



www.DeepakPublishing.com

Stevenson, T. et al. (2015): JoSS, Vol. 4, No. 2, pp. 371–386
(Peer-reviewed article available at www.jossonline.com)



www.JoSSonline.com

Design and Testing of a Cold Gas Thruster for an Interplanetary CubeSat Mission

Travis K. Imken, Terry H. Stevenson, and E. Glenn Lightsey

Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, Austin, TX, USA

Abstract

A cold gas thruster has been developed by the Texas Spacecraft Laboratory (TSL), University of Texas at Austin (UT-Austin), for an interplanetary CubeSat mission called Interplanetary NanoSpacecraft Pathfinder In Relevant Environment (INSPIRE), under development by NASA's Jet Propulsion Laboratory (JPL). This thruster was primarily constructed using additive manufacturing (3D printing) to produce a single, continuous piece that encompassed all of the propellant pipes, tanks, and nozzles. Additive manufacturing allowed the complex internal geometry of the thruster to be fabricated without substantially increasing the cost of manufacturing or the physical size of the thruster. The thruster will serve as the sole actuator for the INSPIRE attitude control system, and is equipped with four converging-diverging nozzles. The thruster was tested extensively in a vacuum chamber, using a ballistic pendulum at a variety of propellant pressures and temperatures, and was found to produce approximately 60 mN of thrust at 20°C, with a specific impulse of 65 seconds. The two flight thruster units will fly on the two INSPIRE spacecraft in 2016, where they will demonstrate the feasibility of deep-space attitude control for CubeSats.

1. Introduction

The use of small satellites, such as CubeSats, has the potential to greatly decrease the cost and development schedules of future space missions. CubeSats, first standardized by California Polytechnic State University, are formed from 10x10x10 cm cubes (Mehrparvar, 2014), and examples such as the 2014 Firefly mission to study terrestrial gamma ray bursts (Rowland, 2011), have shown that satellites under 10 kilograms are becoming more viable platforms for science missions. Another area in which small satellites may soon become prevalent is deep space missions. No CubeSats have yet been

sent beyond Low Earth Orbit (LEO), although several such missions are planned.

The Interplanetary NanoSpacecraft Pathfinder In Relevant Environment (INSPIRE) mission, developed by NASA's Jet Propulsion Laboratory (JPL), will send two CubeSats beyond LEO, with a primary goal of demonstrating small spacecraft survivability in the harsh environment of interplanetary space (Klesh, 2013). A secondary objective of the mission is to study the solar magnetic field. The two spacecraft carry science grade magnetometers, and they will make simultaneous measurements of the magnetic field as they drift apart, to estimate the local turbu-

Corresponding Author: Terry H. Stevenson, terrysteve2@gmail.com

Publication History: Submitted – 03/26/15; Revision Accepted – 09/21/15; Published – 11/04/15

lence in the interplanetary solar wind. A cutaway view of one of the spacecraft is shown in Figure 1.

Both INSPIRE spacecraft have directional X-band antennas that must be pointed at Earth throughout the mission. This in turn requires an active attitude control system. The majority of existing CubeSats with attitude control use magnetic torque rods to apply a moment against the Earth's magnetic field, to rotate the spacecraft. This is not an option in interplanetary space, where the local magnetic field is several orders of magnitude weaker. JPL decided to use small cold gas thrusters for attitude control on INSPIRE, since they can operate just as well in deep space as in LEO, and are suitable for long duration missions.

The INSPIRE spacecraft are 3-unit CubeSats. The small size of these spacecraft, approximately 32 x 10 x 10 cm (3U), imposed a strict volume constraint on the thrusters. Each thruster could only occupy a space of 6.4 x 9.0 x 9.2 cm, including valves, control circuits, tanks, and nozzles. To make the most efficient use of this limited volume, the structure of the thruster was 3D printed. This allowed for greater flexibility in the design process, since, compared to traditional

machining, 3D printing enables relatively lower cost fabrication of more complex parts within a limited volume.

1.1. Background

A cold gas thruster derives all of its energy from a propellant held under pressure. No combustion or electromagnetic acceleration is used; the propellant is simply released through a nozzle to provide thrust. The simplicity of such a system, compared to combustion or electric propulsion, makes it an attractive option for low cost CubeSat and other small satellite missions.

Many propulsion options exist for small satellites, from cold gas thrusters to combustion systems and electric thrusters (Mueller, 2008). Most of the propulsion systems available for CubeSats are single-nozzle devices designed to produce translational maneuvers. Since all CubeSat missions to date have been in Earth orbit, they have been able to use magnetic torque rods for attitude control and reaction wheel desaturation. While no systems are commercially available to provide CubeSats with propulsive attitude control,

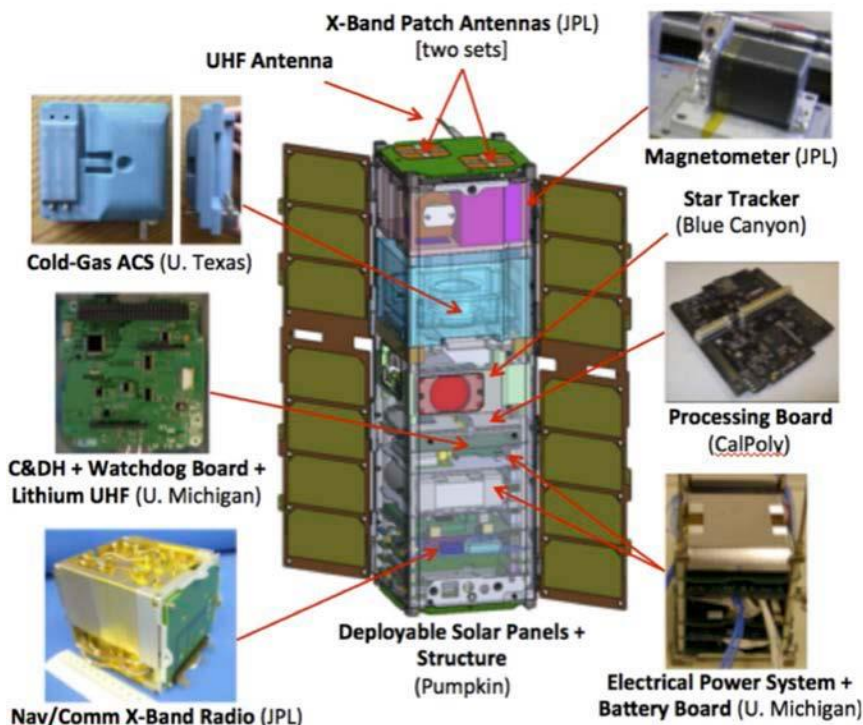


Figure 1. INSPIRE spacecraft cutaway view (Source: NASA Jet Propulsion Laboratory).

such a system was designed by Vacco Aerospace Products (Cardin, 2000). This system used four canted nozzles to provide uncoupled rotation and limited translational capability.

3D-printed thrusters have been used previously on small satellites. The MEPSI mission (Micro Electromechanical system PicoSat Inspector) was a prototype small satellite that was intended to inspect larger vehicles and objects (Hinkley, 2008), using a 3D-printed cold gas thruster for propulsion and attitude control. The thruster used Xenon gas as the propellant, and was successfully demonstrated in space in 2006, on the Space Shuttle mission number STS-116.

