Developing a Plunger-based Liquid Propellant Delivery System for CubeSat Propulsion

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Abstract

The Aerospace Center at the University of Texas at El Paso is currently developing a low-cost 1-N propulsion module for use in 6U CubeSats. This module uses the liquid monopropellant AF-M315E. The fuel delivery system was identified as a subsystem that could be targeted for cost reductions. The current design, which is expected to be tested throughout Summer 2022, uses a plunger-based propellant delivery system instead of a pressurized fuel compartment. Challenges and solutions the team faced are outlined, starting with an overview of the design, then organized by the process of delivering fuel, thermal considerations, interaction with Attitude Determination and Control System (ADCS), material compatibility, ensuring sufficient fuel capacity is in the design, manufacturing, and avionics.

Introduction

CubeSats are a standard for small satellites developed by CalPoly, with each unit (or U) measuring 10 cm x 10 cm x 10 cm. Relatively low price and complexity of CubeSats have led to an increase of popularity in recent years. As their popularity continues to grow demand for propulsion systems with higher delta-V has increased to expand the capabilities of CubeSats. [1] Higher delta-V capabilities would be able to reach higher orbits and greatly increases the versatility of CubeSats. Hydrazine has been a commonly used monopropellant for small satellite propulsion but is known for its high toxicity. In response to the toxic nature of hydrazine, the Air Force Research Laboratory developed the green monopropellant called AF-M315E, also known as ASCENT. In addition to its lower toxicity, AF-M315E has a higher theoretical specific impulse and density than hydrazine. Its significantly reduced toxicity allows for easier storage and handling which could potentially reduce launch processing times and costs. [2] The Aerospace Center located at the University of Texas at El Paso is currently developing an AF-M315E based propulsion module for use on 6U CubeSats. This module, referred to as the Green Monopropellant Engine (GMPE), uses a 1-N thruster and a catalyst previously developed and tested by the Aerospace Center. Market research found that the high cost of propulsion modules is a major concern for universities and small institutions planning CubeSat missions, so the vision for the GMPE is to provide a lower cost solution for CubeSat propulsion.

About the GMPE

While the module's design is still in development, a central feature is the plunger-based fuel delivery system. A CAD image of the current GMPE design is shown in Figure 1, while Figure 2 shows a more detailed design from a previous iteration. Both figures show the fuel tank, electronics compartment, satellite bus interface, and thruster positioning. The outer walls are transparent in both figures to allow for a view of the internal cavities.

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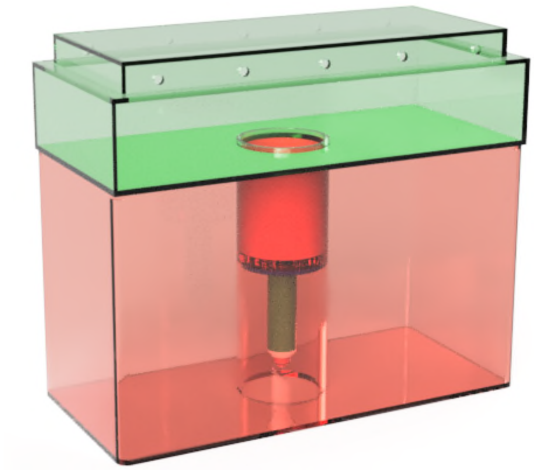

Figure 1. Rendered image showing layout of current GMPE design. The fuel tank is the red region, the electronics compartment and satellite bus interface are at the green region, and the thruster can be seen in the center of the module.

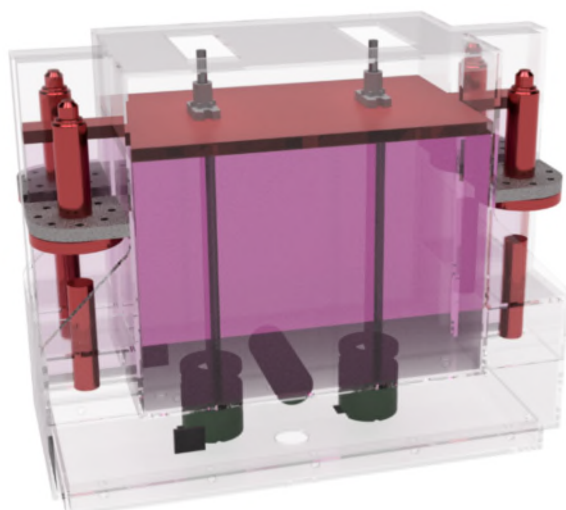

Figure 2. Rendered image of previous GMPE design with four thrusters. The plunger mechanism is shown in red, with AF-M315E being shown in magenta. Motors, valves, and electronics are shown in green.

