Low Cost COTS CubeSat Orbit Determination Solutions for Prototype Propulsion Experiments

In order for new and more effective methods of propulsion to be developed for small satellite use, these often experimental systems must be tested and verified in space. In order to more effectively characterize these new propulsion systems aboard various CubeSat missions, an intermediary module was devised between the CubeSat and the propulsion system. This intermediary module would handle the management of the propulsion system and collection of test data and would, allowing the CubeSat to have a standard module to interface with. In this project, the intermediary module described is developed to test the Starling Ardent propulsion system aboard a future TechEdSat mission. The preliminary design is geared for the Starling Ardent through our testing and simulation, but future missions with other propulsion systems could utilize the same accelerometers and interface between the module and the satellite.

Keywords: *propulsion, spacecraft design, satellite design, COTS, orbit determination*

Introduction

Significance

As small satellites become more widely used outside of education, satellite subsystems and improvements on them tailored to the needs of these smaller platforms will have real impacts on the effectiveness of exploratory and commercial missions that use them. Of these improvements are propulsion systems designed specifically to meet the limitations, needs, and mission profiles of small satellites.

Typically, small satellite propulsion systems are miniaturized versions of larger systems such as bipropellant rocket engines, compressed cold gas thrusters, and electronic thrusters. Bipropellant rocket engines and compressed cold gas thrusters pose a possible explosive hazard to both their rideshare partners and the ISS where they are commonly launched from. Electric propulsion, while extremely efficient, has a high-power demand and produces very little thrust. The Starling Ardent, a version of the Starling thruster with an added resistojet, allows CubeSats to be transported, launched, and deployed with no pressurization or toxicity hazard, and provides cold-gas thruster levels of thrust once in orbit with increased efficiency due to the addition of a resistojet.

Small satellites with powered thrust capabilities are able to carry out missions requiring maneuvering and extend their lifespan far beyond that of unpowered satellites sent into low earth orbit. Additionally, propulsion adds de-orbit capability to small satellites, an important consideration as spacecraft become smaller and more numerous.

In order to test these new and experimental propulsion systems in flight, missions need to be designed with the proper instrumentation to characterize the properties of each thruster aboard a test satellite. A common intermediary module such as this one would make the testing and integration of new propulsion systems easier and more streamlined.

Starling Ardent

Starling Ardent is an electrothermal warm gas generator propulsion system developed by Benchmark Space System. The Starling Ardent is an Azodicarbonamide based, ultra-safe, non-toxic propulsion system; to be first flown aboard an Ames Research Center TechEdSat launching early 2022. The Starling family of thrusters may be filled, packed, and stored indefinitely with no shelf-life degradation and is D.O.T approved for shipment. The Starling Ardent is an evolution of Benchmark's Starling thruster that aims to improve $\square_{\square\square}$ using a resistive heating element.

One Starling thruster is set to fly on the inaugural Firefly Alpha launch in 2021 onboard the BSS1 satellite. The Starling system stores solid AZO powder in a storage tank that remains unpressurized during integration, launch, and deployment. Once in orbit, a pressurization command initiates an exothermic reaction that produces a gas composed primarily of Nitrogen to be stored in an expansion tank which will then be used at mission discretion. BSS, ARC, and San Jose State University are currently developing the flight system with a target $\square_{\square\square}$ of 110s and thrust of 50mN with future iterations to surpass 130s and 100mN. The key attractive feature of this propulsion system is the fact that it stays unpressurized for the majority of key time periods where a pressurized system would bring up safety concerns and risks, this opens up the possibilities of more CubeSats being deployed with propulsions systems where it may not be as accessible for many to conform to the rigorous requirements associated with other propulsion systems.

