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Additively Manufactured Propulsion System

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ABSTRACT

New high-performance, carbon-fiber reinforced polymer material allows additive manufacturing to produce pressure vessels capable of high pressures (thousands of pounds per square inch). This advancement in turn allows integral hybrid propulsion which is revolutionary for both CubeSats and additively-manufactured spacecraft. Hybrid propulsion offers simplicity as compared to bipropellant liquid propulsion, significantly better safety compared to solid or monopropellant hydrazine propulsion, and much better performance than cold-gas or hydrogen peroxide monopropellant propulsion. The safety benefits are especially important for CubeSats because they are generally secondary payloads whose impact on primary payload operations must be minimized. The possibility of safe, high-performance, high-thrust propulsion opens up a huge variety of possible mission scenarios previously unavailable to CubeSat spacecraft. In addition, a "printed in" cold gas attitude control system that draws its propellant from the main thruster's oxidizer tank allows spacecraft pointing, midcourse corrections, and proximity operations with little reduction to the available spacecraft volume. With the advancement in additively manufactured propulsion, CubeSat-sized spacecraft can offer real responsive space capabilities never before possible.

INTRODUCTION

Safe, high-performance primary propulsion and orbital maneuvering systems will enable CubeSats (and other small satellites) to realize their full potential in a variety of civil and military applications. The Experimental Propulsion Lab (EPL) has been developing a high-performance additively manufactured propulsion system that would enable these small satellites to take full advantage of low-cost, responsive launches, since the satellites would have adequate propulsion to quickly move to desired orbits, even if they were launched into less-than-optimal orbits.

To achieve the full potential that CubeSats promise, they must be more mass-efficient, have increased bus power, be more cost efficient, have shorter design and build times, and have significant delta-V available. Eliminating unnecessary mass in the CubeSat structure and more efficiently using the available volume through the use of multi-functional structures is an effective way to reach these goals. Additive Manufacturing (AM) techniques enable this and revolutionize the design, fabrication, and capabilities of CubeSats. With recent advancements in high strength build materials and AM manufacturing processes, bus chassis and major components (including high pressure propellant vessels, combustion chambers, and attitude control thrusters) can be fabricated as a single, monolithic structure. This approach reduces part counts and attachment interfaces, eliminating excess mass and reducing integration and test time. Optimized designs can be created or modified rapidly to respond to changing mission requirements, and can be fabricated in a fraction of the time required for conventional satellites. Bus designs can be easily adapted to specific hardware components, enabling the latest and most capable hardware to be efficiently integrated with the spacecraft. By adapting proven designs and employing repeatable additive manufacturing processes, non-recurring engineering labor and costs are reduced and the reliability of the new designs is enhanced.

The use of AM techniques also enables unique design options to be considered for improving efficiency, options that may be difficult or impossible to implement using conventional fabrication techniques. For example, EPL is using AM to build and test hybrid (solid fuel and liquid oxidizer) thrusters employing a toroidal oxidizer tank, with the combustion chamber and solid fuel embedded in the center of the tank. AM is also used to embed propellant supply lines in the CubeSat structure itself, to feed the cold gas attitude control thrusters from the same liquid oxidizer tank used by the hybrid motor. Without the use of AM techniques, integrating “modular” propulsion systems with a CubeSat would severely limit payload mass and/or spacecraft delta-V. To further investigate the feasibility of this new design medium an additively manufactured propulsion system was developed.

PROOF-OF-CONCEPT DEMONSTRATION

In order to determine if the properties of the new high-strength material were actually suitable for a high-pressure propulsion unit, EPL designed and had manufactured a first-generation proof-of-concept engineering design unit (EDU). This process took 4 months from initial concept to functional prototype.

Figure 1 is the first known functional Additively Manufactured Propulsion System – Hybrid (AMPS-H) motor that is currently patent pending. The AMPS-H was tested during the 2010 Small Satellite conference at the Logan, Utah airport. This EDU was a proof of concept design and demonstrated the ability of the AM process to manufacturer a high performance (Isp >250s) hot gas propulsion system. The motor was static fired for 16 seconds producing 142 N-sec total impulse with a peak thrust of 6.2 lbf. Past limitations with the AM process and low tensile strength build materials did not allow for functional parts to be made that could hold high pressures and temperatures without structural failure or leaking through the part’s structure.

