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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 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 has been assessed using the NPL Metrological High-Speed AFM platform. The work investigated the application of velocity control on image acquisition time and image resolution. Images covering scan areas and speeds in the range of of 95 µm x 95 µm (speed,500 µm/s) to 60 µm x 60 µm (speed 4 mm/sec) were acquired and showed good 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.
keywords: velocity control, high speed atomic force microscopy, nanopositioning

1. Introduction

With the growth in nanotechnology and its move from the research laboratory to the factory there is growing interest in accurate fast multi-axis nanopositioning [1,2]. A quick internet search finds many commercial nanopositiong systems available for a range of applications and budgets. A common issue for all systems is the necessary compromise between range, speed and accuracy. However, in all cases, for accurate nanopositioning it is necessary to assess the stage performance in terms of undesired motion and ideally absolute positioining [2], something which becomes more challenging with high speed operation.

Queensgate is a manufacturer of high-speed, low-noise nanopositioning systems using flexure guidance systems to ensure each axis of movement can be driven linearly and orthogonally with minimal off-axis motion. Piezoelectric actuators drive each axis of their stages to provide the necessary high forces for controlled movement. The stage position is measured using intrinsic capacitive sensors having sub nanometre resolution.

The company's advanced control system allows their stages to operate at over 40% of the stage resonant frequency, four to five times faster than similar systems. Until now, all nanopositioning controllers on the market have been limited to closed-loop position control only. Closed-loop position control delivers good positioning accuracy but is inherently unable to track a moving command such as a sine wave or ramp. Many applications such as raster scanning of a surface require this, but the limitations of position control have always impacted the accuracy of scanning with nanopositioning systems. The faster the stage needs to move, the greater the error in position.

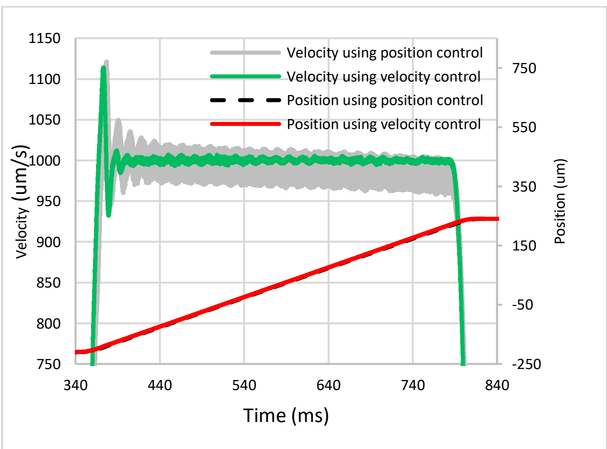


Fig 1: (Queensgate OP-400 objective positioner operating over 400 µm at 1mm/s comparing velocity control with position control, note the two position plots overlay almost exactly

2. Velocity Control

Velocity control was developed to capitalise on the ability to operate at higher speeds than previously possible with the stage. This enabled high-speed imaging at constant velocities while maintaining positional accuracy during a ramp, free from the limitations of position-only control. Low-noise, high-resolution capacitive positioning sensors allow this to be used for any Queensgate stage, with no additional sensors required. The salient points of the control system are:

- Low-noise position measurement provides useable velocity and acceleration measurements after filtering.
- Nested PID loops to control position, velocity and acceleration are employed. PID loops are traditionally used in nanopositioning piezo systems and are well understood. In addition the complexity of the modelling due to potentially substantial non-linearity (piezo actuator hysteresis and off-axis resonances) made control systems such as H∞ less practical. H∞ Control systems express the control problem as

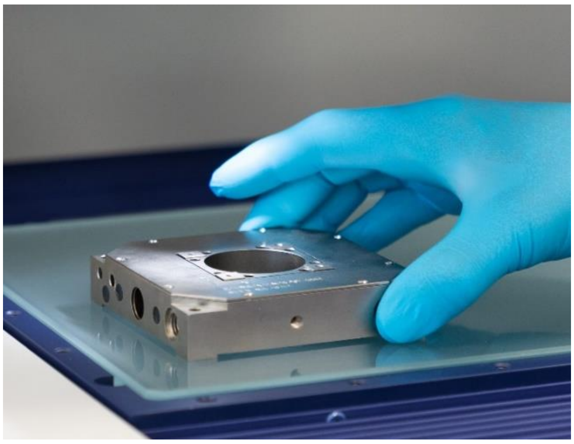
a mathematical optimisation problem and then identify the controller algorithm For optimised performance
- Acceleration/deceleration control is used to reduce the time to reach the required velocity and trajectory planning is used to minimise jerk and reduce ringing/overshoot thereby improving cycle time.

