Patented New Technology Provides Enhanced Positioning Resolution

Abstract

Increasingly, DAC's are a limiting factor in nanopositioning resolution, especially in the latest millimeter-travel stages. A newly patented technology adds up to 10 bits of resolution to virtually any OEM DAC and popular PC analog I/O boards without hardware modifications and with full compatibility with legacy software. Applications range from scanned-probe microscopy and nanofabrication to advanced lithographies and optical tweezers.

Background

Most motion devices are fundamentally analog. Since today's is a digital world, an analog drive command is usually generated by a digital-to-analog converter (DAC) chip someplace in the system (Figure 1). Besides being embedded in digital piezo controllers, DACs are commonly used to command analog servos, either from a card in the user's PC or OEM tool, or embedded into the servocontroller so computer interfaces like RS-232 can be provided.

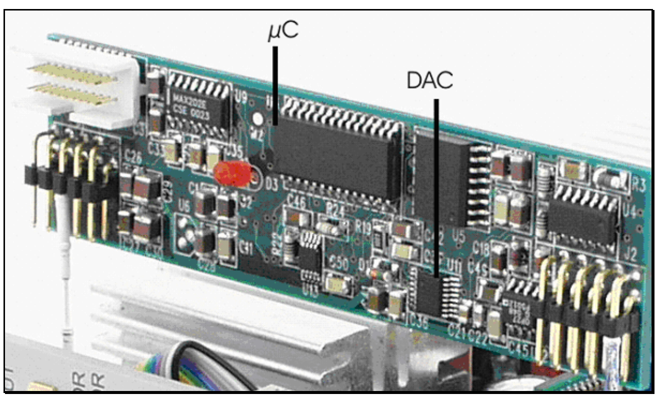

Figure 1. A Digital-to-Analog Converter generates the voltage which, when amplified, drives a nanopositioner.

DACs are nearly universal in nanopositioning applications. In fact, DAC capabilities are one of the most important parameters defining a nanopositioning system's ultimate performance—and its limitations.

DAC Basics

Operation of DACs is simple enough: a digital number goes in, and an analog voltage comes out. The maximum size of the incoming number defines how fine a voltage increment can be commanded. For example, economical 12-bit DAC cards popular for PC applications can accommodate an incoming integer between 0 and [2^{12}-1]: its voltage range is thus divided into 4,096 steps, meaning the resolution is [*Range* ÷ 4,096]. If the voltage range of the DAC matches the analog input range of the nanopositioning system, then the travel range of the motion device is similarly divided into 4,096 possible locations. A 16-bit DAC would divide the same *Range* into 65,536 steps, thereby providing sixteen times finer positioning resolution. (It is important to match the DAC *Range* to the analog input range of the piezo controller. If *Range* is -10V to +10V but the analog input accepts 0 to +10V, one bit of resolution is lost. The number of addressable positions is reduced by two.)

DAC bitness is thus a limitation to piezo nano-positioning system resolution, as shown in Figure 2. Other system characteristics such as amplifier noise also present resolution bottlenecks, but DAC resolution is probably the most frequently-encountered limiter, particularly for longer-travel piezo devices.

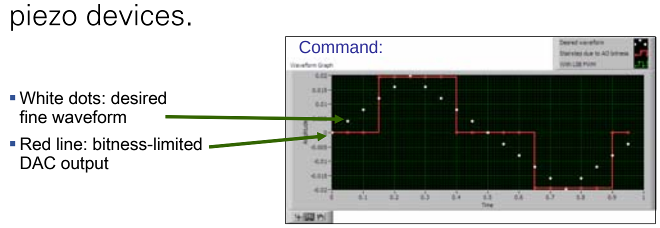

Figure 2. DAC bitness limits fine position control.

