Gimbals Drive and Control Electronics Design, Development and Testing of the LRO High Gain Antenna and Solar Array Systems

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Abstract

Launched June 18, 2009 on an Atlas V rocket, NASA's Lunar Reconnaissance Orbiter (LRO) is the first step in NASA's Vision for Space Exploration program and for a human return to the Moon. The spacecraft (SC) carries a wide variety of scientific instruments and provides an extraordinary opportunity to study the lunar landscape at resolutions and over time scales never achieved before. The spacecraft systems are designed to enable achievement of LRO's mission requirements. To that end, LRO's mechanical system employed two two-axis gimbal assemblies used to drive the deployment and articulation of the Solar Array System (SAS) and the High Gain Antenna System (HGAS). This paper describes the design, development, integration, and testing of Gimbal Control Electronics (GCE) and Actuators for both the HGAS and SAS systems, as well as flight testing during the on-orbit commissioning phase and lessons learned.

Introduction

In January 2004, the President of the United States unveiled the Vision for Space Exploration which charted the path for the return of humans to the Moon and deep space. The first milestone in that plan was an unmanned lunar orbiter to be launched in late 2008. By late 2004, that first mission had become the Lunar Reconnaissance Orbiter, and as 2005 began, development had started at NASA's Goddard Space Flight Center.

With a goal launch date of end of 2008, the mission had only four years to be developed from concept to launch. In addition, the primary mission required that the spacecraft remain in a nominal 50-km polar mapping orbit for a minimum of one year, collecting data over the entire lunar surface under all possible lighting conditions; imposing challenging constraints on SC design. Schedule, cost, mission, and reliability requirements manifested themselves in every aspect of the LRO design.

To meet the needs of a discovery-class mission with an accelerated development schedule, the development, fabrication and testing of the LRO GCE and Actuator subsystems was inevitably fast-paced. Schedule needs of the overall mission required that the GCE/Actuator subsystems provide reliable, environmentally tested flight hardware within 15 months of specification release; just in time for SC integration and test (I&T) activities. Figure 1 shows the layout of the integrated spacecraft, with fully deployed HGAS and SAS.

This paper will discuss the overall design, development, integration, testing (ground and flight), and lessons learned for the GCE and Actuator subsystems of both the HGAS and SAS.

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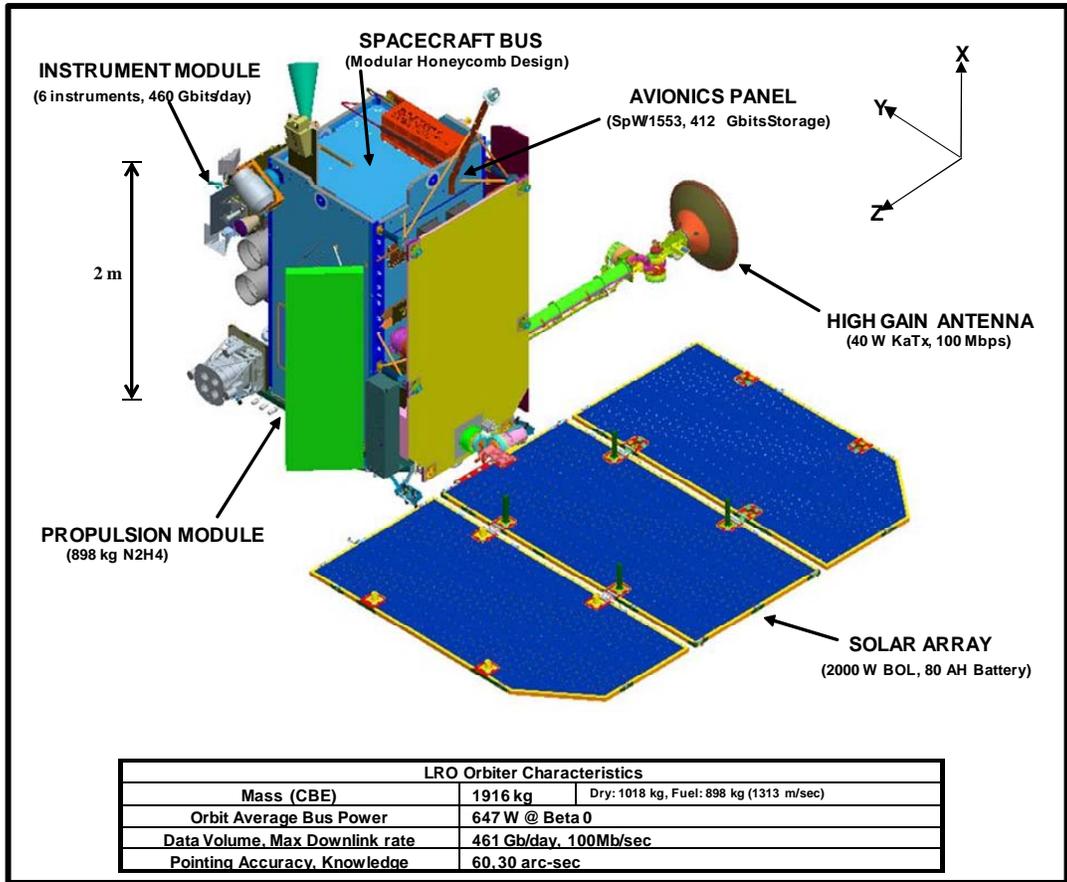
Figure 1. LRO Spacecraft with Deployed Solar Arrays and High Gain Antenna

Design

As described in the Introduction portion of this paper, the Gimbal Control Electronics and Actuator subsystems of the LRO are intended to enable the primary mission objectives, and were required to meet cost, reliability and schedule constraints imposed by the class and short development time of the overall mission.

