Origami-based Drag Sail for CubeSat Propellant-free Maneuvering

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Outline

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Previous Work in Space Sails

- Sails have been used to propel satellites and de-orbit
- Some examples:
  - Joint DLR, JPL/NASA and ESA solar sail[1]
  - Nanosail-D
  - AEOLDOS
- All are single-deployment

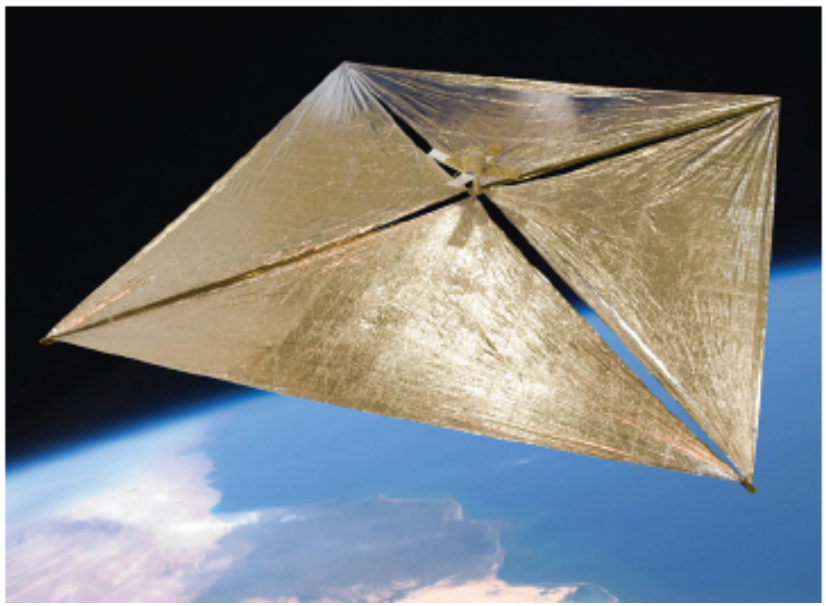

Fig. 1: Nanosail-D (Image Courtesy NASA)

[1] Leipold, M. et al. "Solar Sail Technology Development and Demonstration." Acta Astronautica 52 (2003): 317-326. DOI:10.1016/S0094-5765(02)00171-6

Purpose of Drag Sail Subsystem

- Allows propellant-free maneuvering
- Designed as COTS component for CubeSats
- Intended for use in PADDLES (shown), developed at RPI
- Uses differential drag to perform relative maneuvering

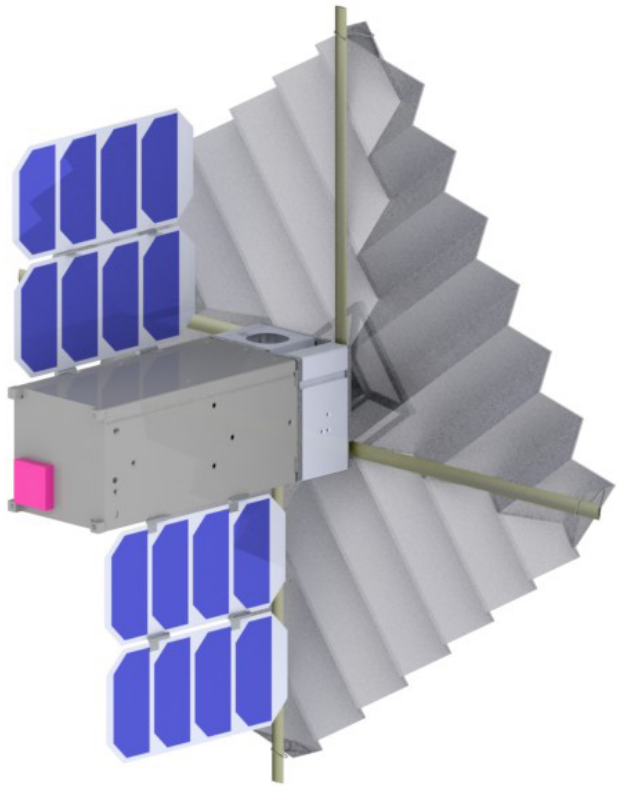

Fig. 2: PADDLES Open Configuration

Differential Drag Basics

- Used when relative orbit is more important than absolute orbit
- Additional drag tends to circularize the orbit
- No thrusters are needed, so no thrust shock and no plume impingement
- Movable panels have been proposed as another method of varying drag

