EARTH, WIND, AND FIRE: THE NEW FAST SCANNING VELOCIPROBE*

C. Preissner[†], S. Sullivan, S. T. Mashrafi[1], C. Roehrig, J. Maser, B Lai, C. Jacobsen, J. Deng, F. S. Marin[2], and S. Vogt, Advanced Photon Source, Argonne National Laboratory, Argonne, IL, USA
[1]University of Illinois, Department of Mechanical Science and Engineering, Urbana, IL, USA
[2]DePaul University, Chicago, IL, USA

Abstract

The Advanced Photon Source Upgrade (APS-U) project will include a suite of new beamlines. In preparation for this, a team at the APS is developing an X-ray microscope with a novel granite (Earth), air bearing (Wind) supported stage to take advantage of the two orders of magnitude increased coherent flux (Fire) that will be available with the APS-U. The instrument will be able to operate as a scanning probe for fluorescence microscopy and as a ptychoprobe for the ultimate in spatial resolution. Both are combined with tomography. The goals for the instrument while operating at the current APS are to demonstrate fast scanning of large samples at high resolution and ptychography at the highest resolution (speed and resolution limited by available flux). This presentation will discuss the unique mechanics, interferometry scheme, the advanced scanning control, and some instrument integration.

INTRODUCTION

The dramatic increase in flux (the Fire) from the APS-U will enable reduced measurement times and increase optical resolution [1]. In fact, to make the best use of available photons and minimize sample damage, the X-ray beam will need to be scanned much more rapidly across the sample than is currently done. The high resolution and fast scanning necessitate a stable instrument platform. A new instrument, the Velociprobe, is being built to explore and push these limits. It will use zone plate optics and be able to operate as a scanning probe for fluorescence microscopy and as a ptychoprobe for the ultimate in spatial resolution. The goal is to scan a 1 µm by 1 µm area in less than 10s with the highest spatial resolution (~10 nm or better in fluoro-microscopy mode).

The goal of a highly stable instrument was considered at each point in the design process. The motion system was designed to minimize the positioning degrees of freedom. The fast scanning control is being developed to maximize bandwidth and disturbance rejection. This will be coupled with state-of-the-art laser interferometry to provide the best possible position information to the fast controller and the image collection systems. This paper covers the overall design of the instrument, including mechanics and controls, and the near-term plans as the Velociprobe is brought online.

INSTRUMENT DESIGN

Mechanics

The Velociprobe consists of a set of granite (the Earth) air-bearing supported (the Wind) coarse positioning X, Y, and Z axes stages. On top of these coarse axes sit the sample stack and the optics stack. The granite coarse stages are used to align the optics to the beam. The optics stack is used for the rapid fine scanning of the beam. The sample stack is used to align the tomographic axis to the optics and to select the region of interest on the sample.

The optics stack consists of a fast (bandwidth of hundreds of Hz) parallel kinematic piezo scanner. The order sorting aperture (OSA) stages are also mounted here. The sample stack consists of a coarse sample X axis, sample tomographic rotation axis, and the X, Y, and Z axes for sample centering. In operation, the optics are aligned to the beam, then the tomographic axis is aligned to the optics. The region of interest is brought to the tomographic axes. The fast scanner is then used to image the sample. The sample region of interest is then indexed to tile out larger sample areas. Basic information about all the axes (except those for the OSA) is shown in Table 1.

