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Development of a Goniometer with Nanoradian Accuracy

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** Brookhaven National Laboratory (BNL), NSLS Beamline X21*
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Abstract

Advanced Design Consulting, Inc. (ADC) designed a super accurate goniometer for applications where nanometer accuracy is required. The system is capable of achieving super accurate resolution, repeatability, orthogonality of motion, and stability, at a wide range of load capacities.

In this paper measurement data obtained from Brookhaven National Laboratory describing the precision, angular accuracy, and stability are summarized.

Keywords: Keywords: Goniometer, Nano Precision, Stability

1. Introduction

There are numerous applications in synchrotron radiation research where angular positioning of X-ray optical elements or analytical components is required to micro and nanoradian accuracy levels. Some of these include precise movement of analyzer crystals, zone plates, polarization analyzers, quarter-wave plates, small mirrors or multi-layers. In these and other cases, crystals must be aligned with high precision and scanned over small angular ranges.

There are various techniques currently used to solve this positioning problem. Most schemes rely upon stacks of circles, arcs, arc-segments or goniometric cradles machined to different radii producing axes with orthogonal rotations about a point. Additionally, there are usually substantial stages and fixtures mounted on these positioners to accommodate large crystals, water cooling mounts or fast response piezo-driven stages.

In this paper, a simple, low cost and robust solution to the problem of nanoradian accuracy angular positioning of substantial (25 lb [11 kg]) loads is presented. This "inverted-joystick" design is capable of achieving highly accurate resolution, repeatability, orthogonality of motion and stability, for a wide range of load capacities. Some aspects of this design are unique and are patent pending in the United States.

2. Design Principles

The "inverted-joystick" design principle is illustrated in Figure 1 in schematic and actualized forms. A large diameter hardened-steel hemispherical section, **A**, comprises the sample mounting stage for the assembly. This mounting hemisphere is pre-loaded against three spherical bearings, **B**, mounted in a triangular 'kinematic' three point contact fashion. The current state-of-the-art developed during decades of bearing technology improvements assures excellent high strength case hardened bearing materials, low rolling contact friction and an extremely small "sphere of confusion" at the projected center of the sample mounting stage. A high-stiffness joystick, **C**, is attached perpendicular to the mounting stage hemisphere at a location between the three mounting bearings. By choosing the length of the joystick in relationship to the radius of the mounting hemisphere and the resolution of available drive motors mounted at right angles to the joystick, the designer can tailor the minimum angularly-resolved motion per motor step. Some aspects of this design are unique and are patent pending in the United States.

A device was tested for angular stability, repeatability and accuracy at NSLS Beamline X21. For this particular device, the design maximum angular adjustment range was ± 8° in all directions. The sample hemisphere diameter was 2 inches, angular resolution was 69.8 nanoradian [4 micro deg, 0.0144 arc-sec], repeatability was 0.698 nanoradian [0.01 micro degree, 0.000036 arc-sec] and load capacity was 25 lb [11.34 kg]

