Assembly and Testing of Additively Manufactured Cold-Gas Propulsion Systems for the VIrtual Super-Resolution Optics Using Reconfigurable Swarms (VISORS) Mission

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The VIrtual Super-Resolution Optics Using Reconfigurable Swarms (VISORS) mission aims to capture images of the sun in unprecedented resolution through a novel formation flying approach. Consisting of two 6U CubeSats, the VISORS mission requires high-precision maneuvering to enable millimeter tolerances in the relative position of the two spacecraft, which orbit 40 meters apart. Each CubeSat features an additively manufactured propulsion system that was tested by the Georgia Tech Space Systems Design Lab before integration with the satellite bus. The systems are tested on a torsional pendulum thrust stand within a thermal vacuum chamber to determine propellant leak rate, thrust, and specific impulse characteristics. While 3D-printing propulsion systems increases CubeSat capabilities in orbit, this emerging technology presents challenges in integration and testing. Small fluid flow components are susceptible to Foreign Object Debris (FOD) and are difficult to replace. This paper discusses some of the current challenges for CubeSat propulsion system integration and testing at a university laboratory and proposes improvements to reduce development time and lower costs.

I. Nomenclature

DSC = Detector Spacecraft
ESD = Electrostatic discharge
FOD = Foreign Object Debris
GNC = Guidance Navigation and Control
IPA = Isopropyl Alcohol
ISO = International Standards Organization
MEOP = Maximum Expected Operating Pressure
NSF = National Science Foundation
OSC = Optics Spacecraft
PCB = Printed circuit board
QA = Quality assurance
SSDL = Space Systems Design Laboratory
TVAC = Thermal Vacuum
VISORS = VIrtual Super-Resolution Optics Using Reconfigurable Swarms

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II. Introduction

CubeSats are becoming an increasingly important part of space exploration as they are less expensive to build and launch than traditional large satellites. As such, they create ideal missions in which universities may participate. Students can partner with organizations such as the National Science Foundation to play a pivotal role in complex missions to space, achieving larger goals in limited volumes[1]. University level CubeSat missions also come with their own unique challenges. Projects are limited by funding, facility space, and the inherent issue of knowledge transfer among graduate and undergraduate students who may be moving in and out of projects.

The VISORS mission is a multi-university project funded by the National Science Foundation that initiated from the CubeSat Ideas Lab in 2019[2]. The mission uses two formation-flying 6U CubeSats, the optics spacecraft (OSC), and the detector spacecraft (DSC) to create a two-spacecraft distributed telescope. Each spacecraft contains an additively manufactured cold-gas propulsion system for maneuvering in orbit, requiring precise maneuvering of each satellite to align properly to capture images of the sun's corona. The relative positioning of the spacecraft during a science measurement is shown in Figure 1.

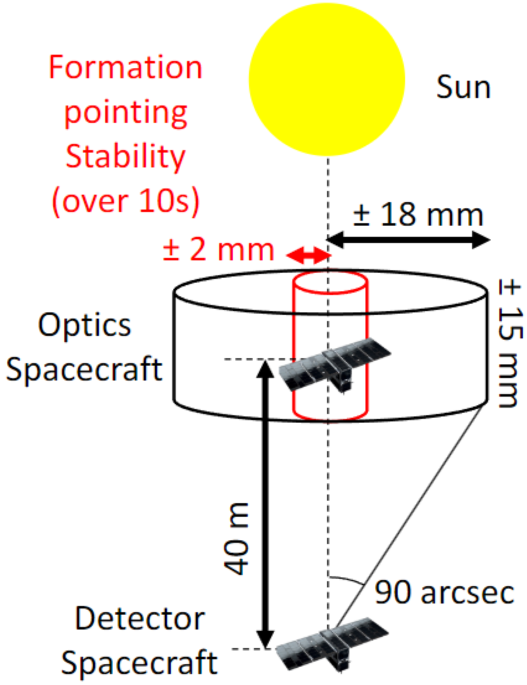


Fig. 1. Relative Position of VISORS Spacecraft During Flight [3]

To achieve the science goals laid out by the VISORS mission, high performance and accuracy in each satellite's propulsion system is imperative. The VISORS propulsion team is responsible for constructing and assessing the performance of the VISORS propulsion systems throughout integration and testing at the Georgia Tech Space Systems Design Laboratory (SSDL).

