Precision Linear Actuator for Space Interferometry Mission (SIM) Siderostat Pointing

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Abstract

"SIM PlanetQuest will exploit the classical measuring tool of astrometry (interferometry) with unprecedented precision to make dramatic advances in many areas of astronomy and astrophysics" (1). In order to obtain interferometric data two large steerable mirrors, or Siderostats, are used to direct starlight into the interferometer. A gimbaled mechanism actuated by linear actuators is chosen to meet the unprecedented pointing and angle tracking requirements of SIM. A group of JPL engineers designed, built, and tested a linear ballscrew actuator capable of performing submicron incremental steps for 10 years of continuous operation. Precise, zero backlash, closed loop pointing control requirements, lead the team to implement a ballscrew actuator with a direct drive DC motor and a precision piezo brake. Motor control commutation using feedback from a precision linear encoder on the ballscrew output produced an unexpected incremental step size of 20 nm over a range of 120 mm, yielding a dynamic range of 6,000,000:1. The results prove linear nanometer positioning requires no gears, levers, or hydraulic converters. Along the way many lessons have been learned and will subsequently be shared.

Introduction

SIM will improve "our understanding of the physical properties of stars, determining the mass, including the dark matter component, and its distribution in our Galaxy, observing the motions of the Milky Way's companions in the Local Group, and probing the behavior of supermassive black holes in other galaxies" (1). Using three interferometers, 1 science and 2 guides, SIM will deliver a dramatically more accurate mapping of our universe as well as a better understanding of the formation and evolution of other planetary systems outside our own. Accurate mapping using interferometers requires high precision actuation, pushing the limit of both the mechanical positioning realm and the electronics/control realms. The required lifetime of SIM is also extremely challenging with a need to meet performance requirements for no less than 5.5 (with a goal of 10) years of continuous science observation. This is approximately 3 million large angle gimbal moves.
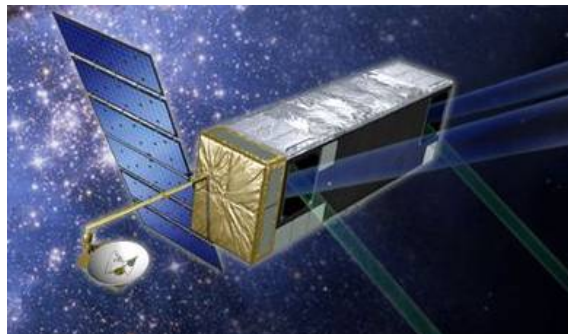

Figure 1: SIM PlanetQuest

While many precision mechanisms are required for SIM to deliver its science data, the Siderostat is the initial pointing mechanism used to direct starlight into the instrument. The Siderostat tips and tilts a 304.5-mm clear aperture optic across a 15-degree Field of Regard (on the sky) via a two-axis hexfoil flexured gimbal mechanism, with a required coarse accuracy of 1arc-second (as) and a fine accuracy of

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5 milli-arc-second (mas) on the sky. Implementing a pair of linear actuators approximately 300 mm from the gimbal axis yields a required linear coarse accuracy of approximately 1 micron and a fine linear accuracy of approximately 5 nanometers. See Figure 2, Potential Siderostat Configurations.
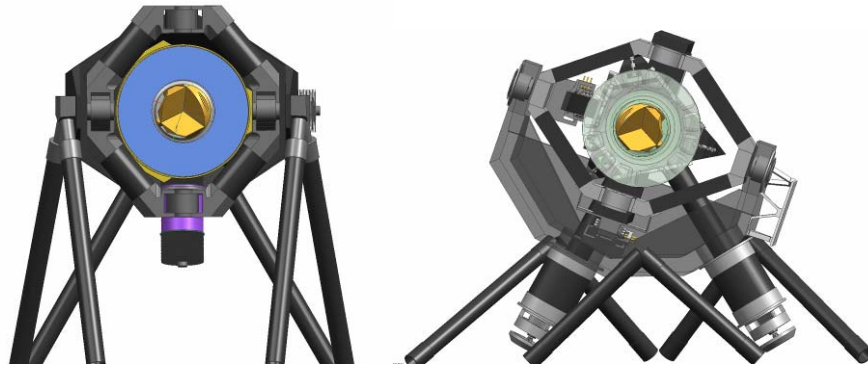

Figure 2: Potential Siderostat Configurations

This paper will discuss the design, build, and test of a linear actuator capable of repeatedly, over long periods of operation, performing submicron positioning maneuvers. The design successfully pushes the limits of mechanical positioning while remaining true to the JPL principles of heritage, simplicity, and robustness. Along the way interesting lessons were learned and will be put forth for the reader's benefit.

Mechanical Design

Generally speaking, design is a continuous balancing act to meet competing requirements. It requires the designer/engineer to carefully balance the design process between many conflicting requirements. In actuator design, if mutually exclusive positioning requirements are equally important a two-stage mechanism is often the solution. Unfortunately, multiple stages add to complexity, mass and cost. In our design, the need for large fast moves, trump the needs for fine positioning, and vice versa. It was originally thought that no single actuator could meet the large stroke, high speed, small incremental step size (actuator resolution), required by the Siderostat. The original intention of our Precision Linear Actuator, Direct Drive (PLADD) was to fill the role of a coarse actuator.