Another 3D-printed cold gas thruster for small satellites was developed at the University of Texas at Austin (UT-Austin) for the LONESTAR (Low Earth Orbiting Navigation Experiment for Spacecraft Testing Automated Rendezvous and Docking) program. LONESTAR is a program of at least two missions overseen by NASA Johnson Space Center consisting of two satellites per mission, built by the University of Texas and Texas A&M University, that will perform relative maneuvers in orbit to demonstrate the feasibility of CubeSat proximity operations, including rendezvous and docking. The UT-Austin satellite, Bevo-2, has a small 3D-printed cold gas thruster to enable translation (Arestie, 2012). This thruster was designed specifically to meet the International Space Station's (ISS's) safety requirements for propulsion systems, and has been approved to be sent to and deployed from the ISS.

The preliminary testing results from the Bevo-2 thruster, as well as the extensive safety reviews it has passed, convinced the INSPIRE design team that a similar thruster, modified for an attitude control role, would be able to fulfill the attitude control requirements of this mission.

1.2. 3D Printing

Additive manufacturing, also known as 3D printing, is a manufacturing technique in which a part is constructed by repeatedly adding material. This is in contrast to traditional removal machining, in which parts are made by cutting away material from a larger piece of stock. Removal machining constrains the

geometry of the part with the requirement that all removed material must be accessible to a cutting tool. This greatly increases the difficulty of producing parts with complex interior geometries, which must typically be made in multiple pieces. Additive manufacturing, by contrast, can print complex interior features, even when they are completely enclosed. There are practical limitations to this, however, since the material is added layer by layer. Some degree of support is required underneath each layer during the printing process, since the material must be supported while it cures. This prevents the printing of large cantilevered features.

The ability to print highly complex interior geometries is a great advantage for small satellite propulsion systems. CubeSats are often severely volume constrained, so propulsion systems must take advantage of every amount of volume allocated in order to maximize propellant loads. A 3D-printed thruster combines propellant tanks, supporting structure, mounting points, feed pipes, and nozzles in to a single continuous structure. This simplifies assembly of the system and minimizes interfaces, each of which represents a potential leak.

1.3. Role of the Thruster

The INSPIRE cold gas thruster is required to fit within a limited volume inside the 3U envelope of the spacecraft. The four nozzles on the propulsion system enable three rotational degrees of freedom, because the module is placed off of the spacecraft center of mass. This system is not coupled, so any attitude maneuvers will also produce a small translational acceleration. However, since INSPIRE has no destination other than interplanetary space, these small deviations are not a concern.

The cold gas propulsion system allows the INSPIRE CubeSats to perform impulsive corrections to the attitude of the spacecraft. Outside of Earth's orbit, satellites can no longer depend on magnetic torque rods for attitude control. Reaction wheels could also have been included for attitude control, but the spacecraft would still require a separate system to desaturate the wheels during the mission. The additional power and volume that would be required by

reaction wheels were not available. The attitude control system has to consume a small amount of power to stay within the CubeSats' limited power budget. The propulsion system electronics consume approximately 0.2 watts when the system is powered and idle. Each valve requires 5.2 watts when open, giving a maximum total consumption of 21 watts, if all four nozzles are opened. Since the thruster is only designed to produce very short pulses, this power draw only lasts on the order of milliseconds, and is well within the capabilities of a small satellite.

Because cold gas systems are only able to use the energy stored in the pressurized propellant, instead of a more energetic chemical reaction, they are not useful to perform large orbit changes or maneuvers. The two INSPIRE spacecraft do not require large maneuvers once they have separated, so the thrusters will only be used in an attitude control role. A secondary thruster operation is the production of very small (approximately 1 m s^{-1}) translations. To allow this without adding more nozzles to the system, each of the four nozzles is angled off of the common plane in the Z-direction by ten degrees (10°). When all four nozzles are fired, the system produces a translation along the Z-axis. This translation is inefficient, but it is sufficient to meet the small translation requirement, and does not increase the complexity or size of the thruster. Figure 2 shows the different nozzle pair combinations that will be used to produce rotation about the three spacecraft axes. Figure 2 shows a

view in the z-direction, so each nozzle is canted 'upwards' in the figure to produce small translations.

1.4. Contributions

The INSPIRE system was specifically developed for an interplanetary CubeSat application. The driving electronics were designed in a way to make the thruster system completely responsive to the main command and data handling computer. This research builds upon previous work, and provides several new innovations to the state of the art, while maintaining the advantages of cost and simplicity that are inherent to this device.

Unlike previous 3D-printed cold gas thrusters, the INSPIRE thruster includes feedback of the propellant state during firings. Pressure and temperature sensors embedded in the propellant tank provide knowledge of the state of the refrigerant before it is expelled into space. The valves can be cycled as fast as two milliseconds per impulse, or kept open for longer periods to elicit preferred larger controlled total impulse.

The INSPIRE thruster was also characterized more extensively in the lab than previous 3D-printed thrusters. Because the spacecraft will be relying on the thruster for attitude control, the impulse provided must be precisely known for all possible states of the thruster. The impulse of the thruster was tested for a wide range of operating temperatures and pulse durations. The behavior of the thruster over a range of

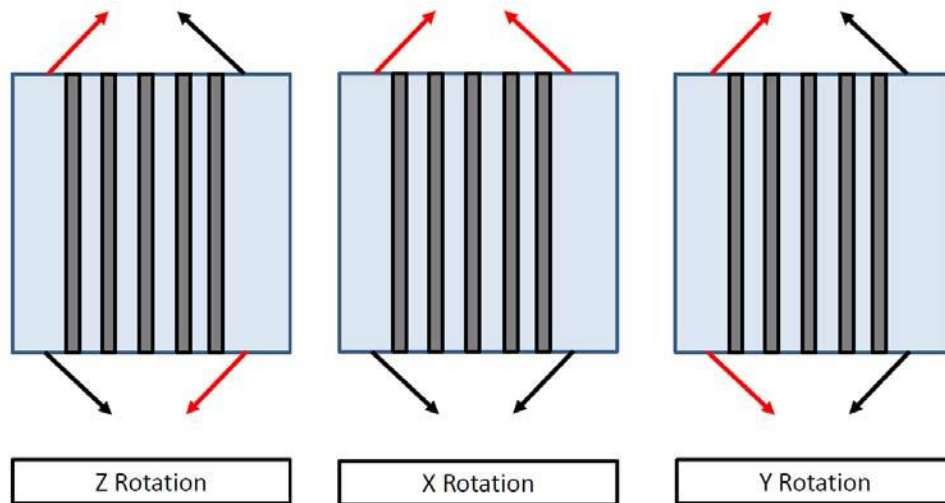


Figure 2. Nozzle pair combinations to produce three-axis rotations.

expansion tank pressures was also characterized. The pressure and temperature sensors embedded in the thruster's expansion tank give the flight computer information about the state of the gas.

The computer uses the collected data to determine the pulse duration needed to produce the required impulse.

2. Design

The thruster stores its propellant as a saturated fluid in the main tank, allowing for a greater density and a higher mass of propellant in the limited volume than a pure gas storage would permit. However, in a microgravity environment, the behavior of the propellant in a saturated liquid-vapor mixture is unknown. If the liquid clings to the walls, it would be expelled through the nozzle if the main tank were exposed to vacuum directly. This would affect the thrust in an unpredictable way. To prevent this, a second tank was designed, called the expansion tank, which holds the propellant in vapor form only. A single valve connects the main tank to the expansion tank, and is opened when the expansion tank pressure is too low. The expansion tank pressure is always held below the saturation pressure of the propellant, to prevent liquid from condensing in the tank. The four nozzle valves all draw from the expansion tank. The plumbing connecting the different tanks and

nozzles is embedded within the 3D-printed material, reducing the total number required parts and hardware interfaces, which simplifies the device and correspondingly reduces the risk of propellant leakage. Figure 3 shows the arrangement of the tanks and valves of the INSPIRE thruster.