III. Design

The VISORS propulsion system design is based off the design of the cold-gas propulsion systems successfully flown on NASA's BioSentinel spacecraft, modified to satisfy the requirements set for the VISORS mission. To allow the two VISORS spacecrafts to move into alignment and maintain their required relative positions, the systems must have six orthogonal thrust directions. Volume constraints drove the sizing of each propulsion system since the OSC and DSC propulsion systems were each allotted volume of approximately 1.1U and 0.9U respectively. The VISORS mission lifetime is largely limited by the propulsion system's ability to continue performing maneuvers in orbit. As such, the combined total ΔV between the two spacecraft must be a minimum of 10 m/s to achieve a minimum of 100 science orbits where imaging requires several propulsive maneuvers to maintain spacecraft alignment. The mission minimum impulse bit requirement of the propulsion systems is 1 mN•s.[3]

The structures of the VISORS cold-gas prop systems are additively manufactured from Somos PerFORM using stereolithography (SLA). A 7-valve manifold attached to the 3D printed structure allows for individual control of each of the six orthogonally oriented nozzles, with a seventh valve for internal propellant management. The propellant is primarily kept in the system's main tank at saturation pressure where the R-236fa refrigerant is stored as a saturated liquid-vapor mixture at saturation pressure. A single solenoid valve runs from the main tank to a secondary tank called the plenum. The plenum is a far smaller volume at 17% of the main tank volume on the OSC and 28% of the main tank volume on the DSC and is kept around 80-95% of the main tank pressure. While the main tank volume differs between the two spacecraft to meet sizing requirements, the plenum volume is identical for both the OSC and DSC. The plenum tank acts as an intermediate storage volume in-between the main tank and nozzles that causes all fired propellant to be in gaseous state, therefore ensuring each firing obtains the highest specific impulse possible while maintaining consistent impulse magnitudes between each firing. A diagram showing a schematic of the fluid flow paths in the propulsion system is shown in Fig. 2, where *TR* indicates a thermistor, and 1/*P* indicates a pressure transducer. These overall flow paths apply to both the OSC and DSC propulsion systems.

