Optomechanical design of a high-precision detector robot arm system for x-ray nano-diffraction with x-ray nanoprobe

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Abstract. Collaboration between Argonne National Laboratory and Brookhaven National Laboratory has created a design for the high-precision detector robot arm system that will be used in the x-ray nano-diffraction experimental station at the Hard X-ray Nanoprobe (HXN) beamline for the NSLS-II project. The robot arm system is designed for positioning and manipulating an x-ray detector in three-dimensional space for nano-diffraction data acquisition with the HXN x-ray microscope. It consists of the following major component groups: a granite base with air-bearing support, a 2-D horizontal base stage, a vertical axis goniometer, a 2-D vertical plane robot arm, a 3-D fast scanning stages group, and a 2-D x-ray pixel detector. The design specifications and unique optomechanical structure of this novel high-precision detector robot arm system will be presented in this paper.

1. Introduction
A traditional way to perform diffraction measurement is to use a diffractometer. In carrying out diffraction measurement using a small focused beam, or nanodiffraction, using a conventional diffractometer faces three major instrument challenges. First, rotation motion of the sample typically has a large (> 10 microns) run-out error known as a sphere of confusion. Second, the circles for vertical and horizontal diffraction angles are mechanically coupled to the sample, causing unwanted displacement of the sample position when the detector is rotated. Three, some x-ray microscopes used for micro- or nanodiffraction require a large vacuum enclosure, making it virtually impossible to use a conventional diffractometer.

For the x-ray microscope for the Hard X-ray Nanoprobe (HXN) beamline at the National Synchrotron Light Source II (NSLS-II) at Brookhaven National Laboratory, which is designed for x-ray microscopy capabilities with an initial goal for a spatial resolution of 10 nm [1], we take a novel design approach for nanodiffraction. In our design, we completely de-couple the detector positioning system from the sample stage stack and use a high-precision detector robot arm system in generating full spherical coordinate motions for an array detector. These degrees of freedom of motion include the horizontal diffraction angle, the vertical diffraction angle, and the sample-to-detector distance (we shall refer to this as detector distance in the rest of the manuscript). When performing Bragg ptychography [2], adjusting detector distance is important because it defines the maximum range of diffraction angle, which contributes to the spatial resolution limit of the reconstruction.
This paper describes detailed optomechanical design and specifications of the high-precision detector robotic arm system which employs a unique vertical plane robotic arm structure with duo-vertical-stages [3].

2. Design requirement for the detector robot arm system
The instrument requirement for the NSLS-II HXN beamline is to achieve a horizontal diffraction angular range from -5 to 65°, a vertical diffraction angular range from -5 to 45°, and a sample-to-detector distance from 0.25 to 0.54 m (0.25 to 2.5 m with base station positioning). The horizontal diffraction angle is produced by using a 2-D horizontal base stage plus an in-plane goniometer. The vertical diffraction angle is achieved using a vertical plane robot arm structure. In addition, a 3-D fast scanning stages group is used to control the detector distance and the detector raster capability to achieve a larger q-range.

The normal load capacity of the custom-built HXN-Z7-47 detector robot arm is 18 kg, which is not only able to handle the total weight of an array detector, such as a TimepixTM QTPX-262K (Amsterdam Scientific Instruments) or other moderate-size detector, and a pair of motorized stages for the area detector raster scan, but also is capable of carrying out the dynamic forces generated during the detector raster scan.

The initial design goal for the unidirectional positioning repeatability of the HXN-Z7-47 robot arm is 20 microns in the experimental station with ± 0.1 °C temperature stability [1]. With better environmental temperature control, positioning repeatability in a few-micron-level should be achievable for the HXN-Z7-47 robot arm system. This is valuable for the future detector upgrade with high-spatial-resolution pixel sizes. Figure 1 shows a 3-D model of the HXN-Z7-47 detector robot arm system with the vacuum enclosure for the NSLS-II HXN x-ray microscope. Table 1 summarizes the main design specifications of the HXN-Z7-47 detector robot arm system.

