Demonstration of closed loop velocity control for fast imaging techniques using high-speed AFM

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Abstract

To address the requirement for high-speed, high-resolution scanning and nanopositioning Queensgate Instruments, a division of Prior Scientific, have developed velocity control for their nanopositioning stages. This has been applied to an XY stage and its potential for use in a high-speed atomic force microscope (HS-AFM) has been assessed using the NPL metrological high-speed AFM platform. Images covering scan areas and speeds in the range of 95 µm x 95 µm (speed, 500 µm/s) to 60 µm x 60 µm (speed 4 mm/sec) were acquired and showed high linearity over the scanning area and a lateral resolution of 2 nm or better. Measurements of calibration gratings are commensurate with those obtained from conventional AFMs at slower scanning speeds.

Introduction

The growth in applied nanotechnology has led to an increased demand for accurate fast multi-axis nanopositioning [1]. A common issue for all systems is the necessary compromise between range, speed and accuracy.

Queensgate's high-speed, low-noise, piezo-driven flexure stages have high linearity and orthogonality with minimal off-axis motion.

Their advanced control system allows the stage to operate at over 40 % of its resonant frequency, *i.e.* 4 to 5 times faster than similar systems. Traditionally nanopositioning controllers have been designed for closed-loop operation delivering good positioning accuracy but inherently unable to track a moving command such as a ramp, as required for high speed-scanning.

Velocity Control

Velocity control capitalises on the ability to operate the stage at higher speeds than previously possible. The features of the control system are:

- Use of existing capacitance sensors
- Low-noise position measurement provides velocity and acceleration measurements after filtering.
- Nested PID loops to control position, based on velocity and acceleration.
- Acceleration control reduces the time to reach the required velocity
- Trajectory planning minimises jerk and reduces ringing/overshoot