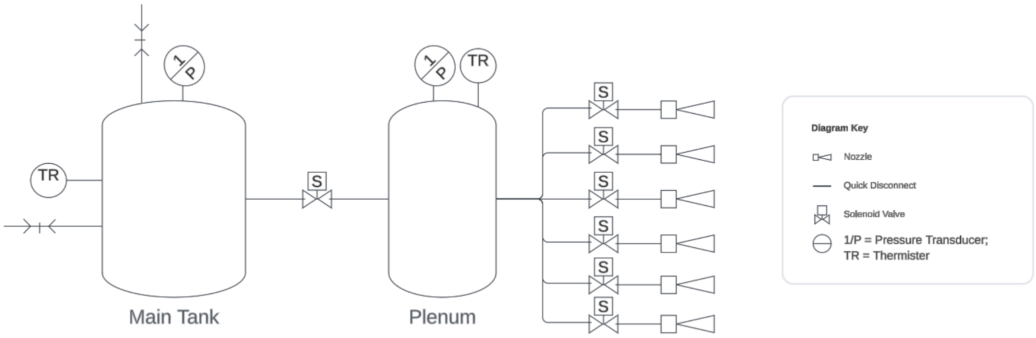


Fig. 2 Fluid flow pathway schematic

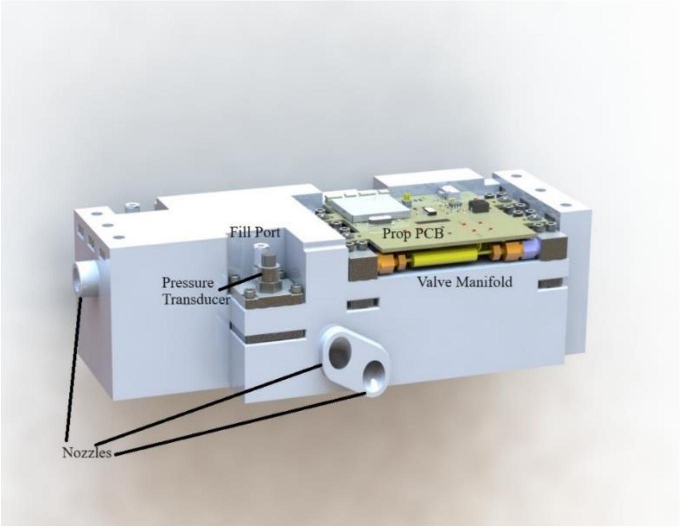


Fig. 3a Annotated OSC Propulsion System

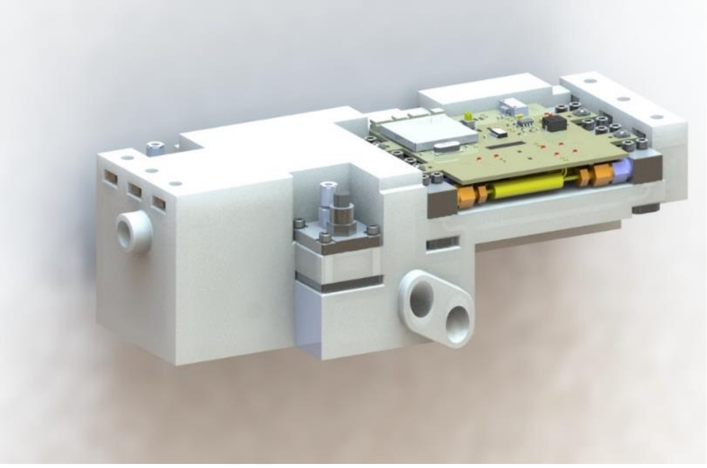


Fig. 3b DSC Propulsion System

To conduct a maneuver, the single valve connecting the main tank to the plenum tank is fired in a closed loop refill operation, where propellant is fired into the plenum in small intervals to ensure that all refrigerant in the plenum exists as a gas. Since the plenum pressure is set to be lower than the main tank pressure, when a small amount of fluid is allowed into the plenum tank, it will expand into a gas. This action is repeated until the measured plenum pressure reaches the desired percentage of the main tank pressure, therefore guaranteeing that most of the propellant in the plenum tank exists as a gas[4]. Refills occur when the plenum pressure drops below the lower refill threshold pressure value set by the spacecraft operator or when commanded to do so. From the plenum, any nozzle can be fired by opening one of the six solenoid nozzle valves, allowing gas to escape from the nozzle, generating thrust.

Figures 3a and 3b show the propulsion system assemblies featuring the 3D printed structure, valve manifold system, thermistors, pressure transducers, and PCB for flight.

IV. Assembly

The assembly of the VISORS cold-gas systems is conducted in an ISO Class 8 clean room[5] to ensure that the systems remain clean and free of foreign object debris (FOD). Before mounting the valve manifold assembly to the structure of the propulsion systems, the valve manifold must be assembled and tested, and the structure cleaned and prepared for assembly. When all components for propulsion system assembly arrive, they are first inspected for defects and then cleaned. Any 3D printing defects or residual pieces of Somos PerFORM not bonded to the structure can have extreme consequences to the system. Since both the valves and nozzles have small openings that could experience blockage if a piece of FOD became lodged in the structure, any residual 3D printing fragments pose a major risk which could endanger the mission if not removed during this step of integration. To remove any small particles internal to the tank volumes introduced by the 3D printing process, the tanks are cleaned by filling the system with isopropyl alcohol (IPA), vigorously shaking the structure, pouring the IPA into a container, and inspecting under a microscope to determine if debris still exists within the tank. The process is repeated until no debris is found in the circulated IPA. Additionally, the VISORS structures used a new method to clean where the structures were filled and submerged in IPA in an ultrasonic bath, which helped loosen any FOD stuck to the tank walls. By using this preliminary cleaning step, the cleaning time was reduced from over two hours to only 45 minutes, saving both time and likely resulting in a cleaner structure. Vibrations from both system vibration tests and launch could dislodge any 3D printing defects that were not removed during cleaning, where they will remain in the structure and could potentially cause blockages in the future, limiting the mission lifetime. The addition of an ultrasonic bath cleaning reduces this potential risk of FOD.

