# Spacial positioning correction for multi-axis nanopositioning stages

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## Spacial positioning correction

All moving systems have some unwanted motion in other axes. For a multi-axis stage, this causes positioning errors in all motion axes. This is most significant for longer-range stages, and can be the principal limiting factor in positioning accuracy. Nanopositioning systems typically specify linearity for each axis individually, but positioning errors over the entire multi-axis movement space can be larger and remain uncompensated.

Queensgate has developed high performance open frame multi-axis flexure stages capable of operation in closed loop over extended ranges (400 µm-800 µm) in X, Y and Z axes. Compared to equivalent existing stages, these stages provide longer operating ranges (2 to 4 times longer than typical), larger aperture sizes suitable for microtitre plates, the fastest step settle times, and improved load tolerance. Increased operating ranges can reduce the amount of image stitching required when imaging large areas, providing increased throughput.

With longer operating ranges, there is a strong desire to improve spacial accuracy. For example, reducing spacial positioning errors would improve accuracy when imaging multiple fields of view to produce 3D images and hence reduce image distortion. The same principles could also be used to improve spacial accuracy of two-axis stages for applications such as atomic force microscopy (AFM).

Spacial position correction in nanopositioning has previously been limited by the difficulty of capturing and analysing sufficient data, and the complexity of developing a suitable correction algorithm, as well as requiring highly-repeatable stage motion in order for correction to be applicable. Initial data on stage performance [1] indicated that stage motion could be repeatable enough to deliver low nanometre spacial errors across the entire volume of motion, and that data capture could be reduced to a level which would be practical for calibration in a production environment.

**NPL stage rig**

The National Physical Laboratory (NPL) – the UK's National Measurement Institute – has developed multi-axis interferometric instrumentation combined with autocollimation for research into accurate nanopositioning [2].

The NPL stage rig apparatus uses three orthogonally mounted NPL Plane Mirror Differential Interferometers to measure the relative displacement between a mirror cube mounted on a stage and a set of reference mirrors. The interferometers are illuminated with light from stabilised helium-neon lasers that have been calibrated against NPL's primary metre realisation laser to give traceable position measurements.

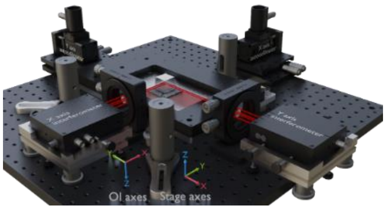


Figure 1. NPL nanopositioning stage characterisation rig.

The stage rig also has autocollimators to measure angular motion of the mirror cube, although this was found to be insignificant for the purposes of this project.

The entire set up is enclosed to reduce thermal and acoustic effects and mounted on a vibration isolation platform. The enclosure contains probes to monitor the environmental conditions, enabling an Edlén correction to be carried out on the interferometer measurements to compensate for refractive index variation.

**Queensgate stages evaluated**

Two stages were selected to have spacial errors characterised and calibrated. To assess three-axis correction, a prototype QGSP-XY-600-Z-600 was used which moves 600 µm in X, Y and Z axes.

To assess two-axis correction, a QGNPS-XY-100D was used which moves 100 µm in X and Y axes only. This is a very high performance stage which has been well characterised for AFM and used in recent work on high speed AFM[1]. Using a "known good" stage also allowed the calibration methodology to be assessed in situations where the errors are smaller and demonstrate the transferability of the error correction techniques.

Figure 2. QGSP-XY-600-Z-600 stage.

Figure 3. QGNPS-XY-100D stage.

**NPL measurement methodology**

For each point in the stage volume of motion, the stage was commanded to move to a position and then allowed to settle for a specified time. Closed-loop control ensured this reflected the displacement reported by the stage's capacitive sensors. The actual displacement was then collected from interferometers, giving the spacial positioning error. A basic raster scan path was used to measure over all points in the volume of motion.

Previous work had established that scanning 11 points in each axis gave sufficient data for mapping spacial positioning errors whilst not imposing an excessive measurement time. For the 3D stage, a total of 1331 (11 × 11 × 11) points were captured at 40 µm (commanded) intervals. For the 2D stage, a total of 121 (11 × 11) points were captured at 10 µm (commanded) intervals.

