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a brand of PRIOR

INNOVATION IN NANOPOSITIONING

High accuracy velocity control at nanometer resolution

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History of Innovation

Queensgate, the nanopositioning brand of Prior Scientific, has innovated - piezo-driven flexure-guided stages for over 40 years.

Queensgate was the first to market with capacitive sensors for high-precision positioning, digital control for improved accuracy, and calibrations stored on the stage for full interchangeability of stage and controller. Our stages can operate at bandwidths over 40% of the stage resonant frequency, four to five times faster than similar systems. The exceptionally low noise control system is important for applications where high stability is paramount.

This performance is based on class-leading work in stage mechanical design, controller electronics, and control software. Controller electronics must be exceptionally low noise while also delivering high power to the piezo actuator. Custom cables are used to reduce cable microphonic noise, and custom connectors ensure compliance with all worldwide standards for electrical safety.

Stages are designed for minimal off-axis motion, with highly linear motion. Queensgate has introduced numerous innovations in stage design, most recently with the SP series of piezo scanners. These provide long-range positioning for large loads such as incubators, with the lowest profile footprint of any comparable stage.

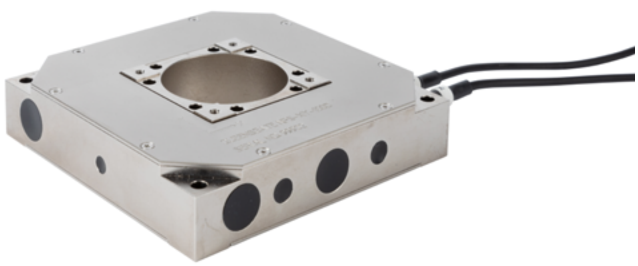

Fig 1. QGNPS-XY-100D XY stage used for testing.

Capacitive sensors mounted on the stage platform ensure stage movement is measured and controlled accurately.

Not only are capacitive sensors the most accurate position measurement technology available for stages, but other methods are unable to meet the performance bandwidth required by Queensgate's high-speed stages.

Queensgate's nanopositioning controllers are fully digital. This enables systems to maximize the performance of high-speed stages with a range of class-leading features. Digital control provides numerous improvements over older analog control systems.

Accurate Position Measurement

Closed-loop control can only ever be as accurate as its position measurement. While capacitive sensors are already designed to be highly accurate, digital control allows this to be further corrected using a quartic function or a more complex cubic-spline algorithm, achieving positioning linearity of better than 0.02% of range on most single-axis stages.

Digital Filtering

A common feature of nanopositioning control systems is notch filtering to prevent the excitation of stage resonance. With digital control, these filters can be set extremely precisely. Stage mechanical design ensures the resonances remain consistent even under substantial changes of load.

Trajectory Control

High accelerations and decelerations tend to excite resonances in the stage and mounting structure. Stepper motor control systems usually incorporate command trajectory control, limiting velocity and acceleration to reduce overshooting and ringing. This is not typically available in nanopositioning controllers due to the lower speeds available. Queensgate stages operate at higher speeds and acceleration, so real-time command trajectory control has been added. This gives significant benefits for settling time, especially with larger steps, as shown in Figure 2.

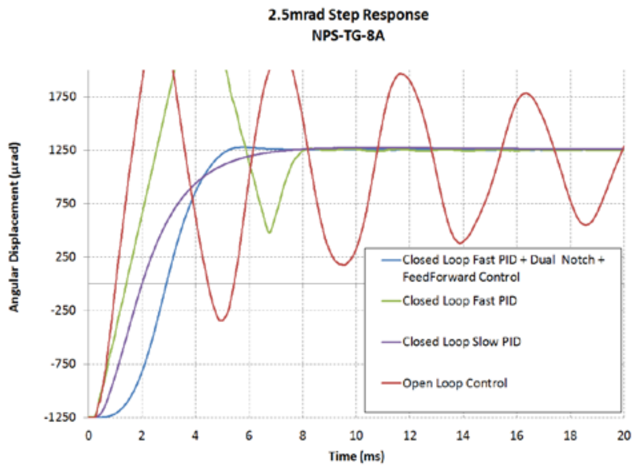

Fig 2. Showing the impact of trajectory control on the step settle time of a tip tilt stage.

