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DESIGN OF THE 3-D PRINTED COLD GAS PROPULSION SYSTEMS FOR THE VISORS MISSION

Samuel T. Hart,[*] Nathan L. Daniel,[*] Mark C. Hartigan,[*]
and E. Glenn Lightsey[†]

The VISORS mission will observe the Sun's corona with the goal of collecting data that can shed light on the mechanisms of coronal heating. This will be accomplished through the use of a diffractive telescope. The telescope requires a focal length of 40 meters, which will be achieved by implementing two precisely positioned 6U CubeSats flying in formation. One spacecraft will carry the telescope optics, and the other will carry the detector. The spacecraft have stringent relative positioning requirements in science operations, which must be maintained during 10 second observations. In order to accomplish this relative positioning, a propulsion system capable of providing precise impulses in six orthogonal directions is necessary on board each spacecraft. Due to the varied shapes and sizes of each spacecraft's respective available payload volume, a different envelope is allotted to each spacecraft's propulsion system. 3-D printing the propellant tanks, nozzles, and tubing into one structure allows the full available propulsion volumes to be used despite their unusual shapes. This has contributed to the design of two low-cost propulsion systems capable of providing a combined total velocity change of 23 m/s. This paper describes the pertinent mission requirements, propulsion system design methodologies, and expected performance characteristics of the thrusters.

INTRODUCTION

As small satellite technology continues to advance, formation flying is being utilized to conduct increasingly complex missions.[1] Multi-satellite formations can potentially allow for certain missions to be carried out for a fraction of the cost of a traditional single satellite concept. The Virtual Super-Resolution Optics Using Reconfigurable Swarms (VISORS) mission, selected during a National Science Foundation (NSF) Ideas Lab held on CubeSat swarms in 2019, is an example of this emerging trend. VISORS will image the solar corona at a high resolution in order to investigate the physical mechanism behind coronal heating. The sensing will be accomplished through the use of a diffractive telescope which employs two CubeSats. The optics will be housed in a 6U CubeSat referred to as the optics spacecraft (OSC). A separate 6U CubeSat referred to as the detector spacecraft (DSC) will contain the detector instrument. The DSC will be positioned 40 meters away during science observations. This focal length would be impractical for a single satellite due to launch

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[*] Graduate Research Assistant - Georgia Institute of Technology, Department of Aerospace Engineering, Atlanta, Georgia, 30332.

[†] David Lewis Professor of Space Systems Technology - Georgia Institute of Technology, Department of Aerospace Engineering, Atlanta, Georgia, 30332.

vehicle size constraints, but through precise relative positioning, VISORS aims to accomplish its scientific goals while occupying only a combined 12U launch volume. The spacecraft relative positioning during observations is shown in Figure 1.

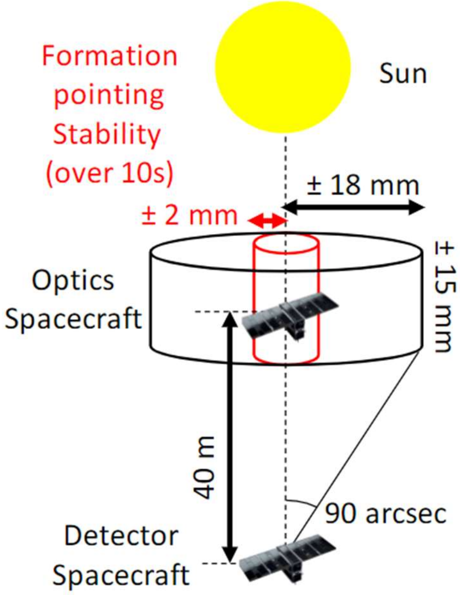

Figure 1. Spacecraft Alignment During Observation.[2]

