Design and Development of the Cassini Main Engine Assembly Gimbal Mechanism

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Abstract

Cassini is an international cooperative effort between NASA, which is producing the orbiter spacecraft, the European Space Agency, which is providing the Huygens Probe, and the Italian Space Agency, which is responsible for the spacecraft radio antenna and portions of three scientific experiments. In the U.S., the mission is managed by NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California. Lockheed-Martin successfully bid on the contract to build the PMS (Propulsion Module Subsystem) for this project.

The Cassini spacecraft will be launched on an expedition to Saturn in October, 1997. Its mission is to enter orbit around Saturn in July, 2004, and to explore its moons, rings, and magnetic environment for four years. Cassini will carry the Huygens probe, an instrument package equipped with a parachute, which is designed to study the atmosphere and surface of Saturn's largest moon, Titan.

Introduction

This paper deals with some interesting aspects of the design and development of the Cassini main engine assembly (MEA) gimbal mechanism. This mechanism is a redundant, two-axis gimbal used for active thrust vector control of the main engine (or backup) during the 11-year mission to Saturn. Cone angle adjustments to the engine are necessary due to center of mass shifting as propellant is consumed and the Huygens probe releases. At the time of this writing, the Thermal Development Unit has been built and tested. The Qualification Unit has been built and successfully passed vibration testing; hot fire testing is underway. The Flight Unit has been built and passed acceptance testing.

Discussed in this paper will be interesting approaches to the design problems associated with extremely tight pointing requirements (3 milliradians) and gimbal freeplay reduction and analysis. An adjustable actuator mount and preloaded bearings were spawned from these requirements. Emphasis will be placed on the benefits of computer modeling, which was used extensively. Results, obtained from testing and analysis, demonstrate the effectiveness of these techniques.

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Brief Description

The Cassini main engine assembly, consisting of two 445-N (100-lbf), bi-prop engines (one as a backup) and associated hardware, is located at the bottom of the PMS.

The MEA includes all the parts suspended from eight tubular struts, which terminate at the lower ring frame of the PMS (Figure 1). In our final design, the engine assemblies are identical, except for their structural attachment parts, which are different due to an eccentric spacecraft center of mass through which the engine centerlines must point at null gimbal position. Each engine is mounted to a circular aluminum plate, which serves as the inner gimbal structure. The inner gimbal plate is supported by diametrically opposed bearings in an outer ring. The outer ring is attached to the main structural plate, called the thrust box, with another set of bearings in pillow blocks. This bearing set axis is orthogonal to the inner bearing axis. All bearings are identical precision stainless steel spherical. The bearing bore and the mating shaft are finished with an anti-friction coating to allow rotation at this interface, or the ball can rotate in its race, thus satisfying a requirement for redundant rotation surfaces. The spherical bearing was a good choice for the gimbal because of its compact size, high load capacity, small angle rotations and slow speeds, misalignment capability, and minimal freeplay.

Customer-furnished Engine Gimbal Actuators (EGAs) were specified to position the gimbal. Since the stroke and speed were pre-determined, a short moment arm was necessary to achieve the required minimum gimbal cone angle. The actuators are DC motor-driven ball screws. An LVDT resides in the hollow shaft to provide a position signal. The actuator attachment to the gimbal is a monoball and pin in a clevis. Attachment to the structure is through a universal joint and flexure. The u-joint and monoball isolate the actuator from bending moments during the angular changes of the gimbal as the actuators stroke linearly. The flexure is essentially a wide leaf spring. The thickness of this cantilever plate, and therefore the spring rate, was tuned to decouple the rocking mode of the gimbaled mass from the structural modes. Mounting the actuators in this manner provided the flexibility to change this one component if testing yielded different rocking modes than predicted analytically.

Mounted to the circular engine plate is a split tubular structure, called the tower. The tower served as the structural interface to the gimbal for the propellant lines, actuators, pressure transducers, filters, and the diode box. In addition, the tower assembly serves as a counterbalance for the rocket engine and heat shield. Through accurate solid computer models of the tower and its components, we were able to determine the center of the gimbaled mass. One of our requirements was a 890-N (200-lbf) maximum axial load on the EGAs. In order to meet this requirement, we were required to balance this assembly within a fraction of an inch of the rotation center point (RCP) of the gimbal. We achieved this goal, despite several re-designs, by iterating with incremental displacements of key components.