Until now, a DAC's limitations were permanent characteristics of the specific chip. A PC user might choose between 12- and 16-bit cards for their PC; higher-resolution cards are uncommon, and most users prefer to stick with popular and well-supported National Instruments I/O cards, which generally top out at 16 bits. Used with PI's P-628.2CD or P-625.1CD PIHera® stages, with 1,000 and 500µm travels respectively, this results in 15 and 8nm resolution. Many applications could use better resolution than that. An entry-level 12-bit card would provide only 0.23 and 0.12µm resolution with these stages—coarser than many motorized stages provide. OEM users might choose an 18-, 20- or 24-bit DAC for their custom circuit design, but many high-bitness DACs are optimized for audio use and can present drift issues or other drawbacks. (Well-designed all-digital controllers like PI's E-710 and E-750.CP put their DAC inside the servo loop, eliminating DAC drift issues.) And sometimes a new design is not economically practical, yet user demands for higher and higher resolution persist.

More performance from existing DACs

Missing in the discussion above is *time*. DACs are typically very fast compared to motion devices, even those as responsive as a piezo-driven mechanisms. A fast analog update rate is what allows DACs to generate smooth arbitrary waveforms. It also means there is unused analog-output bandwidth in a typical nanopositioning setup.

PI's patented[i] HyperBit™ technology leverages this under-utilized time-domain capacity, converting it into many additional bits of physical positioning resolution with no loss of system bandwidth, stability or accuracy. HyperBit™ uses high-frequency modulation of the least-significant bit(s) of a DAC to accomplish this. For example, the LSB can be dithered using pulse-width modulation at a frequency where the system is unresponsive, acting like a flywheel to provide smooth, stable motion with far higher resolution than the DAC's native resolution (Figure 3).

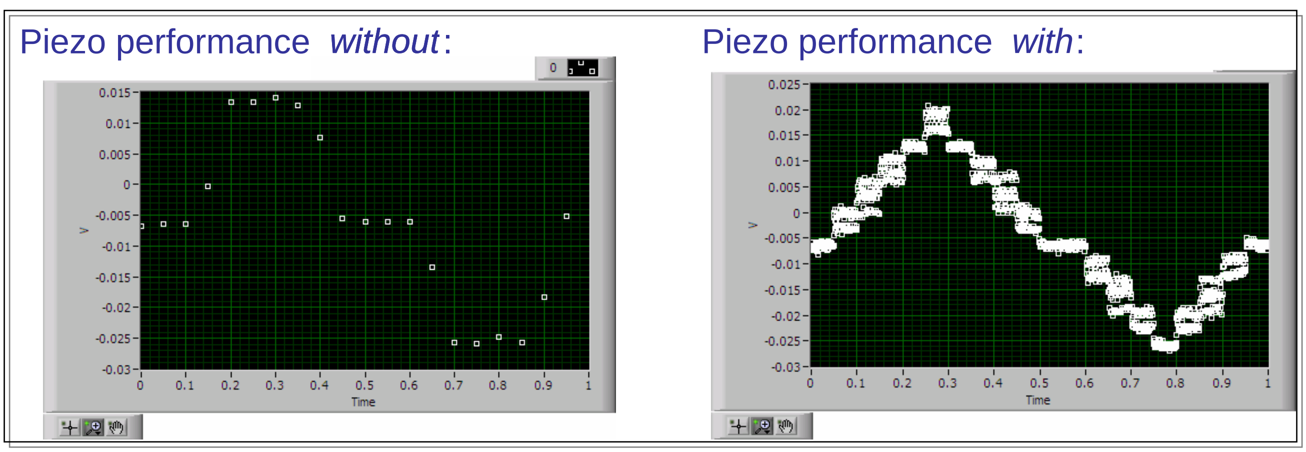

Figure 3. (left) The desired triangle positioning command sequence from Figure 2 is limited by DAC bitness, corresponding to the red lines in Figure 2. (right) With HyperBit™, the desired positioning sequence is achieved, corresponding to the white dots in Figure 2.

