Design of the VISORS and SWARM-EX Propulsion Systems

Samuel T. Hart * and E. Glenn Lightsey†
Georgia Tech, Atlanta, GA, 30332

The Georgia Tech (GT) Space Systems Design Lab (SSDL) will deliver 3-D printed cold gas propulsion systems for the VISORS and SWARM-EX CubeSat formation flying missions. This report provides an overview of the working principle of these and past propulsion systems designed by the SSDL. Further information is provided about the specific designs of each of these systems and the problems encountered throughout the design process. Additionally, recommendations for improvements to future designs are outlined. An analysis of the effects of temperature on these systems is also presented.

Nomenclature

DSC	=	detector spacecraft
EDU	=	engineering development unit
GT	=	Georgia Institute of Technology
OSC	=	optics spacecraft
SSDL	=	Space Systems Design Lab
SWARM-EX	=	Space Weather Atmospheric Reconfigurable Multiscale Experiment
1U	=	a "unit" where a unit is defined as a 1 liter cube
VISORS	=	VIrtual Super Optics Reconfigurable Swarm

I. Introduction

CubeSats are increasingly capable platforms enabling the execution of ever more advanced missions. However, their small form factor is not without its challenges. Some technologies are not easily scalable, and the large technology used on conventional satellites must be heavily modified or redesigned entirely to be suitable for the lower size, weight, and power of a CubeSat. One area of particular challenge is propulsion. The Georgia Tech (GT) Space Systems Design Lab (SSDL) designs, builds, and tests small satellite propulsion systems to solve this problem.

The novel cold gas propulsion systems designed by the SSDL are additively manufactured with propellant tanks, nozzles, propellant management, and fluid routing functions incorporated into a single component called the structure.

*Graduate Research Assistant, Georgia Tech Department of Aerospace Engineering, Atlanta, GA.
†David Lewis Professor of Space Systems Technology, Georgia Tech Department of Aerospace Engineering, Atlanta, GA.

The structure is manufactured from Somos PerFORM through a stereolithography 3D-printing process. It can be designed to efficiently use the complex geometries available within a CubeSat bus, increasing the performance density. An example of one such structure is shown in Figure 1.

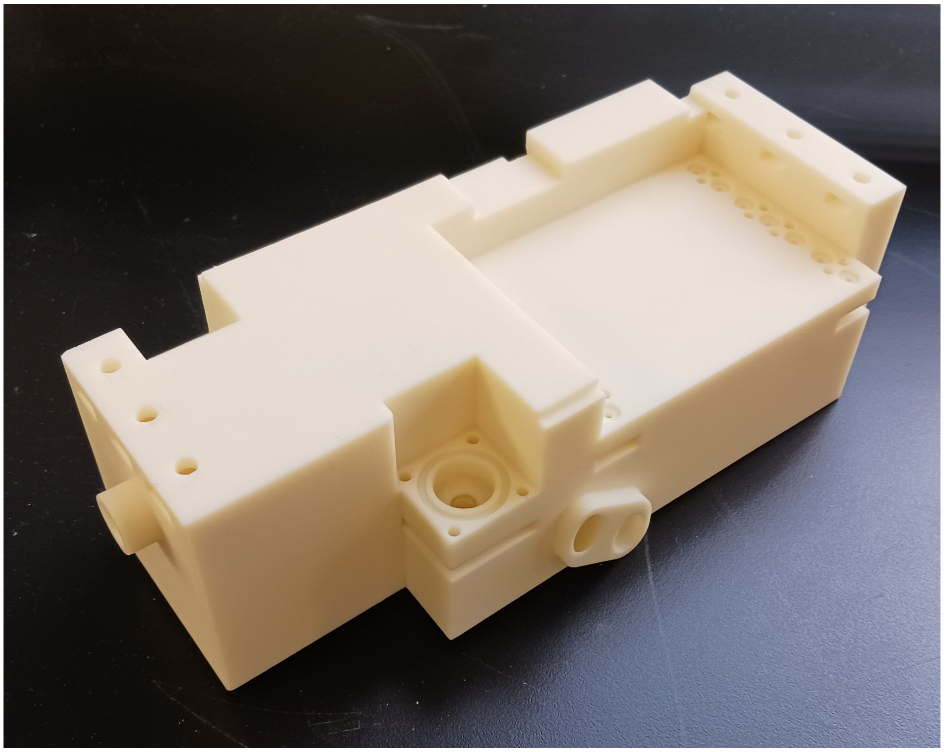

Fig. 1 VISORS propulsion system structure.

All valves, sensors, and control electronics are attached to machined stainless steel components, which are bolted to the structure. Seals are provided by o-rings, which fit into grooves in the structure. Bolt on components allow for modularity, with common component designs that can be reused across multiple systems. This has proven to be highly advantageous as the number of systems designed by the SSDL has grown. The o-ring grooves, ports, and mounting holes are clearly shown in Figure 1.

These propulsion systems use R-236fa as a propellant due to its high volumetric specific impulse, low toxicity, and modest saturation pressure throughout the expected operating temperature range [1]. The propellant can be stored as a liquid-vapor mixture, which is volumetrically efficient. This is beneficial as these systems are generally volume limited rather than mass limited. However, this choice leads to the need to manage a two-phase propellant. The liquid and gas phases of the propellant must be separated, as flowing liquid through the nozzle would be detrimental to the specific impulse of the system. Current systems do this through the use of a two-tank design. An example fluid flow diagram is shown in Figure 2.

The propellant is stored as a two-phase mixture in the main tank. This tank will remain at saturation pressure until

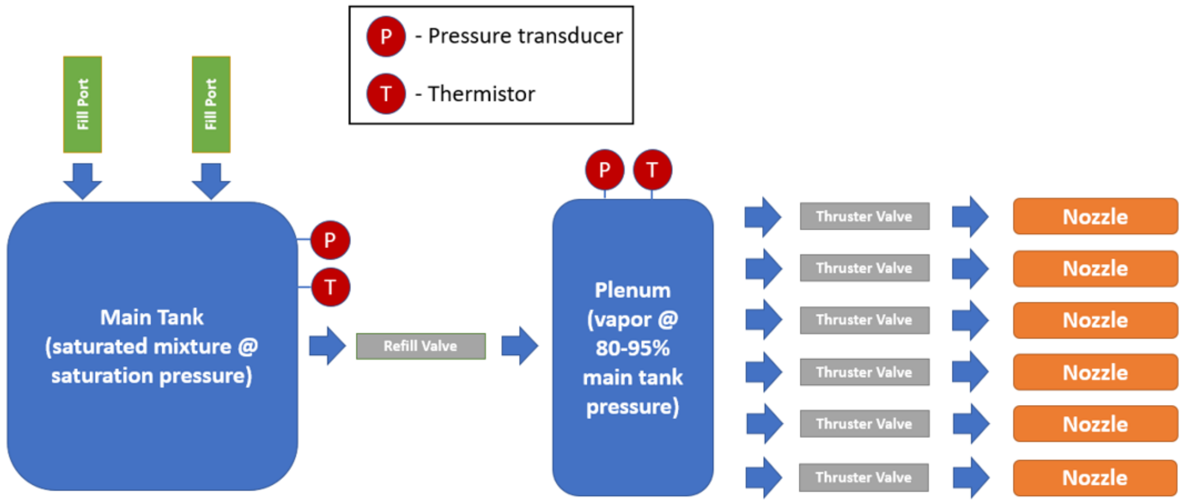

Fig. 2 Fluid block diagram.