Technology Educational Satellite

Technology Educational Satellite, also known as TechEdSat, is a highly experimental nanosatellite rapid technology development and demonstration program run jointly by NASA Ames Research Center and San Jose State University, both located in Northern California. The program was initially started by San Jose State in 2012 and was the first university in the United States to successfully launch and deploy a CubeSat from the International Space Station. Once the feasibility was established, NASA Ames got involved and now TechEdSat has evolved into a fully-fledged CubeSat initiative program with NASA and multiple universities. TechEdSat works as a test bed for highly experimental technologies and technology/science demonstrations to further be space qualified and to validate the technologies themselves for future mission applications.

Not only is TechEdSat focused on technological advancement, it is also a key opportunity of inclusion and diversity. By having students partner with NASA/relevant industry contacts, university students are able to meet with, be advised by, and get support from individuals at a much higher level than normally available. Normally, It would be incredibly difficult for the average student to reach out and establish these kinds of working relationships with people in these positions.

Outline

The introduction of this paper introduces the problem that this project is addressing as well as information about the systems that will be directly involved with the experiment. The literature review section examines background information on similar propulsion systems for CubeSats, it also covers previous experiments like this one to characterize propulsion systems. The methodology section starts with an overview of the mission and a system decomposition of the hardware involved as well as a breakdown of the intermediary module itself and a flowchart of the code. The methodology section then covers the theory of how the experiment will be performed to characterize the thruster, followed by the specific components to be used for the test. The results section shows the STK simulation that was performed to approximate the behavior of the satellite during this test as well as tests developing code to interface the satellite, thruster, and sensors with each other. The discussion section covers what was accomplished, what the potential applications are, and what future improvements to the system are suggested based on what was learned in this project. Finally, the conclusion summarizes the main findings and implications of this project.

Literature Review

CubeSat Propulsion

With the increase of Cubesat developments, particularly in universities, more publications are now discussing design concepts, operations, and testing of propulsion systems on CubeSat missions. For instance, *Lemmer* describes the main design limitations of propulsion systems for CubeSats to be safety limits for propulsion ignition, power and mass limits, valves and inhibits for pressurized propellent tanks, and mission specific limits [1]. Such limits make designing propulsion systems for CubeSats more challenging, hence the need for new technology, like the Starling Ardent, that navigates such limits while ensuring satisfactory performance.

Lemmer also describes how cold gas thrusters have the most flight heritage of all CubeSat propulsion systems[1]. Even though they might offer lower specific impulse (40-75 seconds)[2], cold gas thrusters are desirable due to their simplistic design and operation, reliability, and wide range of propellant compatibility[2] .However, almost all thrusters with publicly available information utilize either a hazardous propellant [1], or a propellant that requires to be pressurized at launch. Both of these introduce more risk to the system and are mitigated by Starling Ardent.

Propulsion System Performance Characterization Experiments

As one of the main goals of this paper is to introduce an experiment to characterize the performance of the Starling Ardent with and without the resistojet, previous publications exhibit similar experiments. *Asakawa et al.* designed an experiment to measure the thrust and the specific impulse of a sub-10-mN CubeSat thruster [3]. The experiment outlines a method to test propulsion systems before going into orbit. It uses an inverted pendulum setup to measure mass changes of the system to calculate the thrust and the specific impulse [3]. The experiment is held in a vacuum chamber, which would be similar to the Starling Ardent testing condition to simulate orbit conditions.

Asakawa et al. also outlined calculation methods to account for mass loss and drift, as well as performance characterization resolution [3]. This experiment was conducted on a propulsion system with a resistojet module, similar to Starling Ardent, which adds to the reasons why such literatures are noteworthy benchmark foundations for in-orbit performance characterization experiments of propulsion systems, as the one proposed in this paper.

