WHITE PAPER

Design and Development of Model-S Thruster Gimbal Assembly with Integrated Launch Lock

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Introduction

Moog Chatworth Operations (MCO) has designed, developed, qualified and flown two-axis thruster gimbal assemblies intended for precision pointing of large Electric Propulsion (EP) thruster used in space applications. These heritage gimbals are equipped with propellant lines, electric power line management, active and passive thermal management hardware which includes a thermal blanket. The heritage configuration was designed to support and operate Xenon Thrusters and other EP thruster in a zero G environment. In the past configurations, the support of the EP thruster during launch and offloading the sensitive components of the gimbal have proven to be a complicated endeavor requiring extensive structure and support mechanism. The motivation behind the gimbal presented here is to present a compact and self-contained gimbal assembly equipped with an integrated launch-lock capable of supporting the EP thruster while protecting the sensitive components of the pointing gimbal assembly.

The new Model-S Thruster Gimbal Assembly (Model-S TGA) presented hereafter is a smaller derivative of the original configuration specifically designed to address Small Satellite applications. The Model-S TGA allows close integration and support of EP thruster, its propellant lines and electrical power lines in a small footprint, occupying minimal envelope which is typically at a premium on smaller satellites.

In addition to the features provided by the heritage gimbal, the Model-S TGA is also equipped with its integrated launch-lock mechanism. The integrated launch-lock mechanism allows the gimbal to support an EP Engine in a zero (nominal) operating position during launch. Once the launch-locks are deployed, the gimbal can then articulate through its operating range avoiding the launch-lock mechanism.

Performance Requirement and key Features

Beyond the basic pointing application of an EP thruster, there are other key design drivers that dictate the configuration of the final mechanism. The development of the Model-S TGA was initiated to address as many of the key design requirements as possible within a small volume and weight limitation often encountered on smaller satellites. While the product presented herein addresses most of the key requirements, some factors such as articulating angle had to be established as hard physical limitation.

The S-TGA is equipped with two stepper motor driven actuators each designed to articulate one axis of rotation in an independent manner. This operation is an open-loop design that is able to point each axis with a resolution of 0.0375 degrees per commanded step. In addition, the target position could then be maintained without application of electrical power which significantly simplifies the command-and-control electronics. Adversely, closed-loop systems require complicated and expensive electronics and position feedback knowledge to continuously point and correct the intended point position.

The payload of the S-TGA is an EP thruster that is equipped with propellant feedlines and electrical power cable. The articulation of the EP can only be accomplished if the propellant lines and the power cable are free to move during the pointing exercise. Since the propellant lines are made of solid wall tubing that are inherently rigid, the propellant lines must be configurated like a coiled spring which will allow bending during the articulation of the gimbal. The spring-like propellant line configuration also has limitations. Flexibility could be increase by increasing the number of coils and reducing the pitch. However, this could have envelope limitations and could result in a longer than desirable propellant line resulting in excessive pressure drop from end to end. In addition, excessive flexibility will have undesirable displacement during launch vibration. Adversely, having a propellant line with fewer coils and smaller coil diameter could result in a stiff structure that would take away from the available motor torque. Also, it could become a life limiting component due to fatigue in long operating applications. Therefore, this configuration is a critical design parameter that needs to be addressed early in the program.

Supporting an EP thruster during flight and ensuring that the vital components of the gimbal such as the actuators and the potentiometer assemblies survive the launch induced loads is one of the responsibilities of the integrated launch lock. However, in addition to this requirement, the vibration and shock induced loading onto the EP thruster must remain within the acceptable limits of the thruster. This requires vibration isolation between the gimbal and the EP thruster to adequately attenuate the loads.