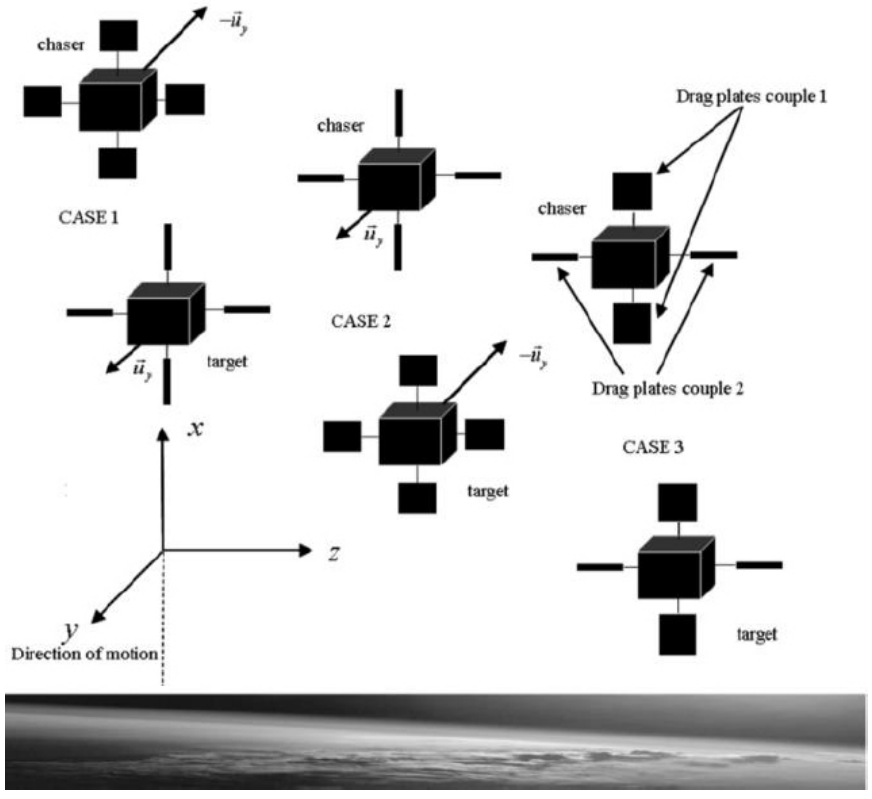

Fig. 3: Varying Drag With Adjustable Panels

Differential Drag Basics

- PADDLES maneuvers by varying the cross-sectional area to vary drag
- Rendezvous between two satellites has already been simulated using STK/MATLAB [2]

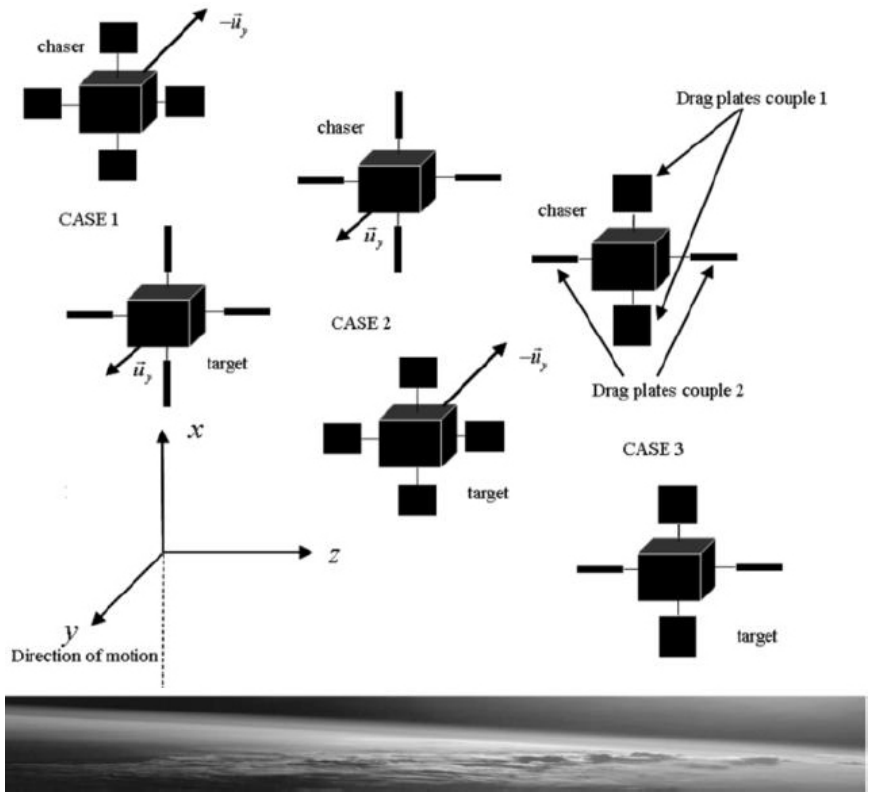

Fig. 4: Varying Drag With Adjustable Panels

[2] Pérez, D. and Bevilacqua, R. "Differential Drag Spacecraft Using an Adaptive Lyapunov Control Strategy." Acta Astronautica 83 (2013): 196-207. DOI:10.2514/1.I010049

Relative Maneuvering with Differential Drag

- Opening the sail sends PADDLES into a lower orbit, closing it maintains the orbit
- The drag sail can remove more energy from the orbit than it takes to open the sail
- PADDLES can only remove energy from the orbit

