Use and Advantages of Direct-Drive Brushless DC Actuators for Precision Instrument Pointing of the Total and Spectral Solar Irradiance Sensor

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Abstract

This paper describes the use of direct-drive brushless direct current (BLDC) actuators for precision solar pointing of the Total and Spectral Solar Irradiance Sensor (TSIS) instrument that is currently flying on the International Space Station (ISS). Advantages of direct-drive BLDC actuators compared to stepper-based actuators are described with an emphasis on the ability to provide excellent disturbance attenuation to base motion jitter. Lessons learned from incorporating direct-drive BLDC actuators into the TSIS system are presented to provide a context of the challenges that are associated with this technology. Finally, measured results from ground testing and on-orbit solar tracking are presented that demonstrate superior pointing performance compared to stepper-based actuators with solar tracking errors of less than 4 arcseconds 1σ per axis.

TSIS Instrument

TSIS is a NASA instrument designed, built, and operated by the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado that continues the 39-year-long record of total solar irradiance (TSI) and 14-year-long record of spectral solar irradiance (SSI) [1]. Both TSI and SSI are critical to long-term climate monitoring. TSI is measured by the Total Irradiance Monitor (TIM), and SSI is measured by the Spectral Irradiance Monitor (SIM). These two sensors comprise the TSIS instrument along with the pointing system that will be discussed in this paper.

TSIS was launched to the International Space Station (ISS) on December 15, 2017 aboard a SpaceX Falcon 9 rocket in the Dragon trunk. It was then installed on the zenith side of the ISS at Site 5 of Express Logistics Carrier (ELC) 3 as shown in Figure 1. After robotic arm installation, the TSIS deployment system rotated the gimbaled instrument suite into its operational position above the ELC. TSIS’s operational position above the ELC allows for a hemispherical view of the sky and solar viewing every orbit during its 5-year mission.

In order to perform solar measurements, TSIS must be pointed directly at the sun with less than 0.017 deg (60 arcseconds) 1σ precision while subject to movement by the nadir-pointed ISS. To decouple the TSIS instruments from ISS motion, the Thermal Pointing System (TPS) was developed. The TPS provides both thermal and pointing control for the TSIS scientific sensors; however, this paper is only concerned with the pointing aspects of the TPS.

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Proceedings of the 44th Aerospace Mechanisms Symposium, NASA Glenn Research Center, May 16-18, 2018
TPS Hardware Configuration
The heart of the TPS is a two-axis, elevation over azimuth gimbal that points the instrument optical bench (including the SIM and TIM sensors) relative to the TSIS base plate as shown in Figure 2. The optical bench dimensions are 1.0-m wide by 0.9-m deep by 0.38-m tall with a moving mass of 83 kg and a rotational inertia of 10.2 kg\(\cdot\)m\(^2\) about the azimuth axis and 3.8 kg\(\cdot\)m\(^2\) about the elevation axis. BLDC actuators are used for both rotational axes and consist of the following key components: BLDC direct-drive motors, 2-speed (1x, 16x) resolvers, brakes, twist capsules for signal/power feed-thru, and output duplex pair bearings. The TPS has a dedicated control electronics box that includes the drive electronics, a flight computer, power handling, and interfaces to the various TPS actuators and sensors. For closed-loop pointing control with respect to the sun, the TPS has redundant High-rate Fine Sun Sensors (HFSS) that are mounted on the optical bench near the TIM and SIM sensors. Finally, as already mentioned, the TPS includes a deployment system that rotates the optical bench to its operational position and holds it rigidly in place. Incidentally, the primary deployment actuator was derived directly from the NICER DAPS actuator that is also flying on the ISS [2].
Gimbal Motion Profile
TSIS follows approximately the same motion profile every orbit as shown by the example flight data in Figure 3. The azimuth axis provides the primary motion of the gimbal over the course of the orbit as it tracks the sun overhead from sunrise to sunset from +110 to -110 deg at a rate of approximately 4 deg/min. The elevation axis accounts primarily for variations in the solar beta angle that varies periodically every 60 days with annual maxima/minima of ±75 deg. Additionally, both axes account for motion due to static and dynamic offsets of the ISS flight attitude relative to the Local Vertical-Local Horizontal reference frame. Also, the TPS points to zenith during every eclipse to support dark space measurements.