Table 1: Velociprobe Axes Listing

Axis	Travel	Design Res.	Model
CRSX	± 12.5 mm	5 µm	Custom
CRSY	± 5 mm	.7 µm	Custom
CRSZ	400 mm	5 µm	Custom
ZPXYZ	30, 20, 30 µm	.1 nm	PI 733.DD
OSAXYZ	± 12.5 mm	1 nm	Smaract SLC-17
SAMCX	± 5 mm	3 µm	Custom
SAMθ	360 deg.	.004 deg.	PI DT-380
SAMXYZ	26 mm	6 nm	PI Q-545

Custom Coarse Stage System

The foundation of the instrument, shown in Figure 1, is the granite coarse positioning stages. The design of these stages was driven by the question: How can the most stable microscope platform for an X-ray microscope be constructed? With this in mind, one of the design considerations was to minimize the number of degrees of freedom. This is because each motion degree of freedom also contributes compliance to the system. This can be particularly true for the degrees of freedom that are used to align the instrument, as they typically carry high loads. In addition, these alignment axes are not used frequently.

* Work supported by: Argonne is managed by UChicago Argonne, LLC, for the U.S. Department of Energy under contract DE-AC02-06CH11357.
† preissner@aps.anl.gov

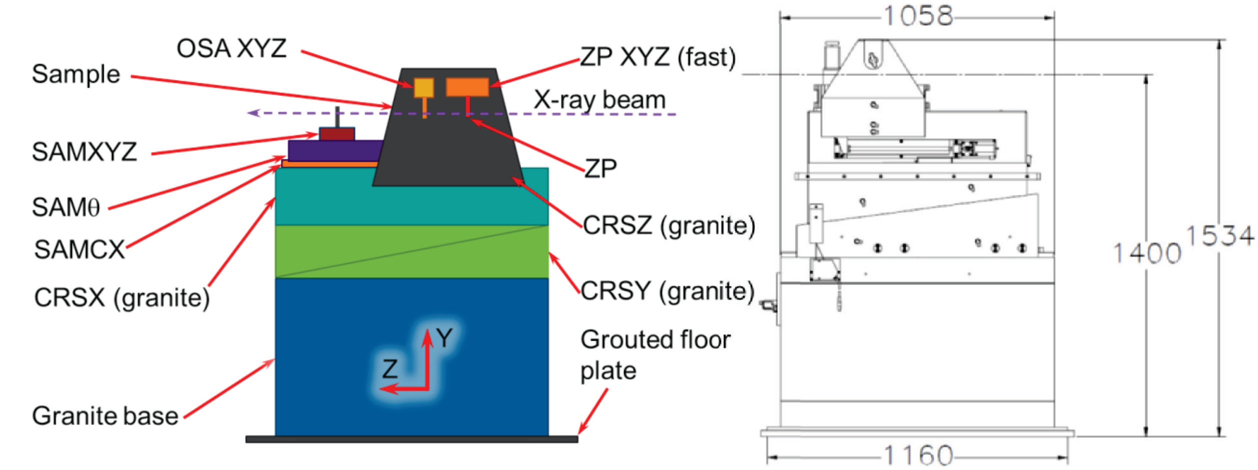

Figure 1: A schematic and line drawing of the velociprobe, showing the various stages. In the schematic on the left, the coarse Z (CRSZ) gantry is shown in the sample-changing position such that the sample stage stack can be seen. The sample, zone plate (ZP), and floor plate are also shown. The mass of the assembly is approximately 3630 kg and it stands about 1.5 m high.

To have motion axes that are not used frequently and reducing the performance potential drove the team to consider alternative. The chosen solution for the coarse positioning axes are granite structures with integrated air-bearing support (and also guiding for Z axis). The implication is that the axes can be moved precisely while moving on the air bearing film, then vented and the structure becomes as rigid as monolithic block of granite. In effect, the coarse positioning stages can be thought of as a shape-changing block of granite—all the advantages of a solid support without the added compliance of motion components. This design enables what the Velociprobe team considers to be the ultimate in stability. In addition, there vertical (Y) axis is novel and bespoke design and for which a patent has been applied [2].

All three coarse axes use the same basic concept, geometry machined directly into the granite to provide integrated air bearings. Typical geometry is shown in Figure 2.

