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New Technology Solves the Resolution/Speed Tradeoff

Scott Jordan, *Nanopositioning Technologies, Polytec PI, Inc., Tustin, CA, USA*

ABSTRACT

The relentless advance of areal densities (Figure 1) surpasses Moore's Law [1] in the semiconductor industry: (logic bits/cm^2 of silicon) ~ 2$^{(\text{year}-1962)/1.5}$. Both foretell the need for higher-resolution processes. But economic prerogatives demand higher throughputs as well. Yet despite harrowing finances, the datatech industry lags in developing metrics (e.g. Figure 2) to support purchase decisions reflecting today's economics.

Worse, satisfying the need for speed grows tougher as resolutions tighten. At issue is not the responsiveness of embedded positioners – piezoelectric positioners are capable of accelerations >10 000g! – it's that their actuation causes recoil impulses to propagate through its load, fixturing, and frame. This causes neighbouring components to resonate. This is unobservable by feedback sensors, so servo adjustments can't help. This is now the worst throughput bottleneck in applications as diverse as track profiling and PTR

WHY SETTLING TIME WORSENS

After excitation, the vibrational amplitude scales as $e^{-t/\tau}$, where τ is the time constant [2]. For damping typical of motorised stages (Table 1, Figure 3), $\tau \sim (W_n\zeta)^{1}$ where ω_n is the angular frequency and ζ is the damping ratio, the ratio of actual damping versus critical damping ($\zeta = C/C_c$).

The exponential decay law is all we need to predict the time impact of areal density trends. Consider actuation of a track-profiling nanopositioner mounted on the motorised stage modelled in Table 2. Settling dwells can exceed 400 ms today. But per $e^{-t/\tau}$, settling adequate for the higher densities a year from now will require more than double that for a ζ of 0.001 and F_{res} of 250 Hz, typical of high – precision structures and fixtures. Physics predicts a dramatic – and costly! – increase in settling time.

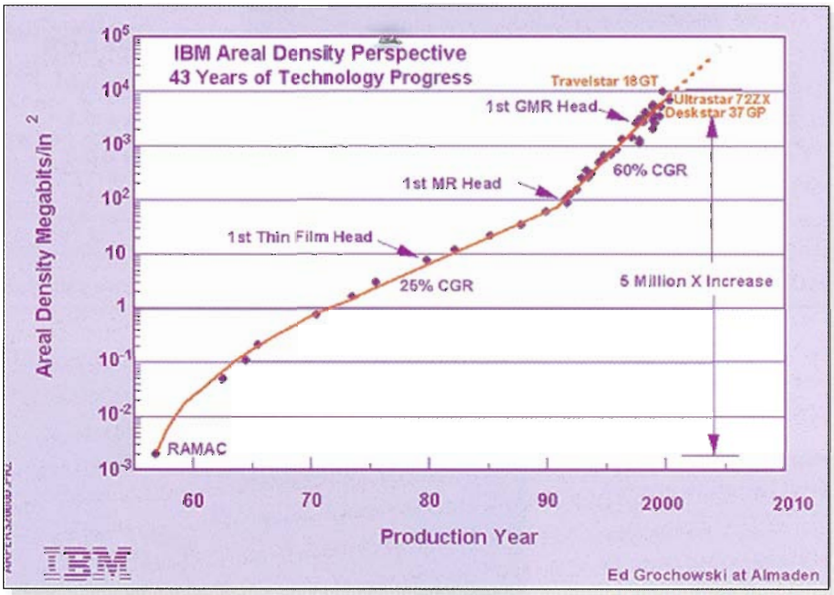


Figure 1
Will tighter process resolutions doom process economics? (Source. http://ssdweb01 storage ibm.com /technolo/grochows/g03 htm)