Easy implementation

HyperBit™ can be implemented in software or hardware. It is available for license by OEM designers, and is a cost-effective software option for research and OEM applications. Implementations and options have included HyperBit-enabled LabVIEW subVIs, a Windows DLL for programmers using C or other popular languages, and HDL for designers using FPGAs. Point-to-point and waveform actuation are supported, open- or closed-loop. Since the time-domain capability of the DAC would otherwise go unused, there is no impact on system bandwidth, responsiveness or speed.

Theory and application

The theory of HyperBit™ is straightforward (Equation 1):

$$\text{Resolution}_{(\text{bits})} \rightarrow \text{Resolution}_{\text{DAC(bits)}} + \log_2\left(\frac{DAC\_rate}{PWM\_Frequency}\right)$$

– Available DAC rate varies from chip to chip, and with interface (e.g., slow PCMCIA vs. fast PCI)

– PWM frequency is chosen to lie in region of sluggish plant responsiveness (e.g., well above F_{res})

Equation 1. Rule of thumb for resolution enhancement

For example, when calling .DLL, .LIB or subVI forms of HyperBit™, the user need only input their DAC's update-rate capability and choose a LSB PWM rate somewhere above their mechanical resonant frequency, F_{res} or at a pole in the system's Bodé response. In principle, *any* clocked DAC with an update rate matching these criteria can benefit from HyperBit™. Figure 4 shows several examples.

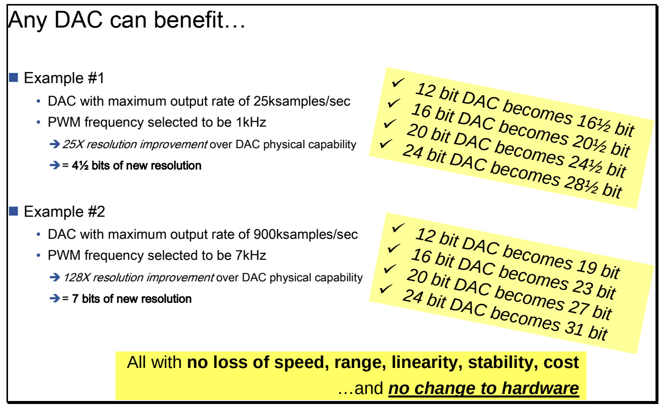

Figure 4. Examples of additional bits of resolution provided by HyperBit™. Virtually any clocked DAC benefits.

Waveform actuation examples

HyperBit™ lends itself well to improving the resolution of waveform actuation in scanning, probing and dithering applications. Figure 5 and Figure 6 document real-time interferometric measurements of a piezo nanopositioning stage when actuated in a variety of waveforms.

In Figure 5, the amplitude of the commanded waveform is ~1·LSB. Without HyperBit™, the resulting motion understandably bears little resemblance to the desired sine, triangle or sawtooth waveforms. With HyperBit™, the desired wavefoms emerge, no longer limited by DAC bitness.

In the high-resolution interferometry shown in Figure 6, the waveform amplitude is ~10·LSB. Without HyperBit™, the waveform shows stepwise behavior characteristic of limited DAC resolution. With HyperBit™, the waveform is significantly improved. It is also interesting to note from Figure 6 that the elimination of DAC granularity will also eliminate the consequent unwanted modulation peaks in the Fourier spectrum for small or slowly-varying motions. This can be important in applications such as nanoindentation, rheology, viscosimetry and apodization, where delicate frequency-domain signatures can have profound import.

