Chemical Engine System Report

ER Rocket Inc.
Embry-Riddle Aeronautical University
1 Aerospace Blvd
Daytona Beach, FL

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I. Engine System

The engine system is one of the most important parts of the Mars transfer vehicle, providing the necessary thrust for key maneuvers such as trans-Mars injection. The RS-25 engine was selected due to its proven performance, extensive flight history, and ability to operate efficiently in space. This report covers two critical aspects of the RS-25 integration: the CAD modeling of its components and the engine mounting system. The CAD development process began with the creation of a comprehensive component list that detailed the dimensions and specifications of individual RS-25 parts. These components were then modeled in CATIA V-5 to ensure accuracy in design and integration with the overall vehicle structure. The second major focus is the engine mounting system, which was designed to provide structural stability, secure the RS-25 in place, and distribute forces effectively throughout the vehicle. The mounting system consists of multiple components, including a thrust adapter, mounting plates, and a connection to the tank's truss structure. Each of these components was carefully designed in CATIA V-5. This report details the CAD modeling process for the engine components as well as the full design and function of the engine mounting system, highlighting how the engine will be securely integrated into the vehicle.

A. Engine Selection Rationale

Originally, the engine that was chosen for the mission was the RL-10B-2 rocket engine, which was selected due to its favorable dry mass and high specific impulse, which seemed to be the ideal balance for efficiency purposes. Unfortunately, it was realized through later analysis that the excessive burn times required by using RL-10B-2 engines would far exceed the safe operation times typically handled by those engines, which would most likely lead to critical failure long before the burns were scheduled to stop. To remedy this issue, two options were explored: using the same engine but firing multiple times at shorter bursts or replacing the engine with a higher-thrust option that sacrifices efficiency for quicker burn time. Since the RL-10B-2 is usually only rated for a few engines refires [1], it was determined that a new engine was the better option and consulted the previously constructed engine database.

Table 1. Engine Swap Performance Comparison

Parameter	RL-10B-2	RS-25
Thrust [kN]	110.1	2,188.1
Specific Impulse [s]	465.5	452.3
Mass Flow Rate [kg/s]	24.1	513.6
Burn Time (total) [s]	> 6 hours	17.9 minutes
Dry Mass (total) [kg]	165164	186,970
Propellant Mass (total) [kg]	6,937,225	4,404,426

Ultimately, a configuration of 6 RS-25 engines was selected for its improved performance. As seen in Table 1, the RS-25's are individually much stronger than the RL-10B-2 engines and together produce a much lower burn time. Another consideration was the higher cost of the RS-25 engines; however, this ultimately had to be accepted since the RL-10B-2 solution was no longer feasible due to the long burn time.

B. Engine Component Dimensional Analysis and Methodology

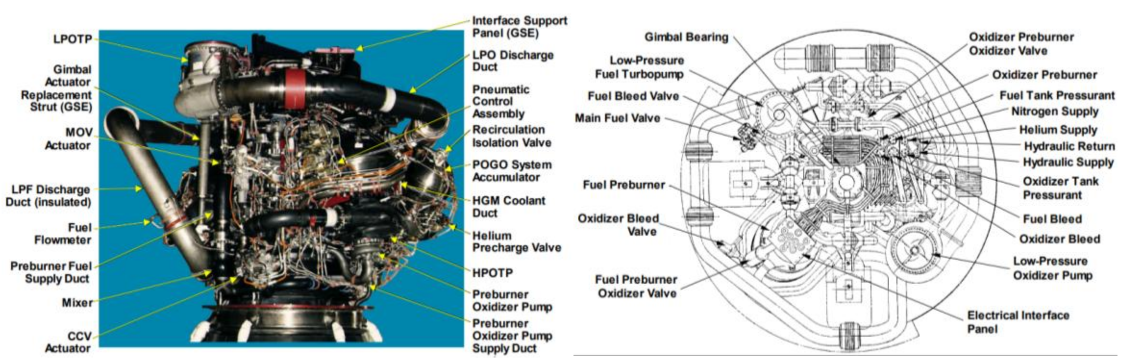

Fig. 1 Reference Images Used for Dimensional Approximations/Analysis

For the CAD assembly of the RS-25 engine, it was first necessary to compile as much data as possible about the necessary components for modeling purposes. Since the RS-25 is a proven engine model, there is no need to model the interiors of each part; therefore, most of the modeling was done with the intent to represent the geometry of the engine as close as possible, to ensure that the Structure and Assembly Teams can have an accurate model for spacing purposes. Another choice was to simplify much of the internal design since it has little effect on the geometry for the aforementioned purposes, so only external parts that stuck out farther than the rest of the simplified engine block were modeled with more detail. The last parts that underwent closer detail were all external connection points. Anywhere the rocket engine would need to interface with outside systems/components was modeled with more detail so that their geometries can be accounted for when assembling the entire rocket, to ensure that each part can correctly connect. There are a few parts that still need further work/analysis before it are updated to accurately interface with external systems, but it can be prepared as soon as those external system details are available.

Table 2. Engine Component Analysis Results

Component	Level of Detail	Height	Length	Width
Low Pressure Oxidizer Turbopump (LPOTP) Source: [2]	Detailed Externally	787.4 [mm]	457.2 [mm]	457.2 [mm]
Low Pressure Fuel Turbopump (LPFTP) Source: [2]	Detailed Externally	609.6 [mm]	457.2 [mm]	457.2 [mm]
Gimbal Bearing Source: [3]	Detailed Externally	330 [mm]	265.52 [mm]	265.52 [mm]
Electrical Interface Panel	Detailed Externally	300 [mm]	450 [mm]	350 [mm]
Engine Controller	Detailed Externally	300 [mm]	150 [mm]	200 [mm]
Nozzle/Combustion Chamber Source: [2]	Geometric/Volumetric	3073.4 [mm]	2387.6 [mm]	2387.6 [mm]
LPOTP Discharge Duct	Geometric	800 [mm]	1535[mm]	1620 [mm]
LPFTP Discharge Duct	Geometric	1542 [mm]	1954 [mm]	1720 [mm]
Total Assembly Source: [4]	Accurate Geometries/Connections	4267.2 [mm]	2560 [mm]	2560 [mm]

As seen above in Table 2, each component that was initially intended for the final CAD assembly is listed with their researched and/or approximated maximum dimensions. The dimensions listed with higher precision were acquired from online blogs and articles discussing some of the main component dimensions, and the lower precision dimensions were estimated from model drawings and images, as seen in Figure 1, using the higher precision "known" measurements as reference lengths and utilizing AutoCAD Web to measure the drawings from the inputted reference lengths. Most of these dimensions were closely followed within ±5% for the actual CAD modeling, with the exceptions displayed in red (closer visual inspection revealed that some of these measurements/approximations were initially wrong and were re-estimated during modeling). The rocket nozzle CAD is based on a calculated bell nozzle profile adapted from another project where our teammates worked on the same engine, with the same 69:1 exit to throat area ratio as confirmed online [4]. Additional surface structural geometry was added onto this profile to give the external portion of the nozzle a more accurate appearance. The only part of the engine assembly that is not included in Table 2 is the engine mounting interface plate, because this part was customized after the mounting assembly was created. The engine mounting interface plate was made to help accommodate the mounting structure by creating a well-supported interfacing surface between the engine and mounting assemblies, so that the mounting assembly could be properly tested for strength. The design of this component was based off of the mounting plates of older RS-25 engines, so that it too can be assumed to work as originally designed.