On LRO, the function of the GCE is to control and drive dual-axis redundant actuators on the SAS and HGAS. The Solar Array System GCE drive enables mechanical rotation of 90° on one actuator and 180° on the other, allowing the Solar Arrays to track the sun in two axes and provide a reliable power source for the Orbiter. The HGAS GCE subsystem drives 180° rotation on both axes, enabling the high-gain antenna to point toward Earth whenever it is in view (providing maximum time for data downlinking and ground system communications). Two redundant, dual disk, incremental encoders – one on the input (fine) and one on the output (coarse) – are integral to the actuator assembly for both the HGAS and SAS GCE subsystems. These encoders provide fine and coarse incremental position sensing with respect to a unique home/reference position located at the center of travel. They also provide a logical state change for each physical motor cardinal step taken, thereby providing an output resolution equal to the cardinal step size. A pictorial view of the LRO actuators and the internal layout of the fine and coarse encoders are shown in Figure 2. HGAS and SAS gimbal systems can be seen in Figure 3.
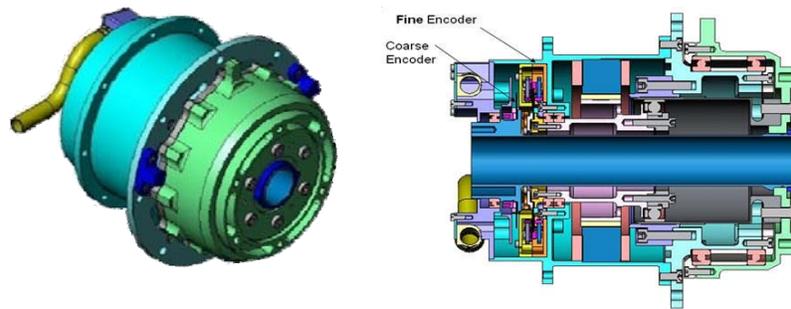
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Figure 2. LRO HGAS and SAS gimbals actuators

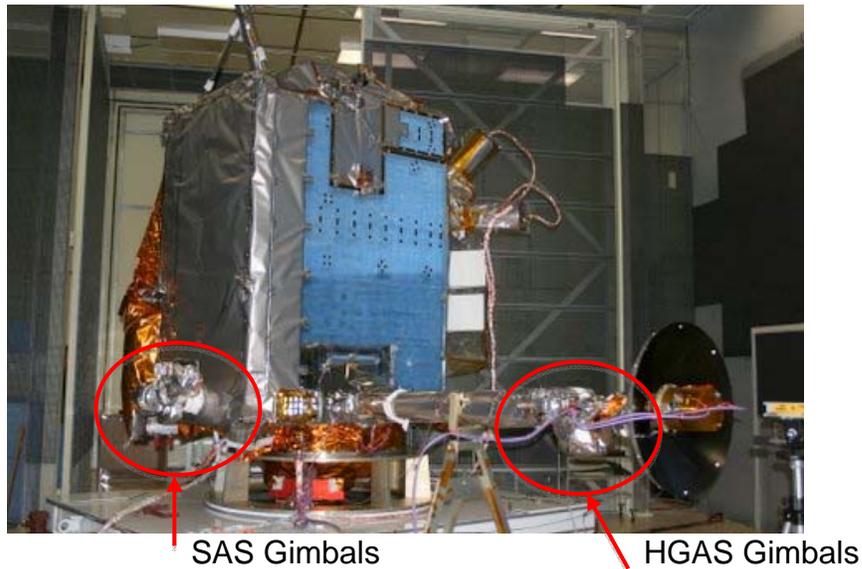
SAS Gimbals   HGAS Gimbals

Figure 3. LRO S/C in the EMI chamber with a removed SA and fully deployed HGA

The GCE/Actuator subsystems consisted of two engineering development units (EDU), three flight boxes, two commercial actuators, and five flight actuators. Each electronics box provides a fully redundant two-axis control or drive for the three-phase harmonic drive actuators.

These gimbal assemblies, including the Gimbal Control Electronics (GCE) and harmonic drive actuators used for the SC deployables were developed by a team comprised of engineers from Goddard Space Flight Center (GSFC), Alliant TechSystems (ATK), Broad Reach Engineering (BRE) and Sierra Nevada Corporation (SNC).

Actuator Selection
In order to meet reliability and schedule constraints, the project leveraged available technologies and in-production hardware, and strove for overall simplicity of design wherever possible. To ensure that reliable, environmentally tested GCE/Actuator subsystems were delivered in time for SC I&T activities, the project selected SNC Actuators, identical to those developed for the Solar Dynamic Observatory (SDO) spacecraft.

These actuators had been extensively tested during SDO High Gain System integration, with performance characteristics shown to meet the basic requirements for LRO's mission. The actuator interfaces were also well understood, allowing subsystem and interfacing system designs to proceed rapidly. In addition, these actuators provided the internal redundancy required by LRO's mission.

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Although the HGAS and SAS inertias differ by a factor of fifty, the analysis showed that the actuators could easily achieve the required torque margins for both systems with optimized motor drive control electronics. Given that the SNC Actuators met the needs of both the HGAS and the SAS, and could take advantage of the development and testing for SDO, these actuators were selected for use on LRO over more optimized but more schedule intensive actuators.

Drive Electronics Selection/Design
Due to the wide range of operational constraints imposed by a lunar mission, such as a challenging thermal environment and the need for extensive ground testing in a 1g environment, a drive electronics system with multiple set points was selected to provide flexibility.