Because the thruster operates in pulsed mode, the valves are only open for a brief period of time (milliseconds) per on-off cycle, and the expansion tank depletes slowly. Several hundred on-off cycles can be performed between recharging periods for the expansion tank without any detectable loss of thrust.

The flight unit thrusters on each INSPIRE spacecraft have a dry mass of 910 grams, and can safely hold a maximum of 180 grams in the main tank, for a total wet mass of 1090 grams per thruster module. The dimensions of the flight unit thruster modules are 90 by 96 by 74 millimeters (0.7U CubeSat volume), with the nozzles placed on the 96 x 74 mm faces. The flight units were delivered to JPL in the spring of 2014 for further testing and eventual integration into the INSPIRE spacecraft. Figure 4 shows the two assembled flight units prior to delivery.

Each thruster unit has a total of sixteen openings in the 3D-printed material: two ports (inlet and exit) for each of the five valves, an interface for the expansion tank sensors, an interface for the fill/drain port, and the four nozzles. Each of these interfaces is sealed with an o-ring in compression. The five valves

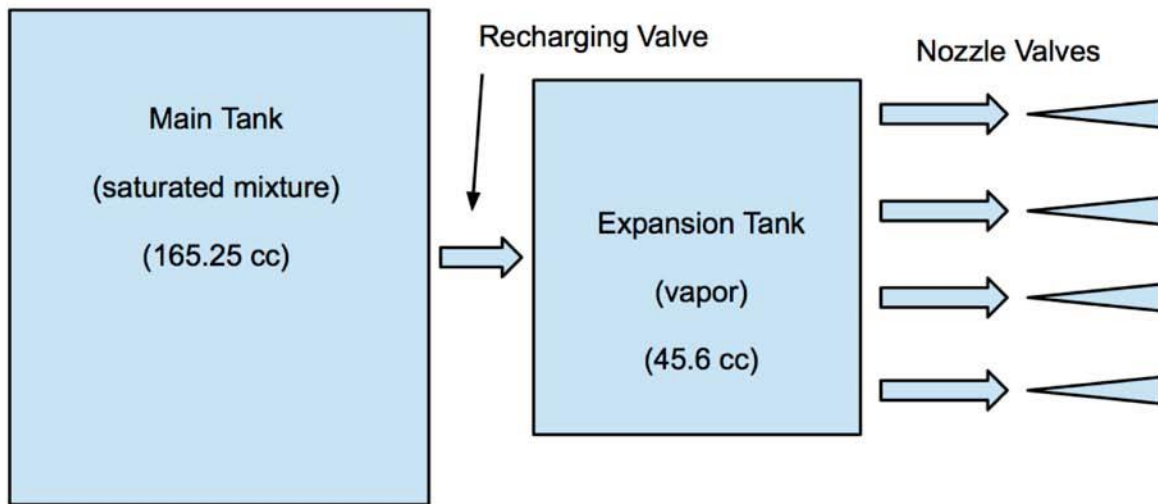


Figure 3. Tank arrangement in the thruster.

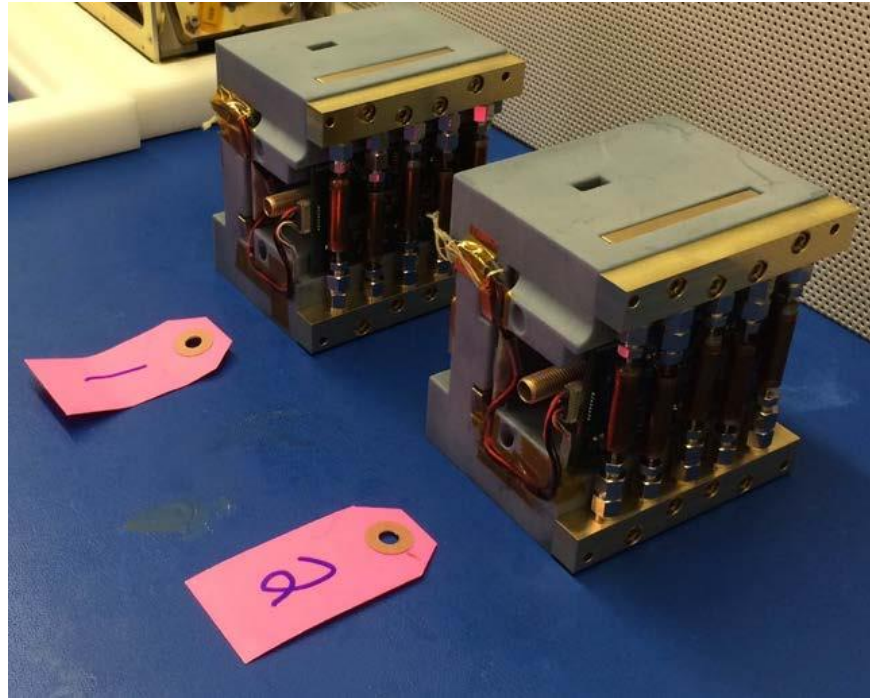


Figure 4. INSPIRE thruster flight units prior to delivery.

are driven with a single serial interface connected to a shift register for simultaneous actuation. Rather than using a pressure regulator, the INSPIRE system controls the thrust and propellant flow through the use of the expansion tank, which is filled by using a closed-loop Schrader valve, similar to what is used on a car or bicycle tire.

2.1. Design Considerations

The two INSPIRE spacecraft have medium-gain antennas that must be pointed toward Earth to communicate. The antenna axis must be kept within a ten-degree cone to meet this requirement. As the spacecraft axis drifts towards the edge of this cone, the thruster will fire to keep it within the cone. This will require one pulse approximately every one to two minutes for the initial 90-day mission, requiring at most 130,000 pulses. These pointing requirements, along with the volume restrictions, were used to size the thruster design. As built, the thruster is capable of producing approximately 1.02 million pulses before the propellant is exhausted. This provides margin to allow an extended mission beyond the first 90 days.

However, the primary purpose of the thruster is simply to demonstrate that deep-space attitude control of CubeSats is possible using a cold gas system, and total operational lifetime is a secondary consideration.

Because CubeSats are traditionally launched as secondary payloads, precautions are taken to ensure that the satellites cannot harm the launch vehicle or primary payloads. The INSPIRE thruster system was designed to meet the safety concerns of JPL, the deployer provider, and any launch provider from which the satellite could obtain a launch.

The propellant chosen was a commercial refrigerant, R236-fa (hexafluoropropane), which is an inert, nontoxic compound (CompCyl, 2013). The NASA definition of a pressure vessel is any container holding a pressure equal to or greater than 100 psia (NASA, 2003). The presence of a pressure vessel on a spacecraft imposes additional safety verifications and increases the difficulty of launching as a secondary payload. R236-fa has a vapor pressure of 100 psia at approximately 56°C (DuPont, 2005). As long as the satellite temperature is demonstrated to stay be-

low 56°C, then the spacecraft will not be classified as a pressure vessel.

To further increase the safety of the unit, the walls of the plastic tank were sized to give a factor of safety of at least 2.5 in all places. Both the main tank and expansion tank were sized to contain hold at least 250 psia. This was verified using finite element analysis on the design. Earlier versions of the thruster have been tested to tank burst, which demonstrated very good agreement with the analytical results in terms of predicted burst pressure and location (Arestie, 2012).

The INSPIRE thruster was required to meet the CubeSat form factor, including being laid out with the same PC-104 standard footprint used on CubeSat electronics boards. The thruster included four passthrough holes for threaded rods used to secure the thruster into the stack with the other components. The nozzles were restricted to two faces of the thruster, because the other two faces were covered by deployable solar panels. The driving electronics had to be compatible with the available data interfaces on the INSPIRE flight computer and the selected valves had to be compatible with the available bus voltage of the spacecraft.