C. Engine Component CAD Models

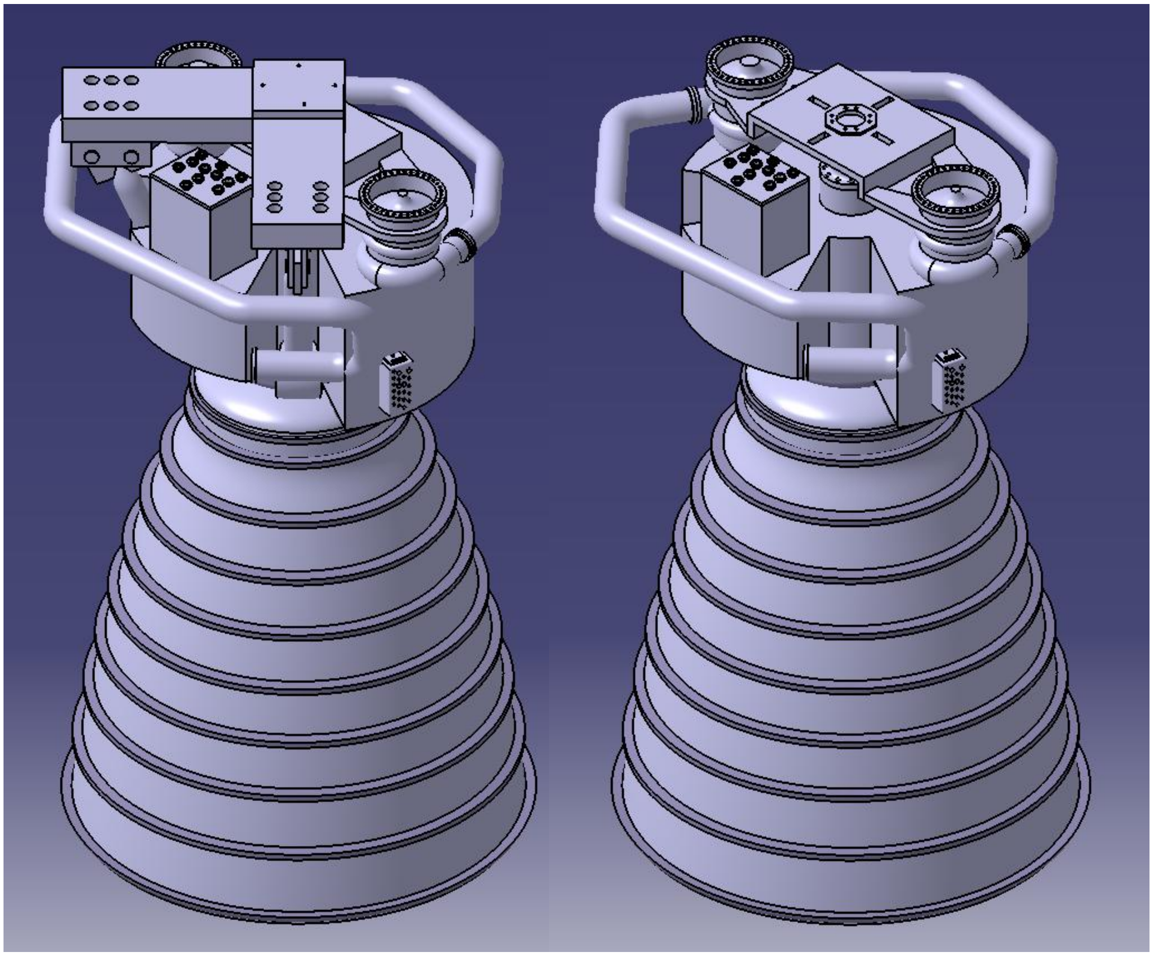

Fig. 2 RS-25 Simplified Geometry CAD Assembly with and without Engine Mount and Thrust Adapter

Figure 2 depicts the assembly of all of the currently modeled CAD components for the RS-25 engine. Included in this assembly are the low-pressure fuel & oxidizer pumps, their discharge ducts, the electrical interface panel, the engine controller, rocket nozzle, and the gimbal bearing. The hydraulic, pressurant, and purge system piping will be added to this assembly, along with the bleed valves, once more information with other teams can be confirmed. In the center of the components is the simplified engine block, which is a cylinder with some extended portions to fill in space between the detailed components, so that the assumed "unusable" volume that is simplified is fully taken up according to estimations from reference images. The following figures show the detailed components up close.

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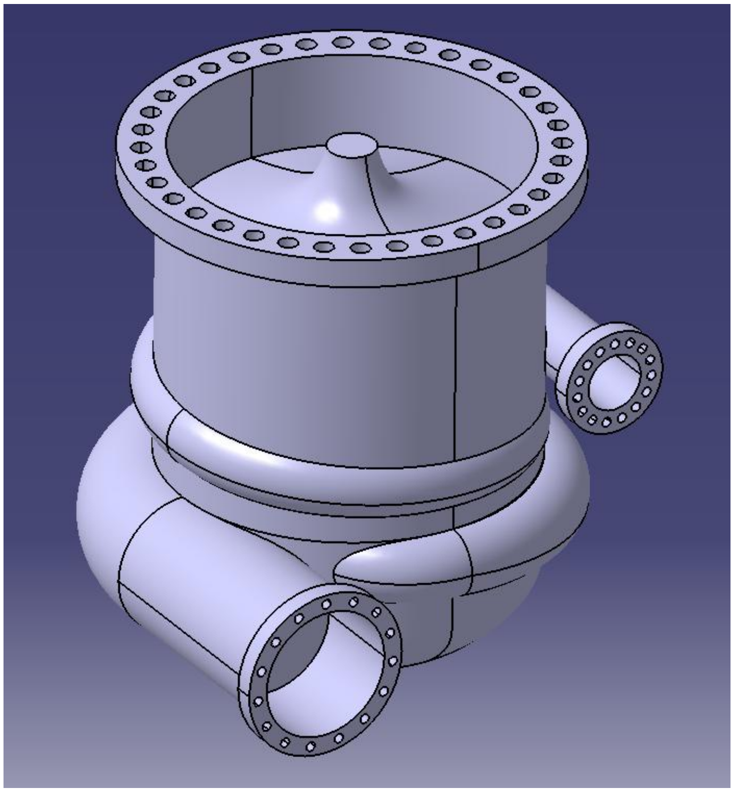