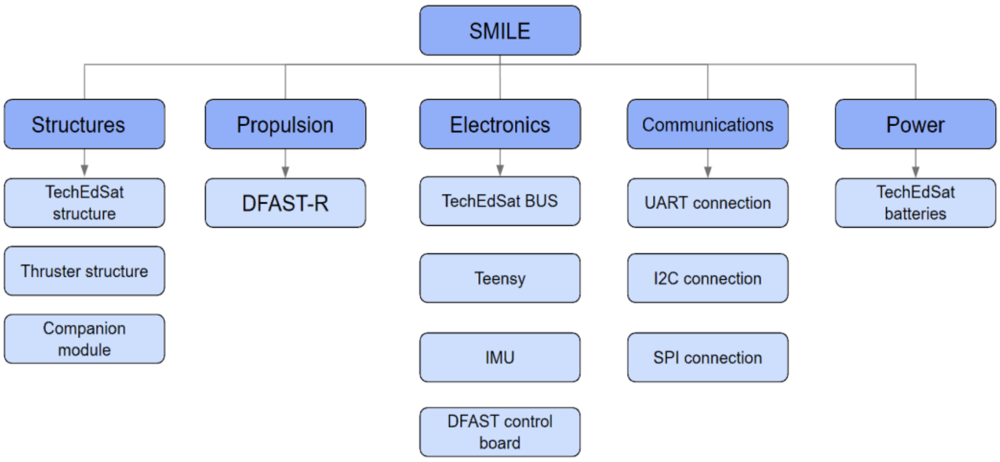
Moreover, *Kramer et al.* described a performance characterization experiment for a CubeSat electric propulsion system [4]. Even though their discussed system produces less thrust and change in orbit than desired in a TechEdSat mission [4], their paper highlighted design caveats beneficial to future missions. Such as, interfacing with the satellite's attitude and orbit control systems to eliminate thrust vector misalignments [4]. Such design considerations are ought to guide future interfacing of propulsion systems and TechEdSat, including Starling Ardent.

Methodology

Experiment Definition

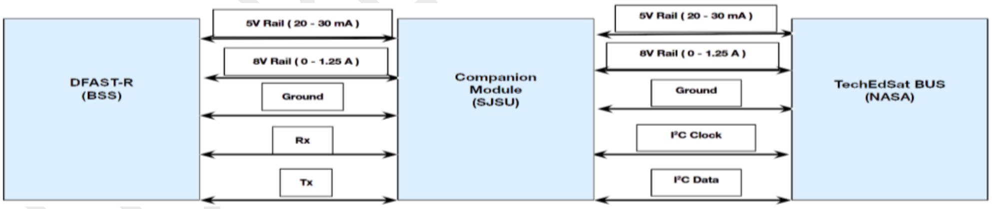
The SMILE project consists of three main sections, the propulsion system, the companion module, and the satellite. The propulsion system and satellite are externally defined systems that the companion module is intended to bridge together. The satellite provides power, attitude control, and data to and from the ground. The propulsion system accepts any diagnostic or firing commands while returning any relevant onboard data. The companion module packages the propulsion system together with accelerometers to allow the satellite to conduct a preplanned propulsion system test with a simple command and is able to process and deliver the data back to the satellite for transmission to the ground. The companion module's overall purpose is to relieve the satellite's computer from handling the propulsion system test as well as to make propulsion system experimentation a more modular package for satellites.