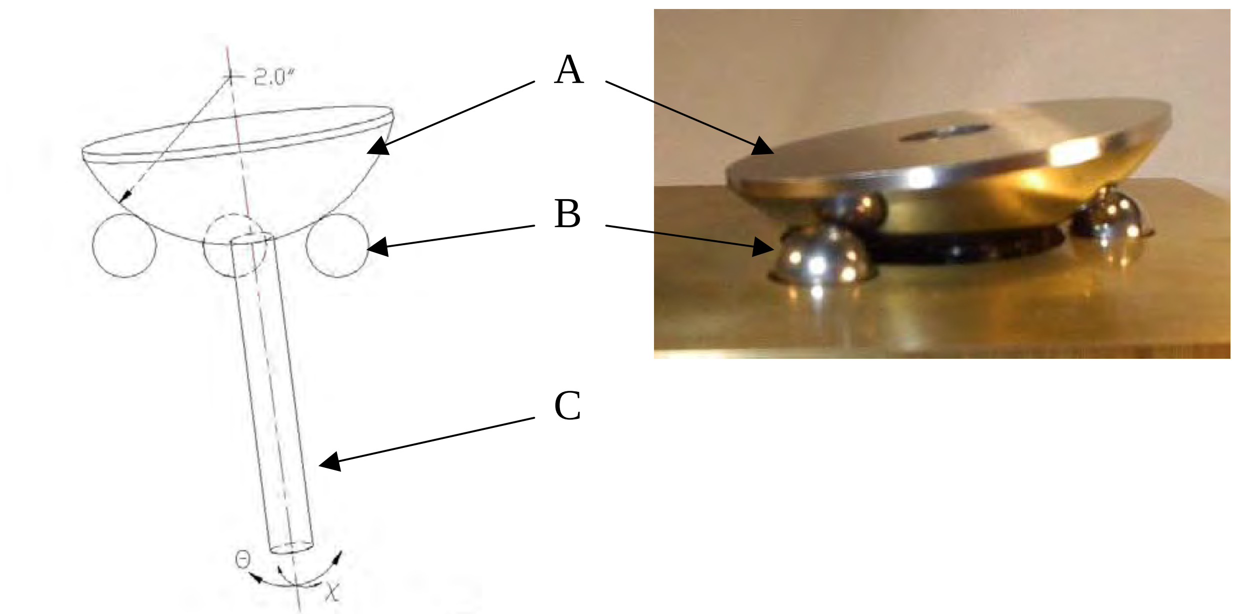

Figure 1: Schematic (left) and actual (right) nanometer accuracy angular positioner. A) Mounting stage hemisphere, B) Guide bearings, C) Joystick

3. Accuracy and Stability Testing

A series of stability tests were conducted at the high-resolution inelastic scattering beamline, X21 at the National Synchrotron Light Source (NSLS), Brookhaven National Laboratory in Upton, N.Y. This beamline [1] consists of a high-resolution four-crystal monochromator with an energy resolution of 0.2 eV between 6 and 10keV, and a toroidal mirror focusing the monochromatic beam into a spot of dimensions less than 0.5 x 0.5 mm^2. The inverted-joystick goniometer was used to align the spherically bent high-resolution analyzer crystal of the Rowland-circle spectrometer with sample, analyzer and detector on the Rowland-circle. The overall energy resolution of the system was 0.5eV. The spectrometer was mounted on the 2θ arm of a 4-circle goniometer, so the spectra could be measured at different scattering angles.

The motivation for using this inverted-joystick goniometer on an inelastic scattering beamline developed from a need to position a large number of focusing analyzer crystals with extreme accuracy and stability. Generally, the inelastic x-ray scattering process suffers from a very small interaction cross section. In order to compensate for inherent losses, an analyzer crystal has to be made as large as possible. Mechanical constraints, however, limit the maximum size of a single crystal spherically bent analyzer. Therefore, several crystals have to be mounted together on one common rotation or translation stage (the Uwe Bergmann approach [2] and aligned individually with computer-controlled motors. Furthermore, these motions have to be reproducible and stable over long periods.

For this series of tests, the inverted-joystick goniometer was mounted atop the existing beamline scanning goniometer, The θ or 'yaw' motion is driven by a Huber 410-goniometer with a 20:1 gear-reducer driven by a Berger-Lahr stepping motor operating in half-step mode, giving a single step size of 1.7 micro radians (100 micro degrees, 0.36 arc-seconds). On top of the θ stage was a small cradle with a Berger-Lahr motor, giving a single step size of 70 micro radians (4 micro degrees, 14.4 arc-seconds) producing a χ or 'pitch' motion. Figure 2 shows the experimental arrangement with the inverted-joystick goniometer (with motor control cover removed) atop the θ and χ stages at X21.