ISS Jitter Environment
When TSIS was directed in 2014 to fly on the ISS, the ISS disturbance environment was poorly understood from a pointing perspective, which led to significant uncertainty in the effect that base motion-induced jitter
would have on TSIS pointing. In particular, very little information was available about ISS jitter and most of it focused on ISS vibration as it related to structural safety at non-ELC locations and not to pointing performance for external payloads on ELCs. The few payload studies that did exist attempted to apply translational acceleration measurements across the ISS structure in order to estimate angular jitter on the ELCs, and these estimates were near or close to the TSIS maximum allowable jitter. Additionally, due to the large physical scale and dynamic configuration of payloads, modules, and visiting vehicles, past predictions and measurements may differ or change spatially depending on mounting location and temporally as the station configuration evolves. Finally, it became clear that no procedural mechanism existed (or will exist) to manage ISS jitter, so instrument payloads (e.g., TSIS) must design their instruments to be robust to ISS jitter based on their own performance requirements and risk posture.

As an aside and a sign of progress, in the past year several ELC-mounted payloads, including OPALS [3], SAGE III, and now TSIS, have been able to successfully measure the jitter environment at their specific ELC mounting locations. It is anticipated that these new measurements will reduce the uncertainty in the ISS jitter environment for future payloads.

**Actuator Selection**

Faced with the uncertain jitter environment and other design accommodations specific to ISS, the LASP engineering team performed a detailed comparison between stepper-based actuators used on similar LASP pointing systems, including the TIM Pointing System for the Glory mission and a previous iteration of TSIS for the NPOESS mission, and direct-drive BLDC actuators. The next section will describe many of the differences in these actuators along with some of the key advantages BLDC motors can offer for precision pointing applications.

For context, it is worth mentioning that stepper-based actuators are usually intended for coarse pointing applications such as solar array drive mechanisms and antenna pointing mechanisms with typical pointing accuracies around 1 degree. By contrast, TSIS requires precision solar pointing with less than 60 arcseconds 1σ of jitter that is only marginally compatible with a common cardinal step size of ~30 arcseconds.

**BLDC Advantages Compared to Stepper-Based Actuators**

This section provides a qualitative description of many of the advantages that direct-drive BLDC actuators provide compared to stepper-based actuators in the hopes that it may be helpful to others trying to select an appropriate actuator type for precision pointing applications. For this comparison of space-borne actuators, it is assumed that the stepper motors are mated to harmonic drive based gear train to increase torque output and reduce step size. It is also assumed that the reader is familiar with both technologies, but expertise at the first-principals mathematical level is not required.

**Continuous Torque Command Authority**

A distinct advantage to stepper motors is their functional simplicity. The controller requests that the motor moves a number of steps (angle) and the motor responds by moving that amount. For simple applications where the step size is small relative to required angular precision, this open-loop approach is ideal for its set-it-and-forget-it simplicity.

However, for more precise applications, these benefits can become a liability. At an abstracted level, the stepper motor operates in a discrete manner as governed by the cardinal step size of the motor in combination with any additional gearing in the actuator. This is accomplished by applying a step change in power to the motor windings that results in a corresponding change in torque to the rotor. This torque moves the rotor along with the load to the next angular position with associated dynamic overshoot. If the desired angle is smaller than the step size, the controller is unable to reduce the angular error. This effect can be reduced somewhat through microstepping, but it comes at a cost of increased complexity and reduced holding torque while still subject to most of the limitations of stepper motors.
Alternatively, BLDC actuators can achieve much finer angular resolution due to the way they operate. Instead of commanding a number of steps (discrete torque step commands), the controller asks the motor to apply a continuously-variable current that translates directly to torque that results in corresponding continuous angular motion. Closed-loop control is then applied to achieve the desired angle with much finer resolution than could be achieved via the stepping approach.

