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A Comparison of the Technological Maturation of SmallSat Propulsion Systems from 2018 to 2020

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ABSTRACT

The maturity in small spacecraft technology is indicated by the continued growth in the number of missions, mission complexity, and the expansion of smallsat subsystem capability. Identified development paths include the consideration of systems and components with flight heritage on larger spacecraft to meet the needs of smaller platforms, the conception of novel technologies specifically designed for small spacecraft, and the incremental improvements every 1-2 years in components where the underlying technology remains unchanged. Progress of overall smallsat technology development is captured in the most recent *2020 State-of-the-Art Small Spacecraft Technology* (SoA) report, the objective of which is to assess and provide an overview on the current development status across all subsystem architectures. The SoA report contains a variety of surveys covering device performance, capabilities, and flight history, as presented in publicly available literature. The focus of these surveys is on devices or systems that can be commercially procured or appear on a path towards commercial availability. The work toward the 2020 edition of the report was managed by NASA's Small Spacecraft Systems Virtual Institute (S3VI) and performed by several contractor staff. The S3VI is jointly funded by NASA's Space Technology Mission Directorate and Science Mission Directorate.

Technological advancement varies across subsystems, and smallsat propulsion technology has had a rapid increase in quantity and type in the last few years that is documented in the SoA report. The extensive efforts made by industry, academia, and government entities to develop and mature small spacecraft propulsive technologies suggest a range of devices with diverse capabilities will become more readily available in near future. While the report uses the NASA Technology Readiness Level scale to measure technical maturity, the "In-Space Propulsion" chapter implemented a novel classification system that recognized Progress towards Mission Infusion (PMI) as an early indicator of the efficacy of the manufacturers' approach to system maturation and mission infusion. Readers of this paper are highly encouraged to refer to the "In-Space Propulsion" chapter for further information on the PMI classifications.

A driving trend captured in the SoA report is that smallsat missions are becoming more complex in the anticipation of using smallsats to collect lunar and deep space science. Smallsat propulsive technology must mature operationally

to meet the needs of the increasing smallsat mission complexity. This paper will expand upon the progression of technical maturation identified in the "In-Space Propulsion" chapter presented in the 2020 report and compare these developmental achievements to the "Propulsion" chapter in the 2018 SoA report. By making these comparisons, the reader will be able to measure the degree of advancement in smallsat propulsion technology that has been made in the last few years, understand the specific development approaches propulsion engineers encounter, and learn about the current trends in smallsat propulsion.

INTRODUCTION

The *2020 State-of-the-Art Small Spacecraft Technology* (SoA) report concentrates on small spacecraft and defines a small spacecraft as <180 kg wet mass. While there is extensive experience in the design and testing of propulsion systems and components for large spacecraft, little flight heritage currently exists on smaller platforms under 180 kg. This is beginning to change as recent efforts have enhanced the capability that was captured in the 2018 SoA report. To bolster this advancement, the 2019 NASA's fourth Tipping Point solicitation included efficient and affordable propulsion systems and awarded three companies to further develop and demonstrate in space beginning in 2021. In addition, NASA's Artemis I mission, expected to launch in late 2021, will deploy thirteen 6U spacecraft of which twelve will demonstrate a miniaturized propulsion system. Six of the twelve propulsive smallsats will enter a stable lunar orbit and other six will escape into a heliocentric environment. The sole 6U spacecraft without propulsion will escape into a heliocentric orbit and naturally drift. The need for functional and available smallsat propulsive systems will continue to support the push forward for innovative systems and in-space demonstrations.

In-space propulsion systems are used for several spacecraft operations such as orbital changes and maintenance (altitude and inclination), attitude control and desaturation of reaction wheels, drag compensation, and deorbiting. Two development approaches have been identified in the expansion of small spacecraft propulsion in both demonstrations and capability. In one development path, systems and components with flight heritage are being reconsidered to meet the needs of smaller spacecraft. This approach minimizes new product development risk and time to market by creating devices similar to those with existing spaceflight heritage, albeit accounting for small spacecraft volume, mass, power, safety and cost considerations. An alternative development path is the conception of novel technologies specifically for small spacecraft. These technologies often use innovative approaches to propulsion system design, manufacturing, and integration. While the development of novel technologies is associated with higher risk and slower time to market, these new technologies strive to offer small spacecraft a level of propulsive capability not easily matched through the miniaturization of heritage technologies.

