New Servo Architectures
- Higher-F_{res} Mechanics
  - Monolithic Multi-Axis Approaches
    - Minimizes Mass
    - Addresses Abbé Error
  - Momentum Compensation
  - Advanced Sensors
- Trajectory Control Innovations
  - Passive
  - Active

On Ringing…

Classically: Amplitude scales as $e^{-t/\tau}$

F_{res} (Hz)	ω_n (rad/sec)	ζ	τ
75	471.24	0.0005	4.244
		0.001	2.122
		0.005	0.424
		0.01	0.212
		0.05	0.042
		0.1	0.021
150	942.48	0.0005	2.122
		0.001	1.061
		0.005	0.212
		0.01	0.106
		0.05	0.021
		0.1	0.011

1) No physical difference between passive and active damping... still turns vibrations into heat over time (…lots of time).

2) Active damping only effective on observable vibrations

The Ideal Solution:

Prevent
motion-driven
vibrations
in the first place

Two Effective Approaches Exist

- **Input Shaping®**
  - Addresses resonances throughout entire assembly: load, supporting structure, ancillary components
  - Settling complete in $t \sim F_{res}^{-1}$
- **Momentum Compensation**
  - AKA Frahm Damping
  - Substantially eliminates inertial loads to supporting structure
  - Ideal for low F_{res} situations

Both are effective against unobservable vibrations using any motion profile

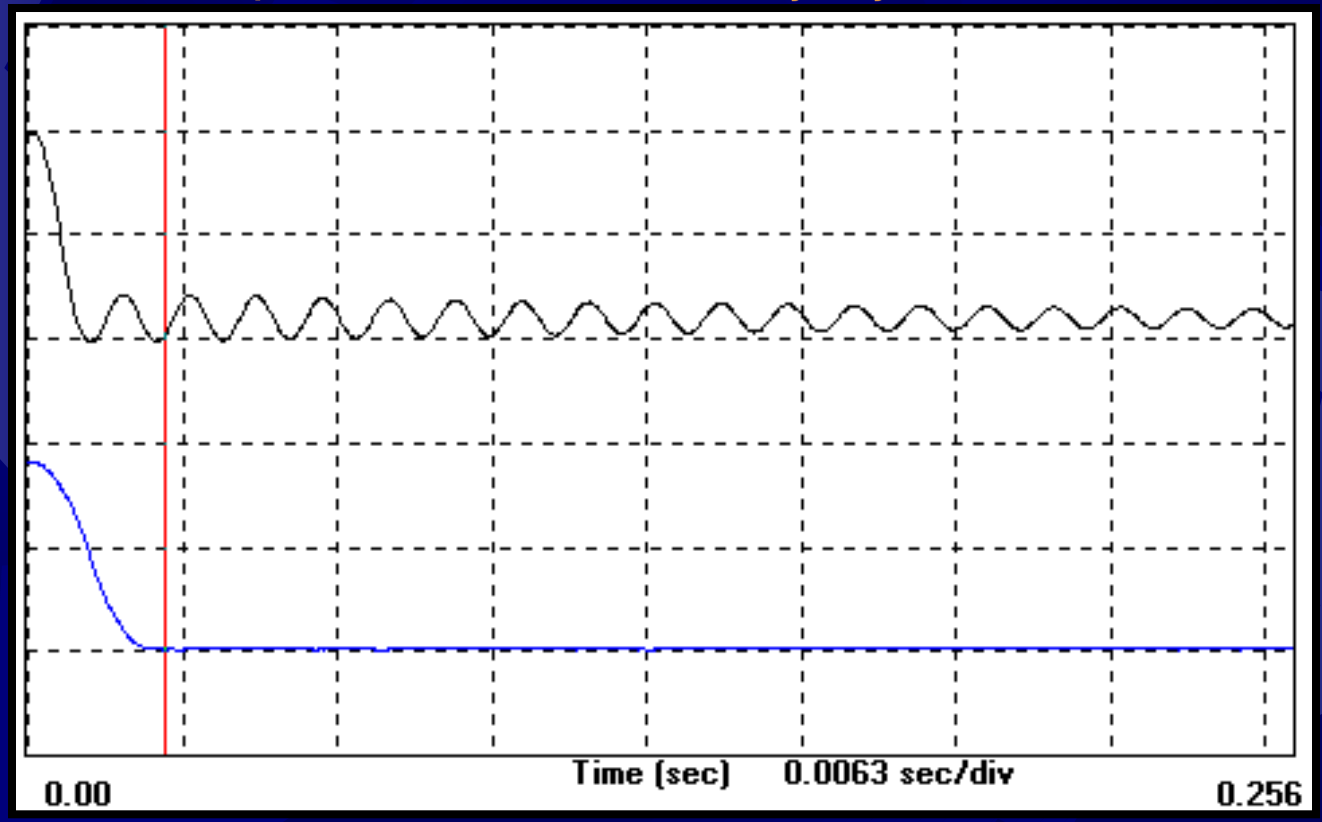
Input Shaping®

- Eliminates recoil-generated structural ringing, fiber pendulation, etc.
- Improves settling time dramatically
- Easily implemented
- Robust
- Patented (MIT, Convolve)

See http://www.convolve.com

Before & After

3um rapid move, stiff fixture on PZT stage.
Fixture position measured in real-time by Polytec laser vibrometer.