The engineering design unit (EDU) was designed to fit within the initial INSPIRE 0.5U volume alloca-

tion, and was compatible with the PC-104 CubeSat standard. The EDU used five valves: one for each of the four nozzles and one for the expansion tank. The valves were sealed into stainless steel manifolds with large steel Swagelok pressure fittings. The thruster was intended to be filled through a small fill hole covered by a sealing plate. Ultimately, it was difficult to load the amount of propellant required for testing in this way, and the filling system was redesigned for the flight unit. The first version of the driving electronics established a functional baseline for controlling the valves and reading data from the sensors. The EDU was completed in June 2013 and moved to JPL for testing over the summer. During this time in California, the unit was loaded with propellant for the first time and characterized in a non-flight vacuum chamber. Figure 5 shows a computer model of the EDU.

Testing of the EDU demonstrated the functionality of the electronics and the command system, and the ability of the thruster to open its valves for very short time periods, on the order of milliseconds. Testing also confirmed that there were no detectable leaks, validating the general design of the metal-to-plastic interfaces. Finally, qualitative data were taken with a ballistic pendulum that showed differences in total imparted impulse over different pulse times and

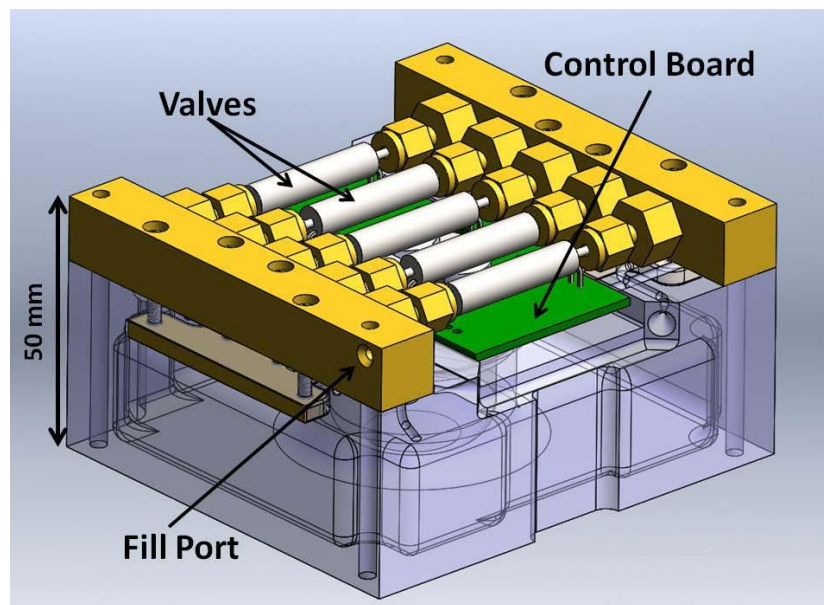


Figure 5. INSPIRE thruster engineering design unit.

at different temperatures. However, these thrust measurements were not rigorous, and only served to validate the concept of operations.

However, the system needed to be modified to meet the changing requirements of the INSPIRE spacecraft. As the rest of the subsystems on the spacecraft evolved, the volume allocated to the thruster grew to a total of 0.7U of volume. The increased volume was straightforward to accommodate, due to the flexibility of additive manufacturing. Due to concerns of contamination and spilling during filling, a closed-loop fill and drain valve was included instead of the screw-sealed filling hole. This new fill system also addressed the filling difficulties encountered while testing the EDU. The sensitivity of INSPIRE's magnetometer payload required a change of material for all metal components from steel to brass. Filters were included upstream of the valves to prevent particles from damaging the valve seals. Because the changes were a significant departure from the EDU, the thruster team decided to create another iterative version of the thruster before producing the flight unit. This version incorporated all of the design changes and was called the Flight Technology Test (FTT) unit, seen in Figure 6. Ultimately, the FTT was

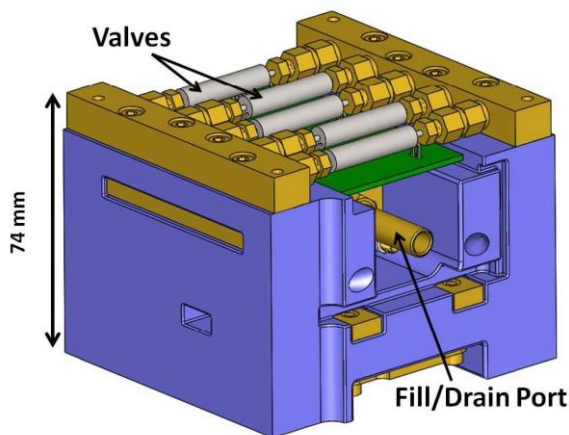


Figure 6. INSPIRE thruster flight technology test unit.

nearly identical to the flight unit. Note the larger size and the addition of a fill port, as compared to the EDU.

Another concern that the FTT addressed was that of processor failure in flight. Interplanetary space has higher levels of radiation than Low Earth Orbit,

where all previous CubeSats have flown. This raises the concern of possible damage to the flight computer that could cause the processor to reset in-flight. If this occurs between a valve open and valve close command, the thruster would hold the valve open until the next command. This would deplete the propellant in the expansion tank and send the spacecraft into an undesirable attitude state. To mitigate this risk, three redundant levels of security were included in the driving electronics to prevent inadvertent firings and allow the thruster to quickly turn itself off, in the event that the flight computer becomes unresponsive.

The first safety is a watchdog timer on the thruster electronics board. This timer will disable power to the valves (turning them off) if it does not receive a high-low signal from the flight computer at least every 100 milliseconds. To operate the valves, the flight computer must send these pulses continuously throughout the entire operation. This addresses the problem of a reset between open and close commands. If the flight computer resets before sending the valve close command, it will also stop signaling the watchdog, which will disable the valves.

The second safety is a “power enable” line that must be held at 3.3 volts for any of the thruster’s logic components to turn on. If the power enable line voltage drops, most likely due to a flight computer reboot, this will disable all commands to the thruster and reset its internal registers. Thus, if the flight computer reboots between commands, all valve states will be reset to the default “closed” state. When the flight computer recovers and begins pulsing the watchdog timer line, the previously open valves will remain closed until the next command is received. This protects against software errors that could cause the flight computer to lose knowledge of the thruster state after a reboot.

The third and final safety is built into the messages that the flight computer sends to the thruster. One of the seven bits was designated as a “safety” bit, and must be set to “1” for any of the valves to open. This safety was designed to protect against random signals being sent from the flight computer. Future thrusters operating in high radiation environments may incorporate a more advanced checksum for every message sent, to add additional security to the system.

2.2. Design Advantages

The 3D-printed cold gas propulsion system has unique benefits compared to other propulsion and attitude control technologies. The relative simplicity of propellant storage and management in cold gas systems leads to a system with few active components. The thruster is simply controlling the flow of the gas from the main tank to the nozzles and does not require any control other than valve actuation. Using cold gas propellants is also safer than chemical systems, because of the physical nature of the gas chosen. Common cold gas propellants include noble gases, nitrogen, and inert refrigerants. Finally, with a simple, 3D-printed system, certification of the systems can be done quickly and thoroughly.

The INSPIRE cold gas systems are also relatively low-cost, compared to other small satellite components. The entire thruster project, including design, development, and verification of the INSPIRE design units and flight systems cost on the order of tens of thousands of dollars, including the student funding to design and assemble the unit. The low cost of the 3D-printed tank is responsible for most of the savings. Additive manufacturing allows enclosed volumes for tanks and pipes to be created without any seals, joints, or interfaces, in configurations that would be very difficult to machine. This direct link from computer design to product also means that the single piece can be quickly analyzed and iteratively modified within the computer and then printed as created. Similar to traditional removal machining, each printing technology advertises tolerances and “resolution levels” that are included in each design.

