Design, Manufacturing, and Testing of Precision Space Flight Qualified Single Degree of Freedom Flexure Based Linear Actuators / Mechanisms

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Abstract

This paper describes the design, manufacturing, and testing of a range of high-reliability, space-qualified single degree-of-freedom (1-DOF) linear actuators used to position optics to a high degree of precision. Danbury Missions Technologies, LLC (Danbury) has developed a series of single-stage linear actuators, which provide extremely repeatable and deterministic nanometer scale output motion with near zero backlash or hysteresis over extended ranges. This paper highlights the design architecture of these actuators, which utilize flexures to transform rotary input motion into precise linear output motion and meet the rigorous demands of launch and space environments. The paper also touches on the key areas of manufacturing and test required to assemble and qualify these actuators including representative test results.

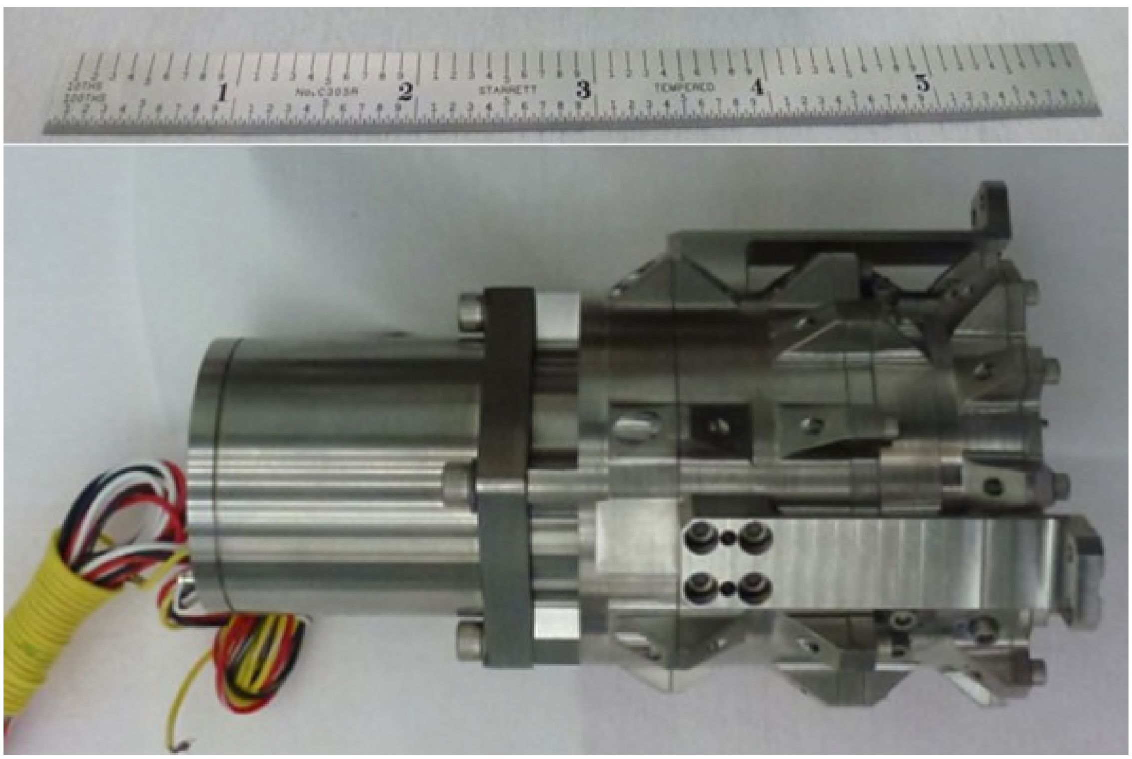

Figure 1. Representative Danbury Flexure-Based Linear Actuator Provides Precision Motion Without Need for Separate Launch Locks

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Introduction

Advanced space-based optical systems require the ability to locate and maintain optical surfaces relative to each other with extreme precision, within the optical frame of reference. The need to precisely position/reposition optics remotely on-orbit typically results from some combination of:

- Active focal correction as a function of range to an image
- Optical misalignments or shifts due to launch
- Optical metering structure dimensional changes due to seasonal thermal effects, and composite on-orbit dry-out.

Additionally, as optical systems continue to increase in size, there becomes a point where there is a need to segment the mirror to achieve the best balance of performance and cost for the optical system. These mirror segments must be precisely aligned to produce a coherent image. This creates yet another demand to precisely reposition optics relative to each other. To achieve the proper mirror surface geometry, the surface figure and rigid body positions of mirror segments must by dialed in by precise actuation to induce the desired precision wavefront quality.