Figure 3 shows equivalent scans of θ (with the nanoradian goniometer fixed) and nanoradian goniometer drive A (with Huber 410 drive θ fixed). Fits of the center of mass (COM) for the curves shifted by <0.0023 deg (8.28 arc sec). The plots are identical to within the error of the position of the fit peak. Figure 4 shows similar scans for χ and the equivalent nanoradian goniometer drive B. A shift of 0.04 degrees, about the width of the peak, and a shift of θ by 0.0053 degrees were found. The problem with motor B or χ is probably due to the backlash correction. Motion in this direction depends more upon gravity, which allows the mount to rotate a small amount. This tiny rotation mixes θ and χ motion components with a small miscut in the crystal and thus shifts the peak in both directions.

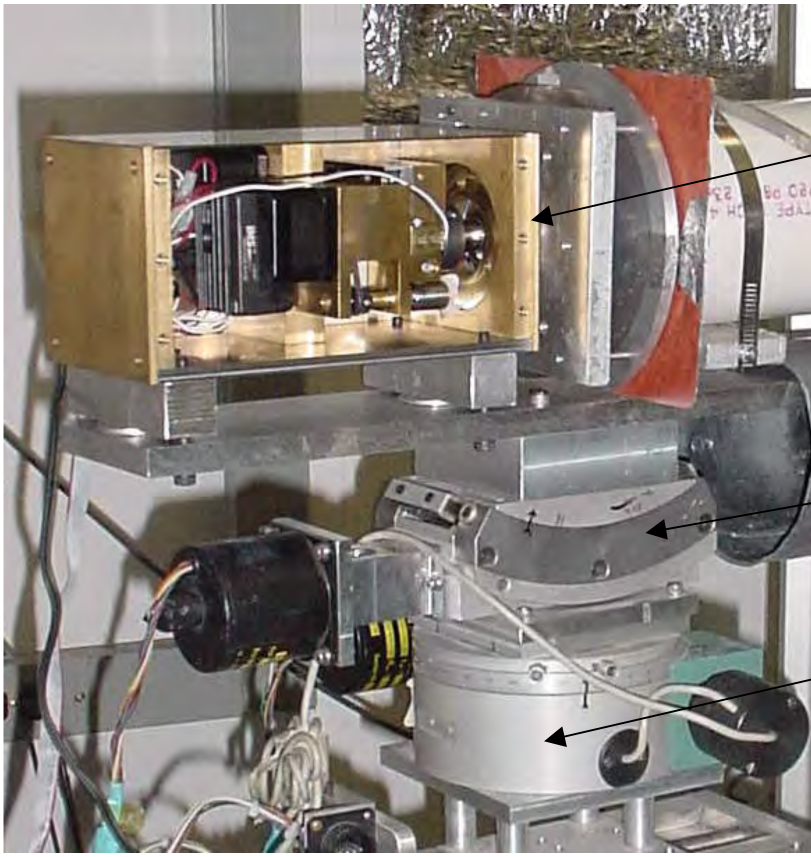

Figure 2: X21 experimental set-up. Nanoradian inverted-joystick goniometer (brass casing) with mounting stage hemisphere to the right (hidden) holding analyzer crystal. The unit sits upon a χ arc segment and a Huber 410 θ rotation stage. The nanoradian goniometer 'A' drive is equivalent to the Huber θ rotation and the goniometer 'B' drive is equivalent to the χ rotation.

The long-term stability of the goniometer was measured in two different ways. For the first series of tests, a normal series of inelastic scattering scans was done at a fixed q and fixed goniometer motor settings by changing the incident X-ray energy. The same energy-range was measured 22 times and, to within statistical error, the data of all scans overlap well as shown in Figure 5. (Two scans made during injections are not shown. During beam injections the incident X-ray intensity varies as optics warm up.) For the second series of tests, the analyzer crystal was shifted to the tail of the inelastic scattering peak (consecutively in A then in B, equivalent to θ and χ), and the intensity was measured every second for about 10 minutes without moving any motors. Small variations are observable, as seen in Figure 6, but they are most probably related to instabilities of the monochromator and the storage ring. A Fourier analysis, Figure 7, of this time series calculates the power spectral density, which is the Fourier transform of the autocorrelation function. The peak around 0.03 Hz is related to the beamline cooling water circuit and the other high-frequency peaks are associated with noise.