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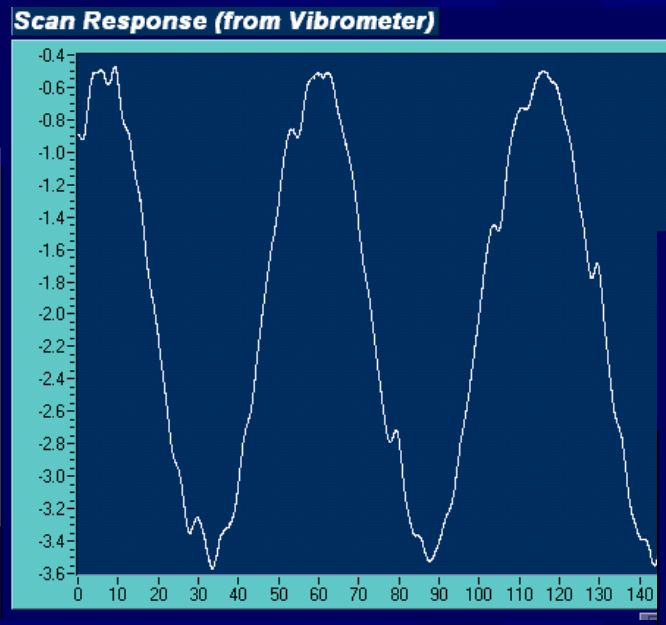
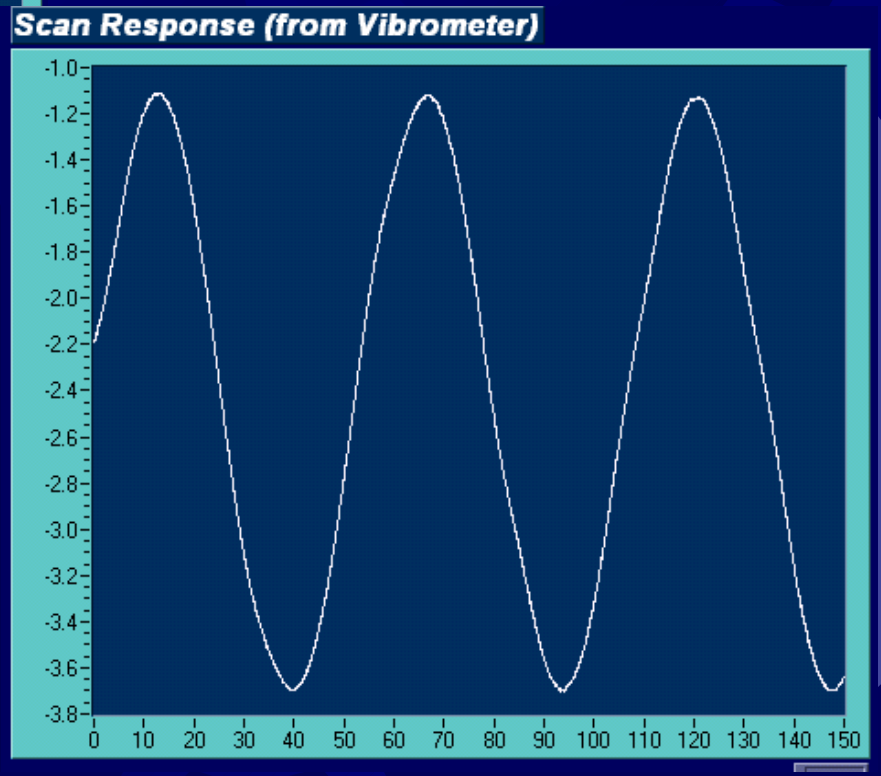
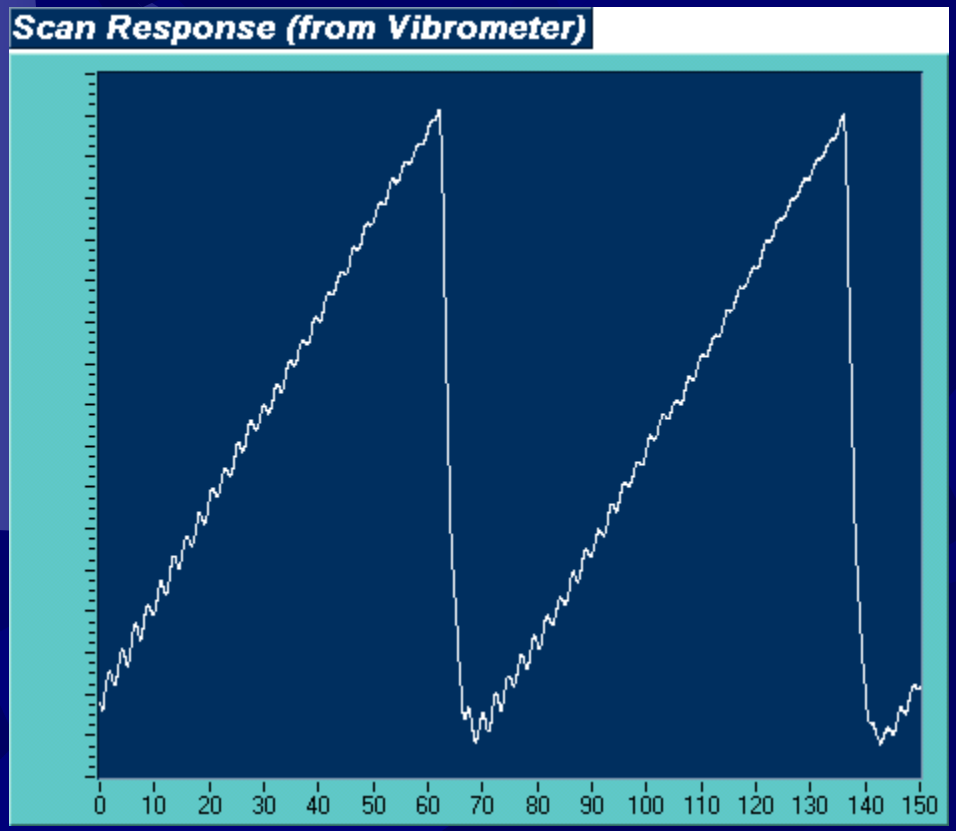
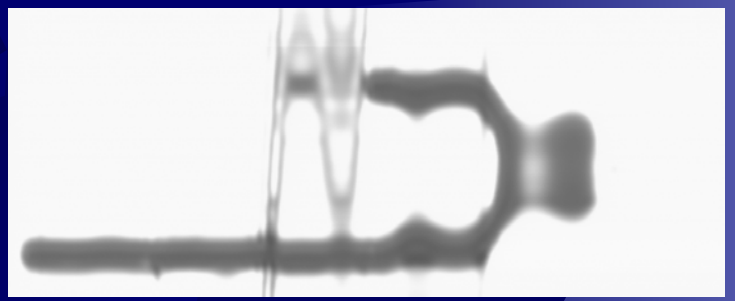
Example: FBG Manufacture



