Propellant-free Spacecraft Relative Maneuvering via Atmospheric Differential Drag

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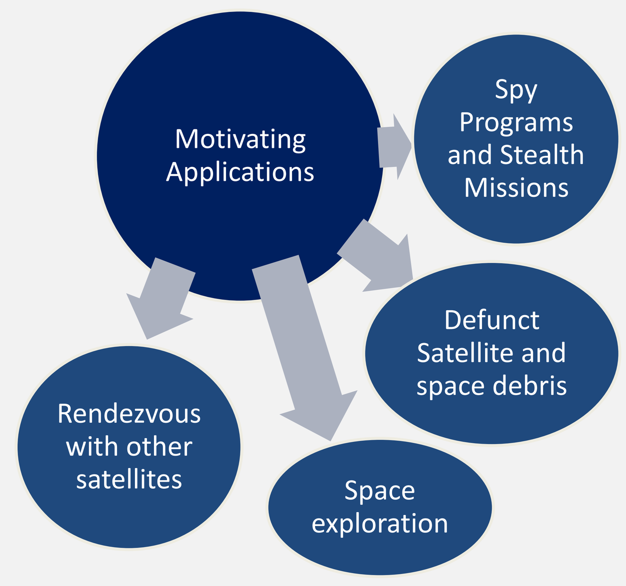
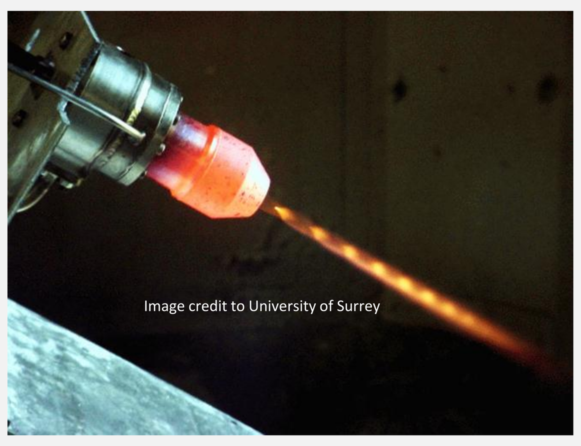
Motivation

Current Problems in Space Industry to be Addressed

- Cost of carrying fuel is high
- Space real estate is limited and valuable
- Satellite detection is performed using reflection and/or heat emissions



Current Spacecraft Maneuvering with Propulsion Systems



- Mission life limited by fuel
- This fuel is expensive: ~$5000/lb to transport it to Low Earth Orbit (<600km)
- Excess heat, dangerously flammable
- Volume cost
- Detectable

Adaptive Lyapunov Control Strategy

A linear reference model is found by stabilizing the Schweighart and Sedwick model using a LQR, yielding the following:

$$\dot{\mathbf{x}}_d = \underline{\mathbf{A}}_d \mathbf{x}_d, \quad \underline{\mathbf{A}}_d = \underline{\mathbf{A}} - \underline{\mathbf{B}}\underline{\mathbf{K}}, \quad \mathbf{x}_d = \begin{bmatrix} x_d & y_d & \dot{x}_d & \dot{y}_d \end{bmatrix}^T$$

A Lyapunov function of the tracking error and its time derivative are found to be:

$$V = \mathbf{e}^T \underline{\mathbf{P}}\mathbf{e}, \qquad \mathbf{e} = \mathbf{x} - \mathbf{x}_d, \qquad \underline{\mathbf{P}} \succ 0, \qquad \dot{V} = \mathbf{e}^T(\underline{\mathbf{A}}_d^T \underline{\mathbf{P}} + \underline{\mathbf{P}}\underline{\mathbf{A}}_d)\mathbf{e} + 2\mathbf{e}^T \underline{\mathbf{P}}(\mathbf{f}(\mathbf{x}) - \underline{\mathbf{A}}_d \mathbf{x} + \underline{\mathbf{B}} a_{Drel}\hat{u} - \underline{\mathbf{B}}\mathbf{u}_d)$$