Actual spacial positions for these commanded points were captured for all axes moving in both directions, to assess repeatable errors caused by hysteretic processes within the stage. The entire measurement process was then repeated 6 times to assess stochastic errors.

There was some misalignment between the measurement axes of the stage and the interferometers. The interferometer data was therefore rotated during post-processing to minimise this effect. This is the equivalent aligning the cube with the mirror axes to minimise cosine error. No adjustment for scaling factors or orthogonality was carried out, since these form part of the errors which are expected to be calibrated out.

**Calibration methodology**

The captured data showed that errors were repeatable and could be accurately modelled with 5th-order polynomials fitted to the three axes of motion.

Similarly to existing linearity corrections for a single axis, the calibration process corrects the (x,y,z) spacial position reported by the stage position sensors. Using the calibrated polynomials, a correction is calculated so that the (x,y,z) position reported to closed-loop control for each axis reflects the true position in that axis. The control loop for each axis can then servo the stage to achieve the desired true position.

The calibration process calculates a least-squares polynomial fit for the dataset points over the three axes. The contribution of each point to the fit can be weighted to allow rejection of outliers. The NPL measurement methodology did not require this, but it will be valuable in a real-world production environment. Further work to develop weighting heuristics will be carried out in the future.

The same algorithm applies for a two-axis stage, except that only a two-axis polynomial plane is calculated.

**Limitations of stages used**

The prototype QGSP-XY-600-Z-600 stage was known to have a substantial error at one end of travel due to a mechanical offset. The decision was taken to reduce the corrected stage range to 400 µm in each axis, to provide a more typical evaluation of error reduction by excluding the erroneous region of travel. The offset was resolved, and future work will characterise the full range of the stage.

The Z axis for the QGSP-XY-600-Z-600 stage was also known to exhibit some hysteretic motion due to the open frame stage design. Most applications will scan each X-Y “slice” before moving up to the next Z position, so will not require random Z movement. The decision was taken to calibrate only in the positive-going direction for the Z axis for this stage.

No limitations were observed for the QGNPS-XY-100D stage.

**Spacial positioning errors measured before calibration**

As expected, the QGSP-XY-600-Z-600 stage showed significant positioning errors over the scanned volume before calibration. Typical errors over the measurement space during the raster scan are shown below.

Table 1. QGSP-XY-600-Z-600 spacial positioning errors on each axis before correction.

| Axis of motion | Error before correction peak to peak |
|---|---|
| X | 5 µm |
| Y | 9 µm |
| Z | 5 µm |

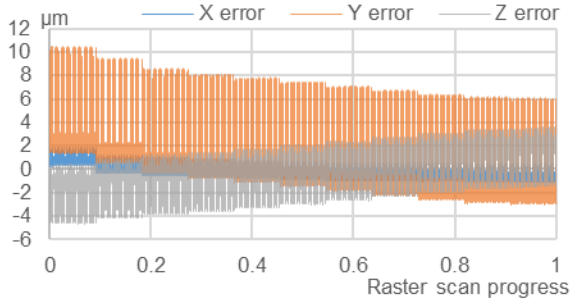

Figure 4. QGSP-XY-600-Z-600 spacial positioning errors on each axis before correction.

Also as expected, the QGNPS-XY-100D stage had substantially lower errors over the measurement space during the raster scan. These were still measurable and repeatable.

Table 2. QGNPS-XY-100D spacial positioning errors on each axis before correction.

| Axis of motion | Error before correction peak to peak |
|---|---|
| X | 800 nm |
| Y | 400 nm |

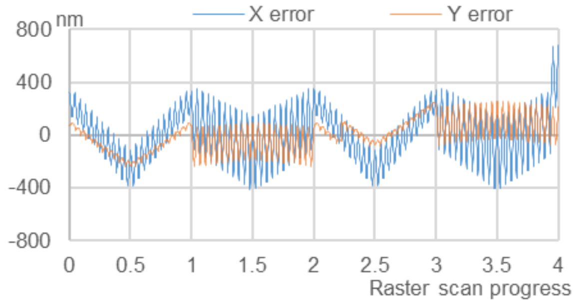

Figure 5. QGNPS-XY-100D spacial positioning errors on each axis before correction.