The relative position will be controlled using a cold gas propulsion system on each CubeSat that will provide precise impulses in six orthogonal directions. The design allows for maneuvering without altering the instrument pointing during observations. The propulsion systems will also transfer the spacecraft between their science and standby orbits. The science orbit is used during observation and requires substantial propellant usage to maintain. The standby orbit positions the spacecraft such that their orbits are passively safe and requires less propellant usage.[2]

The technologies employed in these 3-D printed CubeSat propulsion systems have heritage from NASA's BioSentinel and the DOD's ASCENT missions.[3] The Space Systems Design Lab (SSDL) at the Georgia Institute of Technology (GT) provided similar cold gas thrusters for both of these missions. BioSentinel is scheduled to fly on the first launch of the Space Launch System (SLS), which is expected to occur in 2022. Using lessons learned from these heritage designs, the VISORS propulsion systems have been designed to be cost-effective and volumetrically efficient.

PROPULSION SYSTEM DESIGN

The propulsion systems selected for this mission use a two-tank design. The main tank stores the majority of the propellant as a saturated liquid/vapor mixture. Storing the propellant in this manner is volumetrically efficient, and traditionally these systems have been limited by volume.[4] For this same reason, R236FA is used as the propellant due to its high volumetric specific impulse.[5] The volumetric specific impulse differs from the generally referenced specific impulse in that it refers to the amount of impulse achieved per unit volume of propellant rather than per unit mass.

A second tank, referred to as the plenum, contains only vapor. The plenum ensures that no liquid is allowed to escape through the nozzles, which would be detrimental to system performance. The amount of time the system can continuously fire is determined by the amount of vapor contained within the plenum. When the plenum pressure drops below a certain value, it must be refilled by a solenoid valve connecting it to the main tank. A large plenum would allow for extended continuous firing of the thruster, but the plenum stores propellant inefficiently and directly impacts the space available for propellant storage in the main tank. For this reason, a balance must be struck between the size of the plenum and the size of the main tank. In addition to allowing for complete usage of available volume, 3-D printing enables easy trades between plenum and main tank size during the design phase and a simplified assembly procedure.

The tanks, nozzles, and tubing are all 3-D printed as a single component using stereolithography (SLA). This component is made of SOMOS PerFORM and will be referred to as the structure. SLA is a process which is given slices of a digital model broken into parallel layers fractions of a millimeter thick; then, the machine uses a laser maneuvered by mirrors to selectively cure resin – in this case, PerFORM – layer-by-layer.[6] Designing for additive manufacturing is not as intuitive as for traditional machining, and SLA introduces additional complexities.

Since resin starts as a liquid, complex fluid interactions occur which may affect the way in which material is cured. To hold partially printed areas in place, support structure is intelligently generated and printed in such a way to break away easily post-printing. Due to the intricate internal geometry in the structure, it is imperative that no support is generated internally, requiring complex print orientations. This presents a trade-off between the requirement for no internal supports and impacts to quality that arise from complex orientations.

Tolerancing on printed parts is a function of many variables, such as layer thickness, resin used, and exposure time. As a result, careful consideration of each interface is imperative when designing parts to fit closely and with a vacuum seal against the printed structure. Tighter print tolerances can be obtained with successive refinement of slicer parameters print-to-print; however, this may be infeasible for many projects due to budget constraints. Therefore, tolerances on the 3-D printed structure were designed to be at least twice the amount applied to the machined parts used elsewhere in the system.

Machined manifold blocks allow the propulsion systems' controller boards, valves and sensors to be connected to the structure. O-rings are used to provide seals between the manifolds and the structure. To this extent, this system is similar to those utilized on the heritage missions.[3] The exact design of the system has been shaped by requirements flowed down from the challenging guidance navigation and control (GNC) requirements of the mission.

System Requirements

The VISORS mission concept of operations imposes several requirements on the propulsion systems; the first of which is the requirement that the systems be able to provide thrust in six orthogonal directions. This is necessary because the DSC and OSC must maintain a precise relative position while also maintaining their pointing. Providing thrust in six orthogonal directions negates the need to adjust the spacecraft attitude during maneuvers.

