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AACE – Spring Review

Exploiting Environmental Effects in LEO for Attitude and Orbit Control with the Drag Maneuvering Device: Current and Future Challenges

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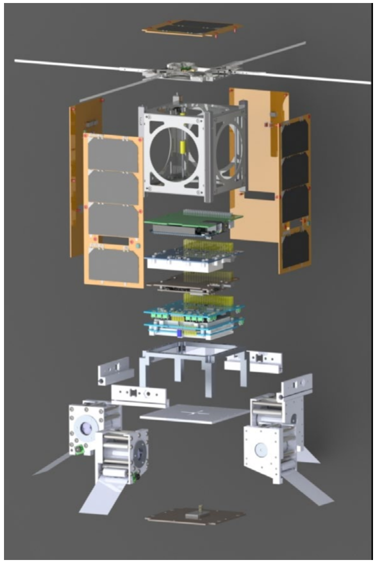
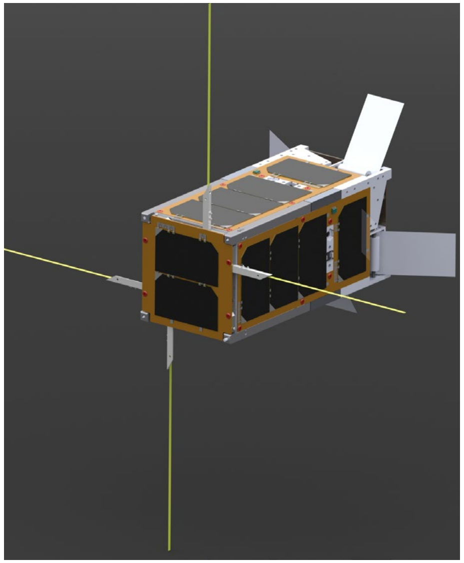
Outline

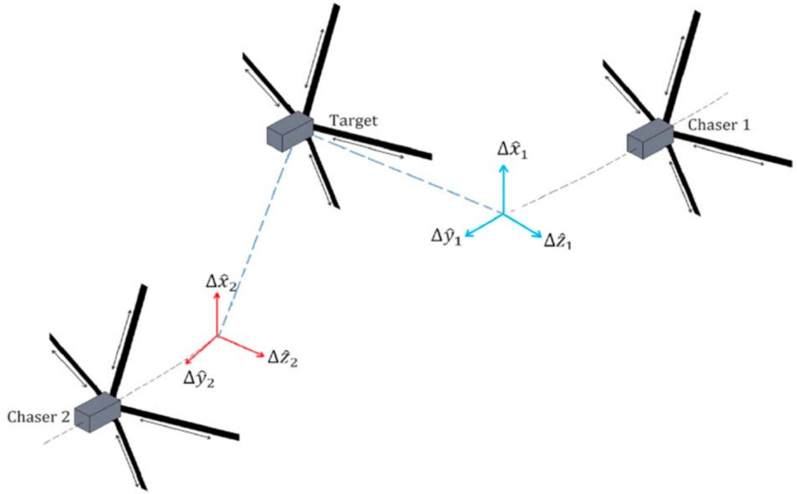
- Review of the problem
- Proposed control strategies
- Progress on the D3 CubeSat mission
- Proposed approach to address next challenges

Problem Review

- ❑ Space situational awareness
  - ❑ Drag-based targeted point re-entry
  - ❑ D3 CubeSat mission, scheduled for launch in late 2021
- ❑ Spacecraft control using environmental forces/torques
  - ❑ Drag-based relative orbit maneuvering for formation flying
  - ❑ Aerodynamic and gravity gradient-based Attitude control







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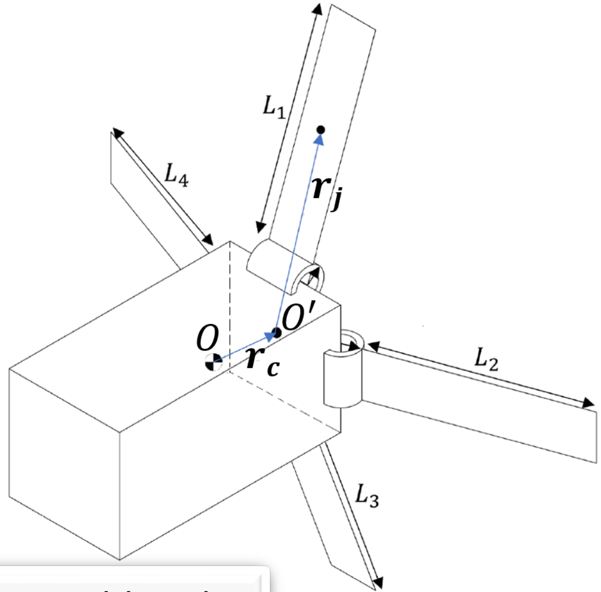
The Drag Maneuvering Device DMD



- Aerodynamic forces

$$\boldsymbol{F}_{D,j} = -\frac{\rho w_b L_j C_{D,j}}{2}\|\boldsymbol{V}_{\perp,j}\|^2 \frac{\boldsymbol{V_r}}{\|\boldsymbol{V_r}\|}$$

$$\boldsymbol{F}_{L,j} = -\frac{\rho w_b L_j C_{L,j}}{2}\|\boldsymbol{V}_{\perp,j}\|^2 \left(\frac{\boldsymbol{V_r}}{\|\boldsymbol{V_r}\|} \times \boldsymbol{n_j} \times \frac{\boldsymbol{V_r}}{\|\boldsymbol{V_r}\|}\right)$$

- Aerodynamic torques

$$\boldsymbol{\tau}_k \triangleq \sum_{j=1}^{4} R_j^{\times} \boldsymbol{F}_{k,j}, \quad k = D, L,$$

- Gravity gradient torque

$$\boldsymbol{\tau_{GG}} = \frac{3GM_{\oplus}}{\|\boldsymbol{R_c}\|^5} R_c^{\times} J \boldsymbol{R_c}$$

The drag maneuvering device enables the CubeSat with modulation of these forces and torques. However, computing their exact value is difficult:

- DMD modifies CoM location R_j.
- DMD modifies inertia matrix J.
- Density ρ is very difficult to accurately predict.
- Drag/lift coeff. C_D, C_L are difficult to compute accurately.