The design approach taken with PLADD is one of simplicity, heritage, and robustness. The initial design required at least 2000 incremental positions per revolution of the nut/motor in order to obtain a linear incremental step size of 1 micron. Figure 3 shows a cross section of the actuator.
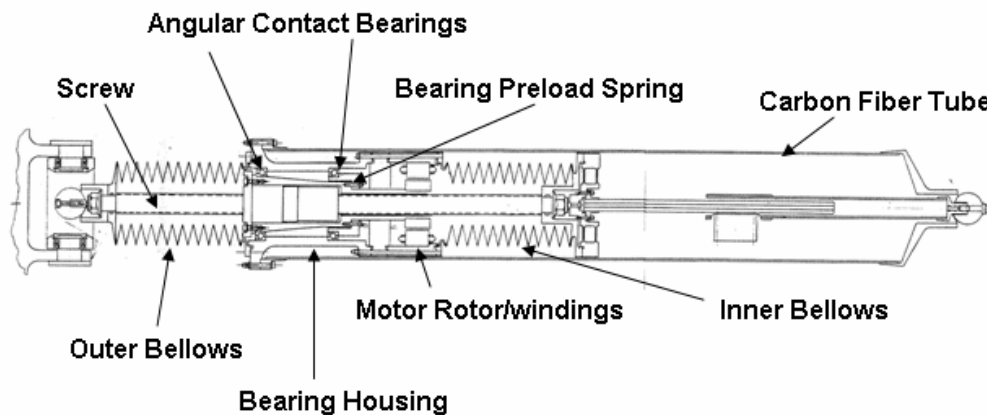
Figure 3: SID PLADD Cross Section View

The bearing housing, as shown in Figure 4, is the center of the actuator, housing the back-to-back duplex angular contact bearings, brake, and motor. Both sets of bellows are suspended from the bearing housing, while the housing bolts directly to the carbon fiber outer tube for thermal stability.
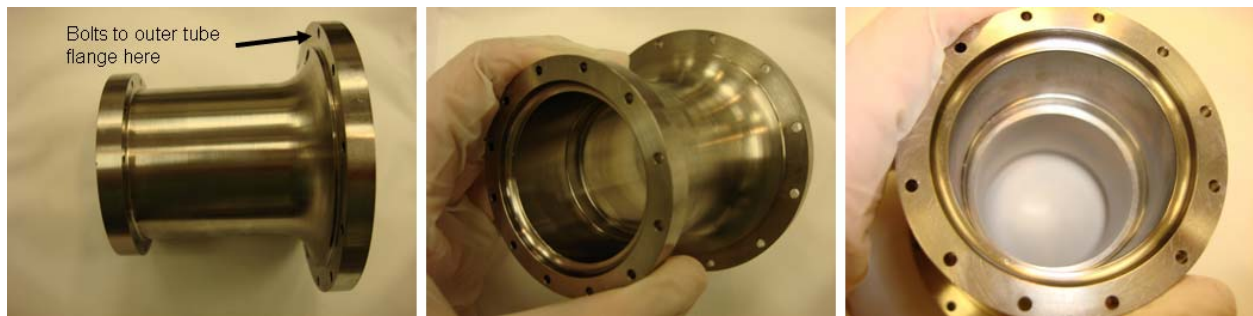
Figure 4: Bearing Housing

The angular contact bearings are assembled into the bearing housing from opposing ends of the housing. The housing is stepped, creating a bearing spacer against which the bearings can be preloaded. The bearings are thin section MPB (Miniature Precision Bearings) angular contact ball bearings with a phenolic retainer ball spacer. The bearings have 440C balls and races. The bearings are shown in Figure 5.

Figure 5: Timken MPB Angular Contact Ball Bearing

The bearing inner races are mated to the motor drive link. As depicted in Figure 6, the inner race of the inner bearing seats on a non-sliding preload flexure. The DC brushless motor rotor is assembled to the rear of the drive link via set screws. The ballnut is mounted to the front of the drivelink via bolts.

Figure 6: Bearing Preload Flexure and Rotor mounted to Drive Link

The motor is coupled to the NSK ballnut by way of an in-house designed and built drive link. The drive link is shown in Figure 7.

The complexity of the mechanism is reduced and backlash of a gear train is eliminated via a direct drive approach. By eliminating mechanical backlash in the actuator the control system is able to actively eliminate any mechanical imperfections in the actuator using feedback from the linear glass scale

encoder mounted to the actuators' output. The direct drive approach also greatly simplifies manufacturing and assembly of the actuator by lowering part count and complexity.

Figure 7: Motor Drive Link

The heart of the actuator is a 12-mm diameter, 2-mm lead, NSK ballscrew mounted onto an NSK Double nut utilizing a spring preload of 130 newtons. The combination can be seen in Figure 8.

Figure 8: NSK Ballnut

The ballnut is connected directly to the drive link via 8 bolts.

Figure 9: Ballnut bolted to Drive Link

The ballnut drive link combination is assembled into the bearing housing with the angular contact bearings, preload flexure, and finally the piezo brake as pictured in Figure 10.

Figure 10: Housing Assembly

The piezo brake consists of a set of flexured levers, preload springs, and guide flexures machined out of a single piece of titanium. The drive-link is radially compressed by the machined springs upon power-off. This constrains the drive link, and thus the ballnut, in rotation. The power must be applied in order to release the brake. The braking force is applied by the compressed preload springs via a wedged preload shim. The preload force is eliminated by the application of power to the piezo stacks.


