Design and Development of a Two-Axis Thruster Gimbal with Xenon Propellant Lines

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Abstract

A Two-Axis Thruster Gimbal was developed for a two degree-of-freedom tip-tilt gimbal application. This light weight gimbal mechanism is equipped with flexible xenon propellant lines and features numerous thermal control features for all its critical components.

Unique thermal profiles and operating environments have been the key design drivers for this mechanism which is fully tolerant of extreme space environmental conditions. Providing thermal controls that are compatible with flexible components and are also capable of surviving launch vibration within this gimbal mechanism has proven to be especially demanding, requiring creativity and significant development effort. Some of these features, design drivers, and lessons learned will be examined herein.

Introduction

The construction of the Thruster Gimbal is modular, as seen in the exploded view of Figure 1. It is comprised of subassemblies in order to facilitate fabrication and assembly and to allow subassembly-level testing. This construction expedites the manufacturing process for the entire Thruster Gimbal Assembly. The modular structural components of the gimbal are the Inboard Platform, the Outboard Platform, and the Gimbal Ring, which is the intermediate gimbal member. Other modular components are the two Rotary Actuators and the Tubing Assembly.

The basic gimbal structure consists of the Inboard and the Outboard Platforms joined together through the Gimbal Ring. The Gimbal Ring is joined to the Inboard Platform on a single pivot axis through two sets of preloaded angular contact bearings. This articulation is the Azimuth axis. Its two points of support are the actuator output bearing set, housed within the Azimuth actuator, and the opposing bearing set, housed in the yoke arm of the Inboard Platform. Both bearing sets are preloaded angular contact pairs, providing rigid and accurate location of the Gimbal Ring.

The actuator bearing set is a duplex set preloaded to meet stiffness and load requirements, while the bearing set on the opposite side is a more compliant duplex set, to meet load and stiffness requirements while accommodating any misalignments. This arrangement is duplicated on the orthogonal Elevation axis. The Elevation actuator is mounted to the yoke arm of the Outboard Platform, with the gimbal ring again attached to the actuator output member. The second bearing pair is again mounted in the opposite yoke arm, supporting the other side of the Outboard Platform on the gimbal ring. Orthogonality of the two separate and independent axes is therefore established by the gimbal ring. This configuration forms a true gimbal, with the axes intersecting at the center of the gimbal ring. The dimension from the interface surfaces of the platforms to the rotational centerlines is common, and therefore the gimbal axes are located at a midpoint between the inboard and outboard platform interface surfaces.

The true gimbal configuration utilizing an open intermediate member (the Gimbal Ring) results in a large clear space on the central axis of the unit. This space is used to accommodate a set of flexible xenon propellant lines, which are routed from the inboard interface to the outboard interface. The size and shape

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of the clearance volume has been thoroughly analyzed to ensure sufficient clearance between the Gimbal Ring and the coiled propellant lines over the full combined range of angular travel of both gimbal axes.