Before assembling the valve manifold structure, the valves must be cut to the correct length. Extreme care must be taken when removing this extra length from the valve stem to ensure no FOD enters the valve, the valve inner diameter remains unobstructed, and the valve stem is not bent or broken. During this process, the valves remain in the open position with nitrogen flowing through to ensure no back flow of FOD into the valve internals. Preparing these valves for assembly highlights the importance of designing systems with human factors in mind, otherwise time consuming and risky procedures like this valve cutting step may become a necessity.

Once the valves are cut, they may be assembled into the manifold configuration. Each valve is fastened to stainless steel manifold blocks using compression fittings. However, there are some human factor concerns when tightening the compression fittings, as given instillation instructions specify to turn the fittings a partial turn past finger tight rather than to a specific torque specification. To ensure that the connection is sealed, nitrogen gas flows through one valve at a time. Commercially available liquid for plumbing leak detection called Snoop[6], is placed at each compression fitting along the valve to identify any areas where poor connections may cause a leak. If any bubbling is detected coming from the manifold there is a leak. This process is typically remedied by first tightening any compression fittings that may be loose, or if a leak is still detected, by applying space-safe epoxy to the areas of concern. An image showing a soapy bubble forming from the connections in the valve manifold is shown in Fig. 4.

Fig. 4 VISORS Valve Manifold Bubbling During Manifold Assembly Process

Ideally, any cases of damaged or unusable parts are caught at this stage in the process. Many CubeSat components, particularly for these propulsion systems, are expensive with long lead times. Budgets and timelines are a large constraint for any space mission, but particularly for university level projects. There is often time and money available in the assembly and testing phase to order new parts, but as the project progresses, it becomes more difficult to replace these parts. As such, taking the time to carefully inspect parts, as well as following all procedures when assembling components is highly beneficial to the risk management of the project.

V.Test

Once the propulsion systems are fully assembled, the structures must be safely pressure tested to ensure the integrity of the assembly. Since the Maximum Expected Operating Pressure (MEOP) is 84.7 psi, the main tank and plenum are filled with nitrogen to 130 psi, over 1.5x MEOP. With this testing complete, the structures can be safely handled at operating pressure without fear of bursting.

With the remainder of the system testing occurring in a thermal vacuum (TVAC) chamber, the systems are baked out to remove any moisture or volatiles that have seeped into the structure during fabrication and assembly, allowing for accurate massing of the system and preventing moisture from condensing on electronics. The bakeout process is a 24-hour procedure in which the systems are heated to 40° C and placed in a high vacuum of 1E-7 Torr. During this process, the systems are monitored to ensure that they remain within the expected operating temperature and pressure. This test also allows for a preliminary check for any leaks that may be in the system.

After the systems are baked out, a full 72-hour leak check can occur to determine the propellant leak rate. The systems are placed in a TVAC chamber and subjected to a thermal cycling process that begins at 0° C, ambient temperature, and then 40° C for 24 hours at each temperature and are weighed before and after each temperature, allowing for an overall leak rate to be obtained as well as temperature specific leak rates. Since varying temperatures change the pressure within the tank, it is expected that higher temperatures would leak faster than lower temperatures. These leak rates must all fall below the leak rate requirement for the mission of 0.0035 g/hr. The VISORS OSC and DSC both pass the leak rate requirement at all temperatures; these values are summarized in Table 1. Once it is known that the propulsion systems do not have significant leaks, they are performance tested.

Table 1. Summary of leak check results

	Cold Leak Rate (g/hr)	Hot Leak Rate (g/hr)	Ambient Leak Rate (g/hr)	Overall Leak Rate (g/hr)
OSC	0	0.001977	0.00155	0.0016
DSC	0.000184	0.00299	0.001828	0.00236

Performance testing is a process used to determine the characteristics of each nozzle. By firing the propulsion systems on a torsional thrust stand (Fig. 5) in the TVAC chamber, the thrust and impulse of each nozzle can be determined and with the mass used during testing known, the specific impulse of each nozzle is characterized. These thrust and impulse measurements provide initial estimates that are used to calibrate the Guidance Navigation and Control (GNC) algorithms.