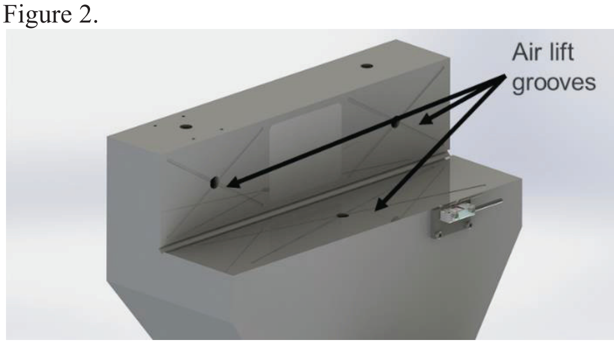

Figure 2: View showing the bottom of the Z axis carriage and the integrated air-lift grooves for the air bearing. Other axes are similar.

The vertical (Y) axis is a friction-locked wedge design. That means that vertical motion is provide through the one wedge being driven against a second wedge. Air bearings enable the motion and when the air bearings are vented, friction prevents the motion of the wedges. Figure 3 shows the force diagram for these wedges.

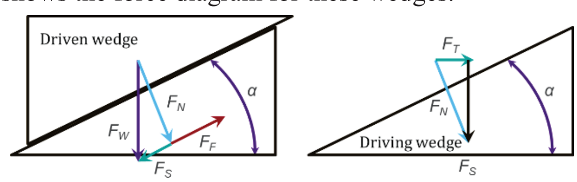

Figure 3: Force diagram of the wedges. F_w is the weight force, F_N is the normal force, F_S is the force along the slope, F_T is the thrust force, and F_F is the friction force. In the case of the Velociprobe, the angle α was chosen to be 7.5 degrees, resulting in approximately 76 mm travel of the driving wedge to move the driven wedge 10mm.

The equations describing the system are:

$$F_W = mg$$
$$F_S = F_W * cos\alpha \; = mg * cos\alpha \qquad (1)$$
$$F_N = F_W * sin\alpha \; = mg * sin\alpha$$

Figure 4 show the results from an analysis to verify that the design is indeed statically stable for the 7.5 degree angle.

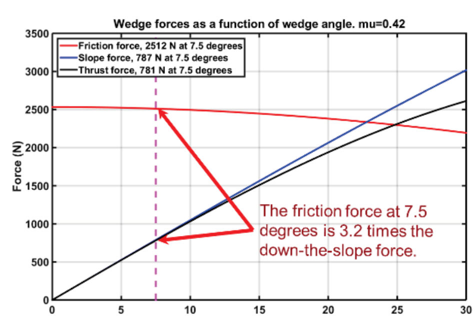

Figure 4: Chart showing that friction is sufficient to ensure stability of the vertical stage.

Each of the wedges have one degree of freedom. The driving wedge (bottom wedge in Figure 5) should be constraint to motion in the horizontal plane, while the

ISBN 978-3-95450-188-5

driven wedge (top wedge in Figure 5) should be constrained to motion in the vertical direction. The driving wedge is guided in the horizontal plane by the air bearing beneath it and a THK LM guide [3]. Decoupling flexures between the THK LM guide and the granite wedge ensure the wedge is not over constrained an allow it to "fly" approximately 5 µm when the air bearing is active. The driven wedge is guided by the air bearing beneath it and by a THK ball spline. Again, a decoupling flexure is used between the wedge and the ball spline to ensure the wedge is not over constrained.

Figure 5: View showing the internal details of the wedge guiding.

The driving wedge is driven with a combination of ball screw and stepper motor. Position is encoded with a Keyence laser displacement sensor. The other coarse motion axes are similar in design, using decoupling flexures to ensure no over constraint and thereby the best stability. The Z carriage has the addition of an air bearing guide in the lateral (X) direction. This decision was made to provide high trajectory accuracy when moving the Z axis to accommodate different optics (change in beam energy).