To address the needs for on-orbit optical correction, Danbury has developed a series of compact modular single-stage linear actuators, which range in size with the ability to be tailored for specific applications. These actuators can be used standalone providing 1-DOF or in a system where up to six degrees of freedom (6-DOF) can be achieved in a hexapod arrangement. To achieve demanding system requirements of positioning highly sensitive optics, each actuator is designed to have the following characteristics:

- High positional precision and accuracy with minimal backlash and hysteresis over large actuation ranges
- High stiffness and load/moment capability acting as a stressed member of the optical metering path
- Ability to withstand launch loads without the need for separate launch locks
- Athermalization to minimize the impact of thermal effects (bulk and gradient) on the optical metering path length
- The ability to maintain precise position unpowered
- High reliability
- No lost motion or missed steps such that the actuator can be used without positional feedback (open-loop),
- Minimal motion biproducts in the non-actuated axes
- Minimized SWaP (size, weight, and power).

This paper focuses on one of Danbury's most recent and most challenging actuators to design, build, and test. This single-stage flexure-based linear actuator, termed the Testbed Actuator (TBA), was developed to challenge the envelope on the competing requirements of range and resolution. We also integrated real-time motor position and output force feedback devices into the TBA to further increase capability and to broaden the list of potential applications. We highlight the design, assembly, test setup, and test results of the actuator. We also discuss key lessons learned and follow-on work being performed to continue to advance the design of precision linear actuators.

Actuator General Design

Each of our flexure-based linear actuators are composed of three main sections which work in concert to be compliant with the demanding list of requirements. These sections are modular such that they can be tailored for each application to optimize range, resolution, and SWaP. The three main sections are depicted in Figure 2:

1. The Motor → typically a unipolar or bipolar stepper motor
2. Harmonic Drive (HD) → single or multiple stage drive gear reducer transmission
3. Rotary to Linear Output Assembly (RLOA) → flexure-based arrangement converting rotary motion from the output of the harmonic drive to linear motion [1]

As noted, the TBA described in this paper also includes an integrated optical encoder for motor position feedback and load cells on each of the flexure athermalized mounting feet to provide force output feedback. A functional diagram of the actuator is illustrated in Figure 3.

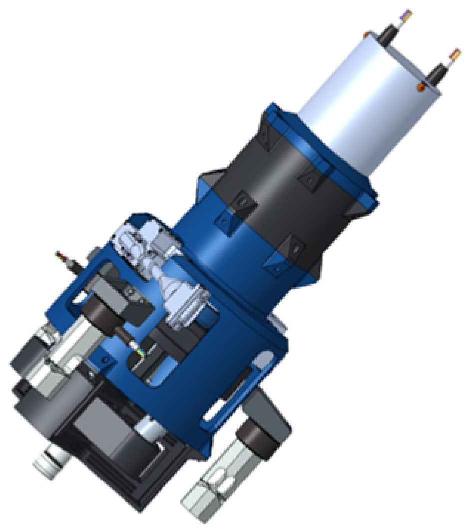

Figure 2. Testbed Actuator General Design

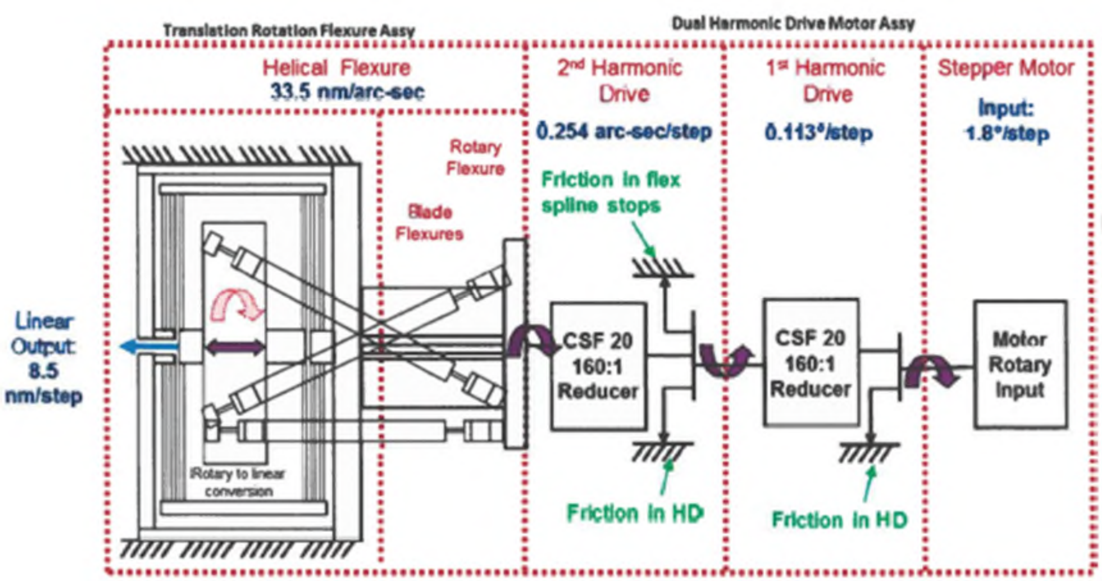

Figure 3. TBA Actuator Functional Diagram

<u>Actuator Motor</u>

Brushless DC 2-Phase Unipolar or Bipolar Stepper Motors are used to drive the linear actuator since they can be driven open loop, minimizing complex and expensive feedback electronics when compared to a servo motor-based actuator. Also, stepper motors provide the benefit of providing an unpowered holding torque due to the motor step detent amplified through the transmission. Unipolar motors are used for applications that do not require image capture during actuation. Bipolar motors are used for applications that require smooth motion outputs during imaging, requiring more sophisticated drive electronics that microstep the motors and current shape as required.