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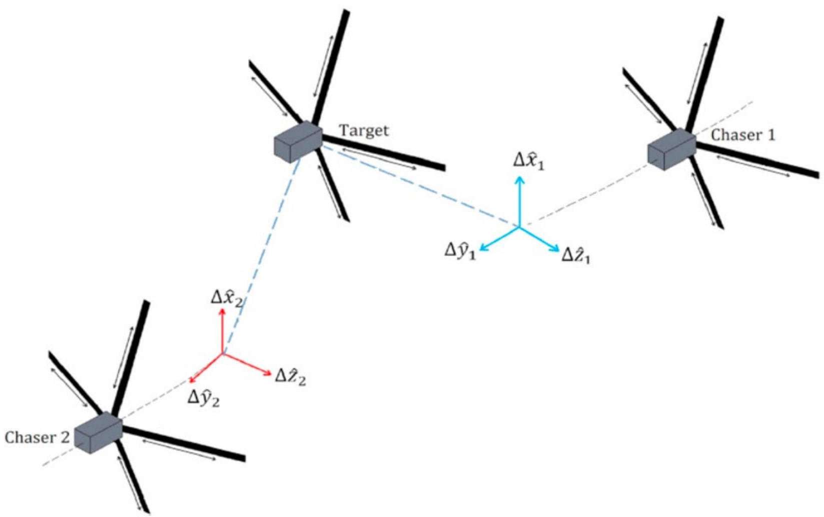
- Relative maneuvering scenario
  - One target and multiple chasers

$$\underbrace{\begin{bmatrix}\Delta\dot{x}\\ \Delta\dot{y}\\ \Delta\ddot{x}\\ \Delta\ddot{y}\end{bmatrix}}_{\dot{X}} = \underbrace{\begin{bmatrix}0 & 1 & 0 & 0\\ b & 0 & 0 & a\\ 0 & 0 & 0 & 1\\ 0 & -a & 0 & 0\end{bmatrix}}_{A} \underbrace{\begin{bmatrix}\Delta x\\ \Delta y\\ \Delta\dot{x}\\ \Delta\dot{y}\end{bmatrix}}_{X} + \underbrace{\begin{bmatrix}0\\ 0\\ 0\\ 1\end{bmatrix}}_{B} u_y$$

Relative motion between the target and a chaser



Differential drag acceleration

$$u_y = \frac{F_{D,i}}{m_i} - \frac{F_{D,t}}{m_t}$$

i: i^{th} chaser
t: target

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Relative Maneuvering

- We designed an adaptive controller to perform drag-based relative maneuvers

$u_y = \boldsymbol{Y\Theta}$ → $\boldsymbol{\Theta} \in \mathbb{R}^6$ contains ρ, C_D for target and chaser, could contain m_t as well

$$\boldsymbol{Y}\widehat{\boldsymbol{\Theta}} \triangleq \hat{\rho}_i(t)\hat{C}_D^i\widehat{\|\boldsymbol{V}_{r,i}\|^2}\bar{u}(t) - \hat{\rho}_t(t)\widehat{\|\boldsymbol{V}_{r,t}\|^2}\frac{\hat{C}_D^t S_t}{2m_t}$$

$$\bar{u} = \frac{S_i}{m_i}$$

S_i ← Cross-sectional area of the chaser

m_i ← Mass of the chaser

$$\bar{u} \triangleq \left(\hat{\rho}_i(t)\hat{C}_D^i\widehat{\|\boldsymbol{V}_{r,i}\|^2}\right)^{-1}\left(\frac{\hat{C}_D^t\hat{S}_t}{2\hat{m}_t}\hat{\rho}_t(t)\widehat{\|\boldsymbol{V}_{r,t}\|^2} - \boldsymbol{K}_{LQR}\boldsymbol{X}\right)$$

$$\dot{\hat{\boldsymbol{\Theta}}} \triangleq \text{proj}\left(2\Gamma\boldsymbol{Y}^T\boldsymbol{B}^T P^T\boldsymbol{X}\right)$$ ← Updates the Estimate of uncertain parameters

Asymptotic stability guaranteed by Lyapunov analysis, proof in:

C. Riano-Rios, R. Bevilacqua, W. E. Dixon, "Differential Drag-Based Multiple Spacecraft Maneuvering and On-Line Parameter Estimation Using Integral Concurrent Learning", Vol. 174, pp. 189-203, Acta Astronautica, 2020

Relative Maneuvering

- Modified adaptive update law to incorporate on-line parameter identification through Integral Concurrent Learning (ICL)

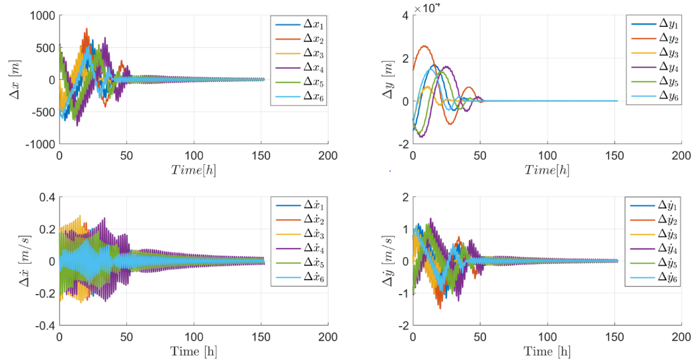
$$\dot{\hat{\Theta}} \triangleq proj\left(2\Gamma \boldsymbol{Y}^{\mathrm{T}}\boldsymbol{B}^{\mathrm{T}}P^{T}\boldsymbol{X} + \Gamma K_{ICL}\sum_{i=1}^{N_S}\left(\mathcal{Y}_i^{\mathrm{T}}\mathbf{B}^{\mathrm{T}}\left(\mathbf{X}(\mathbf{t}) - \mathbf{X}(\mathbf{t}-\Delta\mathbf{t}) - \mathcal{U}_i - \mathbf{B}\mathcal{Y}_i\hat{\Theta}\right)\right)\right)$$

