Team Alien
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Mission Statement

- Extend the mission life of science CubeSats at very low altitudes of around 250 km.
- Reduction of orbital debris and improve mission performance due to a larger optical aperture, with a reduced cost.
- Goal was to design a 1U thruster and aerodynamic stabilization system for integration to a 3U science CubeSat as a zero-impact, add-on module.
● Over 60% of CubeSats launched by universities do not complete their mission.

● These experimental satellites are often launched into crowded orbits with large amounts of debris.

● Current means of de-orbit often require an active triggering method.

● Many stabilization systems are active or require power input, in addition thrusters also often require power to actuate.

Reduce debris through de-orbit, but maintain useful life through stabilization and thrust requirements if initialization is successful.
Background

Figure 1. Distribution of debris with concentrations at 2000 km and in geosynchronous orbit [1].

Figure 2. CanX-7 Drag Sail deorbit mechanism [3].
In order to successfully carry out this mission, specific design requirements were identified for success measurements:

1. The module shall produce enough thrust to compensate for aerodynamic drag.
2. The module shall not utilize any power beyond initial activation for expulsion of cold gas/passive aerodynamic stabilization.
3. The module shall be designed to be integrated into a standard 3U CubeSat.
4. The module shall fit within approximate 1U dimensions and the “tuna can” extensions.
5. The module shall be designed with a maximum extension of 6.5mm around the body.
6. The module shall be designed to operate for at least 7 days.
7. The thruster and aerodynamic stabilization shall be made to operate at an altitude of 250 km ± 10 km.
8. The module shall have a leak rate that prevents it from emptying in less than 100 days.
The solution would be a modular system with completely passive attitude control and propulsion with zero power consumption after initialization.

- Incorporate 4 aerodynamic surfaces.
- Utilize drag present at 250 km.
- Internal tank and nozzle/flow initialization.

Figure 3. Theoretical 1U module on a 3U CubeSat showing folding aerodynamic surfaces and thruster system.
Methodology

- Given the scope of the project, the design of the propulsive unit was split up into four primary systems:
  - Flap Design and Initialization
  - Tank Design
  - Nozzle Design and Initialization
  - Propellant Requirements/Considerations
- Each team member was responsible for a primary system.
- Each primary system was developed out of the requirements matrix shown previously.
- Utilize aerodynamic stability and two-phase cold gas propulsion system.
  - Maximize propellant utilizing liquid.
  - Aerodynamic stability with booms/surfaces.
Previous student research calculated theoretical performance for a 3U system that incorporated a thruster and aerodynamic surfaces.

- The module would occupy 1U and the “tuna can” extension in the P-POD deployment mechanism.
- Thruster provided drag makeup for $3.52 \times 10^{-4}$ N of atmospheric drag.
- Aerodynamic stability was measured in the pitch axis utilizing two 100 cm$^2$ surfaces mounted at 45°.
● Using R-134a for the propellant, and a 25 micron nozzle, the orbit could be extended by 7 days with approximately 600 cm$^3$ of propellant.

● Damping added for aerodynamic stabilization, which produced approximate steady state.

**Figure 4. Aerodynamic simulation showing max AOA at approximately ±2.6°**

*Proof of concept was the primary goal of this project, adherence to the theoretical design was attempted as closely as possible.*
Tank Design

- Aluminum tank
  - Machined plates welded together
- Slits for flap attachment
- Hole for nozzle
- 25.41 in\(^3\) capacity (416.4 cm\(^3\))

Figure 5. Tank design showing the front cap and slots for aerodynamic surface mounts.
• Aluminum 1060 has a modulus of elasticity of 10152 ksi.

• With 382 psi from pressure on the wall at max temp of 80 °C, total force is 6015.75 lbf.

• If wall thickness is 0.25 in², total deformation will be 0.000592 in in each direction.
Aerodynamic Surface Design

- Maximum surface area to maximize drag force.

- Desirable material with low weight, high stiffness.

- Proof of Concept: Use of AM aerodynamic Surface for simplicity sake; actual product may utilize Ti/Al sheets for greater stiffness and weight optimization.

- Stiffness calculations with Nitinol wire showed need for stiffer mounting arms - rolled steel was utilized.
Aerodynamic Surface Design

Figure 6. Aerodynamic Flap with mounting arm.

Figure 7. Close up of aerodynamic flap design.
Converging-diverging nozzle was designed to minimize throat diameter.

20 micron nozzle was the goal and is possible to produce.

- Would cost $1,600 through Potomac Photonics.
- Provide own materials, silicon or aluminum.
- Blank discs were designed at 1 mm and 0.5 mm thickness.