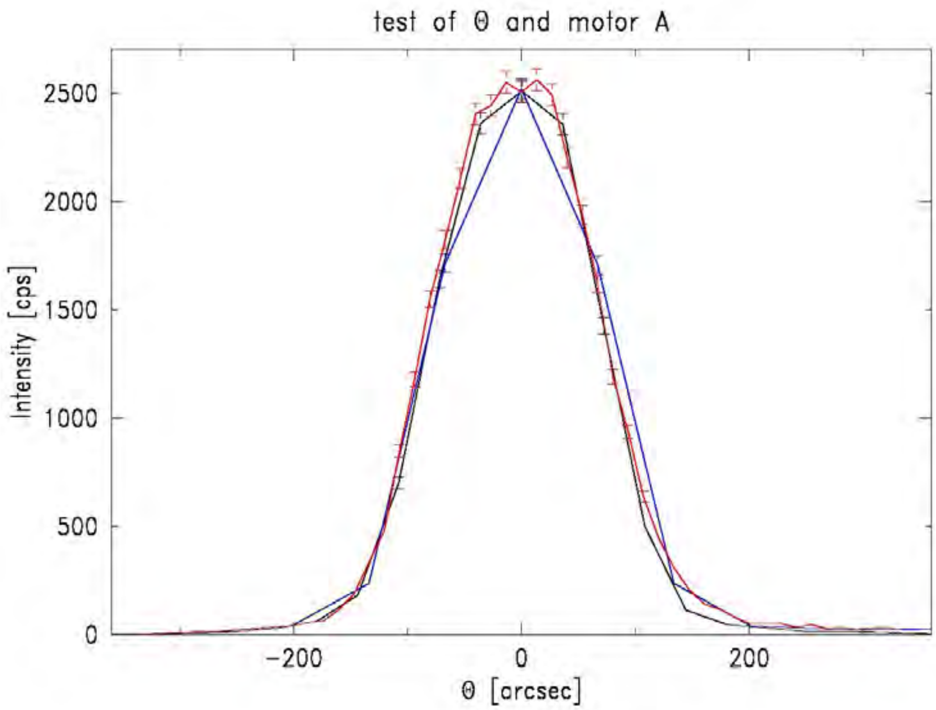

Figure 3: Comparison of Huber θ scan (blue) with nanoradian goniometer motor A motion scans (red and black)