The 3D-printed material chosen for the tank is a commercially available composite material that is generally targeted towards the automotive industry. The manufacturing process is inexpensive for custom parts when compared to traditional machining. The cost of the printed unit is mostly related to the size of the part, rather than its complexity.

3. Performance Analysis and Testing

The INSPIRE mission required precise attitude control to maintain antenna pointing, so its thruster

needed to produce small, well-characterized impulses. The thruster was tested to determine the average thrust, the minimum impulse bit possible and the specific impulse. The thrust properties were measured for a range of different pulse durations, tank pressures, and tank temperatures. The objective of the testing was to determine the performance of the thruster at a range of flight-like states.

3.1. Testing Facility

The INSPIRE thruster testing was carried out in the Texas Spacecraft Laboratory’s vacuum test chamber. The vacuum chamber is a stainless steel cube, with interior dimensions of 61 x 61 x 61 cm, built by LACO Technologies and leak tested to 10^{-8} atm-cm³/s of helium. The chamber uses a 6.6 L/s rotary vane roughing pump to achieve a rough vacuum of 10^{-3} torr, and a 300 L/s Alcatel ATH 300 turbomolecular pump to achieve the normal operating pressure of 10^{-6} torr.

3.2. Test Methodology

The thruster was only designed to operate in pulsed mode, so the test stand was designed to measure the impulse of a short pulse. A rigid ballistic pendulum was connected to a potentiometer, which was used to measure the deflection of the pendulum. A flat plate was fixed to the pendulum and positioned directly in front of one of the thruster nozzles, as shown in Figure 7. If the pulse is sufficiently short that the pendulum does not swing far from the nozzle exit plane during the pulse, then nearly all of the impulse is imparted to the pendulum. If the pulse is too long, the pendulum swings farther from the exit plane, and a significant part of the impulse is not measured.

The pendulum was designed to have a relatively high moment of inertia, but also to be well balanced. The high moment of inertia ensured that the pendulum did not swing quickly. This reduced frictional losses in the bearings, especially the second and higher-order frictional components which were not modeled. Additionally, the slow movement of the pendulum minimized the distance between the

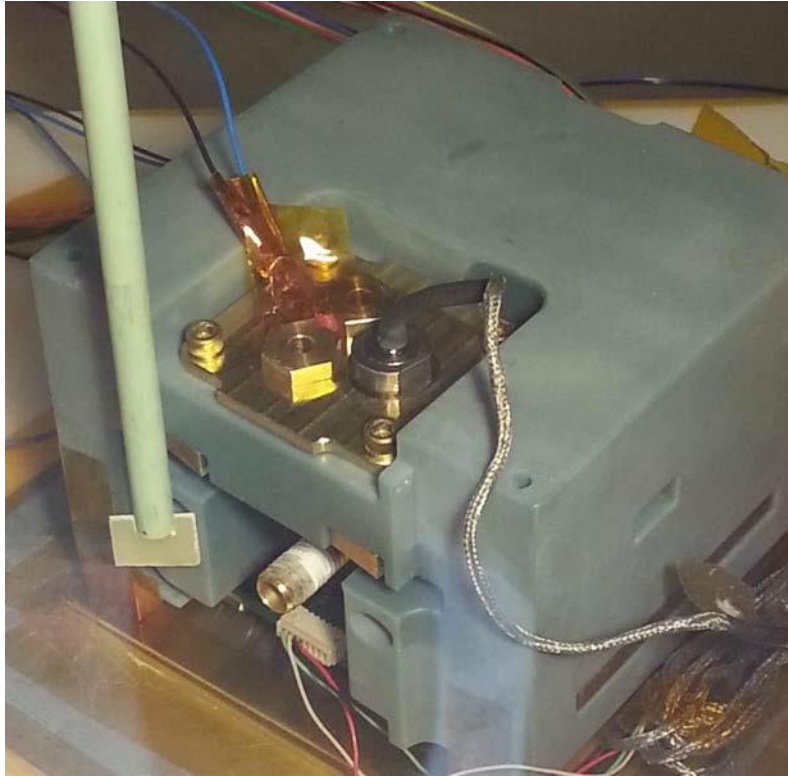


Figure 7. Test setup with FTT thruster and ballistic pendulum (left).

pendulum plate and the nozzle exit plane to ensure that the maximum amount of impulse was captured by the system. The pendulum was also well balanced, with its center of mass located 24 mm below the fulcrum. This balancing increased the angular displacement of the pendulum for a given thrust. The potentiometer used in the test stand measures angles in discrete steps, so doubling the distance the pendulum swings for a given thrust doubles the precision of the thrust measurement.

The ballistic pendulum is simple to construct and operate; however, it has limitations as a thrust measurement device. The pendulum measures the impulse transferred to the thrust plate, not the impulse produced by the thruster itself. The numbers presented here assume complete momentum transfer from the thruster exhaust to the thrust plate. This cannot be verified without extensive flow visualization inside the chamber during a pulse, the equipment for which was not available for this testing.

The thrust stand is useful for obtaining order-of-magnitude data about the thruster performance, as

well as correlating chamber pressure and temperature to impulse, but future testing will use a more reliable apparatus.

The property measured directly by the test stand is the total impulse of an individual firing. However, since the pulse time is known (assumed to be equal to the valve power time), the average thrust can be calculated as well.

Assuming that all of the impulse is imparted to the pendulum instantaneously and ignoring the frictional losses, the initial energy of the system can be found with Equation 1:

$$E = mgh = mgs(1 - \cos\theta). \quad (1)$$

In Equation 1, m is the mass of the pendulum, g is the acceleration due to gravity, s is the distance from the fulcrum to the center of mass of the pendulum, and θ is the maximum deflection of the pendulum. The assumption of an instantaneous pulse was justified during testing with high data rate logging of the pendulum position. The pendulum had an average

deflection of 0.6 milliradians after the two millisecond pulses. This translates to a motion of approximately 0.15 millimeters from the pendulum starting position. Since the primary concern in using the instantaneous impulse approximation is motion of the pendulum during the burn, this justifies its use, although it becomes less valid as the pulse times increase. Using energy, the initial angular velocity can be calculated, as shown in Equation 2:

$$\omega = \sqrt{\frac{2E}{I}} = \sqrt{\frac{2mgs(1-\cos\theta)}{I}}, \quad (2)$$

where ω is the initial angular velocity, and I is the moment of inertia of the pendulum. Finally, the impulse applied can be calculated, in Equation 3:

$$J = \frac{\omega I}{L} = \frac{1}{L} \sqrt{2mgsI(1-\cos\theta)}, \quad (3)$$

where J is the applied impulse, and L is the distance from the fulcrum of the pendulum to the thruster nozzle exit.

The INSPIRE thruster was tested extensively in the laboratory vacuum chamber. Approximately 12,000 thruster firings were conducted at a variety of pulse durations, thruster pressures, and ambient temperatures. Between each thruster firing, the chamber pressure was allowed to return to approximately one microtorr before the next firing. Each pulse was measured by the test stand to determine the thruster impulse.

The test computer controlled the total impulse applied by varying the pulse duration, so a range of durations were tested to characterize the system. The thruster was also tested at a variety of ambient temperatures to determine how it would behave in different operating conditions. Finally, the thruster was tested at various expansion tank pressures, to enable the flight computer to translate the measured pressure sensor data into expected impulse during the mission.