Figure 1 shows a comparison of position and velocity control over a 400 um ramp. 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.

2.1. Proof of Concept for AFM

An application of high-speed scanning that is of increasing interest is high-speed atomic force microscopy where scanning speeds of several millimetres per second are achieved [3-7].

Applications space for this technology is diverse ranging from biosciences to material science [4,6]. High speed scanning is realised using small flexure stages with a range of less than 10 µm and without intrinsic metrology making them susceptible to the nonlinearity and hysteresis inherent in the piezo actuators used to generate the motion. In an effort to bring metrology to this technique NPL and the University of Bristol developed a metrological high-speed atomic force microscope [7] that used interferometers to measure the displacement of a small high-speed scanning stage and that of a larger long range stage used to move the smaller stage so images could be stitched to obtain larger area images.



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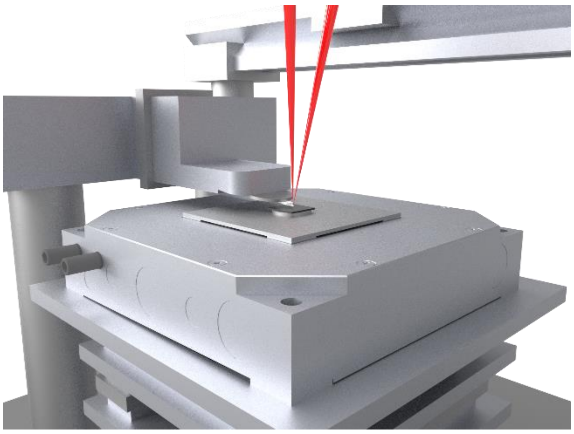


(b)

Fig 2: (a) The queensgate NPS-XY-100D positioning stage used for this work. (b) simplified image showing the positioning stage in place on the NPL HS-AFM.

Testing of the Queensgate stage was performed using NPL's high-speed atomic force microscope (HS-AFM) [7] to demonstrate the speed, resolution, and positioning possible with velocity control. A Queensgate NPS-XY-100 stage (100 x 100 µm scan range) driven by a Queensgate NanoScan NPD-D-6330 controller replaced the XY stage (5 µm x 5 µm scan range) previously used on the HS-AFM (figure 2). Evenly spaced data acquisition at known positions was achieved using constant velocity ramps to acquire measurements at fixed intervals. The AFM image quality was directly dependent on the accuracy of the velocity control. As velocity increased, image quality provided a visual indication of resolution and positioning accuracy at that velocity.

A significant issue for fast scanning can be the extent to which rapid acceleration/deceleration at each end of a ramp excites mechanical resonances and causes ringing in the stage. With closed-loop control and features such as notch filtering, the Queensgate controller was able to substantially reduce these effects. The Queensgate controller's built-in waveform generation included S-curve acceleration/deceleration profiles which provided further significant reductions in ringing.

3. NPL Testing and Results

The stage was set up to continuously oscillate back and forth in both axes using a constant velocity ramp. The two axes oscillated at different rates to give a scan path approximating a raster pattern. Trigger outputs from the Queensgate controller were configured to pulse at the start of the linear region during each ramp (on both axes) to enable PC-based processing to align samples and generate the AFM image.

3.1. Scanning and evaluation of data for large-area, lower-resolution capture

Velocity control provided good imaging at fast-axis rates up to 4 mm/s. Images were collected at speeds from 4 mm/s down to 0.5 mm/s to demonstrate a progressive increase in resolution on the raster axis. Faster scanning speeds are possible but required a greater distance to be allowed for acceleration/deceleration, giving a somewhat smaller linear region for image acquisition.

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. Table 1 (below) gives representative times and resolutions obtained using this slow-axis speed. The fast-axis period is the total time for a bidirectional sweep over the fast-axis, including a fixed turnaround time of 40 ms.