**Minimal Self-induced Jitter**

Because of the step changes in torque application that are described above, stepper motors generate self-induced torque disturbances that result in oscillatory pointing jitter and associated torque disturbances reflected back to the spacecraft. This self-induced jitter is not directly controllable due to the fact that it is a byproduct of the system mechanics, but it can potentially be reduced by several means during the design phase (e.g., microstepping). Because these effects are fixed thereafter, they must be accounted for through appropriate, detailed analysis that demonstrates compatibility with the overall system design requirements. Doing so requires accurate analytic models of the stepper motor dynamics and the control excitation approach. However, these models include inherent nonlinearities (step commands) that complicate standard linear controls analysis. In past LASP programs, significant effort and time was spent modeling, predicting, and communicating the stepper motor disturbances produced by the solar array drives and the instrument pointing system to ensure mutual compatibility with each other and the spacecraft’s attitude control system.

By contrast, because BLDC motors apply torque in a continuous rather than discrete manner, they do not produce oscillatory self-induced jitter like steppers do. This results in greatly reduced angular jitter and torque disturbances reflected back to the spacecraft, both of which are highly desirable goals. And because the torque application is applied continuously, the actuator dynamics of the BLDC motors can be accurately and simply modeled as linear systems that support standard linear controls analysis.

**Increased Active Control Bandwidth**

Stepper motor control circuits typically limit the maximum commanded step rate in order to avoid loss of motor synchronization, and this rate limiting in combination with the discrete step size has the associated effect of limiting the control bandwidth. While this limitation may be acceptable for coarse pointing applications, it can be a hindrance for more precise pointing applications where improved tracking and disturbance attenuation capabilities are needed.

In contrast, BLDC actuators behave linearly and are not rate limited in the same manner, so increased active control bandwidth can be achieved that allows for improved tracking of dynamic inputs and for increased active disturbance attenuation.

**Structural Separation**

A direct consequence of the harmonic drive-based gear train arrangement is that the actuator input and output are structurally coupled about the rotational axis with the coupling primarily determined by the stiffness and damping of the harmonic drive.

By comparison, direct-drive BLDC actuators have very little structural coupling between the input and output about the rotational axes, and the small couplings that do exist are primarily due to bearing friction, back EMF, and harness routing (e.g., twist capsules). Because the pointing goal of TSIS is to point at the sun, which is approximately fixed in inertial space compared to the rotational motion of the underlying spacecraft (ISS), structural separation is an important advantage that will be further expanded upon in the following paragraph.

**Significant Increase in Base Disturbance Attenuation**

When TSIS was comparing direct-drive BLDC to stepper-based actuators for the TPS on ISS, simulations were performed using representative actuator dynamics and load inertias to compare the output pointing responses of both actuator types to base motion disturbances. For an inertially pointed instrument such as TSIS, the objective is for the output motion (i.e., SIM and TIM sensors) to be as insensitive to input base...
motion as possible (i.e., ISS jitter). These simulations were performed by exciting the base of a 1 degree of freedom actuator with a range of sinusoidal frequencies at fixed amplitude and comparing the output motion of the load when operating in both open-loop and closed-loop cases.

The stepper-based actuator results are shown in Figure 4 for open- and closed-loop cases. The y-axis shows the transmissibility, which is defined as the absolute value of the output magnitude to the input magnitude expressed in decibels. The x-axis shows the base excitation frequency in hertz on a log scale.

Examining the open-loop response, three regimes are present in different frequency ranges that are characteristic of a spring-mass-damper system subjected to base excitation. For low frequencies (< 5 Hz), the output motion tracks the input motion identically (0 dB) as a rigid body, which implies that any base motions are replicated exactly in the output. For mid-frequencies near the natural frequency (~11 Hz) of the load/actuator system, the output motion is amplified compared to the input motion by up to 14 dB (5x amplification). And finally, for higher frequencies above the natural frequency, the output motion is less than the input motion, which represents attenuation that is also referred to as seismic isolation. It is worth mentioning that for this characteristic, the larger the output inertia, the lower the natural frequency and the larger the frequency range of passive seismic (inertial) attenuation.