the propulsion system has expended more than 95% of its propellant. A small portion of the propellant is maintained as a vapor in a tank called the plenum. The plenum is maintained at a pressure not to exceed 95% of the saturation pressure of the propellant. This ensures that at equilibrium no liquid will exist in the plenum during nominal operations. Propellant is routed from the plenum through a solenoid valve, and is expelled through a converging diverging nozzle to generate thrust. When the pressure in the plenum drops below a user defined threshold, the plenum is refilled from the main tank. This refilling process is carefully controlled to prevent overfilling or allowing liquid to exist in the plenum. Through the use of this strategy, the propulsion system can routinely deliver a single phase gaseous propellant to the nozzles and ensure that the nominal specific impulse is achieved.

The propulsion system has its own onboard controller, which receives commands, sends telemetry, and controls the opening and closing of thruster valves. This controller is also responsible for refilling the plenum when needed. A simplified diagram of the controller firing and refill logic is shown in Figure 3. The same basic controller is used on all cold gas propulsion systems developed by the SSDL, with minor design changes to meet mission needs. This controller has seen significant updates for the VISORS and SWARM-EX missions, which have resulted in substantially lower power draw than on past systems.

One interesting characteristic of these systems is that their performance is highly temperature dependent. At its heart, this is due to the fact that the system stores its propellant as a saturated mixture. This mixture will inherently remain at saturation pressure, which varies from 12.6 to 84.7 psi over an operating temperature range of -5°C to 50°C [2]. When the system is in the upper end of its operating range, the pressure will be high, and therefore the thrust will be higher as shown in Figure 4. This behavior is fairly intuitive. A less obvious consequence of this phenomenon is the effect on the magnitude of the impulse that can be imparted before the plenum must be refilled. This is shown in Figure 5

The propellant in the plenum is stored as a vapor at a set percentage of the main tank pressure, which is nominally

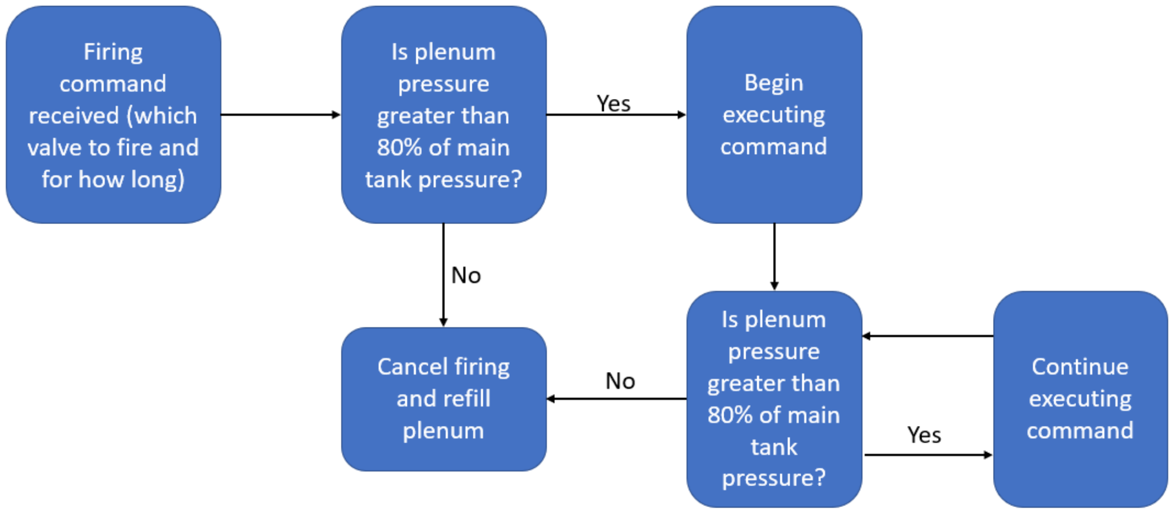

Fig. 3 Firing and refill logic.

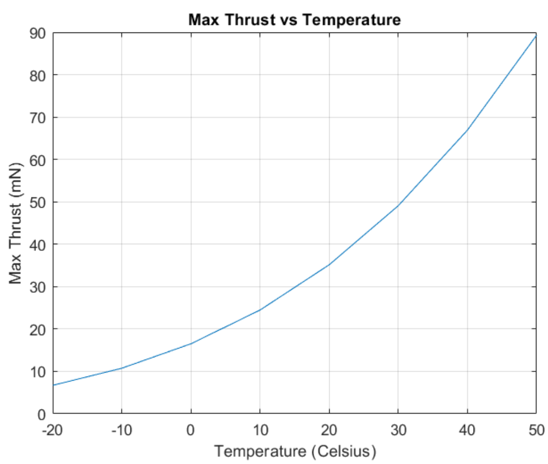

Fig. 4 Maximum thrust output.

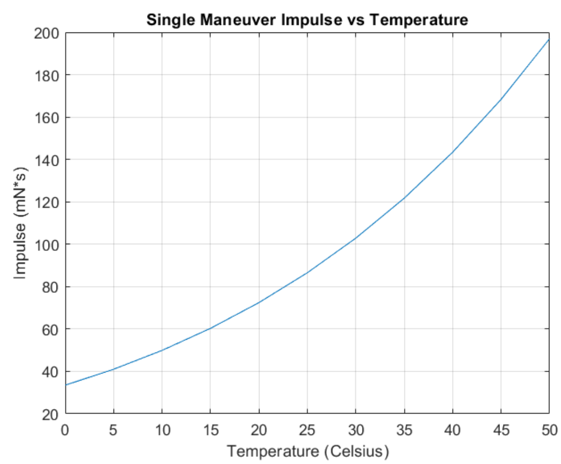

Fig. 5 Total impulse imparted by a single plenum refill.

95%. As the temperature in the main tank increases, the saturation pressure increases rapidly. This causes the pressure in the plenum to rise, resulting in the density of the vapor in the plenum increasing in step with system temperature. This increase in density results in the plenum holding a greater mass of propellant at higher temperatures and ultimately being able to provide a greater impulse before it must be refilled. The analysis of this phenomenon was performed using the CoolProp software package [3].