Figure 11: Piezo Brake

The actuators' driving torque is delivered via an off the shelf DC brushless motor from BEI/Kimco Magnetics as pictured below.
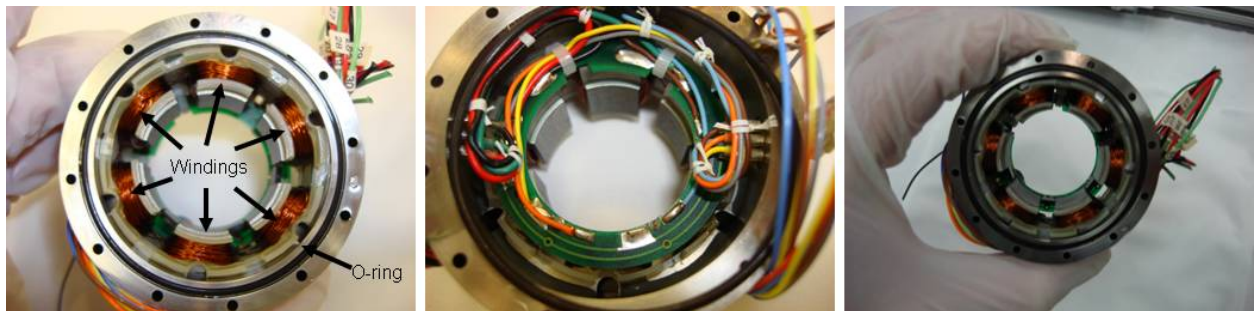

Figure 12: BEI DC Brushless Motor

Long life requirements along with a high correlation between lubricant consumption and life limitation led the team to immerse the mechanical drivetrain of PLADD in oil via a set of hermetically sealed bellows mounted to each end of the ballscrew. The bellows create a constant volume to house Brayco 815Z oil, and subjects the mechanical system to a continuous oil flush. The bellows additionally are used to hold the screw in rotation, thus allowing the rotating ballnut to produce linear motion at the screw. The continuous motion of oil through the mechanical system is conjectured to eliminate many failure modes. This hypothesis is being tested via life tests that are in progress.

The motor windings, piezo brake, and inner bellows are bolted to the outer housing via thru bolts.
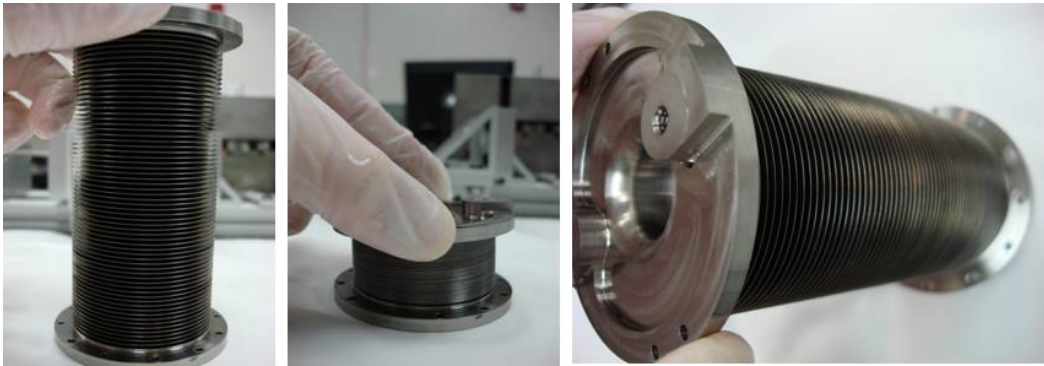
Figure 13: Inner Titanium Bellows
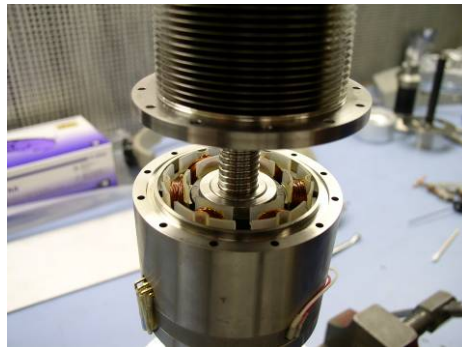
Figure 14: Motor Windings Mounted

A MicroE linear glass scale is connected to the end screw via a set of parallel motion flexures. These flexures provide a thermally stable mount for the glass scale via a low CTE metering rod. The scale is allowed to float relative to the inner tip of the ballscrew, minimizing the coupling of thermal drifts in the parts of the actuator not in the position path. The use of metering rods helps minimize false delta readings at the sensor head. The glass scale is mounted on a carbon fiber rectangular rod. A dummy glass scale is mounted opposite the operating scale to help eliminate bending in the scale due to changes in bulk temperature.
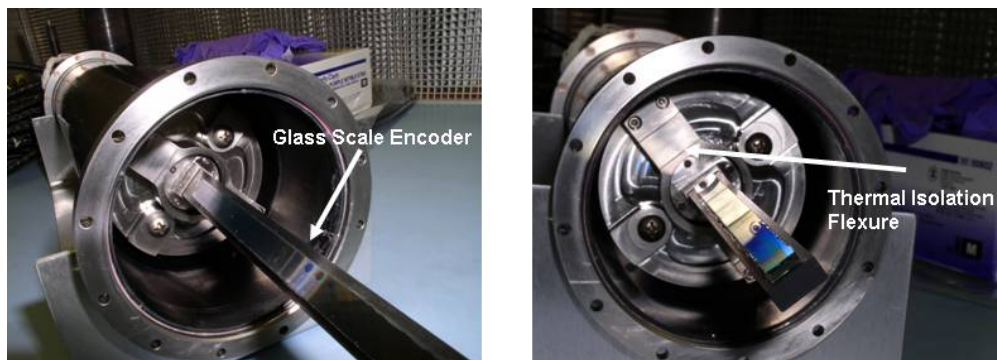
Figure 15: Glass Scale Encoder Mount via Flexures