The integrated Launch Lock Mechanism (LLM) is designed to perform the abovementioned tasks by offloading and protecting the critical gimbal components and the EP thruster. When engaged, the LLM is designed to create a load path in such a manner that it offloads the gimbal where the LLM then becomes the primary load path. The LLM extends the entire length of the gimbal and provides a high stiffness structure when engaged. Release of the LLM is performed by activating two frangibolt actuators. The strain energy release during the deployment of the frangibolt actuators induces shock loads onto the gimbal and its components. By design, this shock load is attenuated and isolated so that the critical components of the gimbal and thruster are not adversely affected.

In addition to the structural development of the S-TGA, other development such as propellant line designs and life testing of the propellant lines, have been conducted to demonstrate torque/flexibility, clamping methodology, packaging and life. Figure 1 below is an abbreviated highlight of the primary components of the LLM used during development.

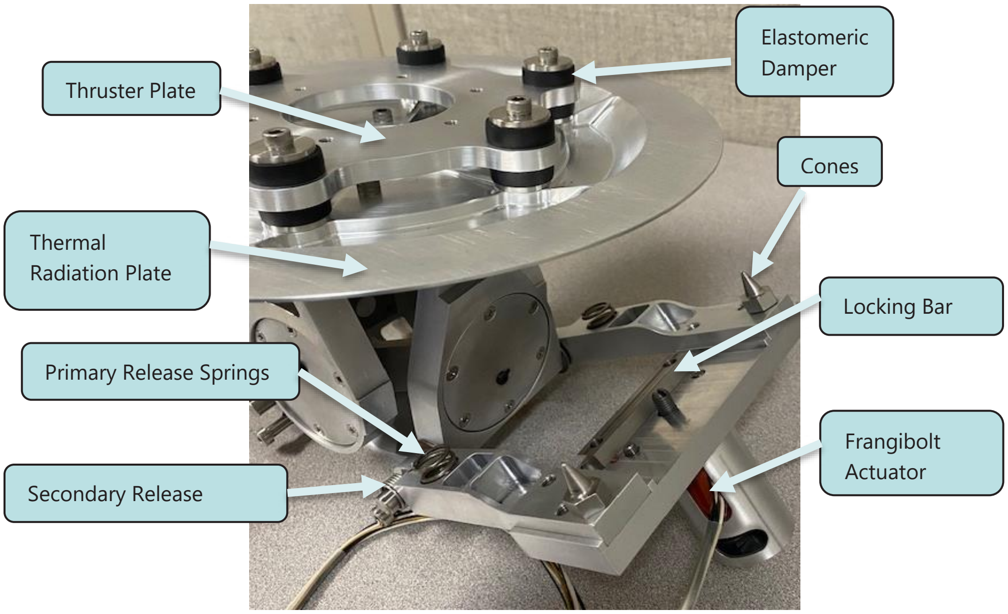


Fig. 1 Launch Lock Mechanism Components

Launch Lock Mechanism Capability and Performance Verification

As noted earlier, the design and configuration of the LLM is such that it is capable of the supporting the payload, offload the gimbal and its critical pointing components during launch vibration and shock induced from its own deployment/separation event as well as spacecraft induced shock loads. In addition, the LLM is designed to limit the exposure of the payload from high shock and vibration loads.

The LLM is equipped with two main locking arms each equipped with two sets of cups and cones that are intimately in contact and preloaded when the locking arms are engaged and kept engaged using frangibolt actuators.

In this configuration, the gimbal is offloaded. The load path from the payload to the spacecraft is now redirected through the locking arms to the base of the gimbal. An additional locking feature is provided using the Locking Bars to enhance the moment load capability of the LLM.

With the application of 28VDC to the frangibolt actuator during the deployment operation, the actuator expands and places the specially designed frangibolt in tension. The frangibolt is designed with a notch that can only tolerate a tensile force of approximately 15,000 N. When this force is exceeded by continuous expansion of the frangibolt actuator, the bolt is fractured releasing the preload and cause deployment of the LLM. Without the bolt forcing the intimate contact between the cups and cones and the wedge bars, the locking arms are forced to separate using a high force low displacement compression spring. Secondary torsional springs are also provided at the pivot point of the locking arms to ensure that once the locking arms are separated/deployed to their maximum open position, they remain in this position for the duration of the gimbal's operating life and don't interfere with normal operation.