Fig. 3 Low-pressure oxidizer turbopump (LPOTP) CAD model

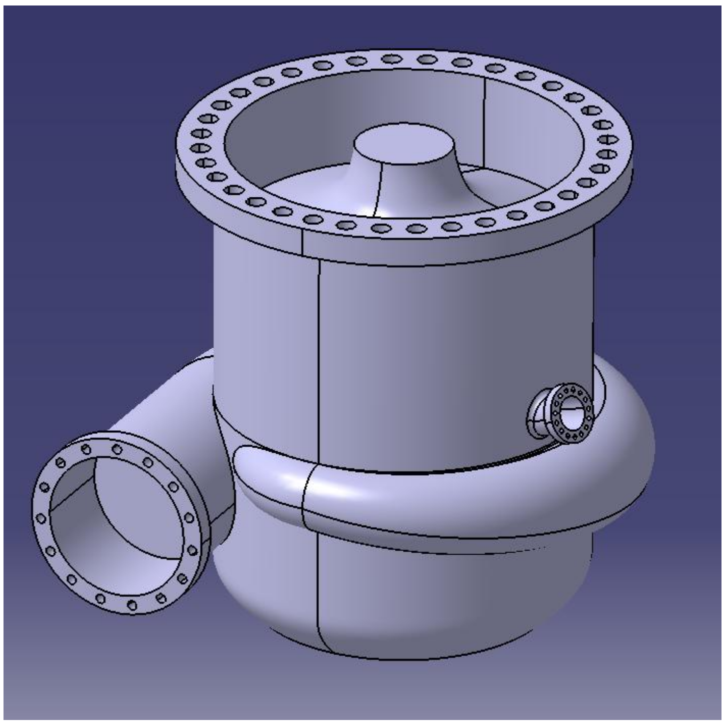

Fig. 4 Low-Pressure Fuel Turbopump (LPFTP) CAD Model

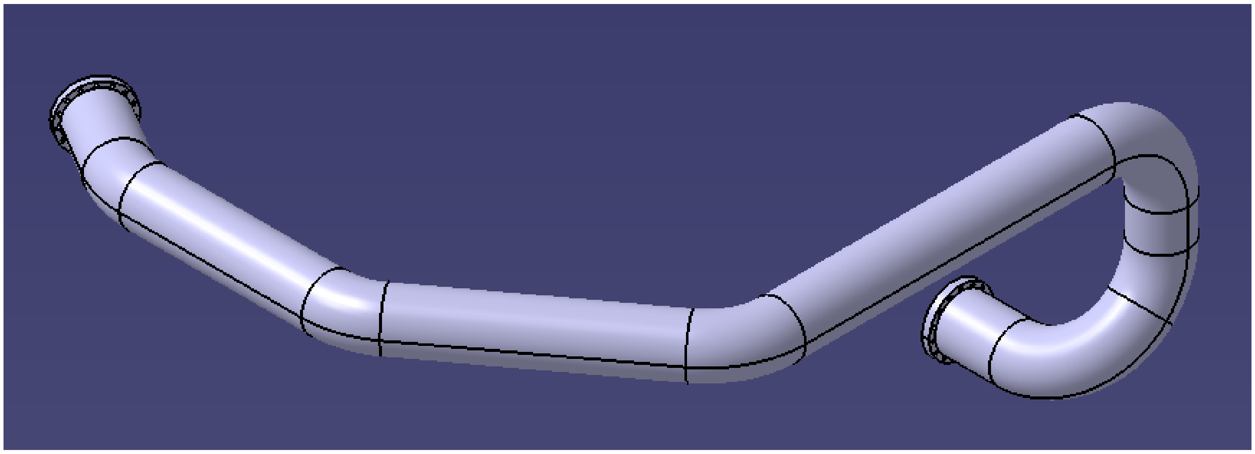

Fig. 5 LPOTP Discharge Duct CAD Model

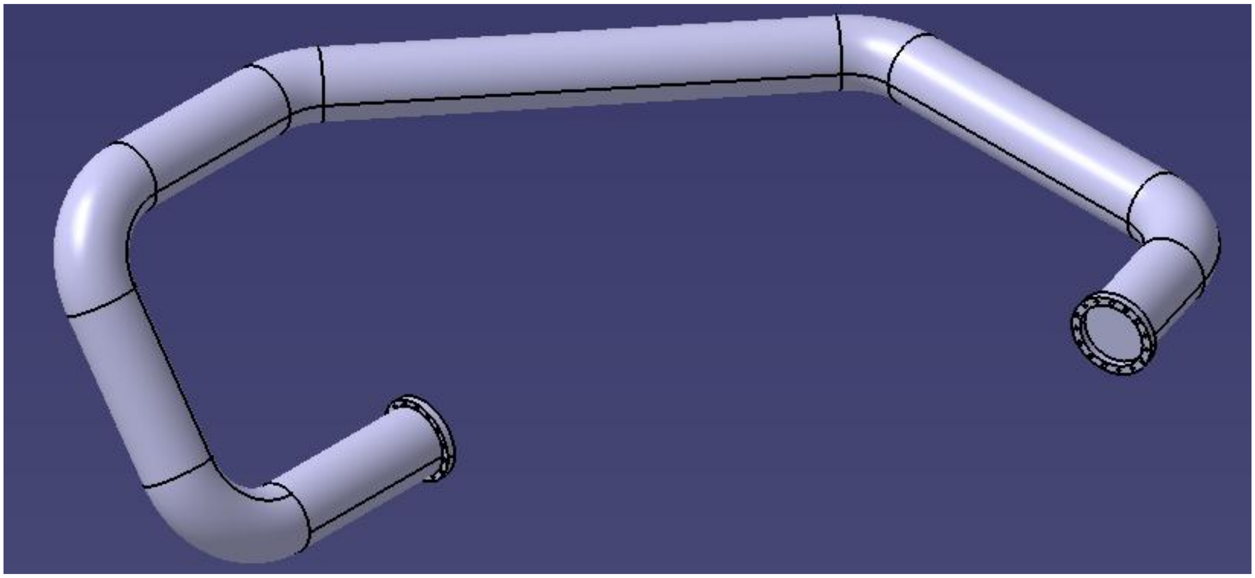

Fig. 6 LPFTP Discharge Duct CAD Model

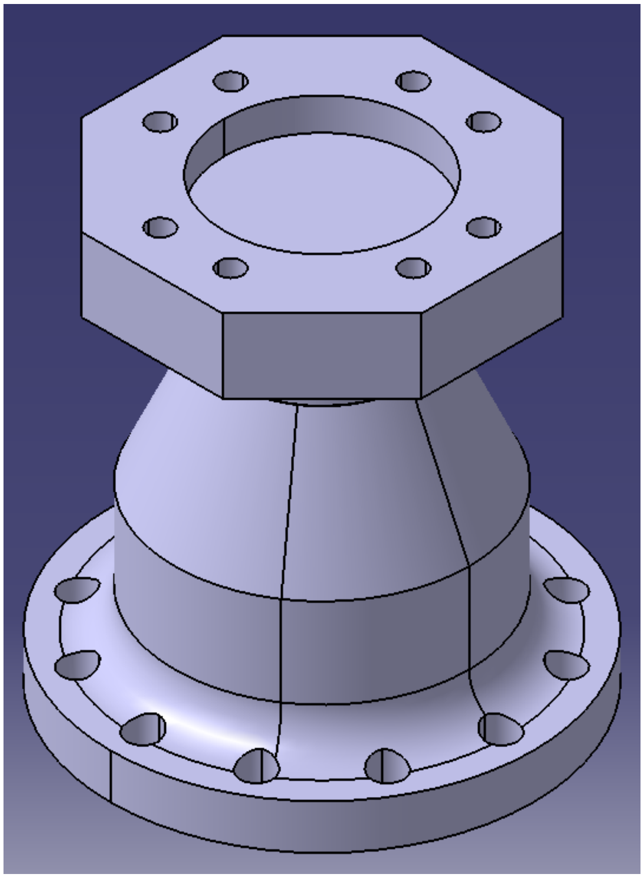

Fig. 7 Gimbal Bearing CAD Model

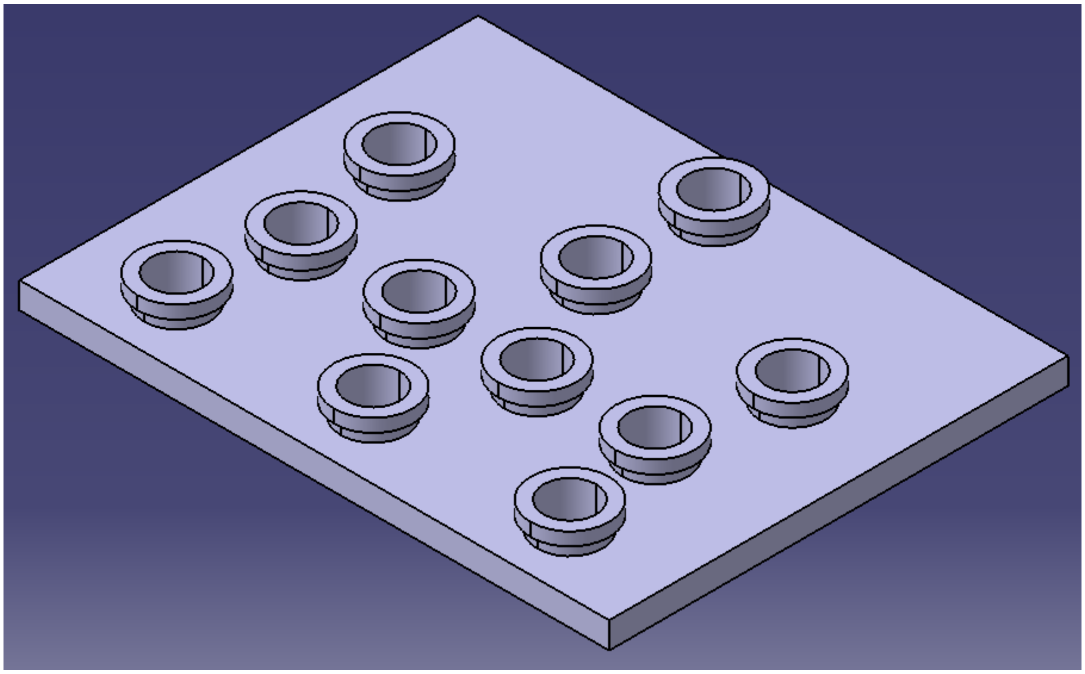

Fig. 8 Electrical Interface Panel CAD Model

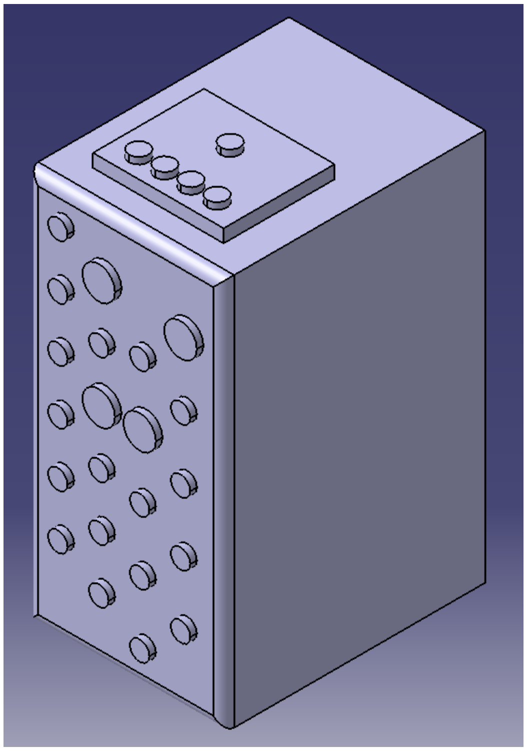

Fig. 9 Engine Controller (Simplified) CAD Model

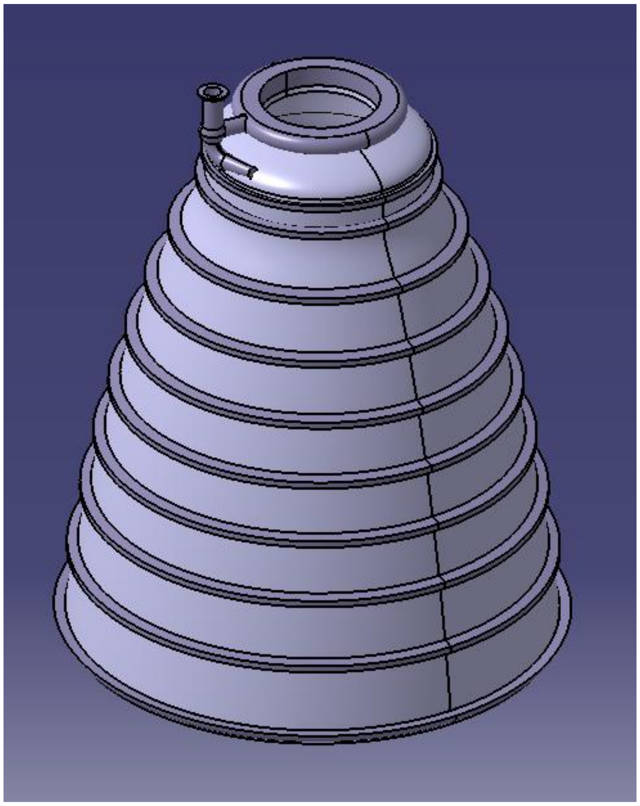

Fig. 10 Rocket Nozzle CAD Model

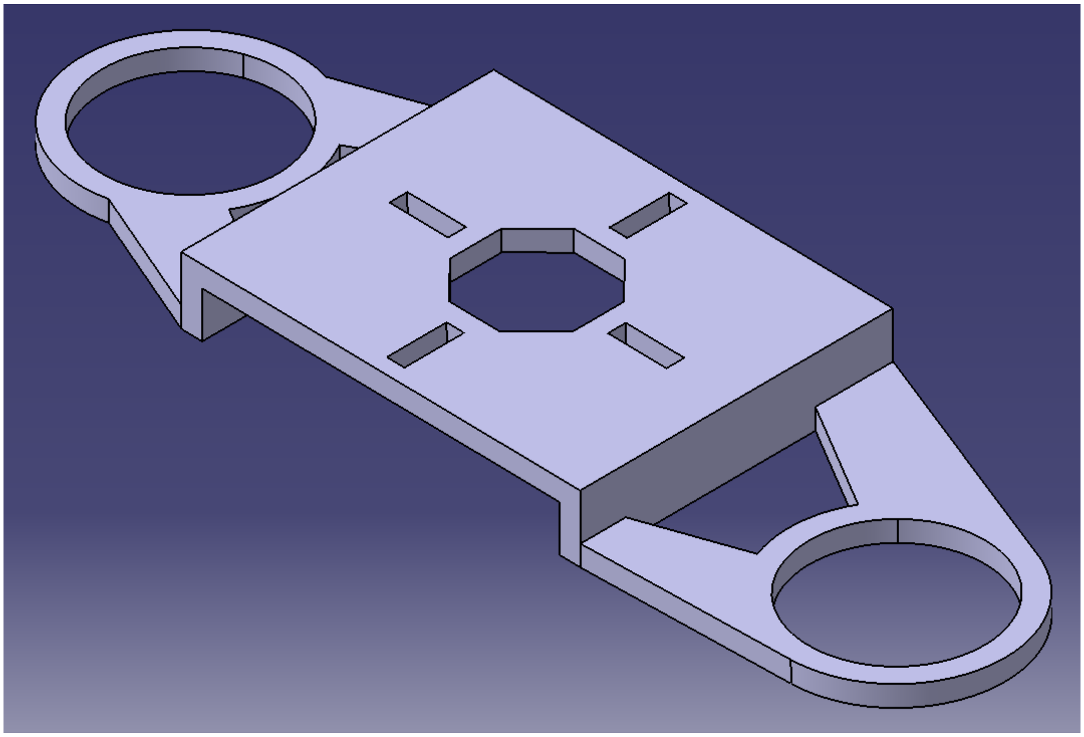

Fig. 11 Engine Mounting Interface Plate

D. Engine Mounting System and Thrust Adapter

The engine mount consists of multiple components designed to provide structural stability, minimize vibrations, and ensure efficient force transfer to the vehicle's main framework. The system is composed of three primary sections: the gimbal mount attachment, the thrust adapter, and the secondary connection to the tanks truss structure.

The engine is initially secured at the gimbal mount, where a titanium alloy Ti-6Al-4V 2-inch-thick plate is bolted to the top of the gimbal structure. This plate is locked in place with a circular titanium alloy Ti-6Al-4V ring installed beneath the existing RS-25 gimbal mount. The ring encircles the gimbal mount to ensure proper alignment and prevent shifting.

The thrust adapter, an 8-inch-thick cross-shaped structure, serves as an intermediary between the engine mount and primary support arms. It is bolted to the engine mount using 0.75-inch diameter bolts and includes two arms (reduced from the original four) that extend down along the sides of the engine, forming a rigid support frame. This change was made to simplify engine attachment and reduce system mass. This design is based on the RS-25 