Faster, Better, Cheaper

From a blank sheet of paper to a finished design, the gimbal mechanism evolved in about the time it takes to have a baby. Well, not quite a blank sheet of paper. Through the miracle of technology transfer, we inherited JPL's preliminary design. At first blush, the JPL concept appeared quite mature and perhaps just needed final polishing. But, as we systematically evaluated the design against the requirements (which, of course, had changed), we realized substantial re-design was needed. Also, many of the conceptual parts were heavy, and some presented manufacturing problems.

The first area of focus was the thrust box, the primary structural plate to which the gimbals and associated hardware were mounted. JPL's design was basically a rectangular box with the bottom machined at compound angles designed to point the rocket engines at the initial cg of the spacecraft. Assorted ribs and gussets were added for rigidity. The gimbal actuators were arranged from the hole centers, outward to the box corners (Figures 2 and 3). This plate configuration weighed approximately 20 kg and was impossible to machine due to asymmetry and complex angles required for the gimbal mounting. To simplify the design, the box bottom was made flat, and the complex angles were designed into the fittings, which now mounted and aligned the engine assemblies. Also, the actuators and attachment fittings were arranged toward the center of the box, thus eliminating the corners which were necessarily massive to react the actuator loads (Figure 4). The re-designed plate was easily machinable and weighed approximately 1/2 of the original. Just as we were about to eat our cake, we realized this approach generated much more re-design.

In order to realize the benefits of the better, cheaper box we had to tip it upside-down, literally — the actuators now had to be mounted outside, rather than inside, the box. This turned out to be a blessing, which facilitated the design of adjustable actuator mounts to precisely point the gimbals without impossible tolerancing of the parts.

The advantages of the new packaging scheme were obvious, but we needed proof that we could meet the basic requirement of a 12.5° half cone angle of gimbal travel. To accomplish this task faster and cheaper, a simplified computer model of the gimbal was constructed, using a tool called "Mechanism Design" by SDRC. This software uses an ADAMS solver but is much more user-friendly. After inputting all the appropriate joints and degrees of freedom and applying a forcing function to both actuators, one could sit back and watch the mechanism do its thing. By incrementally changing various geometric parameters and then re-running the model, the kinematics of the gimbal were quickly characterized. The parameters that could be varied were:

1. The distance above the gimbal axis at the actuator attach points
2. The actuator angle relative to the gimbal axis
3. The included angle between the actuators
4. The distance between the actuator attach points.

The actuators were GFE (government-furnished equipment), and the stroke was fixed. The results were not intuitive. Geometries that looked potentially good produced wild excursions of travel due to "toggling" of the linkage. In general, the best behaved travel patterns were produced by minimizing the offset distance between the actuator attach points and the gimbal centerline and by minimizing the actuator axis angle relative to the gimbal null plane. In a perfect world, both actuators would lie in a plane parallel to the gimbal null plane and be attached at the same point on an axis both normal to the gimbal null plane and passing through the gimbal rotation center. Since two objects cannot occupy the same space simultaneously, this configuration is impossible.

From this exercise, the best candidate was selected, and the strawman model was replaced with a high-fidelity solid geometry model closely representing flight hardware. Running this model took much longer but was necessary to check for possible physical interferences. As it turned out, there were possible interferences, which predicated the need for hard mechanical stops. The same model was refined further with the addition of hardware, propellant lines, and cabling. This ultimate model yielded gimbal mass properties which were needed to compare with the requirement for mass moment of inertia.

Using the computer modeling and analysis techniques saved us the time and expense of creating development hardware. We were able to perform several iterations in a short time. Another benefit of the 3D computer model was a direct link to the two-dimensional line drawings of the detail parts. Fit and tolerance problems were greatly reduced.

Flexlines

One of the stickiest problems that we encountered and did not anticipate was the gimbal flexible propellant lines. For this design task, development hardware took the place of computer models. The solution was more intuitive than analytical. Since the rocket engines can change orientation relative to the surrounding structure and the fuel tanks, flexible fuel lines are necessary. The routing of these flexlines seemed trivial until we built a simplified hardware model to test our ideas. The model was close to flight geometry but with much less detail. The flexhose was a vendor-supplied sample. Its configuration and material were different than our design, but it was close enough for our purposes.