The sensor head is mounted via a set of parallel motion flexures and the composite tube that acts as a metering rod. This completes the thermally stable sensor mount.
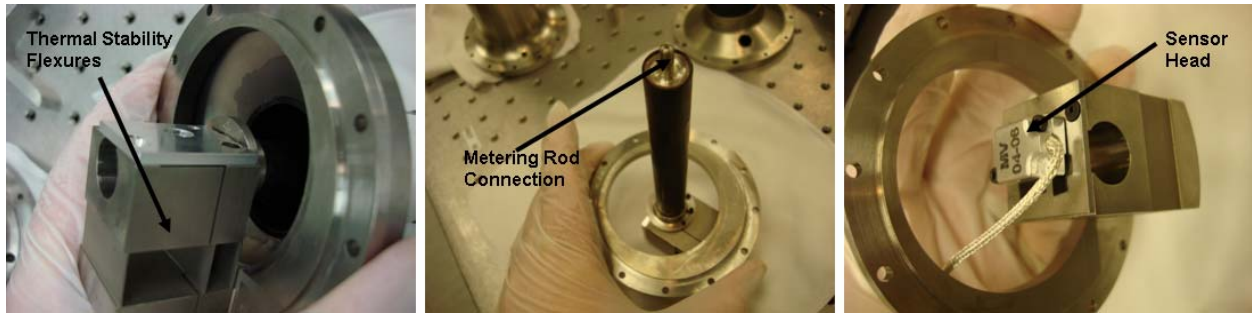
Figure 16: Sensor Mount

All component alignment is achieved via sets of self aligning slip fit radial diameter lips between mating parts. All components are thus axially self aligning to within the tolerances of the slip fits. O-rings are used at all interfaces to eliminate oil leaks.

The actuator connects to ground via a coaxial orthogonal flexure blade flange. The metering rods are hard mounted to each end joint.

Figure 17: Flexured End Joint

Results

The initial resolution requirements for the ballscrew actuator was ±1 micron which was not clearly achievable based on vendor data for ballscrew position as a function of rotation angle. The selection of the Micro-E linear encoder capable of 5-nm position feedback was expected to give position sensing feedback well beyond that which was needed to determine the limits of ballscrew positionability. The direct drive architecture and a preloaded ballnut minimized actuator windup and backlash that enabled maximal position control. Additionally, rather than control the motor commutation based solely on the hall effect sensor as with typical motor control schemes the team also utilized the output sensor data. Since a 3-phase DC brushless motor is being driven, a PID controller reads the linear encoder and outputs 3-phased sinusoidal voltage commands to the 3 motor windings.

Typical trapezoidal commutation uses only the Hall Effect sensors to apply the voltages in a rough way (24 steps per motor rotation). These 3 discrete sensors decode to 6 distinct points per pole, and since there are 4 poles per motor revolution that provides 24 points per revolution. Sinusoidal commutation makes use of the encoder data to fill in the gaps between the Hall Effect transitions and increase the points per revolution from 24 to 409,600. This allows the sinusoidal shape of the back-EMF waveform to be matched much more precisely.

The geometry of the motor is such that sinusoidal commutation converts all of the applied current into useful torque (in the ideal case), rather than into undesirable radial forces. Since all the current is being converted into torque, the variation in torque is minimized and thus torque ripple is reduced compared to

trapezoidal commutation. This is critical for the SIM project because torque ripple induces excess vibrations in the structure that affect other sensitive components of the interferometer.

The results of this architecture were surprising! The PID control loop utilizes 4 position sensor steps to start and stop the screw resulting in repeatable incremental step sizes of 20 nm! This means the DC brushless motor has to be capable of positioning to 100,000 distinct points around a revolution and the mechanical imperfections are beneath the control loop sensitivity. Furthermore, PLADD is able to track a prescribed profile over its entire range with a lag of approximately 16 ± 1.5 microns. However, with correct sequencing or control logic PLADD has an effective positional tracking error of ~3 microns peak to peak at a rate of approximately 3 mm/sec. Below is a short review of the results for a 10-mm move, a 1-micron move, and a 20-nm move. Also included is a discussion of the precision piezo brake effects, future work/improvements, and lessons learned.
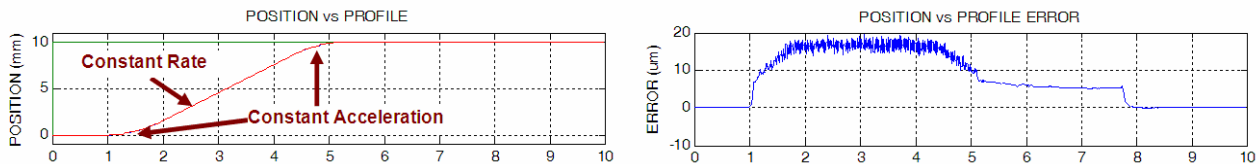
10-mm Slew-Nominal Gains
Nominal gains are the gains chosen for well-rounded performance characteristics for a given move size. There is a nominal set of gains for both high resolution (less than 1 micron) moves and low resolution (greater than 1 micron) moves. The nominal gains were set based entirely by trial and error, and are thus not necessarily optimal in any specific sense.

