



PTERODACTYL: DEVELOPMENT AND EVALUATION OF CONTROL DESIGNS FOR A MECHANICALLY DEPLOYED ENTRY VEHICLE

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CITY OF CUPERTINO SPEAKER SERIES

February 19th, 2020

Cupertino, CA

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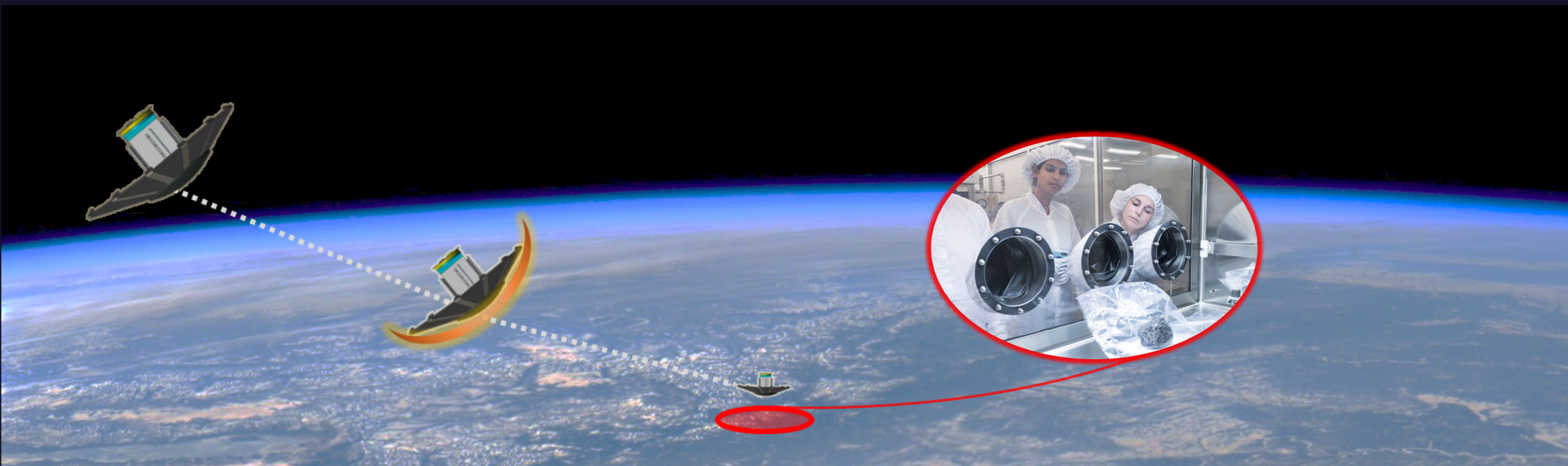
Dr. Stephen Robinson
Brandon Reddish



MOTIVATION, BACKGROUND, & VEHICLE OVERVIEW



MOTIVATION

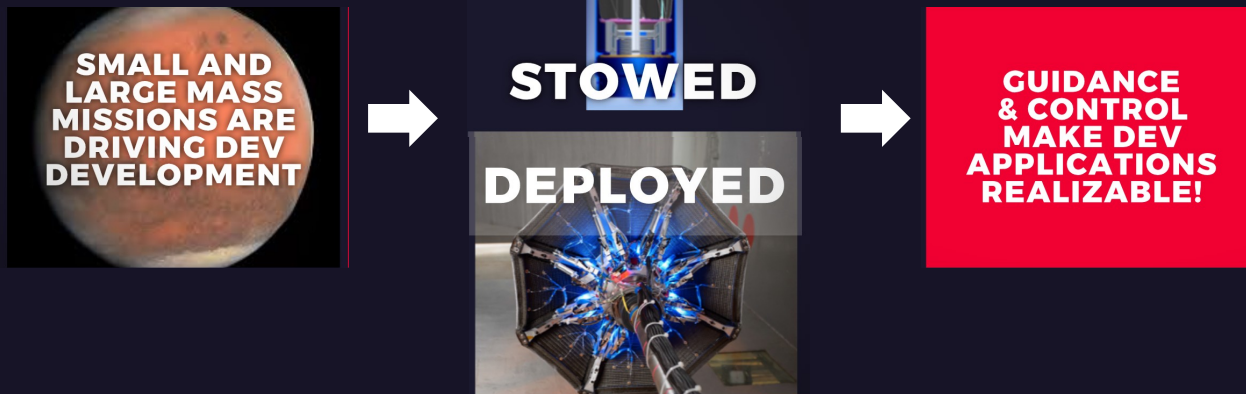


Precision landing close to research facilities reduces operational recovery costs and enables timely sample retrieval



BACKGROUND

NASA's Space Technology Mission Directorate is funding Pterodactyl through the **Early Career Initiative (ECI) Award** to address the need for deployable entry vehicles that can land small and large mass payloads precisely

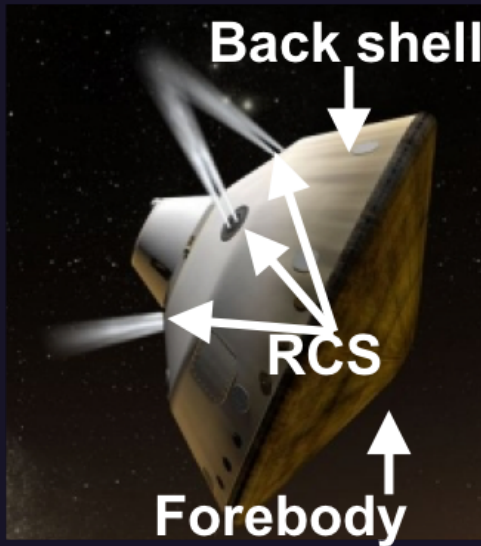


Deployable Entry Vehicles (DEV)