If the desired guidance is a constant zero state vector (controller acts as a regulator) then the time derivative simplifies to:

$$\dot{V} = 2(\beta\hat{u} - \delta), \quad \beta = \mathbf{e}^T \underline{\mathbf{P}}\underline{\mathbf{B}} a_{Drel}, \quad \delta = -\mathbf{e}^T \underline{\mathbf{P}}\, \mathbf{f}(\mathbf{x}), \quad \hat{u} = \begin{cases} 1 \\ 0 \\ -1 \end{cases}$$

Selecting: $\hat{u} = -sign(\beta) = -sign(\mathbf{e}^T \underline{\mathbf{P}}\underline{\mathbf{B}})$ ensures the time derivative to be as small as possible

A critical value for the magnitude of the drag acceleration that ensures Lyapunov stability is found to be:

$$a_{Drel} \geq \frac{\delta}{\left|\mathbf{e}^T \underline{\mathbf{P}}\underline{\mathbf{B}}\right|} = \frac{-\mathbf{e}^T \underline{\mathbf{P}}\, \mathbf{f}(\mathbf{x})}{\left|\mathbf{e}^T \underline{\mathbf{P}}\underline{\mathbf{B}}\right|} = a_{Dcrit}$$

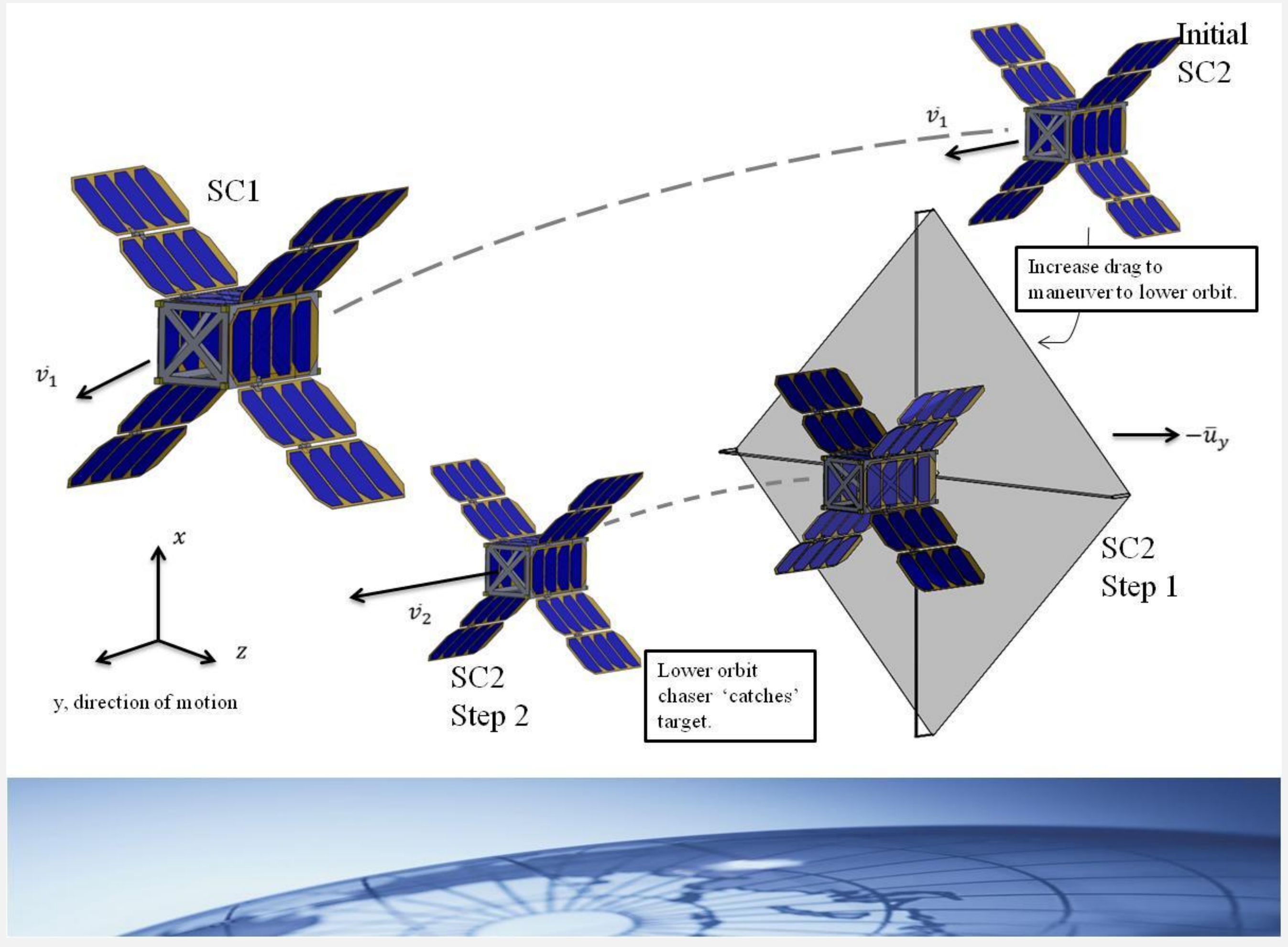
Expressions for the partial derivatives of the critical value in terms of matrices A and Q are found to be:

$$\frac{\partial a_{Dcrit}}{\partial \underline{\mathbf{Q}}} = \mathrm{T}_3^{-1}\left(\frac{\partial \underline{\mathbf{P}}}{\partial \underline{\mathbf{Q}}}\right)\left[\underline{\mathbf{I}}_{4x4} \otimes \mathrm{T}_1^{-1}\left(\frac{\partial a_{Dcrit}}{\partial \underline{\mathbf{P}}}\right)\right], \quad \frac{\partial a_{Dcrit}}{\partial \underline{\mathbf{A}}_d} = \mathrm{T}_3^{-1}\left(\frac{\partial \underline{\mathbf{P}}}{\partial \underline{\mathbf{A}}_d}\right)\left[\underline{\mathbf{I}}_{4x4} \otimes \mathrm{T}_1^{-1}\left(\frac{\partial a_{Dcrit}}{\partial \underline{\mathbf{P}}}\right)\right]$$

Using these derivatives Ad and Q are adapted as follows:

$$\frac{dA_{ij}}{dt} = \kappa_A\left[-sign\left(\frac{\partial a_{Dcrit}}{\partial A_{ij}}\right)\delta_A\right], \quad \frac{dQ_{ij}}{dt} = \kappa_Q\left[-sign\left(\frac{\partial a_{Dcrit}}{\partial Q_{ij}}\right)\delta_Q\right], \kappa_A = \begin{cases} 1 \text{ if } \left|\frac{\partial a_{Dcrit}}{\partial A_{ij}}\right| > \left|\frac{\partial a_{Dcrit}}{\partial A_{kl}}\right| \text{ for } i,j \neq k,l \\ 0 \text{ else} \end{cases}, \kappa_Q = \begin{cases} 1 \text{ if } \left|\frac{\partial a_{Dcrit}}{\partial Q_{ij}}\right| > \left|\frac{\partial a_{Dcrit}}{\partial Q_{kl}}\right| \text{ for } i,j \neq k,l \\ 0 \text{ else} \end{cases}$$