In addition, it was found that the drive system needed to allow micro-stepping with multiple resolution options for micro-step rates. Accurate tracking of the sun on two axes required that the solar arrays be driven at a rate of 7 pulses per second (pps), and their large inertias added the risk that spacecraft jitter may have caused violation of pointing budgets. To minimize the potential effects of SAS tracking on spacecraft stability, the GCE assembly (Figure 4) was designed to provide the capability for micro-stepping at multiple resolutions.
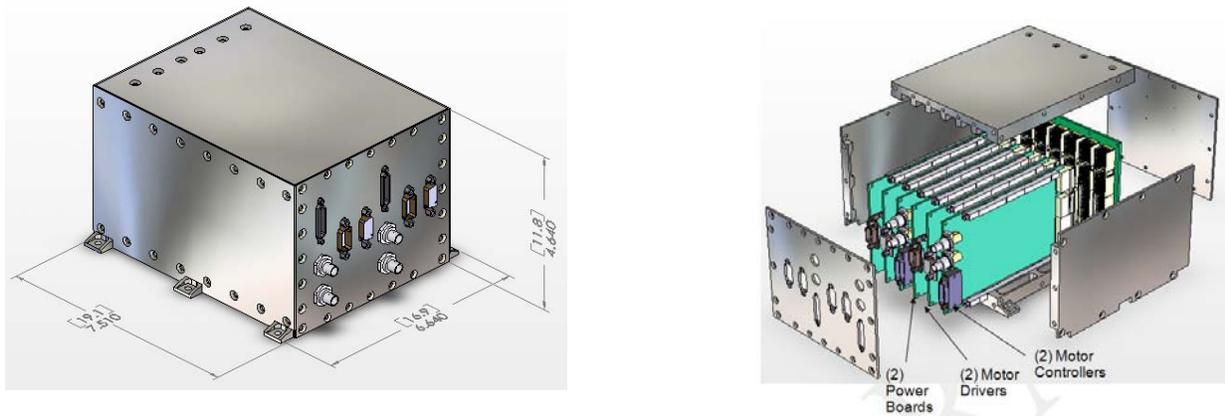

Figure 4. LRO Gimbal Control Electronics Box

GCE Design
To take advantage of the inherent internal redundancy of the SNC actuators, and to improve the reliability of two critical SC control subsystems, the GCE subsystem was designed as a 100% redundant electronics box. The GCE subsystem is comprised of two identical controllers, two identical Motor Driver Boards, two identical DC to DC Converter Boards, two backplanes and the chassis. The spacecraft provides the subsystem a 31-Volt Direct Current (VDC) nominal voltage and Primary/Redundant Side Enabled pulsed discrete commanding to the subsystem. The GCE communicates with the SC via the MIL-STD-1553B bus. A block diagram of the GCE is shown below in Figure 5.
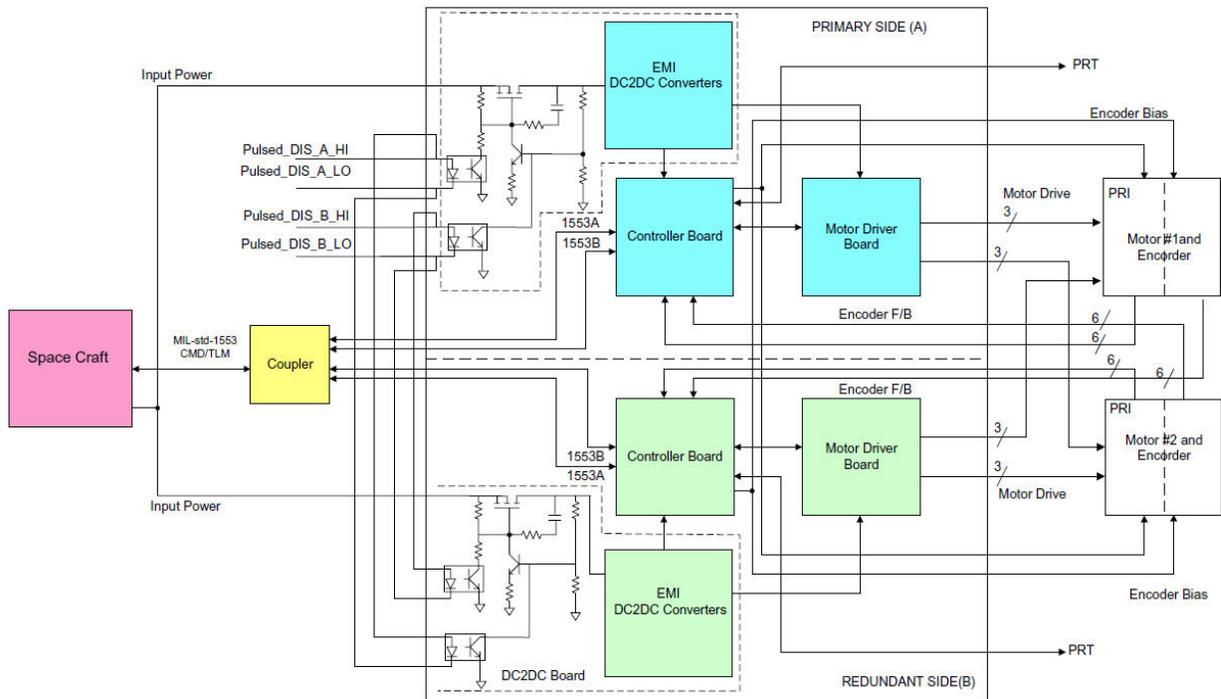
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Figure 5. LRO GCE block diagram

The GCE design maximizes internal mode control capability while minimizing command and control interfaces with the flight software. Major communications and control functions are accomplished by two Field Programmable Gate Arrays (FPGAs). One of these is located on the Controller Card to provide SC command and telemetry interfaces, processing of critical and housekeeping GCE telemetry, operational positioning controls, and automated positioning controls. The other FPGA is located on the Motor Driver card, and controls the stepper motors' commutation sequences, micro-stepping capabilities, programmable power set points, and closed loop current control.