Variation in system performance complicates maneuver planning. It would be possible to regulate the plenum pressure such that it never exceeds some user defined absolute pressure value. To ensure proper operation, this user defined pressure would have to be lower than the lowest expected saturation pressure of the propellant, which occurs when the system is at its coldest operating temperature. Unfortunately, this would significantly limit the performance of the system with respect to both thrust and impulse per plenum refill. At this time, temperature dependence is simply a unique characteristic of these systems that must be accounted for in maneuver planning. The thermistor and pressure transducer in the plenum provide sufficient information to adjust firing times to obtain predictable impulses.

The basic system architecture described thus far has heritage from the BioSentinel and ASCENT missions, which were flown in 2022 and 2021 respectively, and the SSDL has experience building multiple previous iterations of this system [4]. Each iteration has seen incremental improvements to the original design. The VISORS and SWARM-EX propulsion systems are the next step in this series of cold gas thrusters, which will be used on multi-CubeSat formation flying missions.

II. VISORS

A. Mission Description

The VIrtual Super Optics Reconfigurable Swarm (VISORS) mission will use two 6U CubeSats to form a distributed telescope to image the solar corona. These images will give insight into the physical mechanism of coronal heating. The telescope optics will be located in the optics spacecraft (OSC), and the detector will be located in the detector spacecraft (DSC). When positioned as shown in Figure 6, the spacecraft will act as a diffractive telescope with a focal length of 40 m. This concept will allow the VISORS spacecraft to capture images with unprecedented resolution [5].

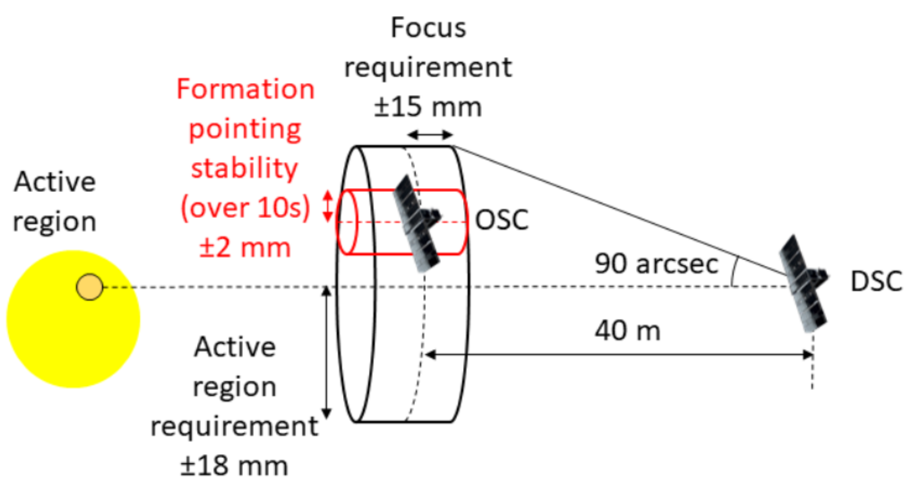

Fig. 6 VISORS spacecraft observation arrangement[5].

The GT SSDL is designing, building, and testing the propulsion systems for these two spacecraft. These systems are similar to systems previously developed by the SSDL, and many lessons learned from previous missions are employed in their design.

B. Requirements and Constraints

Due to the nature of the mission, stringent requirements are placed on the VISORS propulsion systems. The relative positioning of the two spacecraft must be precisely controlled, which requires small and repeatable impulse bits. The spacecraft must also maneuver between a low-maintenance passively safe relative orbit and a higher maintenance science orbit. This transfer requires a relatively large change in velocity, which leads to the need for a larger total impulse capability. Finally, the volumes allocated to these propulsion systems are unusually shaped. This imposes additional design challenges. The most pressing requirements are listed in Table 1.

Table 1 VISORS Propulsion Requirements

Requirement Number	Description
1	Each spacecraft shall host a propulsion system that is capable of providing an impulse along all 6 directions in the spacecraft body frame
2	The propulsion system on each spacecraft shall provide a minimum impulse bit no greater than 10^{-3} N*s.
3	The propulsion system on both spacecraft shall have a cumulative ΔV of 10 m/s.
4	The propulsion system on each spacecraft shall provide a minimum impulse increment no greater than $6 * 10^{-5}$ N*s

C. System Design

The VISORS propulsion systems are designed to operate on the same principles as previous cold gas systems developed by the SSDL. They use the same R-236fa propellant, and their structure is additively manufactured. The OSC and DSC spacecraft each have their own unique propulsion system. Exterior views of the two systems are shown in Figures 7 and 8.

These systems clearly illustrate the benefits of additive manufacturing. The available volumes within the spacecraft are not conducive to traditional propulsion system designs. Additive manufacturing allows these systems to be designed to conform to the available volumes. By fully utilizing all available space, these systems are able to deliver impressive performance within their design constraints. The performance specifications are described in Table 2.

As noted above, the two VISORS propulsion systems are not identical. The DSC propulsion system's volume

Table 2 VISORS Propulsion Performance Estimates

DSC		OSC	
Wet Mass (g)	1278	Wet Mass (g)	1540
Dry Mass (g)	1031	Dry Mass (g)	1117
ΔV (m/s)	8.4	ΔV (m/s)	14.6
Specific Impulse (s)	42.5	Specific Impulse (s)	42.5