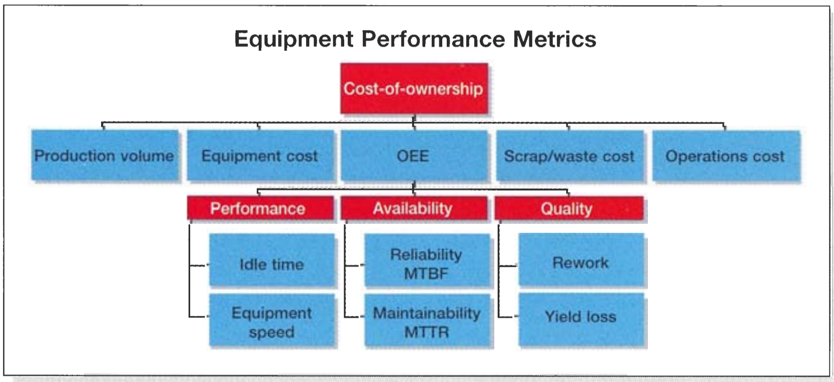


Figure 2
COO is a formal metric for purchasing in the semiconductor industry. Price is but one element. From http://209 67 253 149/semiconductor/archive/jul98/docs/feature2.asp

BREAKING THE LAW

Obviously, motion-generated structural resonances increasingly impact throughput. Fortunately, engineers have several new throughput-enhancing tools available.

LOCK-DOWN AIR BEARINGS

Dover Instruments (Westboro, Massachusetts, USA) introduced high-stability spin-stands (Figure 4) incorporating novel lock-down air-bearings. These address the underdamped resonances of conventional air-bearings. The locked-down air-bearing is highly stiff (high F_{res}) compared to conventional air-bearings or even mechanical bearings and provides unparalleled in-position stability.

INPUT SHAPING™

A patented [3], real-time feedforward technology called Input Shaping™ was developed based on research at the Massachusetts Institute of Technology and commercialised by Convolve, Inc., (New York, NY). It has been implemented in OEM NanoAutomation™ products by PI (Waldbronn, Germany). PI's Mach™ Throughput Coprocessor™ integrates this in its digital controllers (Figure 5).

Mach™ processes the command signal in real time to prevent excitation of resonances. It scales and times transitions in the command so motion-driven vibrations are cancelled. It uses a priori knowledge of resonances as quantified during installation, and does not use feedback. Unlike notch filtering, it is insensitive to

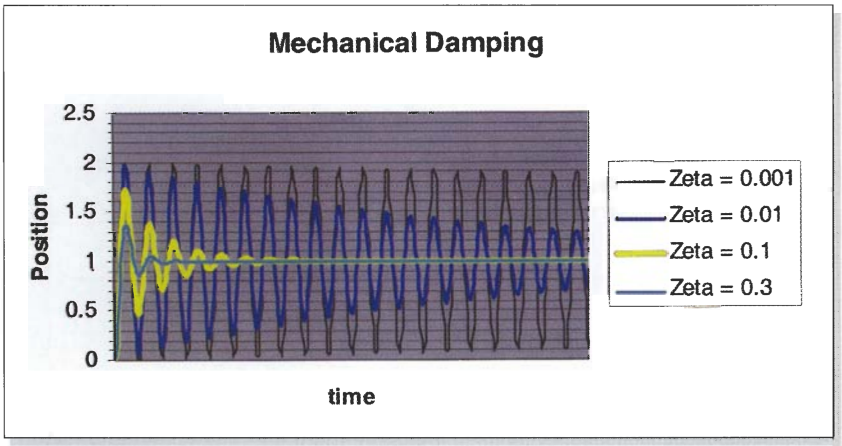


Figure 3 (above)
Vibrational amplitude diminishes as $e^{-t/\tau}$, where $\tau \sim (\omega_n\zeta)^{1}$

Figure 4 (right)
Dover high-stability spin-stand incorporates novel lock-down air-bearings which help deliver high track-profiling throughput

TABLE 1. τ FOR VARIOUS DAMPING COEFFICIENTS, ζ AND RESONANT FREQUENCIES, ω_n

F_{res} (Hz)	ω_n (rad/s)	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
250	1570.8	0.0001	6.366
		0.0005	1.273
		0.001	0.637
		0.005	0.127
		0.01	0.064
		0.05	0.013
		0.1	0.006

TABLE 2. SETTLING TIME OF A TRACK-PROFILING FIXTURE AFTER 12 MONTHS OF AREAL DENSITY GROWTH, FOR A FIXTURE (F_{RES} ~250 HZ) WHICH SETTLES IN 400MS TODAY. A 2MS PIEZO RISETIME IS ASSUMED. EXAMPLES HIGHLIGHTED IN THE TEXT ARE BOLDFACED.