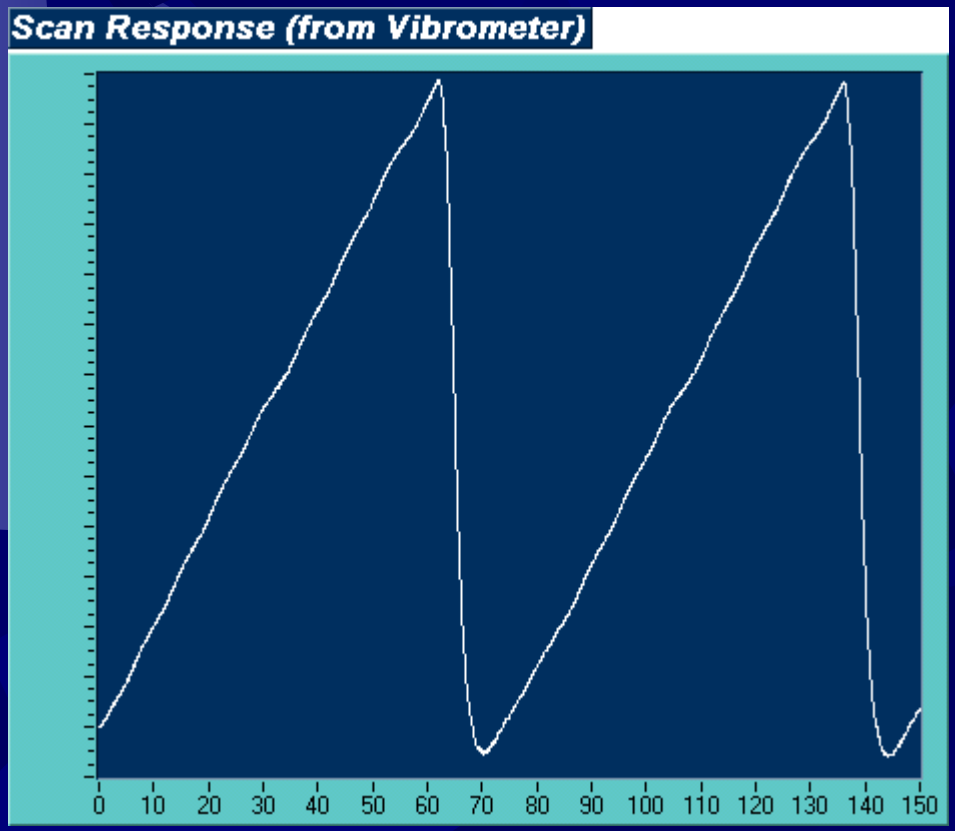


Imaging Example: Before





Imaging Example: After



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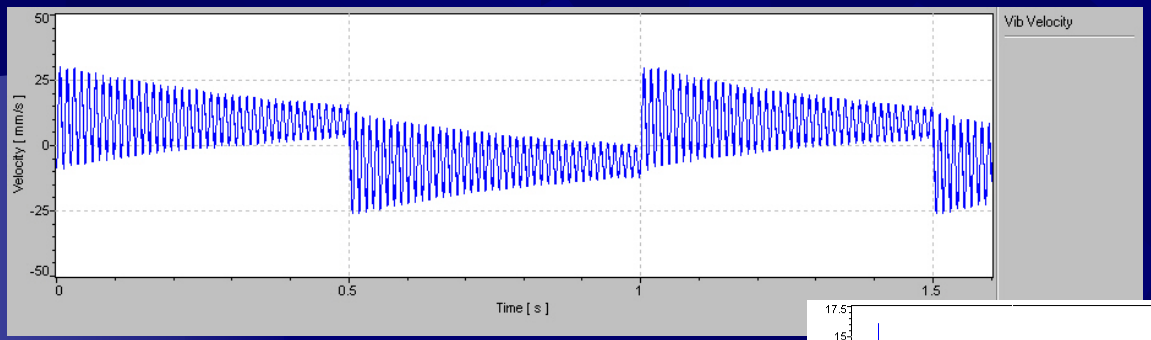
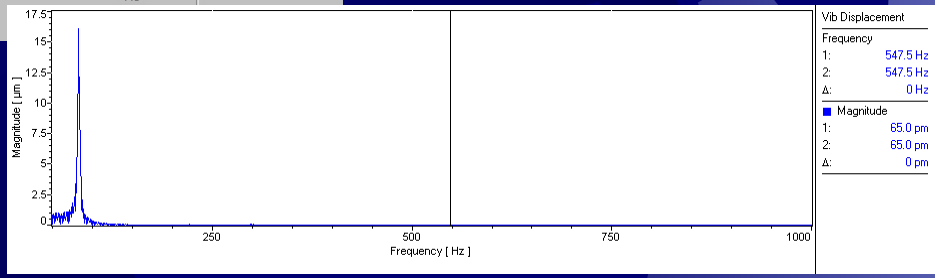
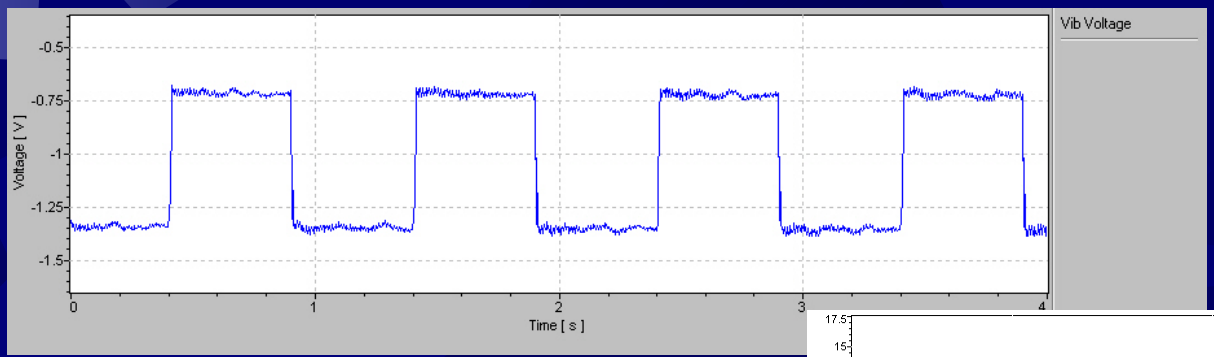
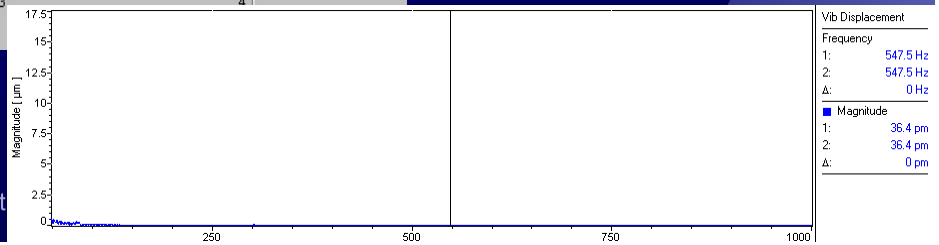
Embedded in MEMS…!







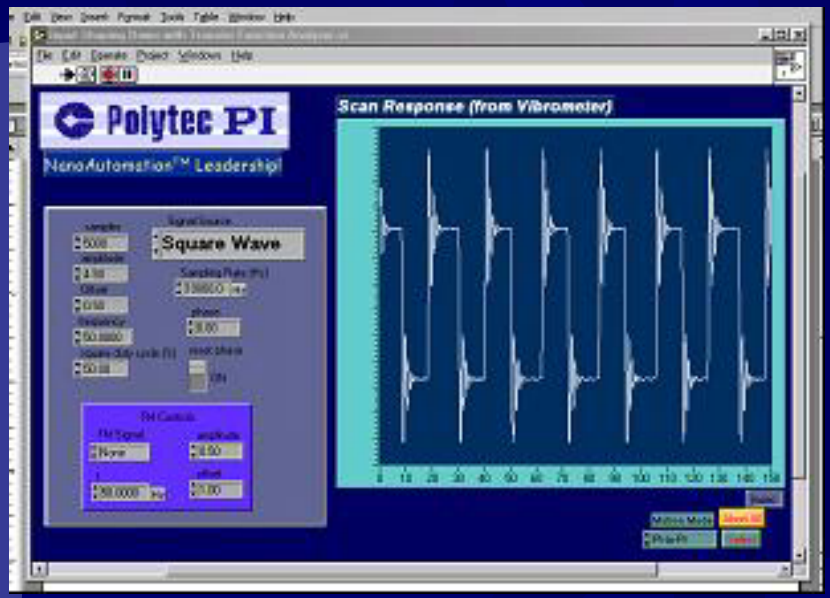


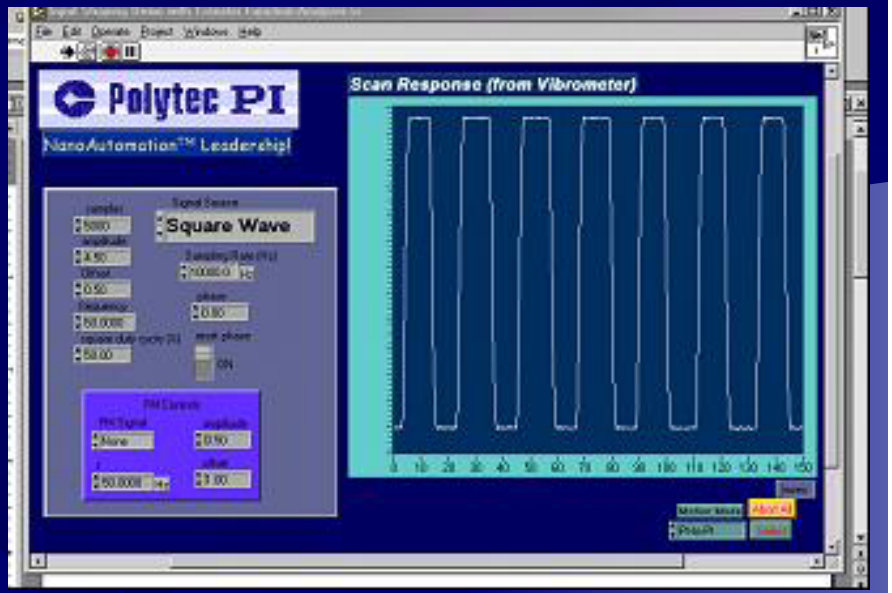
Implementations

- Embedded
- External Upgrade

Momentum Compensation

Complementary Technologies



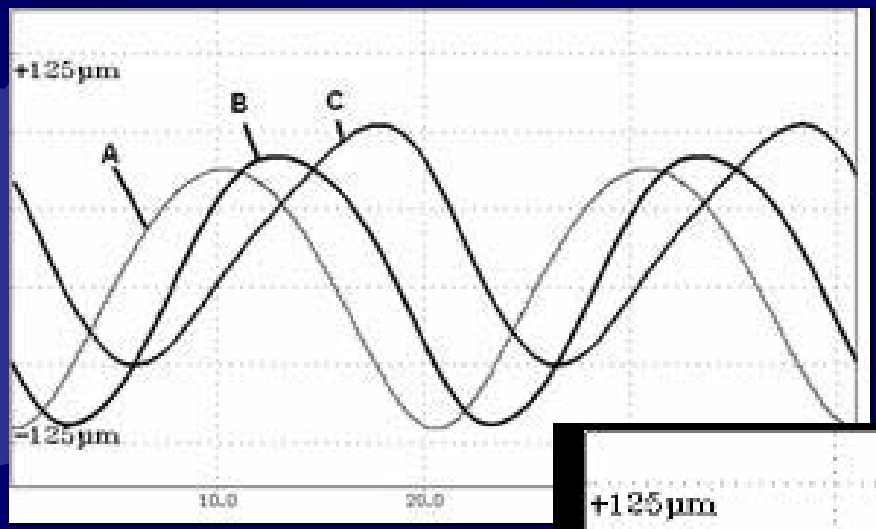


- Momentum Compensation addresses zero-point creep from actuation impulses, prevents structural oscillations
- Input Shaping addresses residual ringing