Actuator Harmonic Drive

Harmonic drive(s) gear reducers are used for the actuator transmission to increase the actuator resolution and amplify the motor output torque. Harmonic drives are chosen for their compact size, high gear output ratios, and minimal backlash / hysteresis, which are all key elements to meet the actuator design requirements. In some instances, a series of two harmonic drives are used in actuators that require very high output resolution.

Actuator Rotary to Linear Output Assembly (RLOA)

The key element to our linear actuator design is a highly engineered rotary to linear output assembly. This completely flexure-based design takes the rotary output motion from the final harmonic drive and translates it into pure linear motion. A fully flexure-based design is used such that the output motion is extremely repeatable, and deterministic being void of any effects due to friction, and lost motion / deadband. The RLOA is designed and analyzed using linear and non-linear finite element analyses (FEA), optimized for range and resolution, while ensuring positive margins for stress and buckling throughout the actuator range. Material choices in the RLOA assembly are critical for optimal actuator performance. The RLOA is responsible for properly constraining and balancing internal forces such that a pure axial motion is output from the actuator. The RLOA is also responsible for providing the actuator with the required load and moment capacities.

Optional Feedback Devices

The modular actuator design allows for optional feedback devices to be integrated if the application requires. It should be noted that feedback devices are not required for standard operation since each actuator is driven using stepper motors, which output through a harmonic drive(s) transmission, and flexure-based RLOA to provide exceptional repeatability without suffering from lost motion. But for instances where feedback is desired, the following options are available:

- High sensitivity radiation hardened optical encoders with 28-bit capability can be integrated to the harmonic drive output to measure absolute angular input into the RLOA. The optical encoder is polled, and position is averaged over a predetermined number of samples. The actuator is commanded to achieve the desired displacement, and the optical encoder is polled again to establish a differential measurement of the motor shaft displacement.
- We have also developed the capability for our actuators to have the option to include strain gages on the RLOA diaphragm to provide correlated (strain to displacement) linear output measurements.
- Finally, the actuators have the option to provide force feedback with integrated force gages installed at the three flexurized mounting interfaces. This option is typically employed for actuators which are used in mirror figure control applications.

Actuator Assembly Overview

Spaceflight actuators and mechanisms are assembled in our cleanroom facilities which are class 10k or better per FED-STD-209E. All cleaning, surface preparation, priming, barrier film applications, and impregnation / lubrication processes are performed internally.

Key design features of the actuator include integral alignment features which aid in assembly, as shown in Figure 4, reduce the risk of misalignment / assembly error, and significantly reduce the need for special complex tooling.

Figure 4. Fixturing and Integral Alignment Features Utilized to Assemble Actuator

Actuator Testing Plan

Each space flight actuator design goes through a full qualification program. The flow of our component flight actuator testing is shown in Figure 5. An initial performance test is performed after the actuator is assembled and baked-out. This is followed by a dynamic characterization in three orthogonal axes to determine the modal frequencies of the actuator, to provide correlation to the FEM, and the data is used for setting up the control constraints during vibration testing. A run-in test is performed for 5% of mission life to ensure the mechanism is running correctly and to properly distribute lubrication prior to Baseline Performance Testing.

Comprehensive Baseline Performance testing fully characterizes the actuator against all performance requirements and provides a baseline set of measurements for all subsequent tests. Environmental testing includes vibration testing, which consists of random vibration and sine-burst in three orthogonal axes enveloping the launch environments and providing workmanship assurance. Thermal Vacuum (TVAC) testing is performed after vibration testing where the unit under test is subjected to numerous thermal cycles including testing over the operational temperature ranges and survival thermal cycling, which properly envelopes the worst case expected on-orbit conditions.

Intermediate Performance Testing is performed after each environmental test to ensure no changes have occurred as a result of being subjected to prior environmental testing. During component qualification testing 2X Life Testing is also performed under vacuum conditions to simulate on-orbit operational environments. At the conclusion of environmental testing, a comprehensive Final Performance Test is performed assessing the actuator against all performance requirements and comparing the test results to those taken during Baseline Performance Testing.