Today's settling time (s)	zeta	In 12 months of 60% areal density growth	X change	w/Mach, 2ms 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

variations in frequency over a range > ±15%. It is effective against multiple resonances, resonances occurring outside the servo loop, and resonances exceeding system bandwidths. Its robustness makes the technique attractive for OEM usage. In particular:

- It requires no changes to application setup, software or servo parameters.
- It cannot degrade servo stability.
- It does not require specific configuration for specific motions.
- It is robust with changes in operating dynamics, such as unit-to-unit variations, or moderate changes in loading.

As a rule of thumb, Mach™ settles a system in about F_{res}^{-1} after the piezo risetime. Per Table 2, our example immediately benefits, with virtually no residual vibration after only 6 ms (including 2 ms piezo risetime) instead of the current >400 ms. After 12 months of areal density progress, this application would require 6 ms to settle with Mach™ versus 980 ms without – a huge improvement. (The effectiveness of the Mach™ technology is essentially unrelated to ζ or settling band.) Figure 8 shows real-world settling data from the Dover high-stability spin-stand, revealing combined benefits of the lock-down air-bearing and Mach™. The tool's PZT stage (Figure 9) is very stiff for a high F_{res}, resulting in <3 ms settling with a 700 g load.

Mach™ also eliminates ringing during scanning, such as in pole-tip recession (PTR) profiling, where one axis scans while the other steps. The motions cause recoil pulses to propagate through the structure. Ringing causes periodic image artifacts. This limits scan velocity and resolution.

Figure 10 (left) shows the resonant reaction of a scanning-microscopy application's optics as visualised by a non-contact Polytec vibrometer. There is visible periodic smearing and banding in the resulting image. Figure 10 (right) shows the optics' behaviour with Mach™ activated. The improvement in scan fidelity is obvious: cyclic inaccuracy is eliminated. The image improves dramatically (Figure 10, right): the central smear and the spot at the right are revealed as a streak of contaminant and a phantom artefact.

ALTERNATIVES

Momentum compensation

This classical technique (Frahm damping) actuates a reaction mass in opposition to the load. It benefits applications with low structural resonant frequencies. Meticulous engineering is required for it to work well. The costly counter-actuation mechanism must be carefully matched to the load, and their centroids must be collinear. Some residual vibration is unavoidable. This can be eliminated by parallel application of Mach™.

Signal preshaping

For applications with continuous, repetitive periodic inputs, a new pre-shaping technique [4] can reduce the rolloff, phase error and hysteresis of the servo, improving the effective bandwidth and allowing more accurate tracking. It is implemented in object code based on an analytical approach where the complex transfer function of the system is calculated, then mathematically transformed and applied in a feedforward manner to reduce the tracking error. It improves the

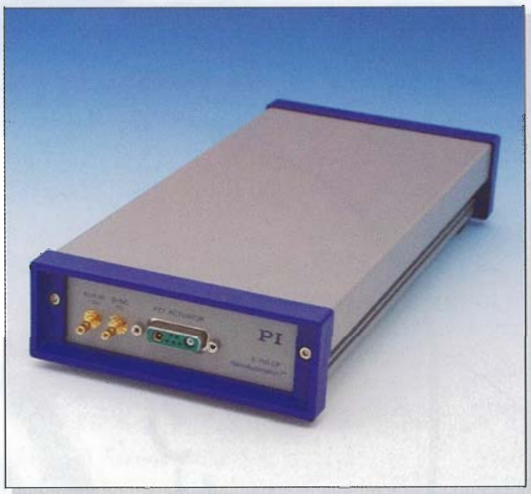


Figure 5
The Mach™ Throughput Coprocessor is integrated into the latest PI digital controllers such as the fibre-interfaced E-750.CP