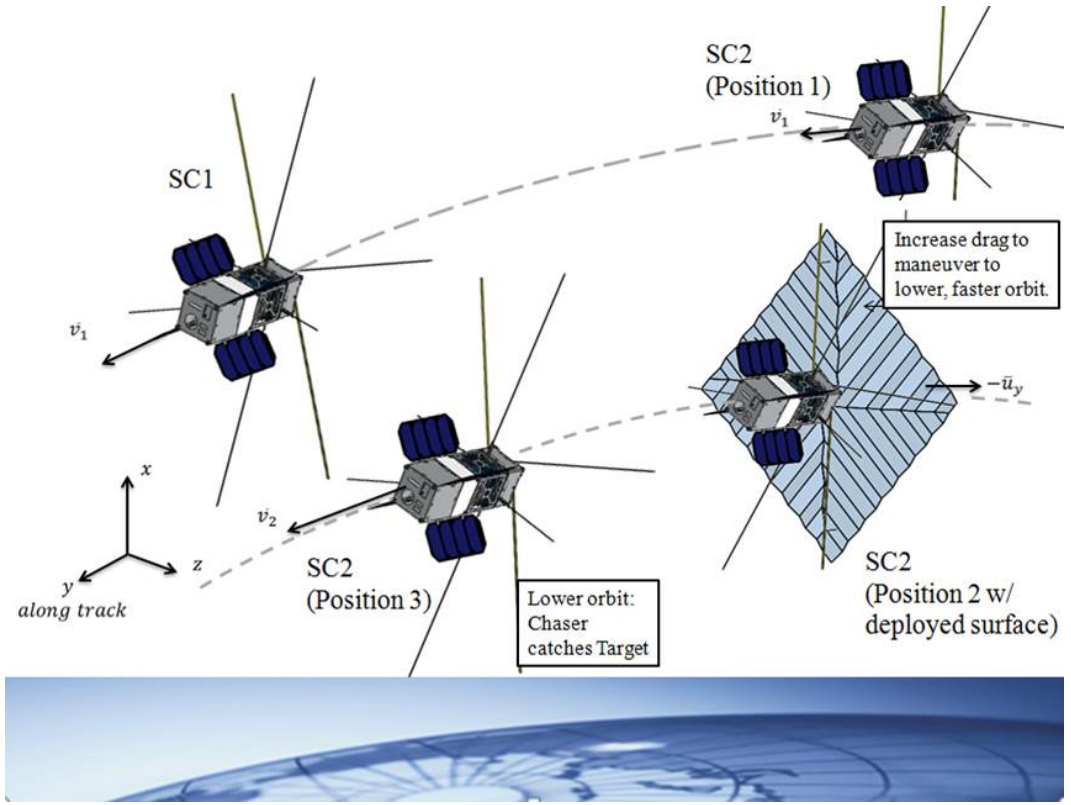

Fig. 5: PADDLES Relative Maneuvering

How do We Create Differential Drag?