The above mentioned LLM must be able to deploy at both hot and cold operating temperatures and the shock loads during deployment must remain within the load capability of its operating components so that its critical components remain undamaged. In addition, it had to be demonstrated that non-simultaneous deployment of both frangibolts would have no adverse effect on the release mechanism and to verify that full deployment of the LLM is possible under such conditions. To demonstrate this, a working prototype was built using flight like LLM and frangibolts actuators. A 3.75 Kg mass simulator was installed onto the Thruster Plate. The gimbal was instrumented with accelerometers and placed in a thermal chamber. The temperature of the chamber was lowered to -35 degree C and the +Y axis frangibolt was actuated. The +Y axis locking arm was deployed and separation was confirmed. Approximately five minutes after the deployment of +Y axis, the -Y axis locking arm was actuated and the locking arm was deployed. The response from the accelerometer at the payload interface is shown in Figure 2 and Figure 3 below.

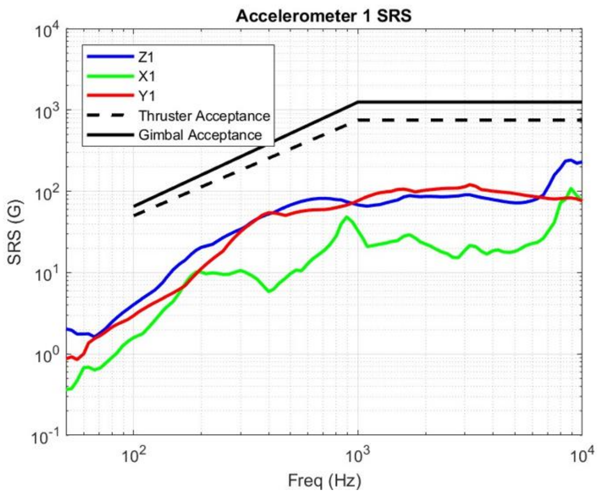


Fig. 2 Result of +Y Launch Lock Release

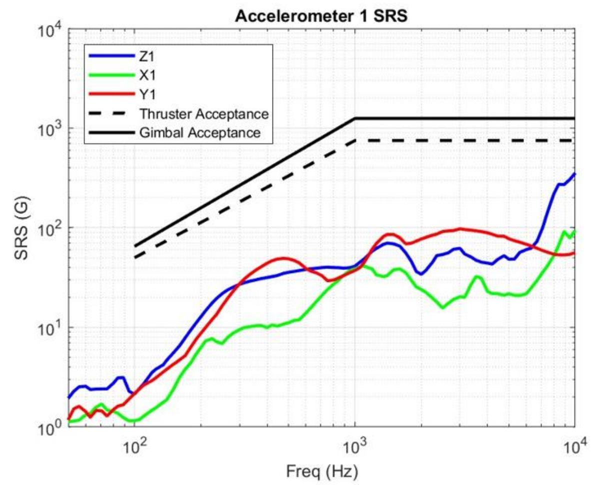
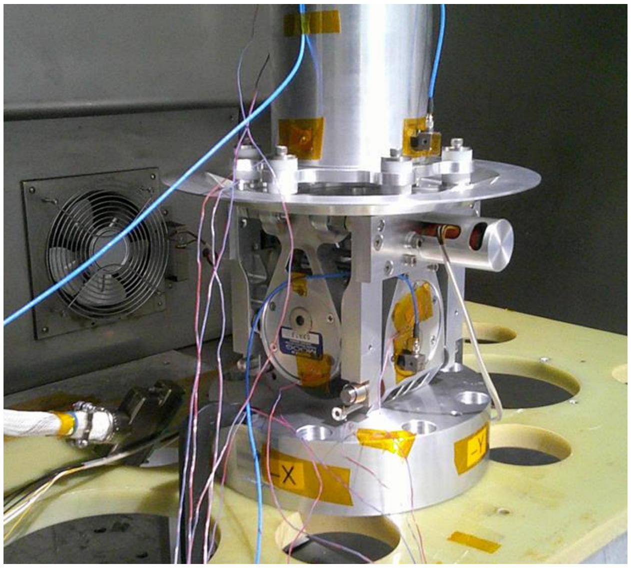


