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Design and Characterization of a 3D-Printed Attitude Control Thruster for an Interplanetary 6U CubeSat

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ABSTRACT

This paper describes the design and testing of a miniature, 3D-printed cold gas attitude control thruster for the NASA Ames Research Center BioSentinel mission, an interplanetary small spacecraft that will be launched on the EM-1 flight of SLS. Earth-orbiting small satellites typically use magnetic torque rods for momentum unloading, but these cannot be employed in interplanetary space due to the lack of a strong external magnetic field. ACS thrusters can be used to unload reaction wheels or used directly for attitude control, regardless of the external environment. By 3D printing the propellant tanks, pipes, and nozzles into a single component, the complexity and cost of the thruster are reduced. The use of 3D printing also allows the thruster to better utilize its allocated volume to store more propellant. This is especially important for strictly volume-constrained spacecraft, such as CubeSats. The thruster has seven nozzles that are printed directly into the surface of the structure. The BioSentinel thruster has been tested at the Georgia Institute of Technology by the Space Systems Design Lab. The thrust of each nozzle has been measured to be approximately 50 milliNewtons, with a specific impulse of approximately 31 seconds.

INTRODUCTION

The increasing capability of small spacecraft, including CubeSats, is driving the development of several missions employing CubeSats beyond Earth orbit. These missions include the Jet Propulsion Laboratory's MarCO, a 6U CubeSat that will travel to Mars as a secondary payload and act as a communications relay for the Mars InSight lander.

The use of small spacecraft in interplanetary missions promises to reduce mission costs and allow more planetary science missions to be conducted. One critical technology to enable these missions are miniaturized propulsion systems, capable of both translational maneuvers and attitude control.

This paper describes the design and testing of one such propulsion system, a 3D-printed cold gas attitude control thruster for the interplanetary BioSentinel spacecraft. At the time of writing, an engineering unit has been built and tested to characterize the system before a flight unit is produced.

Cold Gas Thrusters

A cold gas thruster is a propulsion system in which the propellant does not undergo combustion or electromagnetic acceleration. The propellant is held under pressure in the thruster and released through a nozzle to generate thrust. Such systems have lower specific impulse than combustion-based thrusters or electric thrusters, meaning that they generate less total impulse per unit mass of propellant. However, cold gas thrusters may use inert propellants, which reduces handling risks, and have relatively low power consumption compared to electric thrusters.

Cold gas thrusters have been previously used on CubeSats[1]. The first CubeSat-sized spacecraft known to employ a cold gas thruster in space was the Microelectromechanical System-based PICOSAT Inspector (MEPSI) [2]. This mission involved a pair of spacecraft, deployed in 2006, one of which was equipped with a miniature cold gas thruster. The thruster was used to maneuver the first spacecraft relative to the second spacecraft, and achieved a total ΔV of 0.4 m/s. In 2014, a pair of cold gas attitude control thrusters were developed for the INSPIRE mission, a pair of 3U CubeSats developed by the Jet Propulsion Laboratory to demonstrate small satellite capabilities beyond Earth orbit [3]. In 2015, a cold gas thruster was demonstrated in Low Earth Orbit on the POPSAT-HIP1 spacecraft [4]. This propulsion system used pressurized Argon to provide between 2.25 and 3 m/s of ΔV. The BioSentinel thruster draws heavily on heritage from the INSPIRE attitude control thrusters, and employs the same solenoid valves and propellant.

BioSentinel

BioSentinel is a 6U CubeSat being developed by NASA Ames Research Center to support future human exploration of deep space [5]. The objective of the mission is to study the effects of deep space radiation on living cells. The spacecraft will be launched as a secondary payload on the EM-1 flight of the Space Launch System into a heliocentric orbit. The payload consists of genetically modified yeast cells, and instruments capable of detecting DNA double-strand-break (DSB) events in these cells, as well as conventional radiation detectors. The frequency of these DNA breaks will help to determine some of the health risks of human interplanetary exploration.