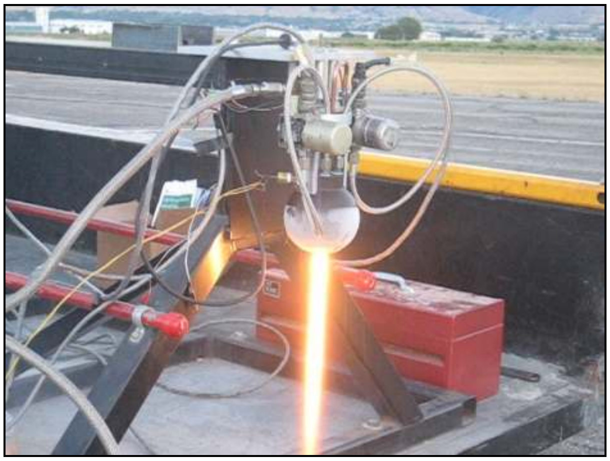

Figure 1: AMPS-H EDU Hot Fire Test

SECONDARY PAYLOAD SAFETY CONSIDERATIONS

When considering which type of propulsion system is best suited for small spacecraft application, several important issues need to be considered. Above all, safety is the primary design consideration with the propulsion system’s performance, reliability, and cost close behind. As secondary payloads, safety for the primary payload must be addressed. With stringent requirements like “secondary payloads cannot add risk to the primary payload’s mission,” small spacecraft have not been allowed any stored energy devices of any kind to be added to their designs. If launch providers and payload customers are to deviate from these “unconditional” types of safety requirements, then a strong argument must be made as to which propulsion system design is the safest, most reliable, and offers enough performance to accomplish desired mission profiles. EPL selected the AMPS-H motor design as the best option for meeting all these strict requirements. Hybrid propulsion offers many safety advantages over many other types of propulsion. First, the propellants are kept separate and typically in two different states (solid and liquid) until mixed in the combustion chamber. Second, hybrid motors are generally simpler than bipropellant liquid engines, often eliminating the need for high pressure sub-systems, multiple valve assemblies, and can use less-toxic propellants. Simplicity of design reduces the number of possible failure modes a propulsion system can experience. Furthermore, the AMPS-H motor design uses a relatively mild oxidizer, nitrous oxide (laughing gas), which is non-carcinogenic, non-cryogenic, needs no unique handling equipment, will not drip onto other components as it is a gas at ambient pressures, and is commonly used at a consumer level (propellant in whipping cream) with a low occurrence of safety problems. Nitrous oxide decomposition requires large amounts of activation energy. Tests have shown that nitrous oxide hybrid motors fail to ignite when a 12kV spark igniter is used. With the use of additive manufacturing, redundant safety features are easily added to the design without adding cost. Safety features such as double-wall pressure vessels, redundant pressure relief valves or burst disks, and even redundant interlocked oxidizer valves are all possibilities if required.

AMPS-H SYSTEM SUMMARY

The AMPS-H system consists of a monolithic toroidal propellant tank with central combustion chamber, ignition, oxidizer flow controls, and nozzle.

Ignition

For safety, all-electrical ignition is used instead of chemical ignition. An electrical current will be used to heat a uniquely designed catalyzed heat exchanger that will decompose the nitrous oxide into a mixture of hot oxygen and nitrogen gas. This hot gas will then enter the AMPS-H combustion chamber and auto-ignite the fuel grain. Once ignition is complete the electrical heater will be turned off, allowing non-decomposed nitrous oxide to continue to feed the hybrid motor. This type of ignition system is designed to be completely de-energized by triple redundant interlocks from the satellite's avionics. Only after ejection from the launch container and completion of charging of the satellite's batteries will this ignition system have enough energy to ignite the AMPS-H motor. This type of ignition system is safe and reliable as it is based on the same proven principles that are used in a hydrazine mono-propellant thruster, where a heated catalyst bed design is used to decompose the hydrazine. If the catalyzed heat exchanger doesn't reach temperatures that enable nitrous decomposition, the hybrid motor will not ignite and the injected nitrous would act like a warm gas monopropellant. Multiple motor restarts which are an essential element of any small satellite propulsion system are easily made available with this type of electrical ignition design.

Design Simplicity

As a general rule, simpler systems tend to be more reliable because they have fewer failure modes. The AMPS-H motor design is very simple because the AM process makes 80 percent of the hardware needed as a single monolithic part (see Figure 2). By integrating the major elements of a hybrid motor (oxidizer tank, fuel grain, forward and aft combustion chambers, igniter port, oxidizer tank fill port, injector port, and safety relief valve port), several types of potential failure modes cease to be possible. Design changes are easily managed by modifying the CAD drawing file. Finite Element Analysis (FEA) can quickly be performed as 80 percent of the design is a single "printed" part with few fastener interfaces to analyze.