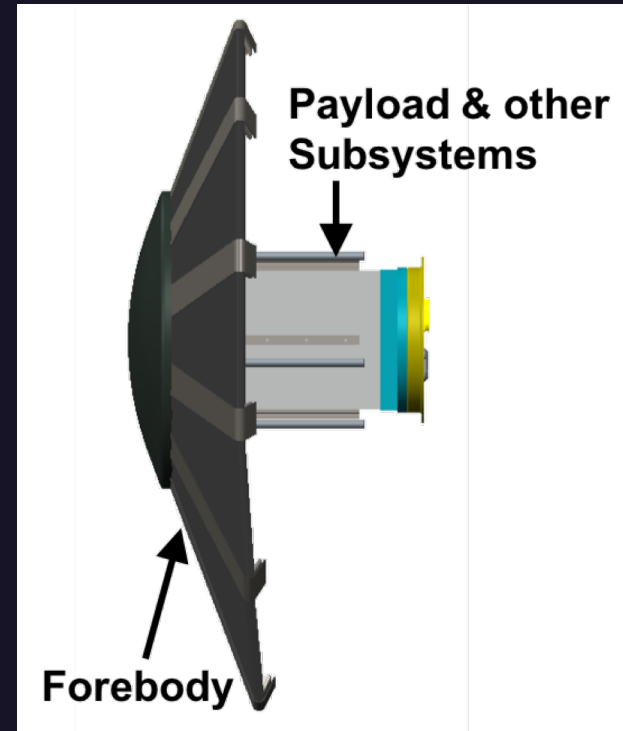


WHY IS THIS A CHALLENGE?

Heritage Entry Vehicle with
Reaction Control System (RCS)



DEVs have no back shell



RESEARCH QUESTION

What control system can be integrated into the DEV structure and enable steering to a target location precisely?



BASELINE MISSION OVERVIEW

Lunar Return mission (Stress case for loads)

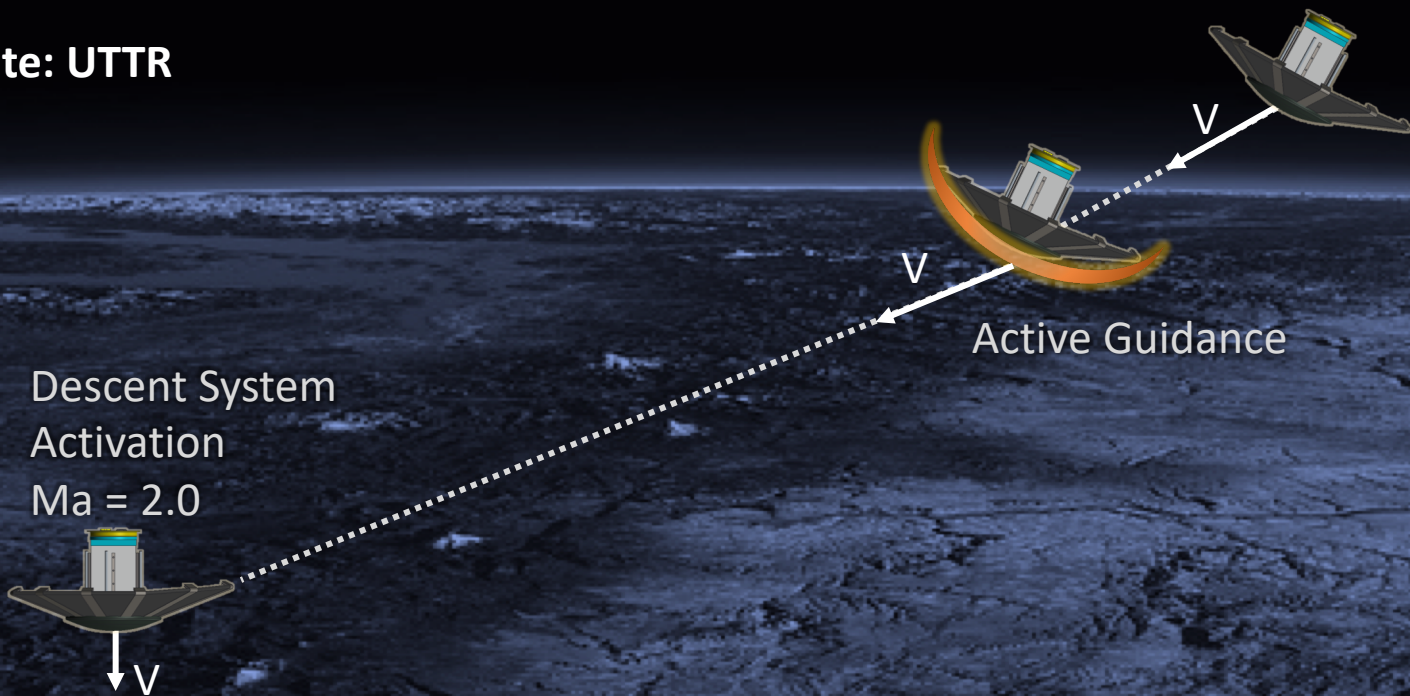
Focused on Entry phase

Target site: UTTR

Entry Interface

$h_{EI} = 122 \text{ km}$

$V_{EI} = 11.0 \text{ km/s}$



Descent System
Activation

$Ma = 2.0$

EARTH



PTERODACTYL BASELINE VEHICLE (PBV)