Figure 1. *SMILE project system decomposition*



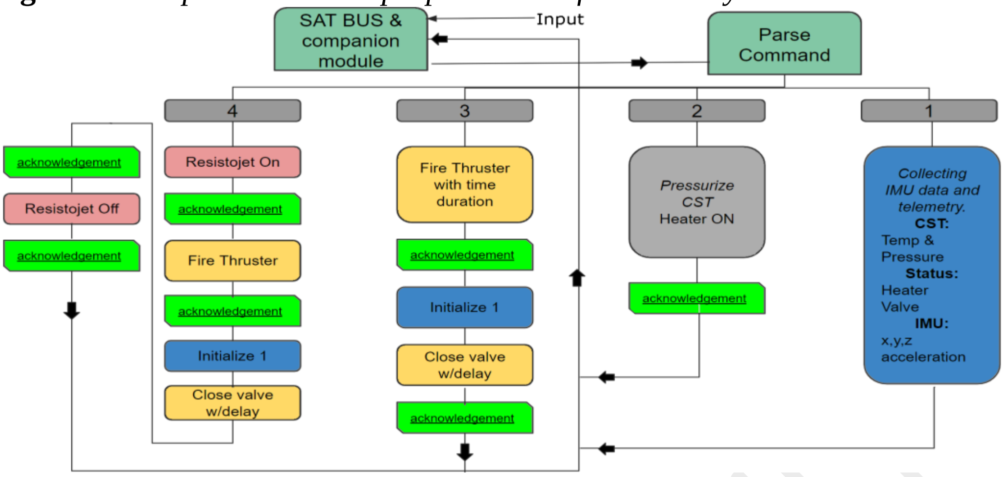
The companion module is intended to connect to the satellite through a single serial connector, requiring only a single I^2C connection and address for communication, ground, 5V for logic power, and raw battery power if needed by the propulsion system. Figure 2 below depicts how the companion module isolates the propulsion experiment from the satellite's computer. The accelerometers would be an integral part of the companion module's circuit board.

Figure 2. *Companion module physical interface with Starling Ardent and TechEdSat*



The companion module is designed to carry out its task with minimal work done on behalf of the satellite. Figure 3 below shows the general structure of how communication with the companion module would be carried out. Commands sent to the companion module's I^2C address would be parsed and used to trigger preprogrammed functionality. In the case of the Starling Ardent propulsion system, one command is to prime the thruster while the other two fire it under different configurations necessary to this particular test plan.

Figure 3. *Companion module proposed code functionality*



Experiment Design

The experimental goal of the project is to measure the ISP of the Starling Ardent propulsion module based on data acquired while the spacecraft is in orbit. In order to do so, instruments must be able to measure the thrust produced by the propulsion module and validate the ground tested mass flow rate. These values are then applied to the equations elaborated upon below to determine the instantaneous ISP of the thruster.

The calculation of the ISP is based off of equation 1,

$$ISP = \frac{F}{\dot{m} \cdot g_0} \qquad \textit{(Eq. 1)}$$

In this case, 'F' is the thrust of the system, 'ṁ' is the mass flow rate and g_0 is the local acceleration due to gravity. As the thrust cannot be directly measured, instead the thrust is calculated using Newton's 2nd Law as presented in equation 2,

$$F = m \cdot a \qquad \textit{(Eq. 2)}$$

With the mass of the spacecraft known, thrust can be calculated by applying a measured acceleration to the above formula. Mass flow is determined using control volume analysis based off of the pressure and temperature of the holding tanks using the relationship according to the Ideal Gas law presented in equation 3,

$$\rho = \frac{P}{R \cdot T} \qquad \textit{(Eq. 3)}$$

With a known tank volume, current propellant mass can be determined through the following relationship from dimensional analysis in equation 4,

$$V \cdot \rho = m \qquad (Eq.\ 4)$$

By taking measurements at regular time increments, average mass flow rate can be calculated and used for the on-flight ISP calculation.

In order to retrieve the needed data, instruments must be used to record tank pressure, tank temperature, and acceleration. As the tank values are retrievable from temperature sensors and strain gauges provided by Benchmark Space Systems, the only remaining instrument needed is an accelerometer or IMU to measure acceleration.

Component Breakdown

The components utilized in this experiment and housed within the SJSU experiment module are a Teensy 4.1 microcontroller, Hillcrest BNO085 IMU, BOB-12009 Logic leveler, and an Integration Evaluation Kit (IEK) from Benchmark that simulates their propulsion system. The microcontroller will receive I2C from the satellite BUS and output UART to the IEK. The logic leveler is used to shift any communication lines as necessary. The IMU will be used in order to characterize the spacecraft during the mission to better understand the propulsion system and its revisions from heritage models.