2020 In-Space Propulsion Chapter Structure

To fully understand our comparison in this paper, the reader should be aware of the notable differences in the 2020 "In-Space Propulsion" chapter from the 2018 "Propulsion" chapter. While both editions list and describe publicly known smallsat propulsion systems, the structure of the 2020 chapter separates itself from the 2018 edition. This adopted structure has a deeper dive in the maturity assessment of each technology, presents operational and integrational considerations for reader's awareness, distinguishes propulsion systems into propulsion components, highlights notable missions of potential significance, and organizes the data to improve overall comprehension on the subject.

The lack of sufficient in-depth technical insight into current propulsion devices found in publicly available data restricted the SoA propulsion authors' Technology Readiness Level (TRL) assessment. A known problem is that flight data is not always available, so the intended spacecraft bus and target environment is commonly unknown in certain subsystem technologies. As most technologies have unique operational requirements that vary in different environments, the device is not guaranteed to function optimally the same in all environments (sun synchronous orbit, geostationary, deep space, etc.). Therefore, instead of assessing each technology's TRL, the authors introduced the Progress towards Mission Infusion (PMI) classification system. The PMI is meant to compliment the known TRL scale and may assist in the down-select of an in-space propulsive device.[1] The PMI is sorted into four broad technology development categories: Concept (TRL 1 – 3), In-Development (TRL 4 – 5), Engineering-to-Flight (TRL 5 – 6), and Flight-Demonstrated (TRL 7 – 9). Each development category is aligned with a TRL value range.

The following sections will highlight the technology advancement of propulsion technologies since 2018. The highlighted technologies achieved "Engineering-to-Flight" and "Flight-Demonstrated" classifications that occurred in chemical, electric, and propellant-less propulsion systems that are included in the 2020 edition.

FLIGHT-DEMONSTRATED TECHNOLOGY (TRL 7-9)

While several devices are still in-development since 2018, there has been an increase in the number of "engineering-to-flight" classified systems for existing smallsat missions expected to launch in 2021 and systems that are recently "flight-demonstrated" since 2018. There has been a large expansion in smallsat electric propulsion (EP) research as there is a high probability that EP will overtake chemical methods for specific in-space applications when anticipated EP "flight demonstrated" systems are available. Propellant-less propulsion technologies have also undergone in-space demonstrations to date and include solar sails, electrodynamic tethers, and aerodynamic drag devices. New technologies are being demonstrated on larger smallsats >100 kg in preparation for their configuration on a nanosatellite platform. These technologies either recently launched and operated or are expected to in 2021.

In light of their widespread use, the EP thruster types that have fueled this rapid expansion are moderately-powered (1–20 kW) hall-effect, electrothermal, and ion thrusters that have arguably now achieved "mature" operational status.[1] The rise in EP research and demonstration is aided by academic engineering programs, high-demand for smallsat constellations, and interest by national space agencies. In addition to the expansion of EP technology, new high-performance monopropellant was demonstrated for chemical systems. There has also been an increase in propulsion systems that use water as the propellant. Table 1 summarizes current flight-demonstrated propulsion systems with their corresponding 2018 development status.

The launch of hall-effect thrusters (HETs) greatly accelerated since 2018 due to the rise in low-Earth orbit constellations. The BlackSky constellation program consists of ~55 kg spacecraft equipped with a Bradford Space Comet-8000 water-based electrothermal propulsion system used for orbit maintenance. The first launch occurred in December 2018, and as of March 2021 there are seven spacecraft in-orbit with the plan to have thirteen spacecraft in-orbit by the end of 2021.[2] The Comet-1000 HET thruster head launched into low-Earth orbit mid-2018 on three 3U spacecraft HawkEye 360 (Cluster 1), and three more 3U's were launched in January 2021 as part of the Cluster 2. Planned for launch later in 2021 are three more clusters of three 3U spacecraft with the Comet-1000 thruster head.[2,3]

The first successful in-space operation of Enpulsion's instantaneous frequency measurement (IFM) Nano Field Emission Electric Propulsion (FEEP) electrospray thruster took place in the second quarter of 2018. Subsequently, three other smallsat missions were equipped with this system though there is limited in-orbit data publicly available making a proper assessment difficult. These smallsat missions include: ICEYE X2 (100 kg, launched December 2018 [4,5]); the Department of Defense-funded Harbinger technology demonstrator (launched May 2019 [6,7]); and the Zentrum für Telematik (Würzburg) NetSat formation-flying demonstrator mission (launched September 2020 [8,9]).