To allow minimal power dissipation in the gimbals, and to provide flexibility in selection of an optimum drive, the GCE design utilized a constant current drive system with pulse width modulated control. The system offers eight current set points ranging between 200 and 390 mA. Operational step rates are commandable in the range of 0 to 67 cardinal steps/sec for flight operation and 0 to 150 steps/sec for laboratory and ground testing. The system also enabled optional micro-stepping, allowing commanding of micro-step resolutions from 0 (1 cardinal step) to 6 (64 cardinal steps), to minimize the effect of tracking motions on spacecraft jitter. Internal electronics condition the actuator motor and output optical encoder signals, providing a closed loop control with resolution of 0.0075° per cardinal step.

The GCE uses five distinct command modes to execute gimbal control; the GCE mode state diagram is shown in Figure 6. In addition to the basic commanding of the gimbals, the GCE also monitors gimbal execution and positional accuracy by way of operational error flags; the Position Error and Step Error flags. During the initialization mode, the GCE sets the "Home" position to 0, and the Position Error flag is checked every time the "Home" marker is crossed to verify that the current position is at 0 counts. Any deviation from 0 indicates positional accuracy violation. The Step Error flag is generated if encoder feedback indicates that the actuator failed to complete a command for the motor to take a step. These operational error flags ensure that the gimbals can be accurately commanded and controlled. The GCE also provides high resolution temperature monitoring for multiple PRT (platinum resistance thermometer)/Thermistor sensors for various LRO SC hardware components.
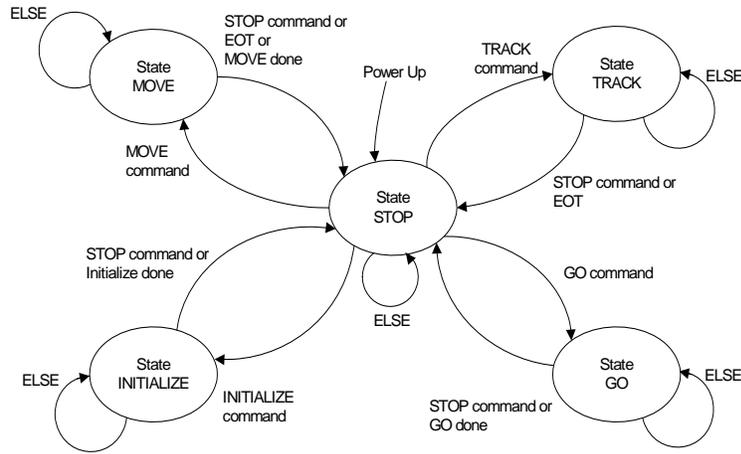
Figure 6. GCE Mode State Diagram

Technical Problems and Solutions

As with all spaceflight hardware, design of the GCE/Actuator subsystems presented many technical challenges. Not only did the systems need to meet flight requirements, they also needed to be able to be efficiently and thoroughly tested in all operational modes.

Re-circulating Current and Motor Current Measurement Distortion
One such challenge was presented by the need to provide an accurate motor current measurement in a pulse modulated system with multiple actuator drive current settings, while operating from an unregulated power bus.

Specifics of the pulse width modulation control produce a re-circulating current (supplied by the actuator coils during dead time), bypassing a sense resistor. Figure 7 shows one possible re-circulating current condition, with all motor driver switches set on HIGH.
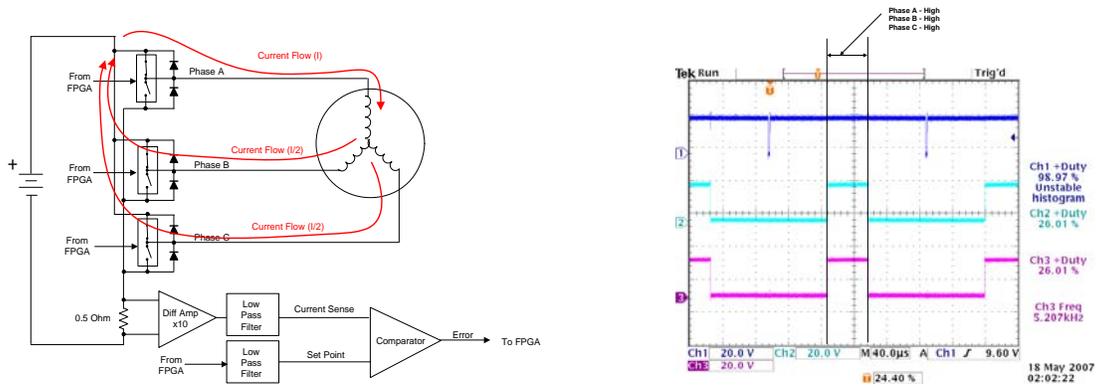

Figure 7. GCE shunt current monitoring, all motor driver switches on HIGH

When all the motor driver switches are set on HIGH, the current is supplied by the actuator coils, re-circulating to the power supply and therefore bypassing the sense resistor. The current then decays based on the time constant of the actuator coils (t = 100mH/69W = 1.4ms), reducing the shunt current measurement, and distorting the motor current value.