Table 1 (Image size over linear region and acquisition times for different fast-axis speeds)

Fast-axis speed (µm/s)	Linear region/ image size (µm)	fast-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

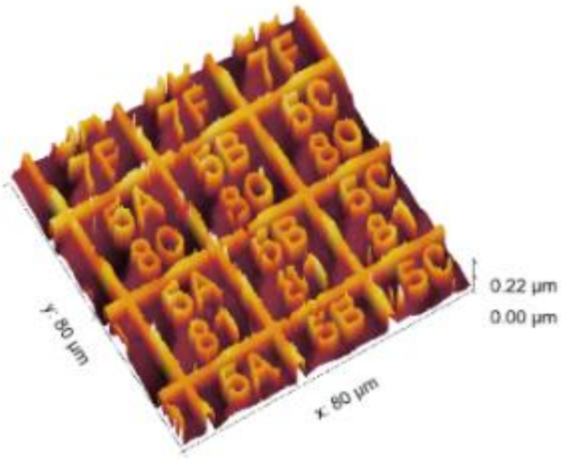


Fig 3: Images were captured at 2000 µm/s, 1nm resolution, 250 scan lines, acquisition time 40 seconds. (Note: The sample had been damaged previously, with some clearly-visible scratches across it.)

The fast-axis resolution was set by the data acquisition system for the HS-AFM which sampled at 2 MHz. This theoretical resolution was calculated as the distance travelled between samples at the specified speed. In practice, this is less relevant for image acquisition than the linearity of motion of the constant-velocity raster, especially at higher speeds. The time required to acquire images at greater fast-axis speeds is naturally reduced because the image size is smaller.

The grid in Figure 3 has a 25 µm pitch. As an identifiable structure, it formed a useful test subject for lower-resolution, full-stage-area image capture. The data was captured with a fast-axis speed of 2000 µm/s and a slow speed of 2 µm/s.

3.2 Image acquisition times for fixed slow axis resolution

A user would typically expect a fixed resolution in the slow axis when identifying regions of interest. Figure 4 illustrates typical acquisition times for capturing the available stage area at a lower resolution when identifying regions of interest and with a fixed slow axis resolution.

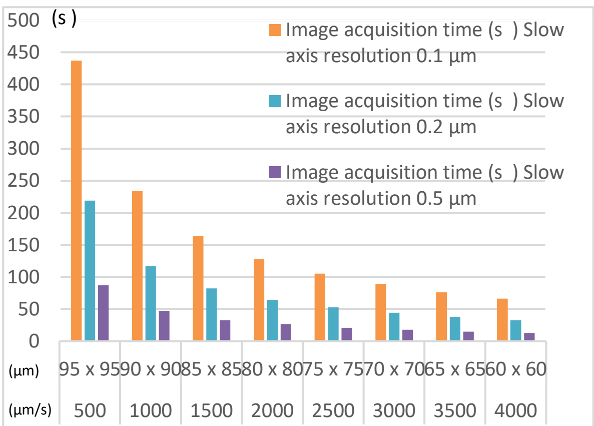


Fig 4: (Typical acquisition time at lower resolution at fixed slow axis resolutions of 0.1, 0.2 and 0.5 µm)

3.3 Image acquisition times for high resolution

Figure 5 illustrates typical acquisition times for capturing a 10 x 10 µm area at higher resolution again with a fixed slow axis resolution.

For smaller high-resolution images, it is likely that a speed of 1-2 mm/s would be a good compromise for improved resolution with acceptable acquisition times.