The first configuration tried was the "McDonald's Arches" (Figure 5). The flexlines are side-by-side in an arch that spans between the engine mounting plate and the thrust box. This configuration was basically the same as that which we inherited from JPL. Rotating the gimbal away from the structural attach point for the flexline produced a high resisting moment; we were attempting to flatten the arch, stretch the hose, and reduce the bend radius simultaneously. Rotating the gimbal out of plane produced contortions in the flexline. We surmised that, due to offset between the gimbal rotation centerpoint and the flexline mounting point, we had introduced a torque into the flexline to which it protested vehemently. The flexline construction is a thin-walled, convoluted titanium core with stainless wire woven overbraid. Pure bending was not a problem, but torquing was forbidden.

To eliminate torque, we had a choice of either some sort of swivel joint (with necessary complexity) or aiming the flexhose end fitting through the rotation center point (RCP) of the gimbal. We took the simpler approach and moved one end of the flexline to the tower, where it could aim through the RCP. This configuration became the "Lazy D". Symptomatic twisting disappeared. But the "Lazy D" was too short; it acted as a mechanical stop to gimbal rotation away from the fixed end. Due to packaging limitations, we could not significantly increase the length in the "real" design. In addition, vibration testing by the flexline vendor produced destructive results for the "Arch" and the "Lazy D" configurations.

A third approach was tried by moving the structural attach point from the thrust box to the lower ring frame above the gimbal. The flexline then hung downward and mounted to the tower at right angles. This was the "J" configuration. Wild contortions were produced by out-of-plane gimbal rotations. Torque reared its ugly head. This behavior was predictable, since the movable end of the hose was offset from the RCP.

Our fourth trial was the "Ess". The "J" tower fitting was revised to aim the hose through the RCP. The hose assumed the shape of a shallow letter "S". Voila, the flexline was now happy. This configuration yielded the lowest forces at the gimbal and was least stressful to the flexline.

These tests were repeated at AVICA , our English flexline vendor, to a higher degree of fidelity with similar results. Gimbal torque tests were performed on the Thermal and Qual units using the "Ess" configuration, both pressurized and unpressurized, with excellent results. These flexible propellant lines are critical to the mission, and their responses are not analytically predictable. The development testing was absolutely required. The resulting final design configuration should meet the requirements for any gimbaled rocket engine.

Engine Pointing Accuracy

Our initial reaction to JPL's requirement of 3 milliradians of angular pointing accuracy for the main engine gimbals was shock, but we needed some data to negotiate a relaxation in this requirement. Initially, the problem was two-fold: initial pointing inaccuracy due to part and assembly tolerance stack-up, and pointing repeatability errors due to freeplay or clearances within the system. There was no practical way to machine everything perfectly, so we were left with two options to deal with the inaccuracies resulting from tolerances: either shim or provide an adjustment. Having an aversion to shimming and its attendant complexities, I opted for an adjustable EGA mount (Figure 6). The final design is a split block with a cavity, housing an adjusting screw. Only one half of the block has threads to match the screw. As the screw is rotated, the threaded piece translates, and the stationary block half absorbs the thrust loads from the screw via thrust washers. When adjustment is complete, bolts lock the two halves together. With these adjusters, we could correct for dimensional deviations. The stationary blocks were machined to different heights and angles to compensate for the asymmetric gimbal geometry.

The adjuster idea solved the aiming problem, but we still faced the freeplay issue. There were several contributors, such as clearances between gimbal bearings and shafts, actuator backlash, and shaft-to-housing clearance. By analysis, we were able to show freeplay alone could yield a pointing error of 15.3 milliradians. By far, the largest contributor to freeplay was the axial clearances at each gimbal axis. This was partly due to the tolerance stack-up of the parts and partly due to thermal expansion and contraction allowance. Our solution to this problem was to incorporate springs on the gimbal axes. The implementation of this idea took the form of preloaded belleville washers (Figure 7). They were chosen for their characteristic high spring rate in a small package. The preload range was high enough to prevent gimbal translation under any predicted loading conditions but still allowed rotation. The small amount of additional friction torque, which the preload created, was not even noticed by the actuators. A precision length bushing and thrust washers were used to determine the initial spring stack deflection and, therefore, the preload. Identical spring stacks were used on one bearing of each gimbal axis. The other bearing on each axis was allowed to float transversely. This gimbal bearing layout had the secondary benefit of allowing thermal growth without binding the bearings. This design has performed flawlessly in all testing, including vacuum firing of the rocket engine which reaches 1316°C (2400°F).

The only remaining source of freeplay was those which we could do nothing about: EGA ballscrew backlash, EGA universal joint clearances, and EGA monoball clearances. These parts were all GFE and were untouchable. Analysis showed that we still had a potential for 6.4 milliradians of freeplay. After much negotiation with the customer, the requirement was relaxed to this value.