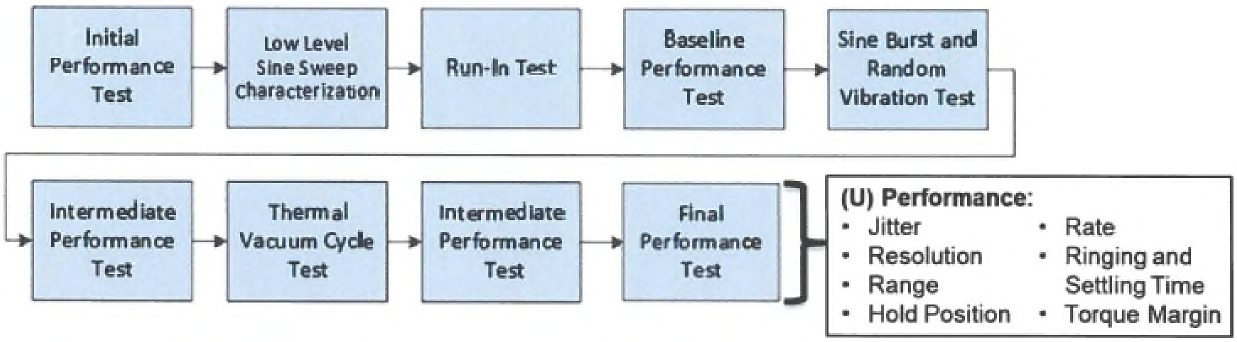

Figure 5. Flight Actuator Testing Flow Chart (Note for Qualification Units a 2X Life Test in Included Prior to Final Performance Testing)

Actuator Performance Test Setup

Performance testing is typically one of the most challenging aspects of the mechanism program for high precision actuators where output resolution is measured in the single digit nanometer range. Very high sensitivity sensors and a test environment, which is both extremely thermally stable and has near zero external disturbances, is required to properly measure the actuator output performance with regards to resolution, accuracy, range, and jitter. We have been successful in providing appropriate test conditions with the use of sensors specifically fixtured for this unique application with appropriate environmental conditions. These fixtures generally include very stiff and well damped interfaces mounted on an isolated granite bench in a room with better than 0.1˚C temperature control. Figure 6 and Figure 7 show a block diagram of the performance test set-up along with an example of a test station utilized to measure 6 DOF.