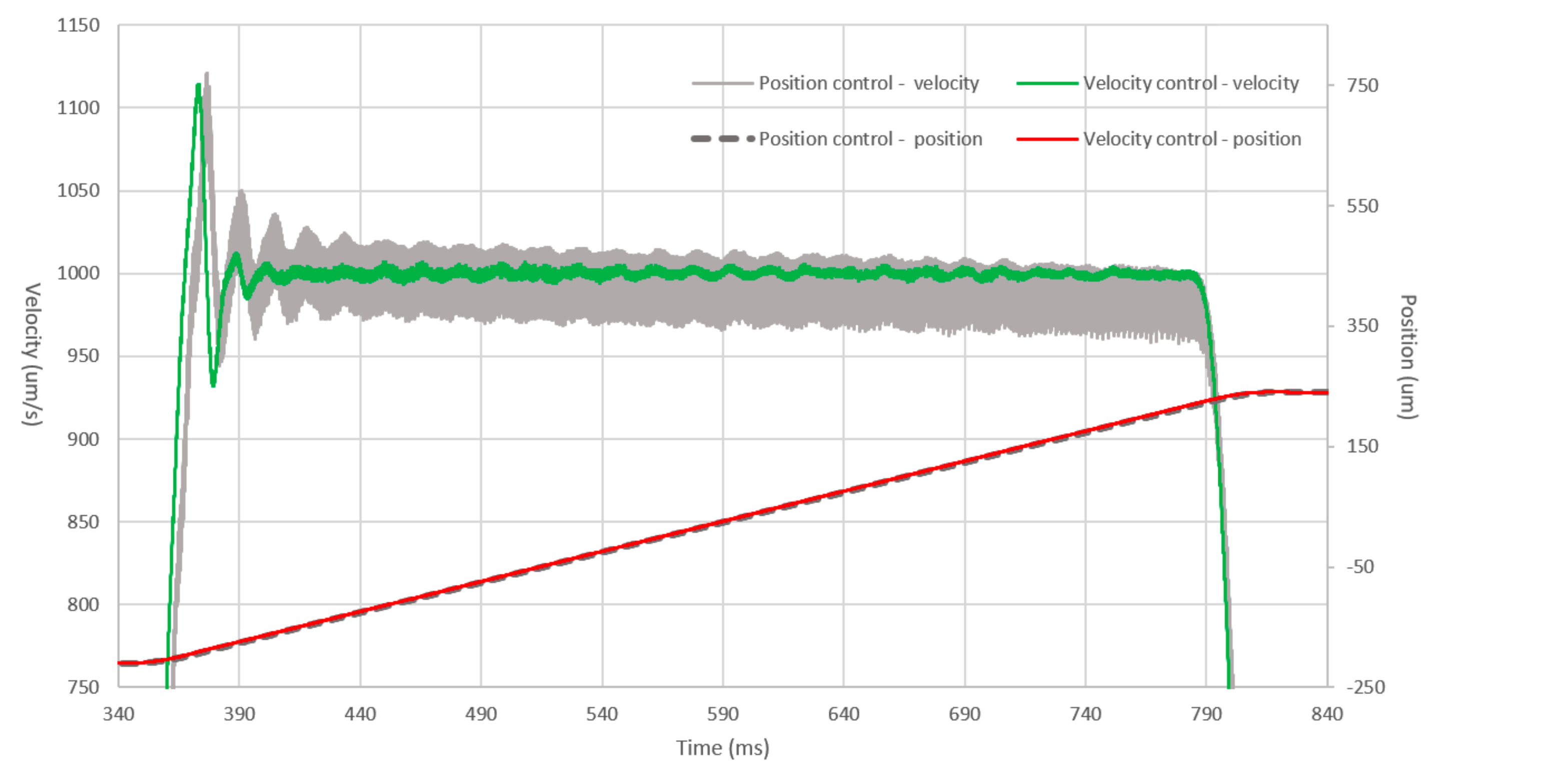

Figure 1. Queensgate OP-400 objective positioner operating over 400 µm at 1 mm/s comparing velocity control with position control. The velocity error is significantly lower with velocity control than when using position control only. Although good position control is maintained using both velocity and position control, the error in velocity is significantly lower when using velocity control. Note the two position plots overlay almost exactly.

High speed AFM

A HS-AFM requires mm/sec scan rates [2], usually realised using small range (<10 µm) open-loop flexure stages which are susceptible to nonlinearity and hysteresis.

A Queensgate NPS-XY-100 stage (100 µm x 100 µm scan range) driven by a Queensgate NanoScan NPD-D-6330 was inserted into the NPL HS-AFM. Evenly spaced data acquisition was achieved using constant velocity ramps to acquire measurements at fixed intervals.

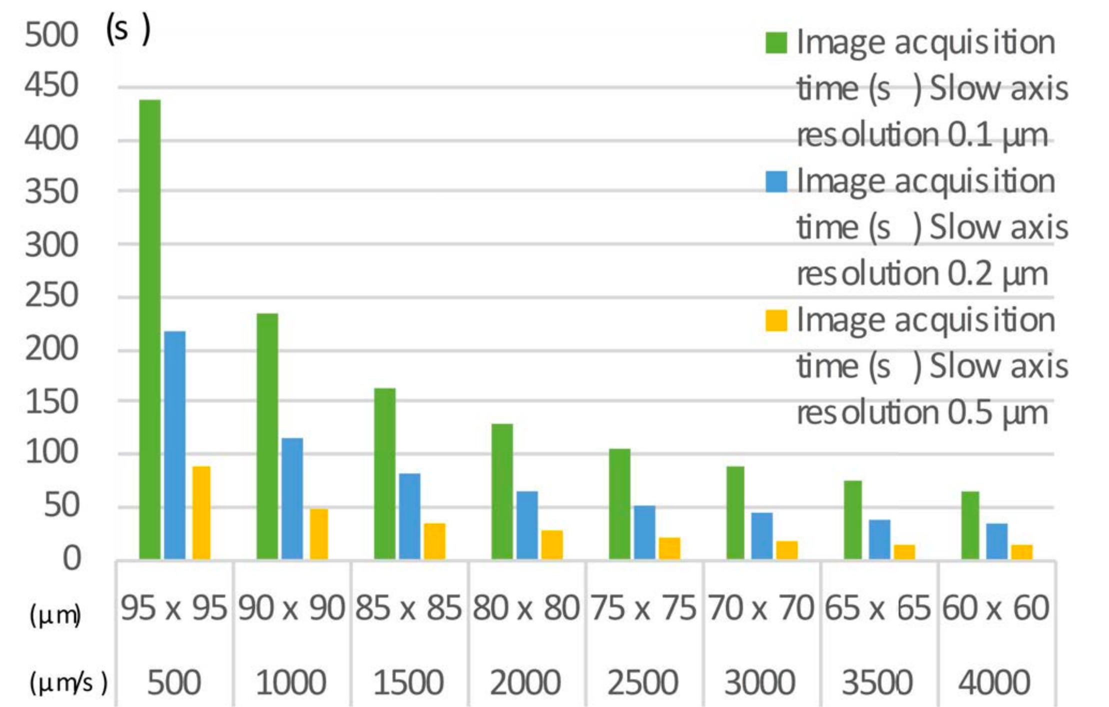

Figure 2. Typical acquisition times as a function of resolution (0.1 µm, 0.2 µm and 0.5 µm)