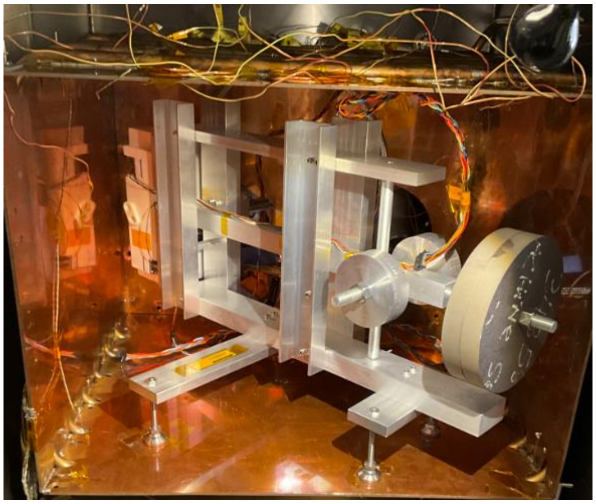
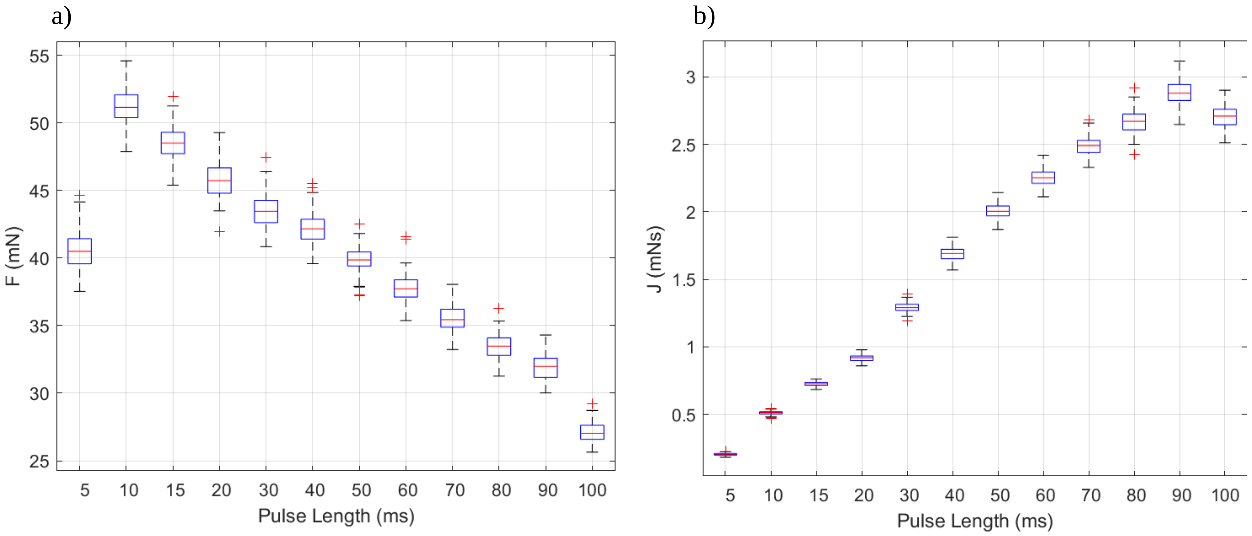


Fig. 5 SSDL Torsional Thrust Stand

The impulse bit measurements shown in Fig. 6 fall below the minimum impulse bit requirements for the system of 1 mN•s and are close to the designed minimum impulse bit of 0.2 mN•s. Variations in filter components and slight differences in nozzle geometry cause the disparity between the nozzle pair performances. Shorter firing times have higher variations due to the valve responsiveness. As the fire time increases, the pressure in the plenum decreases causing the decrease in thrust seen in Fig. 4a and 4c. Further testing will be completed to characterize the DSC propulsion system thrust and impulse and ensure both systems meet the ΔV requirements of 10 m/s.