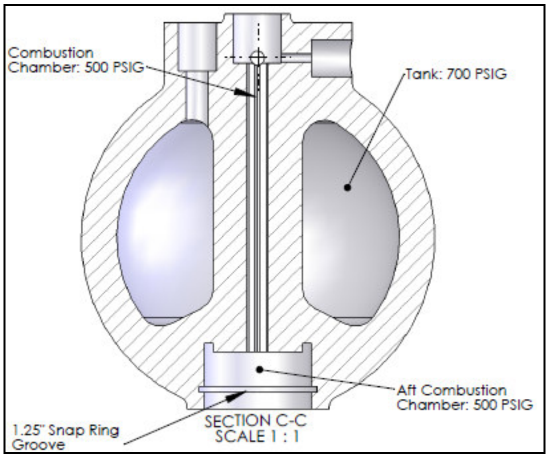

Figure 2: Single Monolithic AMPS-H Motor

AMPS-H Performance

Propulsion performance is another crucial aspect of any spacecraft as it determines the type of missions it can perform. Motor performance, and how it is used in the production of delta-V for the satellite, is generally measured in terms of specific impulse and propulsion system thrust-to-weight ratio. Propulsion systems that have high specific impulse (i.e. ion, plasma, electro spray, etc) are very efficient but usually require long "burns" to build up sufficient delta-V. This often limits the functional life span of the small satellite as they require increased amounts of time to position the satellite in the desired orbit. High thrust/weight propulsion systems on the other hand have the ability to quickly perform orbital maneuvers and position the satellite in the desired orbit. The AMPS-H motor is a high thrust/weight ratio propulsion system with a vacuum Isp > 270 s. With this level of performance, the AMPS-H motor can truly enable small satellites to be operationally responsive by delivering the satellite in its desired orbit in a timely manner. In addition to the AMPS-H motor's performance and safety attributes, the AMPS-H motor has the ability to be completely customizable through the AM process to meet many small satellite mission requirements. Adjusting the motor size adds little cost and time to development schedules.

AMPS-H Engineering Design Unit

The first step EPL took in the investigation of using additive manufacturing to produce a propulsion system was to build a 1U Engineering Design Unit. The AMPS-H EDU was a 10 cm sphere that simulated a possible 1U form factor propulsion system. The AM process used a high strength carbon-fiber filled nylon plastic to produce the AMPS-H motor's oxidizer tank, combustion chamber, and fuel grain as a single monolithic part. With limited volume to work with, the combustion chamber, fuel grain, and nozzle were located inside the oxidizer tank making for a very energy dense design. The fuel grain was "printed" in as part of the hybrid motor's combustion chamber design, eliminating possible leak paths and the need for secondary fuel grain casting operations. Hydrostatic proof pressure testing of the nitrous oxide tank was performed to insure both that the AM part could hold pressure without leaking through the wall of the structure and to verify that the material properties were sufficient to yield a 1.5 factor of safety. Ground support valves were used to load propellant into the spherical tank and then to inject the oxidizer into the combustion chamber. Several cold flow tests were performed to verify flow rates through the injector. These cold flow tests also allowed for the AM nitrous oxide tank to experience real temperature environments that are seen when filling a tank with nitrous oxide. Temperatures as low as -80 ºF can be seen during this filling process. The AMPS-H motor also employed an EPL-manufactured ablative silica phenolic nozzle. This embedded nozzle was designed not only to handle the high temperatures of combustion (> 4000 ºF) but to prevent the heat transfer of those high temperatures to the AMPS-H motor tank wall (see Figure 3). A single-use chemical igniter was employed to start the motor, with the burn time lasting 16 seconds. Chamber pressure measurements were taken during motor firing with a peak chamber pressure of 570 psig (see Figure 4).

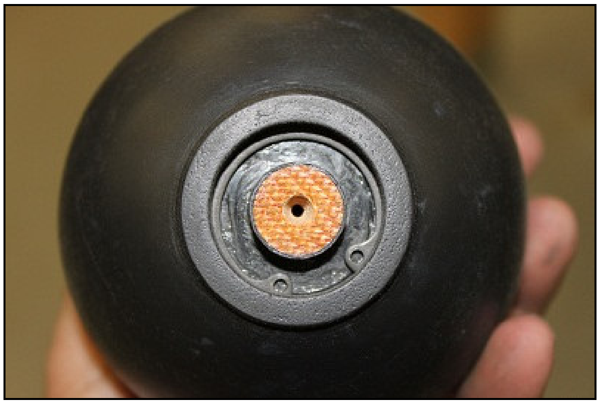

Figure 3: Silica Phenolic Ablative Nozzle

With the data gathered from these tests, EPL had enough justification to further investigate expanding the idea of using the additive manufacturing process to produce an integrated high thrust-to-weight, high delta-V thruster, bus chassis, and cold gas thruster RCS system as a single monolithic part.