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To resolve the problems related to the re-circulating current, the FPGA measures the dead-time using knowledge of the pulse width modulated (PWM) duty cycles. The FPGA calculates the measured current error by computing the amount of measured current distortion (% of time the current is measured) from knowledge of the PWM duty cycles. The commanded set point is then continuously adjusted by multiplying the power set point by the shunt measurement distortion factor, reported in the telemetry as a "power scale factor". Figure 8 shows a simplified model of the current control mode with "dead-time compensation".
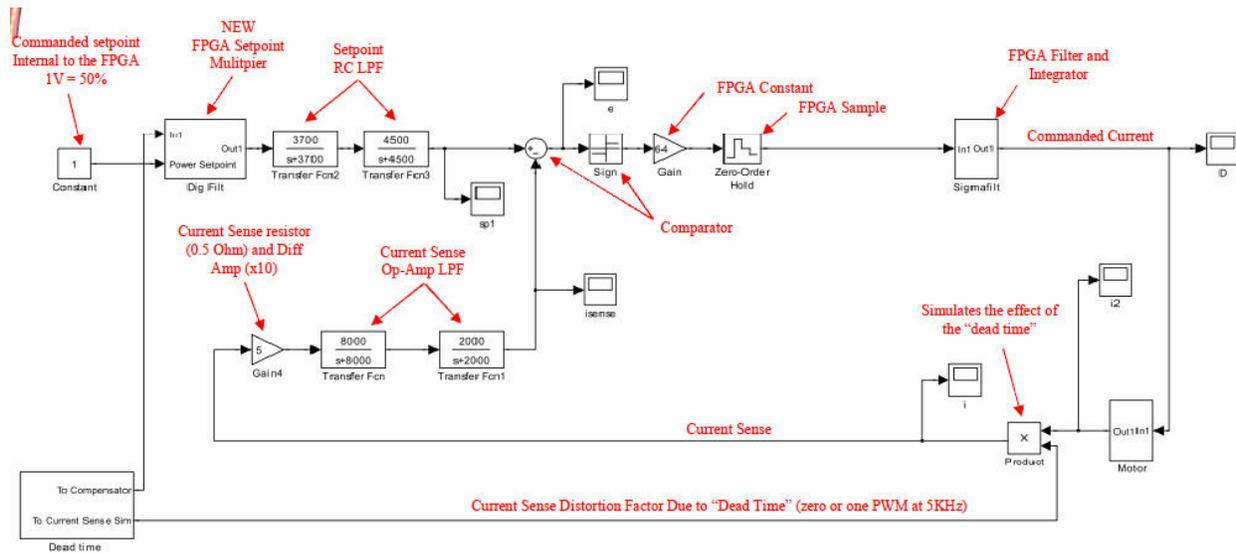

Figure 8. GCE Current Control Mode

Power Return Electromagnetic Interference/Radio Frequency Interference
Another challenge was presented by the design of the gimbal drive electronics power returns. These drive electronics required that the primary (spacecraft) power returns be connected to the secondary returns, and therefore must be isolated from the chassis. To satisfy LRO's EMI/RFI requirements, low noise PRT conditioning circuits were utilized and many other design considerations were implemented.

When the GCE/Actuator subsystem EDU was initially EMI tested, analysis showed significant EMI violations and excessive noise. To resolve the violations and decrease the noise, many modifications to the EDU were made. These included redesign of the power distribution to the motor drive electronics, implementation of constant current source circuitry for temperature monitoring, and a partial re-layout of printed circuit cards. Final EMI and functional testing verified that these design changes successfully resolved all EMI and noise related issues.

Component and System Level Tests

Systems level testing of the HGAS and SAS was particularly critical to mission success. In order to conduct multiple, and often simultaneous, tests, many combinations of flight hardware, commercial equivalents, and Ground Support Equipment configurations were identified, with specific harnesses fabricated.

Although all GCE subsystem testing was done with a dedicated lab-view setup, all system and SC level GCE testing was conducted with Integrated Test and Operations System (ITOS) driven test racks. ITOS would be used in flight for commanding and telemetry monitoring, and provided a flight like ground control environment for testing. Use of the ITOS test racks for testing also allowed the team to develop and become familiarized with ground station telemetry and control pages, used throughout system and Orbiter integration and testing, and in flight. Two sample GCE/Gimbal telemetry pages are shown below in

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Figures 9 and 10; Figure 9 shows a gimbal telemetry display built in an ITOS Java environment, and Figure 10 shows a typical GCE telemetry page.
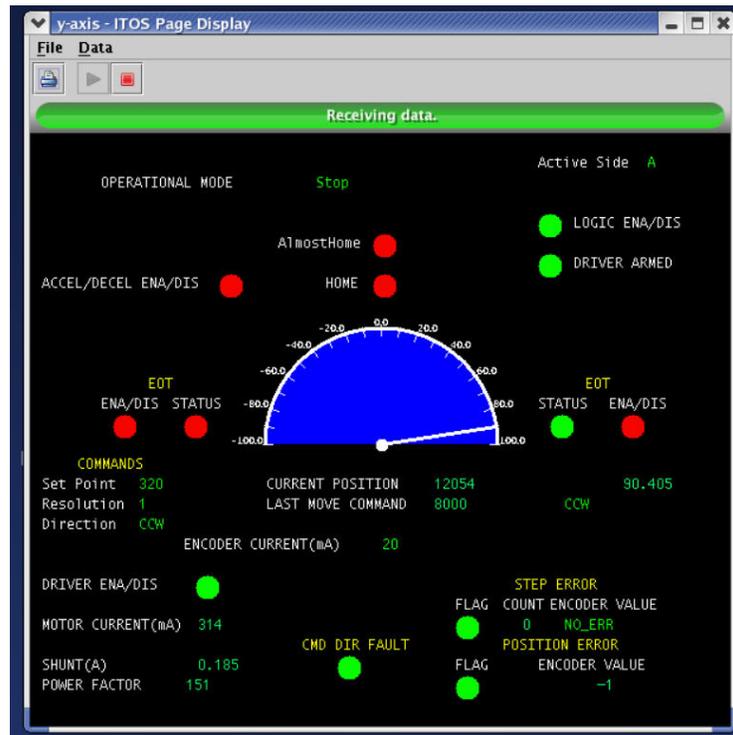

Figure 9. Sample Y-axis Gimbal Telemetry Display

Figure 10. Sample ITOS GCE Telemetry Screen

Specialized test configurations allowed various detailed characterizations of subsystem elements to be developed. This was particularly useful in the case of the HGAS actuators. Although the SAS flight software (FSW) could be ground tested with flight gimbals without solar array panels attached, the HGAS FSW and tracking and control algorithms fully verified in a 1G environment and was mostly conducted with the set of commercial (but otherwise flight like) actuators. Therefore it was critical to characterize the flight units prior to integrating them into the gimbals assembly.

