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Determining Runout and Repeatability for The Rook 3-Axis Cryogenic Nanopositioning System: Error Motion Testing and Analysis

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Introduction

Quantum research requires the precise, simultaneous positioning of multiple experimental components to observe the desired phenomenon. Accomplishing this research requires nanopositioners designed for low-temperature environments often less than 4 Kelvin (K). This paper discusses the use and performance factors of cryogenic nanopositioners consisting of three linear stages, or 3-axis "stacks," which are capable of functioning in extreme conditions to allow the user to repeatably move a sample with precision and accuracy. Applications requiring such positioners include:

- Raster scanning – collecting multiple images in a grid pattern across a sample and stitching them together into a single, larger image.
- Microscopy – acquiring a target position for imaging with an internal or external microscope objective.
- Probing – using radio frequency (RF) or optical fiber probes to acquire data about output signals at multiple target positions across a quantum device.

Given the extremely low temperatures and high vacuum levels of the environments needed to observe a quantum phenomenon, the choices for compatible positioning solutions are limited. Compounding the limited compatibility is a demand for increasingly optimized motion performance parameters of 'runout' and 'repeatability.'

Flatness and Straightness as Key Factors for Determining Mechanical Runout and Accuracy (Error Motion)

Runout refers to a system's ability to be in line with the intended axis of motion. Critical runout performance factors are flatness and straightness. Flatness and straightness are used to help explain how a stage travels about the three axes of motion as in Figure 1 below:

- Transverse axis, lateral axis, or pitch axis (x).
- Longitudinal axis or roll axis (y).
- Normal axis, or yaw axis (z).

As the stage travels along the Y axis, the motion deviates from a perfect line in varying degrees. Straightness error motion (straightness) is defined as linear error motion in the X direction combined with Z-axis rotation. Flatness error motion (flatness) is defined as linear error motion in the Z-axis combined with rotation about the X-axis.[2]

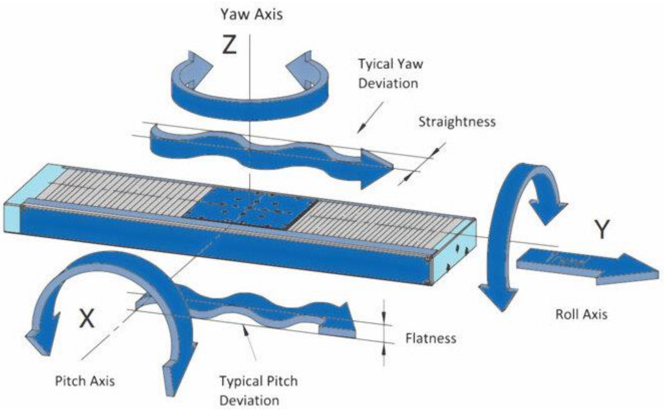

Figure 1: Axis definition and typical error motions of one stage

Since this discussion centers on the ability of an object to travel through three dimensions of space, it is helpful to consider the analogy of an aircraft, which is capable of the same motion and with similar forces acting on it.

Straightness is the motion along the X-axis, or the normal axis is a determination of how well a stage will follow a straight-line trajectory. Flatness on the other hand is a determination of the stage's tendency to buckle or pitch about the y-axis while it is traveling along its theoretical straight-line trajectory. These two parameters are necessary for determining runout and accuracy (error motion).[2]

Stiffness, Mechanical Backlash, and Encoder Performance for Determining Repeatability

Repeatability refers to the system's ability to move away from and then return to a specific target position. It is a critical motion performance measure that allows users to understand if they will be able to successfully use a positioner to easily find their target and reliably return to the same point to measure that target again. As stated by ASME B5.54-2005, repeatability is "a measure of the ability of a machine to sequentially position a tool concerning a workpiece under similar conditions."[4] A similar definition is in ISO 230-2-2006 (E), which specifies "methods for testing and evaluating the accuracy and repeatability of the positioning of numerically controlled machine tool axes by direct measurement of individual axes on the machine."[5]

With respect to nanopositioners, the following factors influence repeatability:

- Stiffness: the result of relative movement between interacting mechanical parts of a drive system that does not produce output motion.[1]
- Mechanical Backlash: also referred to as "play," is a clearance or lost motion in a mechanism caused by gaps between the parts.[3]
- Encoder Performance: the ability of an encoder to provide accurate positional feedback relative to a stage's actual position.