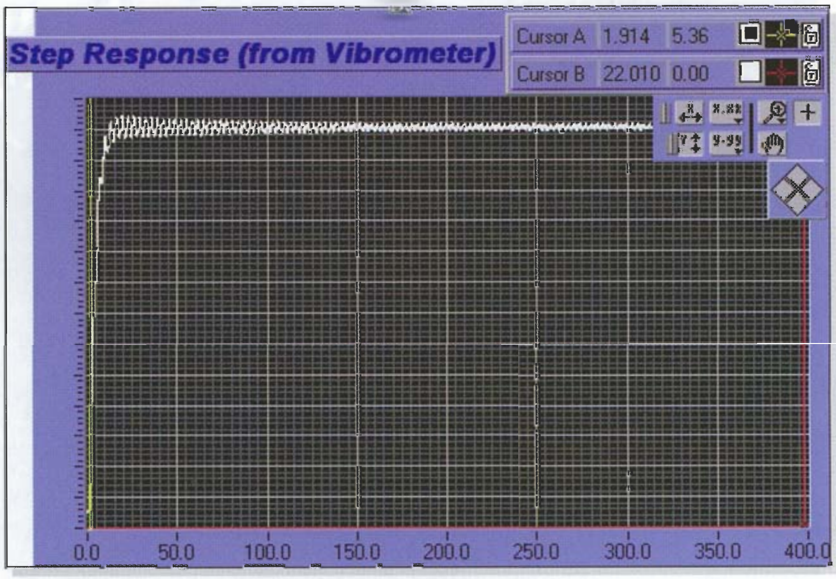


Figure 6
Piezo stages are capable of millisecond-scale step-and settle. However, elements outside the servo loop ring (load, neighbouring componentry...). External resonances are visualised by a Polytec laser vibrometer

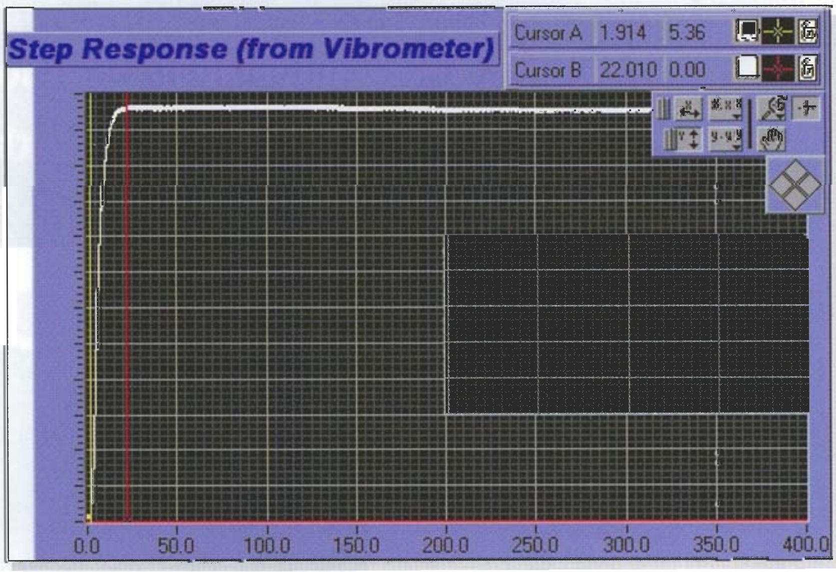
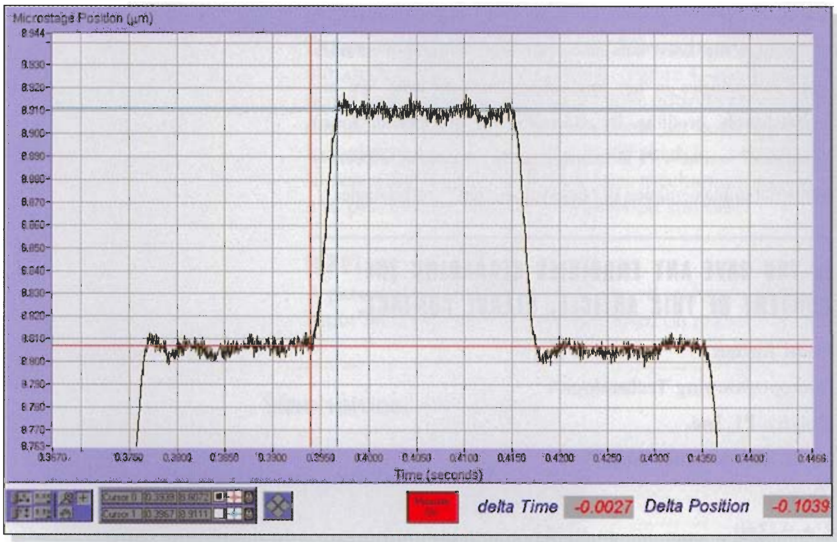