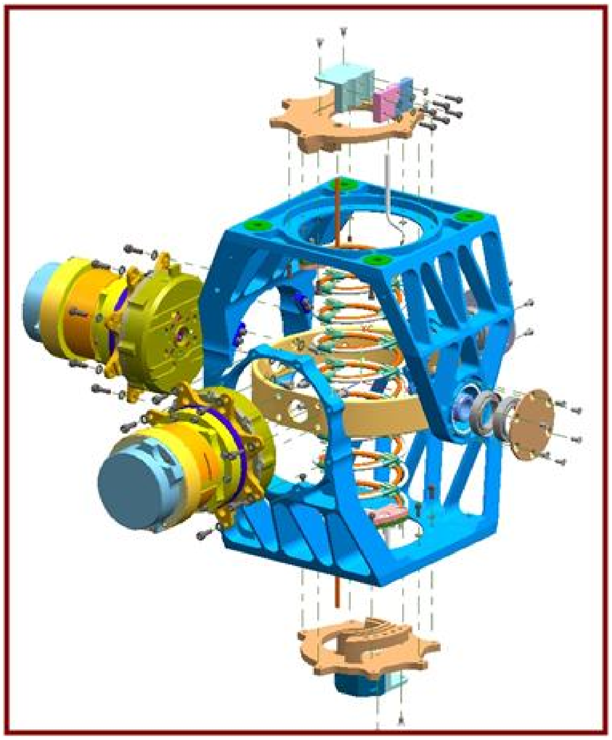


Figure 1. Modular Construction

Rotary Actuator

Two rotary actuators are provided for the articulation of the Thruster Gimbal (Figure 2). The rotary actuators consist of four-phase unipolar stepper motors coupled with Harmonic Drive gear transmissions. These actuators are also configured with large output flanges mounted on preloaded duplex bearing set. This bearing mounting provides a high degree of moment stiffness while causing minimum drag torque reflected to the motor, at the input of the Harmonic Drive gear reducer. A potentiometer is provided for position telemetry. It is located in the rear section of the actuator, with the potentiometer wipers directly connected to a shaft that extends through the length of the actuator from the output flange. Since the output of the actuator is attached to the inboard/outboard platform of the thruster gimbal, the position indication of the potentiometer located inside the actuator correlates directly with the gimbal axis angle.

Inboard and Outboard Platform

The Inboard and Outboard Platforms are almost identical components, with the exception of the mounting hole patterns designed to accommodate spacecraft and thruster mounting interfaces (Figure 3). Other differences between the Inboard and Outboard Platforms are the use of different materials for the mounting spacers, which will be discussed in the “Thermal Control Features” section. Materials for these brackets were selected carefully, due to the requirement for low weight and the critical dimensional requirements for orthogonality and parallelism of the gimbal axes

For simplicity and light weight, the brackets were designed as one-piece machined parts. The basic U-shape and the extensive lightweighting employed in the design mean that a large amount of the original billet material is removed in machining to the net shape. The need for stability of certain critical dimensions in the finished parts- required for gimbal performance- resulted in special design considerations. In addition to light weight, a material exhibiting good dimensional stability over time was needed. After researching the available materials, a 7000-series aluminum was selected as having the best combination of properties. This material demonstrated high dimensional stability in the finished brackets.

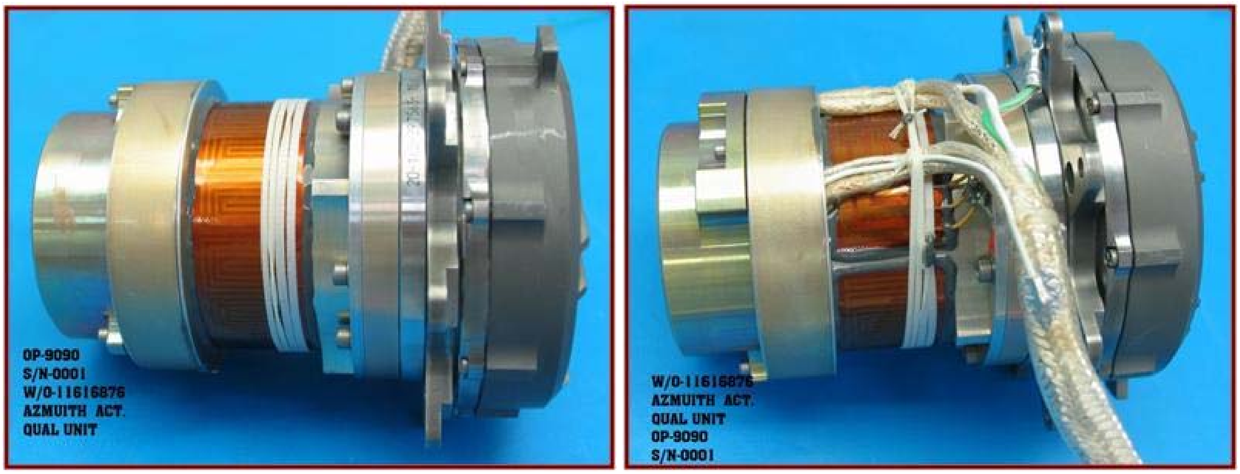


Figure 2. Elevation and Azimuth Rotary Actuators with Heaters

A number of other design features were incorporated to produce a high stiffness-to-weight ratio. These features were carefully implemented in order to avoid weak points in the structure and to avoid interferences over the large articulation range of the gimbal.