A-1 test stand at NASA's Stennis Space Center, which provides lateral stability and prevents swaying during operation [5]. Both of the arms extend downward along the engine's sides, forming a reinforced load path that distributes thrust forces into the spacecraft's main structure. The thrust adapter and all major mounting components are constructed from titanium alloy Ti-6Al-4V due to its high strength-to-weight ratio and ability to withstand extreme temperatures.

At the ends of the thrust adapter's two arms, attachment points are integrated to secure additional arms that hold the engine near the nozzle throat. This configuration ensures stability and prevents excessive movement during full-throttle operation. The thrust adapter is solely responsible for bearing all thrust loads, transferring forces directly into the vehicle's structural framework.

To simplify installation, another 2-inch-thick mounting plate will be included. Neither of the two plates provide structural support but aid in the assembly process. The plate that connects to the gimbal and thrust adapter is pre-attached to the engine before launch inside starship, while the plate that connects to the truss structure on the tanks is installed separately. Once in space, the plate attached to the tanks is bolted onto the thrust adapter, enabling a secure connection between the engine and vehicle structure. Following this step, fuel piping connected to the engine for propellant flow.

To prevent misalignment, the thrust adapter and mounting plates feature four bolt holes, with one hole slightly offset. This ensures that the engine can only be attached in the correct orientation, preventing incorrect assembly and ensuring proper alignment of the fuel piping system.

The set of CAD models below illustrates each of the three main components: the thrust adapter, the gimbal mount plate, and the plate attaching to the truss structure.

