Pure Ionic Electrospray Thruster Control Electronics Architecture and Performance

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1. Introduction

Propulsion has been identified as a critical capability for future SmallSat and CubeSat missions. Due to strict volume constraints imposed by these small platforms, efficient means of propulsion is key to enabling sophisticated missions with large payload mass fraction and ΔV.

Ionic electrospray thrusters are a newly developed electric propulsion technology that have demonstrated order of magnitude mass and power efficiency gains when compared to similar micro electric propulsion options. USC's Laboratory for Exploration and Astronautical Physics (LEAP) is currently researching optimization of ionic electrospray thrusters design[1].To advance the development of ionic electrospray thrusters and their integration into future SmallSat missions it is important to characterize thruster performance as an entire subsystem, with the associated constraints of a CubeSat platform.

This poster presents ongoing work into the design and development of thruster control electronics, meant to drive a thruster pair. Information presented includes preliminary subsystem requirements and design methodology. Additionally, this poster presents experimental results from recent ionic electrospray test campaigns. Additionally, relevant subsystem performance metrics are visualized highlighting the current expected performance to a candidate mission scenario.

2. Physics of Operation

	Colloidal	Ionic
Extraction and Acceleration	Electrostatic	Electrostatic
Predominant Emitted Species	Droplets	Ions
Propellant	Ionic Liquid	Ionic Liquid
Emission site	Capillary tube	Porous substrate
Thrust	mN	µN
Specific Impulse	~800s	>3000s
Maturity	High	Low

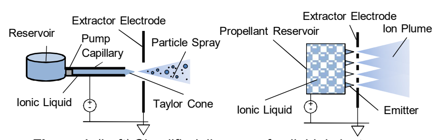

Figure 1: (Left) Simplified diagram of colloidal electrospray operation. (Right) Simplified diagram of ionic electrospray operation. The bubble pattern denotes propellant stored in pores of the reservoir substrate.

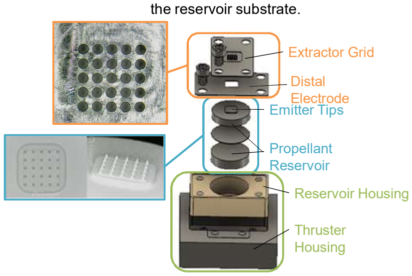

Figure 2: *Construction and primary components of USC Testbed Thruster*

3. Thruster Control Electronics Design

USC's thruster control electronics is designed to operate two thrusters in a self-neutralizing ambipolar pair. The electronics control thruster voltage and polarity, and report back thruster performance parameters. Table 1 lists expected performance parameters of this design.

Other key features include:

- 5V Bus
- I2C Command Interface
- Self-neutralizing ambipolar thruster pair
- Isolated high voltage (2000V) circuit
- Thruster emitted current and intercepted current data acquisition
- CubeSat form factor (<10x10cm)
- External microcontroller

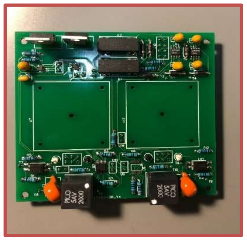

Figure 4: Assembled Thruster Control Electronics

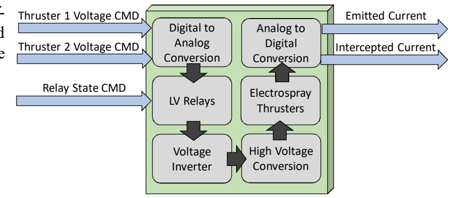

Figure 3: Thruster Control Electronics functional block diagram

Integrated Subsystem Predicted Performance		
Parameter	Value	Unit
Max Current	625	uA
Max Thrust	92.50	uN
Number of Tips	700	-
Max Est. Power	2.97	W
Power Efficiency	63%	-
Thrust to Power Ratio	31.14	uN/W

Table 1: Thruster Control Electronics estimated performance

4.Thruster Experimental Data

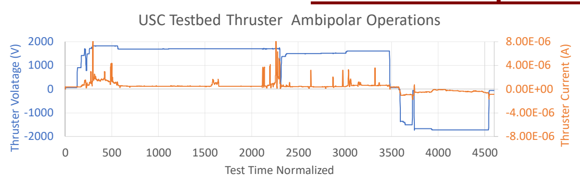

Figure 5: Steady ambipolar thruster operation with localized transients

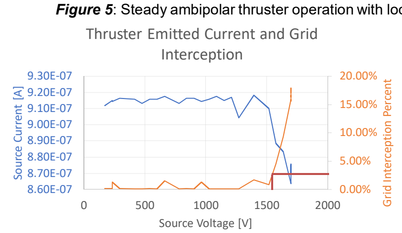

Figure 6: Intercepted current growth leads to inefficiency at high voltages. 3% Interception at V = 1550V

