High-speed, low latency communications for nanopositioning in Single-Molecule Biophysics

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Background

Single Molecule Biophysics (SMB) represents one of the fastest-developing and most advanced fields of application for nanopositioning, with extreme requirements for positioning performance, stability and synchronization Significant recent advancements in SMB instrumentation[i] and other sub-nanoscale endeavors[ii] benefit from leveraging new interfacing technologies offering fast speeds and, especially, low latency. These successes illustrate the inadequacy of conventional interface metrics for architecting time-critical processes.

To assist in choosing communications approaches for SMB, we review available interfaces, throwing a spotlight on new entrants such as LabVIEW™ FPGA (valuable for implementing high-speed, highly parallel custom logic as well as for interfacing) and the Serial Peripheral Interface (SPI), just emerging as a high-speed/low-latency option. The utility of instrument-specific parallel (PIO) and TTL sync/trigger (DIO) interfaces is discussed.

Finally, not to be overlooked is the original real-time interface: analog I/O-- still the most popular way to communicate with nanopositioning hardware. Here some fresh developments are discussed, including new technologies for slaving nanopositioner servos to external sensors for autofocus and tracking, a novel resolution-enhancing technique for analog voltage generation, and a useful method of combining high-speed block-mode and single-point data acquisitions using popular multifunction hardware.

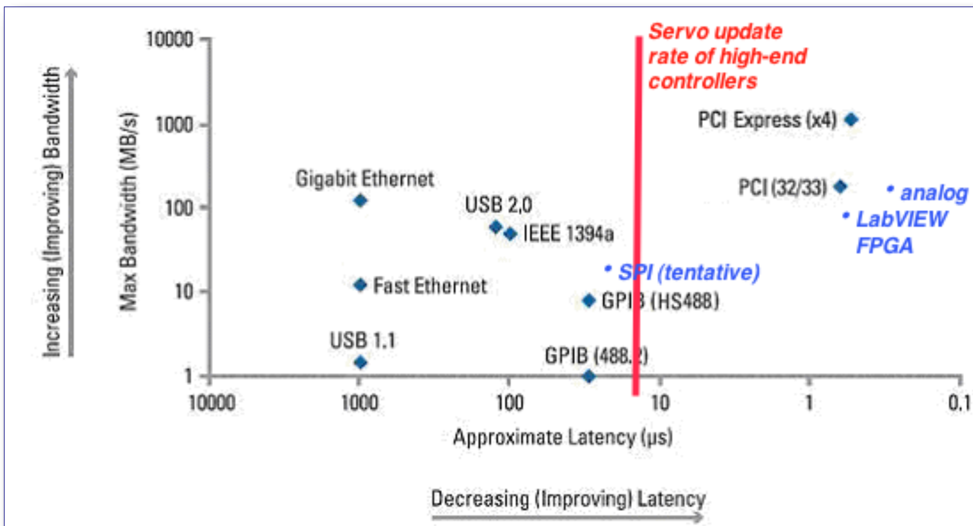


Figure 1. From National Instruments' white paper, "Techniques for Optimizing Instrument Throughput", http://zone.ni.com/devzone/cda/tut/p/id/4911 and updated by the author to reflect new entrants. The trend is towards lower latencies-- of significance for advanced applications such as SMB.

Dueling specifications

Interface specs often focus on metrics appropriate for classes of instrumentation other than nanopositioning. Figure 1 presents some examples. Note how GPIB's throughput is far eclipsed by that of the more modern USB 2, but USB 2 offers worse latency, a specification rarely mentioned.

Motion and nanopositioning controllers mostly communicate in compact strings of ASCII characters. Raw interface throughput is of little utility if transactions are held up by handshaking and other delays that impede responsiveness and add indeterminacy.

Hand-in-glove with interface latency are the synchronization capabilities of the controller. Despite the obviously fundamental utility of being able to determine when motion is complete, or when some internal or external trigger for a motion process is raised, these features often go unspecified. This can force users to program worst-case timing delays in lieu of crisp code tied to actual process progress.

In the following we discuss how the latest interfacing techniques have directly benefited overall application performance such as stability, resolution and accuracy.