Collect Input-output data

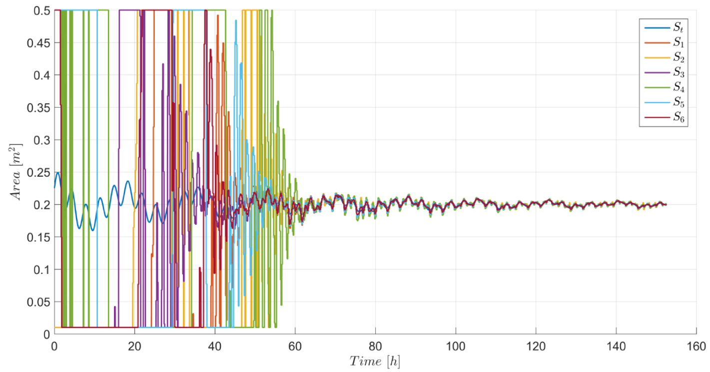
Δt: time between samples

N_s: Number of samples

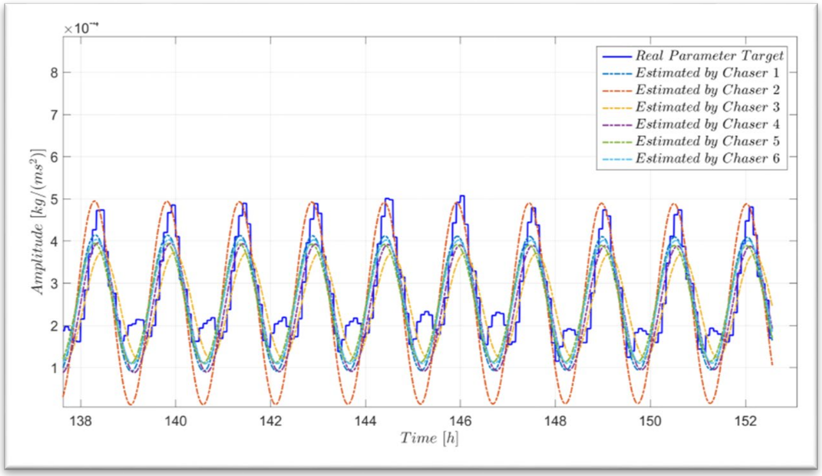
Relative states



Cross-sec. areas



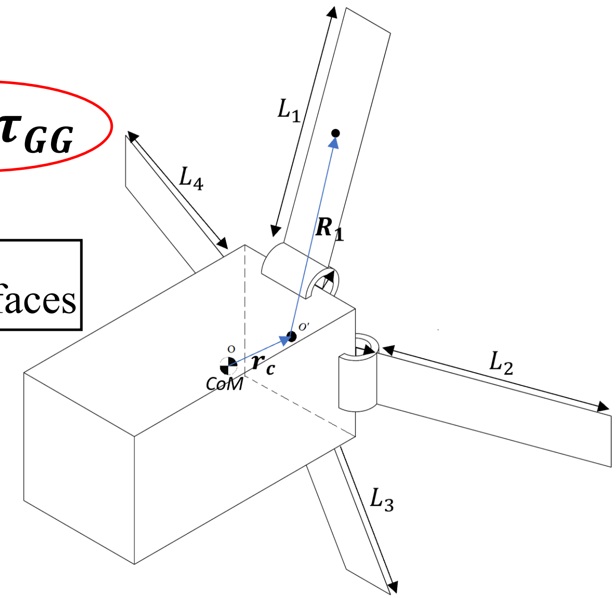
Identified params.



Attitude Control

$$\boldsymbol{\dot{J}\omega} + \boldsymbol{J\dot{\omega}} + \omega^{\times}\boldsymbol{J\omega} = \boldsymbol{\tau_{AT}} + \boldsymbol{\tau_{GG}}$$

All altered by moving the drag surfaces



- GOAL: Vary "Ls" such that the spacecraft orientation follows a desired trajectory w.r.t the inertial frame.
- Auxiliary state:

$$\boldsymbol{r} = \boldsymbol{\tilde{\omega}} + \alpha \boldsymbol{e_v}$$

$\boldsymbol{\tilde{\omega}} \in \mathbb{R}^3$ angular velocity relative to the desired attitude trajectory

$\boldsymbol{e_v} \in \mathbb{R}^3$ is the vector portion of error quaternion

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Attitude Control

$$\widetilde{\boldsymbol{N}} \triangleq -\Delta \dot{J}\tilde{\boldsymbol{\omega}} - \tilde{\omega}^{\times}\Delta J\left(\tilde{\boldsymbol{\omega}} + \widetilde{R}\boldsymbol{\omega_d}\right) - \left(\widetilde{R}\boldsymbol{\omega_d}\right)^{\times}\Delta J\tilde{\boldsymbol{\omega}} + \Delta J\tilde{\omega}^{\times}\widetilde{R}\boldsymbol{\omega_d} + \frac{1}{2}\Delta J\beta\left(e_v{}^{\times} + e_0\mathcal{I}_3\right)\tilde{\boldsymbol{\omega}},$$

$$J\dot{\boldsymbol{r}} = \boldsymbol{f} + \widetilde{\boldsymbol{N}} + \boldsymbol{N_B}$$

$$\|\widetilde{\boldsymbol{N}}\| \leq \sigma\left(\|\boldsymbol{\eta}\|\right)\|\boldsymbol{\eta}\|$$

$$\|\boldsymbol{N_B}\| \leq \zeta_4,$$

$$\boldsymbol{\eta} \triangleq \left[\boldsymbol{e_v}^T \; \boldsymbol{r}^T\right]^T$$

$$\boldsymbol{f} \triangleq \boldsymbol{\tau_D} + \boldsymbol{\tau_L} + \frac{3GM_{\oplus}}{\|\boldsymbol{R_c}\|^5}R_c{}^{\times}J_m\boldsymbol{R_c} - \dot{J}_m\boldsymbol{\omega} - \omega^{\times}J_m\boldsymbol{\omega} + J_m\omega^{\times}\widetilde{R}\boldsymbol{\omega_d} - J_m\widetilde{R}\dot{\boldsymbol{\omega}}_{\boldsymbol{d}} + J_m\beta\dot{\boldsymbol{e}}_{\boldsymbol{v}}$$

$$\boldsymbol{N_B} \triangleq -\Delta\dot{J}\widetilde{R}\boldsymbol{\omega_d} - \left(\widetilde{R}\boldsymbol{\omega_d}\right)^{\times}\Delta J\widetilde{R}\boldsymbol{\omega_d} + \frac{3GM_{\oplus}}{\|\boldsymbol{R_c}\|^5}R_c{}^{\times}\Delta J\boldsymbol{R_c} + \boldsymbol{\delta} - \Delta J\widetilde{R}\dot{\boldsymbol{\omega}}_{\boldsymbol{d}}$$

This term contains only uncertain quantities and measurable states

$$f \triangleq \tau_D + \tau_L + \frac{3GM_{\oplus}}{\|R_c\|^5} R_c{}^{\times} J_m R_c - \dot{J}_m \omega - \omega^{\times} J_m \omega + J_m \omega^{\times} \widetilde{R} \omega_d - J_m \widetilde{R} \dot{\omega}_d + J_m \beta \dot{e}_v$$

$$f = Y\Theta$$

$\Theta \in \mathbb{R}^{65}$ contains uncertain parameters (CoM, ρ, C_D, C_L)

$Y \in \mathbb{R}^{3\times 65}$ is measurable and contains the boom lengths $L's$, Which are the actual control inputs

- We designed an adaptive controller to track the desired attitude trajectory

$$Y\widehat{\Theta} \triangleq \bar{u}$$ ← This is the torque we can generate

$$\bar{u}_d \triangleq -K_1 r - \beta_1 e_v$$ ← This is the torque we design

$$\dot{\widehat{\Theta}} \triangleq \text{proj}\left(\Gamma_{\text{ICL}} Y^T r\right)$$

Attitude Control

$$\chi \triangleq \bar{u} - \bar{u}_d \in \mathbb{R}^3$$

Want to make this as small as possible by changing L's

Hard to solve for L's analytically, then:

$$\min_{L's} \|\chi\| \quad subject\ to \ \{0 \leq L_j \leq 3.7\ m\,, \qquad j = 1,2,3,4$$