Results

STK

In order to validate and simulate the current concept of operations, initial mission parameters were input into AGI's Space Toolkit (STK) software. Using the Astrogator add-on and the known thrust levels and fuel mass gained from BSS, the full mission was simulated beginning from the ejection of the satellite by the Nanoracks deployer on the ISS until the spacecraft dipped below 100km altitude. Further simulations were performed to ascertain the overall orbital maneuver capability of the Starling Ardent when simulated under ideal conditions.

Table 1. *Spacecraft parameters*

Mission Simulation Summary	
Spacecraft Parameters	**Values**
Spacecraft Dry Mass	3.5 kg
S/C Drag Area	0.03 m^2
S/C Drag Coefficient	1.4
Fuel Mass	0.09
Thrust R-on	0.05 N
Thrust R-off	0.05 N
ISP R-on	110 s
ISP R-off	70 s

Table 2. *Initial orbit parameters*

Orbit Properties	
Initial Orbit	**Values**
Inclination	51.6°
Eccentricity	2.62E-4
Perigee Altitude	407.33 km
Apogee Altitude	404.87 km

In Tables 1 and 2, the orbital elements of the ISS were retrieved, and an impulsive maneuver of 1 m/s was performed on the spacecraft opposite the velocity vector. This maneuver replicates the Nanoracks spring deployment and the orbital elements detailed account for this perturbation. Parameters for both resistojet on and off for the system have also been included in the tables.

Table 3. *Resistojet OFF simulation*

Maneuver Properties	
Parameters	**Values**
Perigee Altitude	326.62 km
Apogee Altitude	400.81 km
ΔV (Velocity)	17.43 m/s
Fuel Used	0.09 kg
Total Burn Time	1235 s

Table 4. *Resistojet ON simulation*

Maneuver Properties	
Parameters	**Values**
Perigee Altitude	309.73 km
Apogee Altitude	391.45 km
ΔV (Velocity)	27.38 m/s
Fuel Used	0.09 kg
Total Burn Time	1941 s
Power Used	26.95 Wh

Tables 3 and 4 describe the secondary simulation in which the maximum capability of the thruster is compared with and without resistojet. Both burns began with the same initial pass at orbit apogee, burning until all fuel was used. As can be seen, the resistojet increases the burn time by a significant margin increasing the overall ΔV. The increase in burn time and ΔV demonstrates the thruster's capability as a deorbiting method for low-mass satellites, allowing them to drop into the 300km region where the satellite would begin experiencing significant amounts of drag eventually leading to the desired accelerated deorbit time.

Code Validation

Provided by BSS was a library of python code that would allow a computer to interface with the IEK using a USB cable. With this library, the IEK 's functionality was able to be tested without any additional work. In preparation for a flight model of the system, code was written on the more reliable Arduino system. This code assembled data packets and applied CRC before sending the command over a serial connection from a teensy 4.1 microcontroller to the IEK. The figure below shows that this code was able to get identical responses to the python example code from the IEK.

Figure 4. *C code validation with manufacturer's python script*

Discussion

What this Means

The results of this experiment have shown promising results in developing an orbit determination companion module for propulsion systems on CubeSats. First, the software constructed in this experiment demonstrated functional communication between a satellite BUS, an inertial measurement unit, and a propulsion system. The code is verified against the manufacturer's code which validates the structure of the software and its ability to be changed and adapted as needed by stakeholders. Using this code, the system was able to send and receive commands and record inertial measurements simultaneously, which is required when in orbit. The demonstrated functionality of this software highlights an effective interfacing methodology, especially since the modules have different communication protocols. Even with a different electronic setup, this software offers guidance to establishing communication, collecting measurements, and transferring uplink and downlink data between the three modules.