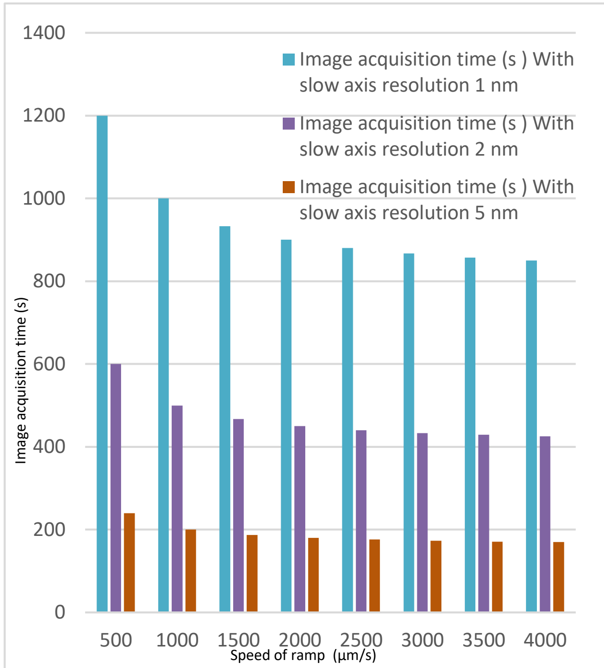
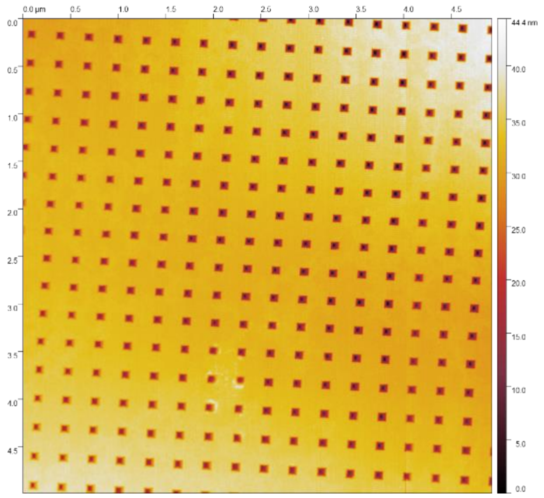


Fig 5: (High resolution image acquisition times at high resolution for 10 µm x 10 µm area)

Some high-resolution images were captured at 0.5 mm/s (Figure 6), Further investigations will report on high-resolution image quality at different speeds and different slow axis resolutions.

Measuring the pitch values from the data in figure 6 we obtain a value of 294.2 nm in the horizontal direction and 302.2 nm in the vertical direction across the image. The values for the pitch measured in different parts of the image were consistent to within 0.2 nm. This small variation in individual measurements of pitch across the grating is indicative of the high linearity of the stage using velocity control. Application of an appropriate scaling factor can then be used to calibrate the stage and hence the AFM as with a non metrological AFM in the usual manner.

Measuring the orthogonality of the grating structure showed no significant distortion due to the scanning. The purpose of this study was to evaluate the potential of velocity control for HSAFM and a further study would be required to fully evaluate the uncertainty of the stage positioning capability.



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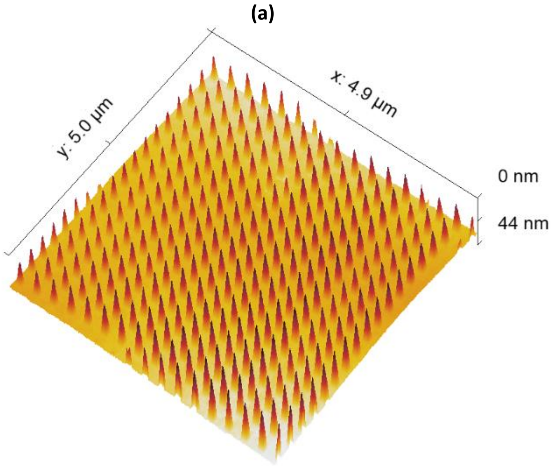

(b)

Fig 6: Scan results for 2D 300 pitch sample with 300 nm spacing between pits, capturing a 5 x 5 µm 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 in order to more clearly show the features.

4. Conclusions

Closed-loop velocity control with a Queensgate NPS-XY-100 stage and controller enables fast AFM to capture high-quality (high resolution) imagery at raster speeds of up to 4 mm/s.

Using this stage provides three key advantages over the previously used stage. The stage can accommodate larger samples (and payloads), its scan area is significantly increased (from 5 x 5 µm to 100 x 100 µm) obviating the need for data stitching in many cases and the linearity of the position data obtainable when interpolating from the constant velocity allows high quality images to be captured without requiring complex post processing techniques to remove piezo distortion or stitching effects.

The study covers AFM as a specific example of where this can be applied. The same technology is equally applicable for other areas requiring measurements at accurate intervals while a nanopositioning stage moves continuously. Examples of these applications are confocal microscopy, surface smoothness scanning, or optical alignment. The Queensgate controller and an appropriate stage can be integrated into any system which requires this performance.

Acknowledgements

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