![Figure 1. 3D models for the the HXN-Z7-47 detector robot arm system with NSLS-II HXN vacuum enclosure. (1) granite base for HXN vacuum enclosure; (2) HXN vacuum enclosure; (3) detector robot arm; (4) granite base for detector robot arm.](image)

| Parameter                            | Value                      | Units |
|--------------------------------------|----------------------------|-------|
| Overall dimension                    | 1700(W) × 2020(L) × 2750(H) | mm    |
| Horizontal diffraction angular range | -5 – +65                   | deg   |
| Vertical diffraction angular range   | -5 – +45                   | deg   |
| Sample-to-detector distance          | 0.25 – 0.54                | m     |
| Sample-to-detector distance (with base positioning) | 0.25 – 2.5 | m     |
| Normal load capacity                 | 18                         | kg    |
| Robot base relocation range          | 2.5 × 3                    | m     |
| Unidirectional positioning repeatability | < 20                      | micron|
3. Design of the horizontal base stages with movable granite base

As shown in Figure 1, the HXN-Z7-47 detector robot arm system consists of the following major component groups: a granite base with air-bearing support, a 2-D horizontal base stage, a vertical axis goniometer, a vertical plane robot arm, a 3-D fast scanning stages group, and a 2-D x-ray pixel detector.

The design of the 2-D horizontal base stage is similar to the robot base stage designed for the hard x-ray nanoprobe at the Advanced Photon Source (APS) Sector 26 [4]. Figure 2 shows a 3-D model of the horizontal base stage with a vertical axis goniometer, and a movable granite base. As shown in Figure 2, a THK™ custom-built 2-D horizontal stage (2) and a Huber™ 430 single-circle goniometer (3) are mounted on a granite base (1) to produce a circular motion centered on the sample position in the horizontal plane [4]. There are three air-bearing skids (4) (Airfloat™ AF-1012) integrated with the granite base to provide the robot base station positioning capability. A laser-based positioning tracking system will be applied to ensure the base position accuracy. Table 2 summarizes the design specifications of the 2-D horizontal base stage for HXN-Z7-47 detector robot arm system.

![Figure 2. 3-D model of the horizontal base stage with a vertical axis goniometer, and a movable granite base. (1) granite base; (2) 2-D horizontal stage; (3) single-circle goniometer; (4) air-bearing skids.](image)

### Table 2. Design specifications for HXN-Z7-47 detector robot arm 2-D horizontal base stages

| Parameter                        | Value                | Unit  |
|----------------------------------|----------------------|-------|
| Overall Dimension                | 1500 (W) x 750 (L) x 221 (H) | mm    |
| Normal Load Capacity             | 500                  | kg    |
| Stage driver type                | Stepping motor with planetary gearhead |       |
| Encoder type                     | Linear grating encoder |       |
| Travel range                     | 1050 (W) x 300 (L)   | mm    |
| Min. incremental motion          | 0.25 – 1.5 microns   | microns|
| Unidirectional repeatability     | ± 5                  | micron|
| Max. speed                       | 600                  | mm/min|

4. Design of the vertical plane robot arm structure

The HXN-Z7-47 detector robot arm system has a unique vertical plane robot arm structure. As shown in Figure 3(left), the vertical plane robot arm structure includes a vertical base (1), two THK™ custom-built vertical linear stages (2) and (3), a robot arm linkage (4), and a 3-D fast scanning stages group (5) to generate the detector distance plus the capability to raster the area detector (6).