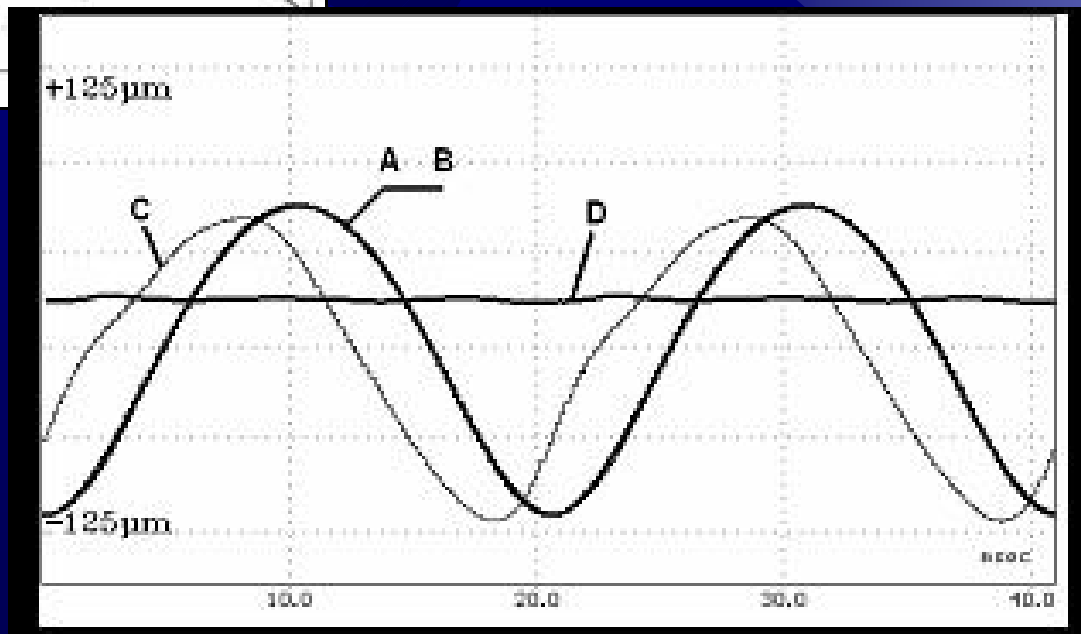
Input Preshaping

- Controls architecture which virtually eliminates following-error in repetitive scanning motions
- Self-teaching implementation takes a few seconds to learn own dynamics
- Typically reduces FE < 2%
- Increases effective bandwidth of system

Input Preshaping



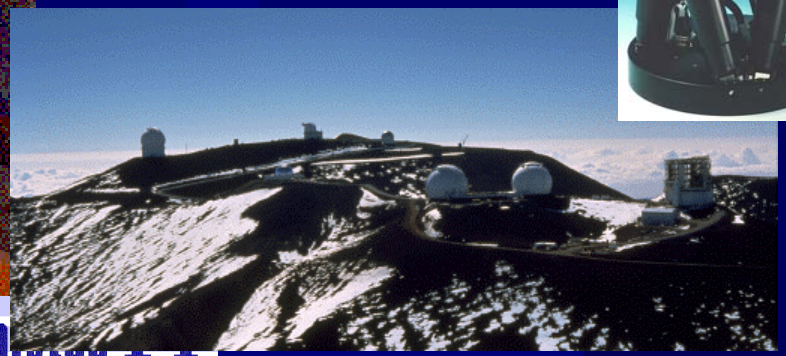
Before



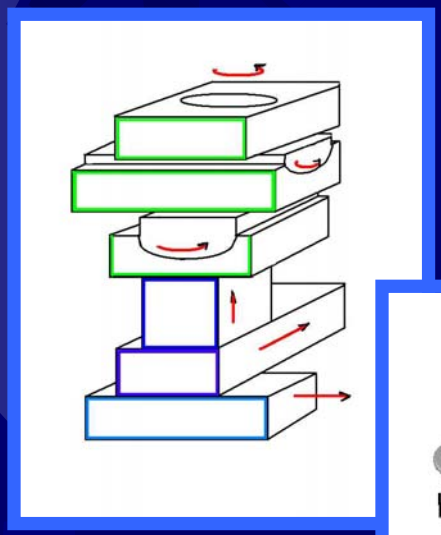
After

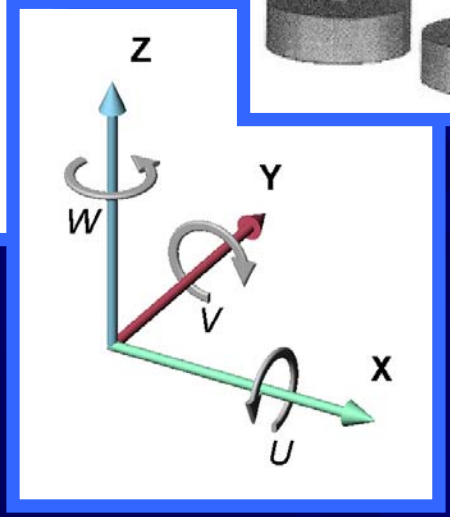
Parallel Kinematics

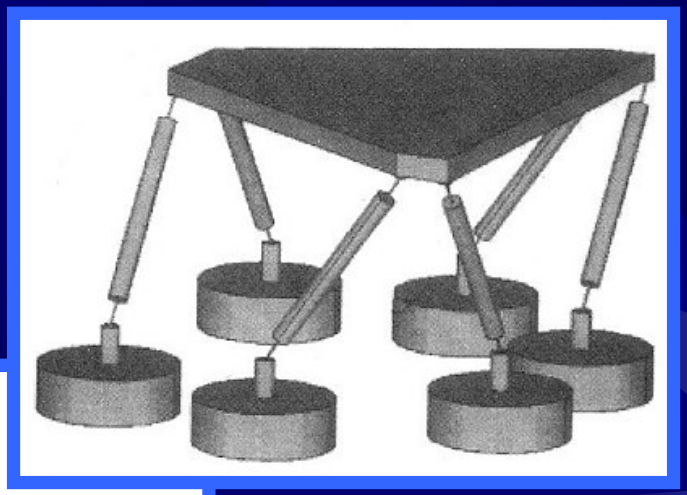
- Hexapod Configuration
  - High stiffness
  - High precision
  - No moving cables
  - 6 DOF
  - Compact