Lessons Learned

Our lessons learned can be summarized as follows:

Flexline lessons

1) The hose length should be adequate for full gimbal travel in any direction, plus enough extra to allow the nominal shape of the relaxed hose to be a shallow double reverse curve, or "S".
2) In the null gimbal position, the entire flexline should lie in the same plane.
3) Under no conditions should torque be applied to the hose.
4) The centerline of the movable end of the flexline should intersect the rotation center point of the gimbal.
5) Get an early start on determining material and vendor. We had a bit of a hassle getting thin-walled titanium with the proper elongation. There is a limited number of vendors who make this product worldwide.

Gimbal geometry lessons (for gimbals of similar design)

1) Maximize the moment arm between the actuators and the gimbal axis.
2) Minimize the distance between actuator attach points at the gimbal.
3) Keep the actuators orthogonal to each other.
4) Keep the actuator plane parallel to the gimbal bearing plane, if possible.

Gimbal kinematic lessons

1) Kinematic modelers, such as "Mechanism Design" by SDRC or ADAMS, can save time in the design development stage.
2) Start with a simplified "stick model" to use computer resources efficiently and to allow quicker iterations of geometry.
3) Replace with a high-fidelity model when a solution is found. Use this model for clearance studies and mass properties.

Pointing accuracy lessons

1) Adjustments are generally preferred to shimming.
2) Reduce or eliminate freeplay, where possible (preloaded bearings).

Computer modeling lessons

1) No development hardware
2) Kinematic verification
3) Clearance/fit check
4) Transition to detailing
5) CAM.

"Better is the Enemy of Good Enough"

This is the message my boss constantly tried to get across during the design development process. Fortunately, with the aid of computer modeling, the CASSINI design engineers were able to evolve and refine the gimbal design through several iterations and still remain on schedule. Other than the usual number of manufacturing and procurement problems, the build of the three main engine assemblies has gone extremely well.

