Piezo control for 1 nm spatial resolution synchrotron X-ray microscopy.

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Abstract. A novel motion control system which utilizes the Power PMAC controller from Delta Tau Data Systems Inc., has been developed for positioning with 1 nm spatial resolution. Present work is a significant step forward towards commissioning of the X-ray microscope which will operate at the Hard X-ray Nanoprobe (HXN) beamline at the NSLS-II. The control system is capable of performing high-speed/high-accuracy on-the-fly scans of the sample with respect to the nano-focusing optics e.g. Multilayer Laue Lenses (MLL) or Fresnel X-ray Zone Plates (ZP) [1]. The Power PMAC controls piezoelectric-based nano-positioning stages using piezo-expansion for short range motion and stick-slip motion for longer travel distances. An EPICS interface to the Power PMAC has been developed allowing for easy integration into a beamline control environment.

1. Introduction

Experiments with nanometer spatial resolution focussed X-ray beams that study phenomena related to elemental composition (via scanning fluorescence microscopy, SFM) or local structure (X-ray diffraction) require accurate positioning of both X-ray nanofocusing optics and samples. During experiments, the sample is raster scanned with respect to the optics. Position stability, down to 1 nm, is required when measurement (e.g. SFM or diffraction) with nano-meter level X-ray beam is performed. Measurements with such unprecedented spatial resolution impose stringent requirements on stability.

In order to achieve the stability requirements, we use active control feedback with optical interferometers to keep track and correct position of nano-focusing X-ray optics (such as MLL and ZP) and sample stage [2,3]. In this paper, we report on the successful use of active feedback loop not only for stationary (non-moving) components of the X-ray microscope, but also active feedback loop for scanning stages. The feedback loop is closed in the Power PMAC controller with quadrature encoder (A quad B) signal generated by Attocube AG interferometers.

2. Experimental arrangement

A typical experiment which can advantageously make use of the actively closed feedback during motion is continuous SFM scan. Unlike a point-by-point scan, during continuous (on-the-fly) scan the scanned/scanning component (sample, or X-ray beam), motion does not stop for acquisition of fluorescence and/or diffraction data. Continuous scans create a substantial speedup of data acquisition.
For instance, a 10 μm x 10 μm fluorescence map (containing 16+ chemical elemental compositions) with pixel resolution of 10 nm (1000 x 1000 pixel image) can be collected within 3 hours with 100 Hz readout, or 20 minutes with 1000 Hz readout. A chemical map, of the same size, acquired by point scan (0.2 s/point) would require 2 consecutive days of synchrotron beamtime (data will be distorted by various instabilities such as injections, beam orbit corrections, etc). Therefore active feedback and shortening data collection time improves stability, and saves user beam time.

The HXN MLL microscope contains about 20 mostly dual (piezo expansion, stick-slip) stages with a total of about 40 motions. Similar type of piezo stages have been used in scanning probe microscopy instruments [4]. The horizontal MLL assembly (used to position the horizontal focusing MLL) has 4 motions (3 translations and 1 rotation). The vertically focussing MML alignment has 5 motions (3 translations and 2 rotations). The Order Sorting Aperture (OSA) implements 3 translation motions and 3 rotations. Finally, the sample stage contains 6 motions. In addition there is a motorized X-ray beam stop, and a motorized tilted mirror is planned for an optical on-axis microscope.

This paper summarizes results of tests performed on the horizontal MLL assembly, where three stacked Attocube AG translation stages were controlled by the Power PMAC and driven by an Attocube ANC-300 piezo driver.

3. Hardware

The control setup consists of a Power PMAC controller, Attocube fiber-optic interferometers, ANC-300 piezo-motor driver, and customized piezo motion stages procured from Attocube AG.