While many CubeSats employ magnetic torque rods for momentum desaturation, the solar magnetic field at 1 AU is too weak for these to be effectively employed in a heliocentric orbit. Instead, this propulsion system will perform the detumble maneuver immediately upon deployment from the launch vehicle. It will also perform momentum management maneuvers approximately once every two days, as the reaction wheels onboard the spacecraft saturate due to solar radiation pressure.

DESIGN OVERVIEW

The structure of the thruster consists of a 3D-printed component and five steel manifolds attached to the printed component and sealed with O-rings. The 3D-printed structure is printed using the selective laser ablation (SLA) technique, and is made from Accura Bluestone. Bluestone is a ceramic-like composite with a relatively high ultimate tensile strength of 66 MPa [6]. The system is shown in Figure 1.

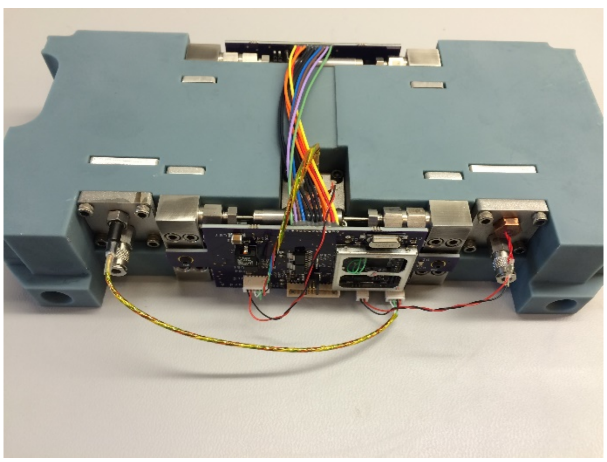

Figure 1: BioSentinel cold gas attitude control thruster.

The printed structure contains two propellant tanks, the main tank and the plenum, as well as the seven nozzles and the propellant feed pipes. The main tank stores the majority of the propellant (up to 200 grams) as a saturated liquid-vapor mixture, while the plenum stores a smaller amount (up to 2 grams) as a vapor alone. The nozzles are supplied directly from the plenum. This arrangement allows the pressure behind the nozzles to be more precisely controlled, and prevents liquid from entering any of the nozzles.

Eight miniature solenoid valves are used to control propellant flow. One valve controls flow from the main tank into the plenum, and each of the other seven valves control flow from the plenum to one of the seven nozzles. These valves are attached with compression fittings to two of the steel manifolds.

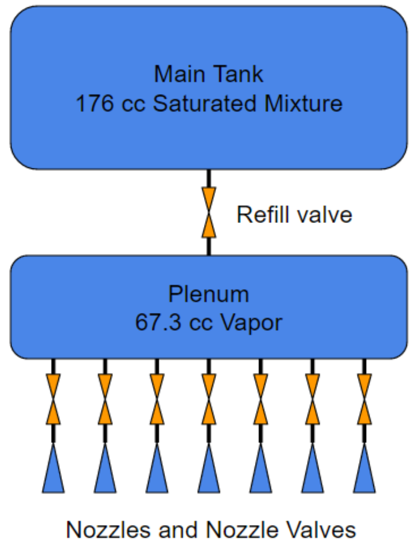

Figure 2: Block diagram of propellant tanks, solenoid valves, pipes, and nozzles.

Electronics

The thruster is equipped with two pressure transducers and two thermistors, which are threaded into the steel manifolds. One pair of sensors is allocated to each propellant tank, so the pressure and temperature of each tank is sampled periodically.

The thruster has two printed circuit boards, attached to the two valve manifolds. Each manifold holds four valves, and the electrical leads of these valves are soldered directly into plated holes in the circuits boards. These boards contain timing circuits to supply the correct voltage to the valves over very precise intervals.

One of the circuit boards also contains an LPC1549 microcontroller, which operates the thruster. The microcontroller operates the power switches that feed the solenoid valves, reads data from the sensors, and communicates with the BioSentinel flight computer over a serial port.