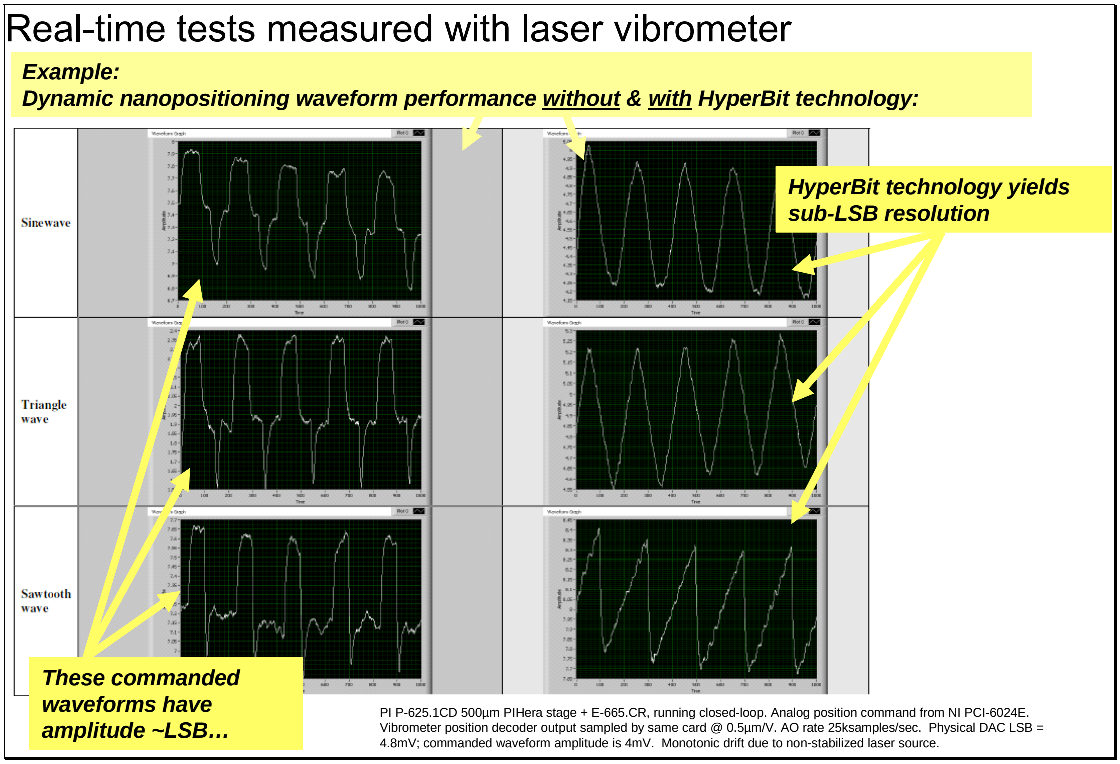

Figure 5. HyperBit™ provides additional bits of resolution in waveform actuation, as in raster scanning and similar applications.