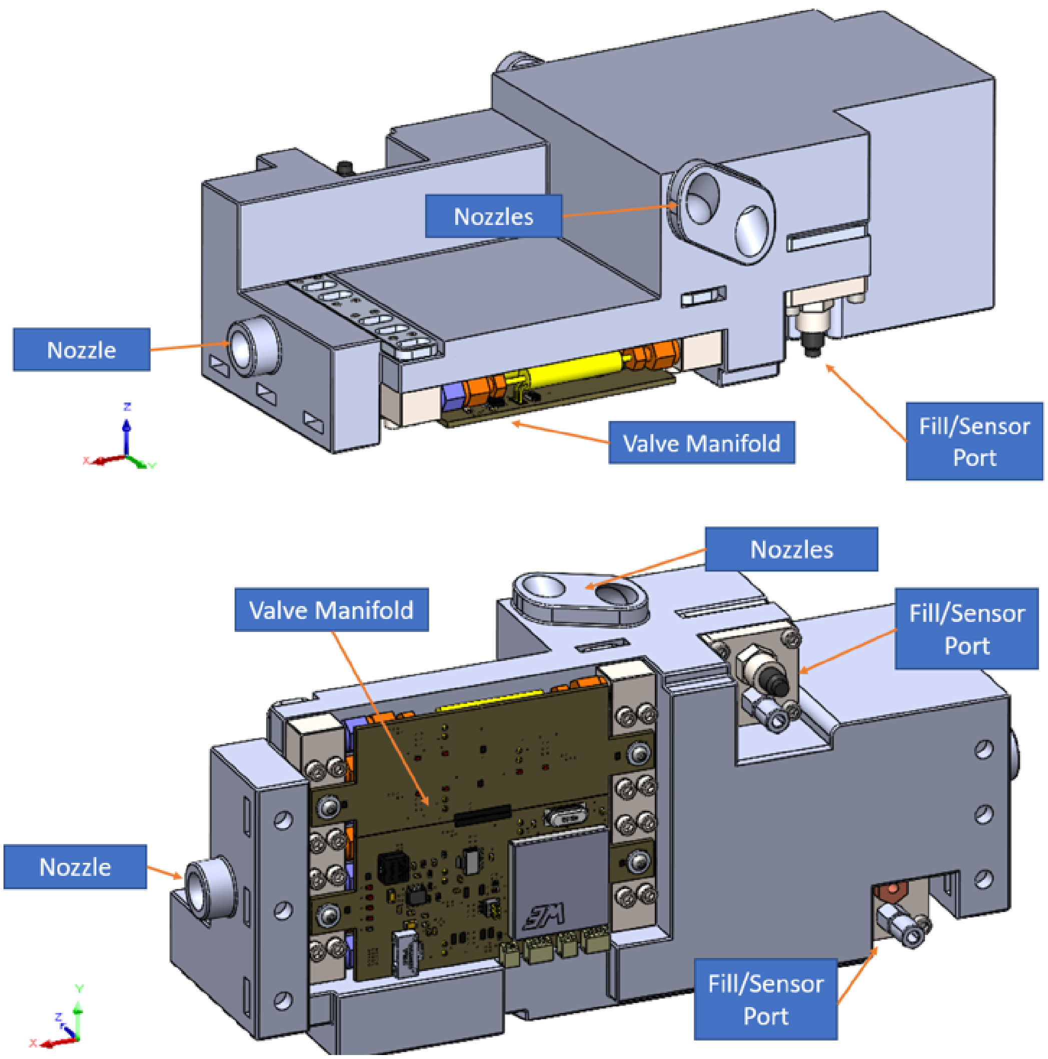

Fig. 7 VISORS DSC Propulsion System

allocation has a section "cut out of it" in order to accommodate an additional star tracker. This is the only noticeable external difference, but internally, the systems are drastically different. The internal tanks and propellant routing are entirely different shapes. The plenum volumes are maintained nearly identical in order to ensure comparable performance, but the main tanks are quite different. The additional volume in the OSC propulsion system is able to be almost solely dedicated to a larger main tank. This allows the OSC propulsion system to provide 74% more ΔV than the DSC propulsion system.

Sensors and fill ports are attached to this system using three separate mounting plates, which can be seen in Figures 7 and 8. This mounting strategy has previously been used on the BioSentinel propulsion system. These mounting plates are necessary because the printed structure is brittle and cannot have threads directly machined into it to allow sensors to be attached. The mounting plates, on the other hand, are metal and allow for easy machining. These plates are

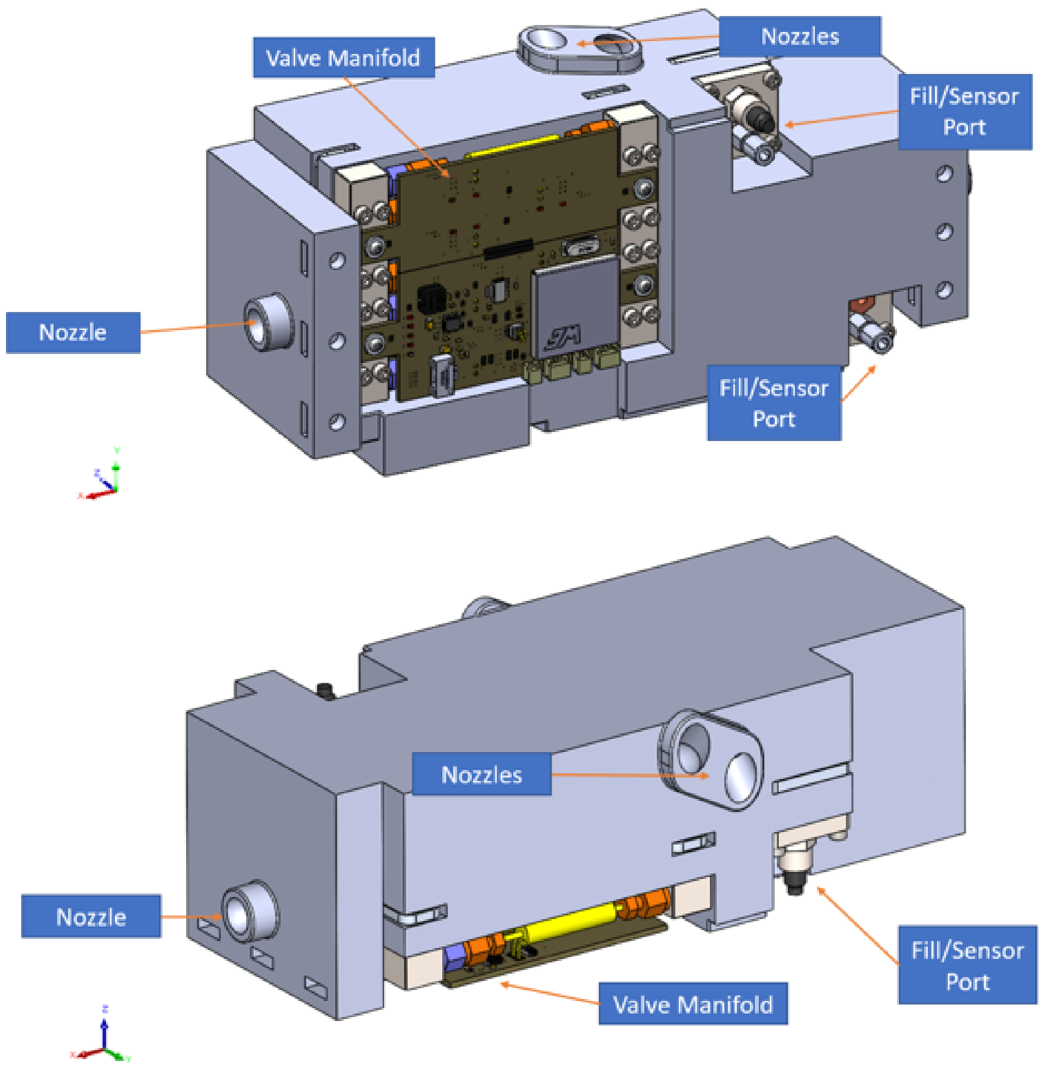

Fig. 8 VISORS OSC Propulsion System

mounted to the printed structure by passing bolts through the plate, through holes printed into the structure, and finally into threaded backplates that slot into pockets in the structure. This assembly is shown under the label "Fill/Sensor Port" in Figure 7. A seal is formed between the mounting plates and the printed structure using o-rings. The o-ring grooves are printed directly into the structure. Therefore, these grooves are not perfect. Their surfaces are often rough and contain many printing defects. Despite these issues, they have been shown through testing to provide a sufficient sealing surface to meet leak rate requirements, with measured leak rates less than 4 mg/day.