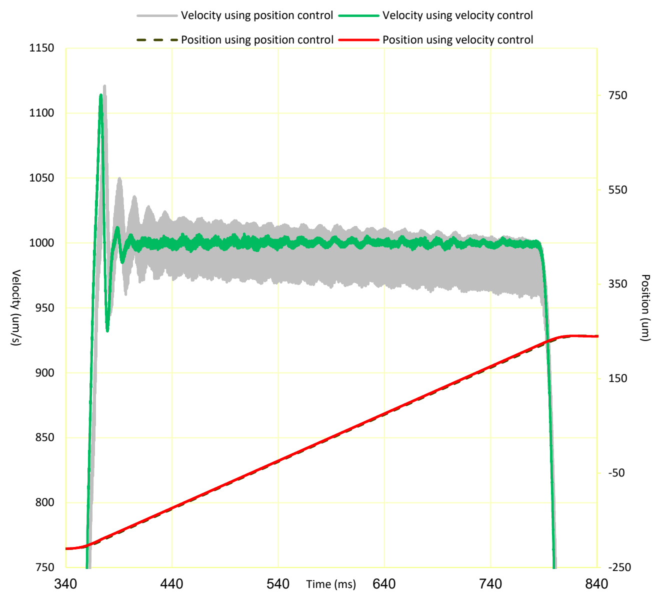

Fig 3: (Queensgate OP-400 objective positioner operating over 400 µm at 1mm/s comparing velocity control with position control, note the two position plots overlay almost exactly

Velocity Control

Until now, all nanopositioning controllers on the market have been limited to only providing closed-loop control of the position. This is ideal when moving to a fixed target position, but tracking a moving command (such as a raster-scan ramp or a sine wave), will always have some residual error. This is an unavoidable feature of the mathematics behind closed-loop position control, and the greater the velocity and acceleration required, the greater the error.

Many applications such as surface scanning rely on the stage following a constant trajectory, and this error will cause the resulting image to be distorted. This error may be small at low speeds, but Queensgate systems are capable of much higher speeds, and at these speeds, the error becomes significant. Various strategies exist to attempt to reduce this error. For example, variable-rate control loops or learning strategies for repeated waveforms, but these do not address the root cause.

To solve this problem, Queensgate has developed a control system that provides closed-loop control of position, velocity, and acceleration. This is configured as nested PID loops to control position, velocity and acceleration. PID loops are traditionally used in nanopositioning systems and are well understood, allowing this to be easily configured by customers. Queensgate has developed strategies to prevent the loops from “fighting” each other and maintain stability.

Velocity control significantly improves positional tracking for constant-velocity ramps, as shown in Figure 3 comparing position and velocity control over a 400 µm ramp at a commanded speed of 1 mm/s. At this speed, position control gave around 5% variation in speed, whereas velocity control virtually eliminated any variation in speed. Acceleration control reduces the time to reach a commanded velocity, allowing the user to use a greater proportion of the stage range for the constant-velocity ramp. Velocity and acceleration control also significantly improve tracking for constantly moving trajectories such as sine waves or spirals.

Other control technologies such as H∞ were considered, but these typically assume that it is possible to model the system linearly and apply mathematical optimization. However, at higher speeds and accelerations, nanopositioning control can become substantially non-linear due to effects such as piezo actuator hysteresis. Excitation of system resonances can also produce substantial errors which the stage cannot easily identify. These factors tend to rule against more advanced control techniques.

Because Queensgate uses high-precision capacitive sensors with high bandwidth for position feedback, it is possible to calculate velocity and acceleration simply from the position measurement. No additional sensors are required, allowing this to be added to the standard Queensgate range of stages and potentially made available to existing Queensgate customers on their current systems simply as a firmware upgrade.