Gimbal Ring

The Gimbal Ring is the structural member connecting the Inboard and Outboard Platforms of the Thruster Gimbal (Figure 3). It is in the load path and is a critical structural component.

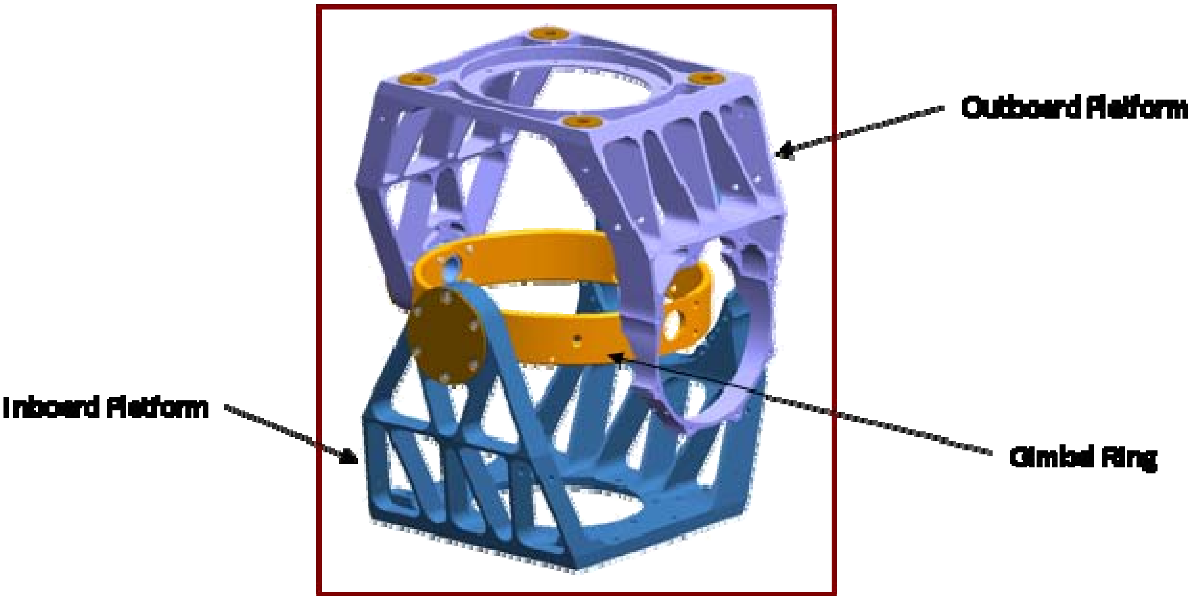


Figure 3. Inboard and Outboard Platform with the Gimbal Ring

The gimbal ring is designed as a large round annular structure, creating a circular clearance volume in the center of the gimbal. Although changing in shape, that volume remains clear over the full articulation range of the gimbal, and can be used for routing the flexible propellant tubing across the gimbal. Early in the gimbal development, it was realized that the propellant tubing design would dictate the size of the clearance volume and therefore the size of the gimbal ring. For light weight and high stiffness, it was desirable to minimize the size of the gimbal ring. However, design of the metal propellant tubing coils for adequate flexibility required a relatively large coil diameter and therefore a larger gimbal ring.

These opposing requirements were resolved through an unorthodox approach to design and material selection. Material selection was the more powerful tool, since the geometry of the gimbal ring is constrained by gimbal and propellant coil dimensions. Available materials were surveyed for the relevant properties, primarily density and bending modulus. Traditionally, titanium alloy has been the material of choice for high stiffness and light weight. In terms of specific stiffness (stiffness per unit mass), however, titanium is similar to other material choices. A more creative approach to material selection was needed.

To best meet the design requirements for the Gimbal Ring, Moog selected an aluminum grade containing reinforced composite material. To produce the gimbal ring, a near-net-shape ring of the material was first forged. Using the material supplier's recommended cutting and fabricating techniques, that billet was then machined to produce the one-piece Gimbal Ring structure.