Interface Speed → *Stability*:

LabVIEW FPGA drives super-fast, super-deterministic interfacing

Single-molecule biophysics applications increasingly rely on fast responsiveness from their nanopositioning controllers. In fact, significant advancements in the field have recently flowed from innovative interfacing and communications architectures (see sidebar). The latest advances in controller architecture promise a further order of magnitude improvement in interface throughput despite a transition from 16-bit interfacing to 32-bit, with consequent improvement in resolution over large travel ranges without zooming.

> *In [previous] work, feedback was performed using a software-based data acquisition program with limited bandwidth (≤ 100 Hz). By implementing feedback through a field programmable gate array (FPGA), we achieved real-time, deterministic control and increased the feedback rate to 500 Hz... This better control led to a three-fold improvement in lateral stability to 10 pm. Furthermore, we exploited the rapid signal processing of FPGA to achieve fast stepping rates coupled with highly accurate and orthogonal scanning.*
>
> --Churnside, King et al [i]

In addition to offering popular communications interfaces like USB and Ethernet, these

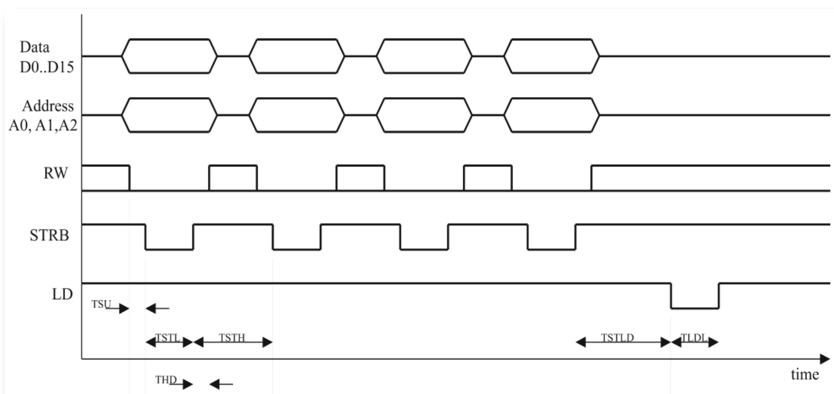


Figure 2. Leapfrogging the latency/determinacy limitations of conventional communications interfaces requires implementation of PIO interfaces offered in high-end controllers, allowing per-servo-cycle application control. Shown: PI E-710 PIO timing.

instruments offer what can only be described as extreme interfacing capabilities via proprietary parallel I/O (PIO) ports which yield per-servo-cycle access for commands and queries. Previously, exploiting such interfaces required construction of custom electronics, presenting their own interfacing and software challenges. Recently, however, flexible logic in the form of Field Programmable Gate Arrays (FPGAs) have become available in software/hardware form factors accessible by users of the popular LabVIEW programming environment, adoption of which is widespread in the SMB community. This has transformed the Field Programmable Gate Arrays--formerly demanding specialized skills to utilize--into *User* Programmable Gate Arrays that any LabVIEW user can leverage. Support for this is a new initiative among nanopositioning vendors.

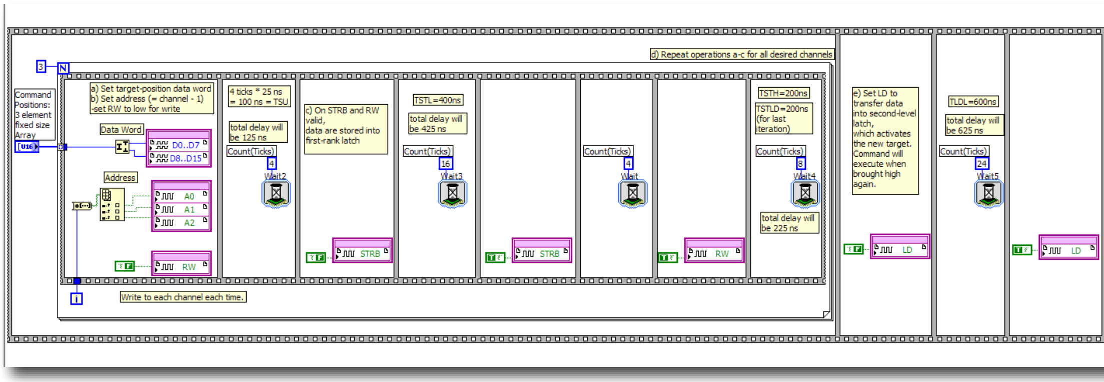


Figure 3. Multi-axis LabVIEW implementation of timing diagram shown in Figure 2, from a driver library provided by PI. This subVI executes directly on the FPGA silicon, independent of software, the computer and its OS, for μsec-scale determinacy and massive parallelism. Axes are commanded with μsec-scale simultaneity at the servo update rate.