Another key requirement imposed is the shape and size of the systems. The DSC and OSC propulsion systems are allotted volumes of approximately 0.9U and 1.1U. The volumes are shown in Figures 2 and 3, respectively.

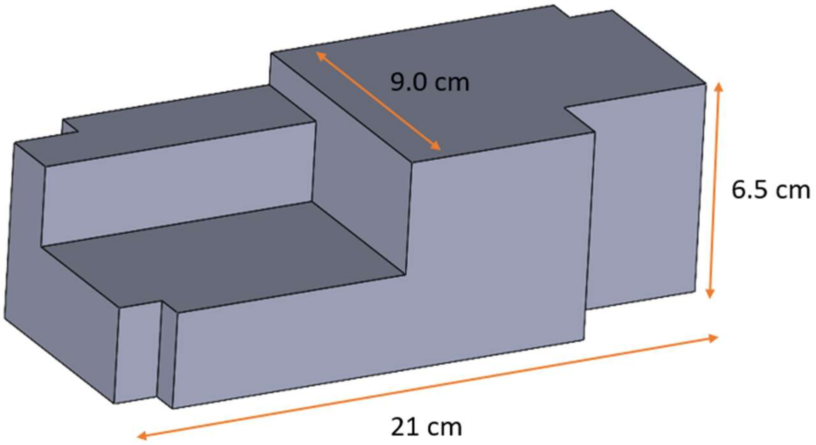

Figure 2. Allotted DSC Propulsion System Volume.

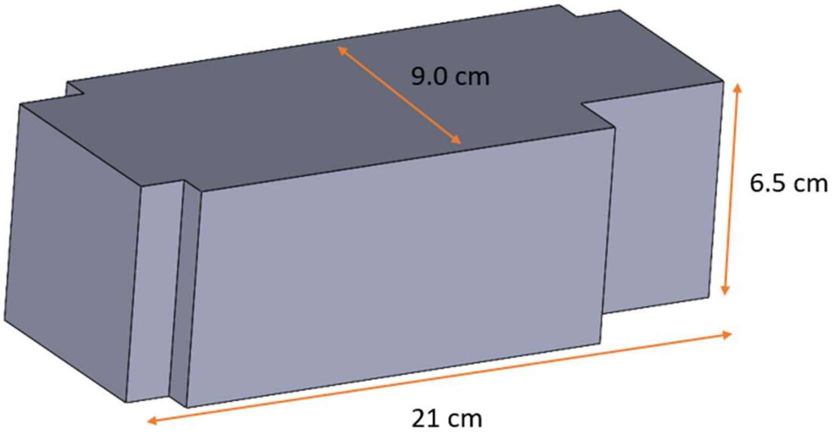

Figure 3. Allotted OSC Propulsion System Volume.

The unusual shape of the DSC volume is due to the presence of an additional star tracker on board the DSC, which is needed to meet the mission's pointing requirements. This star tracker reduces the available space for propellant storage significantly.

The mission's stringent relative positioning requirements, which can be seen in Figure 1, also lead to a strict minimum impulse bit requirement of 1 mN·s for the propulsion system. This requirement ensures that the necessary small changes in spacecraft velocity and position can be made.

Additionally, the VISORS mission lifetime is limited in part by the amount of propellant that can be stored in the propulsion systems. When the two spacecraft are no longer capable of performing maneuvers, no further science observations can be made by the instrument. For this reason, a minimum total delta V requirement of 10 m/s combined across the two systems has been levied on the design. While this is the minimum acceptable value, any additional capability could lead to an increased mission lifetime and a higher probability of mission success. The design is therefore intended to maximize the propellant mass while staying within the allotted volume. This has led to unusually shaped systems that could only be reasonably produced through additive manufacturing.