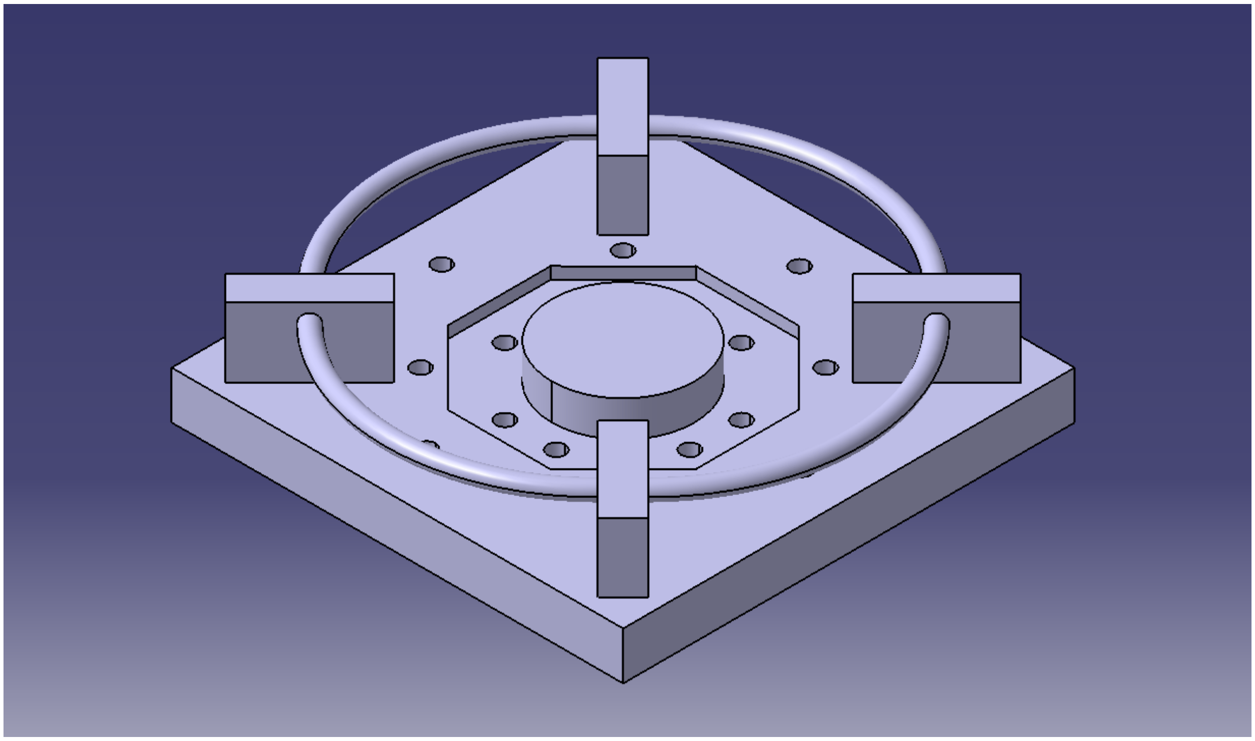

Fig. 12 Gimbal Mounting Plate CAD Model

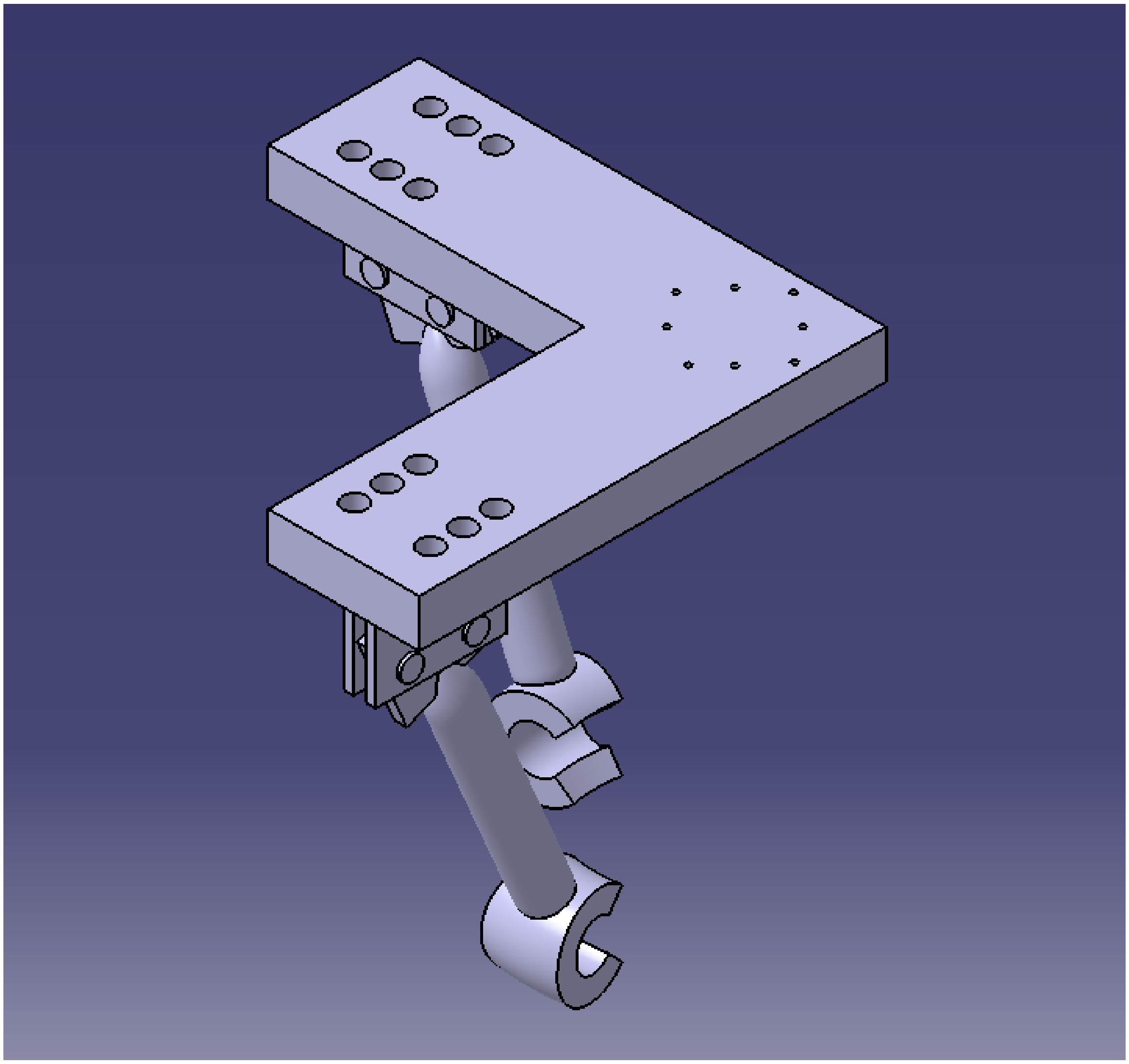

Fig. 13 Revised Thrust Frame Adapter with 2 Arms CAD Model

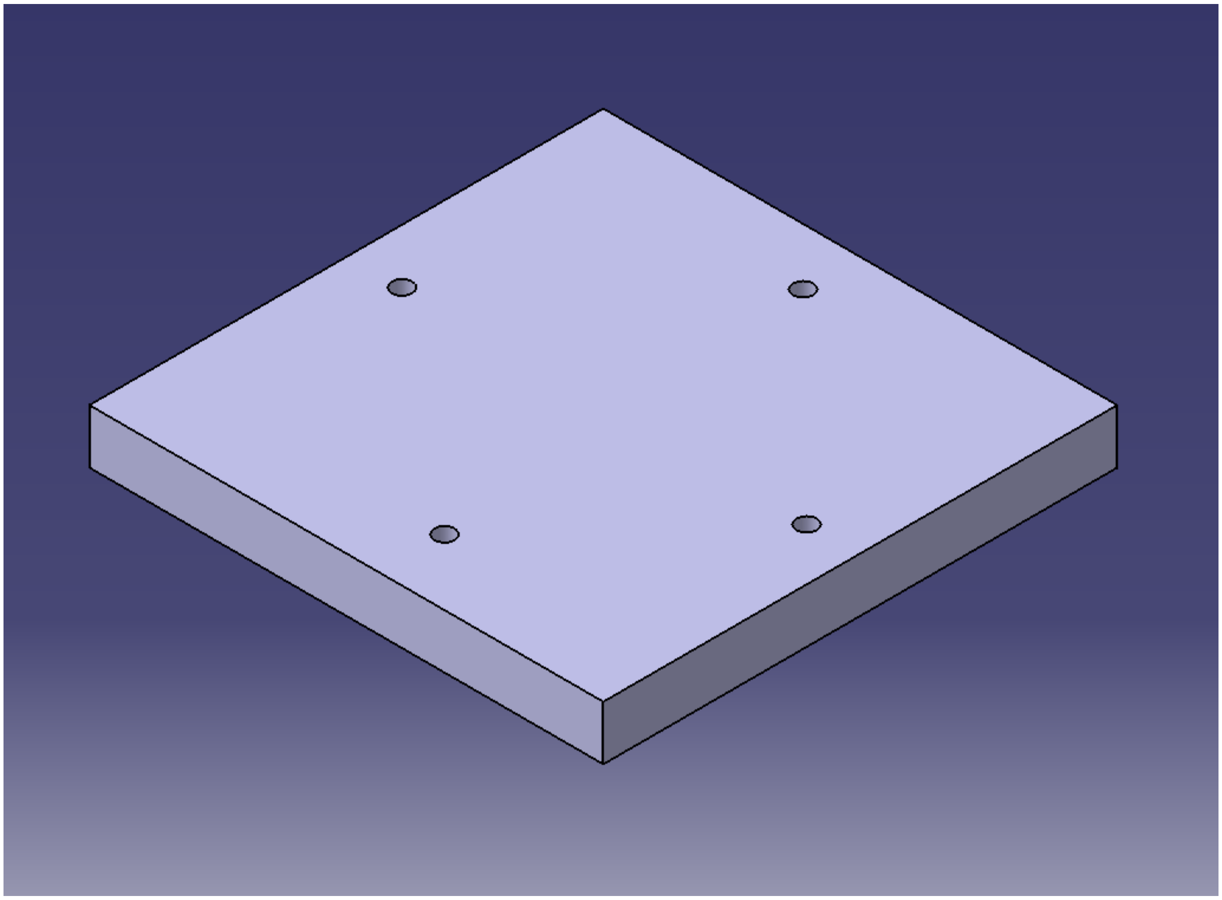

Fig. 14 Mounting Plate Attaching to Tank Truss CAD Model

In addition to the individual components, an assembled CAD model, below, has been created to show how all three parts fit together. This assembled model provides a clearer understanding of the overall integration of the engine mount system, ensuring proper alignment and confirming that all components connect as needed.