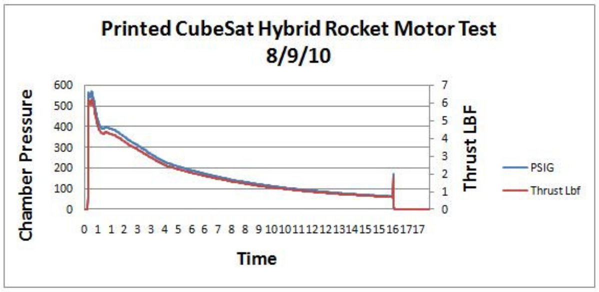

Figure 4: AMPS-H Motor Chamber Pressure Plot

CURRENT DEVELOPMENT

AMPS-H Integrated into a 6-U Chassis

EPL is currently developing a 6U AM bus chassis with an integrated AMPS-H high thrust-to-weight, high delta-V motor and cold gas reaction control system (RCS). This 6U bus chassis will allow for 2.5-3U of payload volume and will be able to produce a delta V of 784 m/s (6U has a density of 1.3kg/U, propellant mass = 2kg). A 6U Engineering Design Unit (EDU) (see Figure 5) is in development and will be used to demonstrate and qualify the AMPS-H motor and cold gas RCS performance. The EDU will be subjected to hot fire testing including demonstrating multiple restarts, RCS firings, and thermal vacuum testing including thermal cycling to the predicted orbit thermal environments.

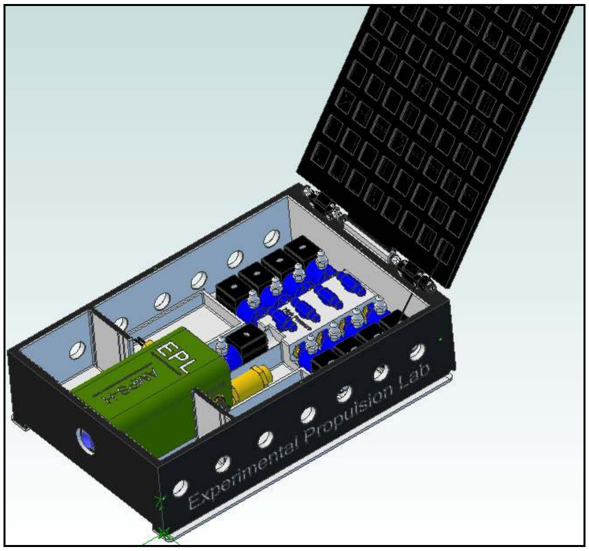

Figure 5: 6U Engineering Design Unit With Solar panel and cold gas RCS

Present efforts are focused on optimization of the motor structure. A new 1.5U AMPS-H motor design has completed hydro burst testing where failure of the nitrous oxide tank occurred at 2,226 psig. At this pressure, and with nitrous oxide as the oxidizer in the tank, the factor of safety for the design is 2.45. Such a high factor of safety may not be required for flight designs but the test provided useful insight into the capability and flexibility of the AM process to produce high pressure leak free vessels. In addition, the burst test article was used to correlate real test data to the finite element analysis (FEA) model. The FEA was able to predict failure within 3% of actual measured stress/strain and accurately predicted the failure mode (see Figures 6 and 7).

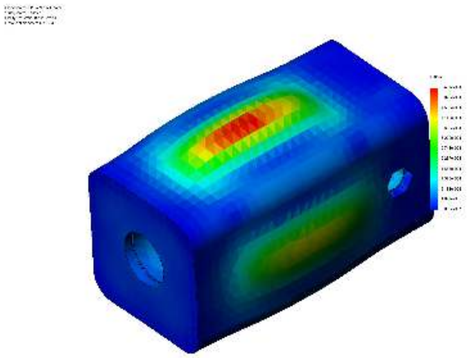

Figure 6: Finite Element Analysis Model

Figure 7: 1.5U AMPS-H Motor FEA and Burst Test Article

Restartable Electric Ignition

In a parallel development effort, a non-chemical-based, restartable igniter was deemed critical to the success of the design.