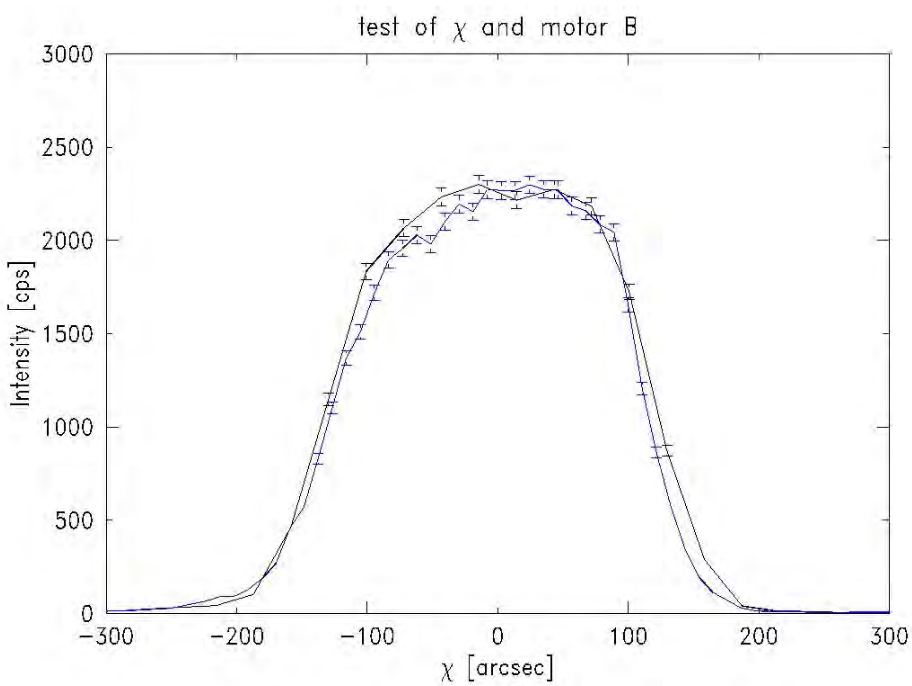

Figure 4: Comparison of χ scan (blue) with nanoradian goniometer motor B motion (black).

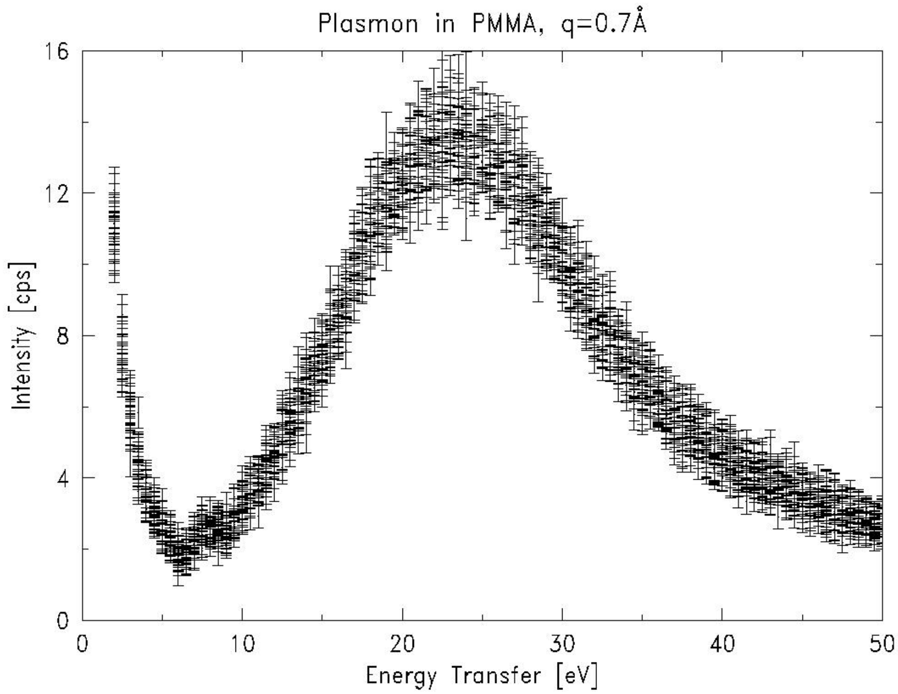

Figure 5: Test of goniometer stability. Twenty-two (22) consecutive energy transfer scans at constant q for PMMA collected with analyzer crystal at fixed position by nanoradian goniometer system.