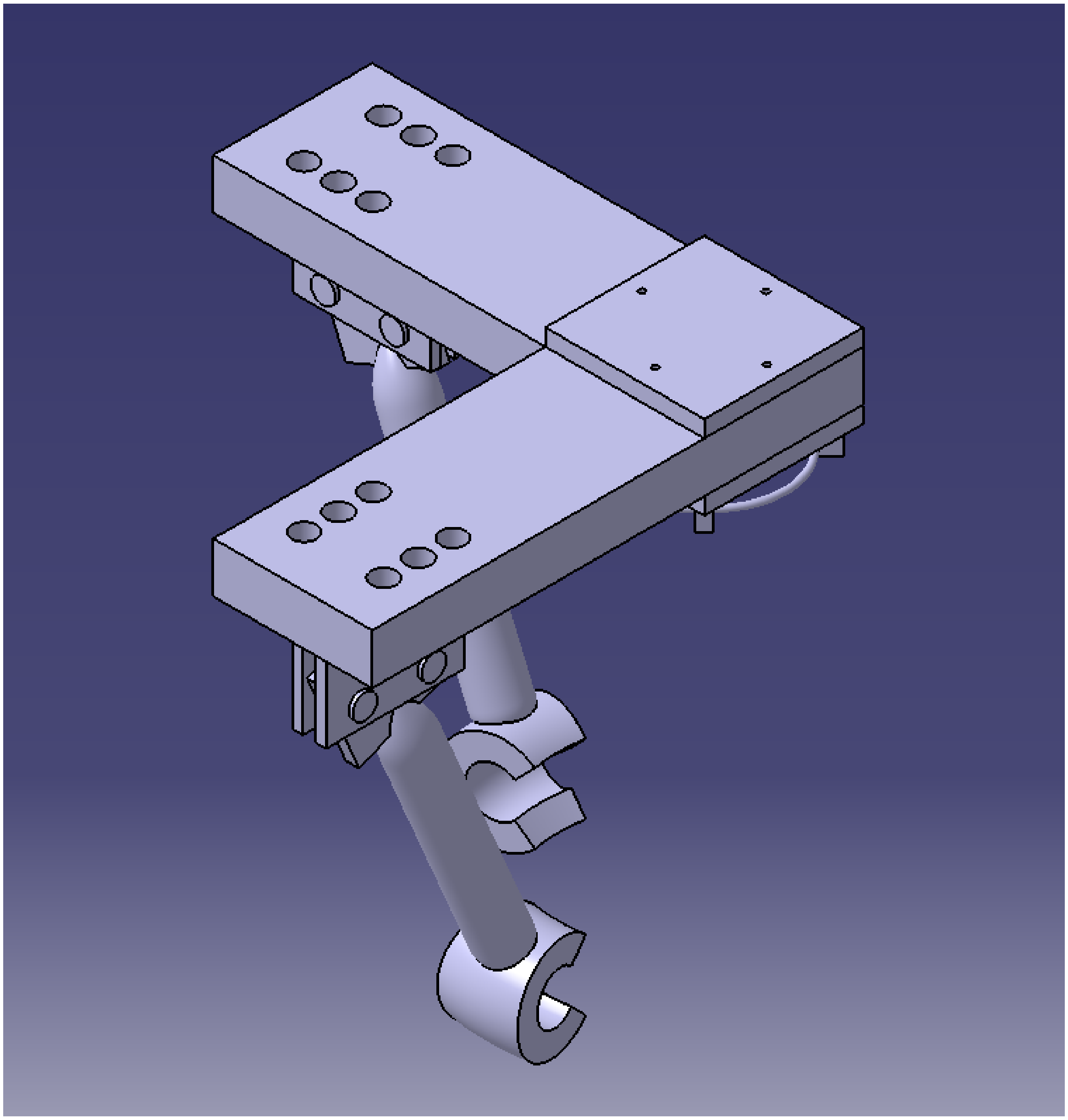

Fig. 15 Assembled Mount Design

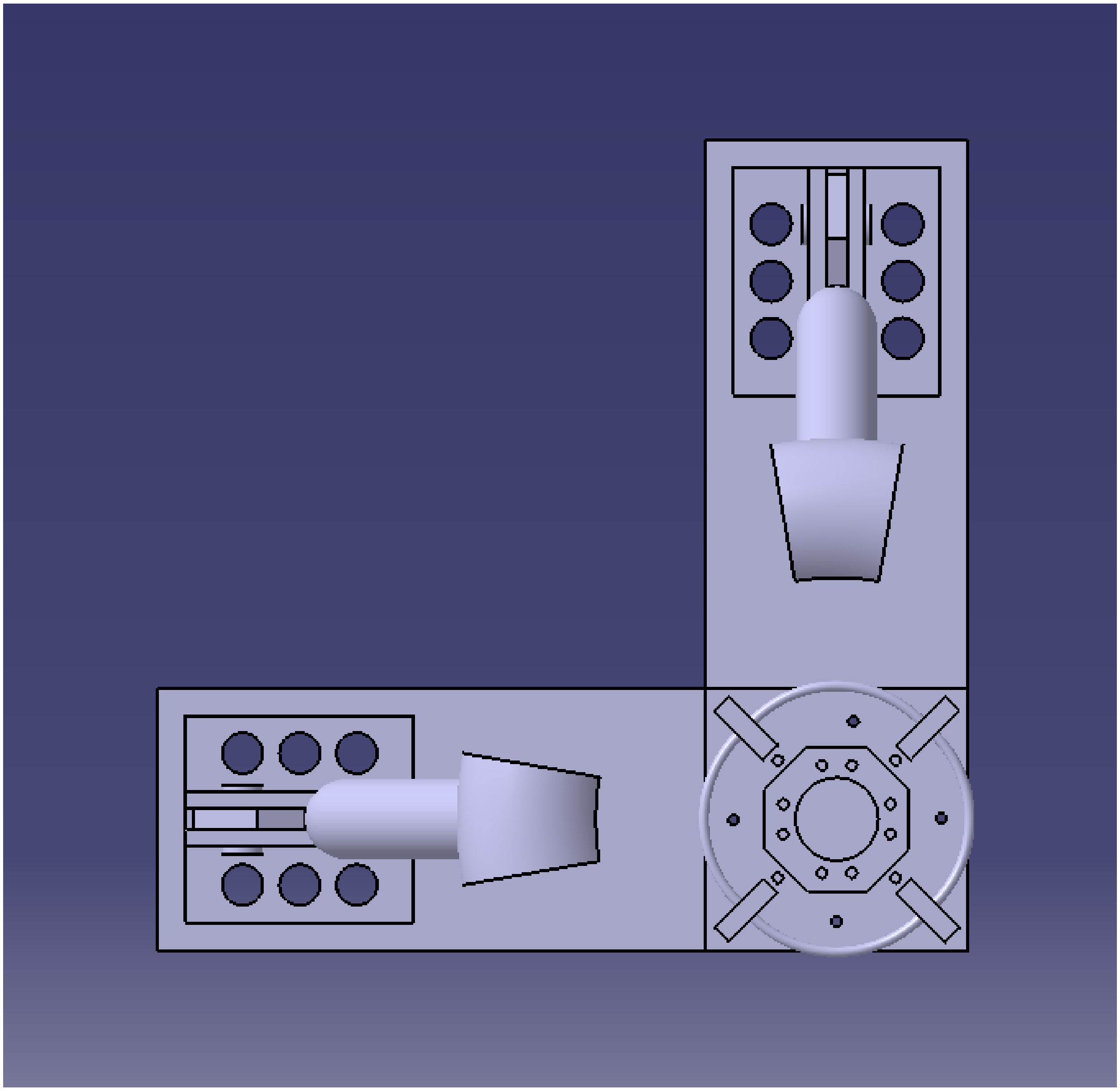

Fig. 16 Bottom View of Assembled Mount

E. Engine Mounting Assembly Testing and Analysis

To ensure the structural reliability and performance of the engine mounting system, a series of analyses were done using CATIA. The tests that were done were deformation under load, von Mises stress distribution, and vibrational behavior.

For the deformation analysis, a static structural analysis was performed to simulate the load applied to the mount during RS-25 engine firing. The thrust adapter and mounting plates were evaluated to determine total displacement under maximum expected thrust. The results showed minimal deformation, indicating that the structure maintains integrity and stiffness under operational loads.

A Von Mises stress analysis was done to identify critical stress concentrations and assess whether the design stays within safe material limits. The peak stress values observed were below the yield strength of Ti-6Al-4V, confirming that the mounting assembly can withstand full-thrust conditions without risk of failure or permanent deformation.

A modal analysis was performed to determine the natural frequencies and vibrational modes of the engine mounting structure. The results verified that the lowest natural frequencies are well outside the expected operational range of the RS-25 engines, significantly reducing the likelihood of harmful resonance. This ensures long-term durability of the system during launch and sustained burns.