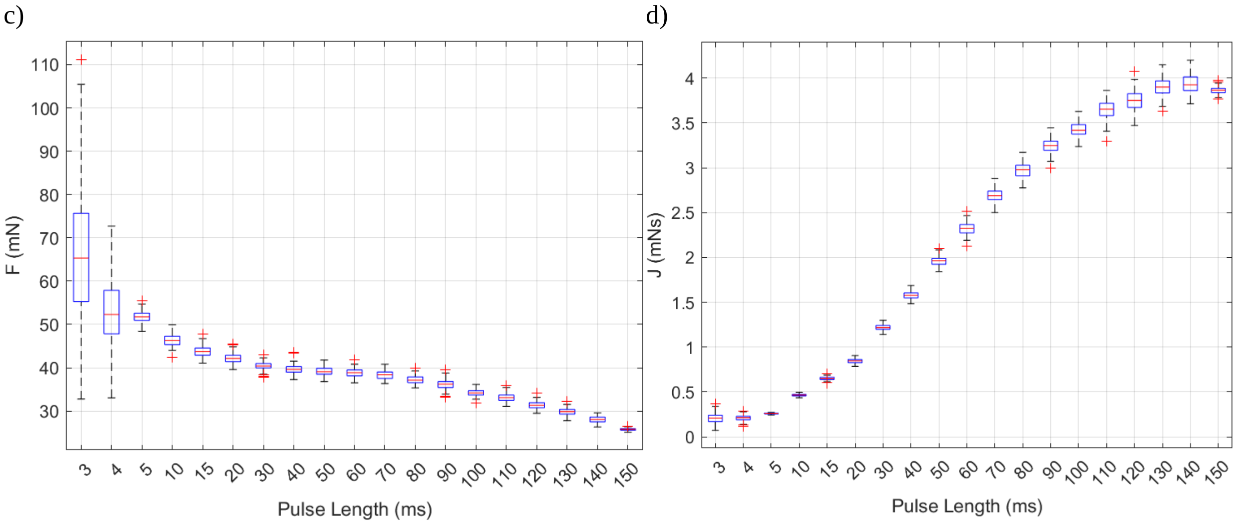


Fig. 6 Thrust and impulse characteristics of the VISORS OSC flight propulsion system. a) Thrust of nozzles 1 and 2, b) impulse of nozzles 1 and 2, c) Thrust of nozzles 5 and 6, and d) impulse of nozzles 5 and 6.

VI.**Anomalies**

Upon initial assembly of the OSC propulsion system, a manufacturing error was discovered in the machined stainless steel valve manifold blocks where all holes were 0.5 mm (about 0.02 in) offset from the specified positions when tolerances were +/- 0.13 mm (about 0.005 in). This manufacturing defect went unnoticed until after compression fittings and filter components were attached and secured with Loctite. Overlooking this error was a long time sink and had the potential to introduce large quantities of FOD during future integration. All components involved were thoroughly cleaned and the valve manifold blocks machined again with the proper dimensions.

During the testing of the VISORS OSC propulsion system, a large leak was detected in the plenum tank that caused the entire volume of gas in the plenum tank to leave the system overnight. Prior to investigating the leak, the team believed that the leak was in the valve manifold. The manifold is the most likely place for a leak to occur due to potential errors in the valve manifold assembly process and leaks have been found here on previous missions. However, after several rounds of applying Snoop to the valve manifold and areas around the fittings, no visible bubbling or other signs of a leak were identified. After ruling out the compression fittings in the valve manifold as the cause of the leak, the team then searched for leaks at the interface between the manifold and structure, since a leak had previously been seen here on a previous cold-gas propulsion mission[7].A thorough inspection yielded no evidence of leaks from the most common sources. During further inspection of the 3D printed structure, the team identified 3D printing anomalies in many of the O-ring grooves, but ultimately determined that these defects were not the cause of the leak. After continued investigation, the team suspected that there may be an internal leak in one of the valves. The system was first pressurized with nitrogen gas, and the plenum tank filled to MEOP. IPA was deposited into the diverging section of each nozzle and observed for five minutes. The team identified bubbling in one nozzle, indicating a leak in the corresponding valve as shown in Fig. 7.