Encoder resolution is increased for moves larger than 1 micron, down to 80 nm due to 22-bit electronics counting limitation. The electronics limitation is a designed in counter size on the FPGA that was not realized to be problematic until late in the build. It is in no way related to the commonly discussed 14-bit analog noise floor in most space electronics. This allows PLADD to cover the entire 120-mm range regardless of the initial zero point location chosen by the operator.

PLADD is able to track a prescribed profile over its entire range with a lag of approximately 16 ± 1.5 microns. However, with correct sequencing or control logic PLADD has an effective positional tracking error of ~3 microns peak to peak at a rate of approximately 3 mm/sec.

In Figure 18, the position command profile is created using constant acceleration to get up to speed, constant velocity for the main portion of the slew, and constant deceleration to approach the command position.

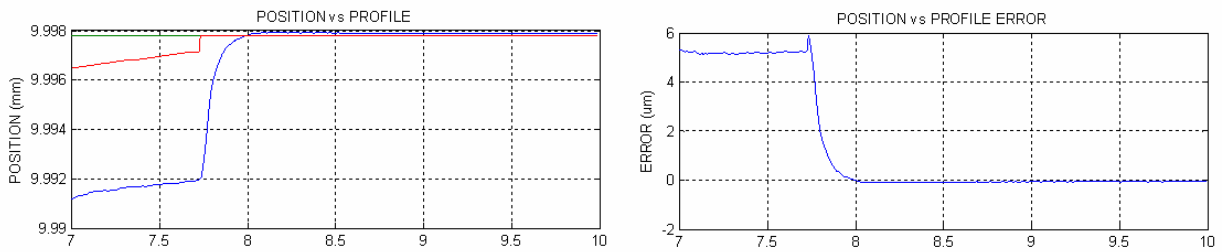**Figure 18: 10-mm Slew (Nominal Gains) - Entire Move**

Figure 19 highlights the 16 micron lag during the constant velocity portion of the slew. It also shows the ~3 um error, peak to peak about the 16 micron offset. The sinusoidal commutation is also clearly displayed in this view.
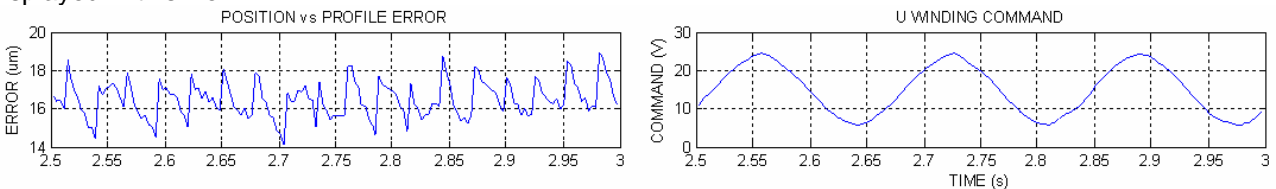
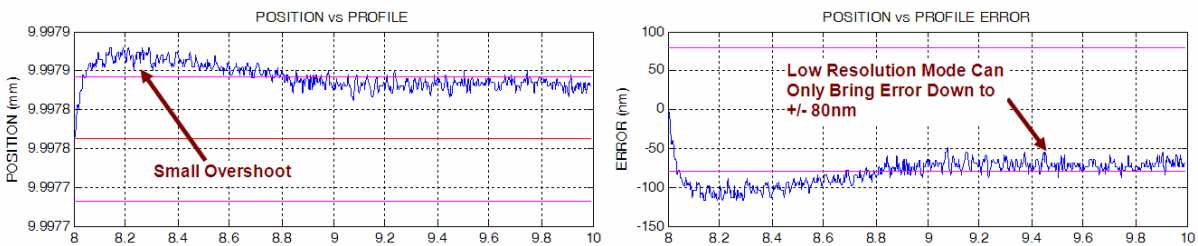**Figure 19: 10 mm Slew (Nominal Gains) - During Slew**

Figure 20 illustrates the end of the slew and the initiation of the integral gain to reduce the steady-state error. The proportional gain primarily contributes to slew performance. However, it can only reduce the error down to ~5 um using the nominal gain value. Once within this 5-micron zone the controller's integral term integrates the error and creates the final step to its commanded position.

Figure 20: 10-mm Slew (Nominal Gains) -End of Slew

Finally, Figure 21 shows the final result of the integral action. There is a small overshoot, which is then reduced to within ±80 nm of the command position. This is the limit of the capability of low-resolution mode, since the PID controller does not see any motion less than 80 nm (due to the previously discussed 22-bit legacy hardware limitation). The actuator could now be commanded with a new set of high-resolution gains allowing the zeroing in of the actuator down to ±5 nm of the commanded position. It is important to note that for large moves, although the actuator can move to within ±5 nm of the commanded position, in reality the overall accuracy of the move is affected by many other contributors, and are not discussed in this paper. The contributors can be, but are not limited to, thermal drifts in the unmeasured structure during the move, grating accuracy of the glass scale, and inter-grating accuracy. Large move accuracies are extremely complex comprising many error sources and are beyond the scope of this paper.
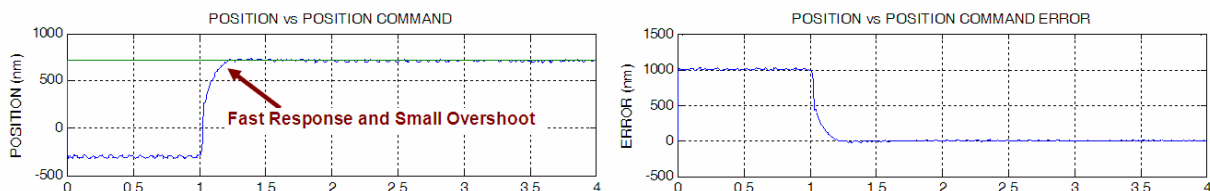