Waveform planning

Motion control systems typically allow the construction of complex waveforms to be played back, but this is not generally available for nanopositioning systems. Queensgate has added this to enable customers to take full advantage of velocity control. This includes a full range of S-curve profiles for smooth acceleration and deceleration, staircase-step move sequences for Z-stacking or raster scans, and a variety of other move types.

The Queensgate controller includes digital trigger inputs and outputs to allow this to be integrated with external electronics. Waveforms can be played automatically on receiving a trigger input pulse, and trigger outputs can be pulsed synchronously with the waveform to activate external equipment such as cameras.

Demonstration Of Performance

An application of high-speed scanning that is of increasing interest in high-speed atomic force microscopy where scanning speeds of several millimeters per second are achieved [1-5]. The applications space for this technology is diverse, ranging from biosciences to material science [3,4].

To use velocity control in a practical application, Queensgate worked with NPL to integrate a Queensgate NPS-XY-100 stage
(Figure 1: 100µm x 100µm scan range) into NPL's high-speed atomic force microscope
(HS-AFM). [6] NPL had previously used a stage operating in open-loop mode, using interferometers to capture positions and interpolate a surface scan. The project intended to use closed-loop velocity control instead, capturing data at fixed time intervals. Any variation in velocity would then be seen as distortion within the AFM image, so image quality could be used as a visual indication of whether the performance was acceptable. AFM scanning would also inherently show any significant movement in the vertical (Z) axis as the stage moves in the XY axes.

NPL had previously been using an XY stage with a 5 µm x 5 µm scan range. With a smaller area, this required software image stitching from a large number of scans, taking significant time. A larger stage can naturally reduce or eliminate this problem. Larger stages typically have greater errors in motion though, presenting a challenge for the Queensgate system in the control technology and the stage design.

A simple 2D raster scan was used, capturing data at scan speeds from 0.5 mm/s up to 4 mm/s. The AFM mounting structure was found to have resonances that required accelerations to be limited, which in turn required greater distance to be allowed for "run-up" and
"braking" at higher speeds. Acceptable results were achieved by allowing 5 µm per mm/s of scan speed at each end for acceleration and deceleration.

It is important to note that no recalibration of the stage/controller was required at this point. An appropriate trajectory profile could be chosen freely, without changes to PID settings which might risk instability.

When scanning larger surfaces, it is common to acquire images rapidly at lower resolution to identify areas of interest before scanning those areas of interest at high resolution. A scan speed of 2 mm/s was found to give acceptable quality for lower-resolution scans, whilst still capturing 80 µm at once (allowing 10 µm each end for acceleration and deceleration). Figure 4 shows the results of using this to scan an 80 µm x 80 µm section of a 25 µm-pitch number grid. As an identifiable structure, this formed a useful test subject for lower-resolution, full-stage-area image capture. With 250 raster scan lines, the image in Figure 3 was acquired in 40 seconds.

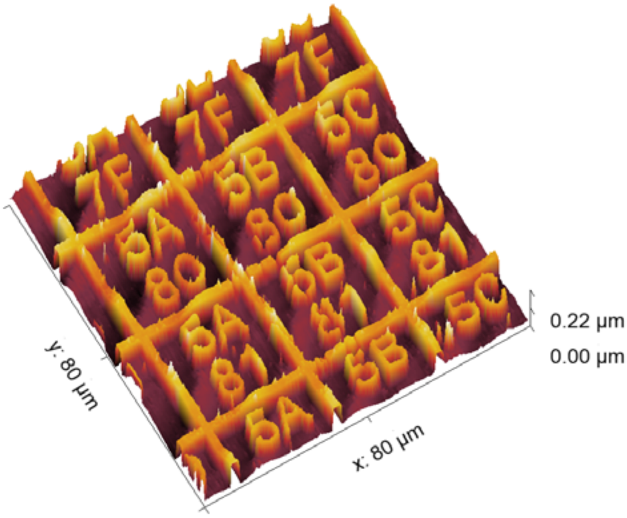

Fig 4: Image captured at 2000 µm/s, 250 scan lines, acquisition time 40 seconds. (Note: The sample had been damaged previously, with some clearly-visible scratches across it.)