Liquid propellants can be difficult to manage in micro-gravity, but a plunger-like fuel delivery system removes some of the challenges normally faced. For example, the plunger system does not require pressurant gas to move the fuel. Removing the need for a pressure vessel increases the space available for more fuel or additional equipment. Similarly, the fuel's flow rate and remaining volume can be easily monitored through the speed and location of the plunger. The plunger operates by using a motor driven piston to decrease the volume of the tank, while simultaneously forcing propellant through feed lines. The piston will be attached to two threaded rods which will be spun by the motors that raise or lower the piston, like how a 3D printer might raise and lower a gantry. Similar systems are commonly used on Earth in laboratory applications. They are particularly useful in applications requiring a well-controlled volumetric flow rate. As previously mentioned, using this system removes the need for flow meters and sensors monitoring remaining fuel in the module's tank simply by using an encoder on the lead screws. Thermocouples and pressure transducers allow for close monitoring the conditions inside the fuel tank. Although the GMPE team was unable to find literature regarding use of motor-powered piston-based fuel delivery systems, previous laboratory testing successfully used a syringe pump for hot fire tests. A summary of major requirements for the GMPE are listed in Table 1.

Table 1. Summary of major requirements for the GMPE.

Requirement	**Notes**
The GMPE SHALL have fully autonomous operations.	The module will have communications with the satellite bus, but not with a ground station.
The GMPE SHALL be able to complete mission with ADCS tolerances of 0.2° to 6°.	Based off tolerances from commercially available CubeSat ADCS.
The GMPE SHALL raise the temperature of the satellite bus no more than 5°C at any time.	
The GMPE's tank SHALL keep the AF-M315E at a temperature between -80°C and 140°C at all times.	Range between glassing and autoignition for AF-M315E.
The GMPE SHALL provide a maximum Delta-V to a 6U CubeSat of 515 m/s.	

Additionally, a brief breakdown of expected costs for the testbed version of the GMPE by subsystem are listed in Table 2.

Table 2. Expected cost of testbed GMPE prototype by subsystem.

Subsystem	**Cost, USD**
Thruster	$2,000
Tank, fuel delivery	$2,300
Heater	$200
Electronics, sensors	$2,000
Thermal Insulation	$800
Total	$7,300

Fuel Delivery

One of the first concerns was that of cantilevering. If the plunger becomes uneven, not only would the predicted tank status become inaccurate, but there would also be the possibility of fuel leaking through a gap in the seal. This issue will be mitigated with the set of threaded lead screws controlling the plunger. One lead screw will be a right-handed screw while the other will be a left-handed screw. Because the lead screws are equidistant from the module's center of mass and will be moving at the same rate and timing, no net angular momentum will be generated from the movement of the lead screws.

Another issue that soon arose was that of possible hydraulic locking, also known as hydrolock. A few steps were taken to mitigate the possibility of hydrolock in the GMPE. First, the tank's total volumetric capacity was made to be larger than the maximum initial fuel volume that would be loaded into the tank. This additional volume was calculated by estimating the thermal expansion of AF-M315E at in the worst-case scenario of reaching 140°C, at which autoignition becomes the primary concern [3]. Then, by monitoring the temperature and pressure inside the fuel tank, adjustments can be made to the position of the piston to accommodate the expansion of the fuel.

Pressure drawdown was a major issue that arose when the team decided to remove pressurant gasses from the system. If the backside of the plunger is in a sealed space, the pressure drawdown from moving the plunger down would quickly overtake the force the motors could exert on the plunger. The team considered using a volatile fluid, such as acetone, to fill a buffer space above the plunger, as shown in Figure 3. As the volume in the buffer zone would increase, the fluid would evaporate and pressurize the buffer space, reducing the effect of the pressure drawdown. The team found that this solution would not entirely fix the drawdown issue. Instead, the backside of the plunger will be exposed to the vacuum of space. With this setup, the plunger will be working with the vacuum rather than against it during hot fires.