Propellant Line Assembly

From the fluid system design standpoint, cleanliness and smoothness of the interior surfaces were the driving requirements for the Xenon propellant tubing. A stainless steel alloy was selected as the tubing material. A small tube diameter supports the small required flow rate, and a nominal wall thickness was adequate to contain system pressure. From the gimbal design standpoint, flexibility of the tubing was most important.

Full articulation of the thruster gimbal is ±35 degrees, on both axes, from the symmetrical or zero position. The metal propellant line assembly must accommodate that range of motion. To incorporate the necessary flexibility into the tubing assembly, the geometry of a large helical coil was selected. The tubing coils can accommodate both axial (stretching/compression) and lateral (bending) deflections. The height of the gimbal and the inside diameter of the gimbal ring allowed a tubing coil design which can accommodate the maximum deflections with acceptable material stresses in the tubing and low torque loads induced on the gimbal actuators.

The geometry of the tubing coil is that of a soft helical spring constrained only at its ends- a necessary feature in the gimbal application. Vibration input to such a structure can induce a large response, and this was a major concern with the tubing coil.

The fluid system design for the thrusters requires two Xenon supply lines. This feature was used to design a vibration-resistant tubing coil assembly. The two lines were designed as concentric coils having the same number of turns end-to-end. The difference in coil diameters resulted to separate natural frequencies for the two coils, and it was thought that tying the two together at intervals would force a response at a different frequency and much lower amplitude (Figure 6, Figure 6a).

An experiment was conducted on an engineering prototype with the inner and outer propellant lines coupled together at every 90 degrees around the coils. Exposure to random vibration showed response at a single frequency, as intended. However, amplitude of the response was still unacceptably high, achieving only a partial solution to the problem.

The vibration concern with the propellant tubing coils arises only at launch, and the stowed configuration of the gimbal at launch is not at the symmetrical or zero position, but rather at the fully articulated position; i.e., +36 degrees rotation on both the X and Y axes. In that gimbal configuration, it was found that the coils could be tied to gimbal structure in order to limit and control the vibration response. Properly spaced flexible tension members performed this function in the launch configuration, and then went slack in all operational configurations of the gimbal, not interfering with coil movement. This solution was implemented simply with tie cords spaced at optimum locations on the tubing assembly (Figure 7). These two design measures produced a tubing assembly with the flexibility to allow full gimbal deflection and the support needed to withstand launch vibration.

Another requirement on the propellant line assembly was maintenance of tubing temperatures conducive to proper performance of the xenon propellant, and therefore heaters were required. Adhesive-backed film heating elements are normally used for this function; however, the 1/8-inch (3.2-mm) diameter propellant tubing did not offer sufficient flat areas for application of the heaters. Further, the tubing coils flex in operation, compromising adhesion of such heaters. A different solution was needed.

The heating elements to be used require flexibility similar to the flexibility of the tubing coils themselves. Therefore, resistive heater wires formed into coils matching the tubing coils were fabricated. The heater wires were sandwiched between two layers of insulating Kapton film (Figure 5).

Figure 4. Outer Propellant Tubing with Heater

Figure 5. Inner Propellant Tubing with Heater

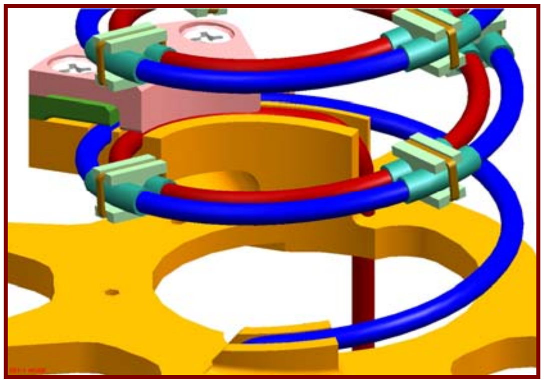
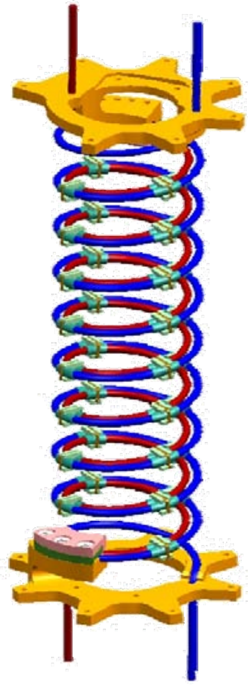