Comparison to serial stack



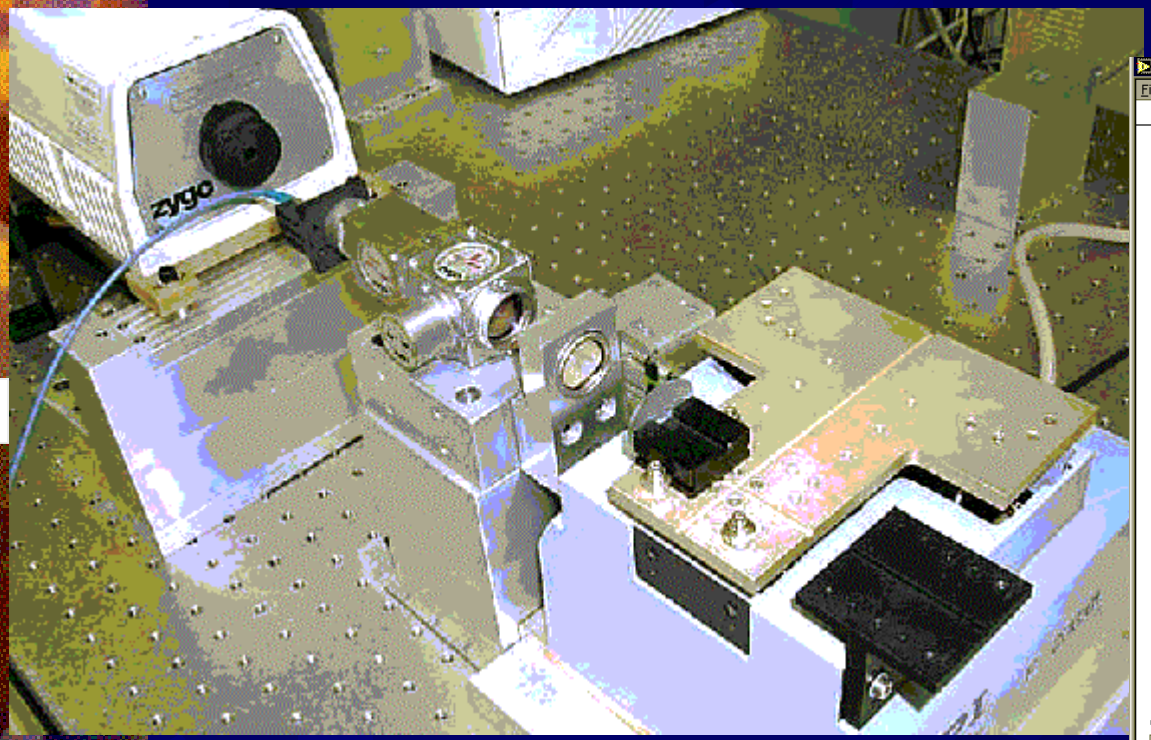


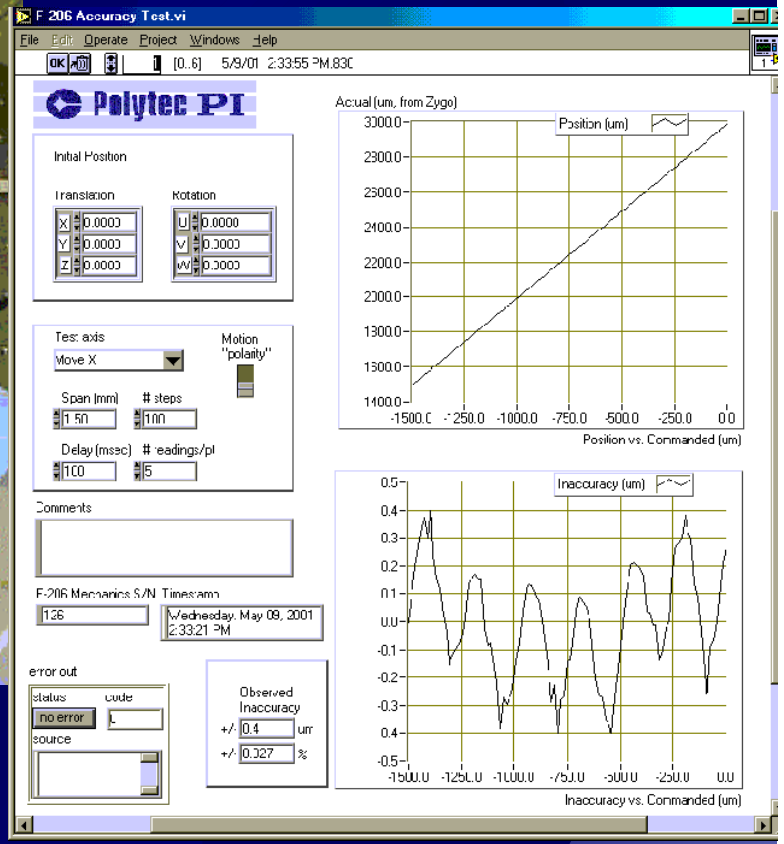


Hexapod Advantages

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

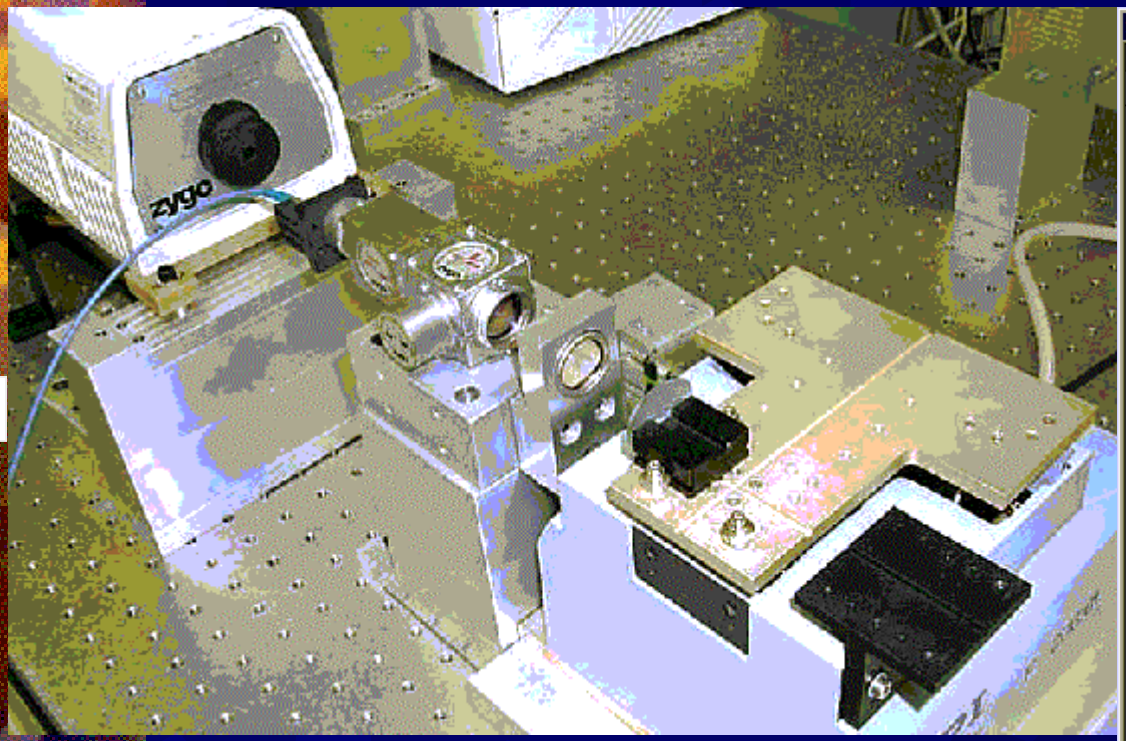
Performance:
Runout & Absolute Accuracy

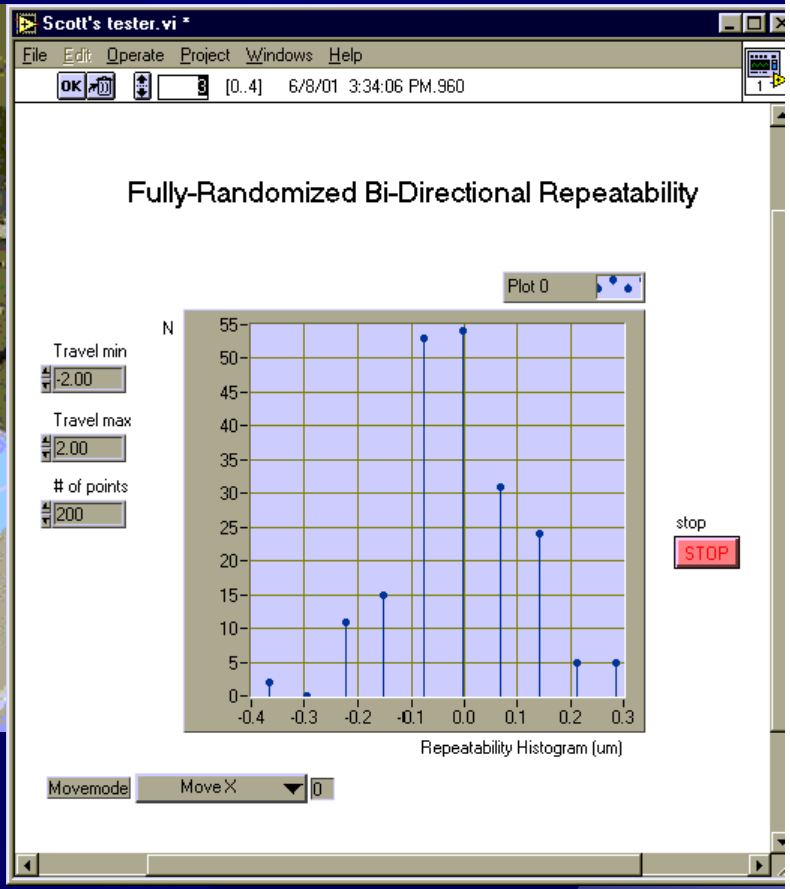




6-DOF performance surpasses *single-axis* capabilities of the world's best stages

