EARTH, WIND, & FIRE: THE NEW FAST-SCANNING VELOCIPIROBE

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APS-U
An opportunity to revolutionize scanning probe microscopies...

- 100X+ increase in brightness
- Micro/nanoprobes are brightness driven
- Possible to get 100% of APS flux into a 300 X 250 nm spot!!!
- Can use increase in flux to:
  - Reduce scanning time
  - Increase resolution
  - Some combination
VELOCIPROBE OVERVIEW

Instrument goals and concept

- **Goals**
  - Build prototype high-speed, high-resolution X-ray nanoprobe
  - Scan a 1µm X 1µm area in 10 seconds or less at 10 nm spatial resolution
  - Extended objects and high spatial resolution through ptychography
  - Fluorescence mapping at better than 50 nm
  - Tomography

- **Concept**
  - Design vibrationally and thermally stable instrument
  - Employ control strategy to reject disturbances and maximize bandwidth
  - Explore nontraditional scanning and image acquisition modes
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ptychography + fluorescence + APS-U flux = need for speed
VELOCIPROBE MECHANICS

- Sample
- OSA XYZ
- SAMXYZ
- SAMθ
- SAMCX
- CRSX (granite)
- CRSZ (granite)
- CRSY (granite)
- ZP
- ZP XYZ (fast)
- X-ray beam
- Grouted floor plate

Dimensions:
- Width: 1058
- Height: 1534
- Depth: 1160
COARSE MOTION CONCEPT

Maximum stability, minimum necessary degrees of freedom

- Coarse axes used only for alignment
- Why compromise stability with compliance from rolling-element bearings?
- Novel concept:
  - Granite stages
  - Travel 25 mm, 10 mm, 400 mm (X, Y, Z)
  - Integrated air bearings guide all axes
  - *Fly-move-land* operation
  - As stable as solid granite when landed
- Designed to be inherently stable
- Mass: \( \approx 3612 \) kg (7946 lb)
- Air bearing lift: \( \approx < 5 \) \( \mu \)m
- Vendor: Starrett Tru-Stone
- US patent in progress: 15/253,092
Y AXIS STAGE (VERTICAL)

Air-lifted, stepper driven wedge-style

- **Motor**
  - Oriental motor PKP268MD14BA-L
  - .9 deg./step, bipolar, 4-lead, 2.23 N*m

- **Drive**
  - THK MDK 1402-3 Ball Screw
  - 2 mm pitch, 145 mm travel

- **Guiding**
  - THK HSR 15A Linear Guide
  - THK SLF 40 Ball Spline

- Theoretical minimum full step
  - 5 µm for driving wedge (horizontal)
  - .7 µm for driven wedge (vertical)

- Encoder: Keyence LK-G80, <.1 µm resolution

- Moving mass ≈850 kg

- Friction-stable 7.5 degree wedge
Y AXIS STAGE

Principle of operation

Driven wedge

Driving wedge

Proper constraints are applied to ensure correct motion
Y AXIS STAGE

Kinematics of wedges

- One axis of motion needed on each wedge ⇒ five constraints are needed
- Driving wedge has THK rail, driven wedge has THK ball spline
- Flexures allow for movement when the air bearing is lifted
Y AXIS STAGE

Wedge forces

- Friction has been measured for the particular granite and surface finish
Y AXIS STAGE

Wedge forces

- Friction has been measured for the particular granite and surface finish
- Stage is rigid when air lift is vented

The friction force at 7.5 degrees is 3.2 times the down-the-slope force.
METROLOGY USING INTERFEROMETERS

Single reference frame with 6 interferometers (only Y and Z axes shown)

- Using Attocube IDS sensors
- Need to accommodate the rotation of sample (cylindrical/faceted reference surface)
INSTRUMENT CONTROL
Optimized negative feedback approach

- $H_\infty$ Mixed-Sensitivity Minimization:
  - Increase tracking bandwidth
  - Increase position resolution
  - Better disturbance rejection
  - Adequate noise rejection
  - Robustness to unmodeled system dynamics
  - Can exploit axes coupling

- Techniques proven in SPM field and for X-ray microscope

- Implemented on fast FPGA hardware
  - NI-9039 cRIO hardware
  - Can implement almost any algorithm

Comparison using an existing instrument

- Resolution:
  - Hinf 3.33 nm vs PID 6.08 nm
  - 45% better than PID

- 3 dB Bandwidth:
  - Hinf 31.2 Hz vs PID 5.6 Hz
  - >5 times better than PID

INSTRUMENT CONTROL

Design process

- Exogenous Inputs, \( w = [r \quad n] \)
- Regulated Outputs, \( z = [z_s \quad z_t \quad z_u] \)
- \( T_{wz} = [W_sS \quad W_tT \quad W_uKS]^T \), t.f. \( w \rightarrow z \)
- Performance objectives are achieved by minimizing the \( H_\infty \)-norm of the closed-loop transfer function matrix \( T_{wz} \) for all stabilizing controllers \( K \).

\[
\inf_K ||T_{wz}||_\infty
\]

Weight \( W_p \) is chosen such that resulting \( S \) has high-pass filter shape

Weight \( W_T \) is chosen such that resulting \( T \) has low-pass filter shape
INSTRUMENT CONTROL

Better dynamics can translate to more efficient scan trajectories...

Lissajous trajectory scanning

Raster scanning

1 ms 2 ms 10 ms 20 ms

INSTRUMENT CONTROL

More efficient scanning can yield more efficient imaging...

Original movie | Sparsely sampled movie

In-painted reconstruction | Error

STATUS...
Granite stage assembly will arrive at APS next Tuesday!
MOLTES GRÀCIES!