BEAM SYNCHRONOUS MOTION: High-Fidelity Simulation and Image-Based Precision Quantification

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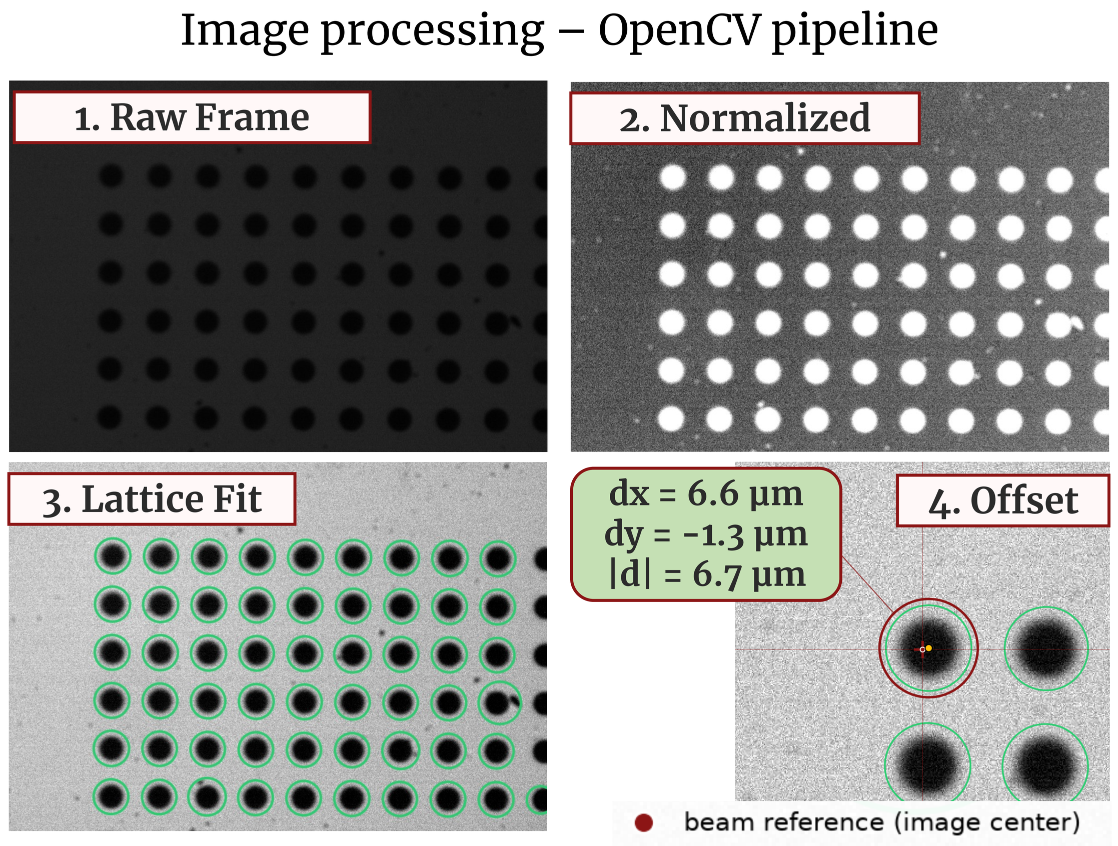
RACING THE XFEL BEAM