Fast Scanning Stage

The PI 733.3DD stage is mounted to the coarse Z gantry, upside down. There is no detriment to this configuration and this allowed for a design that did not have the sample or zone plate highly cantilevered. This is shown in Figure 6.

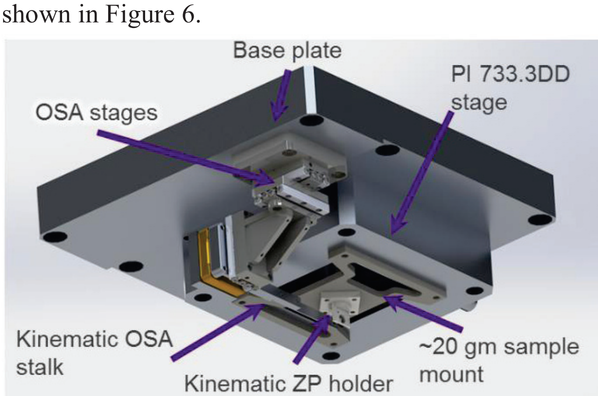

Figure 6: A picture showing the fast scanning assembly, including the PI 733.3DD stage.

Controls and Encoding

The overall control will be handled by a Delta Tau motion controller. This will integrate the coarse motion, fine motion, scanning, and the interferometer signals. The baseline configuration will use the PID controller in the Delta Tau to control the scanning trajectory. In addition, National Instruments (NI) cRIO hardware is being used to develop and implement a set of advanced control strategies. The flexibility of the FPGA in the cRIO chassis allows for a high level of customization. This controller will use an optimized negative feedback architecture and may be combined with model-based feedforward control to increase bandwidth. This technique has been shown to improve performance of similar X-ray microscopes [4]. The Velociprobe team has employed these strategies in other applications, including X-ray microscope hardware [4-6].

A block diagram summarizing the optimal control approach is shown in Figure 7. This approach allows for explicit customization of the dynamics of the closed-loop system by incorporating design objectives of large tracking bandwidth, good positioning resolution, robustness to unmodeled uncertainty, sufficient disturbance rejection and adequate measurement noise attenuation. The trade-off between positioning bandwidth and noise attenuation is addressed in this design. G is a model of the microscope nanopositioning XYZ stages that reflects the dynamics of the whole system, including the sample stage. The nanopositioner performance can be optimized for specific operating regimes. Constraints can be placed on the optimization such that actuator travel range is not exceeded. At the end of the design process, the tracking bandwidth and the tracking error across that bandwidth can be quantified. Additional information on the optimization can be found in [4-6]

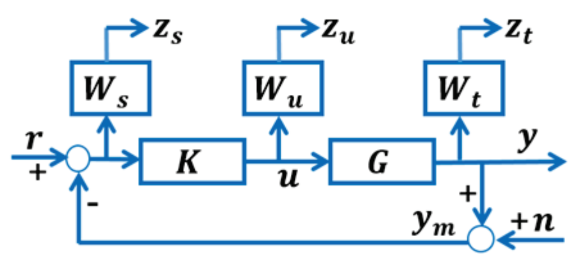

Figure 7: The closed-loop transfer function block diagram for mixed-sensitivity minimization is shown. Here, K is the controller transfer function, G is the model of the microscope dynamics, r the reference signal, u the stage input, and n the measurement noise. W_s, W_u, and W_t are design weighting transfer functions used to shape closed-loop transfer functions to achieve target regulated outputs $z = [z_s \quad z_t \quad z_u]$.

A critical part of the instrument control strategy is accurate position information. The sample and optic positions will be encoded using six axes of Attocube IDS interferometers. In this manner, the error signal used by the advanced control system will be the difference of the sample and optic position. An additional three axes may be included to capture thermal drifts. The IDS sensors have the capability of providing absolute position information. Because the instrument will be operating in atmosphere, the standoff distances of the sensor have been minimized to reduce noise.