When choosing the locations of the sensors in the printed structure, the primary concern is interfacing these sensors with the main tank and plenum. An easily overlooked but equally important consideration is how the sensor wires will be routed to the controller board. The nature of these systems is not to leave any empty space, and, therefore, there generally are not easy wire routing locations built into the system unless one plans them out in advance. In order to resolve this issue, small grooves were designed into the structure specifically to allow wires to be routed from the sensors to the controller. These grooves are designed with minimum wire bend radii in mind, and corners are rounded to prevent any damage to the wires. These features are shown in Figures 7 and 8.

Both VISORS propulsion systems have 6 orthogonal nozzles so that impulses can be provided in any direction without the need to adjust the attitude of the spacecraft. This is critical during solar observations. Due to the positioning of the propulsion system within the spacecraft bus, it is not possible to have the nozzles point through the center of mass of the spacecraft. This results in any impulse also imparting a torque on the spacecraft. The nozzles are designed to be nearly symmetric such that the torque imparted by firing in the +X direction will be counteracted by an equivalent firing in the -X direction, which partially compensates for this issue. Analysis has shown that the planned maneuver profile will not saturate the reaction wheels as a result of these imparted torques, but a more aggressive maneuver profile could. There were brief considerations of adding a seventh nozzle to both the DSC and OSC propulsion systems that would point through the center of mass of the spacecraft, but this proved undesirable. The addition of a seventh nozzle would require an additional thruster valve, which would expand the valve manifold and require it to be relocated. This expansion and relocation proved detrimental to the total impulse of the system, and as a result was decided against. If the propulsion system were located elsewhere in the spacecraft or had access to all six faces of the spacecraft, it would be possible to minimize the torque imparted by thruster firings. Unfortunately, this was not possible.

Because both of the VISORS spacecraft contain delicate optical instruments, it is desired to prevent propellant from interacting with the science payload. To mitigate any risk of propellant entering the spacecraft, all six nozzles are designed so that the exit plane is coplanar with the spacecraft bus. This ensures that the plume does not directly enter the bus. Also, the propellant has not been shown to coat surfaces in a vacuum environment. The nature of the propellant is to remain as a vapor when expelled into vacuum. Furthermore, the exit velocity of the propellant serves to rapidly dissipate the propellant plume.

The original designs of the DSC and OSC propulsion systems faced structural strength issues, as shown by finite element analysis (FEA). Fundamentally, the ideal shape for a pressure vessel is a sphere. Unfortunately, these systems are far from spherical. A particularly problematic feature of these systems is vertices that protrude into the tank volume producing a concave section. This results in large local stresses. Additionally, the main tank is composed of many large semi-rectangular volumes, which generally do not perform well in a pressure vessel. Many design strategies were attempted in order strengthen the systems. These included thickening the walls of the main tanks, increasing fillet sizes in internal corners, adding braces along the tank walls, and adding cross beams within the tanks. Ultimately, the last option proved to be the most volumetrically efficient. The internal design is shown in Figure 9.

The beams within the main tank are visible in the right half of Figure 9. They are placed with the intent of stabilizing the large walls of the main tank and specifically in locations near concave features. A good example of such a feature is shown in the far right section of Figure 9. Note the rectangular section protruding into the main tank. The support

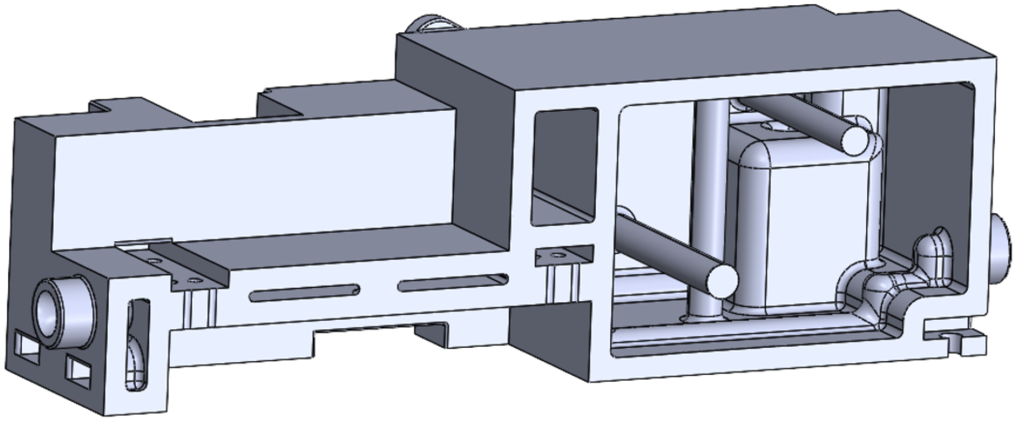

Fig. 9 Internal Structure of VISORS Propulsion Systems

beams used in this propulsion system are one of the unique benefits of an additively manufactured pressure vessel. They provide a structurally sound system without complicating the manufacturing process.

Figure 9 also illustrates the internal complexity of these systems. While no fluid routing components are shown in this cross section, the main tank and the plenum are visible. The main tank is on the right side of the figure and the plenum is distributed throughout the left. These tanks are designed to carefully fit around the various nozzles, sensor ports, and fluid routing components. They are also designed to be accessible to the valve manifold in order to reduce the length of flow passages. This leads to uniquely shaped tanks. Many sections of the plenum are very thin and connected by small passages. This is necessary in order to fully utilize the entirety of the volume allocated to the system. It considerably complicates the design, but the dividends it pays in performance are significant.

Engineering development units (EDUs) of the VISORS propulsion systems are currently being assembled and tested, and flight units are scheduled to be delivered in early 2023. These systems are expected to meet all requirements and significantly exceed the required ΔV. The VISORS DSC propulsion system EDU is shown in Figure 10 as a matter of interest.

III. SWARM-EX

A. Mission Description

The Space Weather Atmospheric Reconfigurable Multiscale Experiment (SWARM-EX) mission aims to study the equatorial thermal and ionization anomalies. SWARM-EX will use a small swarm of three CubeSats to collect plasma and atomic oxygen measurements to better understand these phenomena[6]. Each of the three CubeSats will have an identical propulsion system that will allow them to maintain their formation. The GT SSDL is designing, building, and testing these systems.