Interface Speed → *Accuracy:*

Fast/deterministic interfacing enables picometer-scale absolute accuracies

The same "extreme interfacing" technology described for PIO interfacing supports fast, deterministic analog I/O as well. One challenge for nanopositioning applications is the 16-bit resolution of onboard digital-to-analog converters (DACs) on LabVIEW FPGA-compatible hardware. Fortunately, a LabVIEW FPGA version of PI's patented HyperBit algorithm[iii] is offered. This technology leverages unusable time-domain capability of modern DACs to provide additional positioning resolution (see explanatory video at http://tinyurl.com/hyperbit). Up to 27 bit positioning resolution has been demonstrated using 16-bit NI DAC hardware.

This capability was recently leveraged by researchers at the UK's NPL and Germany's PTB in partnership with PI[iv], for controlling a novel monolithic silicon X-ray interferometer driven by a piezo actuator. This mechanism performs quantized steps at half-fringe spacing via diffraction off the crystallographic (220) planes in silicon. In the first version of this instrument, the steps are localized to ~5-10pm accuracy.

Internalized functionality can be best

A host of situations exist where integrated functionality is superior to what can be achieved in the application's central personal computer. An example is synchronized actuation of two or more axes. While it is possible to command two or more single axis controllers quasi-simultaneously, any latency will manifest itself as a poor coordination between axes, for example resulting in XY motion that traces something like an L rather than a \. Generally speaking, inter-axis coordination is easiest to achieve inside the controller. Otherwise, of the popular conventional communications interfaces only GPIB supports triggering two devices deterministically, and then only if they support such functionality. Conventional analog interfacing is a way besides FPGAs to achieve multi-axis nanopositioning coordination, since common multifunction PC interfaces can readily generate multiple analog outputs with sub-microsecond synchronicity.

A special case of multi-axis actuation is for achieving virtual coordinate systems. As the simplest example, an X,Y stage naturally defines a coordinate system aligned with its physical axes, but some multi-axis controllers allow a virtual rotation of the coordinate system, to X',Y', by scaling each physical axis' motion in real-time according to the trigonometric projection of the virtual axes. Another example is when a workpiece is driven by two parallel actuators (Figure 4); actuated mass is reduced, differential actuation of the actuators yields a rotation capability, and parasitic motions (runout) are automatically compensated. Again, the best place for such coordination is in the controller.