Figures showing deformation, stress distribution, and mode shapes can be found below. These results validate the mechanical soundness of the engine mounting system and support its readiness for integration with the vehicle structure.

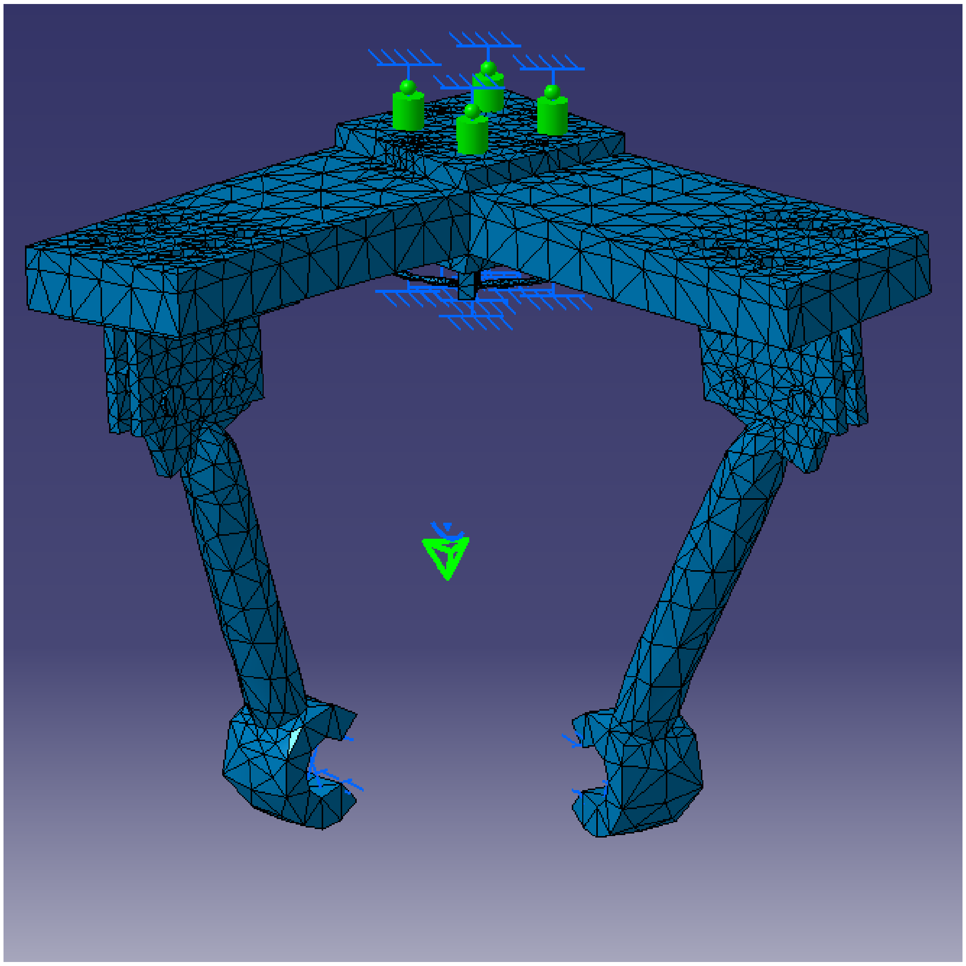

Fig. 17 Deformation Analysis of Engine Mount

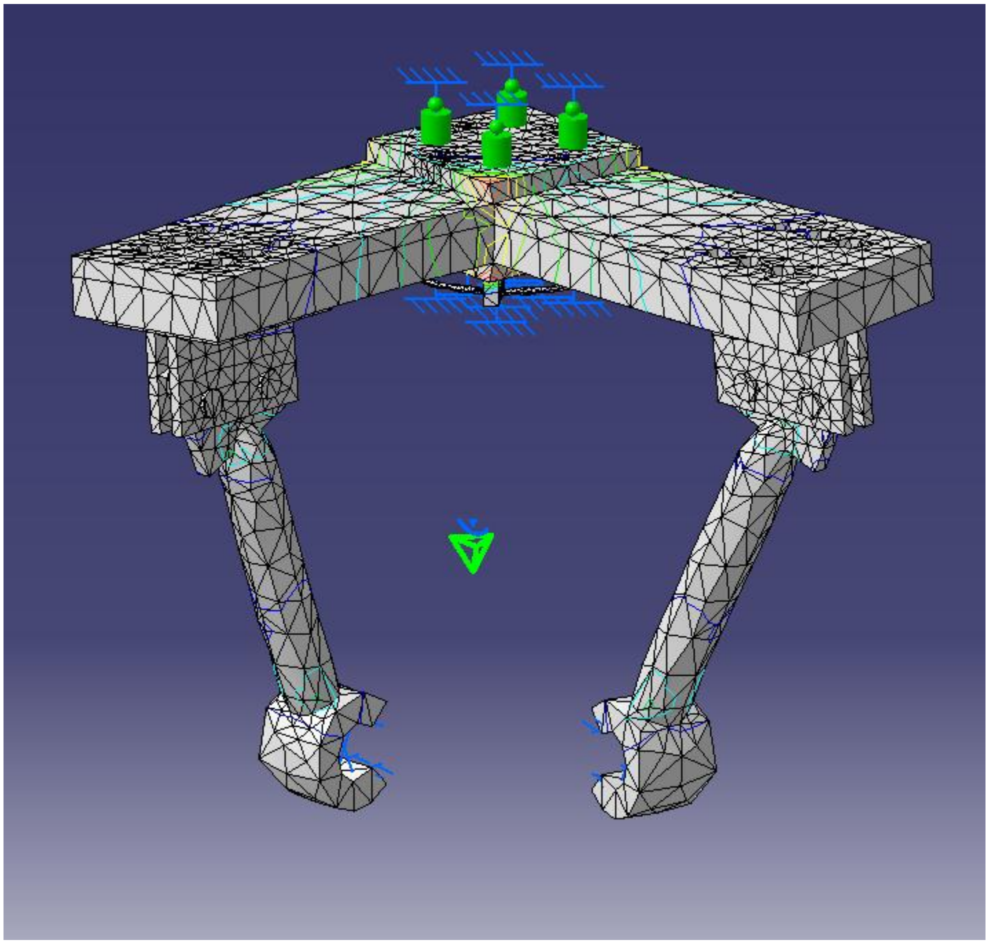

Fig. 18 Von Mises Stress Analysis of Engine Mount

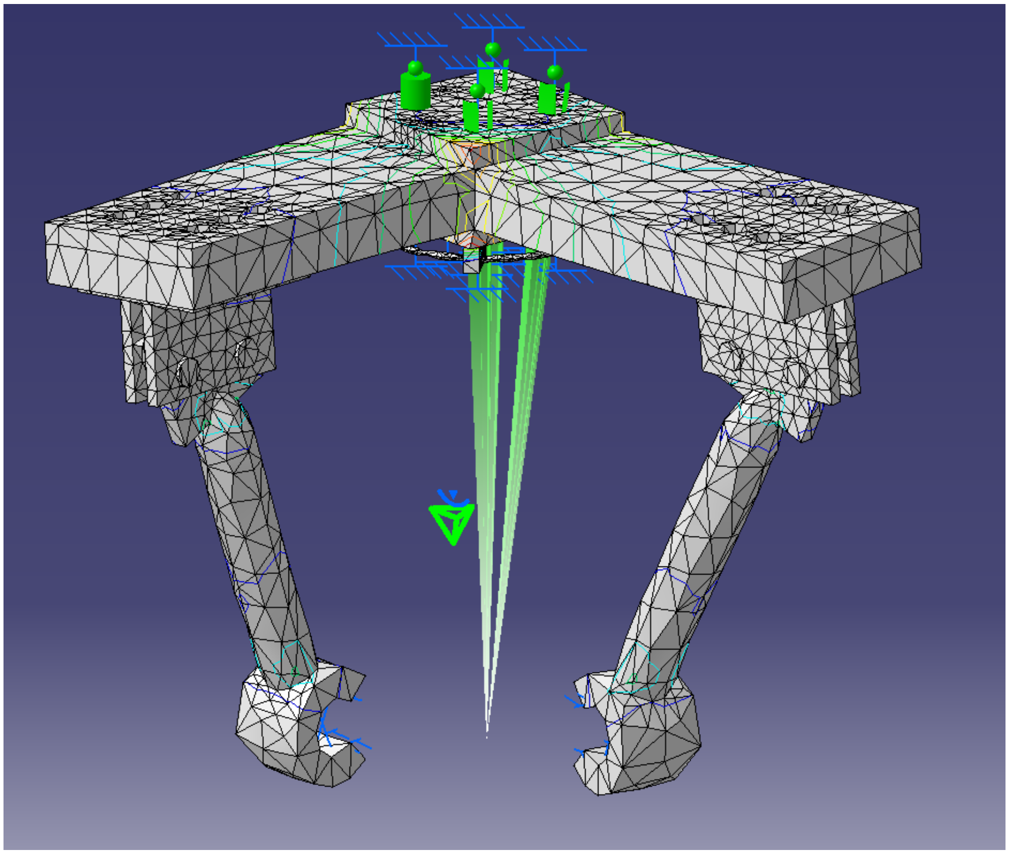

Fig. 19 Vibrational Analysis of Engine Mount

F. Engine System Piping and Instrumentation

This is the overview of the required piping and instrumentation for the engine system. This system features 6 RS-25 re-usable main engines, 10 liquid hydrogen (LH_2) tanks, and 4 liquid oxygen (LOx) tanks. It also includes two pressurant tanks for the depletion of the propellant tanks. LOx tanks will use helium, and LH_2 tanks will use gaseous hydrogen (GH_2) to remain pressurized when emptying.