Any numerical algorithm has residual error, then assume:

$\|\chi\| \leq \zeta_7, \;\; \zeta_7 \in \mathbb{R}_{>0}$ is a known constant

- MATLAB's *fmincon* was used in simulation to solve for L's every 30 seconds
- Globally Uniformly Ultimately Bounded (GUUB) result is guaranteed by Lyapunov analysis, proof in:

C. Riano-Rios, R. Sun, R. Bevilacqua, W. E. Dixon, "Aerodynamic and Gravity Gradient based Attitude Control for CubeSats in the presence of Environmental and Spacecraft Uncertainties," Vol. 180, pp. 439-450, Acta Astronautica, 2021

Attitude Control

Under some additional assumptions, such as:

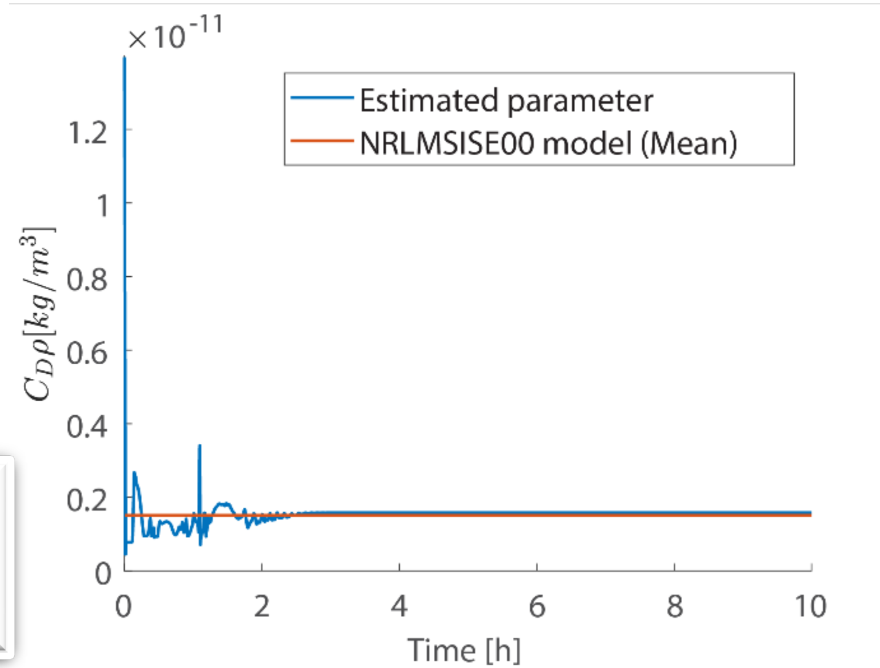
- Accurate models for CoM location and inertia matrix J
- Compensation for average of the product: ρC_D

ICL could also be implemented in the attitude control problem

$$\dot{\hat{\Theta}} = \text{proj}\left(\Gamma_{ICL} Y^T \boldsymbol{r} + \Gamma_{\text{ICL}} k_{ICL} \sum_{i=1}^{N} \mathcal{Y}_i^T (\mathcal{U}_i - \mathcal{Y}_i \hat{\Theta})\right)$$

Collect input – output data

Having redundant ICL-derived information about ρ and C_D may be possible using different portions of the spacecraft dynamics!



Roto-translational control

Relative maneuvering control law:

Assumes that the spacecraft are attitude stabilized

Provides the required total cross-sectional area

- It is a function of the S/C attitude and DMD lengths .

Coupled

Attitude control law:

Does not care about the resulting orbital trajectory

Provides the required torques.

- Depending on how these torques are generated with the DMD, the total cross-sectional area gets modified.

Roto-translational control

Proposed approach

- Incorporate additional constraint to the numerical algorithm that solves for L's

$$\min_{\{L_1,L_2,L_3,L_4\}} \{W_{att} \|\bar{\boldsymbol{u}} - \bar{\boldsymbol{u}}_{\boldsymbol{d}}\| + W_{orb}(S - S_d)^2\}$$
$$subject\ to \left\{0 \leq L_j \leq 3.7m \quad j = 1,2,3,4\right.$$

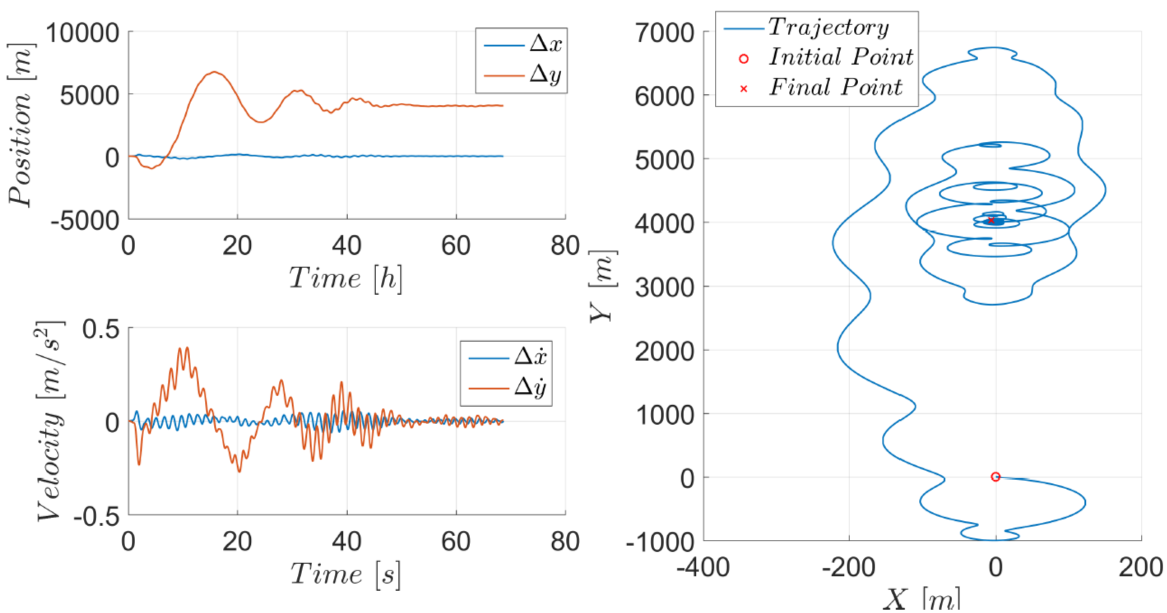
S_k: cross-sectional area, function of attitude states and L's
$\bar{\boldsymbol{u}}$: applied torque, function of attitude/orbit states and L's
Subscript "d" indicates the desired values, provided by the corresponding control laws