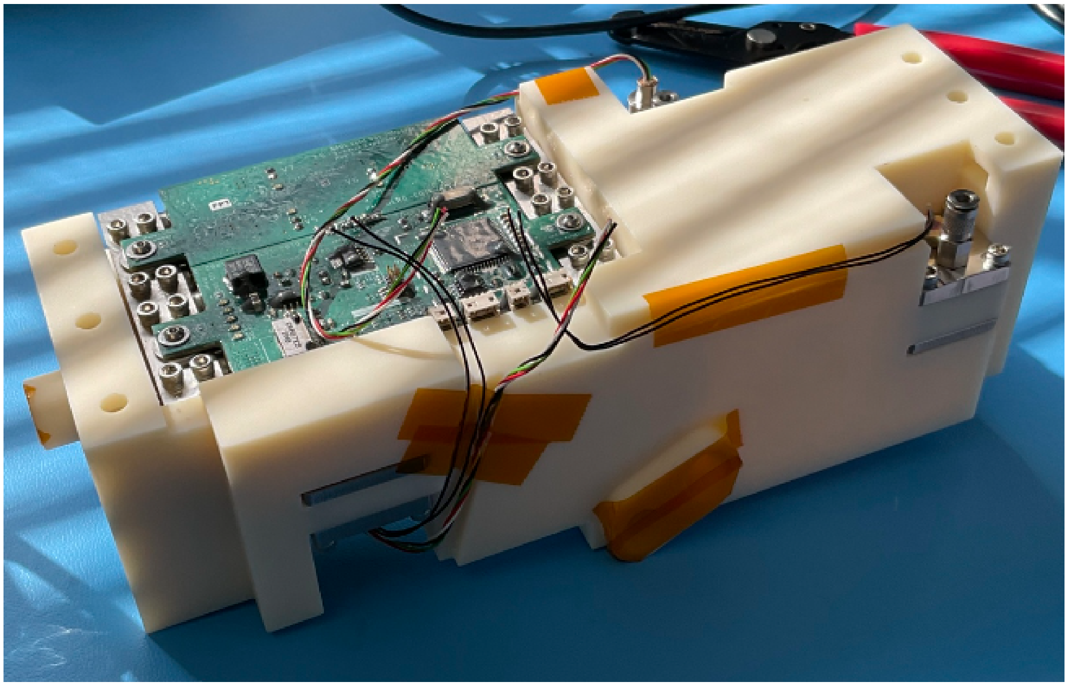

Fig. 10 VISORS DSC Propulsion System EDU

B. Requirements and Constraints

The SWARM-EX propulsion system has many requirements in common with the VISORS propulsion systems. The main differences are that SWARM-EX is only required to provide thrust in a single direction, and it is provided with a smaller and simpler volume allocation. The SWARM-EX propulsion system is also required to provide a significantly larger ΔV than the VISORS propulsion systems. The driving requirements for this system are described in Table 3.

Table 3 SWARM-EX Propulsion Requirements

Requirement Number	Description
1	The volume of the propulsion subsystem shall be less than 0.7U.
2	The mass of the propulsion subsystem shall be less than 700 g.
3	Each propulsion subsystem shall be capable of providing a ΔV of greater than or equal to 15 m/s.

Interestingly, the mass requirement of this system was the driving requirement of the system size, rather than the volume requirement. This is unusual for propulsion systems designed by the SSDL, as they are generally volume limited. R-236fa was chosen as the SSDL's default propellant due to its high volumetric specific impulse, but in this particular case, it is possible that a system that used a more mass efficient propellant may have been able to provide a larger total impulse. However, it was specified in the SWARM-EX propulsion system requirements that the propellant shall be R-236fa, so no other propellant choices were considered for this system.

C. System Design

The SWARM-EX propulsion system began was initially designed to be a 0.5U system. It has since grown to a 0.7U volume, but many of the design choices originally made to make this system fit into such a small volume are still evident in the final design. The system has only one nozzle, which considerably simplifies the design and allows much of the system's volume to be devoted to storing propellant rather than valves, fluid routing components, and nozzles.

In an effort to save volume, this system also eliminated one of the two thermistors that are traditionally added to these propulsion systems. This was done because the temperature of the main tank was not considered to be a necessary measurement. Additionally, if the main tank is at saturation pressure, then the temperature can be determined based on the pressure of the main tank should it be desired.

In another attempt to conserve volume for propellant, the SWARM-EX propulsion system has all of its sensors and fill ports mounted directly into the valve manifolds. This eliminates the need for additional mounting plates and backplates, which consume a significant volume in other systems. The final design is shown in Figure 11.

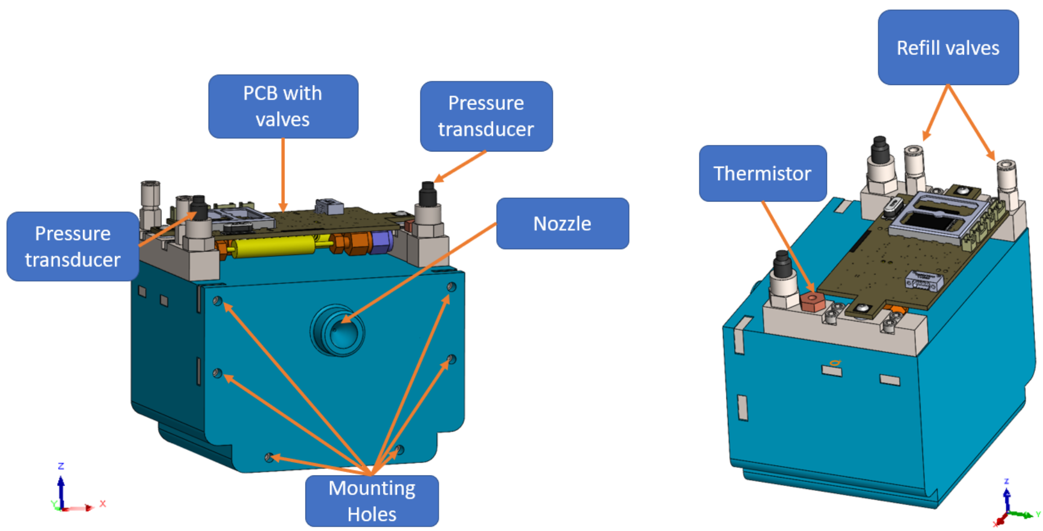

Fig. 11 SWARM-EX Propulsion System

This configuration is not always beneficial, especially in systems such as VISORS, which have large valve manifolds. Placing the sensors in the valve manifold requires the entire manifold assembly to be inset further into the structure of the propulsion system to accommodate the sensor height. This consumes a significant volume that could otherwise be dedicated to propellant. In the particular case of the SWARM-EX propulsion system, this was not a concern. This is partially due to the small footprint of its valve manifold and partially due to the fact that the SWARM-EX propulsion system is mass limited, not volume limited. This design choice decreased the mass of the system, which proved beneficial.

Despite its small size, the SWARM-EX propulsion system is able to provide a substantial total impulse. This is largely due to the design choices outlined above, which allow more of the volume of this system to be devoted to propellant than other systems. It is also due in part to the shape of the volume allocation that was provided to this system. Using only a single nozzle also contributes to the performance density of the system. The performance characteristics of the system are described in Table 4.