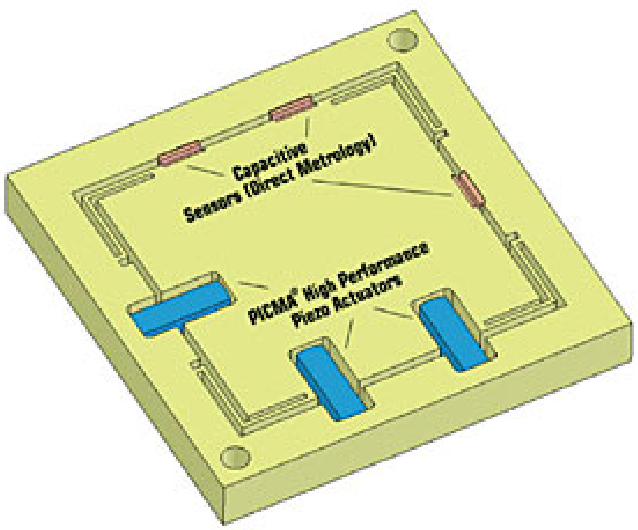
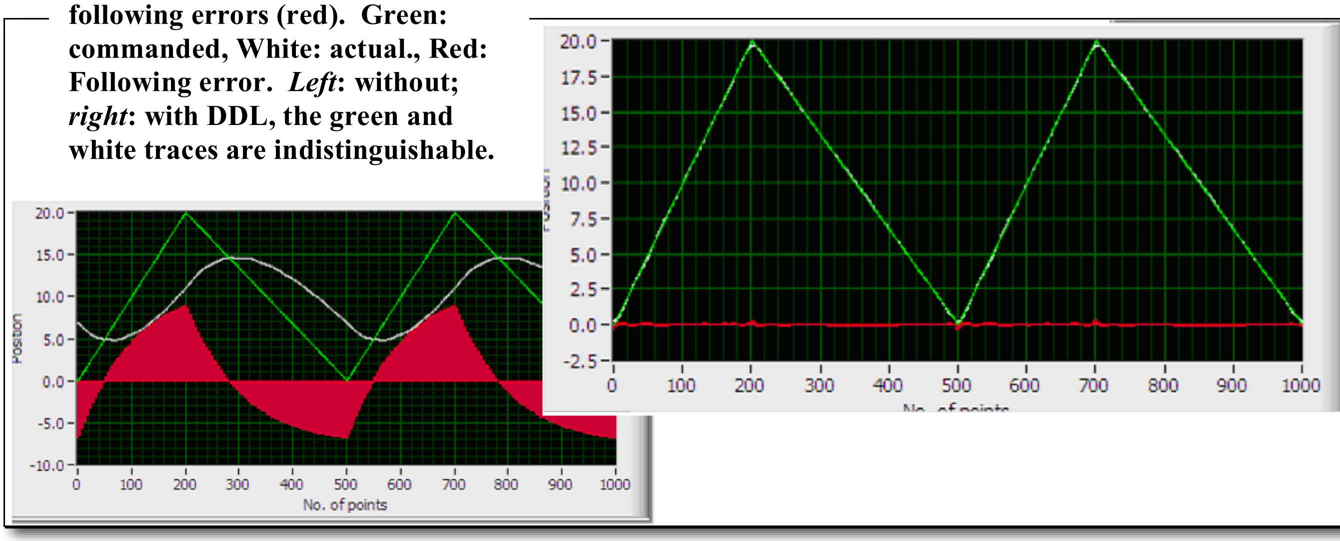


Figure 4. Parallel kinematics designs drive a positioning workpiece with multiple actuators. Capabilities include virtual axes, automatic compensation of parasitic errors (runouts), and lower actuated mass for higher responsiveness vs. stacked multi-axis configurations.

Other examples include advanced control and servo techniques. Dynamic Digital Linearization (DDL) is a case in point; this technology virtually eliminates following-errors stemming from finite system bandwidth. In SMB applications this has particular merit when used to linearize triangle-wave stage actuation in Stokes calibration of trap forces (Figure 5).

Figure 5. Dynamic Digital Linearization is an in-controller technology for eliminating following errors (red). Green: commanded, White: actual., Red: Following error. *Left*: without; *right*: with DDL, the green and white traces are indistinguishable.



Novel real-time capabilities for slaving piezos to tracking and focus sensors

Often, piezo position is best determined by external sensors. Here, avoiding intervening electronics and software is especially beneficial to system throughput and responsiveness. The latest generation of advanced digital piezo controllers provides across-the-board capability for direct integration of external sensors into the servo loop, eliminating latencies.

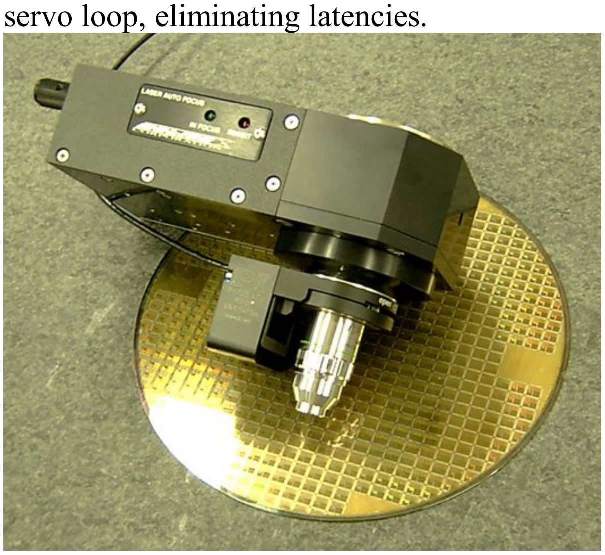


Figure 6. Fast autofocus sensor (courtesy Motion X)

The autofocus sensor shown in Figure 6 is an example. This unit integrates into the microscope optical column and operates with any PIFOC focusing mount to achieve rapid snap-in and real-time image optimization, unlike probe-based mechanisms which monitor sample stage drift only and cannot achieve focus on their own.