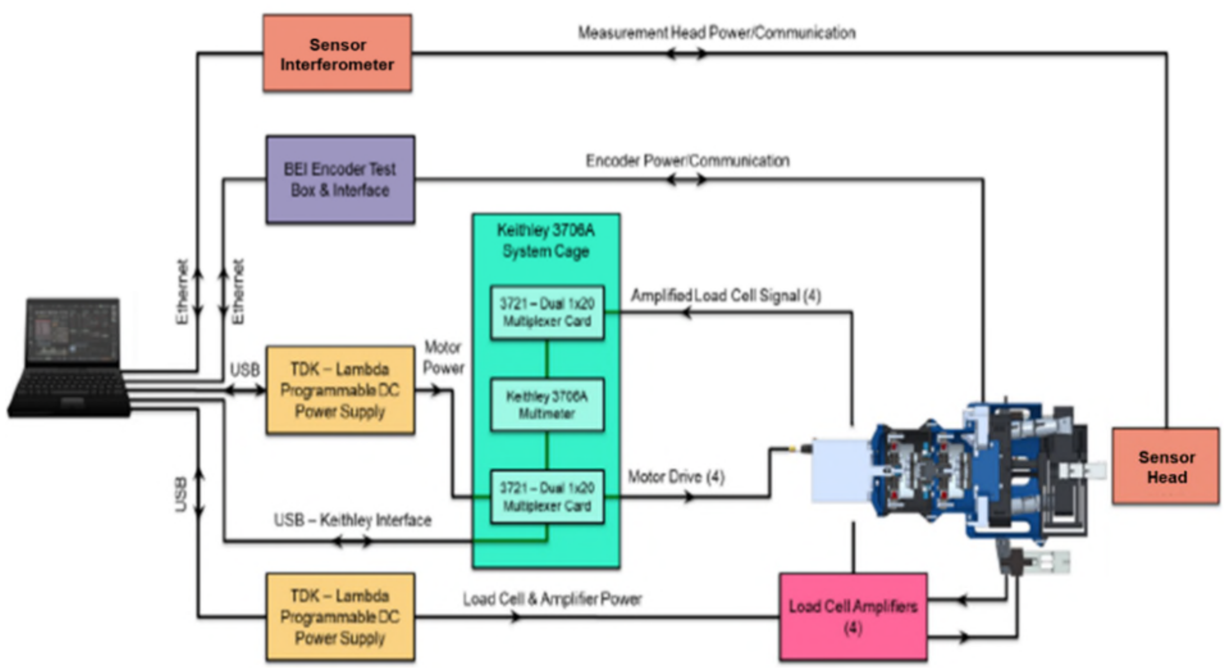

Figure 6. Performance Test Set-Up Block Diagram

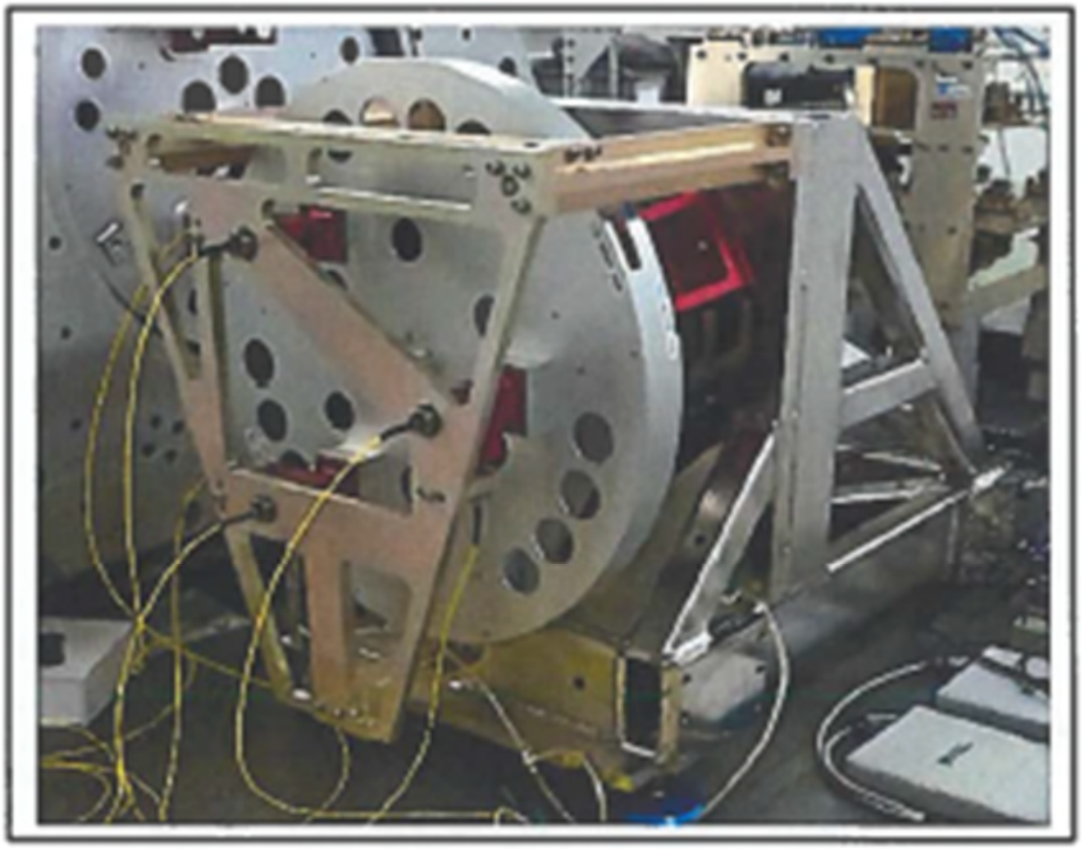

Figure 7. Actuator Performance Test Station Measuring 6 DOF

Actuator Test Results

Table 1 compares design goals to measured test results from the pathfinder high performance pre-production Testbed Actuator, which pushes the state of the art on single-stage flexure-based linear actuation with regards to range and resolution. Subsequent graphs (Figures 8 – 12) provide examples of measured data.

Table 1. TBA Performance Bettered Design Goals for all Requirements.

TBA Performance Parameter	Design Goals	Tested Results	Units
Total Range	≥ ±500	> ±650	µm
Resolution (avg. over range)	≤ 10	6.5	nm
Rate	≥ 700	compliant	nm/sec
Settling Time	≤ 300	compliant	msec
Accuracy	≤ 5	< 3	nm
Backlash over full range	≤ 10	< 3	nm
Hysteresis over full range	≤ 10	< 1	nm
Stepper Motor Torque Margin (per AIAA-S-114A-2020)	≥ 150	compliant	%
1st Mode w/supported mass	≥ 150	compliant	Hz
On-Orbit Life	10	compliant	years
Life Cycles (Full Range)	≥ 10,000	compliant	cycles
Encoder Resolution	≤ 1	< 1	motor step(s)

Non-Linear FEA Output

A non-linear FEA analysis was performed to simulate the input angle from the motor to linear output displacement through the rotary flexure design. The results of the analysis show expected non-uniform step size change about the zero location (the zero location is defined by the initial assembled location). As the input angle increases, the step size decreases in a non-linear fashion until an inflection point is reached where the flexural arrangement effectively causes the step size to go to zero. The reverse direction produces an increase in step size, in a slightly less non-linear fashion as compared to the positive direction, until the maximum displacement is achieved. The maximum displacement is limited by stress, such that a factor of safety of 1.5 on the material yield strength is achieved for the flexural components. The non-linear behavior in step size variation over input angle is due to the cylindrical flexures changing angle with respect to ground. Although the step size is non-linear, the behavior is repeatable and can be characterized during performance testing.

Displacement vs Input Angle test

Figure 8 shows the output data of the Displacement vs. Input Angle test. The graph shows a portion of the test starting at the negative most displacement through the positive most displacement with respect to the zero location. The graph shows a total displacement of the mechanism of 1.4 mm, with a much larger displacement in the negative direction than the positive direction. The non-uniform displacement with respect to the zero location is associated with the non-linear behavior of the actuator.