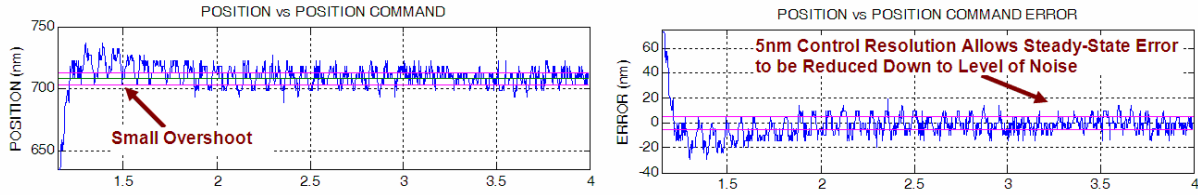**Figure 21: 10-mm Slew (Nominal Gains) - Steady-state Error**

1-Micron Step-Nominal Gains
Full encoder resolution of 5 nm can be used for small moves of less than 20 mm. However, actuator velocity requirements generally lead to the use of high-resolution mode for moves only less than 1 micron. Using a different control resolution changes the scaling of the PID controller and thus a different set of gains are used in high-resolution mode versus the low-resolution mode used for large slews.

Figure 22 shows a 1-um move using nominal gains. Figure 23 focuses in on the last part of the move to show the steady-state error. The nominal gains provide a fast response with minimal overshoot. The steady-state error is improved over the low-resolution mode because the PID controller is able to respond to deviations from the commanded position as small as 5 nm. The background noise in the plot will be further addressed in the Noise and Vibration section of this paper.

**Figure 22: 1-um Step (Nominal Gains) - Entire Move**

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Figure 23: 1-um Step (Nominal Gains) - Steady-state Error

<u>20-Nanometer Step-Nominal Gains</u>
Due to a 4X minimum encoder resolution command limitation within the control system (a legacy piece of hardware originally intended for another use) 20 nm is the smallest incremental step that can be taken. The following series of plots will show 20-nm steps using the same nominal gains as the 1-um steps.

Figure 24 displays a 20-nm move. Overshoot is non-existent, with a move time of roughly one second. At this nanometer level of position control, the noise of the encoder position signal is significant. It has a noise of approximately ±5 to ±10 nm, with occasional spikes of ±20 nm. The nature of this noise is not fully understood, but is conjectured to be from a combination of mechanical (background vibration) and electrical (sensor and wiring noise) sources. Environmental noise and its potential elimination are discussed in the Noise and Vibration, Future Work, and Lessons Learned sections of this paper.
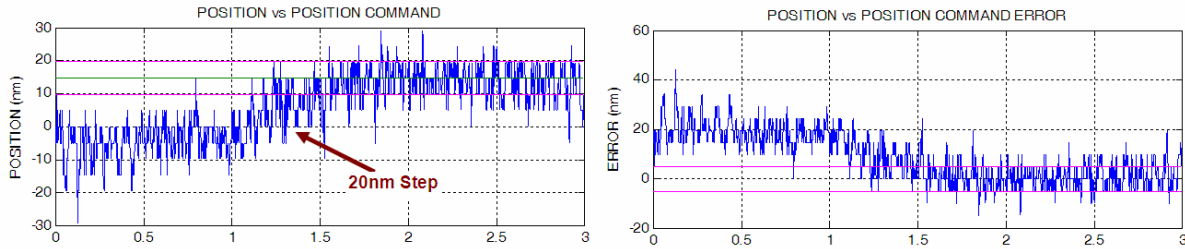

Figure 24: 20-nm Step (nominal Gains)

<u>Noise and Vibration</u>
Nanometer level work requires an extremely quite environment. Vibration and external noise sources can greatly affect test results. All test data was taken in Bldg 318 (Space Interferometry Test Lab), which is specifically designed to be a low noise test facility. The test was performed on an air table separated from the building via an isolation pad. In order to better understand the test noise environment, we sampled 1 second of high rate position data (approx. 1240 samples/second) with no power applied to the actuator. The measurement below is unfiltered data. It is clear that there is a noise disturbance identical to the noise seen when the actuator reaches its commanded position at steady state. This suggests that the noise seen in our position graphs is either environmental mechanical or the electrical noise of the sensor.
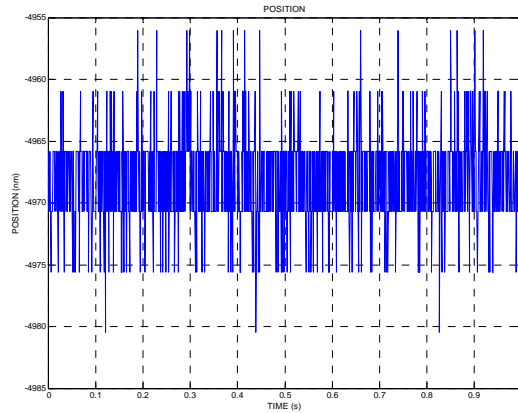
Figure 25: Vibration Measurement - Test Environment and Sensor Noise