Motor restartability is a key element of the propulsion design, since most orbit changes and maneuvers require at least two separate motor firings. While nitrous oxide offers many advantages as an oxidizer, the high activation energy required for decomposition can make motor ignition more difficult, especially if the goal is to avoid chemical ignition for safety considerations.

Several design concepts were developed and tested yielding various results. From these tests it became clear that the final igniter design needed to be safe, small, and reliable. With the previous igniter test data, the team was led to develop a unique catalyzed heat exchanger that would decompose the nitrous oxide into a mixture of hot oxygen and nitrogen gas. This mixture of hot gas would then auto ignite the solid fuel grain. Electrical power requirements for the design are still under development and will be quantified during the test phase of the program. The first igniter test article is currently undergoing development and testing.

MISSIONS EXAMPLES ENABLED BY AMPS-H TECHNOLOGY

Mission Applications

The combination of additive manufacturing and high-impulse maneuvering in a small satellite opens up many mission scenarios. The small size and mass of the satellites enables many to be launched as secondary payloads on a large launch vehicle or as dedicated payloads on a small launch vehicle. Additive manufacturing allows the satellite bus to be manufactured in near-real time, with modular sensor or other packages installed as needed. High-impulse maneuvering enables rapid deployment into the desired orbit, rendezvous, proximity operations, constellation management, or other operations.

Mission Applications Example #1:

Intelligence assets have picked up communications that indicate a high value target will be relocating to a new base of operations. It is decided that twelve Maneuverable Rapid Response satellites (MRRSats), six with signal intelligence sensors and six with electro-optical sensors, will be manufactured and loaded onto a F-22-mounted small launch vehicle for launch in 5 days. They are to be launched into an orbit whose ground track is to cover the target area at the expected movement time. In order to maximize coverage, after the satellites are placed in orbit, they will perform propulsive burns to put them into phasing orbits. After the required number of phasing orbits, the satellites perform burns to return to the original orbit but spaced apart within that orbit. Within approximately 24 hours, all of the satellites are spaced out every 30 degrees in the orbit, alternating between signal intelligence and electro-optical models. This spacing of 7.5 minutes between the satellites greatly increases the chance of getting valuable intelligence data when the target area passes under the orbital track every twelve hours. For additional coverage, additional constellations of satellites with different orbital ascending nodes could be added. When the satellites have completed their missions, they conduct deorbit burns so as to not pose an orbital debris hazard.

Mission Applications Example #2:

Orbital assets have picked up the launch of a satellite from an uncooperative state. NORAD has established orbital parameters but little else is known about the satellite. A scaled-up MRRSats, with intelligence sensors and significant propulsion capability, is installed on an F-22-mounted small satellite launcher. It is launched into an orbit closest to the target orbit as allowed by the launch vehicle. The MRRSats then conducts high-impulse burns to reach the target orbit and quickly rendezvous with the target satellite. It performs proximity operations around the satellite, gathers the desired intelligence information, relays it to other orbital assets or ground stations, and then performs a burn to deorbit and incinerate in the atmosphere.

Mission Applications Example #3:

Changes in the primary and secondary payloads on an upcoming launch have opened up a low-cost ride for small microsats if they can be ready in time. They will be placed into a low-perigee orbit which will decay in days due to atmospheric drag. Several MRRSats are manufactured and test payloads are incorporated into the bus design. When the satellites are deployed, they use their high-impulse propulsive capability to raise the orbit perigee to an altitude where drag is greatly reduced. This allows them to test their payloads for over a year. At the end of the mission, they perform deorbit burns to eliminate orbital debris issues.

CONCLUSIONS

Additively manufactured small satellite bus chassis with high delta-V capabilities could enable new missions never before possible for small satellites. The design and development of science based cubesat missions would be accelerated, reducing labor costs and improving mission affordability. LEO satellites in high-drag orbits could increase their time on orbit, enhancing their scientific value. cubesats could utilize more launch opportunities that offer less than desirable initial orbits as the ability to rapidly move to more optimal orbits is now possible with the AMPS-H motor. The AMPS-H high delta-V propulsion system offers many safety features for small satellites. These safety attributes may help to justify adding propulsion to secondary payload spacecraft.

EPL is actively undergoing qualification testing of the AMPS-H motor to increase the NASA Technology Readiness Level (TRL) from its current level of 5 to 6. Once qualification testing is complete, EPL will be looking for flight opportunities to further increase the AMPS-H motor's TRL.

ACKNLOWLEDGMENTS

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