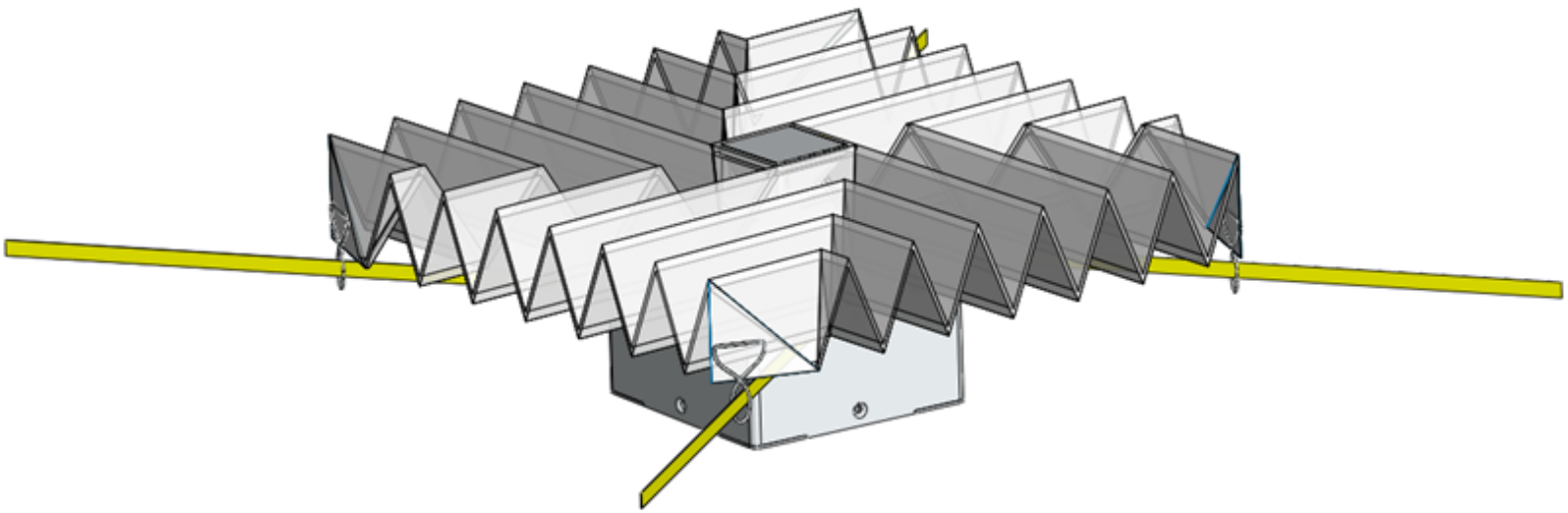

Fig. 6: Differential Drag Sail Used in PADDLES

Sail Folding Details

- Sail folding pattern is derived from existing origami pattern

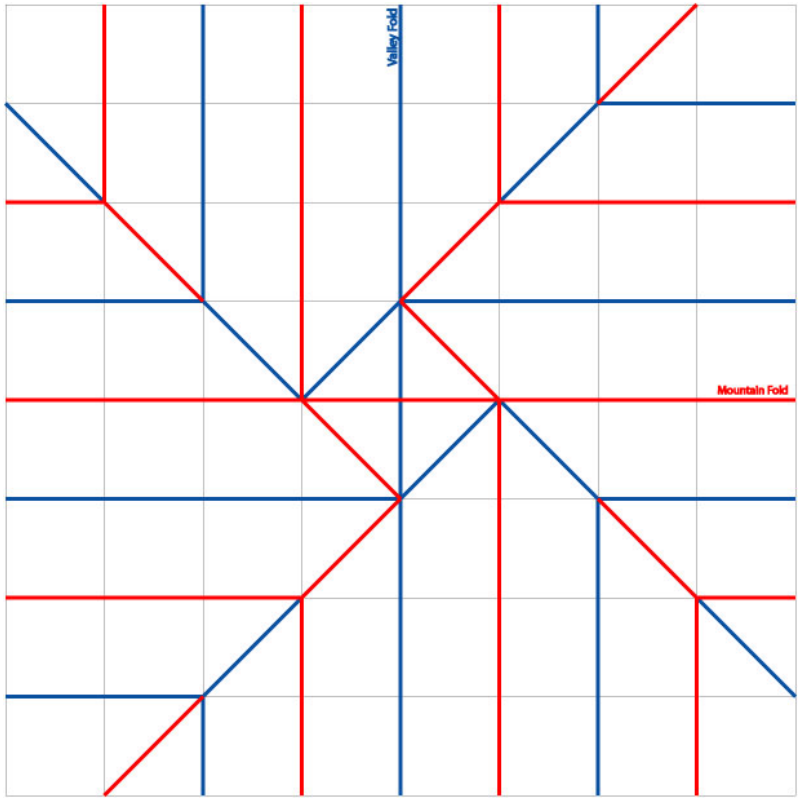

Fig. 7: ADAMUS Flyer Based on Origami Pattern By Jeremy Shafer

Sail Folding Details

- Sail folding pattern is derived from existing origami pattern
- Extending the pattern in each direction allow larger sails

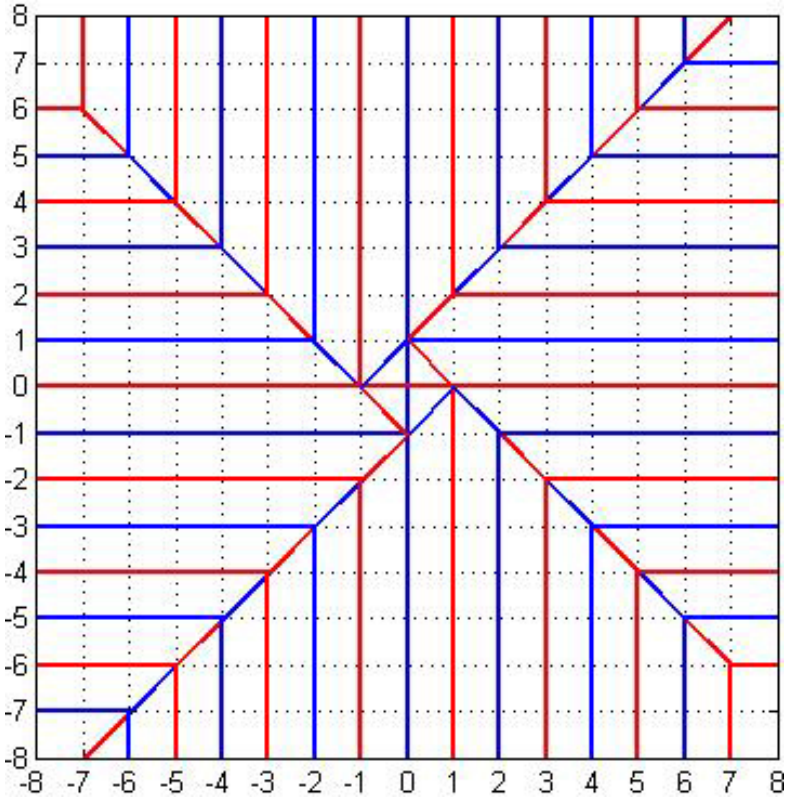

Fig. 8: MATLAB-Generated Folding Pattern

Sail Folding Details

- Sail folding pattern is derived from existing origami pattern
- Extending the pattern in each direction allow larger sails
- Some optimization is necessary to minimize the folded size
- Sail is folded from a Mylar sheet
- 0.2m x 0.2m x 0.5mm case shown