Fig. 3 Result of -Y Launch Lock Release

An evaluation of the plots in Figure 2 and Figure 3 indicates with the deployment of the LLM at -35 deg C the resulting shock loads at the payload were below the maximum allowed levels. This indicates that the secondary spring dampers located at the interface between the gimbal and the payload adequately isolated the payload from excessive LLM deployment shock loads.

Figure 4 shows the test article in the thermal chamber with the LLM engaged. Figure 5 shows the test article at -35 deg C with the -Y axis locking arm disengaged.



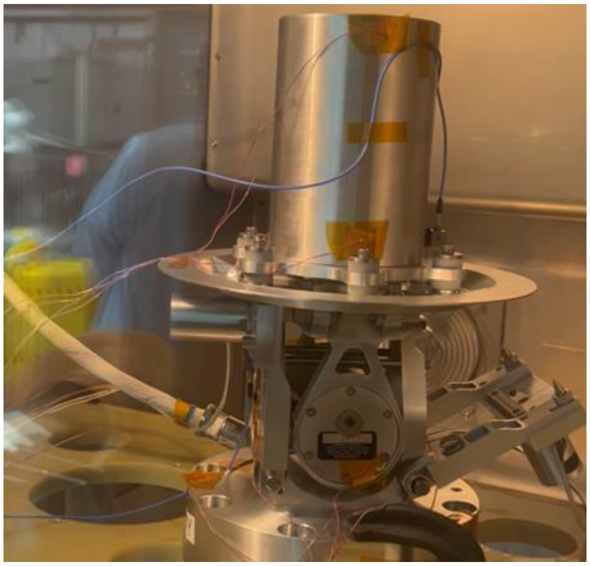


Figure 4 Test Article with the LLM Engaged **Figure 5 Test Article with -Y Axis LLM Disengaged**

At the conclusion of the deployment/shock testing reference above, the test article was exposed to random vibration testing in all three axes. The test was designed to validate that the LLM is capable of handling random vibration at Qualification levels, and ensure that vibration loads at the payload interface are within the acceptable limits for the EP thruster selected for this application.

Figure 6 below shows the analytical versus actual frequency response from an accelerometer located on the Thruster Plate. The solid blue line represents the test data and the dashed blue line represents the analytical data. These two plots track relatively closely especially at lower frequencies. This validates the accuracy of both the model and the analysis.