The characterization of the GCE/Actuator components prior to flight was especially helpful in the identification and isolation of the source of one specific anomaly encountered during flight operations. Figures 11 shows the results of test characterizations for HGAS flight actuator encoder responses when operating at a 67 pps step rate in clockwise (CW) and counterclockwise (CCW) directions. The distinct differences of the signal waveforms illustrated here will be addressed in the Flight Operations section of this paper.
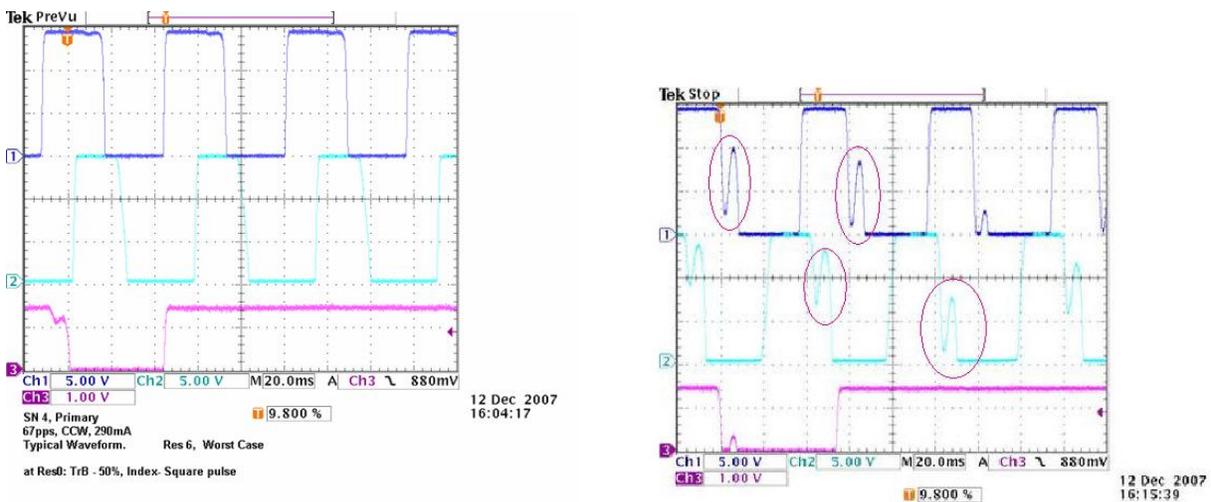

Figure 11. LRO HGAS Actuator Encoder responses at a 67 pps step rate (Left: CCW, Right: CW)

To conduct the necessary HGAS Range of Motion tests with LRO's flight antenna, a special sequence of coordinated motions and tracking rates were developed. These special sequences were intended to enable testing of the entire end-of-travel to end-of-travel range of motions for all quadrants of the two-axis gimbals while avoiding "zippering" in the 1G environment. These special motion sequences and tracking rates were developed from calculations and analysis of torque capabilities that allowed determination of safe start and end positions, while enabling the ground test to exercise slew and tracking rates. Specific current set points for each motion were established to produce a combination of single and dual gimbals motions for the test that would minimize the time required to complete any individual test. These motions were run numerous times during the integration and environmental testing of the spacecraft. The HGAS Range of Motion Profile is shown in Figure 12.
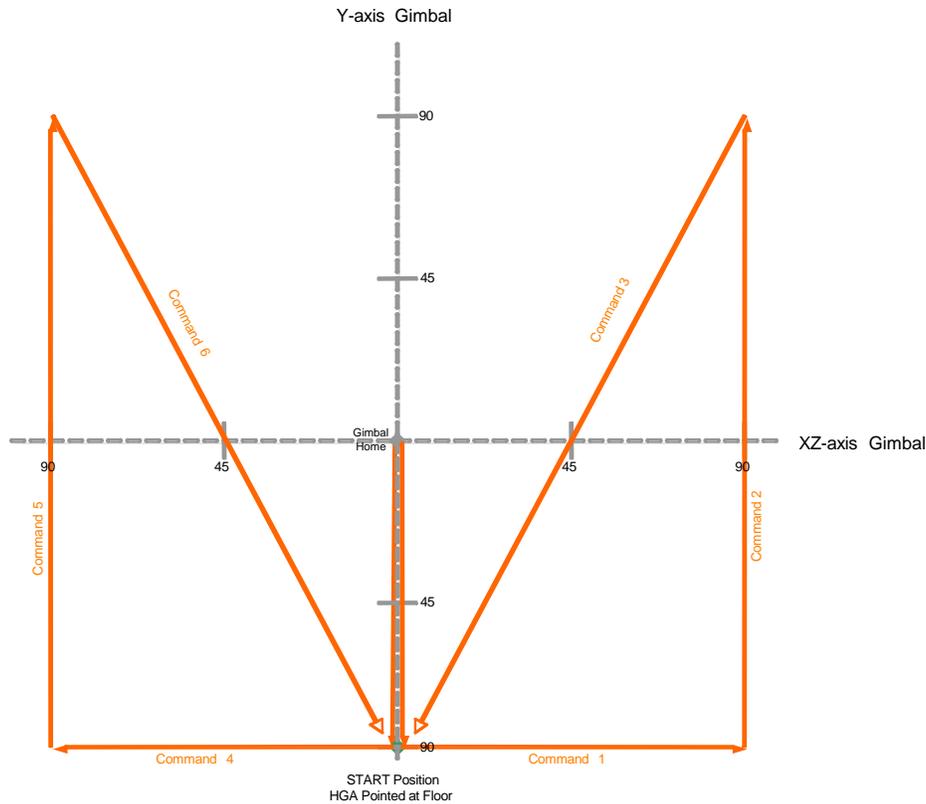
Figure 12. HGAS Range of Motion test profile

Lessons Learned

Although numerous potential improvements to GCE/Actuator requirements, design and operation were realized during the many hours of HGAS, SAS and SC testing, integration and operation, only a few of the most significant are discussed below.