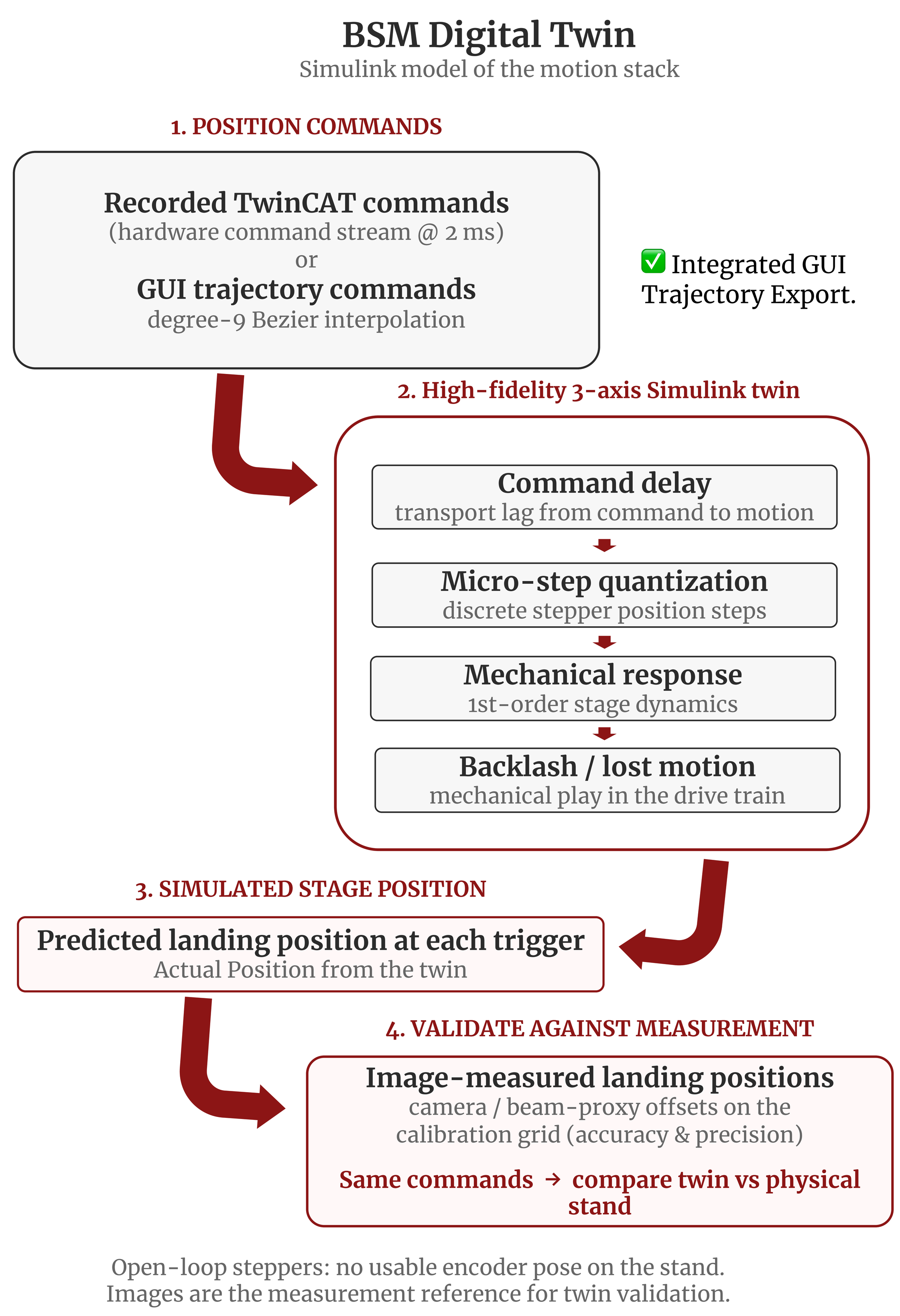
LCLS's High Energy Upgrade will fire X-ray pulses faster than conventional motion control can reliably deliver samples to the beam focus. SLAC's Experiment Controls Systems (ECS) group is developing Beam Synchronous Motion (BSM), a fly-scan control system specified to meet three requirements: (1) deliver samples within 5 µm of the beam focus at 1000 Hz, (2) provide a general interface usable in any hutch without significant customization, and (3) preserve all existing ECS Motion Control System (MCS) features [1]. This project delivers two things for requirement (1): a robust image-based measurement of actual performance, and a validated digital twin of the scan—so controller changes can be tested in simulation before risking beam time on the real system.