Design and Performance

The propulsion systems are functionally identical aside from their printed structures. This includes the driving electronics, valves, and sensors. The mounting and interfacing hardware is also identical, which leads to a configurable design that varies only in the printed structure. This simplifies the overall design and integration of the systems.

A diagram of the fluid flow paths through each propulsion system is shown in Figure 4.

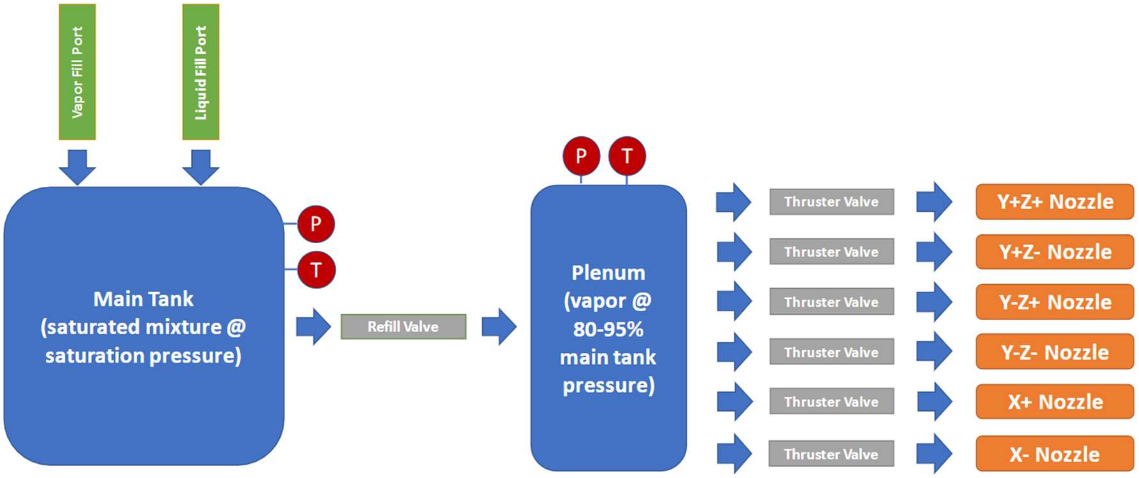

Figure 4. Fluid Flow Schematic with Pressure Transducers and Thermistors Labeled P and T, Respectively.

The main tank holds the majority of the propellant as a saturated mixture. This tank has two fill ports, which allow the thruster to be filled without the use of a pump system. A pressure transducer and thermistor are integrated into each tank. The sensors on the main tank allow for health and status monitoring. These sensors can also be used to indicate when the main tank ceases to hold any liquid propellant, serving as a warning of critically low propellant mass. Since performance of the system varies with temperature, the sensors in the plenum are needed to determine the required firing time to achieve a given impulse. Data from these sensors are also used to determine when to refill the plenum and to estimate total propellant usage throughout the mission lifetime. The tanks are connected by a solenoid valve so that the plenum can be refilled from the main tank. From the plenum, six separate solenoid valves direct propellant to their respective nozzles where the propellant is expanded through a de Laval nozzle to generate thrust.

The as-designed propulsion system assemblies are shown in Figures 5 and 6.