Lack of loadable "Position Register"
One potential improvement to the system would be to have a pre-loadable position register. This would simplify laboratory development and ground level testing, as well as eliminate some confusion when gimbals are deliberately positioned to certain angles prior to system shut down. With a pre-loadable position register, on power up the GCE could be loaded with the default value. If knowledge of absolute position is required for follow-up tests, the register could be pre-loaded with the value corresponding to an actual position, and any further movement, even without system initialization, would reflect absolute gimbal position. In a 1G environment, the initialization is sometimes an undesirable mode, and can be a time consuming operation. Use of pre-loaded position register can be utilized to save time and avoid undesirable operation modes.

An alternative solution may also be the addition of non-volatile memory, where specific system parameters can be maintained at all times.

Acceleration/Deceleration Profiles
One of the original requirements imposed on the GCE by the LRO Design Specification was that acceleration (Accel) and deceleration (Decel) ramping profiles be internally generated. At the time the Design Specification was developed (early in LRO's project life), ACS tracking requirements and controls were not fully defined, making it difficult to establish requirements for the Accel/Decel profiles. As a result,

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it was later found that meeting the specified requirement of no greater than 2 seconds ramping timing to move the high-inertia Solar Array was extremely difficult.

Satisfying the Accel/Decel profile requirements while maintaining the necessary micro stepping resolution, and meeting the requirement to always finish motions at the cardinal step was very challenging. This requirement also presented complications in FPGA implementation of multiple micro-step resolutions and rates. Although the problem was resolved for 90% of possible combinations of micro-stepping resolutions and step rates, the function ended up disabled as LRO's FSW employs its own acceleration and deceleration algorithms. In LRO's case, hard-coded Accel/Decel profiles did not match with control algorithms and were not useful as a tool to reduce SC disturbance.

In addition, LRO's system utilized micro-stepping based on cardinal steps rather than pure micro-stepping; in the LRO system, the micro-stepping was incorporated within the cardinal step and was required to stop at each cardinal step. Implementing Accel/Decel profiles in this system used a large percentage of FPGA capabilities, and made design alterations extremely difficult.

Based on the difficulties encountered, and the ability to provide acceleration/deceleration algorithms via FSW, it may not be practical to hard code Accel/Decel profiles into the GCE.

Constant Current vs. Constant Voltage Drive
Although the use of a constant current motor drive in the system does offer some benefits, it is not clear if these benefits outweigh the complexities they introduce into the system, especially while meeting current (and torque) requirements at Hot and Cold conditions with high set points.

Comparatively, the a constant voltage stepper motor drive delivers better performance at a given set point; the power delivered to the motor in a "Cold" environment is greater than that in a "Hot" environment, providing more balanced torque margins at various ambient conditions.

The constant current drive also introduces complications in accurate monitoring of the actuator current in a pulse-width modulation scheme (as discussed earlier), due to the fact that the sense resistor does not measure the re-circulating ("freewheeling") current flowing in the motor.

Taking these considerations into account, a constant voltage drive may be more appropriate for use in similar conditions.

Two Encoder Current Options
LRO's GCE design specification required two set points for encoder LED excitation. Although this was a proven and uncomplicated circuit implementation, it appears to be excessive requirement for a mission of LRO's duration and radiation environment, especially without including the capability to measure possible read-head performance degradation. Additional command and control functions required significant analysis and testing during GCE development and SC testing. This requirement should be re-visited for similar applications.

HGAS and SAS Flight Operation and Performance

Both the HGAS and SAS subsystems were shown to perform exceptionally well from deployment through slewing and tracking operations at various operational currents and stepping rates.

No Position Errors
No position errors were seen in any mode for either the SAS or HGAS gimbals from launch throughout the commissioning phase. From HGAS and SAS deployment, through the first month and a half of operation, the gimbals were operated at the nominal micro-step and current levels determined to provide required torque margins, satisfy GEVS Gold Compliance, and provide reliable operation in safe hold mode. For the SAS, nominal micro-step resolution is 16 micro-steps per cardinal step at a Y-axis current

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of 320 mA and a Z-axis current of 220 mA. For the HGAS, the nominal micro-step resolution is 16 micro-steps per cardinal step with a motor current of 240 mA on both axes.

Single Step Errors
Although no position errors were encountered, a few single step errors were detected on both systems at the beginning of tracking motions immediately after the initialization sequence. A step error is an inherent feature of the actuator harmonic drive which, occasionally during the first few steps of motion, results in the motor encoder not detecting a step within the time the GCE expects to see a transition. The step errors did not result in any position errors. These single step errors during the gimbal operation are a good indication of the balance between the motor current, encoder LED current and encoder alignment.

SAS Actuator Power Dissipation Reduction
The SAS Y-axis actuator operations also underwent on-orbit testing on July 1, 2009. Prior to testing, analyses were conducted for the worst-case inertia of 321 N-m-s^2 (2841 in-lb-s^2). By reducing the torque factor to 1.25, it was determined that a 240-mA operational current would provide a positive torque margin for the Y-axis actuator. Analyses also showed that slightly increasing the parameter "Number of steps to accelerate inertia to full speed" conservatively set to 15 (with approximately 2:1 margin,) would result in stable operation with both 200-mA and 220-mA currents.

On-orbit testing was executed at both 200 mA and 200 mA for both SAS gimbals, exercised over the full range of motion, and demonstrated reliable, error free operation. To add additional margin, the decision was made to set the Y-axis operational current to 240 mA, reducing actuator power dissipation from approximately 5.5 W to 3.0 W.