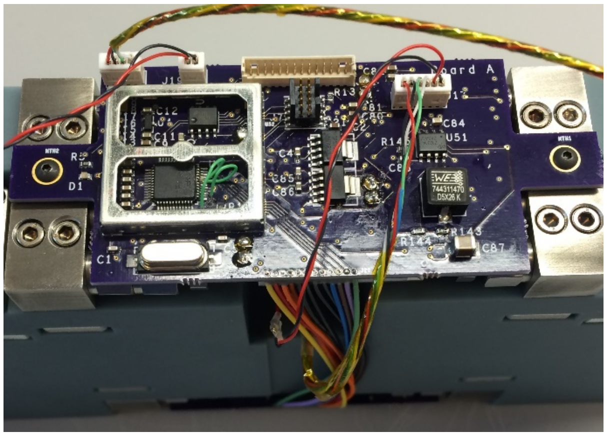

Figure 3: Circuit board, mounted to the thruster. The microcontroller is located in the RF shield (left, cover removed).

Thruster Concept of Operations

Upon deployment from the launch vehicle, the main tank will contain the entire propellant load, and the plenum will be at vacuum. Prior to thruster operation, the plenum will be filled from the main tank until it reaches 95% of the main tank pressure.

As the thruster is operated, the plenum pressure will fall as propellant is consumed. When the plenum pressure falls below a user-defined threshold, the thruster ceases operations and refills the plenum from the main tank. This threshold is nominally set to 80% of the current main tank pressure. Once the plenum is refilled, the thruster resumes normal operations. Approximately two seconds of continuous firing is needed to reduce the pressure from 95% to 80%, and approximately three seconds is needed to refill the plenum back to 95%, when operating at 25ºC.

Propellant

R-236fa, a commercially available refrigerant, is used as the propellant for the BioSentinel thruster. R-236fa, also known as 1,1,1,3,3,3-Hexafluoropropane, is non-toxic and non-flammable [7]. This reduces the safety risk to the launch vehicle and other payloads, which simplifies the flight qualification process.

R-236fa is also storable at a relatively low pressure. Because the propellant is stored as a saturated liquid-vapor mixture, the maximum internal pressure of the thruster is the saturation pressure at the maximum mission temperature. In the case of BioSentinel, this is 50ºC, corresponding to a saturation pressure of 584.2 kPa.

Unfortunately, with a molecular weight of 152.04 g/mol and a specific heat ratio (γ) of 1.069, the refrigerant is not an ideal propellant. The relatively low γ reduces specific impulse, which reduces the ΔV achievable for a given mass of propellant. This is mitigated somewhat by the high density of liquid R-236fa: 1.27 kg/L at 50C. During the design process, the volume restrictions were far more limiting than the mass restrictions. This favors a high density propellant, even one that is less propulsively efficient on a mass basis.

TEST APPARATUS

In order to validate the thruster's design and performance, an engineering prototype unit was fabricated and tested at the Georgia Institute of Technology in early 2015. The thruster testing was carried out in the Space Systems Design Lab (SSDL). The testing was conducted in a microTorr-level thermal vacuum chamber, using a custom-built torsional pendulum thrust stand.

Vacuum Chamber

The thruster was tested in the SSDL's vacuum facility, which consists of a thermal vacuum chamber built by LACO Technologies. The chamber is a stainless steel cube with interior dimensions of 61 x 61 x 61 cm. The system uses a LACO model W2V40 rotary vane pump as a roughing pump, and a Leybold Turbovac 350iX turbomolecular pump to achieve high vacuum. The chamber has a nominal base pressure of 1 microTorr.

The chamber's thermal control is provided by a JULABO FP50-MA heater/chiller, which cycles refrigerant through a platen attached to the interior floor of the chamber. The platen has a nominal temperature range of -40 to +60 Celsius.

Chamber pressure measurements are taken by an INFICON Gemini MPG500 dual Pirani/Cold Cathode pressure gauge. The vacuum chamber is shown in Figure 2.