The isentropic thrust equation for a nozzle expelling into a vacuum is shown in Equation 4 (Anderson, 2003):

$$F = \dot{m}V_e + P_e A_e. \quad (4)$$

In Equation 4, F is the thrust, \dot{m} is the mass flow rate, V_e is the exit velocity, P_e is the pressure at the exit plane, and A_e is the area of the exit plane. The mass flow rate and exit velocities are found with Equations 5 and 6:

$$\dot{m} = \rho^* V^* A^* = \frac{P^* A^*}{RT} \sqrt{\gamma RT} = \frac{P^* A^* \sqrt{\gamma}}{\sqrt{RT}}, \quad (5)$$

$$V_e = M_e \sqrt{\gamma RT}. \quad (6)$$

Here, P^* is the pressure at the nozzle throat, A^* is the area at the nozzle throat, γ is the ratio of specific heats (C_p/C_v) for the gas, T is the temperature of the gas, R is the ideal gas constant and M_e is the exit Mach number. Combining Equations 4, 5, and 6 yields an expression for thrust shown in Equation 7:

$$F = P^* A^* M_e \gamma + P_e A_e, \quad (7)$$

In Equation 7, F is thrust, A^* is a constant, fixed by the nozzle geometry. In this derivation, γ , which is a function of temperature, is treated as a constant. Although it is a function of temperature, the value of γ used here is taken at room temperature, and the thruster's operating temperature is never significantly higher or lower than room temperature. With γ and A^* treated as constants, M_e can be seen to be constant, from Equation 6, and P^* is a function only of γ and the expansion tank pressure. Because none of these terms are dependent on temperature, the thrust is not expected to vary with temperature as long as pressure is held constant. If the temperature inside the fixed volume tank is increased, however, the pressure inside the tank will also increase. This will lead to an increase in thrust, so temperature can indirectly be used to control the thrust by controlling the pressure in the expansion tank.

The isentropic flow equations can also be used to predict the specific impulse of the system. The exit Mach number can be calculated from the area ratio of the nozzle, and the other values are known properties of the system. This approach estimates the specific impulse to be 66.2 seconds.

3.3. Experimental Results

Figure 8 shows the measured thrust from the unit at all five temperatures when the expansion tank was pressurized to 236 kPa. There is a large variation in the thrust measured and shown in the plot. This is due to the difficulty in measuring the thrust over the short duration of two ms. The large error bars in the following figures show the large uncertainty in the measurement of the shortest pulse times. The current testing apparatus has an uncertainty of approximately ± 5.6 mN when measuring the shortest pulses. Higher precision test equipment will be required for future studies to improve upon these results. Figure 9 shows the same data, but replotted without error bars and differentiated by temperature.

As seen in Figure 9, there is no clear systematic variation of the thrust with temperature at a constant pressure, as expected. However, there is a trend of decreasing thrust as the pulse duration increases. This trend can be explained by the dynamics of the test

stand. The thrust is calculated based on the assumption that all of the impulse is applied instantaneously. If the pulse duration is long enough, the pendulum will have time to move away from the nozzle exit plane while the thruster is still firing, and some of the exhaust gas will miss the pendulum plate and not contribute to the thrust measurement. This behavior results in a lower reported thrust for longer pulse durations, when in fact the actual thrust is higher.

At this pressure, the thruster produces approximately 60 mN of thrust, and with a minimum pulse time of two ms, giving a minimum impulse bit of 120 μ Ns. This figure is important for attitude control, assuming precise knowledge of the attitude state. The smaller the minimum impulse bit, the more precisely the thruster can null all body rates of the spacecraft. This gives greater stability to the spacecraft pointing vector, as well as reducing the frequency with which the thruster must fire to maintain a certain pointing accuracy.

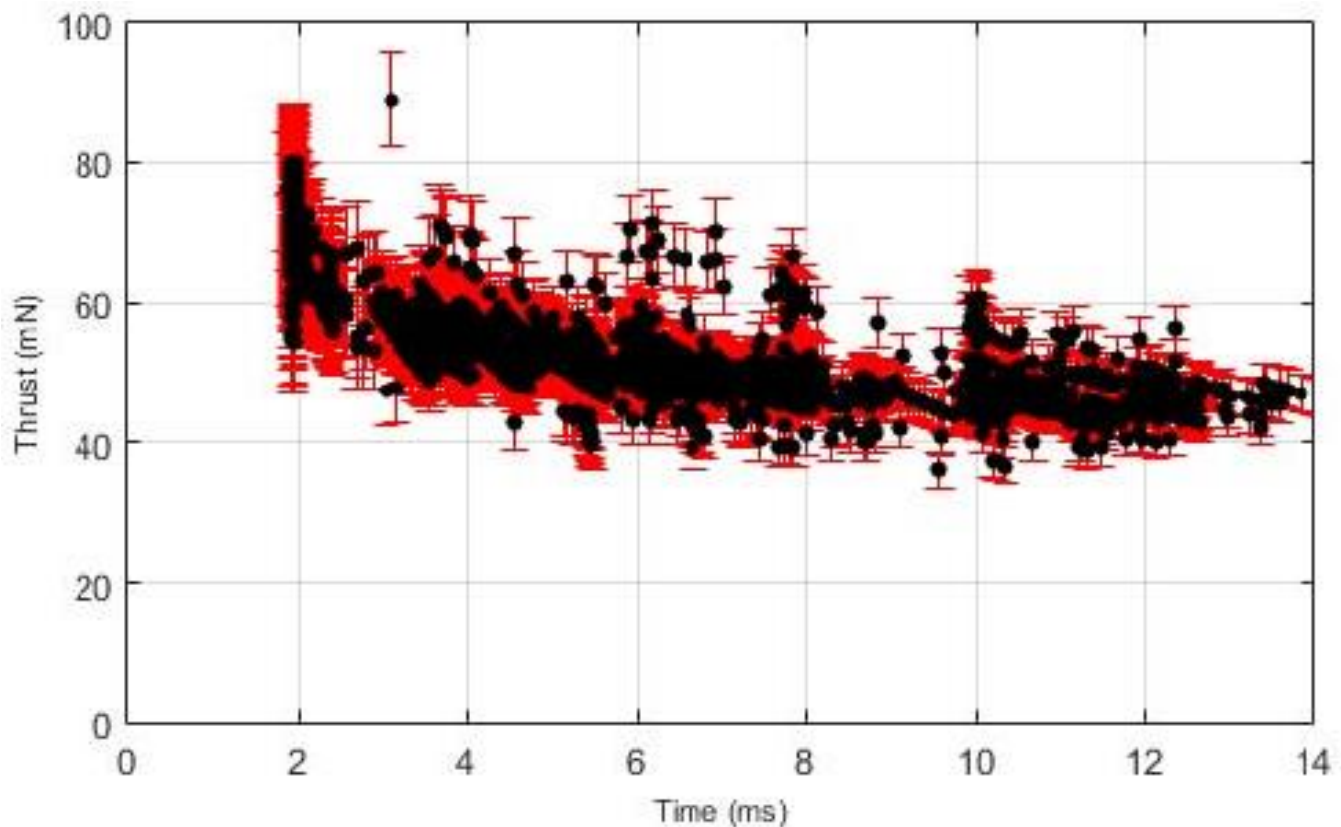


Figure 8. All thrust measurements taken at nominal expansion tank pressure of 236 kPa (34.2 psia). Data points are in black, error bars in red.