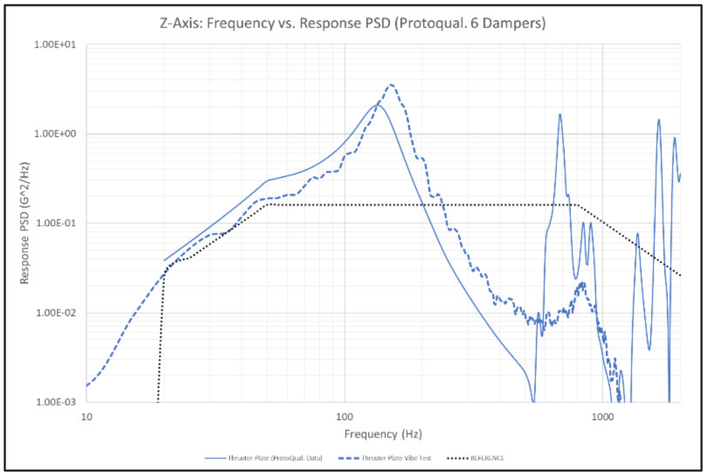


Figure 6 Random Vibration Data vs. Analytical Data

A key requirement for the final development of the Model-S TGA was to demonstrate the effectiveness of the vibration isolators, which are intended to reduce the G loads seen at the payload interface. The original configuration of the development hardware was designed using six supporting locations equipped with elastomeric dampers. To characterize the influence of the dampers, random vibration testing was conducted with all six dampers. Later two of the inline dampers were removed and random vibration tests were repeated. Figure 7 below is a plot of the frequency response recorded at the payload interface in both six (solid line) and four damper (dashed line) configurations.

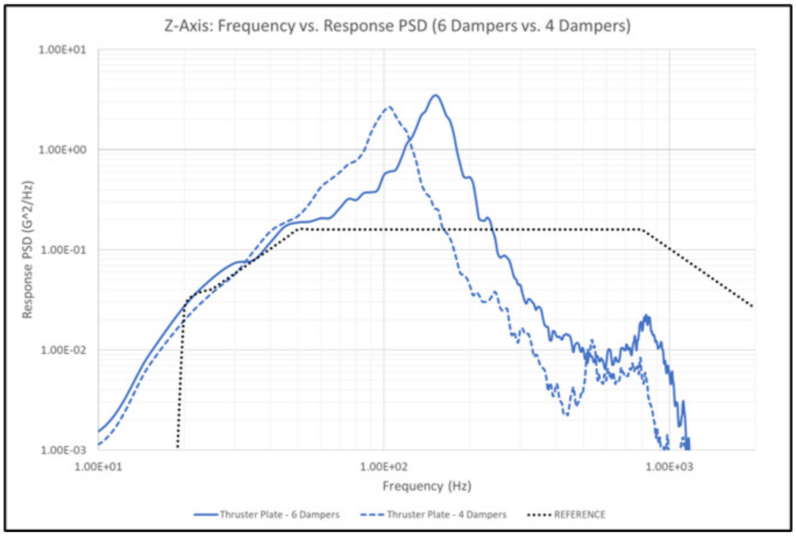


Figure 7 Random Vibration Test Data of 6-damper vs 4-damper Configurations

In comparing test results for the 6-damper and 4-damper configurations, the data demonstrate a frequency shift from 140 Hz to 105 Hz and a reduction in PSD response from 3.4 to 2.7 G^2/Hz, respectively. This data will be utilized in finalizing the damper configuration.

Technical Description of Model-S Thruster Gimbal Assembly

The Model-S Thruster Gimbal Assembly (S-TGA) is a two-axis gimbal with independently operating axes, configured in an orthogonal manner. The articulation of each axis is made possible using Moog heritage Type 1 actuators which are equipped with a 3-phase stepper motor coupled with a strain-wave zero backlash gear transmission. Type 1 actuators are designed to operate in an open-loop manner and are capable of producing unpowered holding torque in the absence of electrical power. This capability can be enhanced if power is applied to the motor windings without commanding stepping sequences.

The output flange of the Type 1 which is attached to the Outboard Bracket of the gimbal is a stiff, zero backlash structural member equipped with a preloaded duplex bearing assembled in a titanium housing for maximum strength, stiffness to weight ratio and thermal compliance.

Opposite from the actuator but located on the same axis of rotation a potentiometer assembly is placed to provide unambiguous and absolute position knowledge of the gimbal's pointing angle. Given the limited operating life and for the benefit of simplifying the telemetry and its electronics, the resistive-track potentiometer is an optimal choice. For this application, an angular displacement results in a change in resistance for the potentiometer which results in a DC output voltage that is directly associated with a specific angular position.

The potentiometer used for this application is designed to operate in a high shock environment. However, to further attenuate the shock loads, the load path is routed through two layers of isolating materials, designed to protect the potentiometer and its vital components during high shock loads.