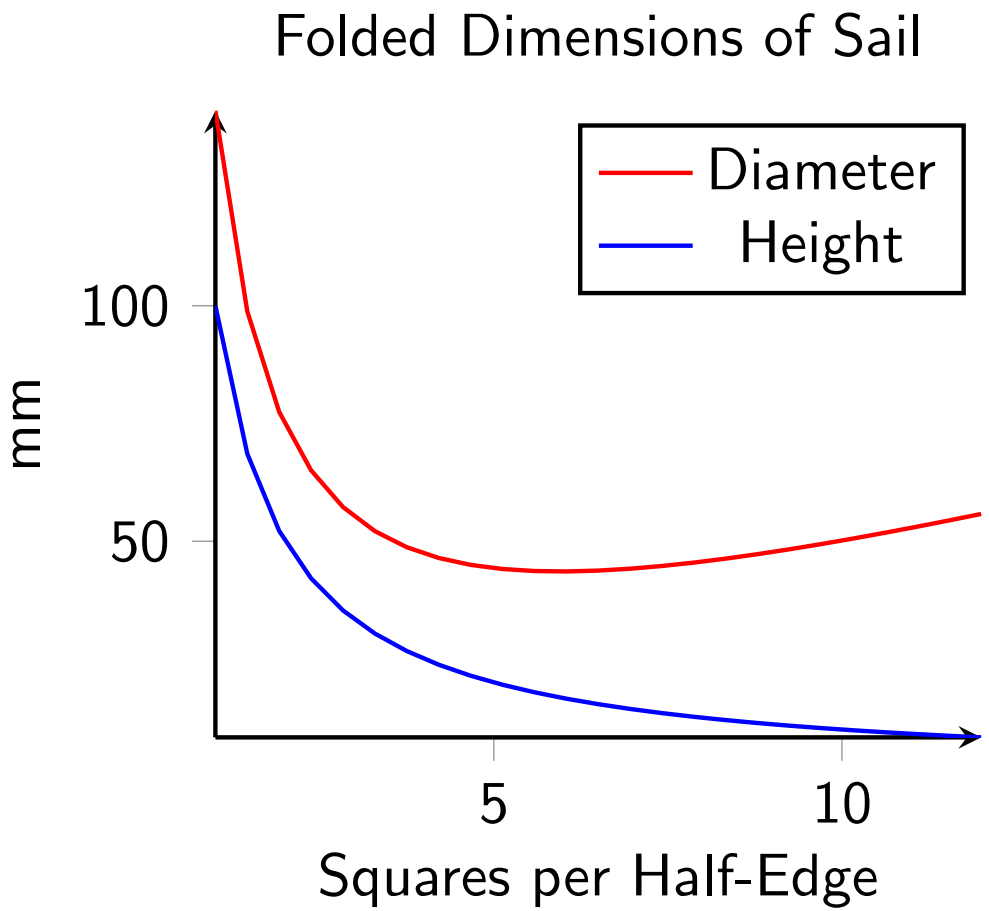

Fig. 9: Folded Dimensions as N Increases

Drag Sail Subsystem Hardware and Operation

- Sail ejects before opening
- Four coiled booms
- Origami pattern for sail
- Rotating the center opens and closes the sail
- Corners of sail track booms
- Stored during launch and ejected prior to use
- 1/2U enclosure
- Power and control connections required