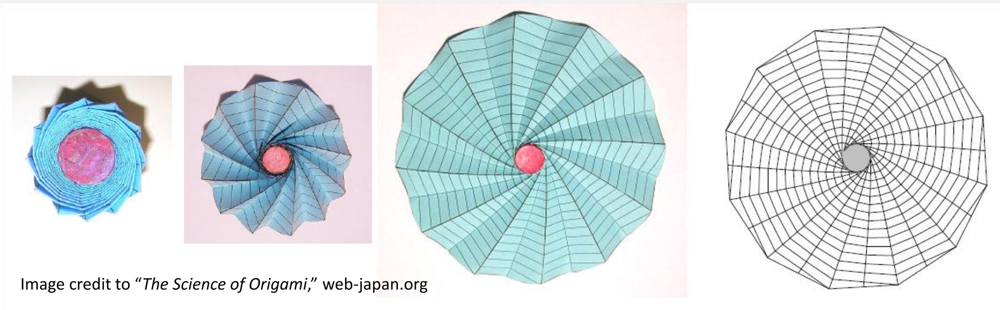
Differential Drag Theory



Allows for controlling relative motion in the orbital plane, without using any propellant at LEO

$$a_{Drel} = \frac{1}{2}\rho\Delta BCv_s^2$$

Origami-based Design

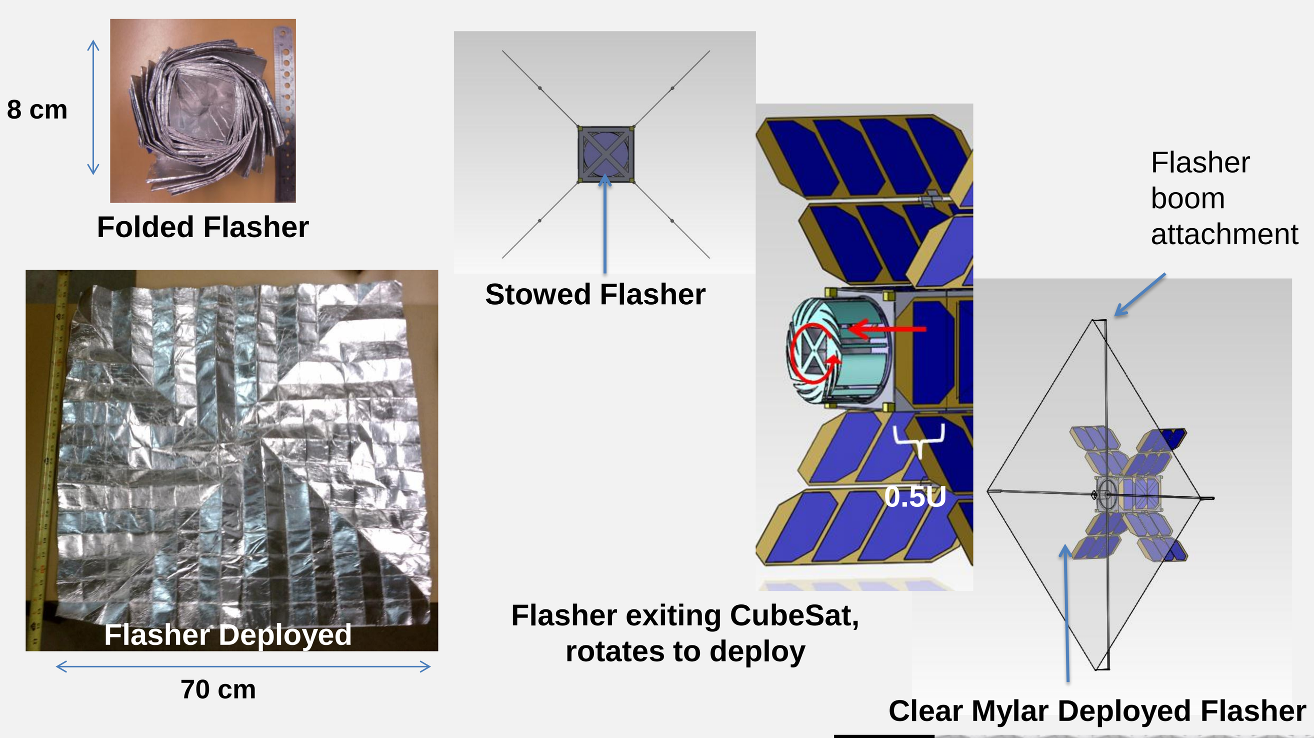


Origami:

Precision Folding Method

Advantage in Spacecraft Design:

Large open surface to folded volume ratio



In Our "Flasher" Design:

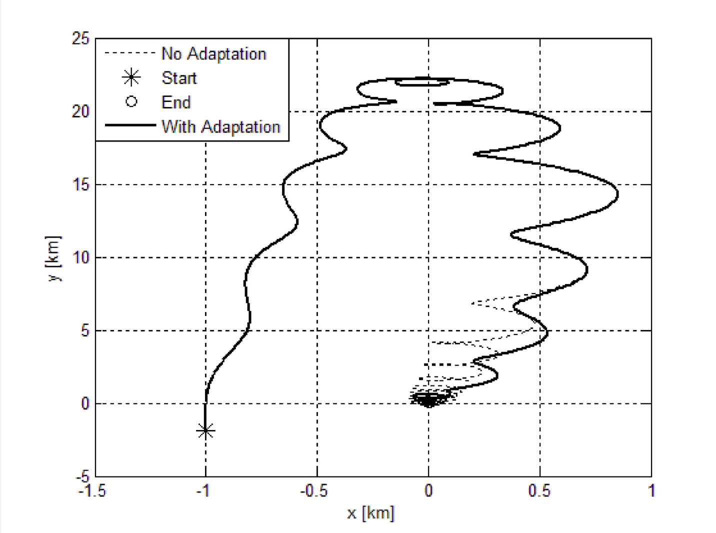
Origami techniques used to compress a 0.5m² surface area into a 10x10x5 cm payload volume

Maneuvering Technique: Center rotation fans out flasher, increasing surface area

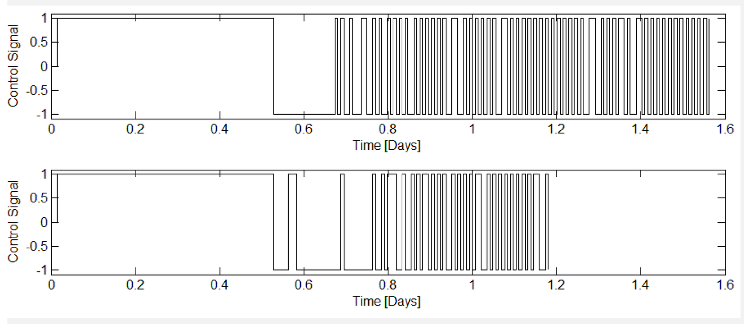
In collaboration with: NANO-M3 DESIGN LAB
Nano/Micro-Scale Manufacturing and Material Design Laboratory
Director: Prof. Johnson Samuel