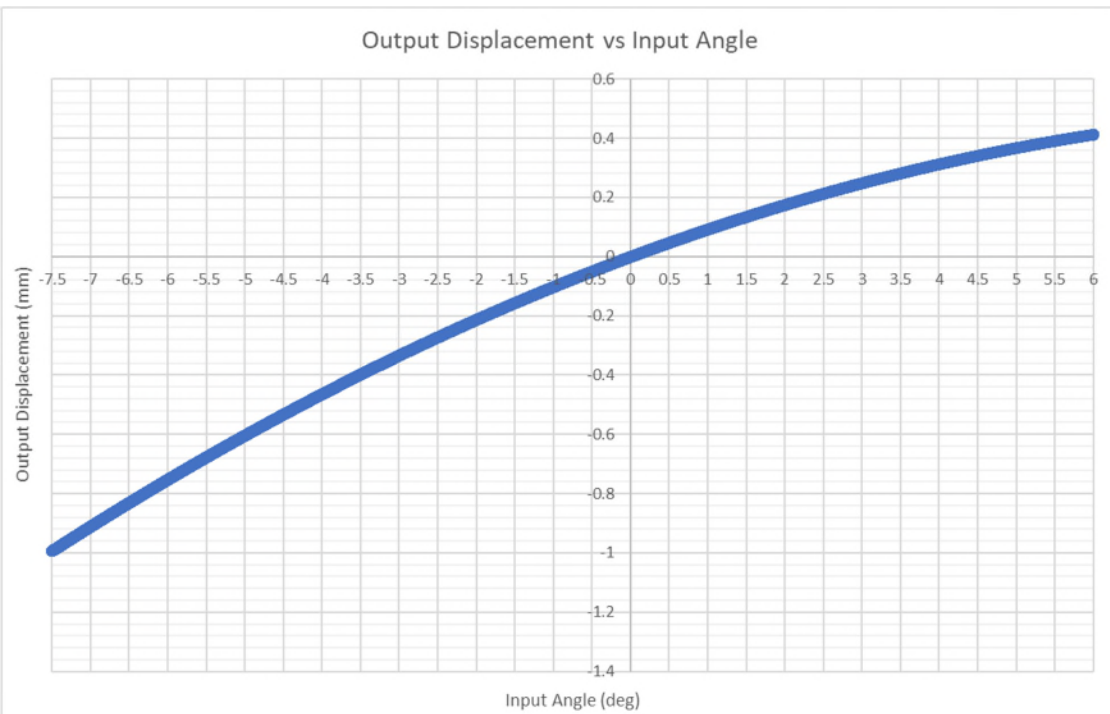

Figure 8. TBA Displacement vs. RLOA Input Angle

Resolution (step size) test

The resolution test shows the step size at the zero location of the mechanism. The test was performed by commanding the mechanism to perform a series of steps in a (+10, -10; -10, +10) pattern. Shown in Figure 9 is a portion of the test. The graph shown is data with the initial ringing of each step removed and the noise in the data removed over the multi-second dwell time. This test shows the average step size at the zero location is 6.8 nm. The steps deviate approximately ±1 nm from the 6.8 nm average over the test.

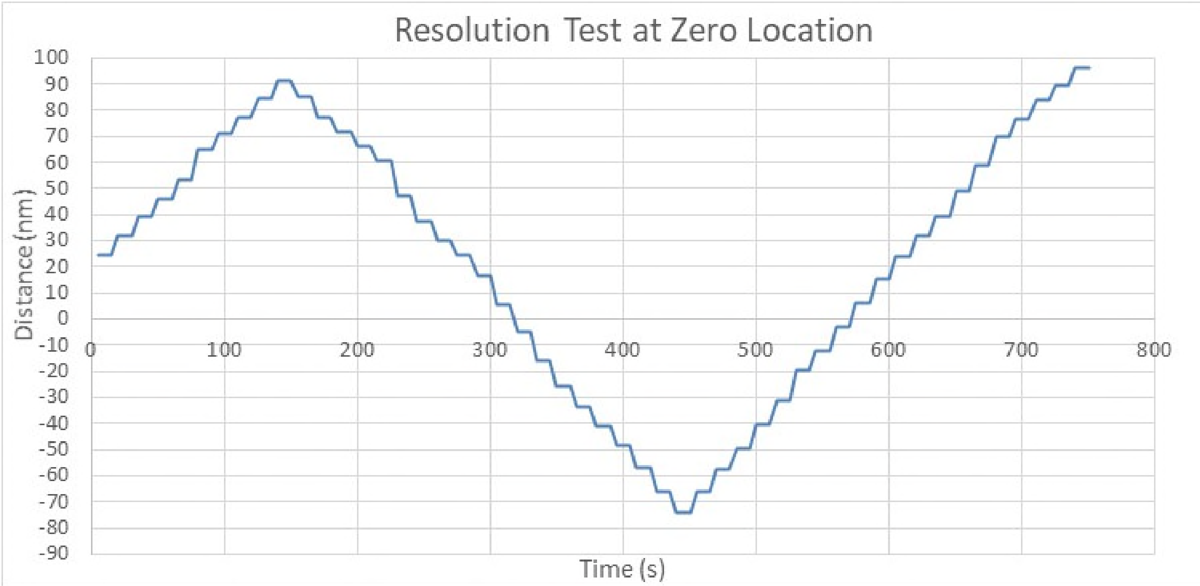

Figure 9. TBA Resolution over Range Data Showing Desired Step Size of 6.8 ± 1 Nanometer.