High performance monopropellant has demonstrated its capability with the launch of the Green Propulsion Infusion Mission (GPIM) in summer 2019. The Advanced Spacecraft Energetic Non-Toxic (ASCENT) monopropellant propulsion system was tested using five Aerojet Rocketdyne GR-1 thrusters and operated on a 160 kg spacecraft. This was first time in 50 years that NASA tested a new, high-performing monopropellant in space.[10] GPIM conducted over 40 orbital maneuvers to test the new technologies and ultimately demonstrated a 50% increase in gas mileage compared to commonly used spacecraft fuel. After a series of deorbit burns, the small spacecraft safely re-entered Earth's atmosphere early October 2020.[10] This achievement has paved the way for NASA's acceptance of ASCENT monopropellant in upcoming smallsat missions, and NASA's Lunar Flashlight mission will also utilize ASCENT monopropellant.

Table 1: Comparison of Smallsat Propulsion Flight-Demonstrated Technology

Propulsion System *Type*	2018 status (TRL 5-6)	**2020 status** **(TRL 7-9)**
GR-1 by Aerojet *Chemical*	Scheduled to launch 2018-2019 on Green Propulsion Infusion Mission a GR-1 thruster TRL 5-6	Launched five GR-1 thrusters summer 2019, operated successfully
Enpulsion Nano FEEP *Electrospray*	First space demonstration of thruster early 2018.	Several more smallsat demonstrations have taken place.
Comet-1000 and -8000 by Bradford Space *Chemical (Water-based electrothermal)*	Both systems have expected launches for mid-late 2018.	Multiple successful launches of the Commet-8000 with BlackSky smallsats; Multiple successful launches of the Comet-1000 on the HawkEye 360 3U

		clusters.

ENGINEERING-TO-FLIGHT TECHNOLOGY (TRL 5-6)

The continued development of electric propulsion and the prospect at the number of demonstrations expected by the end of 2021 have made a sizeable leap forward in the maturity of this technology. Once a space demonstration is achieved, electric propulsion will be favored for orbits beyond Earth (i.e., lunar or heliocentric) on a smaller platform.

In 2019, three companies received a NASA Tipping Point award to design, fabricate, test, and perform mission operations using a developed propulsion system: Accion Systems, Inc (Boston, MA)., ExoTerra Resource (Littleton, CO), and Champaign-Urbana Aerospace in Illinois. Additionally, multiple smallsat propulsion missions are expected for in-space demonstrations by the end of 2021. Table 2 lists the various propulsion systems with their respective 2018 and 2020 development status.

Accion Systems and NASA's Jet Propulsion Laboratory have partnered to mature a propulsion system to demonstrate the same capabilities as those required for the Mars Cube One (MarCO) mission, but with a smaller and lighter system that uses less power. The second generation of the Tiled Ionic Liquid Electrospray (TILE) thruster by Accion could enable more science opportunities with these small, flexible platforms. As part of the tenth round of the CubeSat Launch Initiative (CLSI), BeaverCube is a 3U CubeSat that will demonstrate TILE-2 electrospray propulsion on the Educational Launch of Nanosatellites (ELaNa) 36 mission planned to launch in 2021.[11-13]

The 12U Courier Solar Electric Pressure (SEP) spacecraft bus developed by ExoTerra will demonstrate their SEP system by spiraling to 800 km from a drop-off orbit of 400 km and then deorbiting. The complete system includes its Halo micro hall-effect thruster, propellant distribution, power processing unit and deployable solar arrays, and is expected to operate in space in December 2021.[14-16] CU Aerospace was selected for two of their electrospray micro-propulsion systems that will be integrated on the Dual Propulsion Experiment (DUPLEX) 6U CubeSat mission; one Monofilament Vaporization Propulsion (MVP) [17,18] and one Fiber-Fed Pulsed Plasma Thruster (FPPT)[19-21] In-orbit operations will include inclination change, orbit raising and lowering, drag makeup, and deorbit burns demonstrating multiple mission capabilities with approximately 20 hours of operation for MVP and >1,000 hours for FPPT. Launch is anticipated in mid-2022.[21]

Aurora Propulsion Technologies will demonstrate their Aurora Attitude and Orbit Control System (AOCS) and Plasma Break Module (PBM) on AuroraSat-1, a 1.5U CubeSat that is expected to launch as a rideshare into a 550 km sun synchronous orbit in July 2021.[22] Integrated in the AOCS are six resistojet thrusters for full 3-axis attitude control and 70 grams of water propellant.[23] The PBM is a tether used for actively deorbiting the spacecraft post-mission.