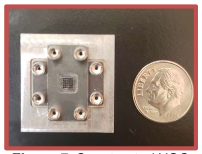

Figure 7: Constructed USC Testbed Thruster

The USC Testbed Thruster (UTT) (Figure 7) is a research grade thruster consisting of 25 micro-machined emitter tips. The UTT has been undergoing a test campaign to characterize individual thruster performance, as well as inform design optimization trades and controller design. Key takeaways from testing include:

- Thruster beginning of life conditioning sees large fluctuations in emitted current
- Steady state operations of an individual UTT is approximately 0.3 µA drives data acquisition resolution
- Grid intercepted current provides a suitable metric to bound thruster operational region
- For this design, thruster voltage needs to be accurately controlled from +/- 1300V to 1800V
- Circuit requires over-current protection from short circuits between the conducting propellant and extractor grid

4.Thruster Subsystem Sizing Analysis

Unlike traditional electric propulsion devices, ionic electrospray propulsion systems scale linearly with the number of emission sites. Similarly, assuming a set diameter for the reservoir substrate, the amount of ΔV scales with reservoir depth.

- ΔV for 8 kg S/C = 193 m/s (<0.25U)
- High ΔV needs large time of flight
- Power limitations occur as number of tips exceeds 25,000 tips
- Existing thruster controller designed to accommodate up to 700 emitter tips

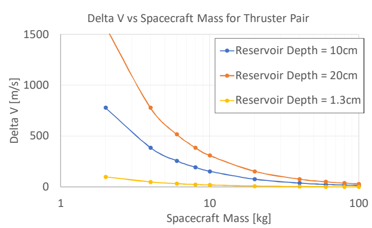

Figure 8: Spacecraft maneuver capability with different reservoir sizes

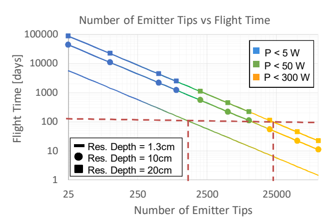

Figure 9: Electrospray maneuver capability is limited to by realistic flight and emitter tip density

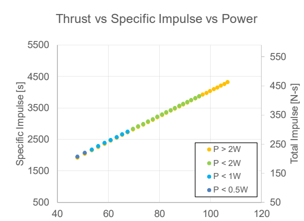

Figure 10: Electrospray thruster theoretical performance variation

6. Mission Design Example

Precision Formation Maintenance

Precision formation maintenance enables complex science missions from CubeSat platforms, such as interferometry, gradiometry, and synthetic aperture radar. Previous studies[2], have precluded the use of micro-electric propulsion due to the maneuver time being a significant portion of the spacecraft period. Assuming a CubeSat class platform, this constraint is easily remedied. Recently published control algorithms[3] for optimized low thrust formation keeping give insight to maneuver capability needed to perform this mission.

Parameter	Value	Unit
a*δa	0	m
a*δλ	-123	m
a*δex	68	m
a*δey	387	m
a*δix	0	m
a*δiy	-449	m
Thrust Constraints	10	uN
ΔV per Orbit	0.9	mm/s
Thruster Duty Cycle	12%	-
ΔV per Year	5.256	m/s

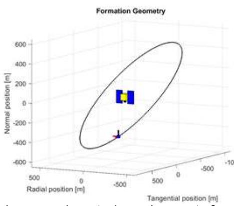

Figure 11: *Formation guidance and control requirements for relative circumnavigation extrapolated form optimized low thrust trajectory[3]*

Figure 11 displays the relative orbit element state and derived maneuver capability necessary to perform formation keeping maneuvers in Low Earth Orbit. With an assumed yearly requirement of appx 5 m/s/yr, the designed electrospray thruster subsystem is adequately sized to provide enough ΔV for a two year mission with assumed formation acquisition costs.

6. Conclusion

An ionic electrospray thruster subsystem capable of performing relevant space missions has been designed and constructed and is currently undergoing checkout and integration with existing test hardware at USC's LEAP. This subsystem and architecture is compatible with current CubeSat bus requirements and is designed in order to reduce adverse affects due to thruster operation.

Future work includes revising the current design to interface the control board directly with a standard CubeSat avionics stack. Additionally, this subsystem will be used in order to perform subsystem level experimentation and beam neutralization experiments in a lab environment.

7. References

[1] Antypas, R. a. (2019). Pure Ionic Electrospray Thruster Extractor Design Optimization. International Electric Propulsion Conference.

[2] Gill, E. and Runge, H. (2004). Tight Formation Flying for an Along-Track SAR Interferometer. Acta Astronautica, 473-485.

[3] Steindorf, L. e. (2017). Constrained Low-Thrust Satellite Formation Flying Using Relative Orbit Elements. AAS, 1-21.

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