The connection between the Type 1 actuator and the potentiometer assembly is via the Gimbal Ring which is centrally located to facilitate the gimbal-like movement of the mechanism. The propellant line assembly and the power cables for the EP Engine are routed through the center of this gimbal ring where the displacement of the coiled propellant lines and the power cable is at the minimum at this location. Ultimately, the Gimbal Ring connects both the X and Y axes to each other at this location.

A subtle difference between the axes of rotation is that the body of the Type 1 actuator for the X axis is stationary and attached to the Inboard Bracket where its output flange is the rotating component attached to the Gimbal Ring. This contrasts with, the body of the Type 1 actuator for Y axis is attached to the Outboard Bracket and is the moving component. The Y axis output flange is attached to the Gimbal Ring, which is the stationary component. The relative motion between the body of the actuators and their respective output flanges is the same for both X and Y axes.

The thermal management of the gimbal is designed with both active and passive components. The Type 1 actuators' thermal prediction requires them to be equipped with foil heaters and thermistors. With the application of approximately 20 watts for a duration of 5 minutes the desired operating temperature is reached at an extreme cold thermal environment.

One passive thermal feature includes the application of the thermal coating to the outside visible surfaces of the gimbal to increase emissivity and thereby improve radiative cooling. A second passive thermal feature is the Thermal Radiation Plate which is located between the EP thruster and the gimbal with an intent to shield the vital components of the gimbal from the thermal energy of the EP thruster plume. The Radiation Plate is then further isolated from the gimbal at its mounting connections using titanium spacers.

The frangibolt is the release/deployment mechanism for the LLM. At the application of 28 VDC power the actuator expands and fractures the bolt that is under preload. Once the bolt is fractured, the threaded piece of the bolt remains in the bracket while the main body of the bolt is released and ejected away along with the body of the frangibolt. To prevent excessive shock and generation of debris, a housing is provided to encapsulate and capture the actuator and its preloading bolt when they become disengaged. A rubber snubber is placed at the rear of this housing so to absorb the impact energy of the separated bolt. In addition to capturing the loose components of the frangibolt during deployment, the housing is designed to be mounted after the installation and preloading of the frangibolt. Figure 8 below is a complete assembly of the Model-S TGA. (Note: The radiation plate can be custom designed for each application, as in this case.)

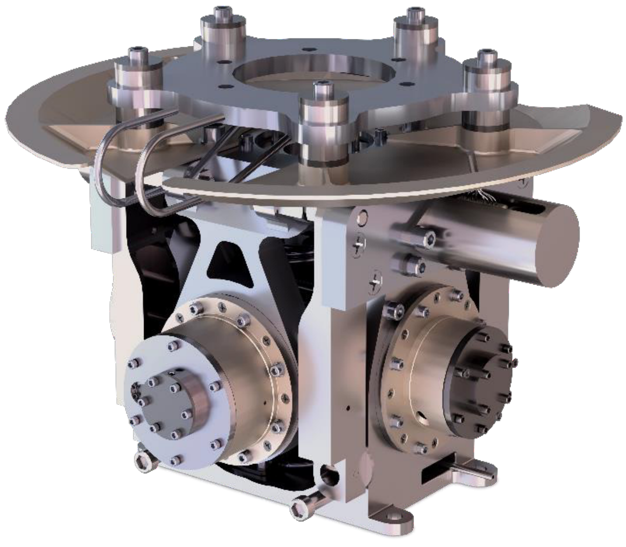
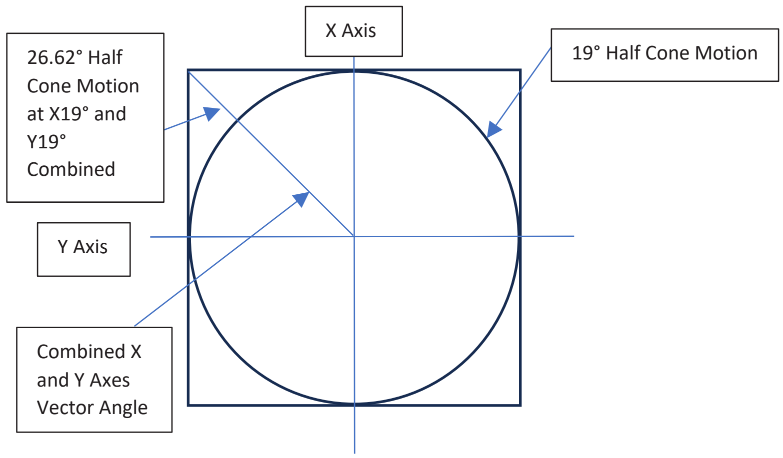