On the second hand, this paper outlined a comprehensive experimental methodology to characterize the performance of a propulsion system on a CubeSat, in addition to orbit determination. Implementing this methodology once the system is in orbit will further verify its feasibility as a performance characterization solution for any CubeSat propulsion system. Combined with software, the setup of this experiment could be developed into a propulsion systems' in-orbit CubeSat testbed. Furthermore, the discussed simulations emphasized how the use of propulsion systems can remarkably elongate the operational time of a CubeSat mission, like TechEdSat. This offers the opportunity for more scientific experiments that require a longer time to be conducted. It also widens the range of applications that CubeSats could be used for.

How it can be Used

With the need to continuously improve and space qualify components, this collaboration with BSS was proposed as a means to help further pave the way for future missions. This project also marks a significant technology demonstration; the BSS thruster module will be the first propulsion system to deploy on a nanosatellite from the ISS. The Starling Ardent/Starling warm gas thruster propulsion system from Benchmark Space Systems will help elevate BSS propulsion solutions as a viable means of thrust for small satellites. The integration and possible flight of this unit will help advancements on multiple fronts.

As a current phase II project in NASA's SBIR initiative, the Starling Ardent acts as a performance model and baseline for future propulsion endeavors. It will also demonstrate the performance of and elevate the TRL of the Starling Ardent when it is used in the target environment. By completing the proposed objectives and goals, future missions and projects will be assisted in three explicit ways: by having interface documentation to follow, TRL elevation of the thruster module and COTS hardware, and having a flight test in the target environment.

Most CubeSats are not equipped with propulsion systems, let alone make it through ISS safety requirements with one. With the success of Benchmark's Starling Ardent, the capabilities of countless CubeSats will be increased, this includes any and all military defense-specific CubeSats. By increasing capabilities, these satellites will be able to perform missions that are longer duration and missions that require any orbital maneuvers. In exchange for these improved CubeSats, any countries utilizing them will be able to increase their defense capabilities and global awareness. The modularity of Starling Ardent will lend itself to ease of integration which in turn will allow for higher levels of accessibility to those in any country of the world wanting to build a CubeSat equipped with a propulsion system.

A huge problem that will grow exponentially if something doesn't change is space debris. Currently, there are many dead satellites orbiting the Earth whose missions have long ended. However, they have no means of deorbiting and are solely relying on time to remove themselves from the many defunct satellites stuck in orbit. This was not as big a problem back when there were not many satellites being deployed, but with the advances in technology we see now, every year more and more satellites are being deployed, this growing problem will show its significance in the years to come. Large satellites stuck in space is an incredibly inefficient use of materials, time, and space. If these satellites were initially built with the capabilities to make significant orbital maneuvers we would not be seeing as much debris in space.

By equipping CubeSats specifically with a propulsion system like Starling Ardent, this problem can be addressed directly and change the trajectory of the growing number of items considered space debris. CubeSats are growing in popularity and are becoming more advanced every year; eventually, many larger satellites will be able to be replaced by CubeSats, this addresses part of the space debris problem. The other parts will be addressed by equipping these CubeSats with a Starling Ardent, by enabling these CubeSats to make orbital maneuvers, they will now be able to extend their mission durations and accelerate their end of the mission via deorbiting maneuvers. By replacing larger satellites with smaller ones that can make orbital maneuvers and if what used to be a multi-month mission can now become a multiyear mission, there will be less of a need to have lots of satellites in orbit at once. On the other hand, once the CubeSat's mission is over, it no longer needs to deorbit naturally, they will be equipped to make a deorbiting maneuver and take itself out of space on command.