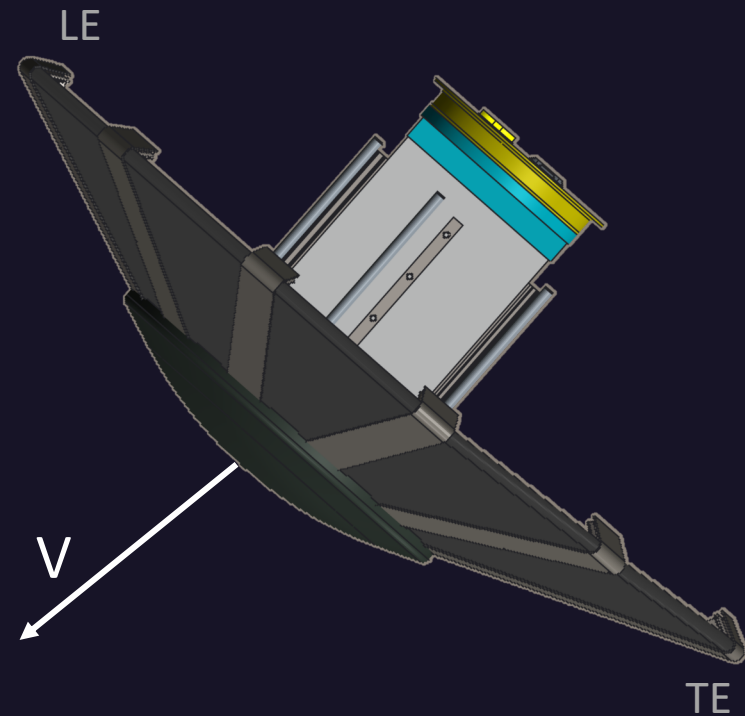
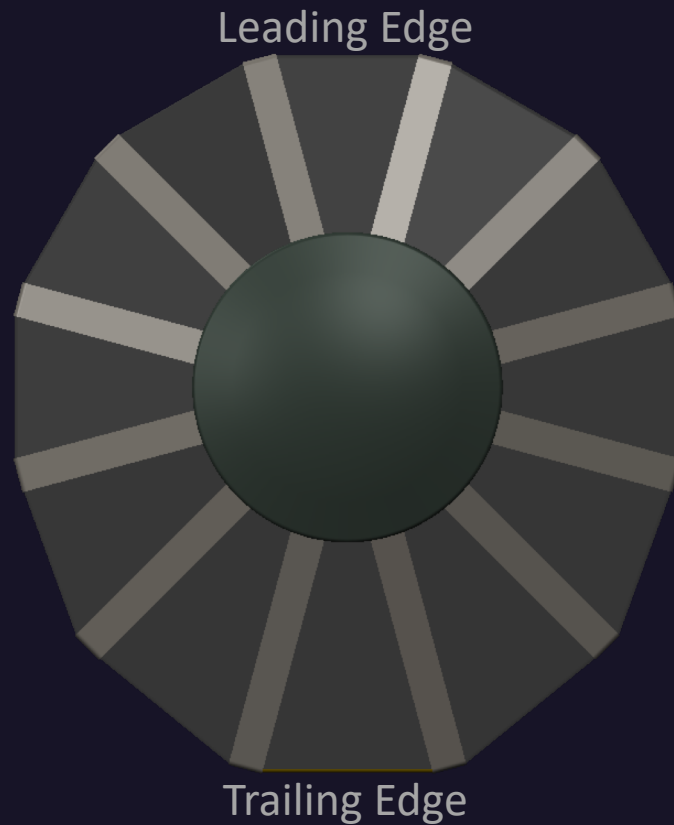
asymmetric

diameter = 1+ m

mass = 59.4 kg

$L/D_{\text{trim}} = 0.2$

$\alpha_{\text{trim}} = -12^\circ$



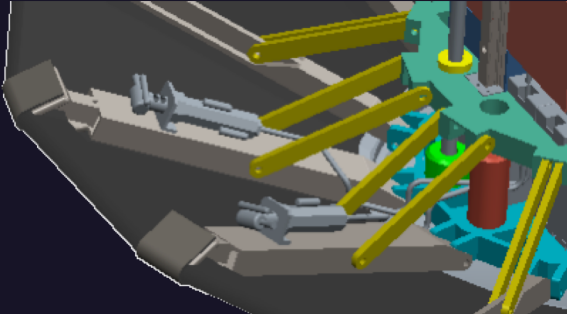
CONTROLS GOALS

Utilize aerodynamic data, mass, and inertia properties of LNA to:

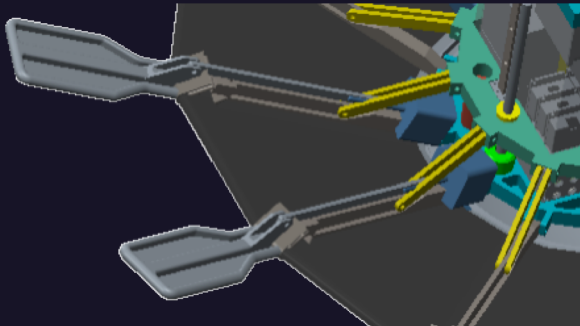
- (i) understand vehicle,**
- (ii) create representation of vehicle,**
- (iii) command vehicle to follow feasible guidance trajectories within mechanical limits & employing unconventional control methods**
- (iv) compare control systems and down-select**