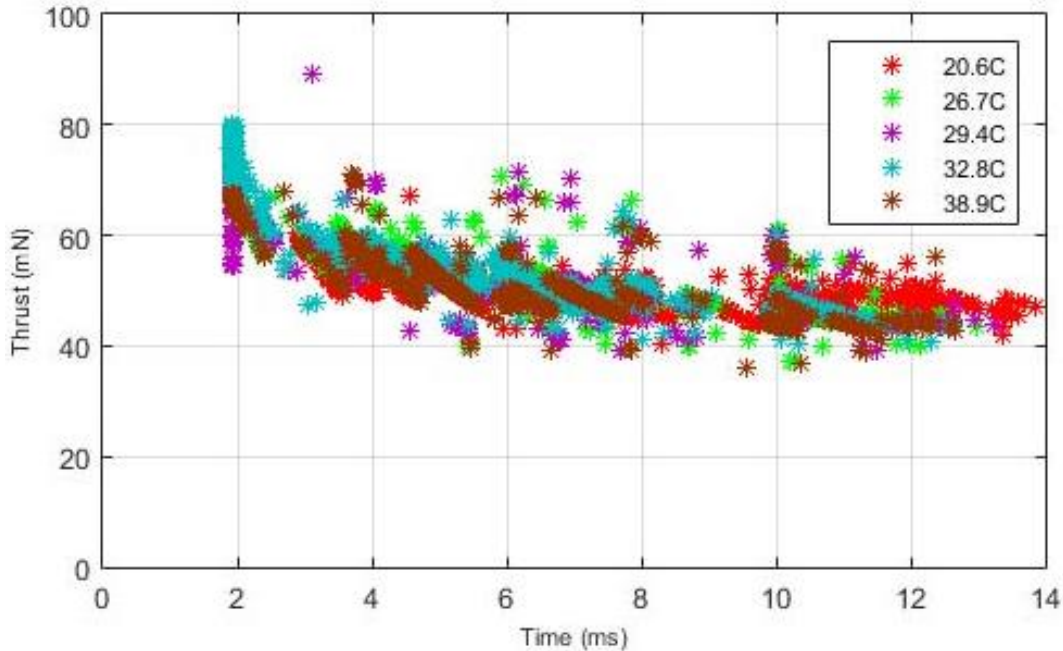


Figure 9. All thrust measurements taken at expansion tank pressure of 236 kPa (34.2 psia), colored by temperature. Error bars are removed for clarity.

The thrust can be modulated by changing the pressure inside the expansion tank. To produce lower thrust, the expansion tank is simply not recharged to full pressure after being fired. There is no way with the INSPIRE thruster to reduce the tank pressure without firing one or more of the nozzles, so any maneuver requiring smaller thrust must be planned in advance.

Figure 10 shows the thrust measured from the unit when the expansion tank was pressurized to only 88.2 kPa (12.8 psia). In this test, the thruster only produced approximately 45 mN of thrust, for a minimum impulse bit of 90 μ N-s. This lower pressure would allow for more precise control of the spacecraft rotation at the cost of reducing the maximum torque that could be applied.

If higher torque is needed, such as for rapid maneuvers, the expansion tank pressure can be raised. Since this thruster is not equipped with any pumps, the expansion tank cannot be pressurized higher than the main tank pressure. The main tank will always be at the saturation pressure for the refrigerant, so the maximum expansion tank pressure is entirely temperature dependent. Figure 11 shows the thrust measured at an expansion tank pressure of 353 kPa (51.2

psia). To pressurize the expansion tank to 353 kPa, the thruster was heated to 32.8°C to increase the main tank pressure, which resulted in increased thrust of approximately 70–100 mN.

3.4. Specific Impulse Estimation

Another important characteristic of any propulsion system is the specific impulse. Specific impulse is a measure of the propulsive efficiency of a thruster, and is proportional to the exhaust velocity of the propellant. Knowledge of the specific impulse is required for mission lifetime calculations, such as delta-V capability.

Specific impulse can be calculated from thrust F , mass flow rate \dot{m} and Earth’s surface gravity g , using Equation 8.

$$I_{sp} = \frac{F}{\dot{m} \cdot g} \tag{8}$$

To estimate the mass flow rate, the thruster produced 3000 pulses, each 20 ms long, giving a total of 60 seconds of “open” time. Between the pulses, the pressure was measured, and the expansion tank was recharged if the pressure had dropped more than

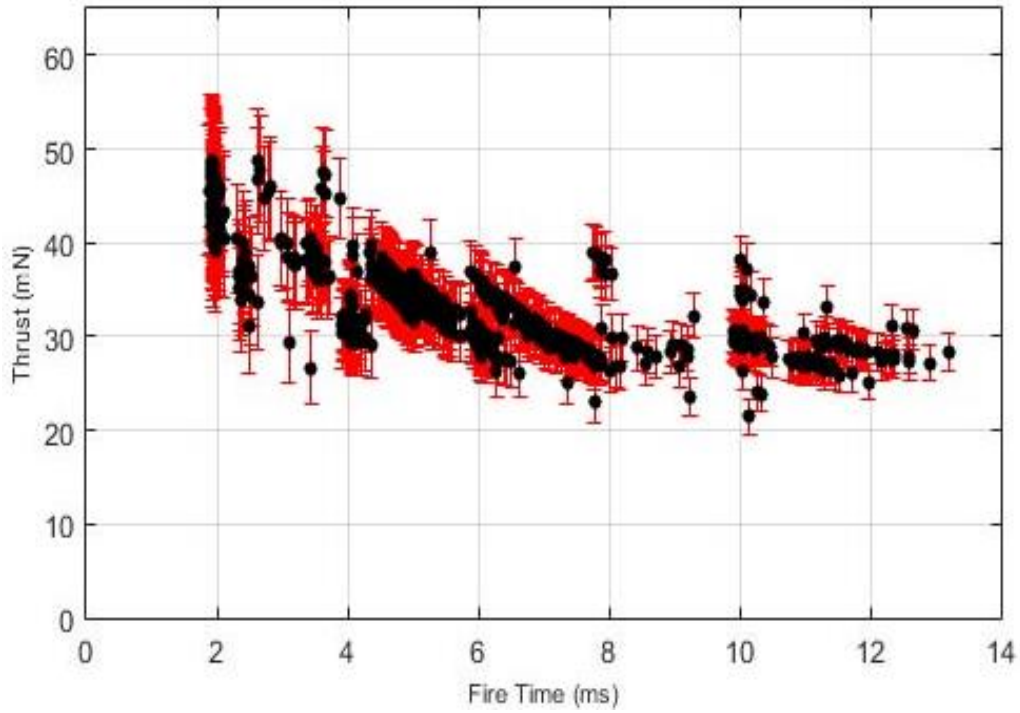


Figure 10. Thrust data measured with an expansion tank pressure of 88.2 kPa (12.8 psia). Data points are in black, error bars in red.