The closed-loop response assumes a control bandwidth that is much lower than the fundamental frequency, which is a reasonable assumption given the need to avoid active excitation of the fundamental mode. The response is nearly identical to the open-loop response, except that the closed-loop control is able to actively attenuate low-frequency base motion. This is an intuitive result given the successful implementation of solar arrays steppers to track the sun in the presence of slowly varying spacecraft base motion.

The key take-away of this plot is that a range of frequencies exist that can pose a risk to precise pointing where base motion jitter is either passed to the output in a rigid body manner or, even worse, amplified to magnitudes larger than the input frequency. If the base motion jitter is well understood and the predicted output is within allowable levels, this uncompensated jitter regime might be acceptable. But in the case of the poorly understood ISS jitter environment and with little margin in the pointing budget, this stepper motor characteristic posed a significant risk to the TSIS TPS jitter performance.

![Figure 4. Stepper Frequency Regimes in Response to Base Excitation](image-url)
Next, open-loop responses are compared between the stepper-based actuators that were just discussed and direct-drive BLDC actuators as shown in Figure 5. Because of the direct-drive aspect of the BLDC actuators that were described earlier as structural separation, the BLDC response has no significant resonance and the rigid body coupling is only present at low frequencies (< 1 Hz). In the same manner as the stepper-based actuators, seismic (inertial) isolation/attenuation is present but at a much lower frequency of ~1 Hz compared to ~15 Hz. This is a significant difference between the two actuator types that is capable of providing significant additional passive attenuation to base motion that increases with increasing load inertia.

![Figure 5. Comparison of BLDC to Stepper Open-Loop Responses](image)

Finally, closed-loop responses are compared between the stepper-based actuators and direct-drive BLDC actuators as shown in Figure 6. The increased active control bandwidth of the BLDC actuator is able to complement the passive attenuation to produce the robust, broadband jitter attenuation that is shown in the plot. The BLDC actuator clearly provides increased attenuation across all frequencies compared to the stepper-based actuator with none of the significant rigid body and resonant susceptibility. For this reason, BLDC actuators were selected to provide a robust pointing solution for TSIS in the presence of the uncertain ISS jitter environment.
Lessons Learned

Although direct-drive BLDC actuators can provide superior pointing performance compared to stepper-based actuators for precision pointing applications, there are associated challenges that were learned first-hand during TSIS development and will be shared here.

Control Electronics Complexity

Stepper control electronics are well understood and relatively easily matched to actuators for most applications. A prime reason is that the electronics operate open-loop with respect to the actuator motion. On the other hand, BLDC actuators require closed-loop control in order to function properly for pointing applications. Properly developing the closed-loop system that consists of the actuator, the feedback sensors, the drive electronics, and the control law is much more complicated than open-loop stepper electronics.

In particular, for TSIS, the electronics and motors were developed concurrently which often resulted in a case of the “chicken or the egg” for development decisions. In order to minimize this effect, prototype versions of the actuators and control electronics were developed and tested together to ensure mutual compatibility. This prototype approach is highly recommended.

Additionally, BLDC pointing performance is directly correlated to the feedback sensor performance, so the feedback sensor electronics are much more critical than they are for stepper-based actuators. Finally, having a configurable control law in software is much more complex and performance critical than most stepper commanding approaches. For all of these reasons, it is critical that sufficient resources are allocated for development of control/feedback sensor electronics and associated software if BLDC actuators are used.

Performance Dependent on Tuning

As originally mentioned, steppers use a simple set-it-and-forget-it control approach that does not require any tuning after they are built. BLDC actuators, on the other hand, require precise and frequent tuning in order to operate properly and meet requirements.
For TSIS, tuning was performed via direct frequency response measurements that applied sinusoidal command signals to the hardware and then measured the system response. Performing these measurements was quite time consuming and also had problems associated with the test hardware that further increased measurement time. On the other hand, the ability to take direct measurements of the system dynamics was enormously beneficial in the ability to tune the system, correlate models, and improve confidence in the system performance.