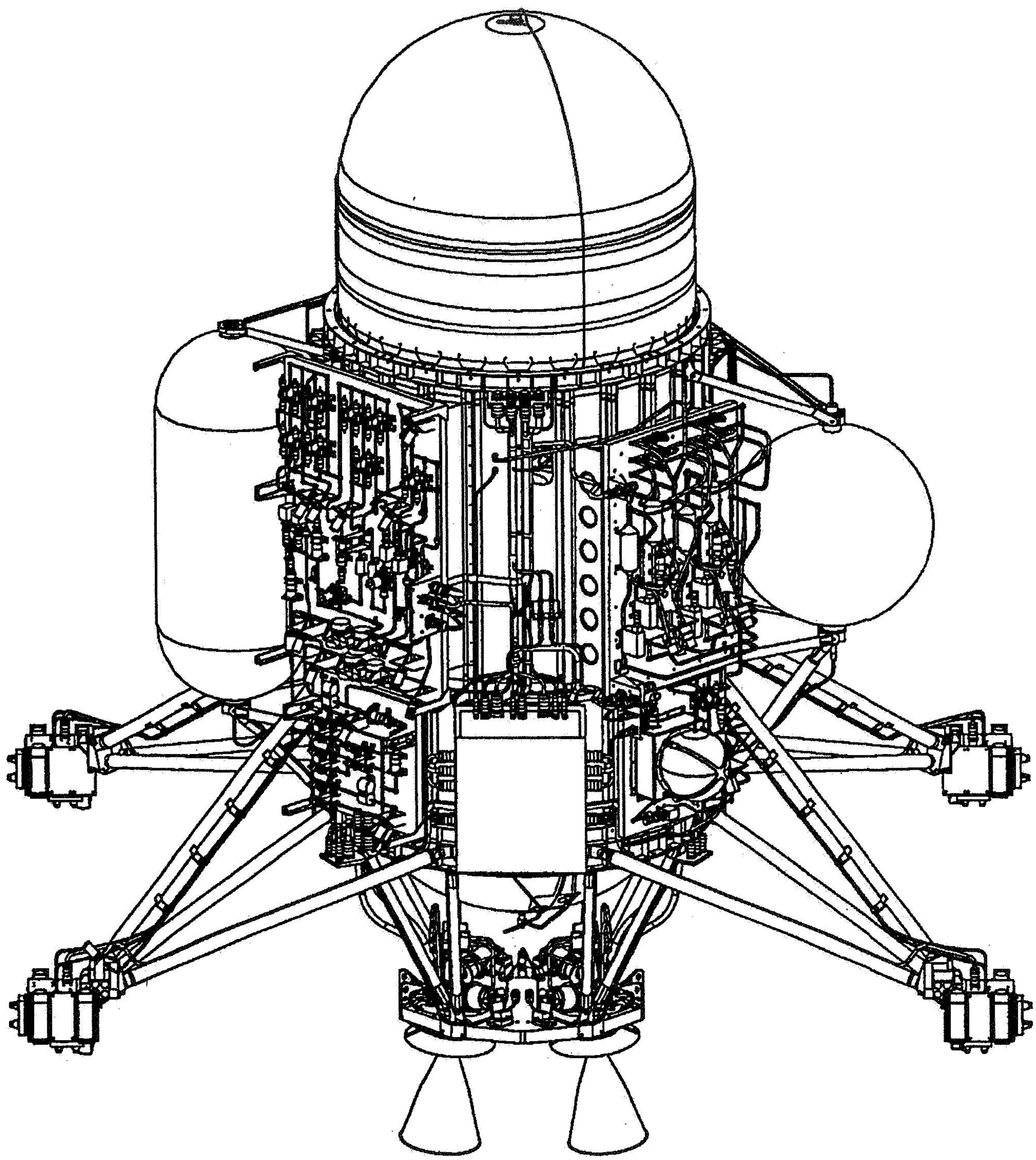


Figure 1. Cassini PMS

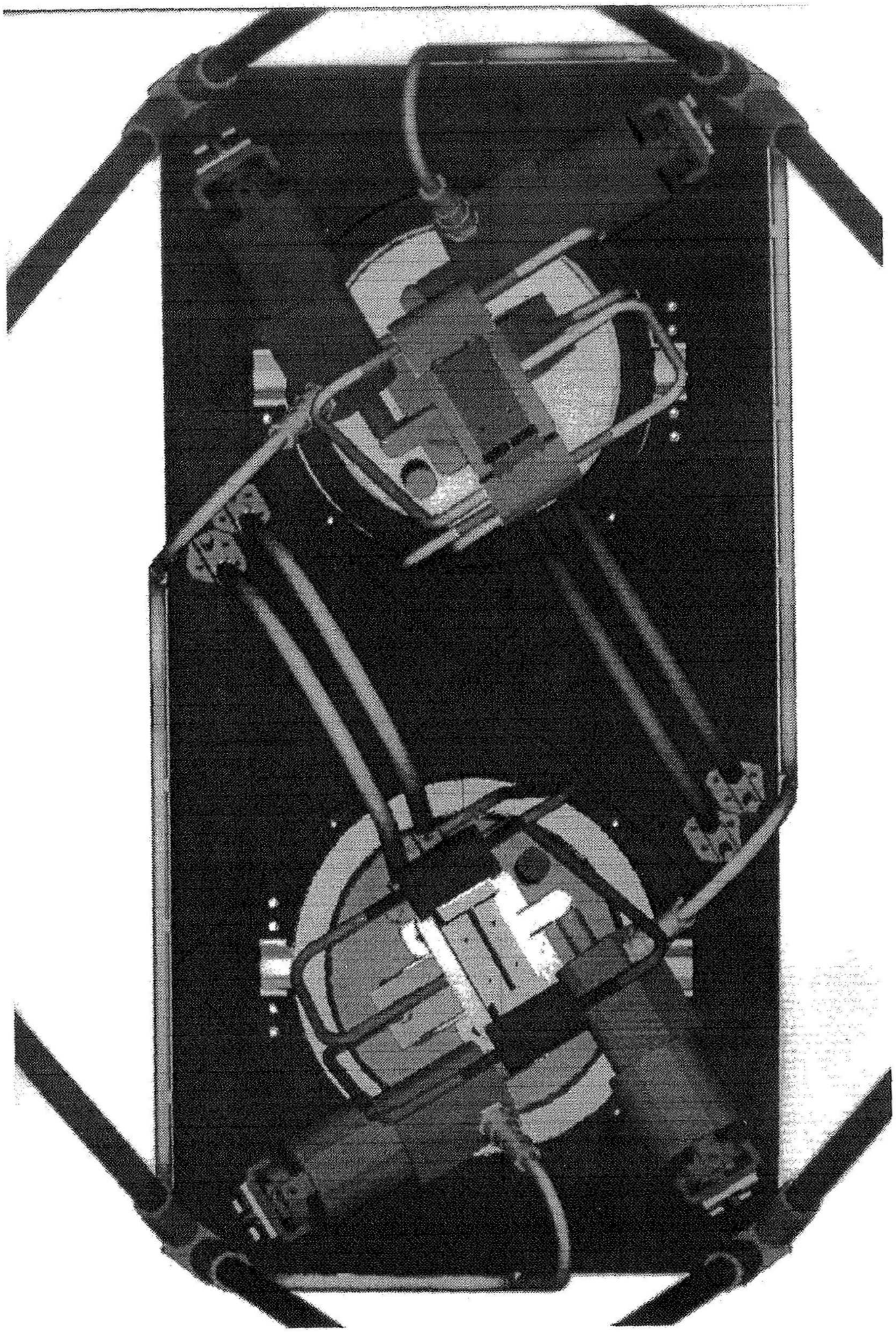