Figure 3(right) shows the robot arm linkage sub-assembly. The sub-assembly consists of a linkage base (1), a high-rigidity linear rolling guide (2), and a pair of high-rigidity cross-roller bearings. The upstream bearing (3) is mounted on the linkage base, and the downstream bearing (4) is mounted on the carriage of the rolling guide. The linkage sub-assembly is connected to the carriages of the two vertical linear stages through the pair of cross-roller bearings. The vertical plane robot arm is kinematically positioned in the vertical plane by the two vertical linear stages. A motorized 3-D fast scanning stages group (5) is mounted onto the linkage base to perform the detector raster scan and adjust the detector distance for the 2-D area detector (6). Table 3 summarizes the design specifications of the HXN-Z7-47 detector robot arm vertical linear stages.

![Figure 3. (left) The vertical plane robot arm structure includes a vertical base (1), two THK™ custom-built vertical linear stages (2) and (3), a robot arm linkage (4), and a 3-D fast scanning stages group (5) to generate the detector distance plus the capability to raster the area detector (6). (right) The robot arm linkage sub-assembly consists of a linkage base (1), a high-rigidity linear rolling guide (2), and a pair of high-rigidity cross-roller bearings. The upstream bearing (3) is mounted on the linkage base, and the downstream bearing (4) is mounted on the carriage of the rolling guide. The linkage sub-assembly is connected to the carriages of the two vertical linear stages through the pair of cross-roller bearings. The vertical plane robot arm is kinematically positioned in the vertical plane by the two vertical linear stages. A motorized 3-D fast scanning stages group (5) is mounted onto the linkage base to perform the detector raster scan and adjust the detector distance for the 2-D area detector (6).](image)
Figure 3. (Left) 3-D models of the HXN-Z7-47 vertical plane robot arm structure: (1) vertical base; (2) and (3) vertical linear stages; (4) robot arm linkage; (5) 3-D fast scanning stages group; (6) 2-D area detector. (Right) 3-D models of the HXN-Z7-47 vertical plane robot arm linkage sub-assembly: (1) linkage base; (2) linear rolling guide; (3) upstream bearing; (4) downstream bearing; (5) 3-D fast scanning stages group; (6) 2-D area detector.

Table 3. Design specifications for HXN-Z7-47 detector robot arm vertical linear stages

| Parameter                                      | Value          | Unit  |
|------------------------------------------------|----------------|-------|
| Overall Dimension (Upstream stage)             | 1520 (H) x 200 (W) x 58 (D) | mm    |
| Overall Dimension (Downstream stage)           | 1788 (H) x 200 (W) x 58 (D) | mm    |
| Travel range (Upstream stage)                  | 850            | mm    |
| Travel range (Downstream stage)                | 1210           | mm    |
| Vertical Load Capacity                         | 60             | kg    |
| Stage driver type                              | Stepping motor with planetary gearhead |       |
| Encoder type                                   | Linear grating encoder |       |
| Min. incremental linear motion                 | 0.8/full-step 0.02/micro-step | micron |
| Min. incremental angular motion                | 2.1/full-step 0.05/micro-step | micron |
| Unidirectional repeatability                   | ±3             | micron|
| Max. speed                                     | 160            | mm/min|

5. Summary
We presented the optomechanical design and specifications of a high-precision detector robot arm system for the scanning x-ray microscope for the HXN beamline at the NSLS-II. Our unique vertical-plane robot arm structure can be adapted to other x-ray microprobes and nanoprobes to enable high-precision x-ray diffraction capability.

References
[1] Preliminary Design Report for Hard X-ray Nanoprobe (HXN) Beamline, 2010 LT-C-XFD-HXN-PDR-001; http://www.bnl.gov/ps/nsls2/beamlines/files/pdf/HXN_pdr.pdf
[2] Huang X, Harder R, Leake S, Clark J and Robinson I, 2012 J. Appl. Cryst. 45 778
[3] Shu D and Chu Y, U.S. Patent application in progress for ANL-IN-13-017
[4] Shu D, Maser J, Holt M, Preisner C, Lai B, Vogt S, Winarski R and Stephenson G B, 2007 Proc. 21st ASPE Annual Meeting (Monterey, CA) p123

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