Tuning was performed quite frequently throughout the integration and test (I&T) program in order to match controller tuning to the specific hardware configuration (mechanical and electrical) that evolved and changed numerous times (10+) during I&T. Taken together with the duration of each measurement, tuning added significant, yet important, time to the program schedule. In the future, a software-based tuning approach may be developed that could reduce the measurement time for each of these tuning activities.

**Center of Gravity Sensitivity**

Because the BLDC actuators are directly coupled, they are particularly sensitive to offsets in the center of gravity (CG) of the instrument payload mass relative to the intersection of the rotational axes in two main ways. First, on-orbit translation disturbances couple into rotational disturbances via the offset CG. Second, ground testing may require offload/balancing ground support equipment (GSE) to account for gravity-induced torques. Additionally, the configuration change associated with any balancing GSE may necessitate separate controller tuning. For these reasons, it is highly desirable to locate the CG of the moving mass as close to the rotational axes intersection as is reasonably possible.

**Bearing Friction Sensitivity**

Bearing friction is a dominant dynamic that affects BLDC motor control and the limits of performance. In general, the friction should be as small as possible and as linear as possible. Of course, this is challenging to achieve given other constraints on the system. In particular, bearings that carry significant launch loads need to be appropriately large and with sufficiently high preload, both of which increase bearing friction.

Although suggested methods exist to select proper preload and Hertzian contact stress, a perfect approach does not exist that is as good as experience with actual hardware. For this reason, early testing and measurements are particularly valuable to understanding and compensating for bearing friction.

**Unpowered Free Motion**

An obvious direct consequence of a direct-drive system with low friction is that it will experience free motion when not powered. This was accounted for by including brakes in the actuator design that operate in the unpowered state. But as an additional mechanism, the brakes added their own complexities to the system design and operation that would have been easily accounted for by detent torque in a stepper-based actuator. Nonetheless, the brakes did function properly and prevent free motion when TSIS is unpowered on-orbit.

**Structural Coupling**

Even though the primary structural mode associated with the stepper-based harmonic drive was eliminated by selecting direct-drive BLDC actuators, structural dynamics still had to be accounted for to ensure successful actuator operation. In particular, it is important to provide frequency separation between the controller bandwidth and the structural modes in order to avoid resonant excitation of those modes. This was accomplished through frequent mechanical design iteration and communication between the mechanical engineers and the controls engineers. Additionally, to reduce risk, modal testing of the TPS structure was performed that was able to identify the structural modes and damping. The measured modes were actually closer to the controller bandwidth than was desired, but frequency response measurements of actuator control loops showed acceptable bending margins without any excitation of the structural modes. This was attributed to higher than originally predicted structural damping, which was attributed to the specific mechanical architecture of the TSIS system. One important lesson learned was that structural damping can be extremely beneficial to ensuring compatibility between the structural and control design,
and that there is no substitute for direct measurements because they may differ dramatically compared to predictions.

End-to-End Testing
Appropriate end-to-end testing is invaluable for any space-borne system, and it definitely holds true for BLDC-based systems because of all the lessons that were previously described. In addition to the prototype testing, frequency response measurements, and modal testing, TSIS performed a rigorous end-to-end test program that exercised every pointing mode in a flight-like manner that even included physical simulations of the rotating ISS with an inertially fixed sun as shown in Figure 7. As the following section will attest, all of this testing contributed positively to the successful operation and performance of the TSIS TPS when it reached orbit.

![Figure 7. TSIS TPS Test Configuration During Subsystem Characterization](image)

Results
In spite of the challenges that were associated with using direct-drive BLDC actuators, excellent results were achieved during the test program and during early on-orbit operations that confirmed the many benefits of BLDC actuators for precision pointing. A small sampling of results is shown in this section.

Stepper Performance Baseline
For comparison, correlated simulation results from an earlier, NPOESS-era of the TSIS TPS design are presented in Figure 8. These results show the residual azimuth axis error of 33 arcseconds 1σ when solar tracking at ~3.6 deg/min without any additional structural error (10 arcseconds 1σ) or spacecraft base motion (41 arcseconds 1σ). This residual motion profile was a consequence of commanding steps at ~8
steps/s which repeatedly excited the first mode (~11 Hz). When considering all of these error sources, the 60 arcseconds 1σ requirement was only marginally satisfied.