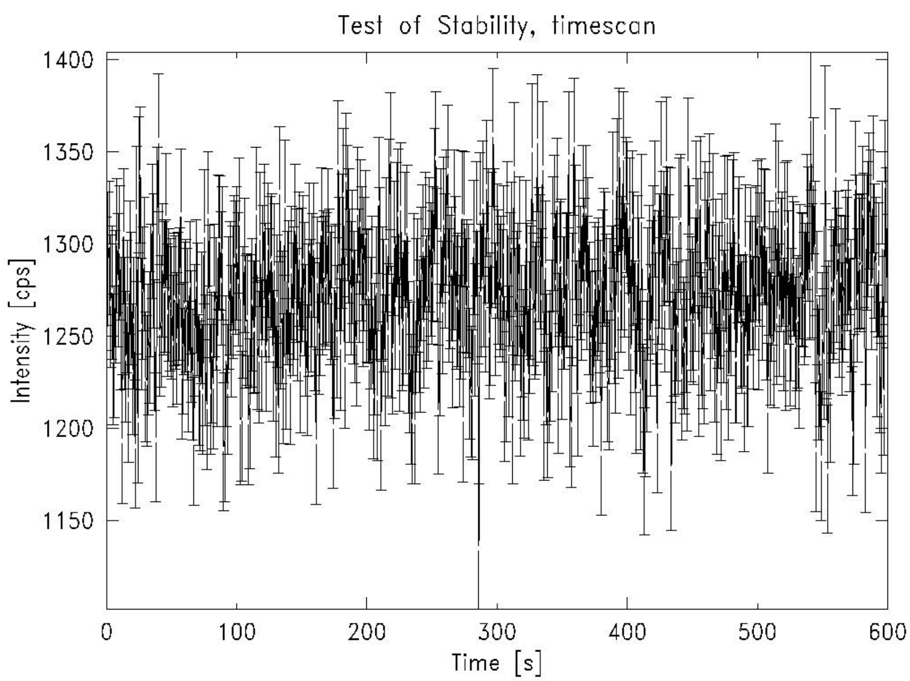

Figure 6: Time stability test. Nanoradian goniometer with analyzer crystal detuned to 50% in θ direction. Goniometer stability over a 10 minute passes is shown. An equivalent stability scan detuned in the χ direction shows similar response. Data is within statistical error range ±35 cps.

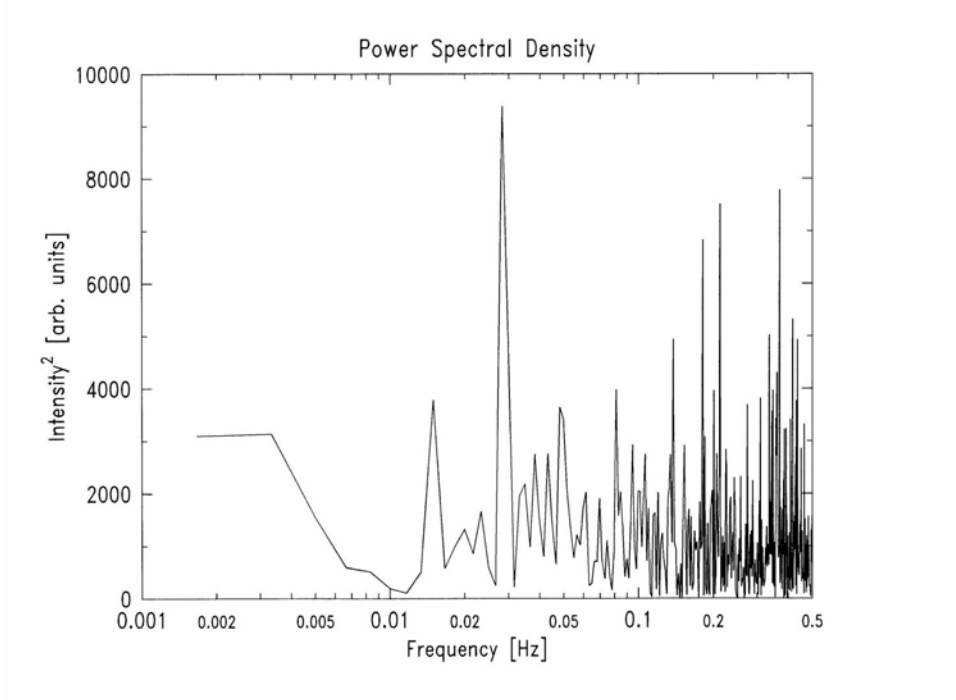

Figure 7: Power Spectral Density (Fourier transform of the time series in Figure 6) showing higher frequency noise peaks and a 0.3 Hz peak associated with beamline cooling-water systems.

4. Conclusion

While testing has not been exhaustive, all indications are that the nanoradian inverted-joystick goniometer design is robust, stable and highly accurate. The system is easily scalable with simple changes in the geometry of the mounting stage hemisphere diameter and joystick length. Further developments should allow this cost effective system to position substantial instrumentation loads reliably to any required accuracy.

5. Acknowledgments

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6. References

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