Figure 2. JPL Layout

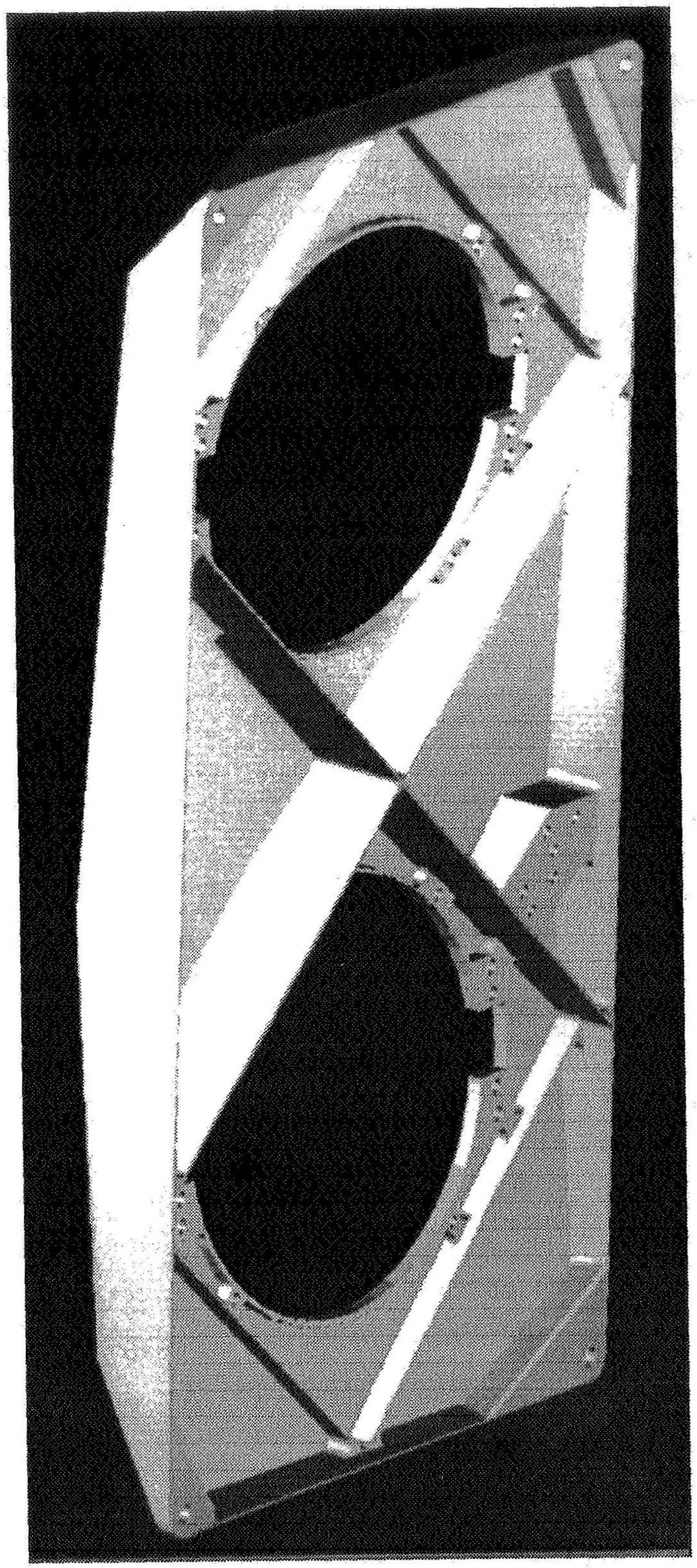


Figure 3. JPL Thrust Box