Current Simulation Results

Rendezvous Trajectory



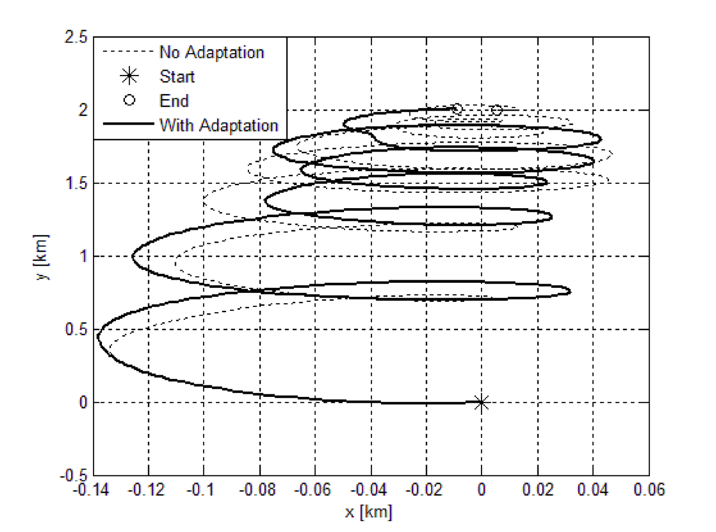
Rendezvous Control Signal



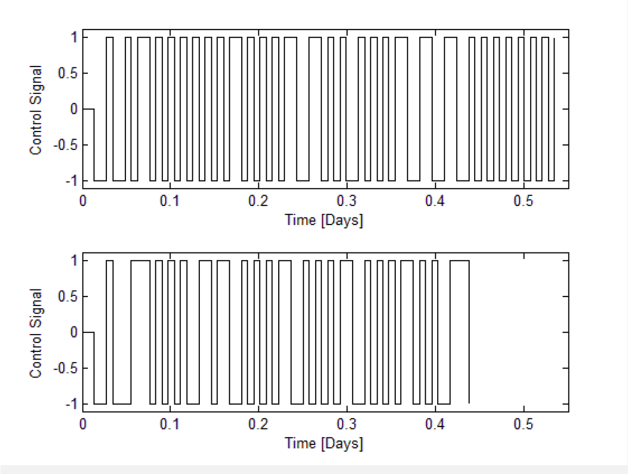
Non Adaptive

Adaptive

Rephasing Trajectory

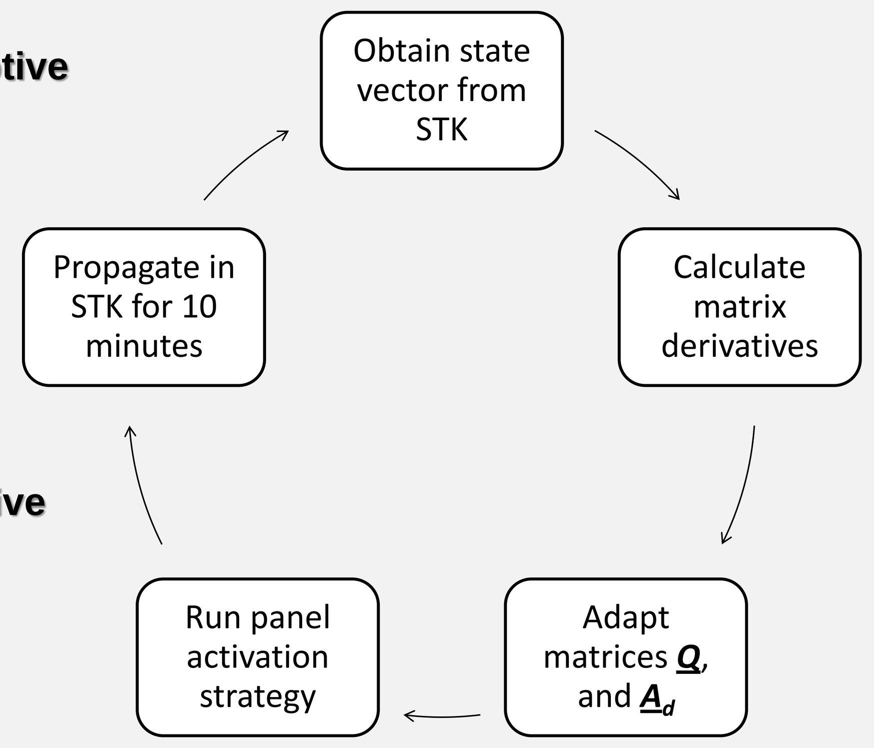


Rephasing Control Signal



Non Adaptive

Adaptive



	Number of changes	Duration (hr)	Percent improvement changes	Percent improvement duration
Rephasing	62	12.8167	27%	19%
	45	10.4333		
Rendezvous	113.00	37.37	50%	24%
	56.00	28.28		

Future Target Agencies

Office of Naval Research

NASA

NSF Cubesat Program

University Nanosat Program

AFOSR

AFRL Space Vehicles

AIAA

SMC Det 12