There were several root causes considered that could cause such an anomaly. The valve was most likely stuck in an open configuration due to FOD, misalignment, internal solenoid spring issues, or a sticky valve. After discovering a similar issue on the DSC propulsion system, both valves were cycled repeatedly by firing the valve. Cycling fixed the leak in the DSC valve. The leaky OSC valve was then flushed with liquid R236-fa, which stopped the leak. Unfortunately, it is still unknown what the main cause of the leak was, though the most likely culprit is simply a sticky valve as this problem had been internally documented on past cold gas missions.

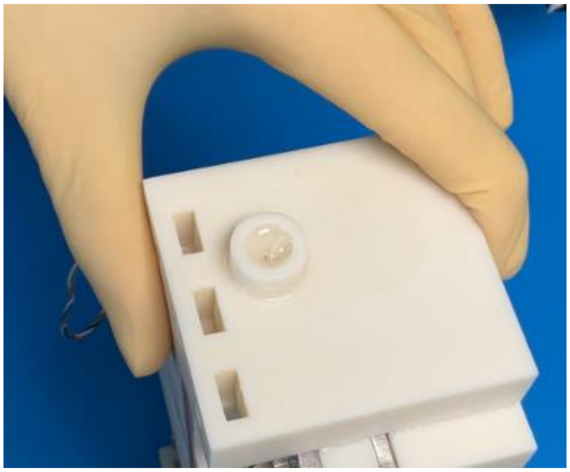


Fig. 7 VISORS Unit Bubbling in Nozzle

VII.Lessons Learned

Many of the challenges discussed in this paper, such as funding and short timelines, are often unavoidable for a university project. However, there are a few main process improvements that will be implemented in future iterations of cold-gas propulsion projects at Georgia Tech. Many of these improvements consider ways to ultimately avoid losing valuable time correcting critical issues throughout the assembly and testing process. Mainly, a procedure will be written that describes a step-by-step process for how to investigate leaks in the propulsion systems. Knowledge transfer is inherently difficult, especially in university settings when there is frequent student turnover and projects span years with multiple student cohorts. However, concise and detailed documentation for not only how to investigate leaks, but where leaks were identified in the past will be invaluable to future researchers by not only saving time but also helping others to identify any leaks before undergoing testing.

In terms of specific hardware, valves should be tested before assembly into manifolds to determine if there are any isolated valve defects. These tests could be done by developing new Ground Support Equipment (GSE) to test that the valves open and close fully and ensure they are usable in flight. Furthermore, although it is unlikely that defects from the 3D printing process caused the leak discussed in the previous section, ruling out 3D printing defects as the main cause of the leak added a significant amount of time to the investigation process. Future projects should endeavor to invest the time and resources in achieving the cleanest 3D printed structure possible up front rather than deal with correcting or investigating any potential issues later. For example, post-machining small features such as O-ring grooves and nozzle throats would significantly increase confidence in critical parts of the structure.

Many of the components used in the VISORS propulsion system had legacy use in previous SSDL cold-gas propulsion projects. While this allowed for an accelerated development of the VISORS propulsion systems, some legacy components brought with them unsolved problems. Troubleshooting anomalies during the integration and testing of VISORS propulsion systems highlighted the need to design components for both assembly and for disassembly to enable easier problem-solving during integration. One such design change needed, and highlighted during this mission, was the placement of the valve solder holes on the propulsion electronics. One valve was placed close to the propulsion system microcontroller, under the RF shield mounting plate, making it difficult to unsolder the controller board from the valve manifold when the need arose. This example is indicative of a larger necessary improvement in human factors within the project at large. System components should not only be designed for ease of integration and use, but also for de-integration when necessary. Particularly with complex systems, difficult de-integration risks compromising the system while trying to fix an issue.

VIII. Conclusion

Two additively manufactured propulsion systems have been assembled and are ready for integration into the VISORS spacecraft. Though challenges faced along during assembly and testing have pushed back delivery, these systems exceed all requirements. These systems demonstrate the ability to produce relatively low-cost CubeSat propulsion systems that allow for precise spacecraft maneuvers and showcase the successful use of a 3D printed structure. Many lessons were learned during assembly, highlighting the importance of documentation and acceptance testing. Future improvements can be made to similar cold-gas systems to ease manufacturing and troubleshooting processes.

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