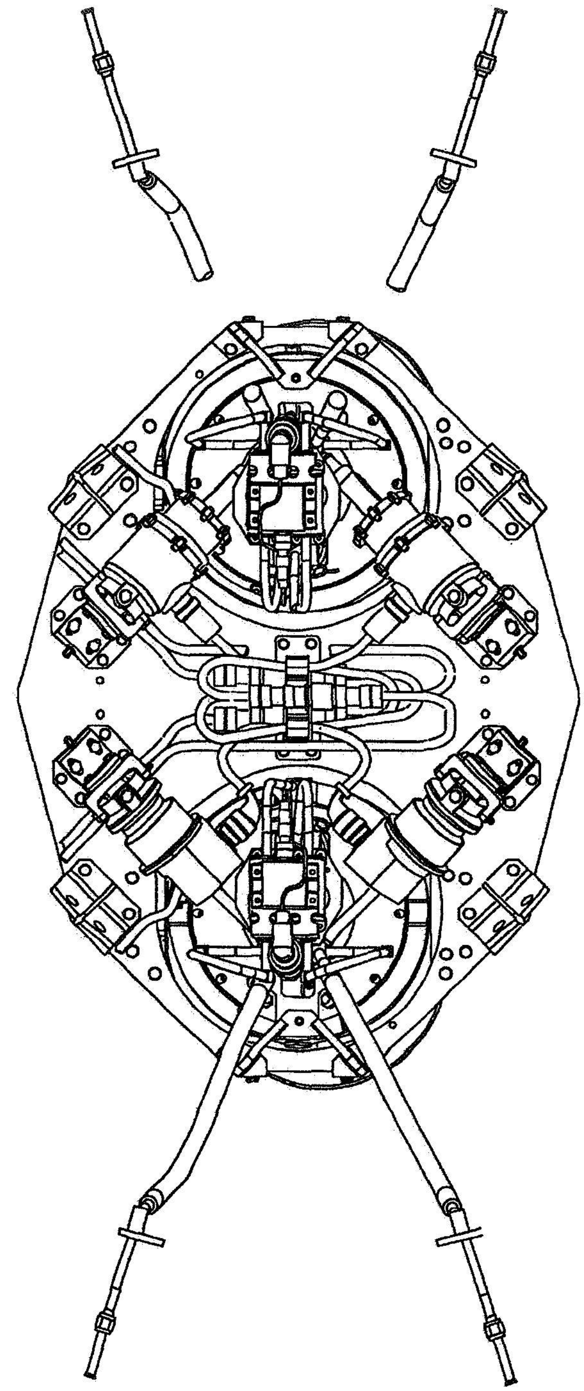
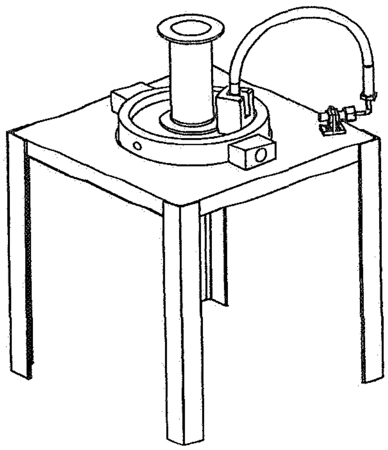
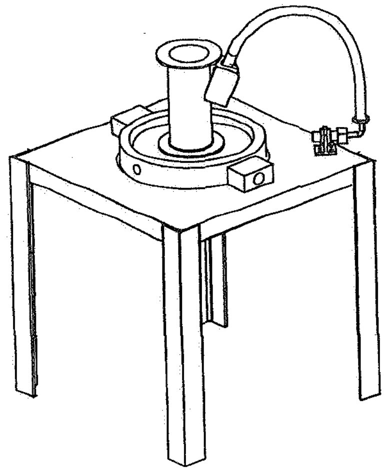