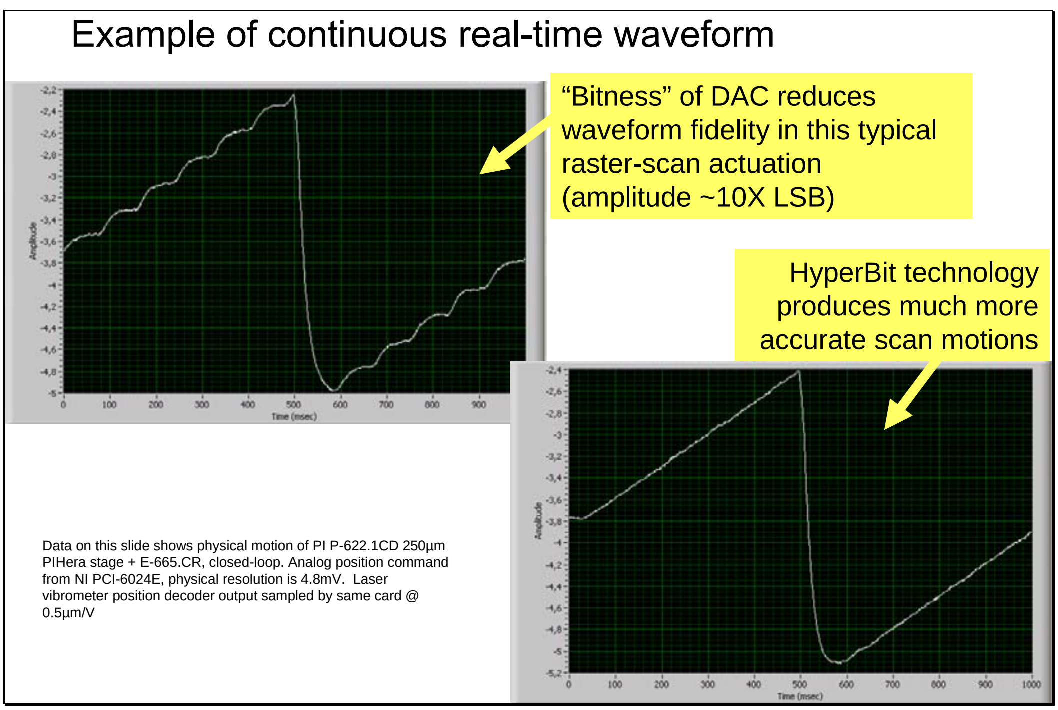

Figure 6. High-resolution interferometry of raster scan, of amplitude ~10·LSB. (left) Bitwise step activity of DAC can be seen. (right) HyperBit™ adds additional resolution, improving the dynamic accuracy of the scan.

Extreme Makeover

The preceding examples illustrate HyperBit™ adding additional bits of resolution to motion commands on the order of a few LSB. But HyperBit™ can allow you to achieve sub-LSB commands as well. Figure 7 shows the results of using HyperBit™ to command a sawtooth wave of amplitude ~1/12·LSB. Without HyperBit™, this would be equivalent to commanding DC.