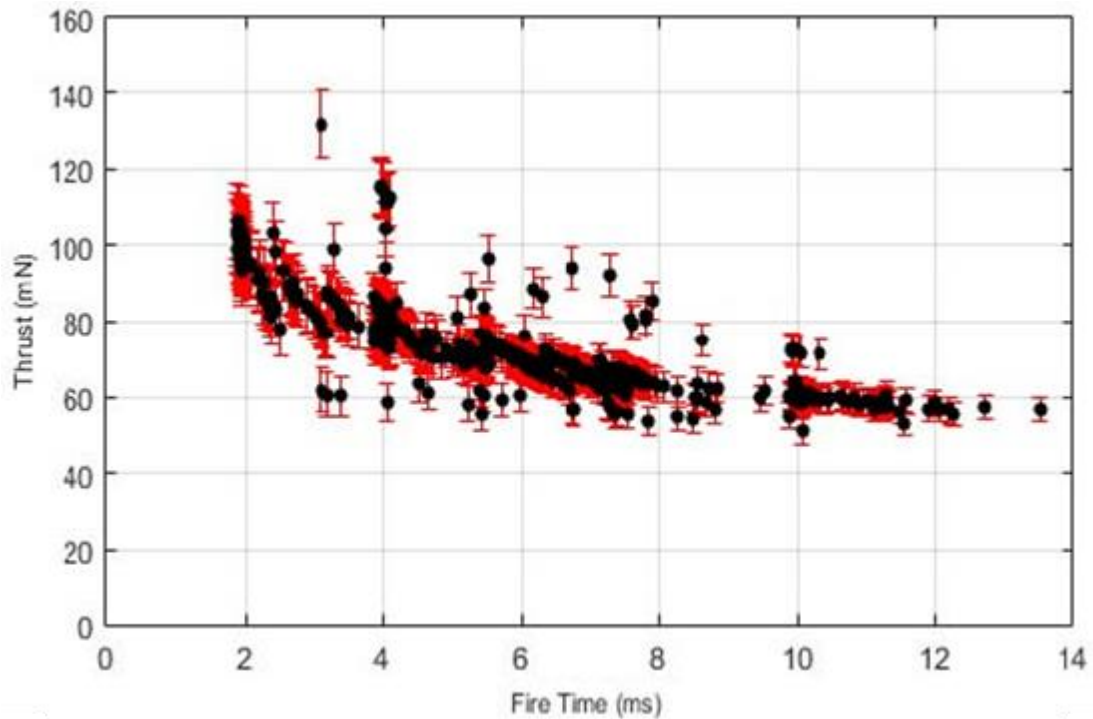


Figure 11. Thrust data measured with an expansion tank pressure of 353 kPa (51.2 psia). Data points are in black, error bars in red.

5% from nominal pressure of 236 kPa (34.2 psia). The thruster was massed before and after the firings, and lost 5.6 grams over the course of the test. Using a thrust value of 60 ± 5.6 mN, the experimentally determined specific impulse for this system is 65 ± 6.1 seconds. This compares well with the theoretical value of 66.2 seconds. There are many reasons why the true value may be lower than the theoretical, including transient effects of valve actuation and boundary layer effects in the nozzle. These phenomena were not investigated during this project.

4. Further Research

While the INSPIRE 3D-printed cold gas thruster is a capable attitude control thruster, it is a first-of-its-kind device, and there are many improvements that can be made to the design. Future versions of the thruster could require more localized processing capability. The INSPIRE thruster relies on the flight computer to command the valves open and closed. To do this, the flight computer must know the average thrust produced by one pulse of a given duration. If the thruster was equipped with a microcontroller, the spacecraft computer could simply send a command for a certain magnitude of impulse, and the thruster, using the information available from its sensors, could compute the needed pulse duration and fire the appropriate nozzles. The thruster could also autonomously monitor the expansion tank pressure and refill it from the main tank when needed.

Another improvement under consideration is the use of new materials to construct the tank. Since the INSPIRE mission began, more 3D-printed materials have become available that may have superior physical properties. Increased strength, improved printing resolution and decreased mass would all improve the performance of the thruster. Different materials may also allow higher-pressure propellants to be used, increasing the thrust of the system.

More extensive testing of the INSPIRE thruster would most likely focus on increasing the precision of the impulse measurements. The test stand can be made more precise in two ways. First, and most directly, a more precise potentiometer could be used. The potentiometer used in testing this unit had ten

bits of precision, but more precise potentiometers are available. The largest difficulty lies in finding one that will operate in the test chamber, since many lubricants break down in vacuum. Alternatively, the test stand could be more balanced. This would reduce the maximum impulse that it could measure, but would more precisely measure small impulses. Future testing may also depart from the ballistic pendulum method entirely, and mount the thruster itself on the test stand. This would measure the thruster more directly, and eliminate the uncertainty due to the physics of the exhaust plume-thrust plate interaction.

5. Conclusion

If small satellites are to operate successfully beyond Low Earth Orbit, they will require more capable propulsion systems than currently exist. INSPIRE will demonstrate many technologies required for such interplanetary missions, including the 3D-printed cold gas thruster described in this paper. The low cost and flexibility of the 3D-printed thruster module lends itself to small satellite missions, which are growing increasingly attractive because of their overall low cost and short development times. The 3D-printed thruster makes efficient use of its available volume, an important property of any small satellite subsystem. The thrust testing that was presented has shown that the impulse performance of the thruster is repeatable, which is required for precise attitude control. The low cost, small volume, and reliable thrust performance make this unit well suited to performing small satellite attitude control.

The two INSPIRE spacecraft are scheduled to fly in 2016, and the results presented here were used to characterize the attitude controllers for the spacecraft. In addition, data collected during the mission will be used to verify this testing. The lessons learned from this activity have already been incorporated into similar flight unit thrusters for other CubeSats.

Acknowledgements

The authors would like to thank the graduate and undergraduate students involved in the UT-Austin Texas Spacecraft Lab. Particular thanks are due to

Sean Horton and Parker Francis for their assistance in the design and assembly of the thrusters. The authors would also like to thank the INSPIRE project engineers and scientists at the Jet Propulsion Laboratory for providing this opportunity, as well as for their support and expertise throughout the project. This research was financially supported by the California Institute of Technology Project Number 1475499.

References

- Anderson, J (2003): *Modern Compressible Flow with Historical Perspective*, 3rd ed. New York: McGraw-Hill.
- Arestie, S; Lightsey, G; Hudson, B. (2012): Development of a Modular, Cold Gas Propulsion System for Small Satellite Applications. *Journal of Small Satellites*, Vol. 1, No. 2, pp 63–74.
- Cardin, J. and Acosta, J. (2000): Design and Test of an Economical Cold Gas Propulsion System, presented at the 14th AIAA/USU Conference on Small Satellites, Logan, UT. Available at: <http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=2111&context=smallsat> (last accessed September 18, 2015).
- CompCyl Services (2013): Material Safety Data Sheet R-236FA Hexafluoropropane. Available at: http://www.compcylserv.com/uploads/MSDS-_R236FA_Refrigerant.pdf (last accessed December 2, 2014).
- DuPont. (2005): Thermodynamic Properties of HFC-236fa. Available at: http://www2.dupont.com/Refrigerants/en_US/assets/downloads/k05720_Suva236fa_thermo_prop.pdf (last accessed November 11, 2013).
- Hinkley, D. (2008): A Novel Cold Gas Propulsion System for Nanosatellites and Picosatellites, in *Proceedings of the 22nd Annual AIAA/USU Conference on Small Satellites*, Logan UT.
- Klesh, A. et al. (2013): INSPIRE: Interplanetary NanoSpacecraft Pathfinder In Relevant Environment. AIAA SPACE 2013 Conference and Exposition, San Diego, CA.
- Mehrpavar, A. et al. (2014): CubeSat Design Specification Rev. 13. Available at: http://www.cubesat.org/images/developers/cds_rev13_final2.pdf (last accessed February 5, 2015).
- Mueller, J. et al. (2008): A Survey of Micro-Thrust Propulsion Options for Microspacecraft and Formation Flying Missions. 5th Annual CubeSat Developers Workshop, San Luis Obispo, CA. Available at: http://mstl.atl.calpoly.edu/~bklofas/Presentations/DevelopersWorkshop2008/session2/4-MicroThrusters-Juergen_Mueller.pdf (last accessed September 15, 2015).
- NASA (2003): NSTS 1700.7B, App. A. Available: http://snebulos.mit.edu/projects/reference/NASA-Generic/NSTS_1700-7B.pdf (last accessed March 19, 2014).
- Rowland, Douglas E. et al. (2011): The NSF Firefly CubeSat Mission: Rideshare Mission to Study Energetic Electrons Produced by Lightning, presented at the 2011 IEEE Aerospace Conference, Big Sky, MT, March 5–12. Paper 2.0403.