Cislunar Explorers: Lessons Learned from the Development of an Interplanetary CubeSat

Cislunar Explorers is a student-run mission to build and launch a pair of -3U L-shaped lunar orbiters (named Hydrogen and Oxygen). It will be launched as a single 6U CubeSat as part of NASA’s Artemis-1 mission (formerly known as Exploration Mission One or EM-1) on the Space Launch System (SLS). As part of the CubeQuest Challenge, the mission is competing for the Lunar Derby and Spacecraft Longevity prizes by reaching and maintaining a circular orbit around the Moon. After separating from each other, both spacecraft will demonstrate water electrolysis propulsion, multibody optical navigation, passive spin-stabilization, and the operation of femtosatellites below low Earth orbit.

Water Electrolysis Propulsion Operation
Two electrolyzers, located in the water propellant tank, produce gaseous hydrogen-oxygen mixture from the water which is directed through the flame arrestor into the combustion chamber. When the system reaches its critical pressure, a glow plug is activated, which ignites the gaseous mixture. This is ejected through a nozzle, producing thrust. This process can continue as long as there is sufficient water for the electrolyzers to produce gas. One of the main advantages of this system is that it utilizes passive pressure-bearing components. The flame arrestor and check valve are pressure-driven, unpowered devices that inhibit the flow of hydrogen and oxygen from the combustion chamber before performing a burn. The propulsion system consists of a series of terrestrial vacuum-sealed components to carry the gaseous products of the electrolysis process.

Optical Navigation Operation
The Op-Nav System provides autonomous position and attitude determination using low-cost optics and minimal computing power. The spacecraft relies on three onboard cameras to obtain images of the Sun, Moon, and Earth. The software analyzes these images to determine the apparent distance and body center. These measurements are compared with a table of ephemerides and unit vectors to each celestial body in the spacecraft body frame are generated. These measurements are used to create a transformation from the spacecraft body frame to an Earth-Centered Inertial frame. Position, velocity, and attitude determination are performed by a pair of Unscented Kalman Filters. A three-axis gyroscope provides spin measurements for attitude propagation. These quantities are telemetered to the ground station for planning open-loop reorientation maneuvers to align the main thrusters in the direction required by burns during the mission. There is less than 100 km expected error by end of mission.

Subsystems complement each other to reduce the cost and complexity. Water not only serves as the propellant for the propulsion system, but also as a radiation shield, electronics heat sink, and nutation damper. Each spacecraft’s spin provides attitude stabilization, separates electrolyzed gas from the water in the propulsion tank, simplifies the active attitude control system, and enables the optical navigation system to cover a panoramic view around the spacecraft.

3D printed titanium water tank with internal electrolyzers

Challenges and Lessons Learned
Software:
- Increasing complexity due to pushing functionality to meet autonomous real-time mission operation requirements.
- Difficulty designing easily testable flight software.
- Development complications were brought on by unnecessary features when implementing open source flight software frameworks.

Hardware:
- Delays due to long turn around times for outsourced production of vacuum compatible plastic and metal 3D printed materials.
- Metal 3D printed parts while providing optimized designs and easier integration ended up proving to be a constant source of cost overruns and schedule delays due to excessive and specialized post machining due to:
  - Errors and tolerancing issues on component and complex features were missed on delivery inspection.
  - Post machining on weld hardened material.
- Difficulty in sealing vacuum fittings that interfaced with the material.

Programmatic:
- Creating viable low energy trajectories was labor intensive, required significant time, and had to be redone with every launch delay.
- Getting earlier experience with chosen hardware would have reduced late-stage risk. Hardware “quirks” that required operational changes to work around manifested late in development.
- As observed with other academic programs, student turnover over such a long development period led to unnecessary repeated work and periods of uncertainty over past design, requirements, and trade outcomes. “Second system” decisions that broke continuity or complicated the onboarding process had long-lasting negative effects on productivity.

Conclusions
Interplanetary space exploration brings some of the most complex engineering requirements for smallsats to date. Technical and development problems were documented for the wider scientific and academic community to learn from. See the submitted paper for more in-depth information.

Acknowledgements
- The National Space Society for their guidance and support
- NASA’s Space Technology Mission Directorate and Centennial Challenges Program Office Staff
- Kyle Doyle, Courtney Rials and Dean Lander for their contributions
- Cornell University student team members past, present and future

Authors: Aaron Zicherman, Kelly Jawork, Aaron Buchwald, Abhinav Naikawadi, Elliot Kauf, George Razoukos, and Zakoworotny. Oren Alon, Sydney Rzepka, Van Adams, Curran Mulhberger, Mason Peck

For more information contact: apv24@cornell.edu