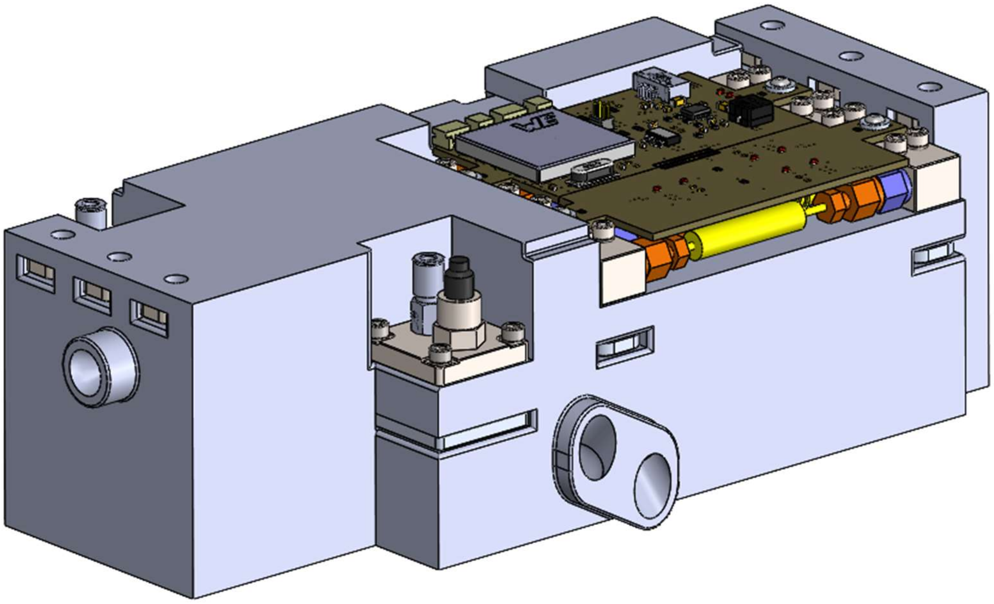

Figure 5. OSC Propulsion System.

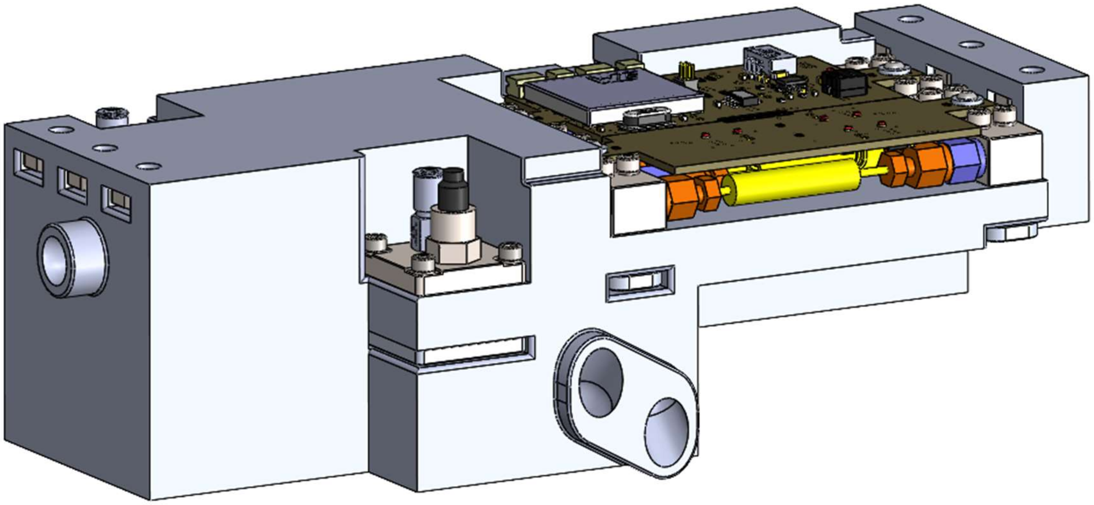

Figure 6. DSC Propulsion System.

The solenoid valves are shown in yellow. The driving electronics, mounted directly above the valves, are shown in brown. These components are mounted to traditionally machined stainless steel manifold blocks. Fluid is able to flow through the 3-D printed tubing within the structure, into the manifold blocks, through the valves, and then out of the opposite manifold block. From there, the propellant carries on through additional 3-D printed tubing and out through the nozzle. The manifolds allow the valves to interface with the printed structure without threading into the plastic.

The manifolds themselves are secured through the use of steel backplates, seen below the manifolds. Through holes are printed into the structure, which allow bolts to interface with just the steel manifolds and backplates. This is beneficial as the plastic structure is not suitable for threading.