The on-orbit testing, and the implementation of the test and analysis findings, was in response to Thermal team requests to minimize motor power dissipations effects on SAS Y-axis actuator temperature.

Delta Angle Violation Anomaly
A single type anomaly, initially detected by the Guidance, Navigation and Control (GN&C) team, was occasionally observed on the HGAS gimbals during slewing operations at 67 pps in the CW direction, referred to as a Delta Angle Violation (DAV). The first HGAS DAV happened at 2009-170-01:07:30.43345. DAV flags are generated by the FSW if the difference between two consecutive samples of position telemetry data, sampled at 200-ms intervals, exceeds 14 counts, which corresponds to the fastest allowable rate of 67 steps per second. The source of this error was traced to the **flight** actuator's encoder operation associated with misalignment and amplified by the operation in the micro stepping mode. This also explains why the error was never seen during ground tests or simulations, during which the **commercial** encoders were used.

The anomaly mechanism can easily be seen by analyzing the plots shown in Figure 11. When the GCE reads a proper track transition (level change exceeds the conditioning circuitry threshold) it updates the position counter by increasing the count for CW corresponding transition or decreases it for the CCW corresponding transition. When the "wiggle" occurs, it causes the GCE to increase the counter on the lowering transition prior to the "wiggle." It then decreases it on the "wiggle-up" transition (since this is the proper CCW corresponding transition). This results in the net zero count change with the following "wiggle-down" transition producing a legitimate step count. If the position telemetry counter is sampled prior to the "offsetting wiggle" it would produce an extra step count, which should happen at a later time. A similar scenario could occur on either the A or B track. Since the position counter is sampled asynchronously with the DAV flag, occasional violations are produced.

This anomaly can be easily resolved by switching from micro-stepping (which is not required for the HGAS operation) to cardinal stepping, but since this anomaly does not affect gimbal operation or the control algorithm, the HGAS operational mode was not changed.

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<u>Effects of Micro-Stepping on Spacecraft Jitter</u>
Further testing was conducted to study the effect of various micro-step resolutions on SC jitter. The plots in Figure 13 show the motor winding currents at 2 micro-step and 32 micro-step resolutions, and indicate why some improvement of SC jitter at higher micro-step resolutions was expected.
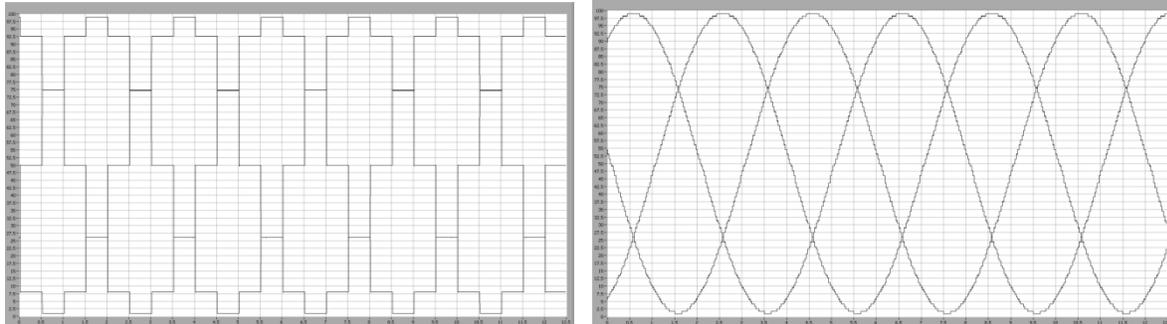

Figure 13. Actuator winding currents at 2 (left) and 32 (right) micro-steps per cardinal step modes

In addition, a Gimbal Step Resolution Experiment was conducted on the LRO Solar Array Gimbals to determine the effects of the different step resolutions on spacecraft Jitter and Attitude Error. The test entailed running the Solar Array gimbals in track mode, using three different step rates or resolutions: cardinal, 16 micro-step, and 32 micro-step. The experiment was conducted on consecutive orbits in the sequence indicated in Table 1.

Table 1. Timeline for SA Gimbal step resolution experiment

Test Timeline	
Time	Event
2009-183-21:42:00	SA Y Gimbal stopped, commanded to cardinal stepping
2009-184-01:07:44	SA Y Gimbal stopped, commanded to micro step with resolution of 32
2009-184-03:00:00	SA Y Gimbal stopped, commanded to micro step with resolution of 16

To analyze the data, MATLAB was used to generate a Power Spectral Density (PSD) plot of the Spacecraft Body Rates for each of the three test cases. In order to obtain more information about the difference between the spacecraft's response to various gimbal micro-step resolutions, the time history of the Attitude Error and IRU rates was calculated. The variance in the data is shown in Table 2 for SC body rates and Table 3 for Attitude Error.

Table 2. Variance for SC Body Rates for full data set

Body Rates (asec/sec)	X Variance	Y Variance	Z Variance
Cardinal	27.4473	110.3259	8.2311
Micro 16	20.9319	113.7145	8.0349
Micro 32	22.2692	84.5873	7.4360

Table 3. Variance for SC Attitude Error for full data set

Attitude Error (asec)	X Variance	Y Variance	Z Variance
Cardinal	16.1147	21.4523	4.8761
Micro 16	4.4508	13.0828	2.1641
Micro 32	2.5229	8.2906	2.2742

After analysis of the results, it was determined use of the 32 micro-step resolution significantly improves attitude and jitter performance, in comparison to use of cardinal stepping.

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Conclusion

On-time hardware delivery, successful SC integration and test, and six months of successful on-orbit testing and operation have demonstrated that the GCE/Actuator team, and the overall LRO Project team, used a viable approach for the rapid design, development and integration of critical spacecraft subsystems.

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