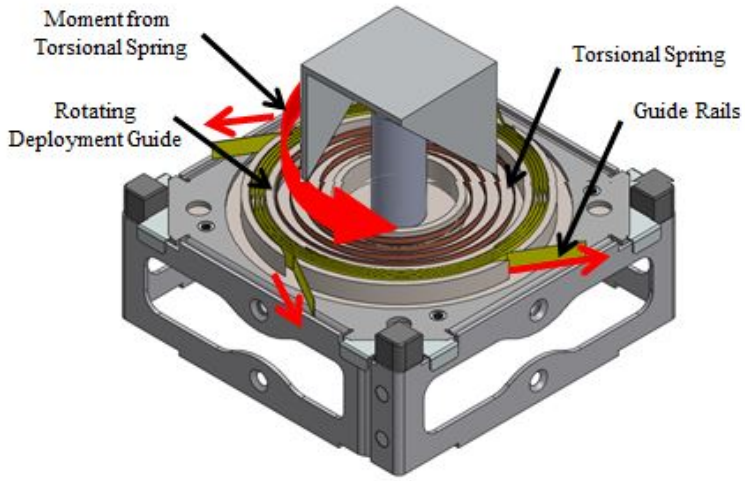

Fig. 10: Direction of rotation of the drag sail when opening

Drag Sail Subsystem Hardware and Operation

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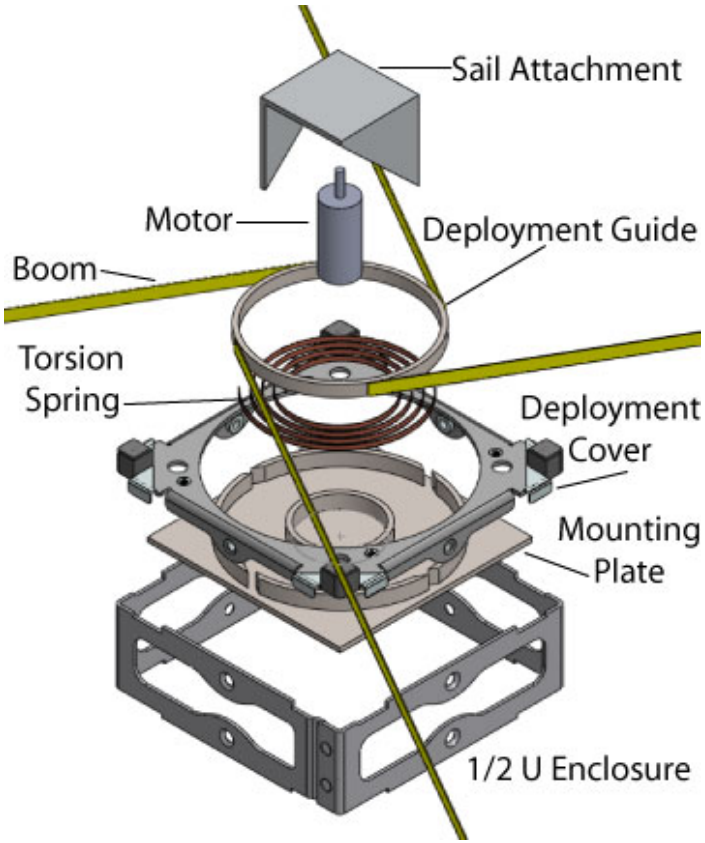


Fig. 11: Sail subsystem exploded view

Hardware Details

- Faulhaber motor is designed to work in space (although not space-tested)
- All other parts are manufactured in house
- Compatible with CubeSat standards