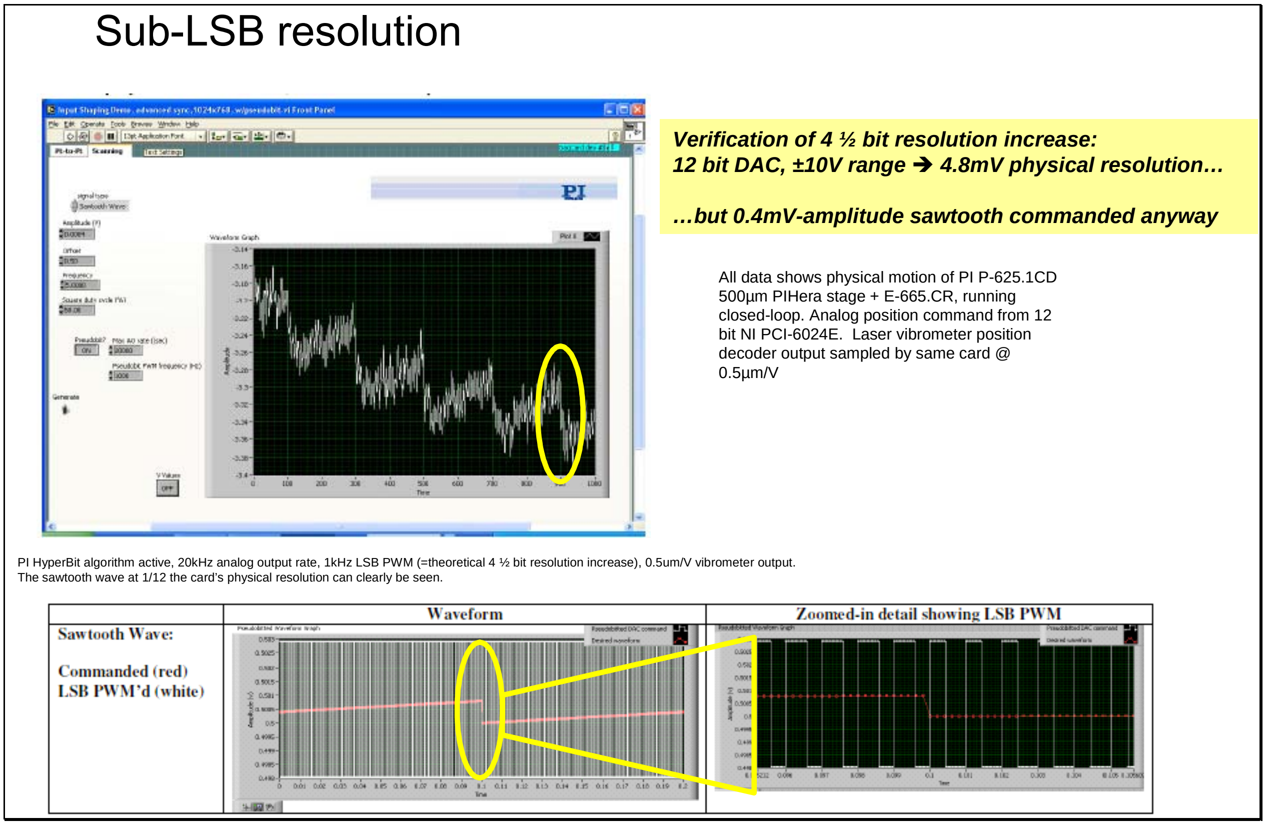

Figure 7. A low-level look at the patented HyperBit™ technology: in this extreme real-time interferometric example (which tested the limits of the metrology used!), HyperBit™ clearly allows a sawtooth waveform to proceed even though its commanded amplitude is 1/12 the electronic resolution of the DAC. The additional resolution in this case is ~4½ bits. The bottom graphs show the desired waveform (red line) and the actual LSB PWM waveform executed by the DAC.

Applications beyond nanopositioning: Licensing offered!

HyperBit™ is a fundamentally flexible technology which can benefit virtually any application where the DAC update rate exceeds the responsiveness of the rest of the system. It works equally well in open- and closed-loop situations. In closed loop systems it can exist upstream or downstream from the servo.

PI USA is seeking non-competitive licensees in many fields. Some possibilities are listed in Table 1 below.

▪ Test & Measurement
▪ Active optics, beam stabilization & pointing, galvanometers
▪ Electro-Optic devices
  ▪ AOMs
  ▪ Fabry-Perot
  ▪ Cavity tuning & Stabilization
  ▪ Liquid crystal elements
  ▪ Spatial and spectral modulators
▪ Large-area/high-resolution E-beam and ion-beam deflection
  ▪ Microscopy
  ▪ Spectroscopy
  ▪ Lithography
  ▪ Milling
	▪ AFMs, scanning microscopies, NSOM, nanomanipulation
	  ▪ Facilitates large-area processing
	  ▪ Reduces higher-order granularity-driven dynamics & artifacts
	▪ MEMS actuation
	  ▪ Electrostatic, thermal, electromagnetic
	▪ Nanopatterning
	▪ Precision metering & forcers
	▪ Motion control
	  ▪ Microsteppers, voice coils
	▪ Data storage microactuation
	▪ Holographic random-address access
	▪ Audio

Table 1. Potential licensed applications for HyperBit™ outside of the field of nanopositioning. Possibilities include both new designs and upgrades to existing equipment.

Conclusion

HyperBit™ is an exciting and easily-implemented advancement in digital control of analog processes. By converting unused time-domain DAC capability into enhanced system resolution, HyperBit™ extends the performance of even the best available DACs. At the same time, existing DAC-driven equipment can be upgraded inexpensively, without hardware redesign or changes.

Consult with your PI sales and applications professional today for information on leveraging this technology in your application.

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[i] *Protected by US Patent #6,950,050, foreign Patents pending. HyperBit™ is a trademark of PI (Physik Instrumente) L.P.*