Table 4 SWARM-EX Propulsion Performance Estimates

Wet Mass (g)	668
Dry Mass (g)	452
ΔV (m/s)	17
Specific Impulse (s)	42.5

The volume allocation for the SWARM-EX propulsion system is a nearly perfect rectangular prism with indentations along four of its edges. This volume can be used much more efficiently than a complex volume, such as the one assigned to VISORS. This is because any wall of the structure must have a certain minimum thickness to ensure its structural rigidity. On a system that has a high surface area to volume ratio, there will be significantly more volume dedicated to walls and less volume dedicated to propellant storage. Additionally, if parts of the volume allocation are thinner than double the minimum acceptable wall thickness, they simply cannot be used to store propellant. On systems like the VISORS propulsion system, these problems occur frequently. A near-cube has a much lower surface area to volume ratio. This is partly why the SWARM-EX propulsion systems hold nearly the same mass of propellant as the VISORS DSC propulsion system while occupying roughly $2/3$ the volume. For a further demonstration of this phenomenon, see the thin horizontal section of the VISORS DSC propulsion system structure on the left side of Figure 9. It is nearly too thin to store propellant, and the inefficiency is made clear.

Another space-saving design on the SWARM-EX propulsion system is the small backplate inserts. On most systems developed in the SSDL, including the VISORS propulsion systems, long backplates are slotted into the structure below the valve manifolds. They are as long as the manifold is wide. The manifold then bolts into these backplates. The design of the SWARM-EX system placed the valve manifold mounting points along the edge of the structure, as seen in Figure 11. Thanks to this placement, it was possible to design small threaded inserts that slot into the structure directly below the mounting points and only under those mounting points. These small tabs replace the usual valve manifold backplates and result in a significant volume and mass savings. The mounting tabs are the two small gray pieces on the +X face of the right most image in Figure 11.

Future systems may incorporate many of the design methods used in the SWARM-EX propulsion systems to obtain a similar performance density when mission requirements allow for it. It is likely that these changes could offer significant performance gains with minimal to no losses of capability in most cases.

An EDU of the SWARM-EX propulsion system has been assembled and delivered. A second EDU of the

SWARM-EX system has been built with minor modifications from the first version. This second unit will be used for the purpose of further characterization testing and future troubleshooting. The second EDU is shown in Figure 12. This system has already demonstrated that the modifications made for ease of assembly were effective.

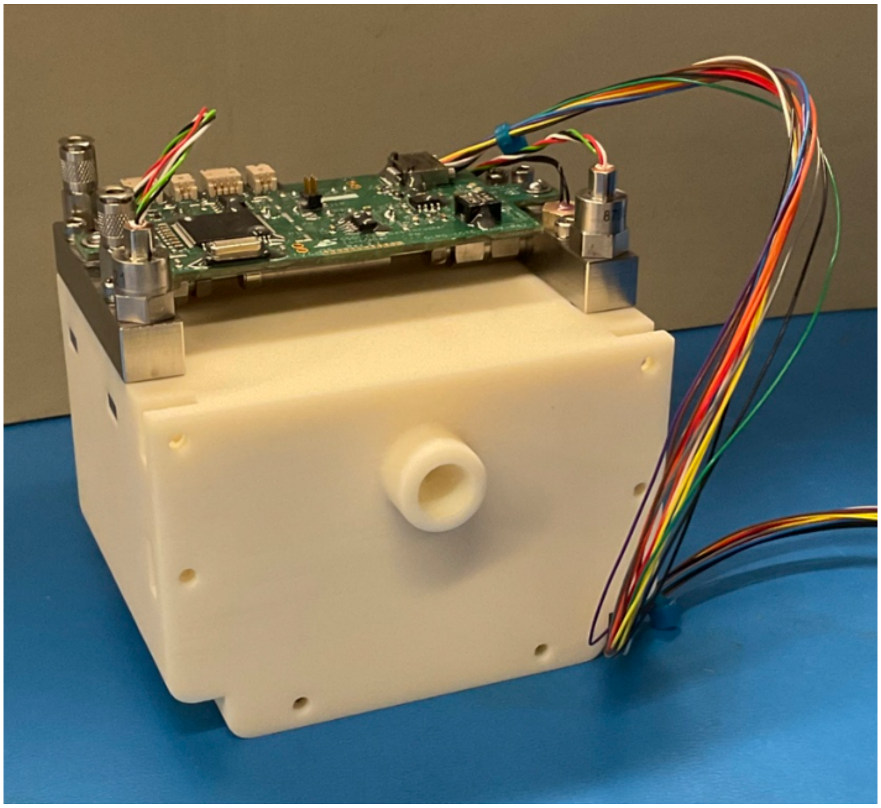

Fig. 12 SWARM-EX Propulsion System EDU

IV. Improvements to Future Systems

In the design, assembly, and testing of these systems, some areas for future improvements were discovered. One simple improvement has already been implemented on the SWARM-EX propulsion system. There is no need to have a thermistor in the main tank. The data is not used in any way by the thruster controller. By eliminating this component, one conserves mass and volume that could be better allocated to propellant storage. If one did wish to know the temperature of the main tank, this could be derived from the pressure reading in the main tank. As long as there is still a saturated mixture in the main tank, which will exist until the system has expelled more than 95% of its propellant, pressure and temperature can be directly correlated using the saturation curve.

Another simple improvement would be to eliminate one of the two fill ports. There are currently two ports because the system is loaded with propellant using a gravity-fed system. This works well and eliminates the need for a pump, but it would be beneficial if the system could be fueled using a single fill port. This can be achieved rather simply through the application of heat. The main tank of the propulsion system should have a rough vacuum pulled on it prior to beginning propellant loading. This is easily accomplished through the use of a venturi pump. Once a rough vacuum is achieved, a metal cylinder containing liquid propellant can be suspended above the propulsion system with a tube leading from the base of this cylinder to the propulsion system. By connecting the tube to the base of the cylinder, liquid can be drawn out. Once the cylinder is connected to the propulsion system and the flow of propellant is allowed to begin, it will slowly stabilize with only a small amount of liquid propellant in the propulsion system. To load additional propellant, the cylinder can be heated either through the use of a resistive heater, a heat gun, or simply by placing one's hands on it. This heating will warm the cylinder and thereby increase the pressure in the cylinder. This additional pressure will drive liquid propellant into the propulsion system. Once in the propulsion system, the propellant will cool, which will lower the pressure. This will allow the full volume of liquid propellant to be loaded into the propulsion system. If necessary, one could attempt to actively cool the propulsion system simultaneously to accelerate this process, but this has not proven to be necessary in preliminary testing. A diagram of the proposed propellant loading system is shown in Figure 13. Not only has this method proved effective in fueling the VISORS propulsion system EDU, but it has proven to take a comparable amount of time to the gravity fed filling system.