Figure 4: Georgia Tech SSDL thermal vacuum chamber.

Test Stand

The test stand used for the BioSentinel thruster is a torsional pendulum design. The thruster is mounted to the stand on a bracket at the end of an arm. The arm is allowed to rotate through a small angle on an axle, which is attached to the test stand frame by two flexural pivots. The flex pivots have effectively zero static friction, and very low dynamic friction, which reduces energy losses in the oscillation of the system and improves the accuracy of the thrust measurement.

The opposite end of the swing arm holds two 2.25 kg steel disks, mounted on a threaded rod. The disks can be rotated to move along the rod to balance the mass of the thruster. The primary purpose of the balancing is to reduce the bending load on the flex pivots, which are not designed to support large loads in that way. However, the thruster's mass is not completely balanced, to allow the stand's zero position to be adjusted by moving the leveling feet. The test stand, with the thruster installed, is shown in Figure 3.

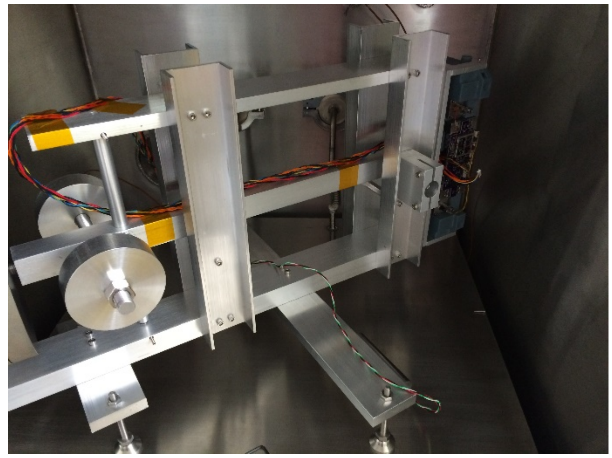

Figure 5: SSDL thruster test stand, with BioSentinel thruster installed (right).

The position of the arm is measured by a MacroSensors DC750-125 linear variable differential transformer (LVDT). The LVDT housing is mounted to the frame of the test stand, and the core is mounted to the arm. The LVDT has a sensitivity of 3.175 V/mm over a range of ±3.175 mm. The LVDT voltage is measured by a National Instruments data acquisition (DAQ) card with a 16-bit analog to digital converter.

The thruster is installed on the stand such that the nozzle to be tested is aimed perpendicular to the swing arm and in the horizontal plane. When the thruster fires, it produces a torque on the arm, and the arm begins swinging. The natural period of the test stand arm is approximately 10 seconds, and the thruster firing times are on the order of 10 milliseconds or less, so the firing can be treated as an instantaneous impulse.

Data Processing

The test stand responds to the impulse as an underdamped pendulum, with a period of approximately 10 seconds, and a damping ratio of approximately 0.02. Both of these values were determined by allowing the stand to oscillate freely for 200 seconds after an impulse was applied, then fitting a single damped sinusoid to the resulting waveform. The natural frequency is sensitive to the orientation of the thruster on the stand, and must be re-measured when the thruster is reoriented.

After a typical firing with an impulse magnitude on the order of 200 μN-s, the test stand requires approximately 10 minutes for the oscillation to dampen until it is indistinguishable from noise. To reduce the time required to carry out a test campaign, the oscillation of the stand is not fully damped between firings. A method was developed to determine the change in angular momentum of the test stand, and thus the impulse applied, despite this prior motion. A damped sinusoid was fit to the data before and after each impulse, with the impulse approximated as instantaneous. The change in angular velocity between the pre-firing and post-firing functions can then be determined.

A plot of LVDT voltage from the stand during a typical test is shown in Figure 4. Note that the impulse was applied 18 seconds into the sampling, while the test stand was still oscillating from a previous impulse.