Unidirectional and Bidirectional Repeatability

Unidirectional repeatability defines the encoder performance when approaching from one side of the target, whereas bidirectional repeatability defines encoder performance as approached from either side of the target. Unidirectional repeatability is easier to achieve and hence affords voluminous data sets with ease.[1] The majority of nanopositioner developers settle on unidirectional data sets to qualify their products.[5] Bidirectional repeatability is more demanding in that certain forces placed on the driving mechanisms only become apparent during a reversal of motion.[1] A high degree of bidirectional repeatability presupposes a higher level of unidirectional repeatability. Improving bidirectional repeatability performance must consider the mechanisms required to drive and control a stage[1]. This level of accountability provides users with a more reliable and intuitive positioning device.

Other Runout and Repeatability Considerations

Both runout and repeatability are factors in error motion. It is important to note that factors outside of the mechanical design can impact runout and repeatability error rates. Examples include:

- Quality of the mounting surface.
- Length of travel.
- Size of the stage.
- Payload.
- Mounting orientation.
- Magnetic field, electromagnetic radiation, or other external forces.

A high-quality integrated 3-axis stage capable of returning optimal runout and repeatability performance measures has the potential of offsetting the error rates.

Typical Cryogenic Motion Challenges

How manufacturers measure and report motion performance often differ from a customer's use case, making it difficult for customers interested in a 3-axis positioning solution to evaluate their options. For example, unidirectional repeatability performance looks great on a specification sheet, but one would not experience this performance unless the stages are used in this limited manner, i.e., approaching the target point from the same direction every time.

Additionally, it is common for manufacturers to publish specifications for a single stage measured under some "ideal" conditions on a test bench, whereas a quantum researcher typically assembles the stages into a multi-axis stack and cools them down to 4K in a cryostat's vacuum chamber. Consequently, performance to key critical specifications of repeatability and runout is thus invalidated due to the convolution of multiple stages and the varying magnification of angular error motion (pitch and yaw from Fig. 1) across three stacked stages working in concert. The combination of these considerations are likely to undermine a customer's confidence that their stack will perform to the manufacturer's published specifications in the final cryogenic use case. Potential consequences to customers may include:

- Unexpected motion and inability to meet published performance specifications in a cryogenic environment.
- Inability to reliably measure the same, correct target across multiple image-capture scans.
- Stitching images (where multiple images are combined to form one, larger coherent picture) may be more difficult if the precise coordinate for each image is not predictable or verifiable.

High-level Solution

Determining a 3-axis cryogenic nanopositioning solution with optimal repeatability requires one of two approaches:

- Purchasing three individual linear stages from a supplier with the expectation that the customer will assemble the components.
- Purchasing a fully integrated and factory-tested 3-axis positioning solution. Locating a supplier who will sell a pre-assembled 3-axis stack.

With The Rook™, Montana Instruments provides a nanopositioning solution with the proven ability to reliably repeat stage motion in all axes with precision and accuracy, i.e. enhanced multi-axis performance. The positioner was tested to specification while operating at 4K under vacuum in a Cryostation® and considered to have the most accurate representation of sample motion. When installed, The Rook integrates with the Galaxy control software which makes automatic, temperature-dependent parameter adjustments to ensure the nanopositioner meets target specifications across varying temperatures. Accurate expectations of sample motion provide customers with improved efficiency of experimental execution by minimizing the need to recollect data due to positional inaccuracies.

Metrology Test Procedure

Interferometry and autocollimation are the main methods used in characterizing nanopositioner motion. As shown in Figure 2, the reflector/mirror fixture is mounted to the top of the nanopositioner.