Performance:
Bi-Directional Repeatability





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

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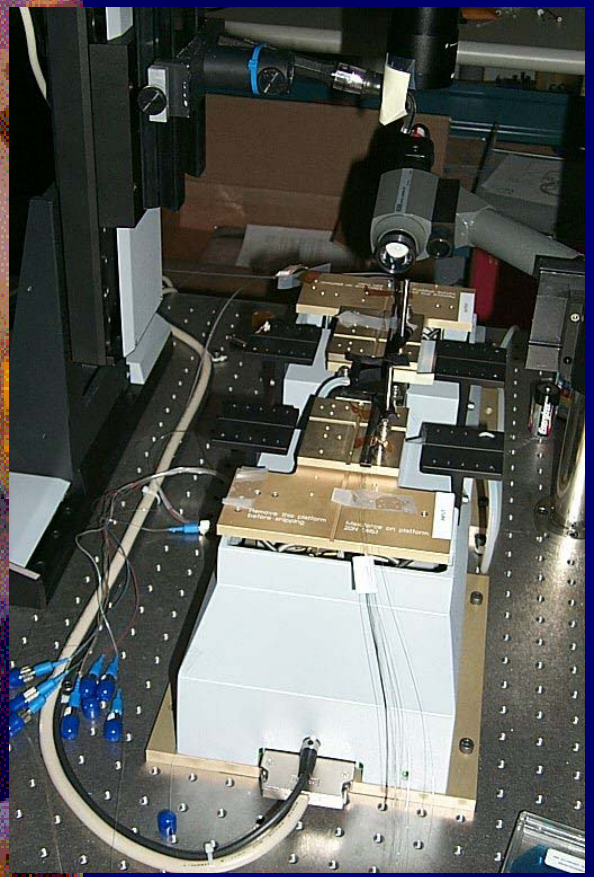
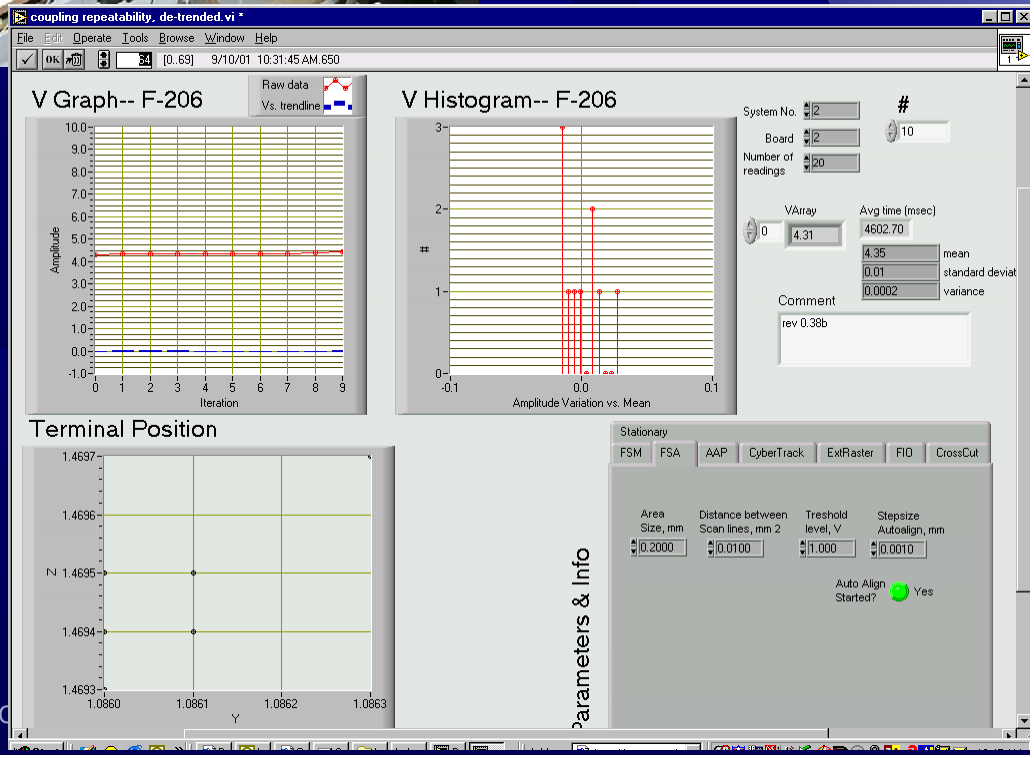
An Enabling Technology:
Example: Waveguide Test





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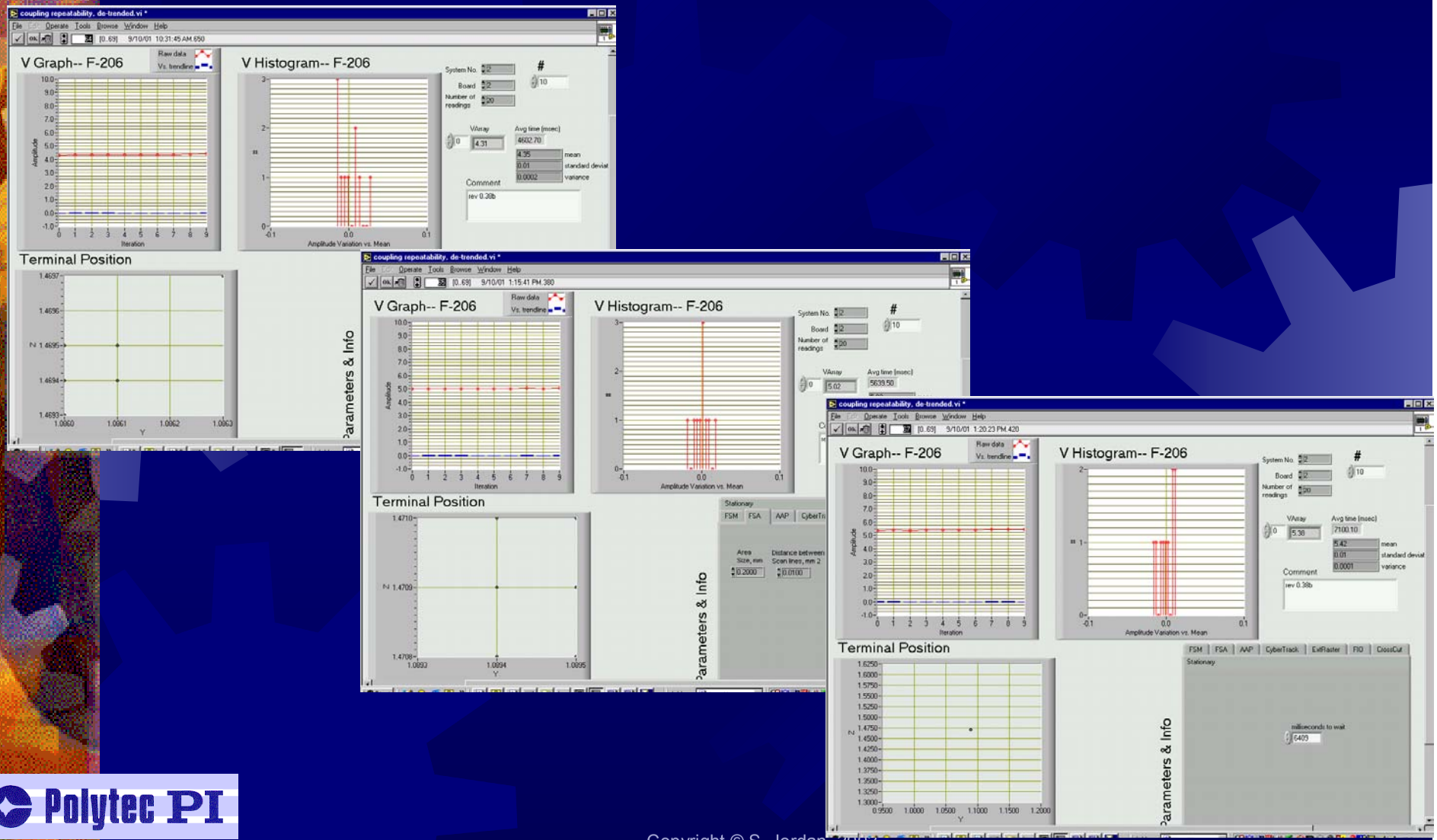