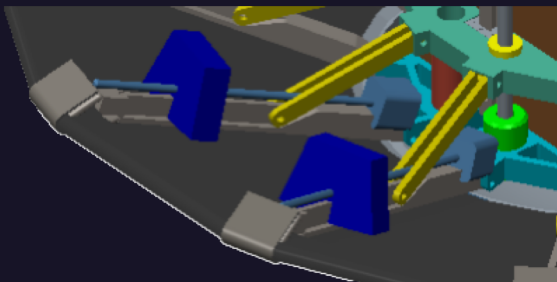
CONTROL SYSTEM DESCRIPTIONS



- Reaction Control System (RCS)



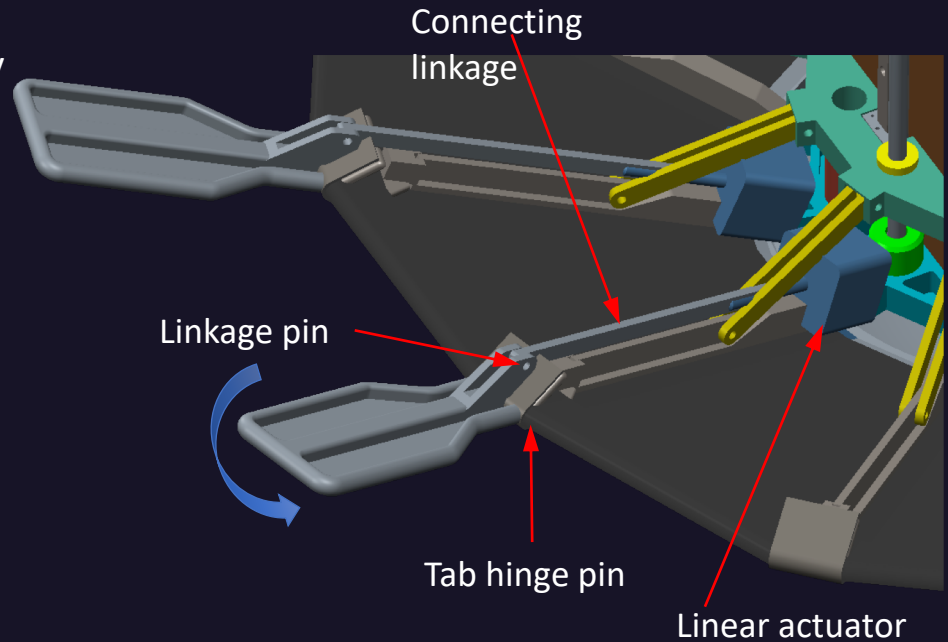
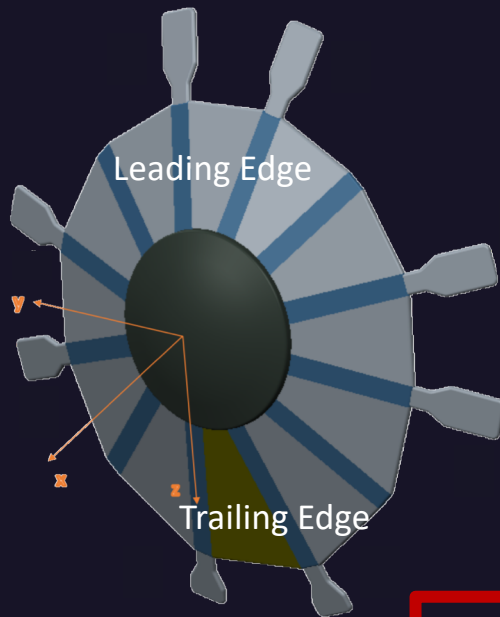
- Flap Control System (FCS)



- Moving Mass Control System (MMCS)

FLAP DESIGN

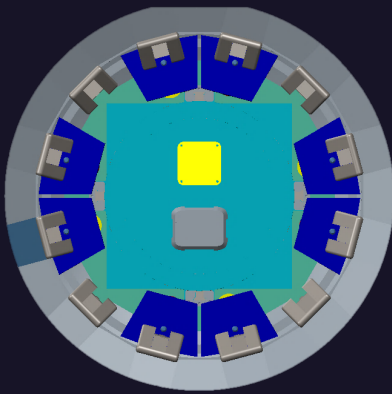
8 flaps to increase control authority, reduce of multi-axis coupling due to flap locations, & satisfy packaging/stowing constraints



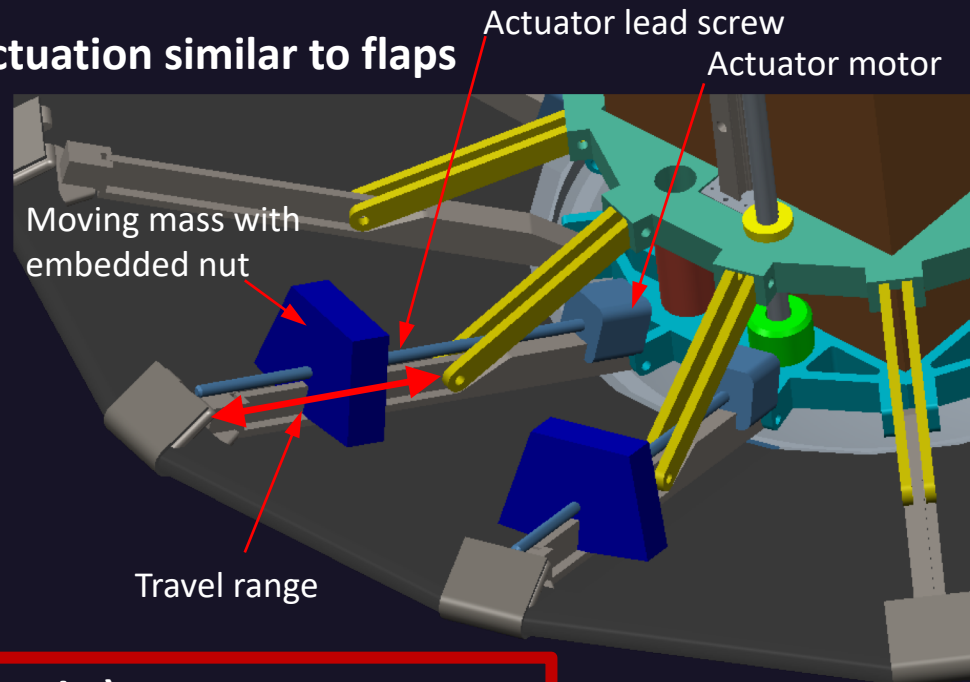
- **Mass: 75.7 kg (updated after TPS sizing)**
- **Deflection Range: -45° to $+20^{\circ}$**