Step Resolution and Encoder Feedback

Figure 10 shows the encoder feedback (orange dashes) overlayed on the step resolution test. The encoder shows a strong correlation to the measured step size. The encoders ideal resolution is about 52 counts per step of the mechanism. The data shows an encoder deviation of ± 3 counts on average with some outliers being off by 7 counts. At the center of travel, where the step size is approximately 6.8 nm, the average encoder deviation equates to ± 0.4 nm, which is within 6% of the step size. The results of this test show that the encoder strongly correlates to the step resolution of the actuator over the range of the actuator.

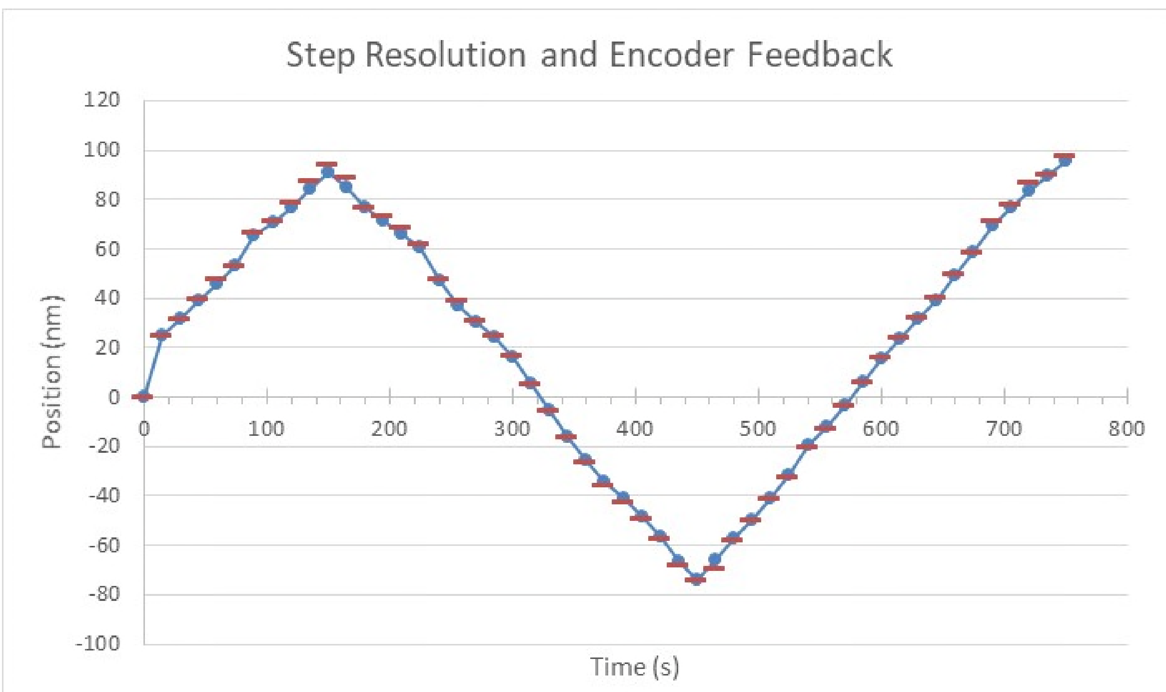

Figure 10. TBA Step Resolution compared to Optical Encoder Data

Hysteresis Test and Backlash Testing

Figure 11 and Figure 12 show the results of the hysteresis and backlash tests. The tests were performed in multiple iterations of positive and negative step transitions to observe what motion was lost due to change in directions. For the hysteresis test, we repeated a ± 40 steps over several ranges. The average loss from reversing direction per step was 0.27 nm. For the backlash testing, we repeatedly changed direction with different numbers of steps before returning to a net 0 step position. After multiple iterations of motion, the total loss of position was 1.7 nm. The step positions for each test, were an average over a multi second dwell at each step.