The sensors and fill ports can be seen at the front center and rear left on Figures 5 and 6. The printed structure, including the nozzles, tanks, and tubing, is shown in gray. The nozzles are mirrored to the sides of the system that are not shown. This nozzle configuration is necessary because the propulsion unit only has access to five faces of the spacecraft. While it would be ideal to have a nozzle positioned on each of the six faces of the spacecraft, this is not feasible due to placement constraints. The design shown here was deemed to be the best alternative. Due to the nozzle positioning, the system will inherently impart moments on the spacecraft when firing, but analysis has shown that this can be compensated for though appropriate maneuver planning. As shown, the full allotted volume is utilized for both systems. This enables each spacecraft to maximize the available propellant storage volume.

The expected system performance specifications are shown in Table 1.

Table 1. System Performance.

	DSC Propulsion System	OSC Propulsion System
Wet Mass (kg)	1.28	1.54
Dry Mass (kg)	1.03	1.12
ΔV (m/s)	8.4	14.6
Minimum Impulse Bit (mN·s)	0.2 (nominally)	

As would be expected from its larger volume, the OSC propulsion system has a larger mass. The majority of this additional mass is in the form of propellant. The larger propellant mass ratio is achieved because no additional "startup costs," such as additional volumes occupied by valves or the plenum, are incurred. This allows nearly all of the additional volume to be allotted to the size of the main tank.

The propulsion systems are capable of providing a minimum impulse bit of 0.2 mN·s at nominal operating temperature, outperforming the required 1 mN·s requirement. Additionally, the two systems together are capable of providing more than double the required 10 m/s of total velocity change. This will allow for a larger number of propulsive maneuvers to be made, potentially leading to a longer mission lifetime and a higher chance of mission success.

Prior to manufacturing, the tank designs were tested using finite element analysis (FEA) to confirm their viability for flight. The systems were designed to withstand two and a half times the maximum expected operating pressure during nominal mission operations, which corresponds to 1460 KPa experienced by the main tank, plenum, and piping. For simplicity, only the two highest-load circumstances both units will experience were analyzed – these were determined to be launch and on-orbit during a maneuver.

During launch, only the main tanks will be pressurized; however, they will experience extreme static and vibrational loading (approximated to a rough upper bound of 50 times Earth's surface gravity). Interestingly, this loading generates an order of magnitude less stress than pressurization of the propellant.

During an on-orbit maneuver there is the possibility of all internals being pressurized – this includes the main tank, plenum, piping, and nozzles. Therefore, pressure was applied to all of these surfaces. Judging from the results shown in Figures 7-10, the DSC and OSC both experience slightly greater stress in the on-orbit cases, but still remain under the yield strength of SOMOS PerFORM (80 MPa) with a 2.5 Factor of Safety.[7] More precise numbers can be found in Table 2 below.

Table 2. Finite Element Analysis (FEA) Performance.

Tensile Strength (MPa)		80
Maximum Expected Pressure (KPa)		584 @ 50ºC
Factor of Safety		2.5
Maximum Stress	DSC (MPa)	71.2
	OSC (MPa)	76.5