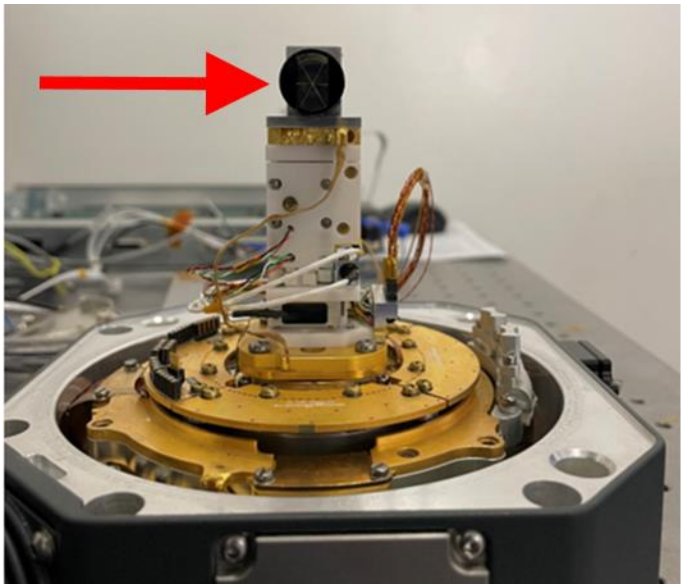

Figure 2: Reflector/mirror mounting fixture.

This mounting fixture allows the positioning of the reflector and mirror in such a way that linear displacement data (using Renishaw XL-80 interferometer) and angular deviation data, both yaw and pitch (using a Micro-Radian ThetaScan TL-40 Small Target Laser Autocollimator) can be obtained for all the axes of motion (x, y, z).

After the cryostat's vacuum housing is placed in position, the autocollimator and interferometer optics are placed and aligned through the windows of the chamber.

All optics need to be positioned and aligned for the data collection on each axis separately. (Figure 3).

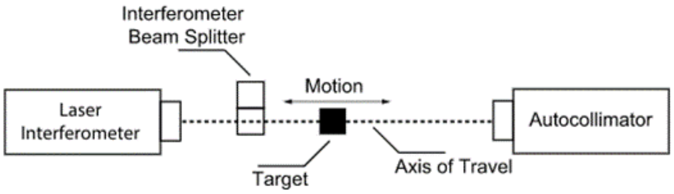

Figure 3: Metrology layout.

When measurements are taken on a particular axis of either x or y, the remaining axis is positioned in the middle of travel. When not under conditions for testing, the z-axis is positioned at the negative end of travel. Similarly, when taking measurements on the z-axis, the remaining two axes are positioned near the middle of their travel range. For each axis test, the chamber is cooled down with a target temperature of 4K. Once a stable target temperature is reached, the axis under test is moved to its negative limit, and readings are taken at 100 µm increments (in a closed loop) as the stage travels the full range and back to the starting position. Multiple runs of this bidirectional data collection are completed for each axis.

Analysis Procedure

Data is gathered from both the interferometer and autocollimator as the nanopositioner makes incremental steps (acquiring target points) along the measured axis. The angular data (both pitch and yaw) from the autocollimator readings are used to derive values for straightness and flatness by numerical integration against the displacement readings of the interferometer. The incremental linear displacement readings of the interferometer and the corresponding encoder readings are used to derive bidirectional and unidirectional repeatability as well as the linear accuracy of each axis.

Bidirectional and unidirectional point repeatability is derived throughout the 3D motion envelope from:

$$3D\ Repeatability = \left(R_{xi}^2 + R_{yj}^2 + R_{zk}^2\right)^{1/2}$$

R represents the bidirectional or unidirectional repeatability of each x, y, or z axis with respect to the i, j, and k target positions. Closed-loop incremental motion is measured using interferometer data and feedback from the encoder.[3]

Required Tools and Equipment

The ThetaScan TL-40 Autocollimator and E2 digital controller meet the Swiss Federal Institute of Metrology (METAS) calibration standard of 0.8% error tolerance for +/- 3600 arc seconds. Readings, however, are typically well below +/- 1000 arc seconds which has an error tolerance of 0.1%.

The Renishaw XL-80 laser interferometer is calibrated in linear measurement mode to be within +/0.5 ppm. Renishaw certificate No: 67H343-210601-00.

Conclusion

Many cryogenic nanopositioner manufacturers do not align their performance test procedures with the use cases of researchers with novel experiments in non-standard laboratory environments. This is more reason for potential customers to demand higher testing standards from a positioner supplier so they can have confidence in high-quality results. The Rook™ is the only 3-axis nanopositioner on the market to provide such confidence with key-critical performance validated at the top of the positioner in a cryogenic use case.

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