Figure 6. Propellant Line Assembly with Spacers



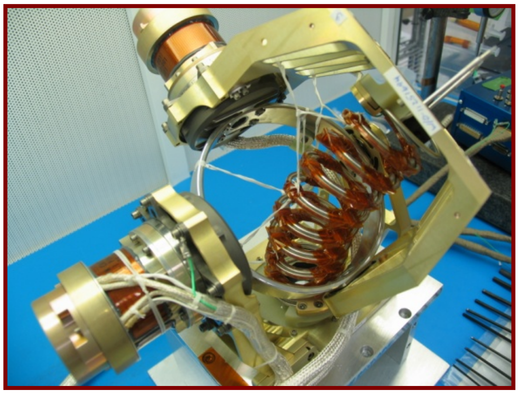


Figure 7. Fully Articulated Assembly with Restraining Cords

Figure 6a. Propellant Line Assembly

Thermal Control Features

The operating environment of the Thruster Gimbal presents a number of challenging thermal design problems. As discussed above, the propellant supply lines are furnished with heaters. Heaters are also provided for the gimbal actuators. For temperature monitoring and control, thermistors are located on the propellant lines near the Inboard and Outboard Platforms as well as on the actuators.

The location of the thruster gimbals on the spacecraft is such that they are exposed to extreme temperatures and temperature gradients. In the worst case, the gradient from Inboard to Outboard can be as high as 100 deg C. This extreme thermal condition was mitigated by tailoring thermal conductivity at the gimbal interfaces. At the Inboard Platform interface with the spacecraft, a set of four aluminum spacers were used to promote conductivity. At the Outer Platform interface with the thruster assembly, four spacers were used to limit heat transfer from or to the thruster assembly and to promote isothermality of the gimbal structure.

The spacecraft operating scenario results in the Thruster Gimbal being exposed to a deep space view, and the resulting extreme cold, for extended periods of time. A flexible multilayer insulation blanket encapsulating the entire gimbal was used to protect against the resulting radiant heat loss, and, again to promote isothermality of the gimbal. Innovative design of the Multilayer Insulation Blanket (MLI) was required to accommodate the large travel angles of the gimbal. A camera bellows type of construction was used, and was found to offer minimum additional torque load on the gimbal actuators (Figure 8).

Figure 8. Multilayer Insulation (MLI) Blanket

General Performance of the Thruster Gimbal

Thruster Gimbal Specifications

Physical Characteristics	
Dimensions	22.23 x 12.7 x 12.7 cm (8.75 x 5 x 5 in)
Weight	< 5 kg (11 lb)
Payload Weight	22.7 kg (50 lb) (externally supported)
Performance	
Total rational range of travel	±36.5 degrees in two axis
Angular resolution of gimbal	0.01125 degree
Angular velocity	1 deg/sec (nominal)
Angular accuracy of gimbal	Under 0.02 degree
Operating temperature range	-20° C to +80° C
Power Requirements	
Power Consumption	22 watts max. per actuator

Lessons Learned

The motor in the elevation and azimuth actuators is a four-phase 1.8-degree hybrid stepper, wound for unipolar excitation. The motor design has high magnetic efficiency, allowing it to produce high output torque and unpowered holding torque at relatively low power levels. The high magnetic efficiency results in part from a small motor air gap. The air gap is the radial clearance between teeth on the moving rotor and opposing teeth on the stationary stator core. Although it is important to maintain a small air gap in order to achieve optimal motor performance, it is equally critical to ensure that the clearance between parts in the air gap is maintained. It was recognized early in the development phase that diligent measures would be required to insure consistent air gap dimensions in production units. All elements affecting air gap variations were thoroughly analyzed and a Critical Clearance Analysis report, based on worst case values, was generated.

Approximately 26 actuators were produced (some shown on the completed gimbals in Figure 9). In thermal cycle testing, one axis of a thruster gimbal stopped operating during a high temperature portion of the cycle. As a troubleshooting step, the chamber temperature was lowered. The affected actuator then resumed normal operation. The preliminary conclusion was that the anomaly was temperature-related.