METHODOLOGY

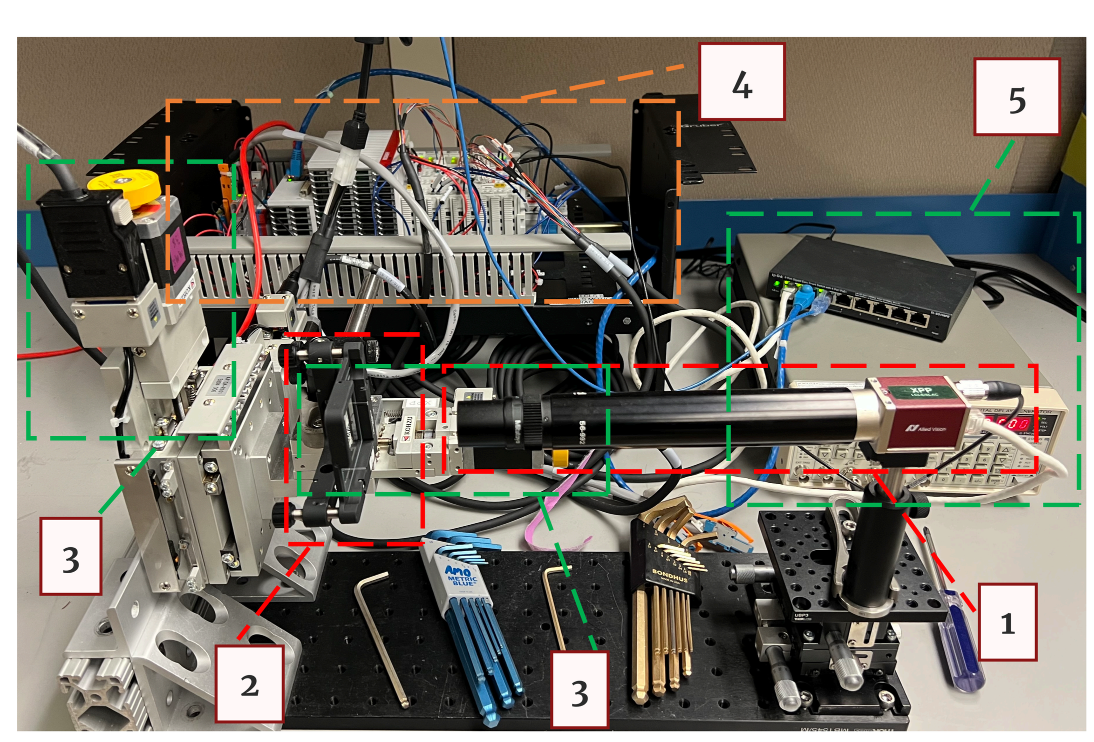
Image processing – OpenCV pipeline



A fixed camera acts as a beam proxy at image center. Each frame is contrast-normalized, then calibration dots are segmented and localized to sub-pixel centers. A uniform lattice fit recovers pitch and micron scale. The intended target is selected within a search gate, and the offset from the beam reference is reported as dx, dy, and radial $|d|$ in microns—the accuracy and precision metrics for the motion system.