MASS MOVEMENT DESIGN

Mass size limited by stowed state

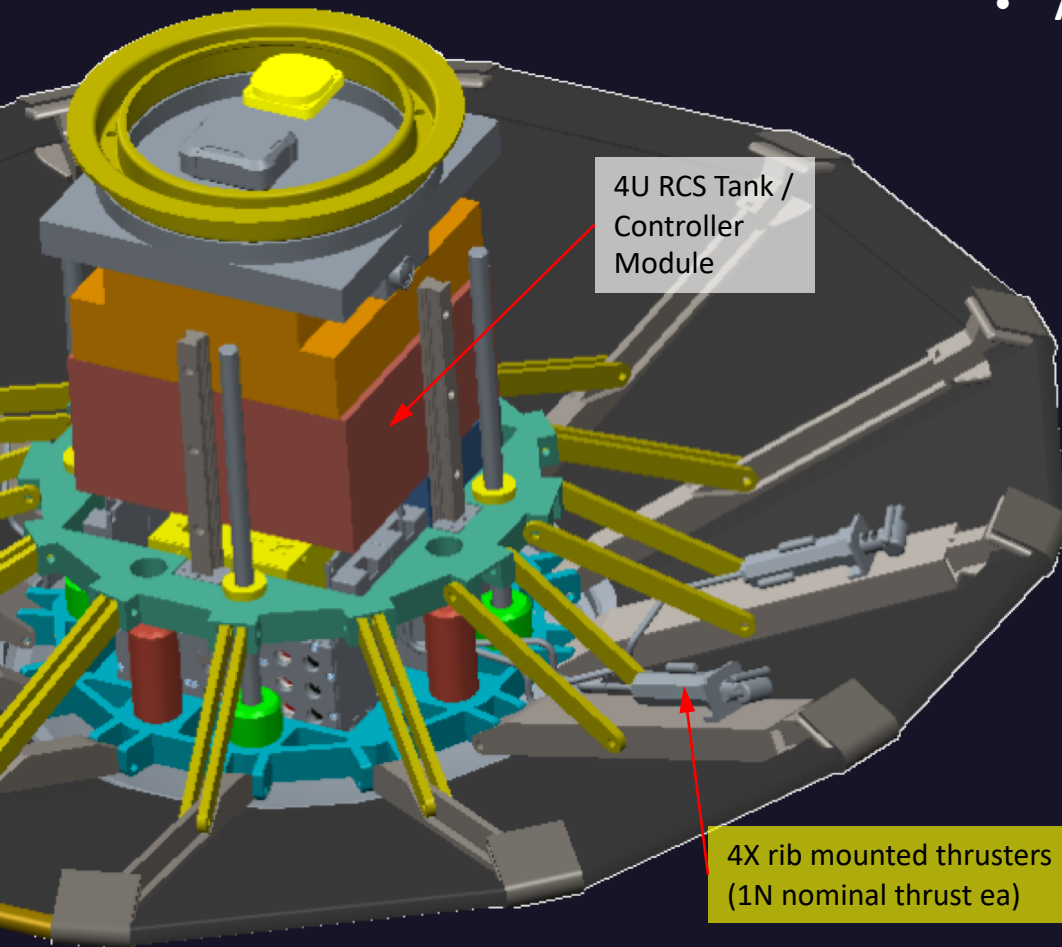


Actuation similar to flaps



- **Mass: 80.1 kg (>ABC max allowable of 77 kg)**
 - Moving masses sizes: 2 kg each

RCS DESIGN



4U RCS Tank /
Controller
Module

4X rib mounted thrusters
(1N nominal thrust ea)

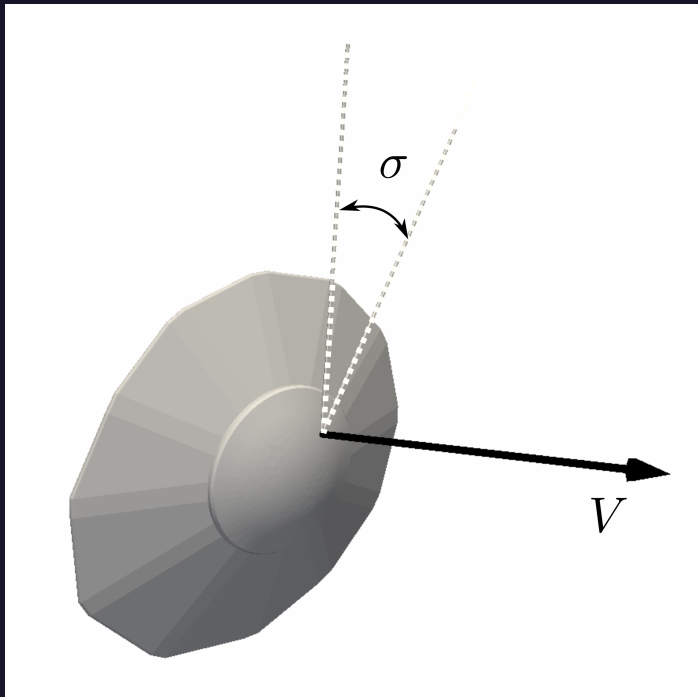
- APL performed an RCS sizing study
 - ➔ Recommended locating thrusters at a larger reaction radius
 - ➔ Recommended Hydrazine or Green Prop to provide adequate Impulse