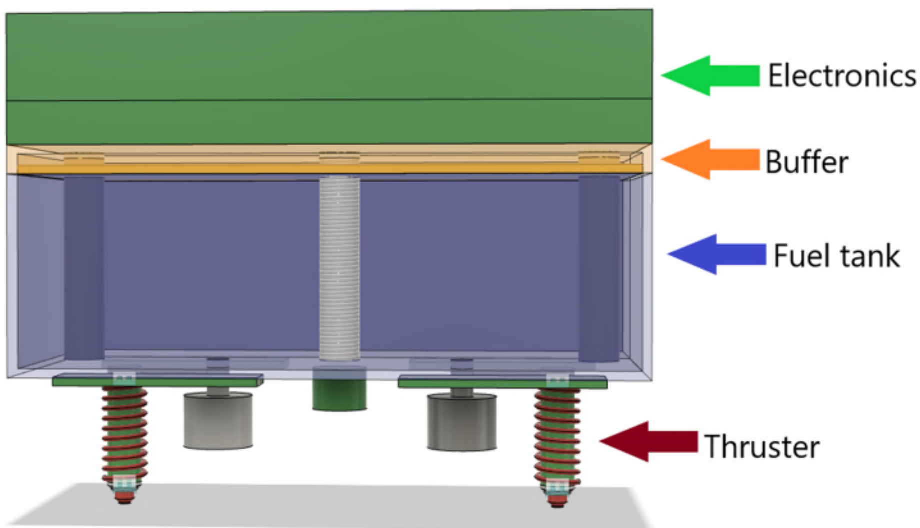

Figure 3. Diagram depicting the proposed buffer area in an earlier GMPE design.

Next, the team had to ensure that the motors controlling the lead screws would be able to provide sufficient torque to move the plunger. In addition to this, encoders on the motors would have to provide a high enough resolution so that the tank's status could be properly monitored. First, the motor's torque output, T, the diameter of the shaft, d, gear reduction, N, and efficiency, η were used to find the motor's force output, F. This was done using Eq. 1.

$$F = \frac{T}{d} N\eta \qquad \text{Eq. 1}$$

A higher gear reduction ratio reduces the maximum speed of the motor but allows it to provide a higher force to the plunger. To ensure the new speed of the motors would still be high enough to provide the necessary flow rate, the speed at which the plunger would need to move was found. The speed at which the plunger would need to move along the vertical axis, v_{va}, was found using the volumetric flow rate, $\dot{V}$, and the plunger's surface area, A, using Eq. 2.

$$v_{va} = \frac{\dot{V}}{A} \qquad \text{Eq. 2}$$

The conveying speed of the lead screws, v_c, was then used to find the maximum required rotations per minute, RPM, that the motors would need to provide. This was found with Eq. 3. The resulting RPM value was then compared to the manufacturer's specifications for the gearmotor in consideration.

$$RPM = \frac{v_{va}}{v_c} \qquad \text{Eq. 3}$$

Thermal Considerations

Because of the high temperatures at which AF-M315E decomposes, careful consideration was given to the thermal aspects of the design. First, an analysis using AGI's STK software was conducted to estimate the range of temperatures the GMPE might experience during a mission. Then, a thermal analysis of the module was conducted to find the maximum temperature it would reach with no thermal insulation. The setup to this problem is shown in Figure 4. Because the resulting tank temperature was above AF-M315E's autoignition temperature, layers of insulation were added to the design until a satisfactory maximum temperature was obtained. This was achieved with 15 layers of MLI, for a maximum temperature of around 32°C at the boundary between the MLI and wall.