Figure 7
Mach™ eliminates motion-driven ringing of components outside the servo loop. Settling after risetime completes by $t \sim F_{res}^{-1}$



effective bandwidth by a factor of 10. It is more effective than classical phase-shifting approaches in reducing tracking error in multi-frequency applications. It can be combined with Mach™ to address resonances outside the servo/feedback loop.

Active isolation systems

Isolation structures have evolved to advanced systems controlled by DSPs and motion transducers. The controls strive for zero motion and are sometimes claimed to damp vibrations caused by onboard equipment. However, this is a feedback situation. By definition, time is required to sense and act upon disturbances, and there is a threshold to the system's sensitivity. (Mach™ prevents vibrations rather than sensing them.) Some systems offer position feedforward to help maintain levelness when large motion stages are slewed. The technique is no more effective than basic isolators for onboard motions on the submicron scale, or out of the XY plane.

Motion controls with "active damping"

Some DSP-based motion systems are available which claim active damping capabilities. The drawbacks noted above for the case of active isolators apply here as well.

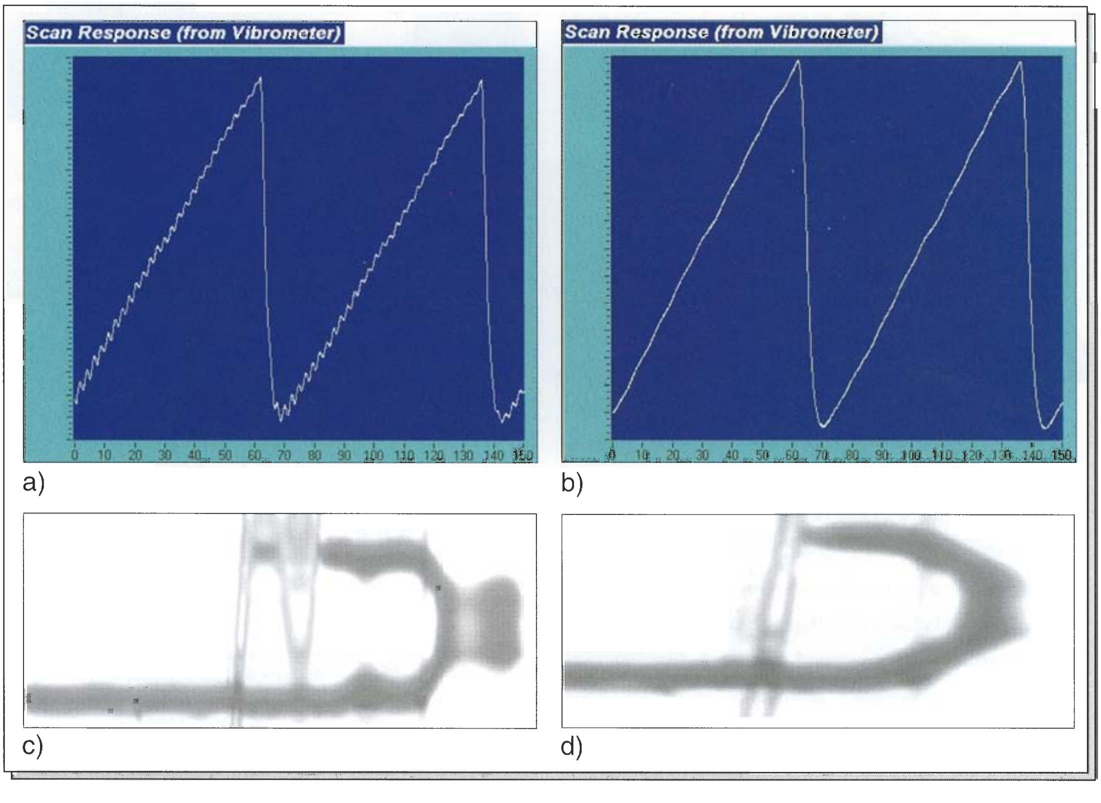
Posicast

Posicast control, a technique developed in the 1950s, is a form of pole-zero cancellation that reduces residual vibration for the case of single resonance modes. However, it has achieved little acceptance because it is highly dependent on knowing the exact frequency and damping of the vibration to be cancelled. It is further limited because it is an analogue technique that requires exact timing. This can be problematic on digital control systems with a fixed update frequency. In contrast, Input Shaping™ was developed to specifically address the short-

Figure 8 (top)
100 nm move-and-settle to <10 nm in <3 ms with 700 g load. (Courtesy Dover Instruments.)