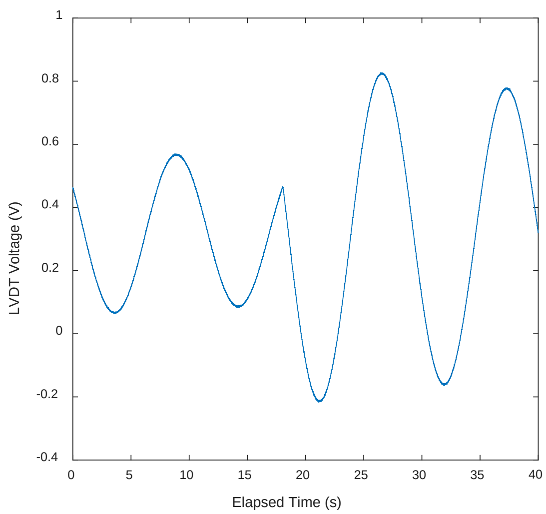

Figure 6: Typical LVDT voltage during a test, with an impulse at 18 seconds.

The LVDT voltage is converted into angular position using the LVDT sensitivity and the test stand geometry using the following equation:

$$\theta = \sin^{-1}\frac{V}{sR} \qquad (1)$$

Where θ is the angle (in radians) of the test stand arm; V is the LVDT voltage; s is the sensitivity of the LVDT (in V/mm); and R is the radial distance (in mm) from the axis of rotation to the LVDT.

After the voltage waveform is converted to angular position, two exponentially decaying sinusoids are fit to the data using a least squares approach. The equation to be fit is:

$$\theta = \begin{cases} A_1 e^{-\lambda t}\cos(\omega t + \phi_1) + b & t < t_f \\ A_2 e^{-\lambda (t - t_f)}\cos(\omega t + \phi_2) + b & t \geq t_f \end{cases} \qquad (2)$$

where A_1 is the amplitude (in radians) of the oscillation before firing; A_2 is the amplitude of the oscillation after firing; λ is the damping ratio of the test stand; ω is the natural frequency (in radians per second) of the test stand; ϕ_1 and ϕ_2 are the phase of the oscillation (in radians) before and after the firing, respectively; b is the zero offset of the test stand; t is the time elapsed since data collection started; and t_f is the time at which the thruster was fired. Of these parameters, only ω and λ are known, the others are estimated by the least squares algorithm. The sinusoids are constrained to match at the t_f, which is approximated as instantaneous.

The angular velocity of the stand can be found by differentiating equation (2), and using the parameters found by the least squares algorithm. This method is more resistant to noise than simply using numerical differencing to estimate angular velocity changes near the firing time.

To determine the instantaneous change in angular velocity due to the firing, the angular velocities of the pre-fire and post-fire sinusoids are computed at t_f. This angular velocity change is converted into an impulse using:

$$J = \frac{I\Delta\omega}{L} \qquad (3)$$

where J is the impulse (in N-s) of the firing; I is the calculated moment of inertia (in kg-m^2) of the test stand rotor about the axle; Δω is the instantaneous angular velocity change (in rad/s), found from differentiating equation (2); and L is the measured perpendicular distance from the thruster nozzle to the test stand axle.

Because the thruster firing durations are three orders of magnitude lower than the test stand period, it is not possible to resolve the thrust curve as a function of time using this test apparatus. However, the average thrust of the system over the duration of the pulse can be calculated simply as:

$$\bar{T} = \frac{J}{\Delta t} \qquad (4)$$

where $\bar{T}$ is the average thrust over the firing period; J is the total impulse produced by that firing determined from equation (3); and Δt is the commanded duration of the firing. The thrust during the actual firing is not constant, however, average thrust values are useful for comparisons between pulses of different durations.

TEST RESULTS

A test campaign was conducted at Georgia Tech to determine the thrust level produced and the specific impulse of the thruster. The focus of this test campaign was on very short pulsed operation, since this is the expected operating mode of the thruster during the mission.