CubeSat Proximity Operations Demonstration (CPOD) is a mission led by Tyvak Nano-Satellite Systems, Inc., and incorporates a micro CubeSat cold gas propulsion system built by VACCO Industries Inc. It has gone through extensive testing at the US Air Force Research Lab and endurance tests consisted of more than 70,000 firings. This mission is expected to launch in 2021.[24,25]

NASA Ames Research Center and NASA Glenn Research Center are working on the Pathfinder Technology Demonstrator (PTD) missions which consist of a series of 6U CubeSats that will be launched to test the performance of new subsystem technologies in orbit. Tethers Unlimited, Inc. has developed a water electrolysis propulsion system called HYDROS-C suitable for nanosatellites that was selected for the first PTD CubeSat mission that launched January 24, 2021.[26]

Table 2: Comparison of Smallsat Propulsion Engineered-to-Flight Technology

Propulsion System *Type*	2018 status (TRL 4 – 5)	**2020 status** **(TRL 5-6)**
Micro CubeSat Propulsion System by VACCO *Chemical*	Endurance tests consisted of more than 70,000 firings	Expected to launch in 2021 on CubeSat Proximity Operations Demonstration 3U spacecraft
All Artemis I 6U propulsion systems, **see Table 3**	Expected to launch late 2018	Expected to launch late 2021
HYDROS-C by Tethers Unlimited *Chemical*	planned for launch early 2019	Launched Jan 2021 on PTD-1
TILE-2, -3 by Accion Systems *Electric*	Has info on an obsolete product (TILE-5000)	Expected to launch BeaverCube (expected launch in 2021), and DUPLEX 6U mission (2021 launch)

The twelve 6U secondary payloads on NASA's Artemis I that will carry on-board propulsion systems have undergone extensive testing the past few years and some started qualification testing in the fall of 2020. The propulsion systems on these CubeSat missions are beyond the in-development phase and are now being engineered-to-flight, unlike their status in 2018. Table 3 describes the propulsive system to be demonstrated on each mission. The launch of these spacecraft will not only greatly improve research in their respective mission objectives but will also verify the development of several types of smallsat propulsion systems.

Table 3: Twelve Artemis I 6U Spacecraft Propulsion Systems

CubeSat Payloads & ***Propulsion Type***	**Propulsion Payload**	**Ref**
TeamMiles *Electrical Prop*	Twelve ConstantQ iodine-propellant thrusters made by Miles Space to provide primary propulsion as well as 3-axis control	27,28
Cislunar Explorers *Chemical*	Water electrolysis system developed by Cornell University	29,30
Biosentinel *Chemical, Cold gas*	ACS cold gas propulsion system developed by Lightsey Space Research	31
Lunar Flashlight *Chemical, monopropellant*	Pump-fed system that has four 100-mN ASCENT thrusters	32
LunIR (SkyFire) *Electrospray*	Demonstrate electrospray propulsion to lower the spacecraft's orbit	33
CubeSat for Solar Particles (CuSP) *Chemical, Cold gas*	Micro-Propulsion System (MiPS) (VACCO Industries)	34
NEA Scout *Propellant-less, solar sail & chemical, cold gas*	(Primary) 85 m^2 solar sail & (secondary for steering) VACCO cold gas MiPS	35
Lunar IceCube *Electric, Gridded Ion* Thruster	Busek BIT-3 propulsion system with solid iodine propellant	36,37
Lunar Polar Hydrogen Mapper (LunaH-Map) *Electric, Gridded Ion Thruster*	Busek BIT-3 propulsion system with solid iodine propellant	38
EQUULEUS *Chemical, warm-gas propulsion system*	AQUARIUS (AQUA ResIstojet propUlsion System) propulsion system consisting of eight water thrusters also used for attitude control and momentum management	39
OMTENASHI *Chemical*	Solid rocket motor slow the nano-lander as it descends to the Moon	40
ArgoMoon *Chemical, monopropellant*	Micro Propulsion System (MiPS) by VACCO	41

CONCLUSION

The past few years have witnessed a giant leap forward in small spacecraft propulsion, particularly EP technology. Given that the previous decades of EP research have been directed at the proliferation of these thrusters, recent in-space demonstrations on smallsats have become more prevalent. The number of smallsat propulsion missions has increased and a variety of technology have been demonstrated and researched. Hall-effect thrusters have seen a rapid expansion in smallsat missions with the support and increased interest in smallsat constellations. The demonstration of high-performance monopropellant on GPIM paves the way for upcoming missions beyond Earth orbit. The next step will be to identify remaining challenges related to the operation of mature technologies and to increase the number of in-orbit demonstrations on nanosatellites.

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