Fast-axis speed (µm/s)	Linear region/ image size (µm)	Raster-axis period (ms)	Maximum raster axis resolution (nm)	Number of fast-axis scan lines	Image acquisition time (s)
500	95	460	0.25	413	190
1000	90	260	0.5	346	90
1500	85	193	0.75	293	57
2000	80	160	1.0	250	40
2500	75	140	1.25	214	30
3000	70	127	1.5	184	23
3500	65	117	1.75	158	19
4000	60	110	2	136	15

Table 1. (Image size over linear region and acquisition times for different fast-axis speeds) To provide consistency for all scan speeds, the slow-axis was ramped at 1/1000th of the fast-axis speed and set to give identical X and Y dimensions for the image. The fast-axis period is the total time for a bidirectional sweep over the fast-axis, including a fixed turnaround time of 40 ms. The fast-axis resolution was set by the data acquisition system for the HS-AFM which sampled at 2 MHz.

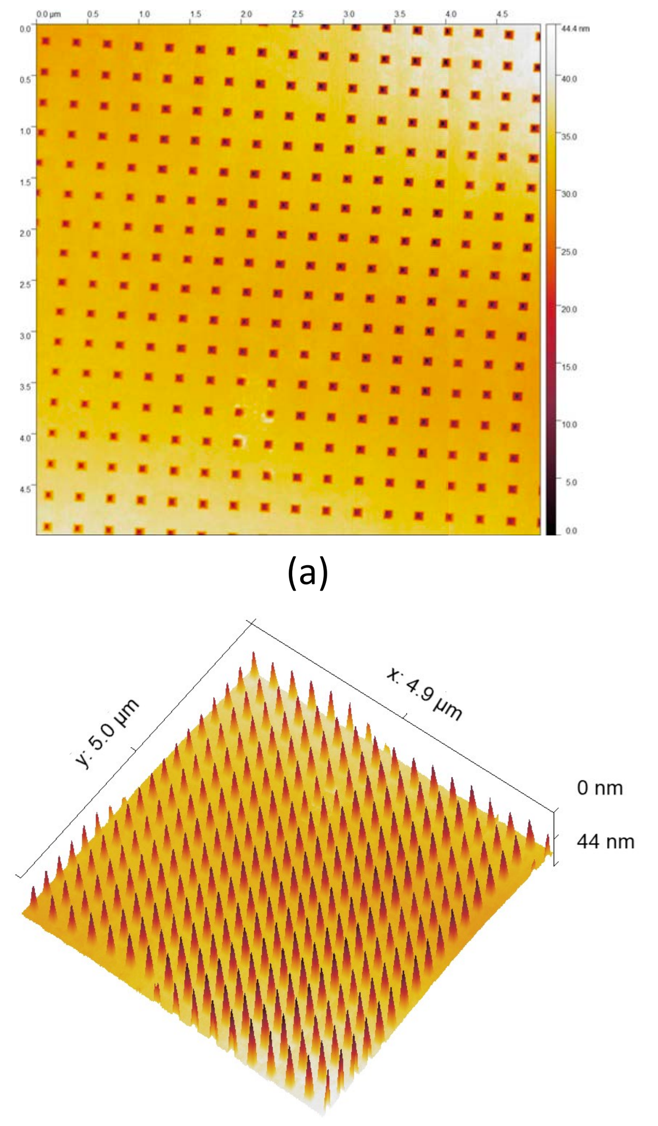

Figure 3: Scan results for a 2D 300 pitch sample with 300 nm spacing between pits, capturing a (5 x 5) µm^2 area with a 0.5 mm/s raster. Shown as (a) 2D data and (b) as 3D data. The 3D data has been rotated so it is viewed from below to highlight the features. The pitch values from this data are 294.2 nm (horizontal) and 302.2 nm (vertical). The pitches measured in different parts of the image were consistent to within 0.2 nm. This small variation across the grating indicates the high linearity of the stage using velocity control.

Conclusions

- Successful integration of a closed-loop velocity control stage into a HS-AFM operated with scanning speeds up to 4 mm/sec and a lateral resolution of 2 nm.
- The stage can accommodate larger samples (and payloads) than conventional HS-AFM stages,
- Scan area is significantly increased (from 5 µm x 5 µm to 100 µm x 100 µm) obviating the need for data stitching: linearity of the position data obtained when interpolating the constant velocity data yields high quality images without requiring complex post processing to remove piezo distortion or stitching effects.
- This technology has benefits for other nanopositioning applications *e.g.* confocal microscopy, surface texture metrology and optical alignment.
- The Queensgate controller and an appropriate stage can be integrated into any system which requires this performance.

[1] Torralba M, Valenzuela M, Yagüe-Fabra J A, Albajez J J and Aguilar J J 2016 Large range nanopositioning stage design: a three-layer and two-stage platform *Measurement* **89** 55–71

[2] 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)

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