**Spacial positioning errors measured after calibration**

The correction algorithm was implemented in firmware, and the polynomial parameters calculated from the previous measurements were used to calibrate the stages. The measurement process was then repeated.  Note that graphs are scaled as the "before" equivalents for comparison.

The QGSP-XY-600-Z-600 stage showed clear improvements in spacial positioning accuracy. As expected, best results were seen with the "fast" raster direction in the Y axis, which is the "inner" axis for the stage configuration.

Table 3. QGSP-XY-600-Z-600 spacial positioning errors on each axis after correction.

| Axis of motion | "Fast" raster axis | Error after correction peak to peak | Fraction of original value |
|---|---|---|---|
| X | X | 0.5 µm | 10% |
| Y | X | 6 µm | 33% |
| X | Y | 2 µm | 40% |
| Y | Y | 0.5 µm | 6% |
| Z | Both | 2 µm | 40% |

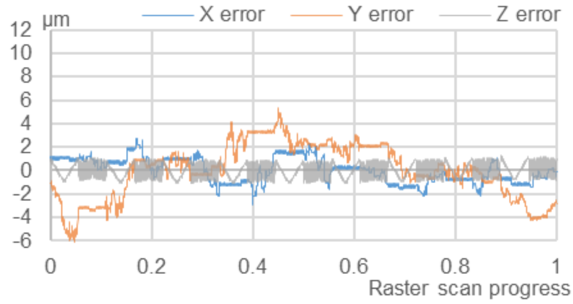


Figure 6. QGSP-XY-600-Z-600 spacial positioning errors on each axis after correction (scaled as figure 4 for comparison).

Significant improvements were observed with the QGNPS-XY-100D stage. Since this stage is stiffer and operates over a shorter range, non-repeatable errors are much lower and hence are more amenable to calibration. Errors in X and Y were reduced by an order of magnitude. For the XY stage, the "inner" axis for the stage configuration is the X axis, and best results were seen with the "fast" raster direction on this axis (scans 1 and 3).

Table 4. QGNPS-XY-100D spacial positioning errors on each axis after correction.

| Axis of motion | "Fast" raster axis | Error after correction peak to peak | Fraction of original value |
|---|---|---|---|
| X | X | 30 nm | 4% |
| X | Y | 70 nm | 9% |
| Y | Both | 30 nm | 8% |

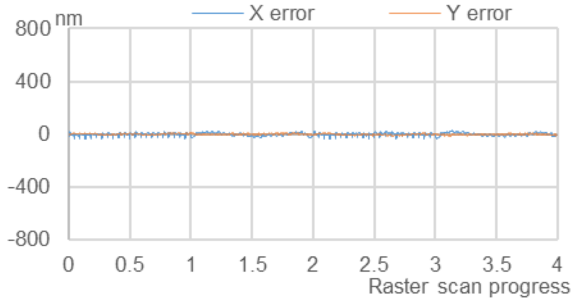


Figure 7. QGNPS-XY-100D spacial positioning errors on each axis after correction (scaled as figure 5 for comparison).

**Future development**

Queensgate will develop the prototype firmware for the correction algorithm into full production-quality firmware and implement the calibration process within operations. To facilitate future developments (as described later), this will permit up to 7th-order polynomials to be used.

Thereafter it is expected that this will be used as standard to improve the performance of all Queensgate XY and XYZ stages.

Queensgate would particularly like to use multi-axis correction with tip-tilt stages. These are known to have very large cross-coupling errors between the two rotational axes due to their construction. This construction makes it likely that the errors will be substantially repeatable, giving far greater accuracy on Queensgate's existing stages.

**Conclusion**

This project has demonstrated that significant improvements in spacial positioning errors for multi-axis stages can be achieved with a measurement and calibration methodology which is practical for production.

It should be noted that the improvement on the large multi-axis stage achieved performance in-line with the uncompensated shorter range XY stage. This achieves performance on a large range stage suitable for use in high precision applications such as AFM. Further improvements are likely using the more typical unidirectional imaging. It is also anticipated that the correction will be more effective on the XY only version, the QGSP-XY-700, as it is stiffer and has fewer degrees of freedom.

**Acknowledgements**

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**References**

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