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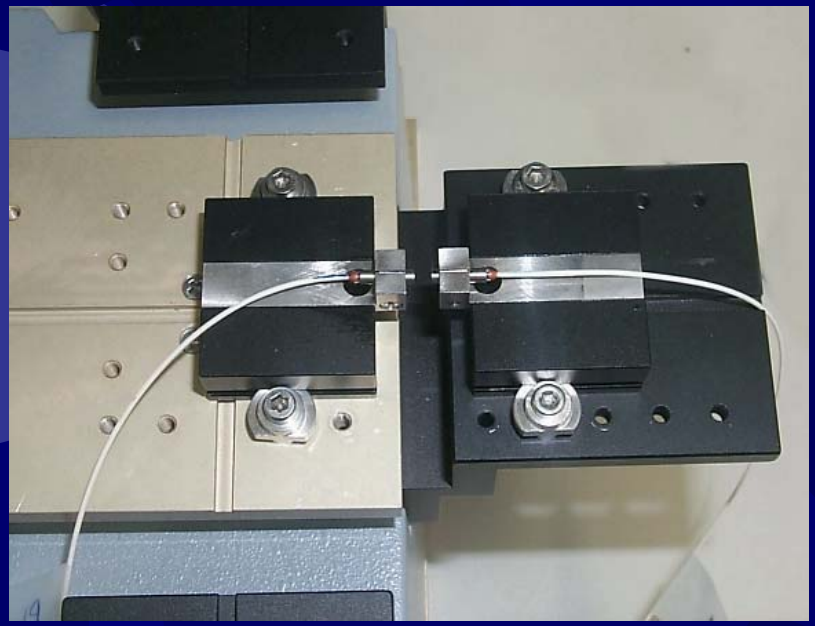
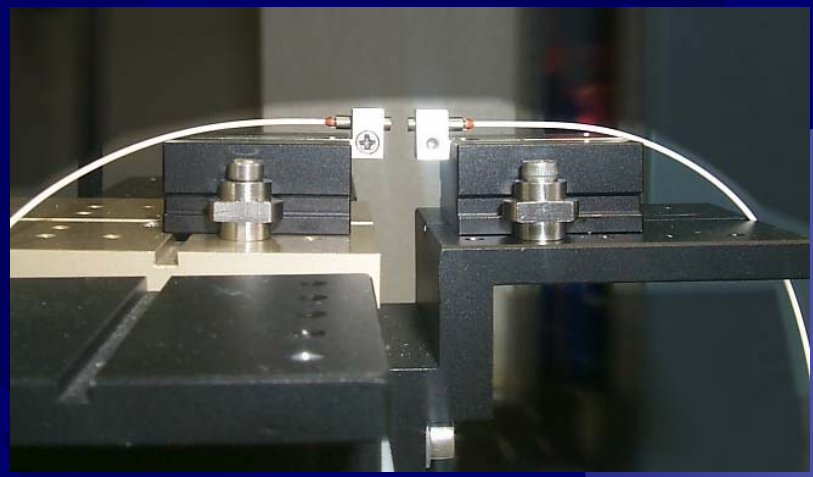
An Enabling Technology:
Example: Collimator Alignment