Direct integration of the focus sensor into the controller servo-loop provides especially crisp and stable focusing over the full range of the PIFOC. The data shown in Figure 7 is from a laser interferometric vibrometer and documents the millisecond-scale snap-in of a piezo-driven P-725 PIFOC when optimized via the autofocus sensor in Figure 6, as directly interfaced to the piezo controller. Both analog and digital controllers can provide autofocus with this approach; tracking of fiducials for XY stabilization is an analogous application in the image plane itself.

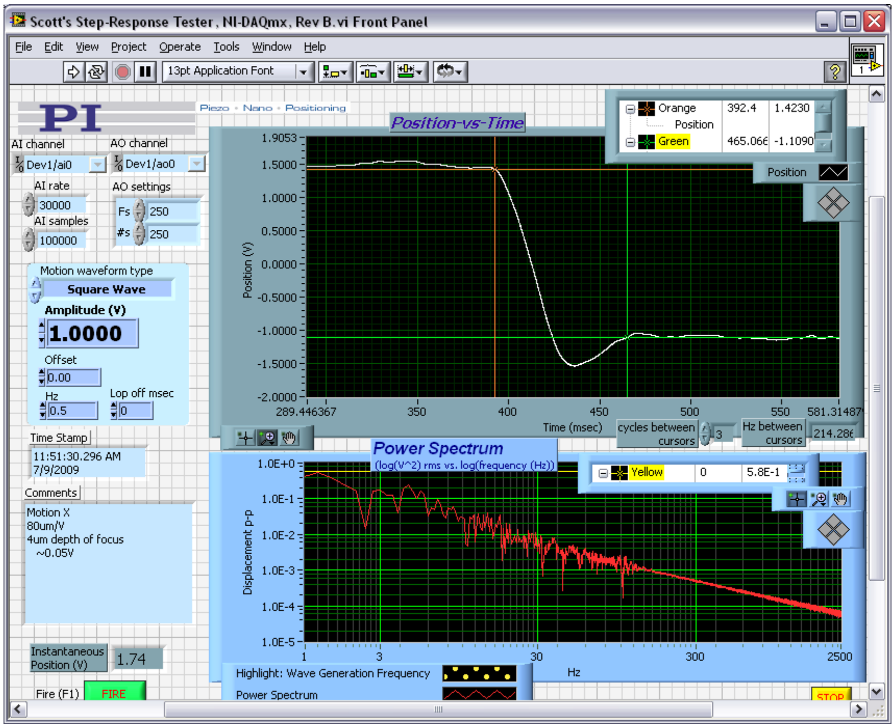
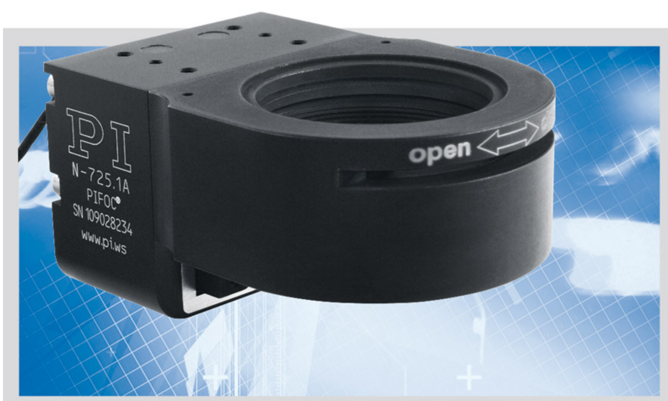


Figure 7. 60msec capture of focus demonstrated by laser vibrometer independently measuring PIFOC position vs. time.

The direct-interfacing technique has been extended to new long-travel piezomotor-driven PIFOCs as well. Figure 8 shows fast snap-in over nearly the full 1mm travel range of this new class of focusing mechanisms.