Table 3. Piping and instrumentation bill of materials (BoM).

Instrument	Quantity	Cost ($k)	Subtotal ($k)	Vendor
Propellant (liq.) Actuated Valve	22	20	440	VACCO
Pressurant (gas) Actuated Valve	9	10	90	
Mass Flow Sensor	20	30	600	
Temperature Sensor	20	5	100	Scientific Instruments
Pressure Transducer	27	5	135	WIKA
Check Valve	41	8	328	Parker
Relief Valve	9	6	54	Emerson
Pressure Regulator	9	15	135	Parker
Actuated Purge Valve	12	10	120	Moog
Flow Restrictor	12	2	24	
3-way	9	10	90	*Custom*
Total ($M)			**2.116**	

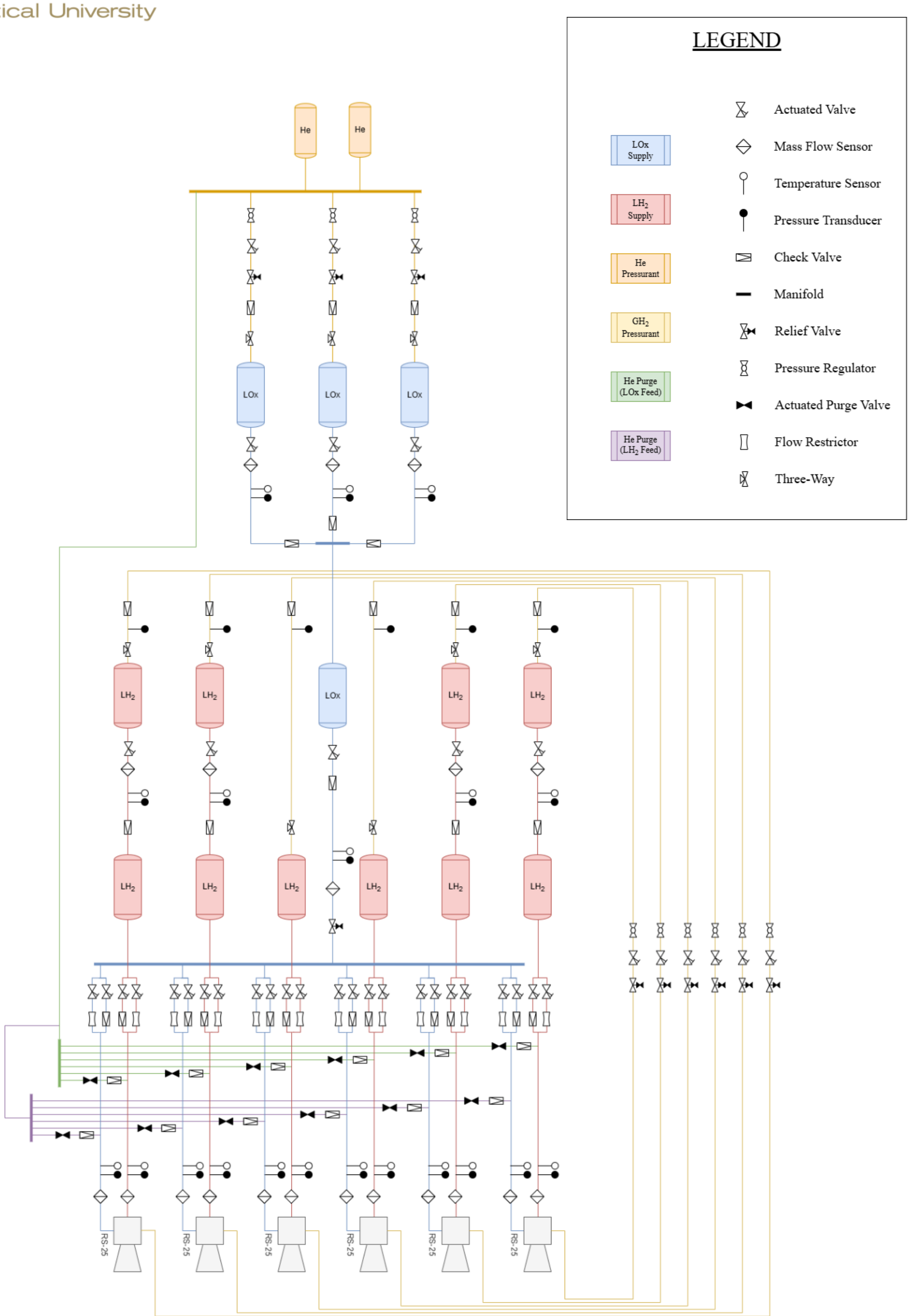

Fig. 20 Engine System Piping and Instrumentation Diagram (PID)

The feed system has three main purposes other than providing propellant to the engines. These include maintaining propellant tank pressures, purging feed lines pre-burn (for clearing), and cryogenic pre-conditioning pre-burn (directly after purging).

Pressurants are a necessary part of maintaining the structural integrity of the fuel and oxidizer tanks and also serve a role in preserving the quality of the fuel and oxidizer themselves. Since the structural integrity of the tanks is partially reliant on the pressure differential across the inner and outer surfaces, maintaining high pressure is important for both boil-off and the tank ullage itself. The inclusion of pressurants aid the tanks in structural integrity during rapid accelerations (such as each engine fire), ensure even stress distribution within the tanks, and facilitate propellant management by aiding turbopumps on the main engines. The pressurants for the system are helium and GH_2 for the oxidizer and fuel, respectively. Helium is pre-stored in a tank and gradually fed into the three auxiliary oxygen tanks as it empties into the main feeder LOx tank. GH_2 is continuously fed into each fuel tank with exhaust from the RS-25 pre-burners. Each tank feeds a single engine, with four of them equipped with an auxiliary tank as only four tanks of fuel are left over after the first burn.

The purging system serves a critical role in maintaining both the engines' and feed lines' operational integrity throughout the duration of the mission, especially since our mission includes multiple re-fires of each engine. These systems have tendencies to gradually build up contaminants within the engine structure, ranging anywhere from unburnt fuel, biproduct gases, corrosion, and even grit from the engines wearing over time. While some of this debris is accounted for in the design of the engine and is acceptable for a certain number of re-fires or burn time, it is important that it's purged from the system after each fire so that it does not accumulate and increase internal damage to the engine over time. The unburnt fuel once the engines are shut down is the most common need for purging, since hydrogen will eventually become gaseous and easily permeate and spread throughout the engine, and oxygen will also become gaseous and cause additional corrosion due to its reactivity. Other wear-based purging is taken care of throughout those same fuel purges after each engine fire, ensuring that the debris does not build up to dangerous amounts. It is important to note that the residuals from manufacturing will be cleared by purging on the ground before being launched. The purges for our mission use the same helium supply that is used for the LOx pressurant and is used for each propellant main feed line. The helium is routed from the supply to two separate manifolds, one for the LOx feed lines and one for the LH_2 feed lines. Each manifold then branches into each individual feed line for purging post burn.

The pre-cryogenic conditioning cycle (chilling) loop prevents flash vaporization during burn as well as cavitation and other undesirable effects by cooling the feed lines that the propellants travel through. In each engine's feed line for both propellants, a small parallel branch is added with another actuator and flow restrictor which can be opened to allow a trickle flow directly after purging.

II. References

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[5] Bergin, C. “Busy Summer of SLS Engine Testing on the Stennis A-1 Test Stand.” *AmericaSpace,* 10 August 2017. [Online]. Available: https://www.americaspace.com/2017/08/10/busy-summer-of-sls-engine-testing-on-the-stennis-a1-test-stand/. [Accessed: 4 March 2025].