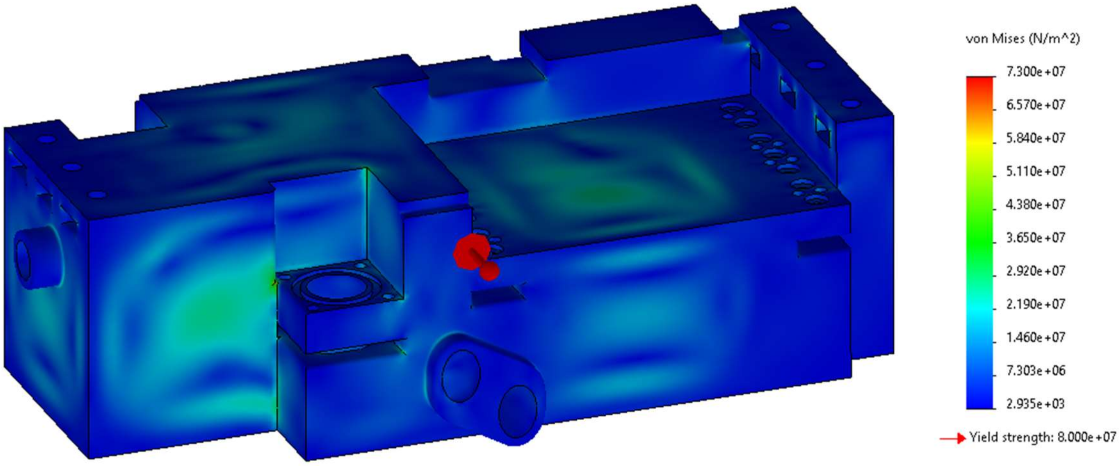

Figure 7. FEA Results, OSC in Launch Configuration.

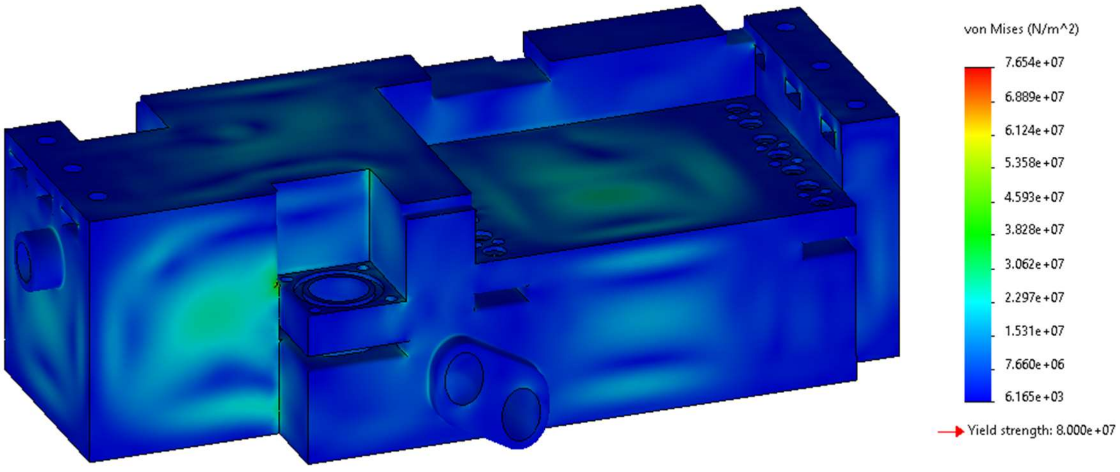

Figure 8. FEA Results, OSC in On-Orbit Configuration.