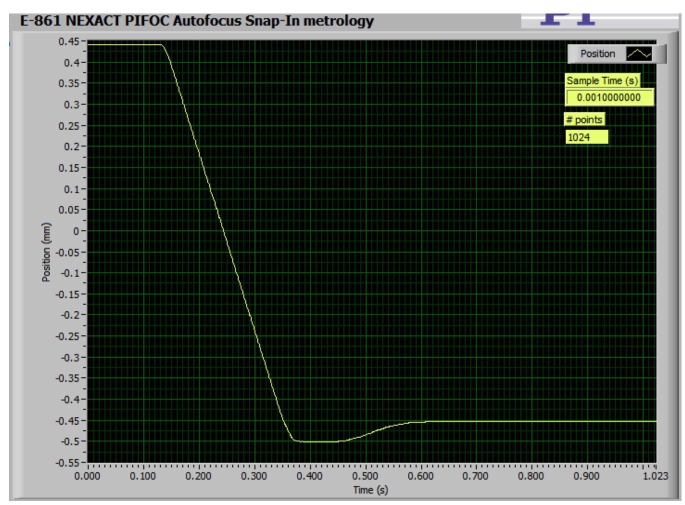


Figure 8. The new generation of piezomotor-driven PIFOCs provide up to 1mm travel with high stiffness. The graph shows focus capture over nearly the full travel range.

A consequence to all that fast motion …and a solution

The confluence of:

- Advanced controllers with faster, lower-latency interfaces,
- Multi-axis parallel-kinematics piezo stages with high natural resonance frequencies,
- New personal computer interface technologies including user-programmable FPGAs, and
- High-bandwidth internal and external sensors

…means many enabling things for applications, but also one drawback to consider: the stability of the rest of the instrumentation setup when subjected to the high-dynamic actuation of the piezo device.

In particular, the rigidity and stability of the coarse XY substage which supports the piezo fine-positioning stage in most SMB applications becomes even more critical as the fine-positioning stage is commanded in higher and higher dynamics and with more continual motion. The nanoscale lubricant film present in all screw-driven mechanisms poses a formerly intractable problem for stability in SMB usage, and eliminating the screw mechanism through integration of a long-travel piezomotor has proven effective for providing nanoscale stability over many minutes.[v]

Figure 9. By eliminating the leadscrew assembly, piezomotor long-travel stages provide mm-scale positioning with $0.1\mu m$ resolution and nanoscale long-term stability.

Teaching analog new tricks

The original fast/deterministic interfacing

Even as newly capable digital interfaces are popularized among piezo nanopositioning controllers and other instruments, analog interfacing remains popular for its immediacy and versatility. Today's multifunction cards for personal computers offer a wealth of functionality which is accessible via popular programming environments like LabVIEW. Formerly, programming was left as an exercise for the user, but factory-supported LabVIEW subVI libraries are now offered which adhere to the PI General Command Set standards (so products and interfaces can be swapped with little or no change to application code). The library includes HyperBit as a built-in option to provide many bits of additional resolution beyond the typical 16 bits of most multifunction hardware-- of increasing importance as piezo device travels lengthen.

The hardware's advanced synchronization capabilities are supported as well. Multiple analog input channels can be acquired synchronously with analog waveform output to support scanning applications.

Of course, many users develop their own code based on National Instruments' NI-DAQmx driver, which is natively supported by LabVIEW. This opens the door for additional enabling innovations, such as the technique recently developed by the author (Figure 10) to allow real-time sampling of block-mode acquisitions, which formerly could be reviewed only upon completion of the block's acquisition. This was initially developed for a nanotribology application where collision detection logic needed to run at all times. Software loop times limited acquisition rates to a few hundred Hz, and utilizing this technique improved that by five orders of magnitude.