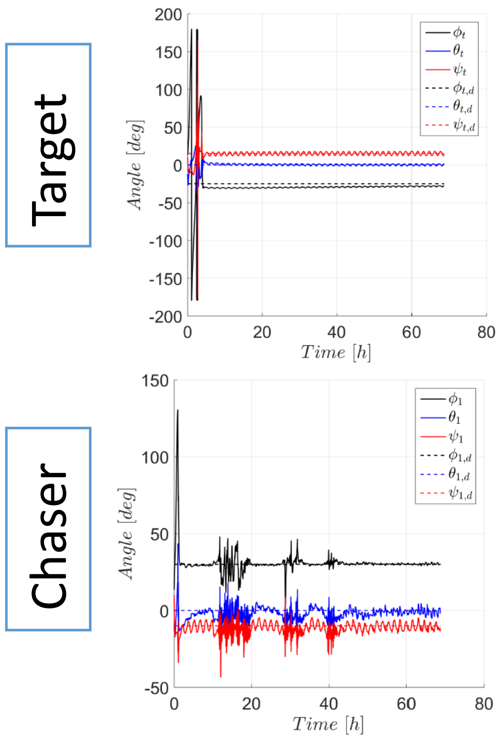
W_{att} and W_{orb} are user-defined weights used to prioritize between attitude and orbit controllers.

Roto-translational control

Simulation:

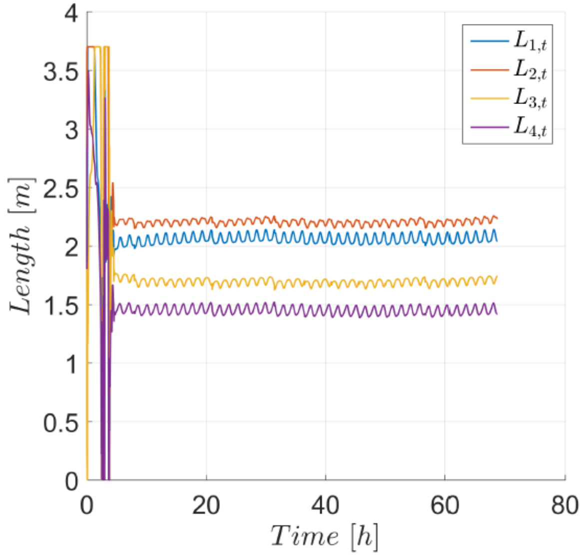
- Proposed maneuver: spacecraft are deployed simultaneously; the chaser is tasked to perform an along-orbit formation with 4km separation w.r.t. the target.
- Both spacecraft are tasked to achieve a desired constant orientation w.r.t. the orbital frame.



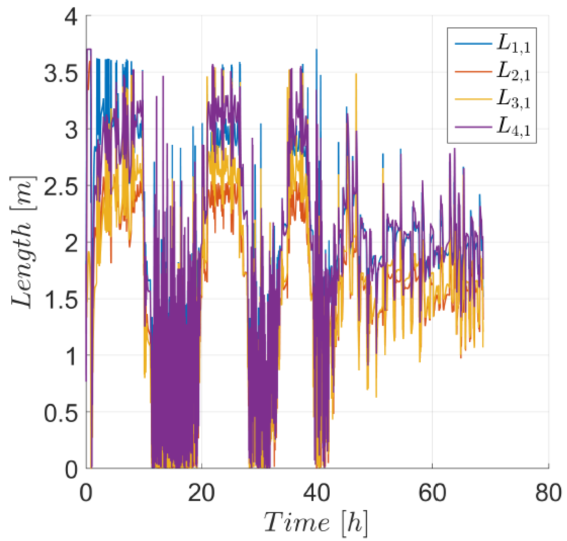


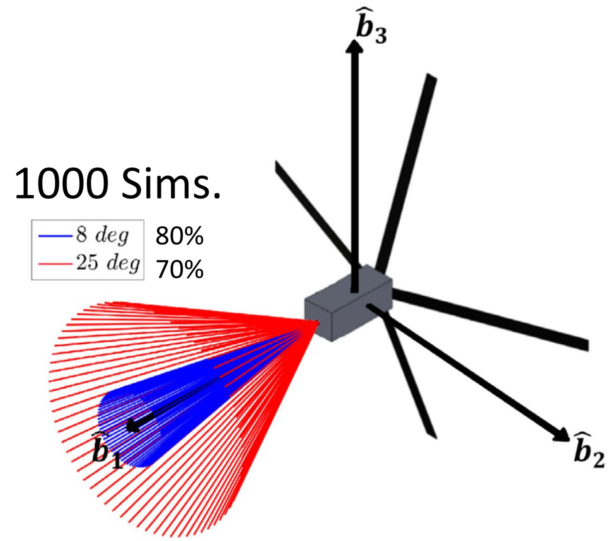
Roto-translational control

Target



Chaser





Due to the use of aerodynamic forces, and the location of the center of pressure, attitude can be effectively controlled inside a cone.

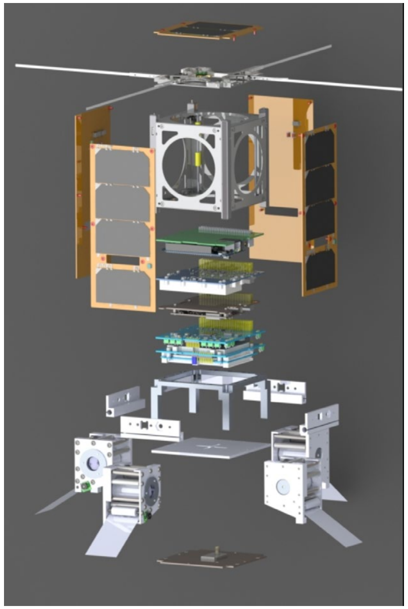
Frequent comment: Influence on the flexible appendages?

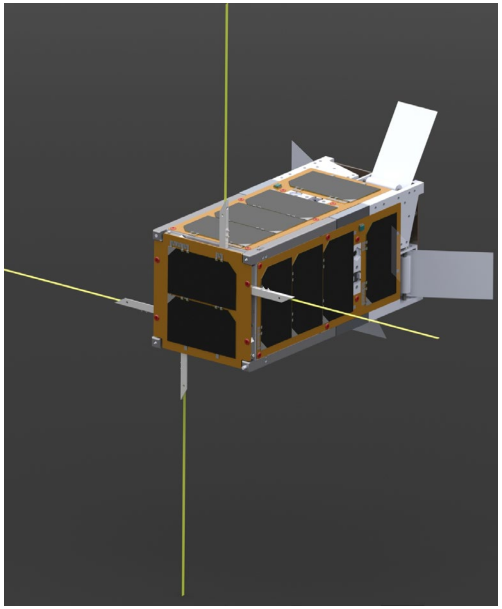
D3 CubeSat

D3: Drag De-orbit Device, now called Drag Maneuvering Device (DMD)

Main mission:

- proof of concept for the deployable surfaces
- Validate a drag-based targeted point re-entry algorithm by modulating the device





Passive attitude stabilization: keep roll, pitch and yaw bounded (+/- 20 deg) with drag and gravity gradient torque.