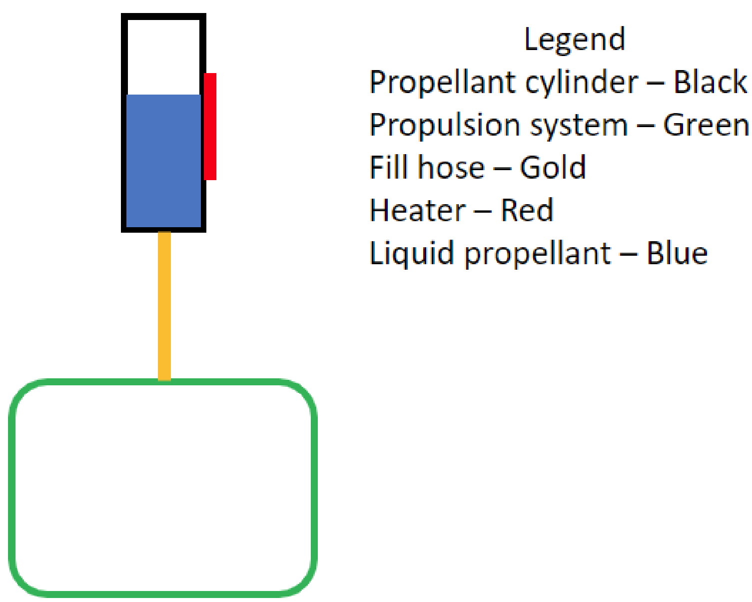

Fig. 13 Proposed Filling System

Another area for improvement in the design of these systems is tolerancing. The additive manufacturing process cannot meet the same tolerances that are possible in traditional machining. Surfaces also generally do not have a smooth finish. This can be problematic when a system is composed of multiple small components which must be fitted together precisely. The backplates of the propulsion systems generally slot into small, deep pockets in the structure. These pockets are especially challenging to print and very challenging to alter after printing. This has resulted in some systems being either impossible to assemble or requiring significant alterations prior to assembly. While these systems were designed with the manufacturer's stated printing tolerances in mind, this proved insufficient. Future systems should be designed with the expectation of poor tolerances in sharp corners in pockets. An easy workaround is to design pockets and backplates that have significant fillets in their corners. Another is to design the pockets to leave a large clearance for the backplates.

A more challenging issue for these printed structures is designing o-ring grooves. These features are small and require a smooth surface. Unfortunately, that is not generally possible with an additively manufactured structure. Sometimes these surfaces can be improved in post processing using simple hand tools. Often though, these imperfections must be accepted as they are. In the future, o-ring grooves should be post-machined when location and budget permit. Note that this may be challenging due to the brittle nature of the Somos PerFORM material.

Another issue related to the additive manufacturing process is cleaning. These systems have complex internal geometries, and the printed structures are

A final consideration for future system design is designing for assembly. When designing these small and complex systems, which frequently appear larger on one's computer monitor than they are in real life, it is easy to forget the scale of the components. It is equally easy to forget that the system will one day be assembled by human hands with standard tools. This results in a lack of consideration of how those hands and tools will interact with the small clearances in the assembly. A perfect example of this is seen in the valve manifolds. The valves are so closely spaced that multiple wrenches have had to be machined specifically to fit over the valve fittings and tighten them in place. Often a number of these wrenches must be used in the course of tightening a single fitting. This is a sign of a poorly designed system. It is very volumetrically efficient, but it puts the rest of the assembly at risk during assembly. The custom wrenches are prone to bending and skipping, and it takes only a small amount of force to permanently damage the sensitive components used in these systems. Future designs should take this into account when possible.

V. Conclusion

The VISORS and SWARM-EX propulsion systems are fully designed, and engineering development units are currently being assembled and tested. These units will continue to undergo environmental and performance tests to fully characterize the systems. Once testing is complete, the flight units will be assembled, tested to ensure they perform as expected, and delivered. All systems are scheduled to be delivered in early 2023.

Thanks to the lessons learned on past projects, these systems are highly capable and represent the state-of-the-art in cold gas propulsion for CubeSats. With that said, there will always be room to further refine these designs. These systems, like those that came before them, will serve as the basis for the design of the next generation of propulsion systems developed by the SSDL.

Funding Sources

This material is based upon work supported by the National Science Foundation under Award No. 1936663 and Award No. 1936665.

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-2039655.

Acknowledgments

I would like to thank my teammates: Nathan Daniel, Mackenzie Glaser, Mark Hartigan, Kian Shirazi, Kevin Tong, and Sam Wood, as well as my advisor, Dr. E. Glenn Lightsey, for their support. Without them, none of this would be possible.

References

[1] Stevenson, T., Glenn Lightsey, E., and Sorgenfrei, M., "Development and Testing of a 3-D-Printed Cold Gas Thruster for an Interplanetary CubeSat," *Proceedings of the IEEE*, Vol. 106, No. 3, 2018, pp. 379–390. https://doi.org/10.1109/JPROC.2018.2799898, conference Name: Proceedings of the IEEE.

[2] DuPont, "HFC-236fa-SI.pdf," , Nov. 2022. URL http://www.allchemi.com/download/tables/HFC-236fa-SI.PDF.

[3] Bell, I. H., Wronski, J., Quoilin, S., and Lemort, V., "Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp," *Industrial & Engineering Chemistry Research*, Vol. 53, No. 6, 2014, pp. 2498–2508. https://doi.org/10.1021/ie4033999, URL http://pubs.acs.org/doi/abs/10.1021/ie4033999, _eprint: http://pubs.acs.org/doi/pdf/10.1021/ie4033999.

[4] Stevenson, T., "DEVELOPMENT OF MULTI-FUNCTIONAL STRUCTURES FOR SMALL SATELLITES," Ph.D. thesis, Georgia Institute of Technology, Dec. 2018. URL https://ssdl.gatech.edu/sites/default/files/ssdl-files/papers/phdTheses/StevensonT-Thesis.pdf.

[5] Koenig, A., D'Amico, S., and Lightsey, E. G., "Formation Flying Orbit and Control Concept for the VISORS Mission," *AIAA Scitech 2021 Forum*, American Institute of Aeronautics and Astronautics, VIRTUAL EVENT, 2021. https://doi.org/10.2514/6.2021-0423, URL https://arc.aiaa.org/doi/10.2514/6.2021-0423.

[6] Agarwal, R., Oh, B., Fitzpatrick, D., Buynovskiy, A., Lowe, S., Lisy, C., Kriezis, A., Lan, B., Lee, Z., Thomas, A., Wallace, B., Costantino, E., Miner, G., Thayer, J., D'Amico, S., Lemmer, K., Lohmeyer, W., and Palo, S., "Coordinating Development of the SWARM-EX CubeSat Swarm Across Multiple Institutions," 2021, p. 12. URL https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=5104&context=smallsat.