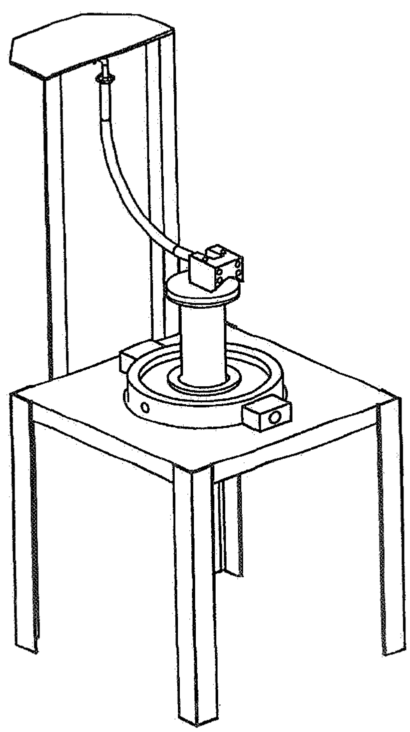
Figure 4. Revised Layout



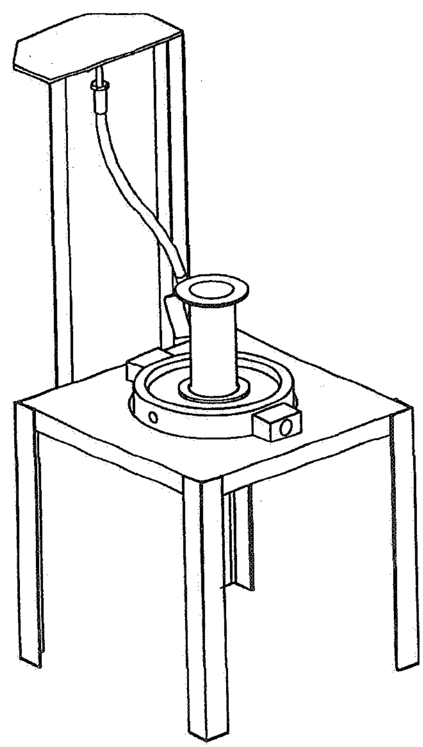
MacDonald's Arch



Lazy D



J Configuration



Esse Configuration

Figure 5.

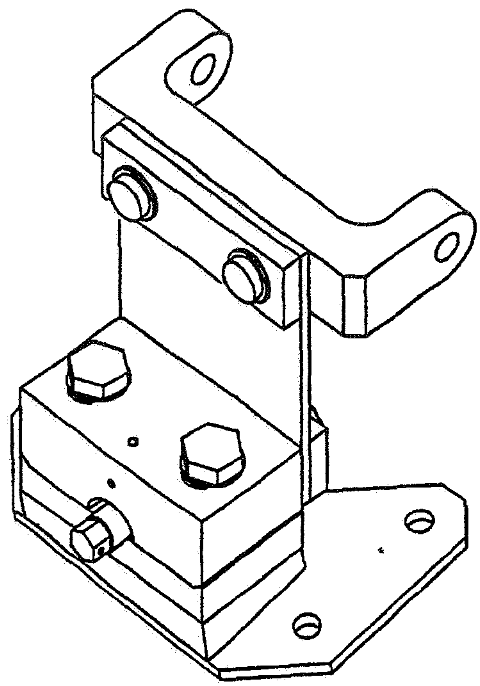


Figure 6.

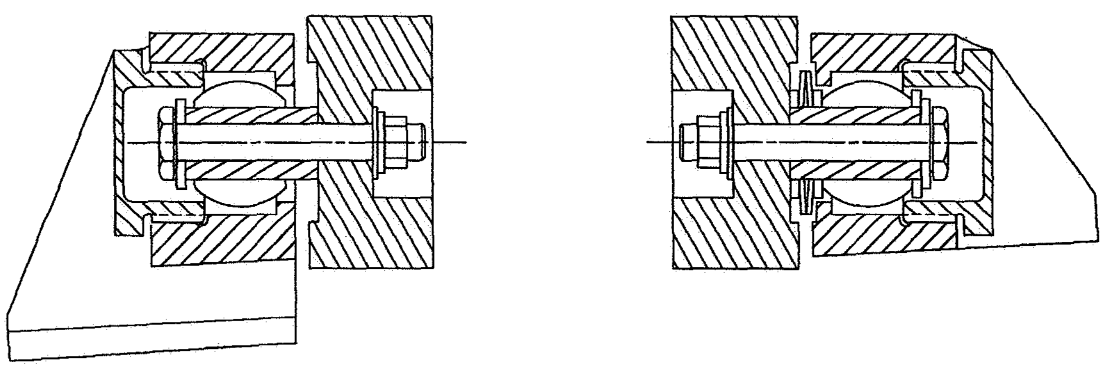


Figure 7.