- **Mass: 69.1 kg**
- **Capability:**
 - 1N thrusters on lateral ribs
 - Thrust reaction radius: 0.39m

GUIDANCE COMMANDS

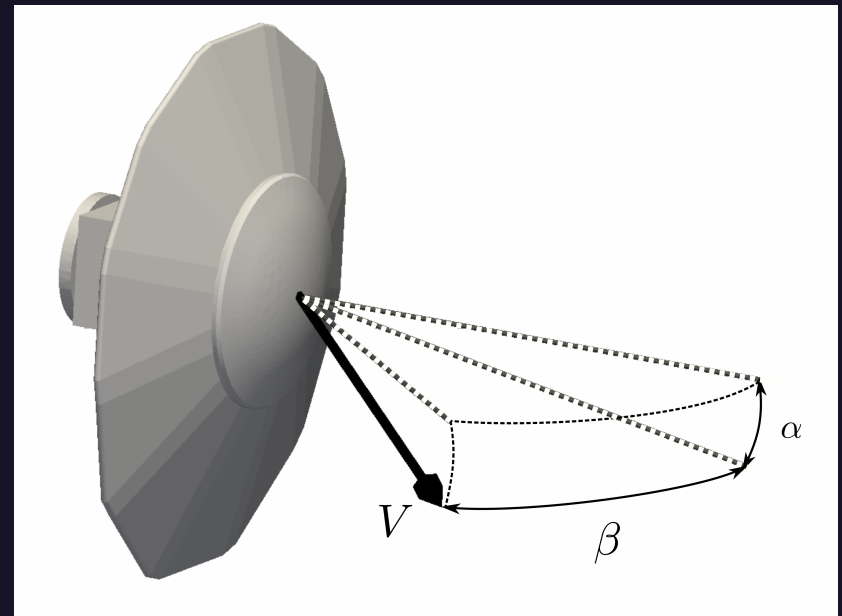
Heritage:

bank (σ) commands

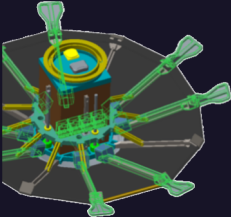
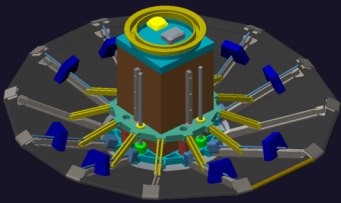
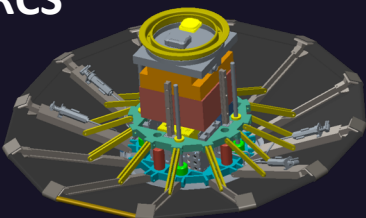


Alternative:

angle of attack (α) and side slip (β) commands

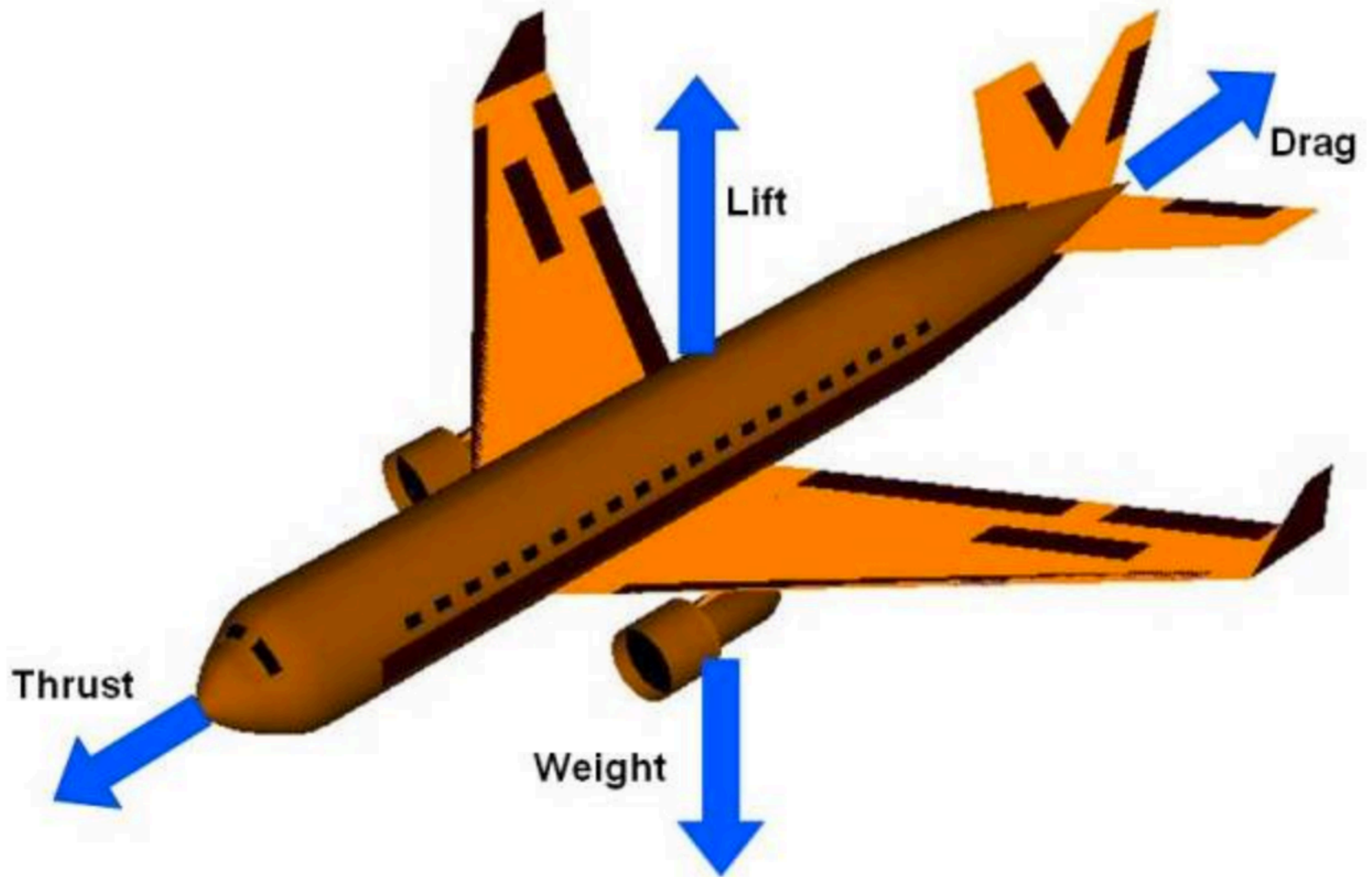


CONTROL SYSTEM DESCRIPTIONS

Configuration	Capability	Control Outputs	Requirements
Flaps 	α/β <u>Decoupled</u> down/cross range control OR σ <u>Coupled</u> down/cross range control	Flap Deflection Angle	Map flap deflections (in/out of the flow)
Moving masses 		Mass movement distance	Map mass displacement as fraction of maximum distance
RCS 		Moments/torques required	Map thruster selection & duration