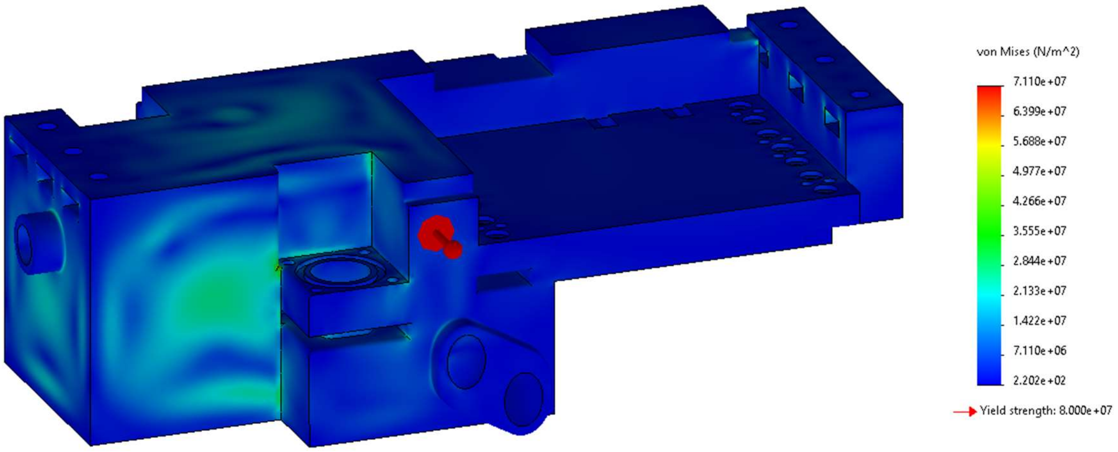

Figure 9. FEA Results, DSC in Launch Configuration.

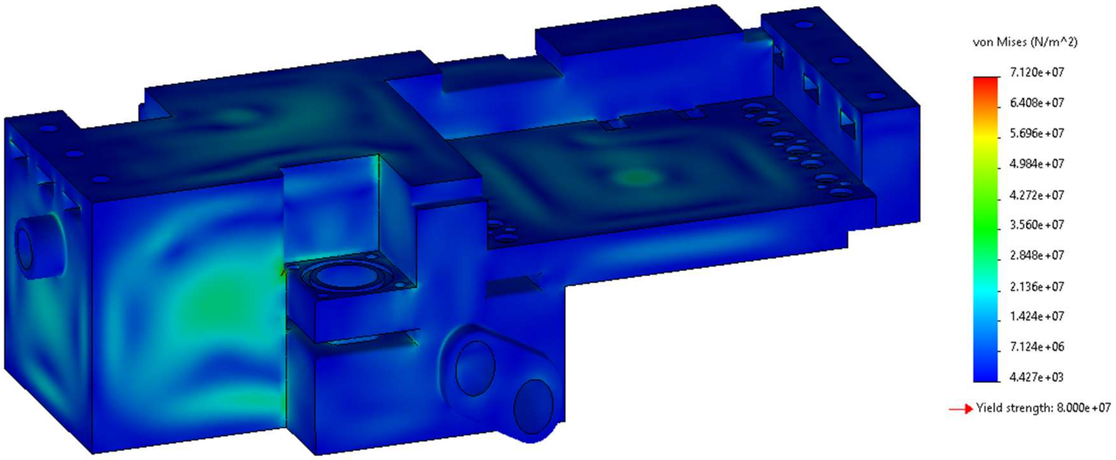

Figure 10. FEA Results, DSC in On-Orbit Configuration.

As seen in Figures 7-10, the majority of stress concentrations are along the large walls near the main tank. Additional stress concentration points are found internal to the structure near these locations. Cylindrical beams have been designed into the tanks in order to provide additional structural support to these walls. This method showed significant reduction in stress concentrations with minimal impact on total propellant volume.

NEXT STEPS

With the design of the propulsion systems completed, the next step will be to build an engineering design unit (EDU) of each propulsion unit. The designs of the electronics and software have heritage from previously delivered systems, but the 3-D printed structures will need to be tested substantially to verify performance. Additional environmental testing will be performed on all components of the systems. Assembly and testing of these EDUs is scheduled to be completed in the spring of 2022. After EDU testing is complete, the flight units will be assembled and tested. The flight units will then be integrated with the spacecraft, with a spacecraft delivery date set for 2023.

CONCLUSION

3-D printed cold gas propulsion systems have been designed for each of the two 6U CubeSats that are used on the VISORS mission. These systems build upon heritage from past systems that were developed by the GT SSDL. They have been designed specifically to meet the challenging relative positioning requirements of the VISORS mission. The propulsion systems provide a combined 23 m/s of velocity change, exceeding the mission requirements and allowing for more maneuvers and a possible extended mission lifetime. Work will continue on both systems, with flight unit delivery scheduled for 2022 and spacecraft delivery scheduled for 2023.

ACKNOWLEDGMENTS

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