3.1. Motion Controller

The versatility of the Power PMAC makes it an excellent choice for X-ray microscope control. Not only does it have the ability to close a position feedback loop onto a digital A quad B encoder signal, but also on an analog feedback voltage produced by resistive or capacitive sensors (read by a 24-bit ADC UMAC card at servo frequencies). The latter sensors can be used in harmful X-ray environment where traditional optical encoders can be damaged by radiation. Additionally, sin/cos 1 Vpp analog signals are read with 16k multiplication, an increase over 4k multiplication with Delta Tau’s previous generation controller, the Turbo PMAC. The piezo expansion is controlled with an accuracy of 18-bit DAC. These high precision features offered by the Power PMAC allow the HXN X-ray microscope to deliver sub-10 nm spatial resolution.

The motion controller consists of a UMAC chassis with a Power PMAC controller card, ACC-24E3 (digital encoder, 18-bit DAC) cards, and ACC-24E2S cards. We added an ACC-36uk (version with 24-bit accuracy) ADC card for voltage driven feedback loops such as capacitive sensors, ACC-14E for TTL control, and ACC-28E for 16-bit ADC. When available, Dsub-15 connector options for the PMAC accessories were purchased for easy connectivity.

3.2. Interferometer

We used two different models of fiber-optic interferometers from Attocube AG. First interferometer is capable of measuring displacement on 12 independent axes powered by a single laser diode (AttoFPsensor). The AttoFPsensor interferometer provides single ended encoder output for each axis and requires conversion to quadrature signal before signal is accepted by motion controller. The newer FPS3010 model requires custom interconnects of encoder quadrature signal from HDMI connector with other DB-15 inputs/outputs of Power PMAC cards.

4. Results

A number of motion tests were carried out to verify the performance of the closed feedback loop. One of the important tests is verification of the absence of parasitic motions. The example of absence of parasitic motion is illustrated in Figure 1, where the Z translation motion does not result in observable translations in X or Y directions (in the stage containing XZY motion axis of MLL horizontal assembly).
The stacking of the stages in Figure 1, is such that in standard beamline coordinates X (lateral) translation carries the Z (along X-ray beam) translation, which in turn carries the Y (vertical) translation stage.

**Figure 1.** The XYZ stage of the horizontal focusing lens of the MLL microscope shows no XY (green, red) parasitic movement when the Z axis (along X-ray beam) motion is performed (blue plot). The inset plots show details of the position with closed loop interferometer feedback under ambient conditions.

**Figure 2.** Closed loop piezo-expansion ramp motion of MLL-H X-axis with interferometer feedback implemented. The position error (red/right) is within $\pm 2$ nm of requested position.

**Figure 3.** Stick-slip motion is used for long travel range (1.0 $\mu$m – 2 cm) of optics components and sample with interferometer feedback. The position error (red/right) is within $\pm 2$ um of requested position.
Figure 2 illustrates a closed feedback loop where ramping is implemented. Such ramping (continuous velocity) motion is typically used for continuous scans, and it is seen that deviation from a requested position does not exceed 2 nm (Fig. 2) during piezo-expansion and about 2 µm (Fig. 3) during stick-slip closed feedback motions, respectively.

5. Control flow
As shown in Figure 4, the quadrature input from an interferometer enters the Power PMAC controller through Digital Encoder Mezzanine board. The stick-slip is controlled by a step/direction output of the encoder board, which for ANC-300 is further converted to CW/CCW pulses (not shown). The piezo expansion is controlled by Acc-24E3 18-bit DAC amplifier output.

6. Conclusions
Recent developments in control technology and piezo motion have made possible continuous scans that improved both stability and substantially reduced data collection time, at the same time providing nm-scale spatial resolution. Integration of different positioning devices (controllers, interferometers, piezo drivers, etc.) required manufacturing of a number of custom transition boards where interferometer signals have been brought together to connectors available on motion controller, and piezo drivers. Nanometer-scale spatial resolution measurements confirmed the validity of the approach used to implement scanning algorithms and corresponding hardware.

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8. References
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