The AquadB signals are made available to both the Delta Tau system and the cRIO system. The Delta Tau motion controller will integrate the coarse and fine motions and provide clock signals for image acquisition. For initial operations, the internal PID controller in the Delta Tau will be used to control scanning. When used with the NI hardware driving signals to the PI scanner will be provided from NI analog output modules.

Different data collection strategies will be explored with the Velociprobe. With the advanced control strategy, the scanning bandwidth will be known and the system should track any signal within that bandwidth with a known error (1% is target). This will enable not conventional imaging trajectories [7]. In addition, the close coupling of the interferometry and imaging should provide accurate position information for any image, regardless of the accuracy of the scanning trajectory. Both approaches will be explored.

NEAR-TERM PLANS

Figure 8 shows the coarse motion assembly during manufacture. The coarse motion system will be fully tested and the fine motion systems integrated. The advanced scanning controller will need to be redefined to account for all of the dynamics of the assembled system. High-level control software will also be tested. The intent is to test with beam before the close of 2016.

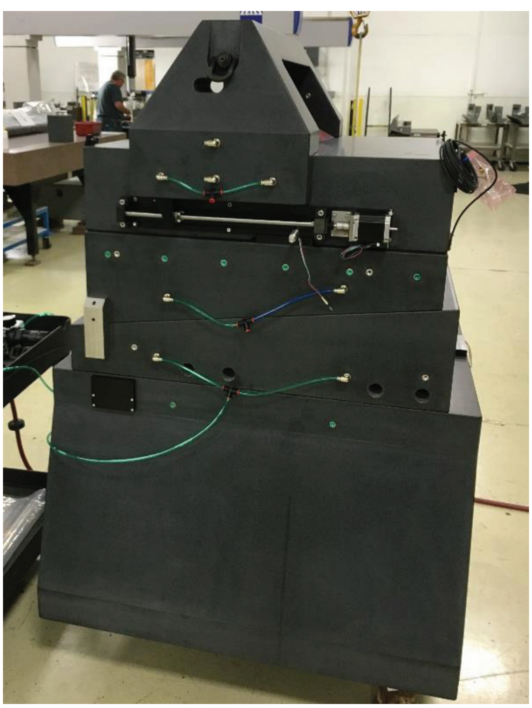

Figure 8: A picture of the Velociprobe granite stage system during final assembly and test.

ACKNOWLEDGMENT

The authors would like to acknowledge Travis Traut and Dennis Ethan of Starrett Tru Stone in Waite Park, MN for their help in the production of the velociprobe.

REFERENCES

[1] J. Maser, B. Lai, T. Buonassisi, Z. H. Cai, S. Chen, L. Finney, S. C. Gleber, C. Jacobsen, C. Preissner, C. Roehrig, V. Rose, D. M. Shu, D. Vine and S. Vogt, Metall. Mater. Trans. A-Phys. Metall. Mater. Sci. 45A (1), 85-97 (2014).

[2] Preissner, C. A., D. Vine, et al. (2016). Method and Apparatus for Implementing ultra-high stability, long-vertical travel stage. U. S. P. a. T. Office. USA, Argonne National Laboratory. Application 15/253,092.

[3] THK America, Inc.

[4] Mashrafi ST, Preissner C, Salapaka SM, Zhao H. Something for (almost) Nothing: X-ray Microscope Performance Enhancement through Control Architecture Change. ASPE 28th Annual Meeting. 2013.

[5] Lee C, Salapaka SM. Robust Broadband Nanopositioning: Fundamental Trade-offs, Analysis, and Design in a Two-Degree-of-Freedom Control Framework. Nanotechnology, Volume 20, Number 3, 2009.

[6] Sebastian A, Salapaka SM. Design Methodologies for Robust Nanopositioning. IEEE Transactions on Control Systems Technology, Volume 13, Number 6, 2005.

[7] Sullivan, S. Optics Express, Vol. 22, Issue 20, pp. 24224-24234 (2014)