Figure 9 (above)
Ultra-stiff NanoAutomation™ stage optimises Fres, provides 15μm travel with sub-nm resolution

Figure 10 (right)
Use of Input Shaping™ improves micro-optical scan accuracy from ~1 μm to better than ~0.05 ~μm. Total width of "J" feature is ~2 μm



comings of Posicast. Input Shaping™produces exact solutions for digital control systems where multiple resonances exist. The Input Shaping™ solution is robust in the real world where the measurement of the frequency may be imperfect or varies from unit to unit or from day to day.

CONCLUSION

Progress in the technology industries is illuminated by the staggering trends seen in areal density growth and Moore's Law. But the profitability prerogative makes this a major headache for the tool or process designer, as higher densities make for exponentiating settling times.

Recent mechanical and control advancements address this problem at its root: by eliminating settling-time by preventing the excitation of the resonant modes of the stage, load, fixturing, frame and componentry.

REFEREONCES

[1] Source: Intel Corp. See http://www.intel.com/intel/museum/25anniv/hof/moore.htm; also see http://webopedia.internet.com/Hardware/Microprocessors/Moores_Law.html

[2] A fine reference for the physics of resonant vibrations is *Modern Control Engineering* by Katsuhiko Ogata (Prentice-Hall, 1970, ref. pp. 271-272). A remarkable on-line reference can be found at http://bits.me.berkeley.edu/~beam/spr95/theory/detsys/detsys_1.html.

[3] The Mach™ Throughput Coprocessor™ is protected by one or more of the following US and foreign Patents licensed from Convolve, Inc.: US 4,916,635; US 5,638,267; 0433375 Europe; 067152 Korea, and other Patents pending. Mach™, Throughput Coprocessor™ and NanoAutomation™ are trademarks of Polytec PI, Inc. Input Shaping™ is a trademark of Convolve, Inc.

[4] R. Glöß, New Methods of Signal Preshaping Strongly Increase Bandwidth of Closed-Loop PZT Actuators, Physik Instrumente (PI), Waldbronn, Germany