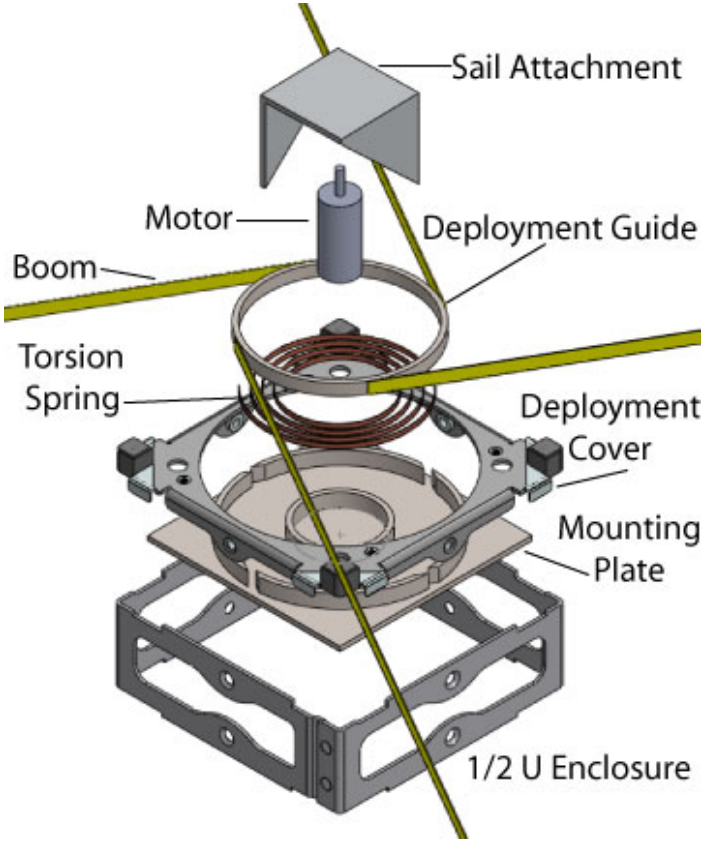


Fig. 12: Sail subsystem exploded view

Sail Deployment and Operation

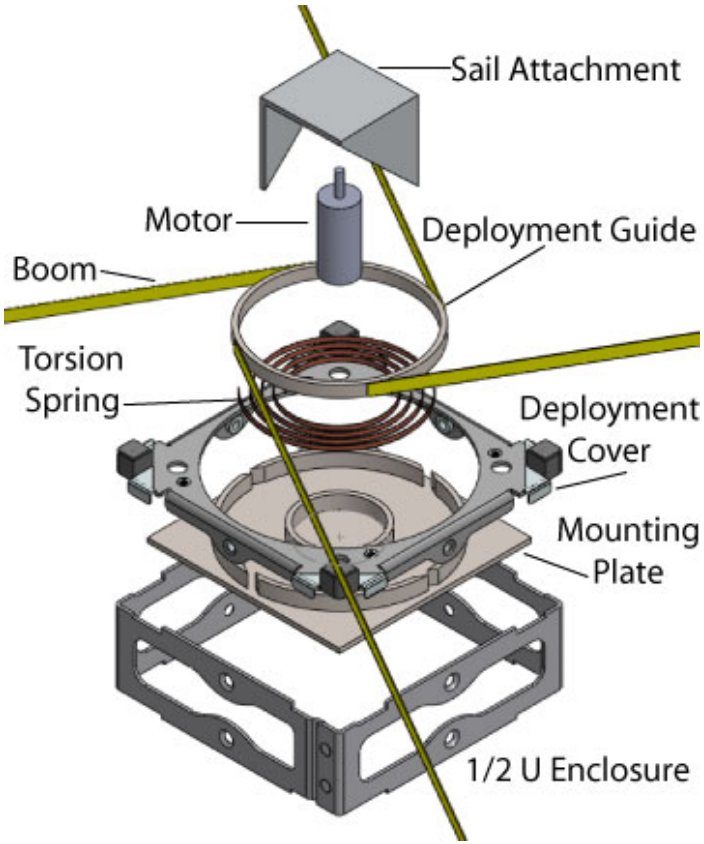


Fig. 13: Sail subsystem exploded view

Fig. 14: Sail Prototype Operation

Preliminary Testing Results

Table 1: Sail Fatigue Test Results

Sail	Successful Cycles	Comments
A	300	Encapsulation Failure
B	200	Incorrect command to motor
C	698	Encapsulation failure
D	2500	Successful
E	3000	Successful
F	4000	Successful

- Only anticipate a few open-close cycles
- Sails were initially failing at the slider attachments
- Improving the construction prevents fatigue failure
- Further testing is necessary for space qualification