Simple nozzles were design instead and machined in aluminum discs in the USNA machine shop.

- Diameter of approximately 0.254 mm and half angles of about 45° and 65°.
- Issues include off-center drilling and “lip” before converging-diverging section under microscope.
Figure 8. Nozzles drilled into aluminum discs by the USNA machine shop.

Figure 9. Blank aluminum discs for outsourcing.
Initially discussed the use of valves for flow initialization

- Standard solenoid valves require power to actuate and are normally used in short bursts.
- Could use latching valves but these typically have a high leak rate and are not viable for this type of application.

Decided to employ a plug-actuation mechanism that would require power only once.

- Used a mount that would screw into the tank using NPT fittings.
- O-ring allows for interchangeability between nozzles for testing.
- Used Glenair Pyrotechnic-Free Space Release mechanism to actuate the plug (spring loaded).
Nozzle and Flow Initialization

Figure 10. Glenair Pyrotechnic-Free Release Mechanism and schematic [7].

Figure 11. Nozzle mount showing from left to right: O-ring, spring plug, nozzle disc, and release mechanism.
Propellant Considerations

- **Performance**
  - Low thrust
  - High $\Delta V$

- **Thermodynamic properties**
  - Two phase saturated liquid at low temperatures
  - Easily compressed into liquid form --> higher storage density

- **Membrane**
  - Liquid ingestion in the nozzle
  - RAMPART Design
    - 100 microns diameter, 500 microns depth
    - Surface tension
  - Metal screen

Figure 12. Performance characteristics of cold gas propellants [9].
Figure 13. Propellant State for R-134a in 2.5 L Tank [9].
Figure 14. RAMPART phase-separating membrane [10].
Figure 15. Advantech Testing Sieve [11].
Propellant Considerations

- Practical considerations
  - Safety
    - Low skin exposure
    - PPE
    - Proper ventilation
  - Storage
    - Cool, dry, ventilation
  - Use
    - Only restriction: heat transfer fluid
  - Cost
    - No restrictions on purchasing
    - Commercially available
    - Relatively inexpensive
    - ~ $20 for 12oz canister

Figure 16. 12oz canister of R-134a [12].

Figure 17. R-134a MSDS Sheet [13].
Final design successfully incorporated three of the four primary systems in the module.

- Were able to add tank, aerodynamic surfaces, and nozzle actuation system.
- Due to testing constraints and safety concerns, the R-134a propellant was not tested.

Design was approximately 1U (with “tuna can” extension) and did not exceed the 6.5 mm extension around the spacecraft body.

- Could be further refined to fit exactly into the “tuna can” and utilize an additively manufactured shell.
- Need front plate for tank as well as pressure and temperature sensors and fill valve.
Prototype Design

Figure 18. Final modular, add-on design showing aerodynamic surfaces extended and nozzle plug actuated.
Two distinct tests were conducted to show this was a viable design and show proof of concept.

The first test involved flow of the nozzle and demonstrated the actuation system.

- Manually actuated the plug due to price constraints.
- Utilized balloon pressure and colored powder to visualize flow.

The second test involved deployment of aerodynamic surfaces utilizing a burn circuit.

- Tied wire to the resistor and around the surface mounts.
- Ran current through the resistor to melt the wire.
- Also used this to demonstrate plug actuator for system test.
Verification Testing

Figure 19. Experimental set-up for flow testing showing the balloon attached to the nozzle mount.

Figure 20. Module ready for system test showing the aerodynamic surfaces mounted to the sides.
Flow Test (Video)
Deployment Test (Video)
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Conclusions

- Overall, it was shown that this type of module could be designed successfully.
  - Under approx. 1U (with “tuna can” extension).
  - Incorporated deployable aerodynamic surfaces with <6.5mm clearance.
  - Nozzle actuation system to expel cold gas using power only at initialization.

- It is likely that this design could be refined to perform close to simulated results.
  - Incorporate R-134a as the propellant.
  - Smaller nozzle.
  - Space rated status would need some form of temperature control and pressure sensor.
Future Work and Lessons Learned

Future Work:

• Design module for full space-rated status.
• Implement refined aerodynamic surfaces, temperature and pressure sensors, fill valve.
• Reduce tank factor of safety and increase module internal volume.
• Fully test R-134a in the system.
• Integrate a more robust burn circuit.

Lessons Learned:

• Realistic goal setting before project acceptance.
• Understand the cost associated with space systems and full testing.
• Issues can arise with testing safety or lack of centralized knowledge.
References


Thank you. Questions?