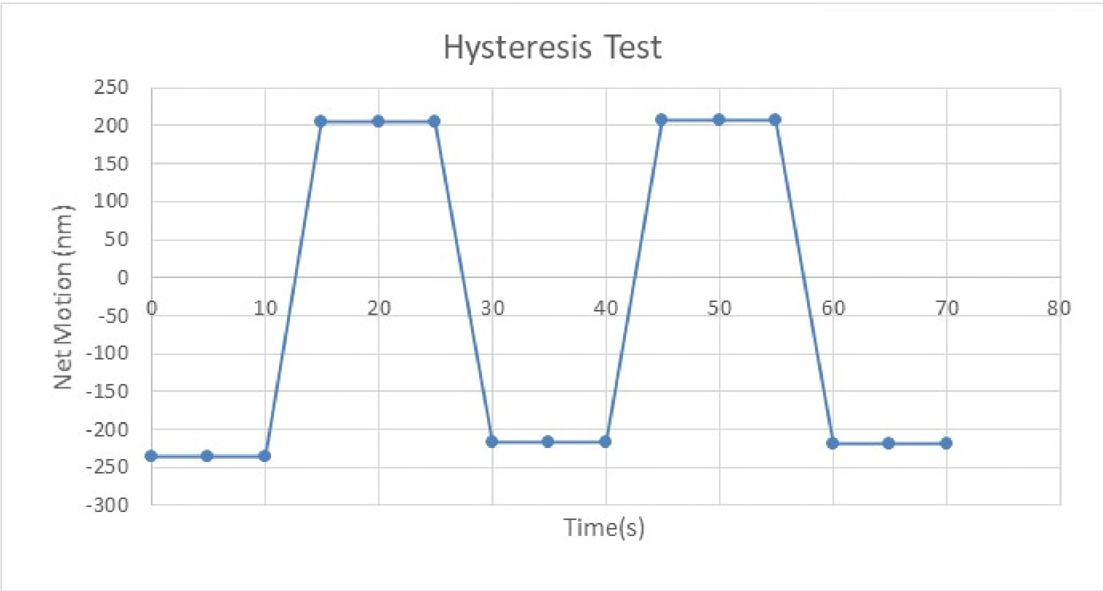

Figure 11. TBA Hysteresis Test Results Show Excellent Performance

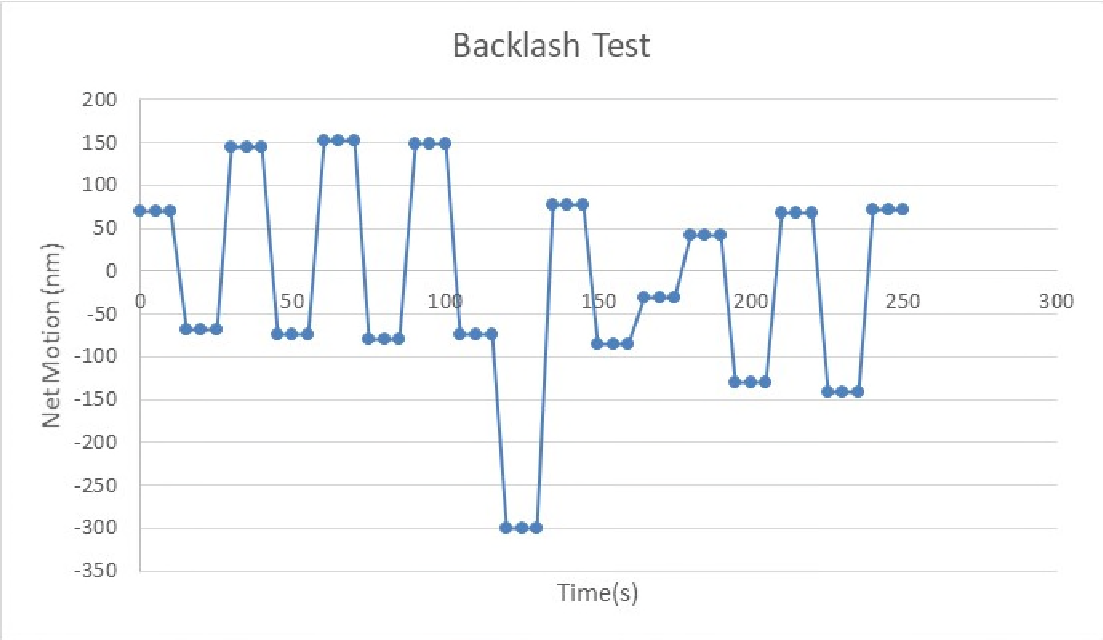

Figure 12. TBA Backlash Test Result Show Near Zero Actuator Backlash

Conclusion

The mechanism performed as expected and made repeatable (to single nanometer) steps. The design and configuration of this actuator provided a plethora of range (1.4 mm of travel) with nanometer level precision. The encoder follows the motion of the mechanism to within 6% of each step taken (resulting in an average encoder deviation of ± 0.4 nm). The backlash and hysteresis tests show there is little to no backlash from the dual stacked harmonic drives and very little hysteresis in the system. The range and resolution of this actuator, in combination with its deterministic and repeatable behavior and stiffness capabilities, has pushed the boundaries and capabilities of what is possible. Going forward we would like to better optimize the center of motion of the mechanism and reduce the change in step size over the range.

References

1. Booker, Jesse W. (2017). *Actuator device and method of converting rotational input to axial output with rotary flexure mechanism*. (US 9787157 B2). United States Patent Office.