Future Work

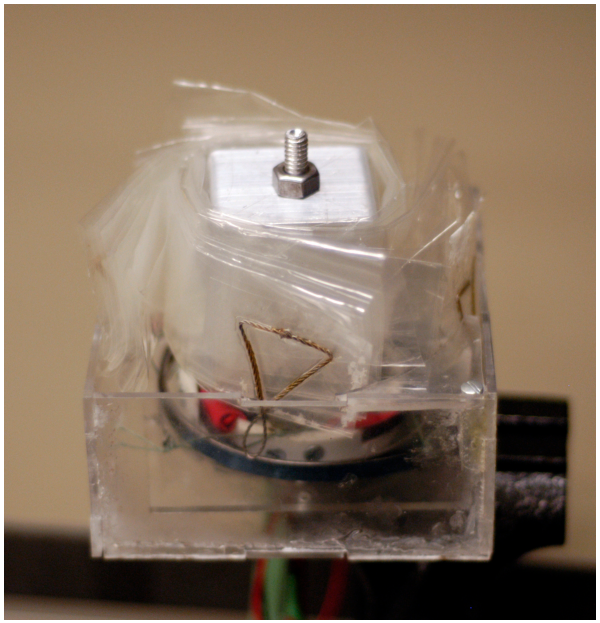


Fig. 15: Current Prototype of Drag Sail Subsystem

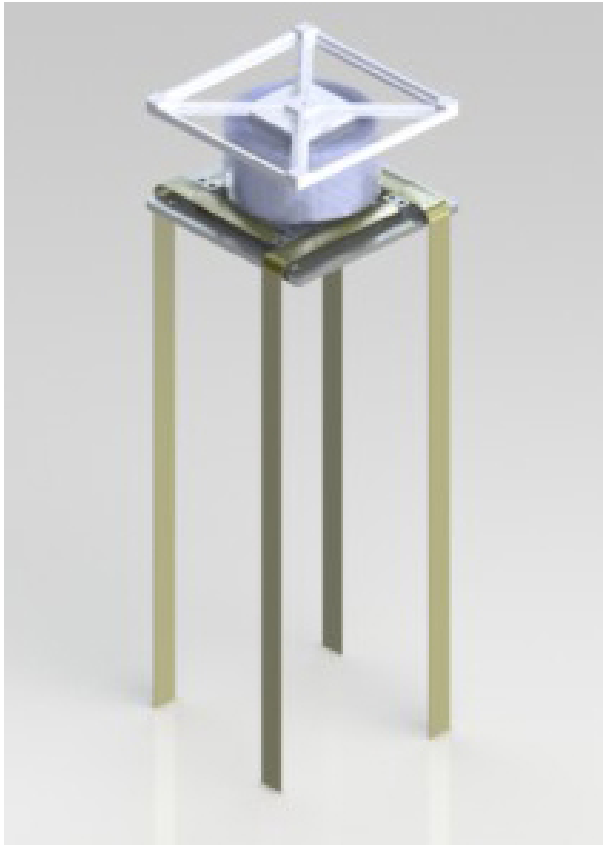


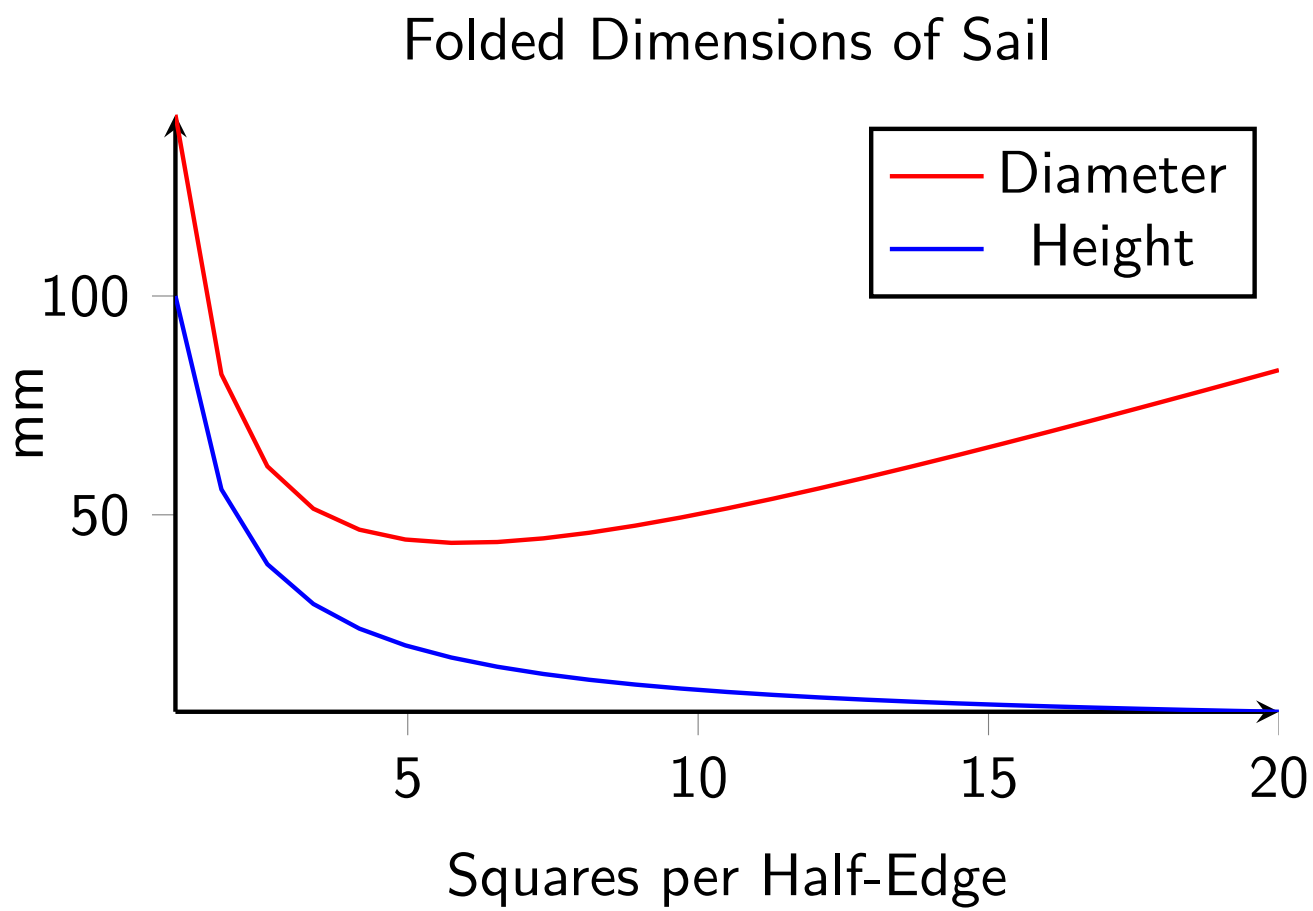
Fig. 16: Deployment Method in Progress

Summary and Conclusions

- Created deployable retractable $^1/_2$U drag sail subsystem
- Drag sail is used to maneuver PADDLES using differential drag
- Intended to be used as a COTS component for CubeSats
- Successful prototype fatigue testing
- U.S. Patent pending
- Differential drag used to maneuver
- Requires no propellant

Reference Slides

Sail Folding Equations



Sail Folding Equations

$$p_f = \frac{\textit{minimum thickness}}{\textit{actual thickness}} \quad 0 < p_f \leq 1$$

$$d = \underbrace{\sqrt{2}\frac{l}{2N}}_{\text{Center}} + \underbrace{\frac{2(N-1)t}{p_f}}_{\text{Wrapping}}$$

$$h = \frac{l}{2N}$$