Test deployer design and performance.

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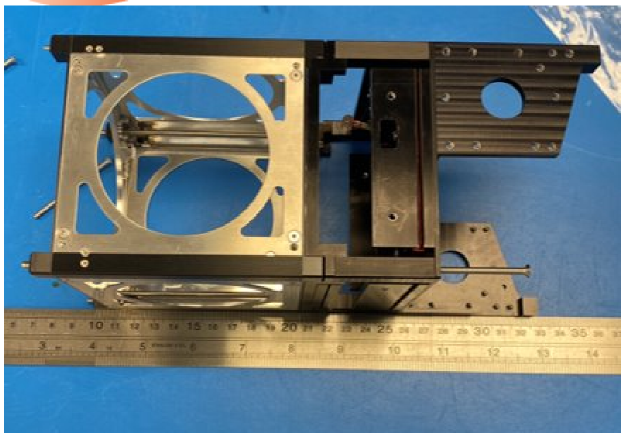
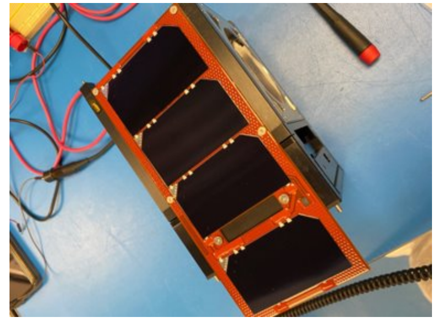
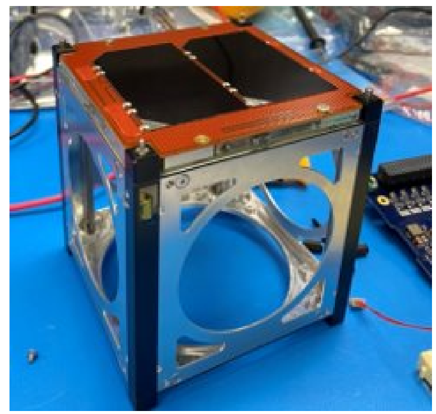
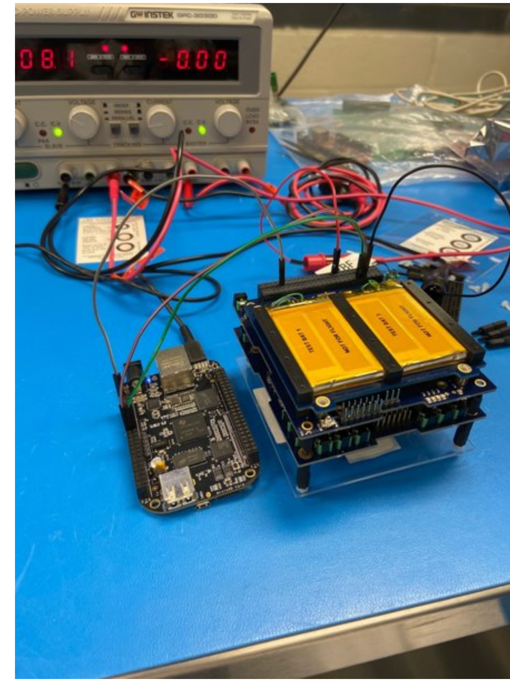
D3 CubeSat

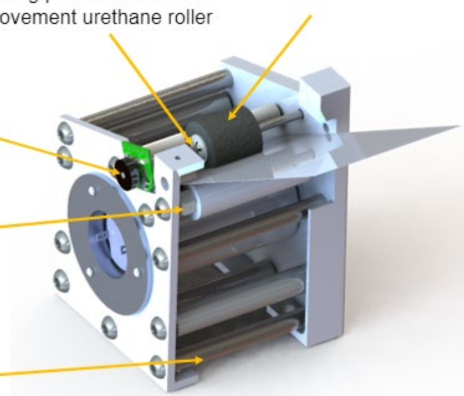


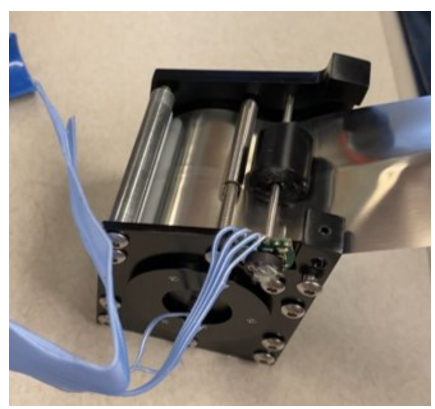


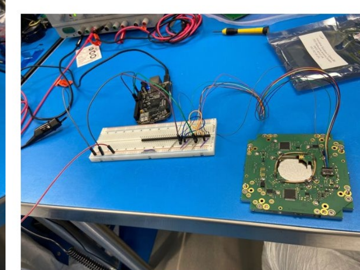




ROS







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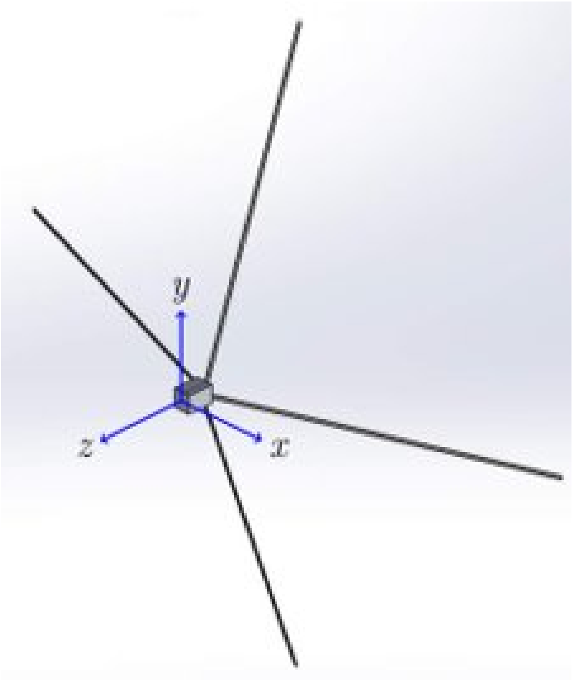
D3 CubeSat