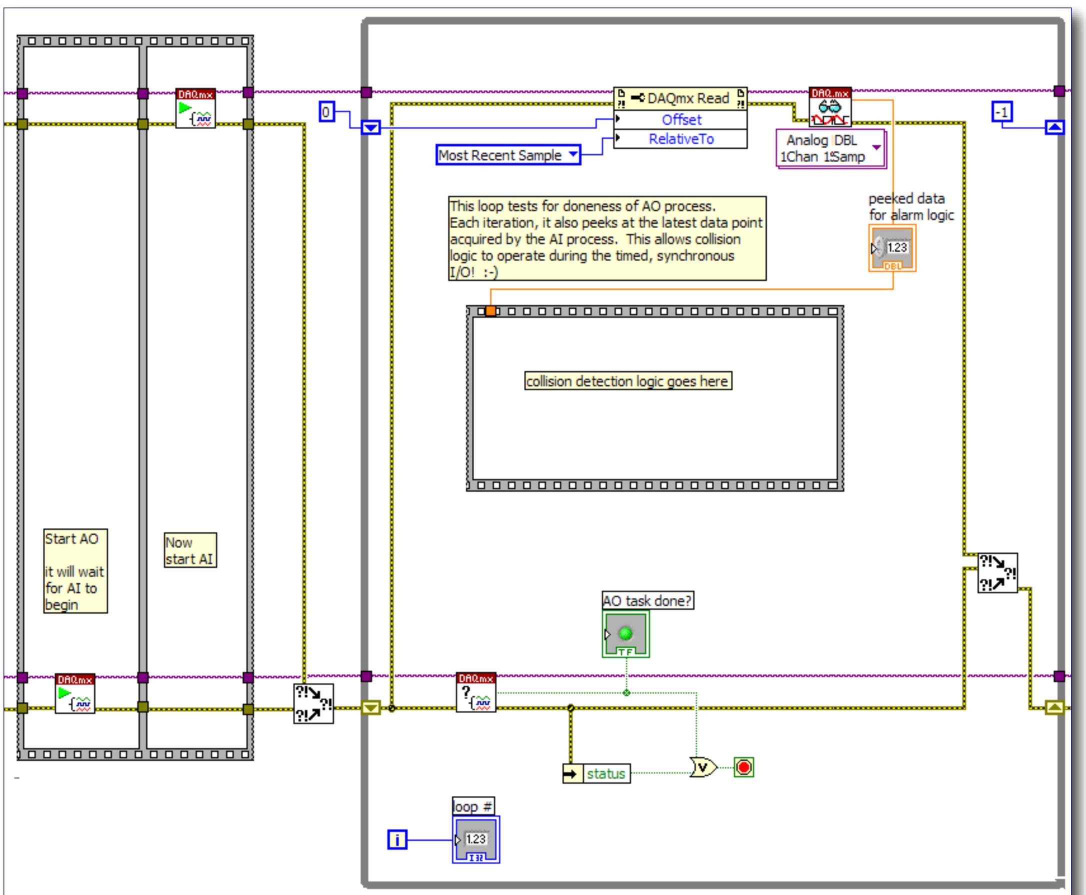


Figure 10. A novel technique of potential interest to SMB applications allows real-time monitoring of block-mode NI-DAQmx acquisitions. It is shown as implemented in a synchronous analog acquisition process during waveform output.

Future trends

Increasingly, application throughput and the time granularity of control determines the capabilities of SMB applications. Leveraging new interface techniques that reduce latency and improve determinacy has helped drive application capabilities. This trend will continue as nanopositioning capabilities keep pace with emerging needs.

On the near horizon is Serial Peripheral Interface (SPI) communications, just emerging in nanopositioning instrumentation in 2011. This promises inexpensive and highly deterministic digital interfacing at or near the servo update rate of many controllers, supporting a large or complete subset of the controller's command set. Many SPI connectivity options are emerging, including:

Figure 11. PI's E-712 controller represents the leading edge of nanopositioning controls targeted for SMB applications. With servo update rates to 50kHz and interface options including USB, RS-232, Ethernet, PIO, TTL, analog, and soon SPI, it is ready to enable the next generation of biophysics exploration.

- Cost-effective protocol converters which connect via USB 2. Unfortunately many of these will inherit at least some of USB's shortcomings, though proprietary solutions for latency minimization may prove effective for improving on native USB latencies.
- PCI and PCIe adaptors for in-PC integration.
- LabVIEW FPGA is already readily connected to SPI interfaces.

Meanwhile USB 3 and Light Peak interfaces are also imminent in PCs and can be expected to be integrated into instrumentation in the coming years.

Conclusion

As time-critical processes become increasingly central to SMB research and advancement, the importance of vendor selection will only grow. Select a vendor who understands your application and can partner with you to ensure success.

References

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[ii] Yacoot, A; Kuetgens, U. and Jordan, S (2010), A digital based servo-control system for x-ray interferometers, presented at Nanoscale 2010, Brno, CR

[iii] Jordan, S., U.S. Patent 6950050, 2005

[iv] Yacoot, A; Kuetgens, U. and Jordan, S (2010), A digital based servo-control system for x-ray interferometers, presented at Nanoscale 2010, Brno, CR

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