Figure 9. Completed Gimbals

The gimbal was disassembled and the problem traced to one of the actuators. Actuator disassembly then further isolated the cause of the problem to the motor. Motor disassembly showed rub marks on the rotor with matching marks on the stator. These marks were consistent with a condition causing the rotor-to-stator clearance to be lost, with resultant physical contact.

The Critical Clearance Analysis was revisited, and no errors in the methodology or calculations were found. However, it was noted that the analysis assumed a uniform coating of insulating material thickness on the critical rotor and stator surfaces. This assumption was investigated further.

The magnetic materials susceptible to corrosion are protected by a thin film of epoxy material- a so-called ‘wash coat’- which forms a barrier coating over the otherwise vulnerable surfaces.

Wash coat application is a standard and well established process used on virtually all Moog motors. However, the majority of motors produced are of the three-phase permanent magnet stepper design, with relatively larger air gaps not requiring extremely tight control on coating thickness.

The conclusion of the investigation was that the actual thickness of the wash coat in places exceeded dimensions assumed in the Critical Clearance Analysis and, together with differing thermal expansion coefficients and/or thermal gradients in the motor assembly at high temperatures, caused the closure of the air gap and resulting stoppage of the motor. Figure 10 and Figure 11 demonstrate the radial location where the air gap closure occurred.

Figure 9. Rotor

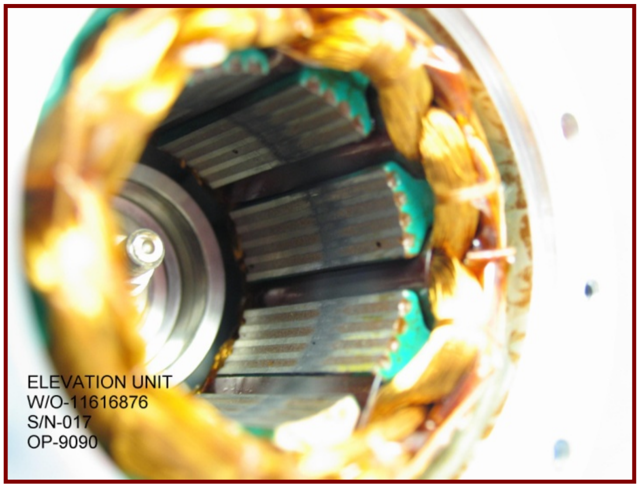


Figure 10. Stator

Conclusion

Design and development of the Two-axis Thruster Gimbal was completed largely free of interruptions and course corrections. However, a significant number of up-front analyses were precipitated by the stringent operating, performance, and weight requirements. In addition, a Monte Carlo analysis was performed to predict performance in simulations using randomly selected thermal and operating parameters. To further ensure successful production of flight hardware, several Engineering units of varying degrees of complexity were built and tested. By the conclusion of the Final Design Review, an extraordinary amount of analytical and test data had been accumulated, indicating a well conceived and low risk design approach.

A large part of the development effort was focused on the mitigation and suppression of, and compensation for, the extreme thermal conditions to which the gimbal would be exposed. Heaters which could be mounted on moving and flexing members were developed, as well as complex, flexing thermal blankets designed to contain thermal energy and promote isothermality. Aggressive weight reduction measures were also implemented in order to achieve an optimized design with adequate margin.

Unique testing methods were developed, enabling testing of the Thruster Gimbal with simulated payload and launch lock mechanisms in order to emulate flight-like test conditions with high fidelity.
Despite the up-front development effort and the extensive analyses performed to lower and/or eliminate risk, an oversight in process selection allowed a test anomaly to occur. A motor fabrication process commonly used for Moog motors, but inappropriate for the optimized Thruster Gimbal motors, was used. The process was modified to specifically address the unique characteristics of the Thruster Gimbal. Numerous other process improvements were implemented as well as the specific testing measures used to isolate and correct the observed anomaly.

Moog has successfully produced a number of the Thruster Gimbals, and has recently concluded a second life test program, demonstrating 2X life. This follows the original life test program which successfully demonstrated 1.5X life.

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