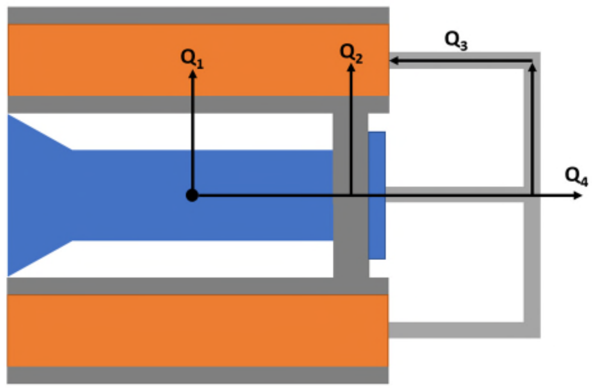

Figure 4. Setup for thermal analysis for the GMPE, seen in a cross-sectional view of the module. The propellant tank is shown in orange, while the thruster is shown in blue. Gray lines represent walls and fuel lines.

Other Considerations

Considering the small size of a CubeSat, saturation of the ADCS must also be taken into account. Due to the placement of the thruster, three different torque cases can arise due to misalignment. The first is the simplest case where no misalignment is present, and no torque is created as the force passes through the center of gravity. Misalignment in one plane (Figure 5) is referred to as "simple misalignment" while a misalignment in two planes is referred to as "complex misalignment." These misalignments are likely to occur as a result of slight imperfections during the manufacturing process. The exact extent of these misalignments will depend on the tolerances used when manufacturing the thruster, tank, flange, and feedlines.

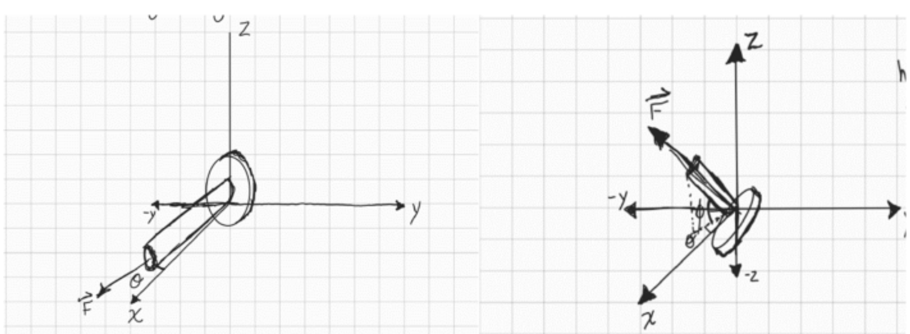

Figure 5. Simple (left) and Complex (right) misalignment depictions

The torques created will depend on which case is encountered once the module is manufactured. Each case will result in different allowable firing durations. While users would be free to add additional equipment to the satellite bus for further desaturation to achieve longer firing durations, the module was designed with the assumption of only having the rotation wheels as a desaturation device.

Additionally, selection of materials is a crucial step in the development of the propulsion module. Two main sections can be identified: wet and dry. Wet interfaces refer to portions that will be in contact with the propellant, such as the propellant tank and feed lines. Since the propellant is corrosive, only certain materials can be used in this section. Proven compatibility of stainless steels series 300 and Ti 6Al-4V with the propellant can expedite the material selection process [4]. If the system requires a different material for any wetted components, it is highly recommended to avoid Fe, Ni, Cu, and some transitions metals, since these could decompose the propellant and hinder performance [3]. For any other dry component, depending on the mass budget, aluminum is an excellent choice due to its low density.

Manufacturing proved to be more difficult than initially expected. The nature of the design relies on a uniform and even tank design and any deviations could lead to increased resistance on the plunger mechanism or, with enough imperfections, a complete loss of function for the plunger. Another point of concern is the pointing accuracy of the thruster. Ideally the thruster is pointed axially such that it does not create any torque, as mentioned in the ADCS section, however this is extremely difficult and costly to achieve. The design must therefore carefully balance small tolerances with the available budget for manufacturing.

Conclusion

The development of a plunger-based propellant delivery system as opposed to a traditional pressurized propellant delivery system has led the development team to encounter a variety of important considerations. Issues such as hydraulic locking, cantilevering, ensuring sufficient motor torque, thermal management, and selection of compatible materials have been addressed. Additionally, although the plunger-based delivery system requires unique support equipment of its own, the team found it to be more compact than what as anticipated for a pressure-based fuel delivery system. As the prototype phase of the project approaches, these key lessons will be used to continue to improve the GMPE design.

References

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