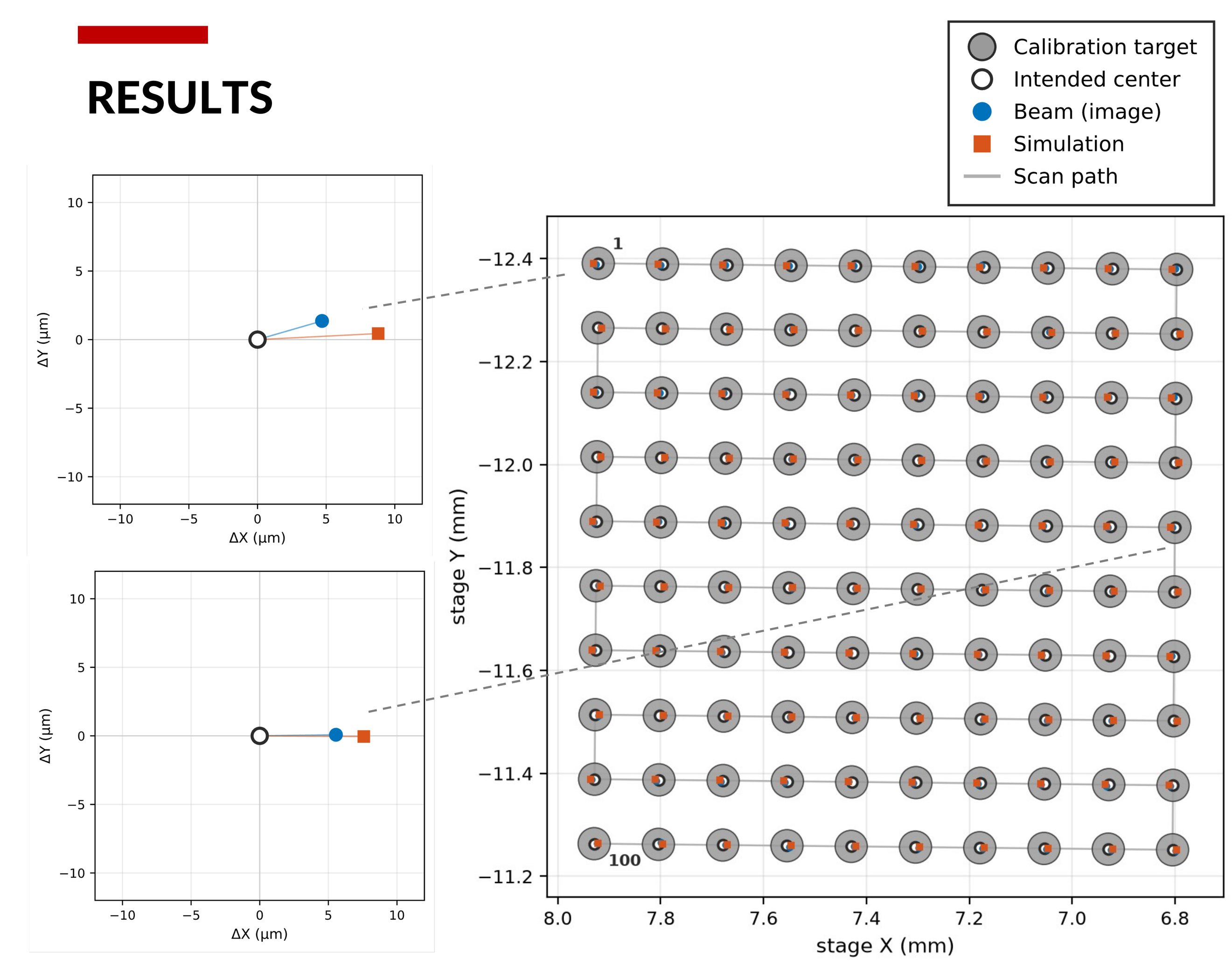


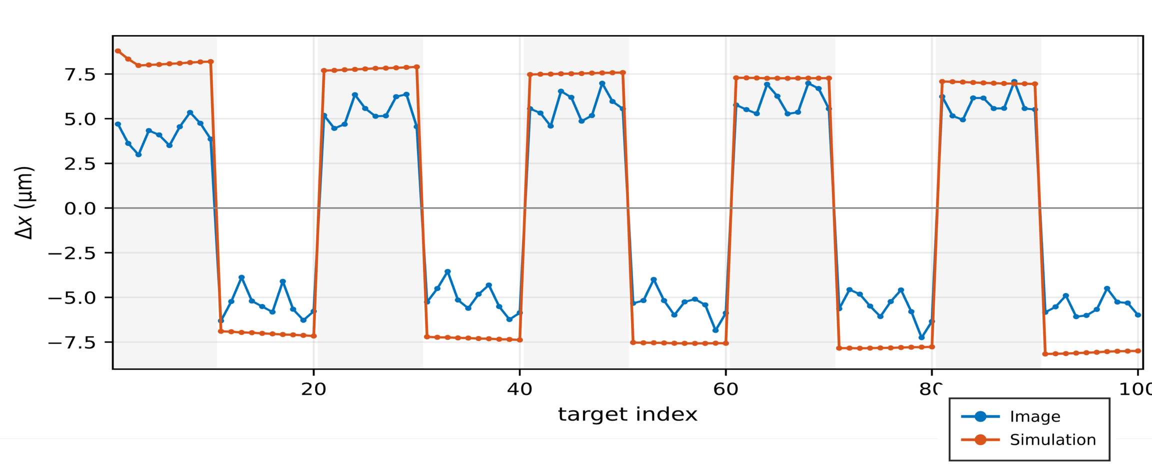
EXPERIMENTAL SETUP

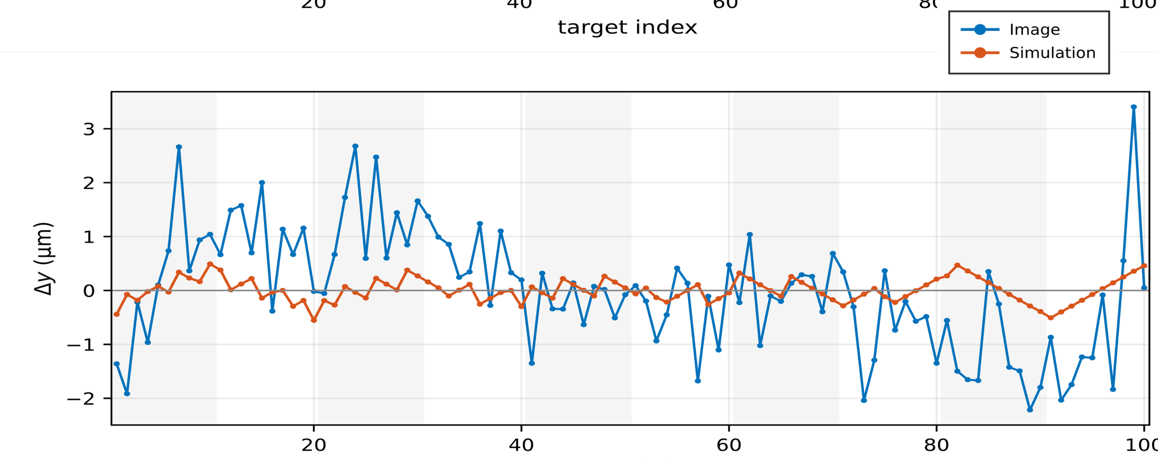


1. Camera: Mako G-234B (1936×1216); beam = image center, **2. Grid:** Edmund #58-509; 0.125 mm pitch; 0.0625 mm dots, **3. Motion:** Open-loop steppers + EL7062 (CSP); 0.5 mm lead , **4. PLC:** Beckhoff CX5240 + TwinCAT, **5. Triggers:** EL1252 timestamping; 10 Hz latch for this test campaign

RESULTS







The image pipeline recovers a clear landing signature on a 10×10 serpentine fly-scan (100 targets): mean absolute offsets of **5.4 µm in X** and **0.9 µm in Y** (mean radial ≈ 5.5 µm), with radial precision ~1–2 µm (1σ) across repeats. A defocus run still assigns all 100 targets (~5.8 µm mean radial), confirming robustness under degraded focus.

Driven by the same position commands, the Simulink twin reproduces this X lag structure and stays near zero in Y (**~7.6 / 0.2 µm mean** |X|/|Y|), with few-micron twin–image residual. Relative to BSM's 5 µm requirement, performance is already near-spec; the remaining gap is largely systematic timing/lag—exactly what a validated twin is built to diagnose and reduce before beam time.

CONCLUSION

We established optical ground truth for open-loop BSM and a digital twin that matches the measured landing signature. Image-based accuracy/precision (**~5.5 µm** mean radial; **~1–2 µm** precision) and twin–image agreement at the few-micron level provide an acceptance path for future GUI/controller changes. Performance is already near BSM's **5 µm** delivery target; remaining error is largely timing/lag and is now diagnosable in simulation. The path forward is twin-guided optimization, then hardware validation with the same image pipeline.

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REFERENCES

[1] N. Lentz et al., "A motion control system for fly scans synchronized to X-ray pulses", in Proc. ICALEPCS2025, Chicago, IL, USA, Sep. 2025, pp. 312-319. doi:10.18429/JACoW-ICALEPCS2025-TUCG003