For high-resolution scans, a lower speed of 0.5 mm/s was used. This gave slower scans but with better image quality. It should be noted that this is still exceptionally fast for AFM scanning, especially for a nanopositioning stage operating in closed-loop control. Figure 4 shows the results of using this to scan a 5 µm x 5 µm section of a pitch spacing grid with pits spaced at 300 nm intervals. With 1000 raster scan lines at 5 nm intervals, the image in Figure 4 was acquired in 4 minutes. The image is rotated to be viewed from below so that the detail can be seen more clearly.

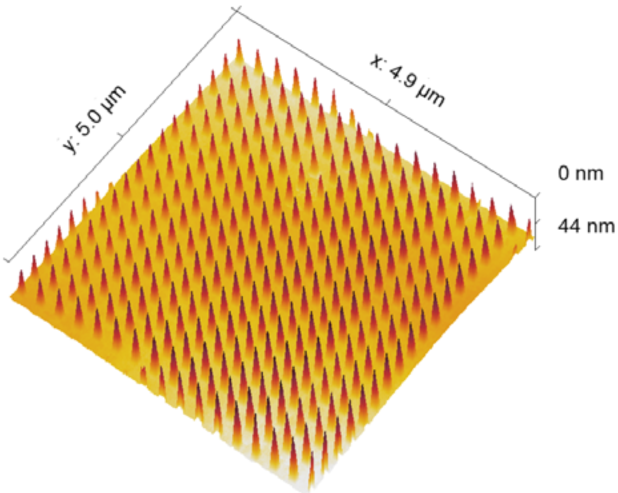

Fig 5: Image captured at 0.5 µm/s, 1000 scan lines, acquisition time 4 minutes

Measurement of the image showed pitch spacing of 302.2 nm on the vertical raster axis (an error of 0.7%). Pitch spacings measured around the image are consistent to within 0.2 nm (0.06%), suggesting that any error in velocity is highly consistent and so could be calibrated out if the stage was to be used in a production AFM system. No significant deviation in orthogonality was seen, showing that the XY axes maintain good control. The image also shows a very low deviation in the Z-axis over the measurement surface.

Application Of Innovation

With these features available and proven, Queensgate intends to pursue areas of interest where these innovations can be leveraged. Surface scanning applications are an obvious target and microscopy applications where high-speed Z-stacking is required for real-time imaging.

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Queensgate wants to thank Professor Andrew Yacoot and Edward Heaps from NPL (National Physical Laboratory) for their expert assistance with this investigation under their Measurement for Recovery program.

References

1. Ando T 2019 High-speed atomic force microscopy Current Opinion in Chemical Biology 51 105-12
2. Payton O D, Picco L and Scott T B 2016 High-speed atomic force microscopy for materials science Int. Mater. Rev. 61 473–94
3. Ando T 2012 High-speed atomic force microscopy coming of age Nanotechnology 23 062001
4. Mikheikin A et al 2017 DNA nanomapping using CRISPR-Cas9 as a programmable nanoparticle Nat. Commun. 8 1665
5. Heaps E, Yacoot A, Dongmo H, Picco L, Payton O D, Russell-Pavier F and Petr Klapetek P 2020 Bringing real-time traceability to high-speed atomic force microscopy Meas. Sci. Technol. 31 074005 (11pp)
6. Bartlett G, Heaps E, Clarke J, Frost S, Patel J, Levy S, Raby A, Yacoot A 2021 Demonstration of closed loop velocity control for fast imaging techniques using high-speed AFM Conference Proceedings Euspen's 21st International Conference & Exhibition, Copenhagen, DK, June 2021 P4.12 (p255)

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