Thrust Measurement

To characterize the thrust level of the system, each of the seven nozzles were fired a minimum of four hundred times. Pulse durations of 3, 5, 7, and 10 milliseconds were studied, with at least 100 firings of each nozzle for each pulse duration. The seven nozzles were found to produce repeatable thrust levels, within experimental error.

The average thrust was found to vary with pulse duration, with higher average thrust at shorter pulse times. A plot of the average thrust as a function of pulse time for one of the nozzles is shown in Figure 5.

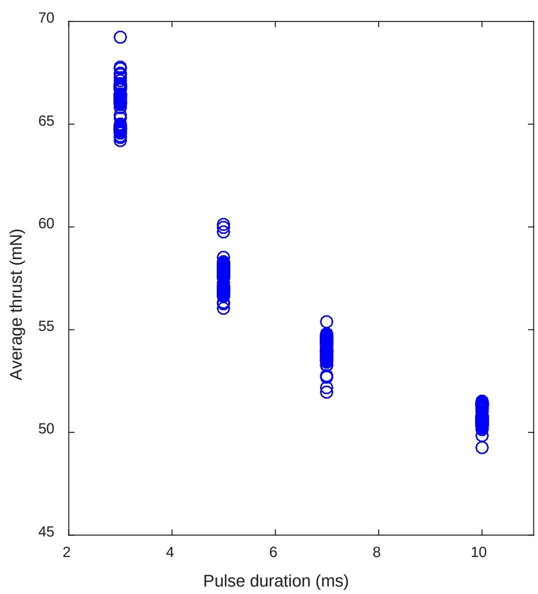

Figure 7: Average thrust per pulse versus pulse duration for nozzle 2.

The 3 millisecond pulses produced an average total impulse of 198 μN-s, which corresponds to an average thrust of 66.1 mN. The 10 millisecond pulses had an average total impulse of 507μN-s, for an average thrust of 50.7 mN, or a 23% decrease compared to the 3 millisecond pulses.

To rule out a timing error in the firing circuitry, the valve voltage was measured during repeated firing, and found to differ from the commanded firing time by no more than 10 μs, which is not large enough to explain this variation. Likewise, there was no detectable pressure drop in the plenum over a 10 millisecond firing, which places the maximum pressure drop below 540 Pa, which is not large enough to explain this effect.

The cause for this thrust decrease is believed to be the closing time of the solenoid valves. The valves are normally held closed by a spring, and open when the solenoid is energized. If the valve takes several milliseconds to close, and still allows some propellant flow during that time, each pulse would effectively be lengthened by a constant amount. This would have a greater effect on the apparent average thrust of the shorter pulses, since the additional "on" time is a greater proportion of the total "on" time of a shorter pulse.

During the testing, the thruster was reporting pressure and temperature measurements in both propellant tanks. Figure 6 shows a plot of impulse produced by a series of 1200 5 millisecond pulses, along with the plenum pressure at the moment the thruster was fired.

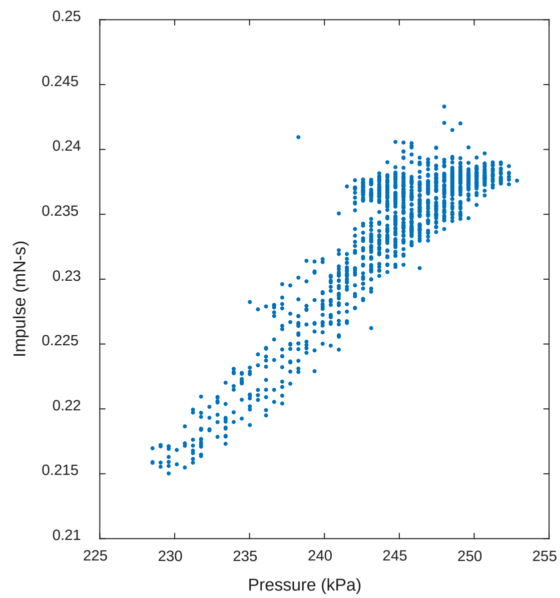

Figure 8: Impulse produced versus plenum pressure for 1200 5 ms pulses. Note that the discretization of the pressure values is caused by the microcontroller's analog to digital converter.