Disturbance Transfer Function Measurements
As previously described, frequency response measurements of the BLDC actuators were performed frequently throughout the test program, and these measurements included different transfer functions including the transfer function shown in Figure 9. This plot shows the modeled and measured “input” disturbance transfer function that is an indication of how well the closed-loop BLDC actuator is at attenuating torque disturbances. This disturbance transfer function was selected because it can be readily measured in the lab, whereas the previously discussed BLDC closed-loop transmissibility transfer function in Figure 6 would require a shaker-table approach for direct measurement that was beyond the scope of the TSIS program. The as-built system agrees extremely well with the modeled dynamics and shows robust, broadband disturbance attenuation that far exceeds a stepper/harmonic drive-based actuator and serves as the best measurement of robust disturbance attenuation for this system.
Ground-Testing Solar Tracking Errors

After the BLDC control loops were properly tuned using the frequency response measurement approach previously discussed, steady-state solar tracking tests were performed using the test apparatus shown in Figure 7 that included ISS base motion simulated by a rotational stage and a fixed solar simulator.

Figure 10 shows the steady-state solar tracking errors (self-induced jitter) for the azimuth axis during ground testing as measured by the High-rate Fine Sun Sensor (HFSS). The HFSS errors are shown in magenta/red, and an independent angular measurement was provided by a ring laser gyro (RLG) shown in blue that tracks the HFSS errors throughout the dataset. The measured HFSS error is 6 arcseconds 1σ over this dataset, and the RLG error is slightly less at 4 arcseconds 1σ because it is only measuring the mechanical motion and not the optical noise from the solar stimulus. This dataset was of high importance during the test program because it demonstrated that the BLDC actuators were capable of providing very low self-induced jitter compared to the 60 arcseconds 1σ requirement and compared to the stepper motor results from Figure 8.
On-Orbit Solar Tracking Errors

As encouraging as the ground-testing results were, the true test of pointing performance was only possible with the TPS operating on-orbit. During the early-orbit commissioning program, all of the TPS functionality was exercised, which provided an opportune time to record high-rate 200-Hz measurements that are not available during nominal operations and are able to reveal high-frequency pointing characteristics.

Figure 11 shows the azimuth and elevation solar tracking errors as measured by the HFSS at the native control execution rate of 200 Hz. The measured pointing performance was slightly improved compared to the ground-test measurements with 4 arcseconds 1σ in the azimuth axis and 2 arcseconds 1σ in the elevation axis. Additional high-rate and low-rate pointing measurements from throughout the flight mission are all consistent with these results. This performance easily satisfies the jitter requirement of 60 arcseconds 1σ and is a dramatic improvement compared to the stepper actuator approach from the TSIS NPOESS-era in Figure 9. This significant improvement in pointing performance is a direct consequence of using direct-drive BLDC actuators instead of stepper-based actuators that will allow the TSIS scientific sensors to perform their critical measurements while pointed directly at the sun.
Conclusion

Direct-drive BLDC actuators were selected and used for 2-axis solar pointing of the TSIS instrument payload on the ISS and have provided improved performance compared to stepper-based actuators due to a number of advantages. These advantages include continuous torque command authority, minimal self-induced jitter, increased active control bandwidth, and structural separation, all of which produce a dramatic increase in base disturbance attenuation and greatly reduced tracking errors.

As part of implementing the BLDC actuators for TSIS, many challenges were overcome and lessons were learned regarding control electronics complexity, the importance of controller tuning, sensitivity to center of gravity and bearing friction, how to account for unpowered free motion, the effect of structural coupling to closed-loop control, and the importance of end-to-end testing.

Pointing performance was greatly improved compared to stepper-based values as evidenced by the ground-test measurements of the disturbance transfer function that shows excellent broadband attenuation and of the solar tracking errors that show significantly lower self-induced jitter. The culmination of this effort are the on-orbit results that show solar tracking errors less than 4 arcseconds 1σ per axis, which provides ample margin compared to the requirement of 60 arcseconds 1σ.

References