Surfaces are 3.7 m long.
Surfaces manually bent to add stiffness

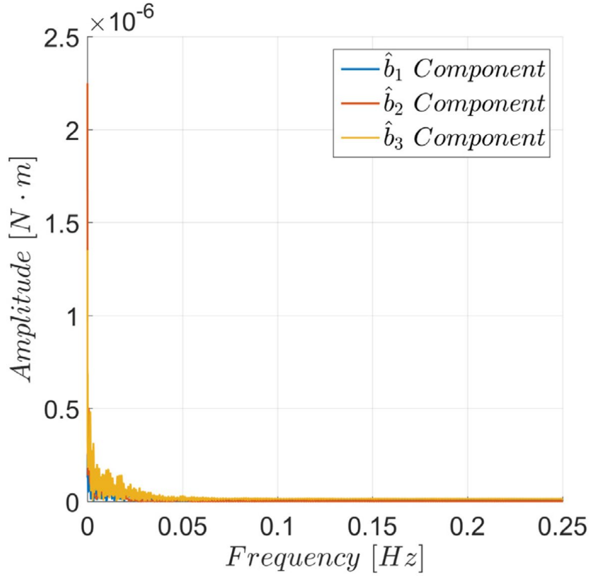


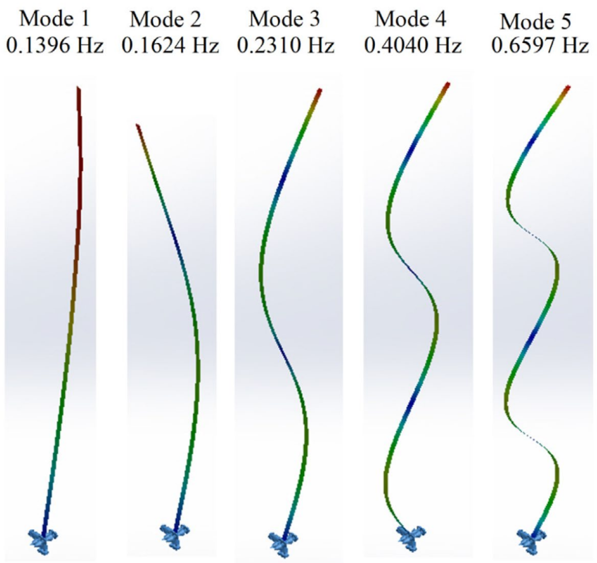
Natural frequencies and damping ratios are difficult to accurately compute due to the manual process, potential effects of the launch, etc.

How can we evaluate the effect of the applied torques on these flexible appendages?

Flexible Body

- Current approach: Compare FFT VS Vibration modes obtained with SolidWorks





- Can we do better? Incorporate influence of flexible bodies into the attitude dynamics. for a standard spacecraft:

$$J\dot{\boldsymbol{\omega}} + \delta^T \ddot{\boldsymbol{\eta}} = -\omega^{\times}\left(J\boldsymbol{\omega} + \delta^T \dot{\boldsymbol{\eta}}\right) + \boldsymbol{u}$$

$$\ddot{\boldsymbol{\eta}} + C\dot{\boldsymbol{\eta}} + K\boldsymbol{\eta} = -\delta\dot{\boldsymbol{\omega}},$$

$\boldsymbol{\eta}$: modal coordinates
δ: coupling matrix (constant)
C: Damping matrix (constant)
K: Stiffness matrix (constant)

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Flexible Body

$$J\dot{\boldsymbol{\omega}} + \delta^T \ddot{\boldsymbol{\eta}} = -\omega^\times \left(J\boldsymbol{\omega} + \delta^T \dot{\boldsymbol{\eta}}\right) + \boldsymbol{u}$$
$$\ddot{\boldsymbol{\eta}} + C\dot{\boldsymbol{\eta}} + K\boldsymbol{\eta} = -\delta\dot{\boldsymbol{\omega}},$$

$\boldsymbol{\eta}$: modal coordinates
δ: coupling matrix (constant)
C: Damping matrix (diagonal, constant)
K: Stiffness matrix (diagonal, constant)

- Control objective: Attitude tracking (i.e. $||e_v||, ||\omega|| \to 0$ as $t \to \infty$)
- Since C and K are difficult to compute, can we estimate their real values using ICL?

- Proposed approach: Design an ICL-based adaptive controller for attitude tracking and online estimation of C and K:

desired attitude: q_d and ω_d → Error quaternion e and relative angular velocity $\tilde{\omega}$

- Auxiliary state: $\boldsymbol{r} \triangleq \tilde{\boldsymbol{\omega}} + \alpha \boldsymbol{e}_v$
- Open-loop error system:

$$J_m \dot{\boldsymbol{r}} = \delta^T \left(C\dot{\boldsymbol{\eta}} + K\boldsymbol{\eta}\right) - \omega^\times \left(J\boldsymbol{\omega} + \delta^T \dot{\boldsymbol{\eta}}\right) + \boldsymbol{u} - J_m \left(\widetilde{R}\dot{\boldsymbol{\omega}}_d - \tilde{\omega}^\times \widetilde{R}\boldsymbol{\omega}_d - \alpha \dot{\boldsymbol{e}}_v\right)$$

Flexible Body

- Define: $Y\boldsymbol{\Theta} \triangleq \delta^T\left(C\dot{\boldsymbol{\eta}} + K\boldsymbol{\eta}\right)$

- Design: $\boldsymbol{u} = J_m\left(\widetilde{R}\dot{\boldsymbol{\omega}}_d - \tilde{\omega}^\times\widetilde{R}\boldsymbol{\omega}_d - \alpha\dot{\boldsymbol{e}}_v\right) + \omega^\times\left(J\boldsymbol{\omega} + \delta^T\dot{\boldsymbol{\eta}}\right) - Y\widehat{\boldsymbol{\Theta}} - K\boldsymbol{r} - \boldsymbol{e}_v$

and

$$\dot{\widehat{\boldsymbol{\Theta}}} \triangleq \operatorname{proj}\left(\Gamma Y^T r + \Gamma K_{ICL}\sum_{i=1}^{M}\mathcal{Y}_i^T\left(J_m\left(\boldsymbol{r}(t) - \boldsymbol{r}(t-\Delta t)\right) - \mathcal{U}_i - \mathcal{Y}_i\widehat{\boldsymbol{\Theta}}\right)\right)$$

where

$$\mathcal{U}(\Delta t, t) \triangleq \int_{t-\Delta t}^{t}\Big[\boldsymbol{u}(\sigma) - \omega^\times(\sigma)\left(J\boldsymbol{\omega}(\sigma) + \delta^T\dot{\boldsymbol{\eta}}(\sigma)\right) + \\ - J_m\left(\widetilde{R}(\sigma)\dot{\boldsymbol{\omega}}_d(\sigma) - \tilde{\omega}^\times(\sigma)\widetilde{R}(\sigma)\boldsymbol{\omega}_d(\sigma) - \alpha\dot{\boldsymbol{e}}_v(\sigma)\right)\Big]d\sigma$$

$$\mathcal{Y}(\Delta t, t) \triangleq \int_{t-\Delta t}^{t} Y(\sigma)d\sigma$$

- Assumption: Finite excitation condition is satisfied after $t = T$, $\bar{\lambda}$ is positive user-defined constant.

$$\lambda_{min}\left\{\sum_{i=1}^{M}\mathcal{Y}_i^T\mathcal{Y}_i\right\}\geq\bar{\lambda}$$

- Stability result (preliminary): GUUB.