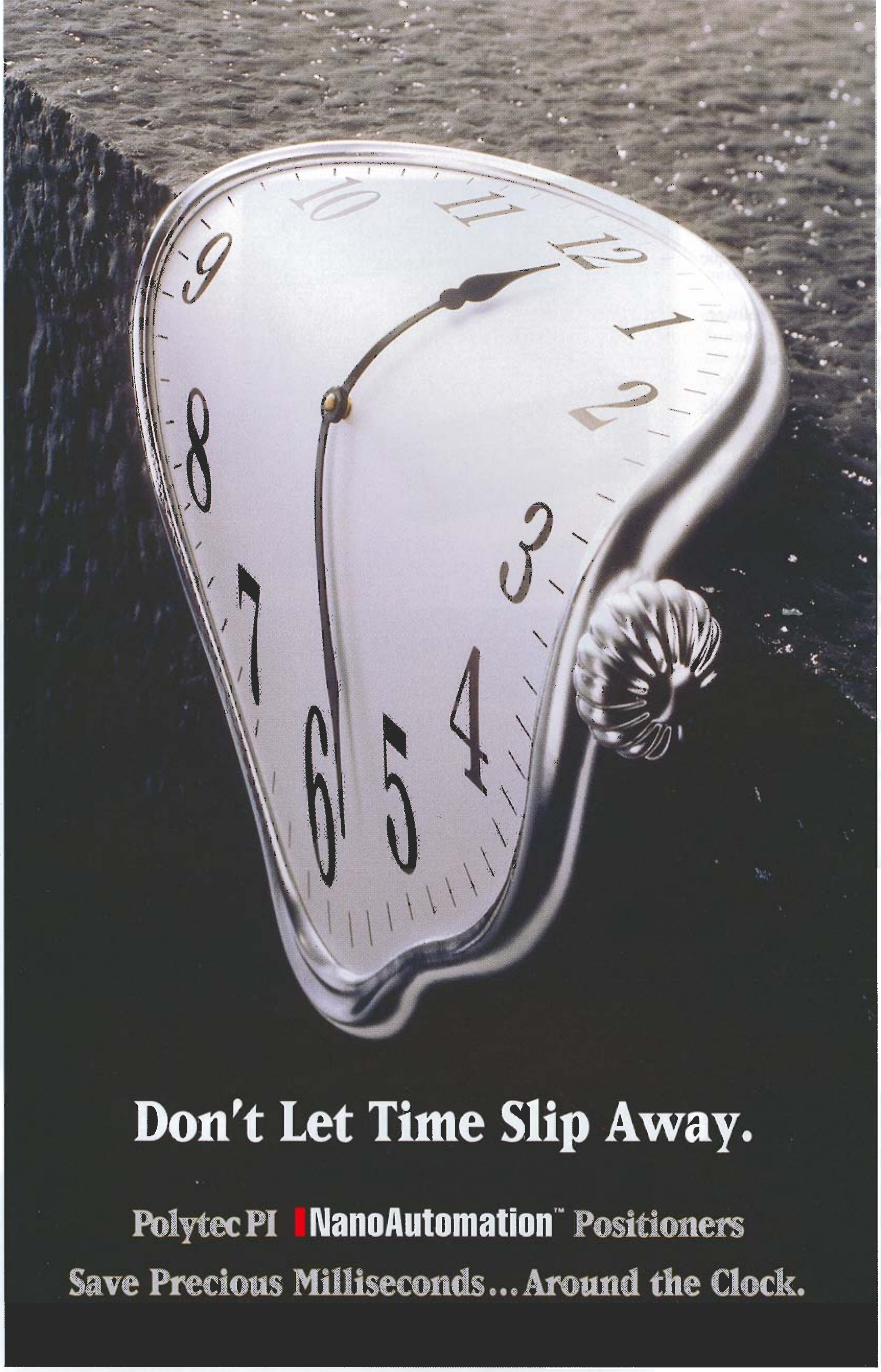
ABOUT THE AUTHOR

Scott Jordan is Director, Nanopositioning Technologies at Polytec PI, Inc. He has eighteen years of experience in the photonics, semiconductor and mass storage fields. His education spans physics (MS, physics, University of California, Irvine, 1983) and high-tech business development (MBA, Finance and New Venture Management, University of Southern California, 1984). His career has included a range of product development, marketing, research and general management roles. He has led several high-tech endeavours to rapid growth through technical and market innovation and close partnership with customers and suppliers. His invention of micro-optical automated alignment techniques remains a significant contribution to ultra-precision process automation. Another was co-development of six-degree-of-freedom production test interferometry, and early work in laboratory and process automation tools. One focus for him at PI is to leverage the latest sub-nanometer and throughput-enhancement technologies in key applications such as head test and scanned-probe profiling. By addressing the overlooked "fourth dimension" – time – PI is focusing on key economic aspects of industrial implementation of NanoAutomation™ technologies.

IF YOU HAVE ANY ENQUIRIES REGARDING THE CONTENT OF THIS ARTICLE, PLEASE CONTACT:

Scott Jordan
Nanopositioning Technologies
Polytec PI, Inc.
1342 Bell Avenue, Suite 3 A
Tustin
CA 92780
USA

Tel: +1 (714) 850-1835
Fax: +1 (714) 850-1831
General E-mail : info@polytecpi.com
Scott Jordan personal: scottj@ca.polytecpi.com
Web site: www.physikinstrumente.com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