Figure 8 Model-S Thruster Gimbal Assembly

Thruster Vector Orientation in X, Y and Combined Angles



Model-S TGA Capability and Performance Summary

Description	Units	Capability
Pointing Resolution	Degree	0.0375
Pointing accuracy	Degree	0.025
Articulating Angle	Degree	±19 maximum
Number of Axes		Two orthogonal axes intersecting (true gimbal) and independently operated
Payload Capacity	Kg	3.75
Operating Speed	Deg/sec	3.75 maximum
Operating Voltage	VDC	28
Operating Current	Amp	0.269 (current limit setting)
Operating Power per Axis	Watt	4.5
Motor Configuration		3-phase, stepper
Position Knowledge		Potentiometer - absolute position sensor
Position telemetry accuracy	Degree	1
Torque Capability	Nm	8
Unpowered Holding Torque	Nm	3
Number of Propellant Lines		2
Size of Propellant Lines	mm	3.17 OD x 2.36 ID
Power Cable Management		External or Internal to the gimbal
Thermal Management		Heaters on the actuators
Launch Lock Mechanism Actuator Type		Frangibolt
Envelope (with the launch locks engaged)	mm	171.5 Height x 247.7 X 247.7
Mass	kg	4.8 (Mass includes Radiator Plate and Interconnecting Thruster Plate)

Conclusion

The two-axis heritage gimbal equipped with a number of features uniquely suited for EP thruster applications is the basis for this development. The newly developed gimbal presented here is a more compact and lighter weight version of the original and is, designed to serve the smaller payload and satellite markets. Unlike the original configuration where traditionally ample volume at the outer surface of the spacecraft has been available, the newer and smaller satellites have a premium on space thus limiting the design freedom to a great extent. This limitation along with other kinematic constraints such as the management of sold wall propellant lines and power cable have forced the design to integrate features like launch locks which occupy a much smaller envelope/volume as compared to the heritage configuration. Imparting the responsibility of the gimbal/LLM of supporting the mass of the EP thruster during launch dynamics burdens the gimbal with ensuring that the launch loads are not so amplified that they exceed the capability of the EP thruster. In addition, the responsibility of thermal management and compliance is also passed on to the gimbal as it is between the high heat generating EP thruster and the spacecraft. Therefore, the final configuration must address number of different requirements ranging from operational to mechanical and thermal support.

Model-S TGA is a compact structure designed to function as a plug-in between the EP thruster and the spacecraft. Early in the development, a trade study was performed to study the effect of supporting the EP thruster during launch dynamics without the use of additional launch locks. Given the targeted size and envelope of the gimbal and the intended payload capacity of the Model-S TGA, it was determined that an integrated launch lock would be the most optimal design for this class of gimbal offering. For larger payloads and given a larger gimbal mass budget, development of other types of gimbals not equipped with launch lock could be studied. However, the development of the Model-S TGA represents an almost 1:1 ratio between the mass of the gimbal and mass of the payload that it is designed to support during launch. This implies that a highly efficient configuration/mechanism has been achieved given all environmental and operating constraints that are associated with typical EP thruster support and operation.