Figure 26 shows a 30-point moving average of the steady state error of the actuator with the actuator powered on and attempting to hold a position. Averaging decreases the steady-state error down to ±4nm. The average position is -0.2 nm with a standard deviation of 1.14 nm.
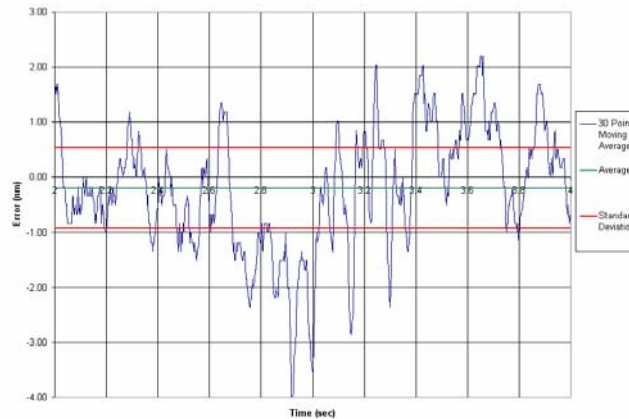

Figure 26: Steady State Error, 30-Point Moving Average

Piezo-Brake Effect

Creating a brake for an actuator performing nanometer size moves is not an easy job. In order to achieve high braking forces, PLADD is equipped with a piezo-actuated brake mechanism. This is required in a coarse stage/fine stage configuration where the coarse stage is turned off and locked while the fine stage operates. A brake is also a necessity when the actuator moves periodically. Through the use of a custom piezo brake and correct power shut off sequencing, the SID team was able to brake the actuator with minimum disturbance. The correct sequencing of the brake and actuator control power off must be performed in order to achieve the best results.

Figure 27 shows a 200-nm step at one second with the brake engaged at the third second. Since the PID controller remains on during the slow braking, it recognizes and corrects for the brake-induced drift, bringing the actuator back to its commanded position. At the ninth second, the power is removed from the motor.

The current brake design degrades the relative accuracy of the move and also requires much longer times to reach a position and stop. The SID team believes that some design alterations could create a brake with much less induced drift. Also, if the actuator were to be used as a fine actuator it could potentially always be powered on, thus requiring no brake.

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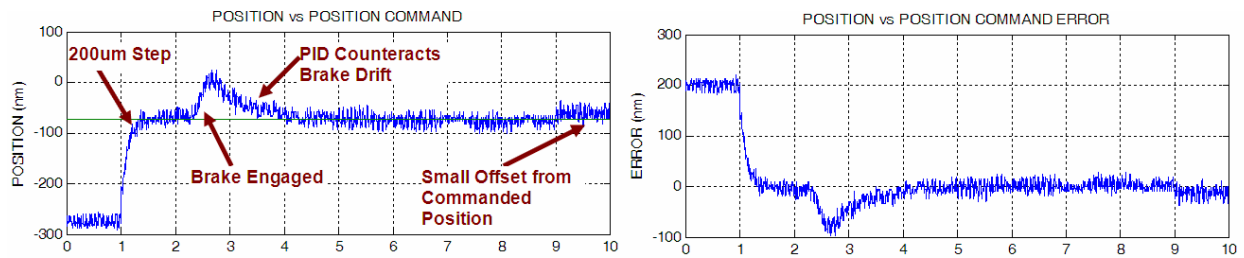
Figure 27: Brake Test (Good Sequencing)

Future Work

To potentially reduce the incremental step size of PLADD down into the 2-5 nm range, we plan on taking the following steps:

Mechanical Modifications

MicroE Mercury II Encoder—Micro E recently introduced its next generation Mercury II encoder capable of obtaining 1.2-nm LSB. Installing this improved read head would allow the controller to attempt moves as small as 4.8 nm.

Mechanical Disturbance Isolation—While the current test setup utilizes an extremely quiet building, an isolation pad, and an air table there are potentially further layers of isolation that could be added to the test setup. Potential gain can be had by installing an isolation layer of foam padding between the test fixture and the table. The row of actuators is also currently mounted along one edge of the air table.

Control Modifications

PLADD's control logic is derived from code developed by JPL's Ted Kopf for the Mars Exploration Rovers. Many elements of the code can potentially be improved to optimize PLADD's performance. The following is a list of potential adjustments.

Filter Encoder Count—The value read from the encoder has high frequency noise of +/- several bits. Currently, this value goes directly into the PID controller. Placing a filter in front of the controller would clean up the signal so that the PID command does not react to small noise variations. This could improve performance for very small step sizes.

Adjust Rate Filter—There is already a filter inside of the PID controller on the internally generated rate signal. However, the time constant of this filter was set for an entirely different application (MER motor control) that used very different encoders. Adjusting this filter could help make the derivative gain useful for this application.

Adjust Controller Scaling—The PID controller scaling was set for a very different application (MER motor control) and is not ideal for the SID ballscrew. Adjusting this scaling could result in performance benefits due to finer tuning of the PID gains.