- For $t < T$, $\boldsymbol{y} = [\boldsymbol{r}^T \quad \boldsymbol{e}_v^T]^T$

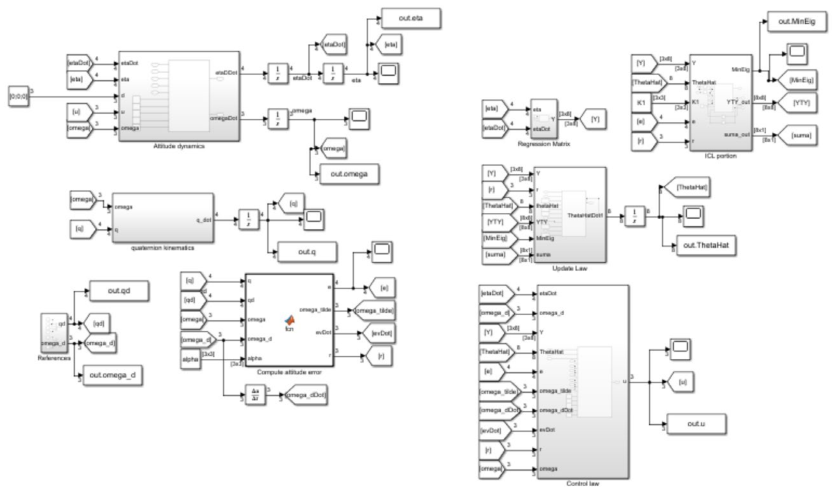
$$\|\boldsymbol{y}\|^2\leq\left(\frac{\lambda_2\|\boldsymbol{y}(0)\|^2+\xi_2}{\lambda_1}\right)\exp\left(-\frac{\lambda_3}{\lambda_2}t\right)+\frac{\xi_2-\xi_1}{\lambda_1}$$

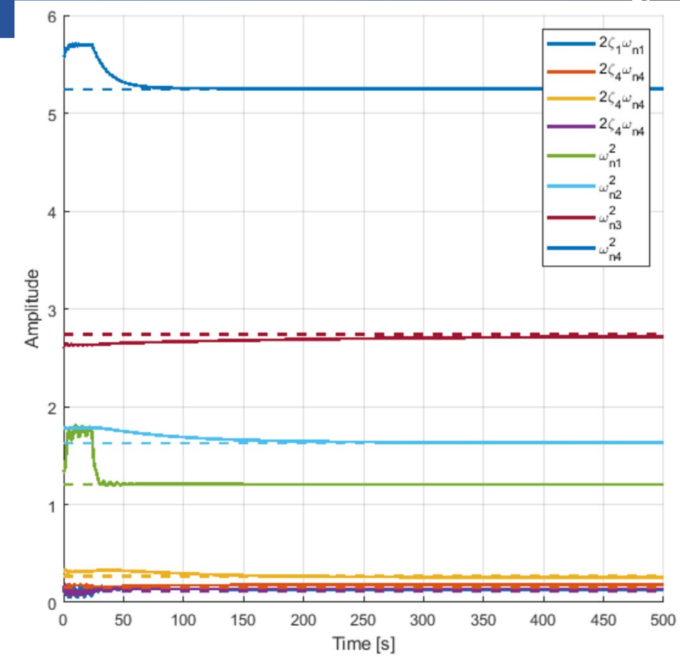
- After $t \geq T$, $\boldsymbol{z} = \left[\boldsymbol{r}^T \ \ \boldsymbol{e}_v^T \ \ \widetilde{\boldsymbol{\Theta}}^T\right]^T$

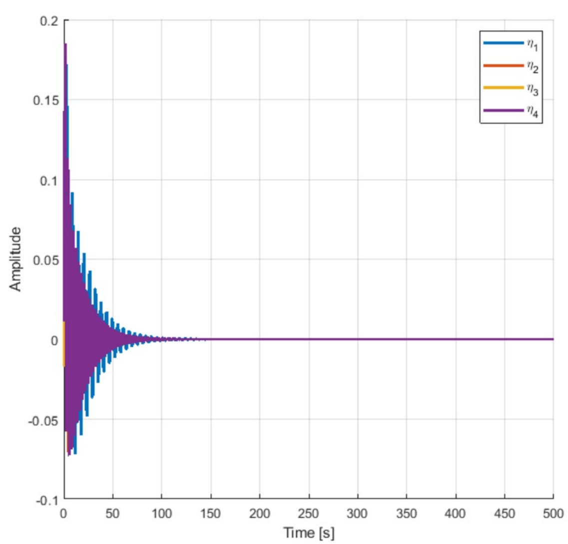
$$\|\boldsymbol{z}\|^2\leq\frac{\lambda_5\|\boldsymbol{z}(0)\|^2+\xi_2}{\lambda_4}\exp\left(\frac{\lambda_6}{\lambda_5}T\right)\exp\left(-\frac{\lambda_6}{\lambda_5}t\right)+\frac{\xi_4-\xi_3}{\lambda_4}$$

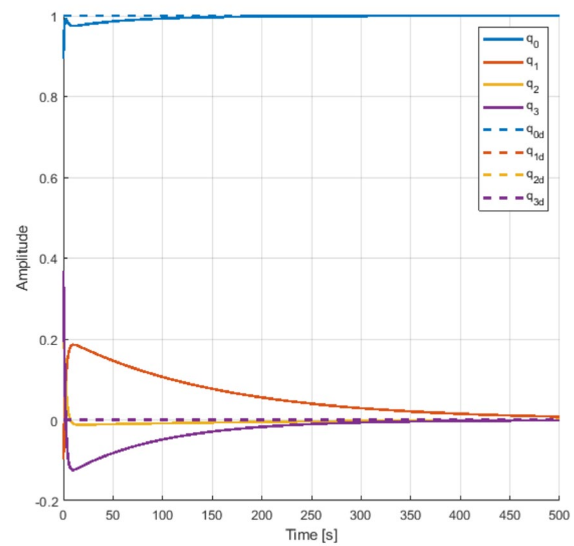
Flexible Body

- Preliminary simulation (not DMD-equipped CubeSat):









Next:

- Incorporate of flexible appendages into the DMD-equipped CubeSat dynamics.
- Evaluate performance of the designed controller.
- Try to relax the requirement of $\boldsymbol{\eta}$ and its time derivative being measurable.

Conclusion

- We have demonstrated in simulation the performance of a roto-translational adaptive controller using environmental forces and torques for DMD-equipped CubeSats.

- The D3 CubeSat will validate the design of the retractable deployers and the performance of the “dart” configuration for passive attitude stabilization and modulation of the drag acceleration.

- Preliminary design of an adaptive attitude controller that estimates the damping and stiffness parameters associated with the spacecraft modes has shown potential for its future improvement and implementation into the DMD-equipped CubeSat problem

Thank you