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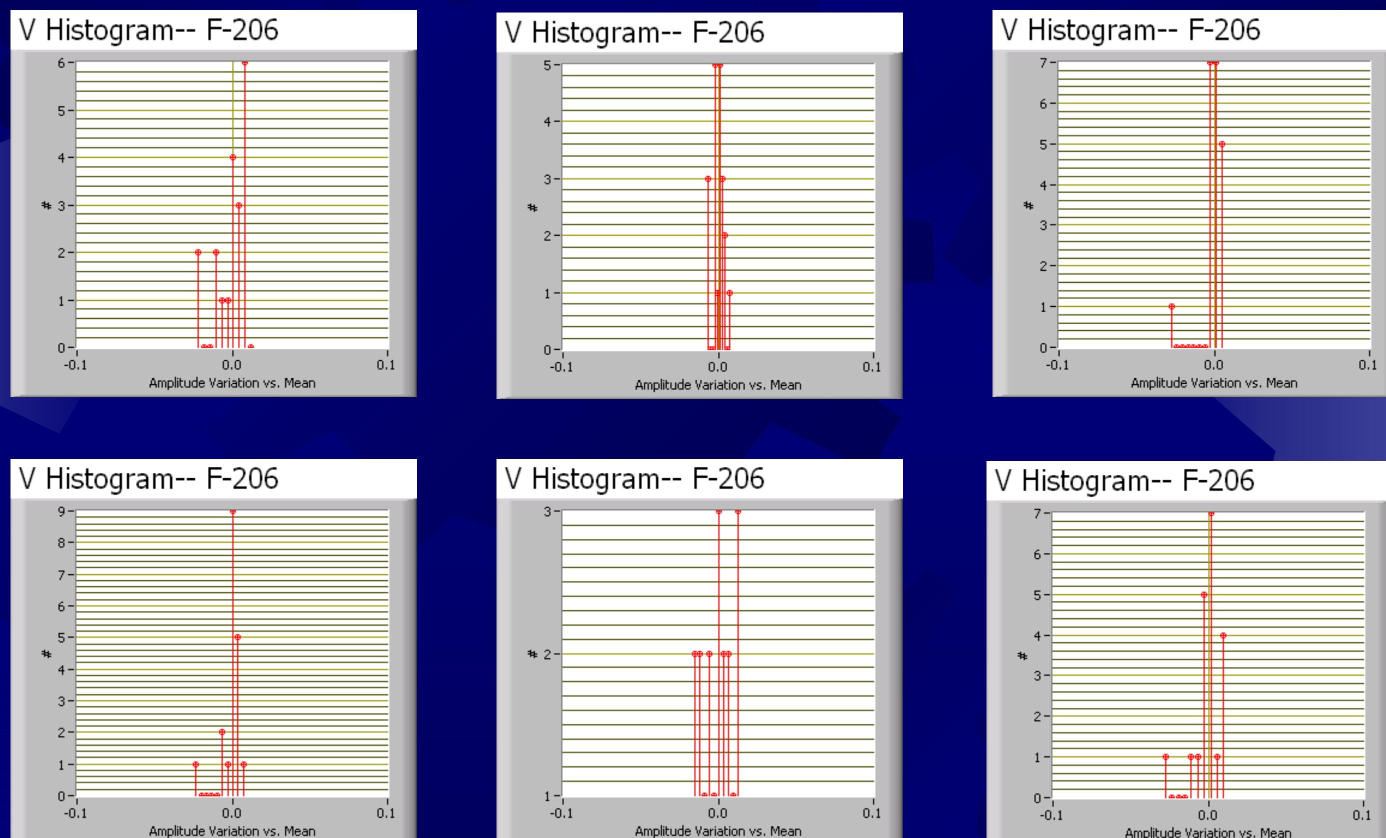
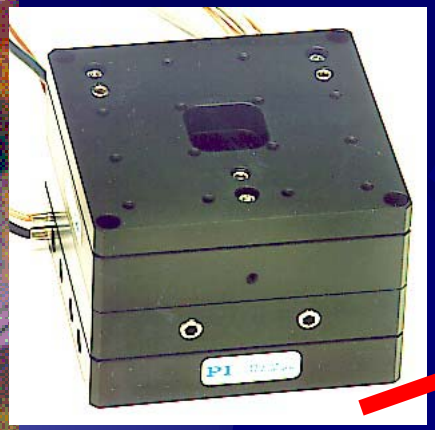
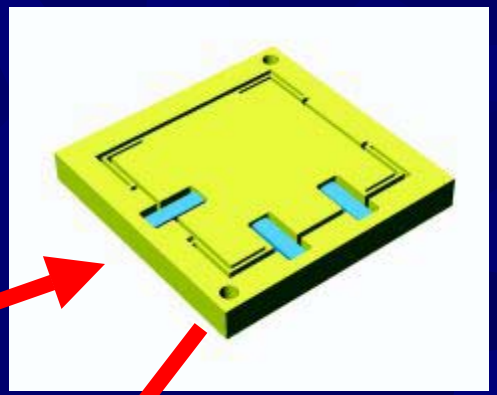
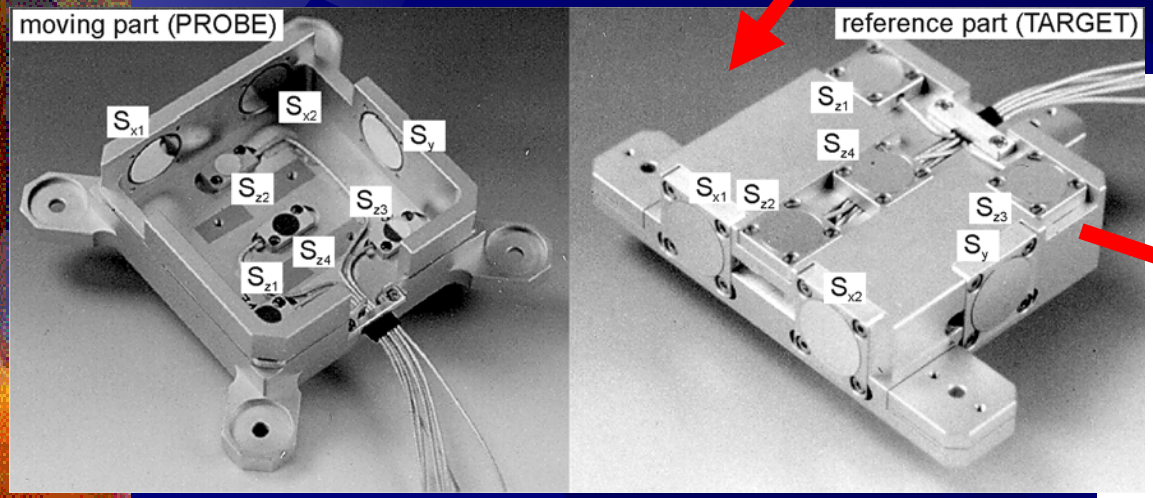


Planar Parallel Kinematic Designs

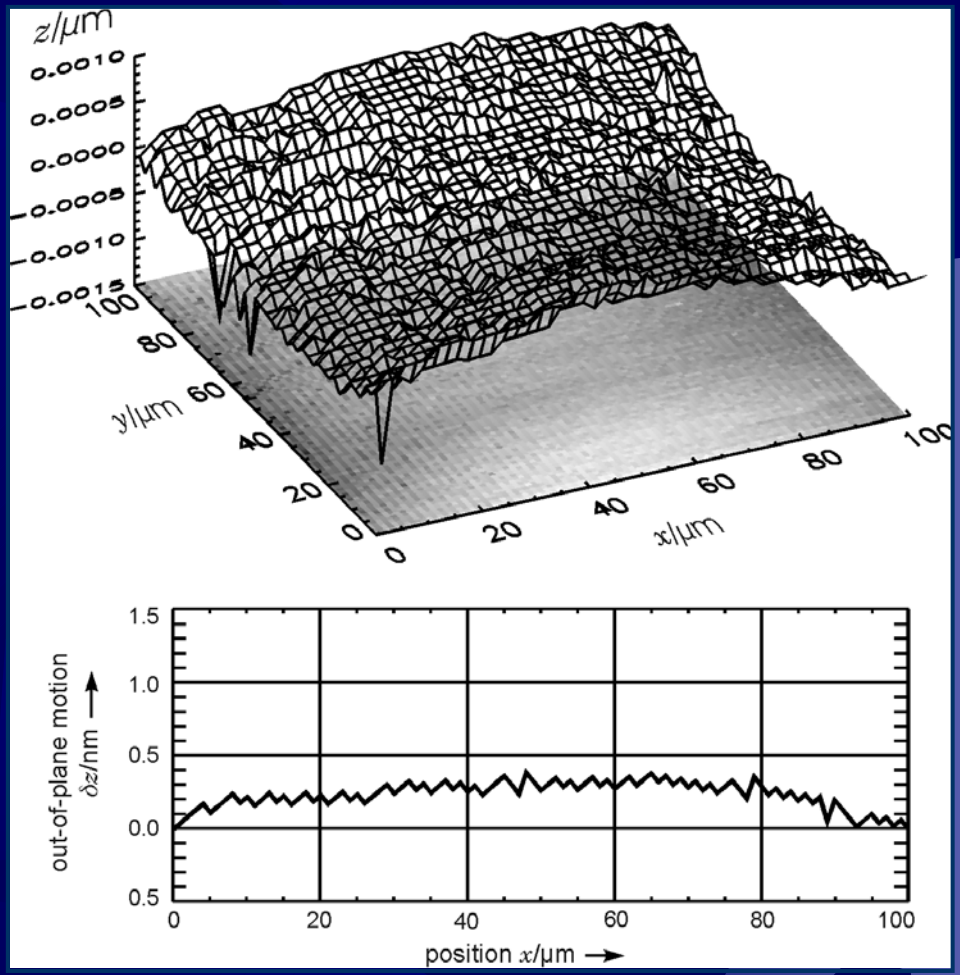






Benefits

- Higher throughput
- Reduced errors
- Improved orthogonality
- Improved out-of-planarity



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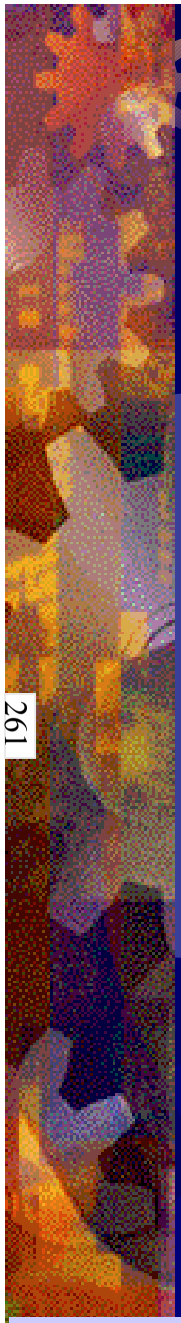

$$\text{NanoAutomation}^{\circledR} \equiv \lim_{t \to \$} \frac{d(nm)}{dt}$$

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