As expected, higher plenum pressures produced higher impulse for the same commanded pulse duration. This information, along with the impulse versus commanded pulse time, will be used by the BioSentinel ADC system to determine the commanded firing time needed for each maneuver.

Specific Impulse Measurement

The specific impulse of the thruster was calculated by firing the thruster repeatedly while recording the impulse produced, and measuring the mass change throughout the test. The following equation was used to determine specific impulse:

$$I_{sp} = \frac{\sum J_i}{(m_1 - m_2)g} \quad (5)$$

where I_{sp} is the specific impulse (in seconds); J_i are the impulse of each firing (in N-s); m_1 is the initial mass of the thruster (in kg); m_2 is the final mass of the thruster (in kg); and g is the standard gravitational constant (9.8066 m/s^2). In specific impulse calculations, g is only used as a normalizing constant, so it is an exact value.

The thruster was commanded to produce 1200 pulses, each one 5 milliseconds long. The test stand recorded the impulse produced by each of these pulses, and measured a total impulse of 280 ± 14 mN-s. The thruster was massed before and after this test, and found to have lost 0.90 ± 0.02 grams. Using Equation 5, the specific impulse was determined to be 31.7 ± 1.7 sec. The test was conducted over a period of 20 hours, during which the temperature of the system varied from 25.2ºC to 26.9ºC.

Total Impulse

The total impulse of a propulsion system can be calculated using the specific impulse and the propellant mass:

$$J = I_{sp} m g \quad (6)$$

Where J is the total impulse; I_{sp} is the specific impulse; m is the total propellant mass; and g is the gravitational constant. For the BioSentinel thruster, the specific impulse is 31.7 seconds, with a maximum propellant mass of 200 grams. This yields a total impulse of 62.2 N-s.

CONCLUSION

A miniaturized cold gas attitude control thruster has been developed for the BioSentinel interplanetary CubeSat. An engineering unit has been built and tested on a custom micropropulsion test stand in the Georgia Institute of Technology's Space Systems Design Lab.

The engineering unit's average thrust level was found to vary with the pulse duration, with higher thrust levels for shorter pulses. This is believed to be a result of slower than expected valve closing times. This effect will be examined in greater detail before the flight unit is fabricated.

The thruster was found to produce between 50 and 60 milliNewtons of thrust over pulse times of 3 to 10 milliseconds. The specific impulse of the system was measured to be 31.7 seconds, giving the thruster a total impulse of 62.2 N-s.

ACKNOWLEDGMENTS

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REFERENCES

[1] J. Mueller, J. Ziemer, and R. Hofer, "A survey of micro-thrust propulsion options for microspacecraft and formation flying missions," in *5th Annual CubeSat …*, 2008, pp. 1–19.

[2] D. Hinkley, "SSC08-VII-7 A Novel Cold Gas Propulsion System for Nanosatellites and Picosatellites," 2003.

[3] T. K. Imken, T. H. Stevenson, and E. G. Lightsey, "Design and Testing of a Cold Gas Thruster for an Interplanetary CubeSat Mission," *J. Small Satell.*, vol. 4, no. 2, pp. 371–386, 2015.

[4] G. Manzoni and Y. L. Brama, "SSC15-IV-5 Cubesat Micropropulsion Characterization in Low Earth Orbit," in *29th Annual AIAA/USU Conference on Small Satellites*, 2015.

[5] M. Sorgenfrei, T. Stevenson, and G. Lightsey, "Considerations for Operation of a Deep Space Nanosatellite Propulsion System," in *AAS GN&C Conference*, 2016.

[6] 3D Systems Corporation, "Accura ® Bluestone ™," Rock Hill, SC, 2015.

[7] DuPont, "Thermodynamic Properties of DuPont ™ Suva® R-236fa," Wilmington, DE, 2005.