Improvements and Future Plans

There are many areas that the project can be improved upon. First and foremost are the components being utilized. In this first iteration of the SMILE module, a Teensy 4.1 was used as the module's main computer while this microcontroller is adequate for ground testing, the next revision must utilize the Teensy 3.5. This is to take advantage of the larger feature size of the main processor and the lower frequency of the ARM CORTEX-M4 in order to minimize single-event upsets caused by stellar radiation. The next hardware change would be to the Hillcrest BNO085 IMU. While it works as a good test bed for coding and communication architecture practice, the accelerometer does not meet the requirements laid out by the flight experiment. In order to move into proposed flight hardware, an accelerometer with a lower noise density and overall higher sensitivity must be utilized. The accelerometer proposed to fulfil this requirement is the Murata SCL3300 three-axis MEMS inclinometer. This was chosen due to its low noise density sensitivity being at least two orders of magnitude higher than the mission requirement. Further, this accelerometer also has manufacturer flight heritage with the initial successful vacuum testing being done at SJSU and Mars' Ingenuity helicopter currently flying with an earlier iteration of Murata's inclinometer series. For these reasons, the Murata SCL3300 is a logical, cost effective avenue to investigate for the purposes of this experiment.

Table 5. *Proposed future components*

Component	Feasibility (X/10)	Justification
Murata SCL3300	9	- Extremely affordable - Flight heritage architecture (Ingenuity SCA100T-D02) - Low noise density (0.001 °/√Hz) - Higher sensitivity (0.000818m/s²)
Teensy 3.5	9	- Extremely affordable - Lower frequency processor (180 MHz) - More rad tolerant from larger feature size (90 nm)
BOB-12009 Logic Leveler	10	- Required for 5V step down to 3.3V

The next area to address would be to move from breadboard ground tests to PCB ground tests. This reflects a much more realistic mission simulation and a closer look at what is needed in terms of circuit protection when it is integrated into the Satellite BUS. The footprint of the PCB must be adapted for the future also, as the final hardware design will be constrained by the mission geometry limits. In addition, the ground test currently does not need any circuit protection implementation as a power supply is being utilized. Though, once the PCB design is tested circuit protection methods and PCB design workmanship must be implemented in order to reach a proper flight version in a timely manner.

Another critical component of this experiment that must be improved upon for a realistic mission simulation and for mission execution is the software. Currently the code being used for the breadboard ground testing is a simple script that satisfies the initial ground test requirements to simply validate the architecture and verify the concepts being laid out. For future iterations it is imperative that a proper code with modular design and communication failsafes is developed that will enable realistic ConOps simulations and module functionalities.

Conclusion

With the need to continuously improve and space qualify components, this collaboration with BSS was proposed as a means to help further pave the way for future missions. This project also marks a significant technology demonstration; the BSS thruster module will be one of the first propulsion systems of its kind to deploy on a nanosatellite from the ISS. The Starling Ardent/Starling warm gas thruster propulsion system from Benchmark Space

Systems will help elevate BSS propulsion solutions as a viable means of thrust for small satellites. The integration and possible flight of this unit will help advancements on multiple fronts.

As a phase II project in NASA's SBIR initiative, the Starling Ardent acts as a performance model and baseline for future propulsion endeavors. It will also demonstrate the performance of and elevate the TRL of the Starling Ardent when it is used in the target environment. By completing the proposed objectives and goals, future missions and projects will be assisted in three explicit ways: by having interface documentation to follow, TRL elevation of the thruster module and COTS hardware, and having a flight test in the target environment.

References

[3] Asakawa J, Nishii K, Nakagawa Y, Koizumi H, Komurasaki K (2020) Direct measurement of 1-mN-class thrust and 100-s-class specific impulse for a CubeSat propulsion system. *Review of Scientific Instruments 91,035116*

[4] Kramer A, Bangert P, Schilling K (2020) UWE-4: First electric propulsion on a 1U CubeSat-in-orbit experiments and characterization. *Aerospace 7(7), 98.*

[1] Lemmer K, (2017) Propulsion for CubeSats. *Acta Astronautica 134, 231-243*

[2] Mani K, Cervone A, Topputo F (2019) Combined Chemical-Electrical Propulsion for a stand-alone Mars CubeSat. *Journal of Spacecrafts and Rockets 56(6), 1816-1830*