Add Bits to PID Controller Position Value—The PID controller currently uses 22 bits for the position value. For this application, the limited number of bits forces a choice between high resolution and large range. Increasing the bits allocated for the position value would allow high resolution control over the entire ballscrew range. This modification is tied in with the scaling modification listed above, as the scaling is effected by the number of bits.

Control Down to Encoder LSB—The PID controller does not allow delta position commands less than 4x the encoder resolution. It might be worth investigating the reason for this in detail to figure out if it is feasible to remove that limitation. The idea is to find out just how far down we can push the incremental command resolution.

Reduce Encoder Noise—The encoder noise is probably due to a combination of mechanical and electrical sources. Investigation into the nature of this noise might lead to ways to reduce it. One idea is to improve the shielding of the cable between the encoder read head and the encoder interpolation module. This cable transmits sensitive analog signals that are susceptible to noise.

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Gain Calibration—By calibrating gains for many different move sizes and adjusting the command software to generate such commands on a per move basis PLADD could improve many performance parameters such as response time, overshoot, lag, etc.

Lessons Learned

1. **Nanometers are really, really small.**
When working in small numbers it is easy to forget how small nanometers truly are. In real life mechanical terms a nanometer is approximately 1/50,000 of the diameter of a human hair. When dealing with numbers of this size, deflections of mechanical components can play a large role in performance. Movements may not be actual position changes, like one is familiar with, but instead a "wind up" or deflection of the mechanical components in the drive-train. A well-designed system should minimize these effects. The remaining system deflections can be actively eliminated by employing an encoder in a location such that it measures the output of the actuator that one is interested in controlling. Also, environmental noises, especially when not in a "quite" building may completely overwhelm any experimental results

2. **Nanometer incremental step size is achievable with no gears, levers, or hydraulic reducers.**
This one speaks for itself. It also was something I never expected possible.

3. **Sensor technology is the limiting factor for fine positioning when proper mechanical design considerations are taken.**
Sensor technology is a fast growing field. As the sensor technology progresses one should not hesitate to take advantage of technology. This especially applies to space-flight applications where a fear of the unknown can often be crippling, especially when attempting to actuate mechanisms with finer resolutions and more precision.

4. **A clear path for oil circulation/pumping shall be designed into the system to avoid excessive driving loads.**
In designing our actuator a clear path for the oil to pass was not considered. Upon complete assembly and operation it was discovered that much of our reserve torque was required to force the oil lubricant through the motor, screw, nut, bearing assembly. This leads to a reduced maximum velocity and an increased input of heat into to the actuator under continuous operation.

5. **Full alignment adjustability makes everyone's job easier. Access to the sensor without disassembly is vital to technician (or assembling engineers') sanity.**
The actuator's design requires that the sensor is housed inside a carbon fiber tube. The sensor cannot be tested for functionality or alignment until the actuator is assembled. There is also no way to easily adjust the sensor once it is determined it is not aligned properly (inevitable, as it is practically impossible to blind assemble the sensor in perfect alignment). This requires that the actuator be slightly disassembled, shims guessed on based on previous experience and the whole procedure repeated. This can be extremely frustrating and time consuming. This problem may be eliminated as sensor technology improves and alignment tolerances grow. However, until then be sure to design in alignment adjustability and allow for active alignment post-assembly.

6. **Instrument thin section bearing should be used with caution as they are extremely easy to damage.**
We ran into a few issues with the handling of the thin section bearings during disassembly of the actuators. More than one bearing was lost as a result of improper handling by technicians. Take caution with your technician choice and your handling procedures.

7. **Obtain external mechanical noise measurements to isolate electronics noise and environment noise.**
If external sensors are not used to measure the mechanical environmental noise it is impossible to troubleshoot noise issues between the mechanical and electrical systems. The use of a local mechanical

noise sensor can help in this process greatly. This is something we did not foresee, and thus we are still uncertain as to the root of our environmental noises.

8**. Be aware that bellows buckle in proportion to their linear stiffness. Be cautious when using them to react torque over a large stroke.**
PLADD's design uses titanium bellows to react out the rotational torque in the screw. Our bellows are extremely soft as they must travel 120 mm full stroke. The first buckling mode of the bellows occurs when a torque is applied. The bellows collapse down as it buckles. The torque required to induce buckling is directly related to the linear stiffness of the bellows. This phenomenon was ignored during design. Fortunately our actuator works at the bitter edge of buckling, but does not buckle. Rotational alignment of the bellows is also critical to buckling, as a misalignment, or initial rotational load lowers the buckling torque drastically.

Conclusion

The SIM Siderostat team successfully outperformed our initial goal of less than 1-micron repeatable incremental step size by a factor of 50. We strongly believe we will attain incremental step sizes of 2-5 nm for large ranges given the current sensor technology. Through the elimination of gears and their inherent backlash we have been able to show that the mechanical system is not the limiting factor in fine positioning applications, if appropriate design considerations are taken into account. We have realized that sensor technology more than any other factor is the limiter with regards to fine positioning over large ranges. We hope to be able to further develop this novel linear actuator concept and to eventually use it on SIM in our PLANETQUEST, and many other future projects.

Acknowledgements

References

[1] Edberg, Stephen J, "SIM PlanetQuest: A Mission for Astrophysics and Planet Finding", NASA/JPL White Paper, May 2005
[2] Koenig, John, "SIM Siderostat Ballscrew Testbed Electronics Report", JPL, Feb 2007
[3] Moore, Don, "Actuator Logs and Assembly Notes", JPL, 1999