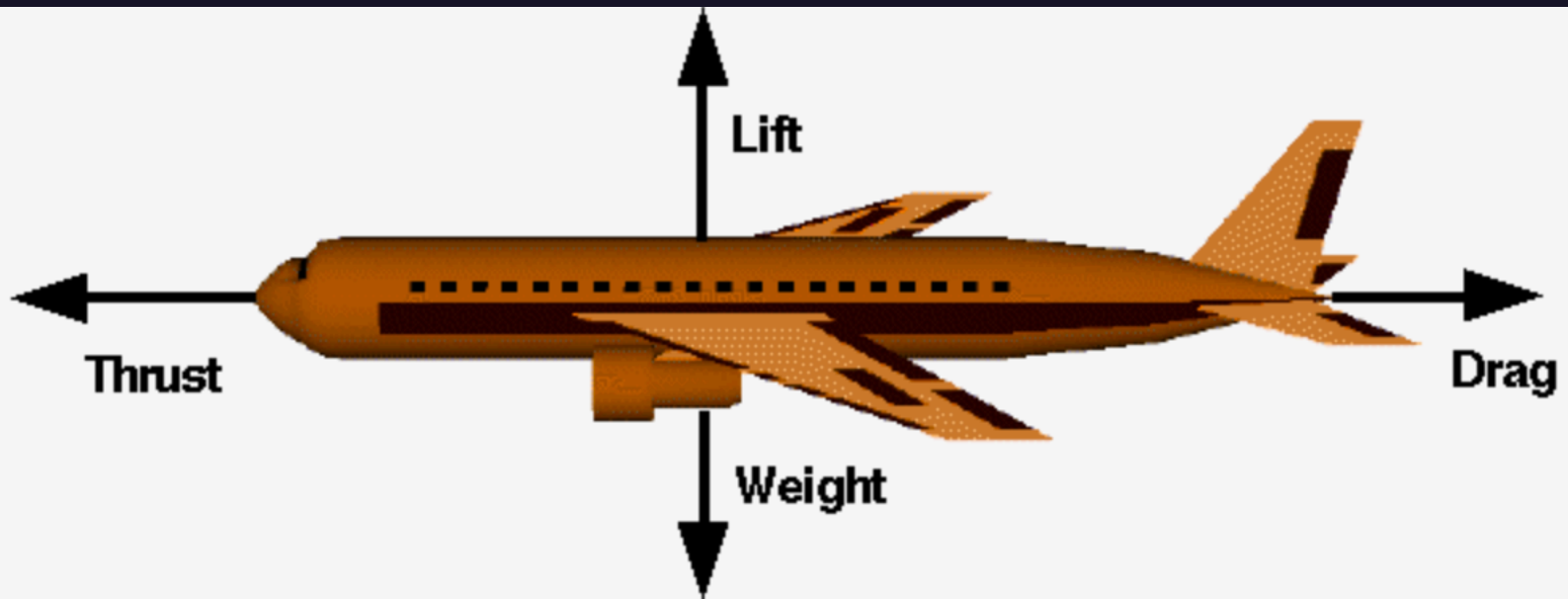
SIMULATION DEVELOPMENT & CONTROL DESIGN





Credit: <https://www.grc.nasa.gov/www/k-12/airplane/forces.html>

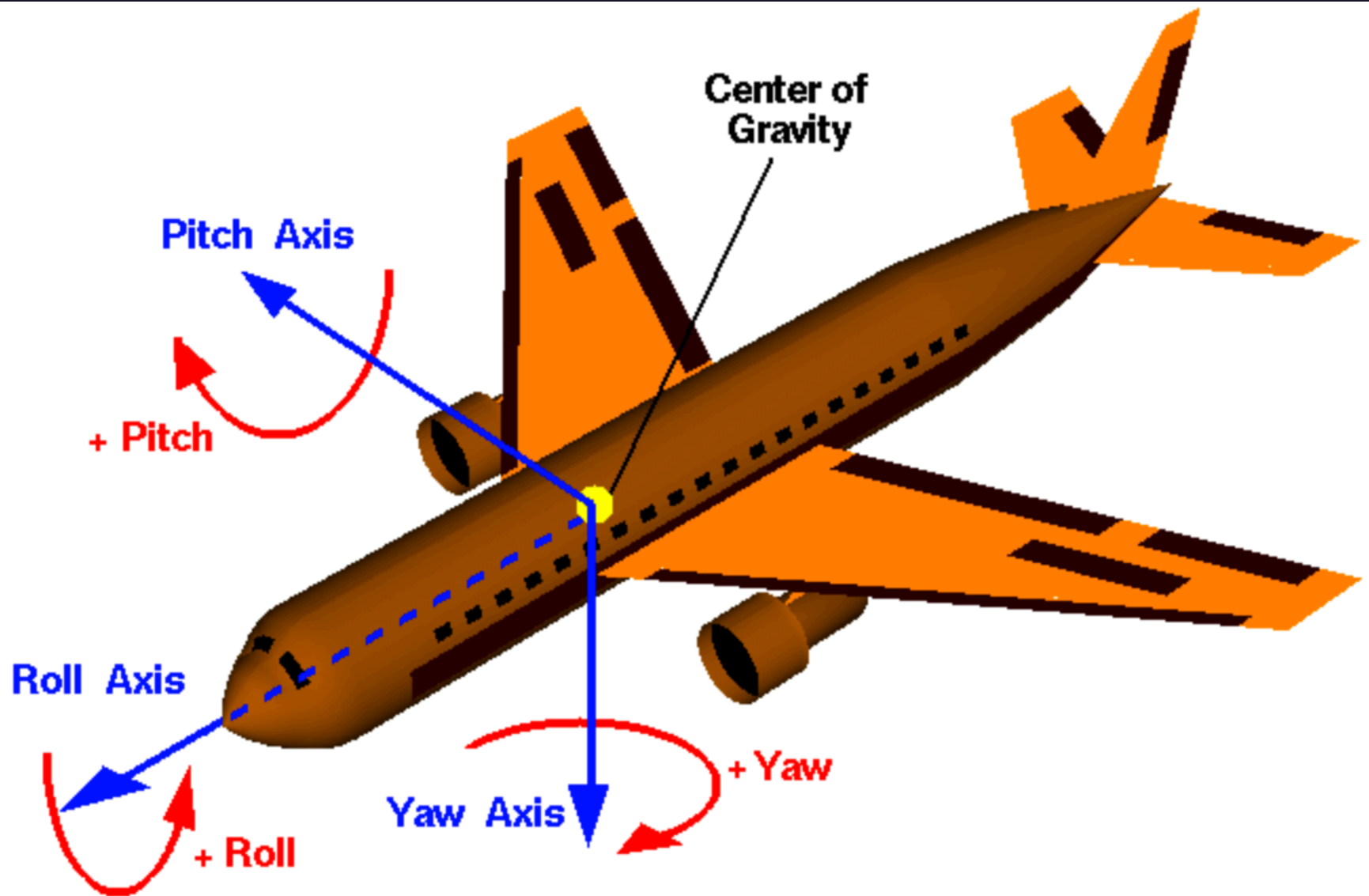




Flight Condition	Effect
$\text{Lift} > \text{Weight}$	Plane Rises
$\text{Weight} > \text{Lift}$	Plane Falls
$\text{Drag} > \text{Thrust}$	Plane Slows
$\text{Thrust} > \text{Drag}$	Plane Accelerates

Credit: <https://www.grc.nasa.gov/www/k-12/airplane/forces.html>





Credit: <https://www.grc.nasa.gov/www/k-12/airplane/forces.html>



KEY ELEMENTS

- Represent non-linear vehicle EOMs in state space form and derive linear controller
- Consider non-linear EOMs

$$\begin{aligned}\dot{V}(t) &= -\frac{g[z(t)]}{m} \sin[\gamma(t)] - \frac{1}{m} D(t) \\ \dot{\gamma}(t) &= \left(-\frac{g[z(t)]}{m V(t)} + \frac{V(t)}{z(t)} \right) \cos[\gamma(t)] + \frac{1}{m V(t)} (L(t) \cos[\sigma(t)] - S(t) \sin[\sigma(t)])\end{aligned}$$

Drag, Lift, & Side Forces

$$\begin{bmatrix} \dot{p}(t) \\ \dot{q}(t) \\ \dot{r}(t) \end{bmatrix} = \left(\mathbb{I}_b^{B/B_{cm}} \right)^{-1} \left(\begin{bmatrix} \mathcal{L}(t) \\ \mathcal{M}(t) \\ \mathcal{N}(t) \end{bmatrix} - \begin{bmatrix} p(t) \\ q(t) \\ r(t) \end{bmatrix} \times \mathbb{I}_b^{B/B_{cm}} \begin{bmatrix} p(t) \\ q(t) \\ r(t) \end{bmatrix} \right)$$

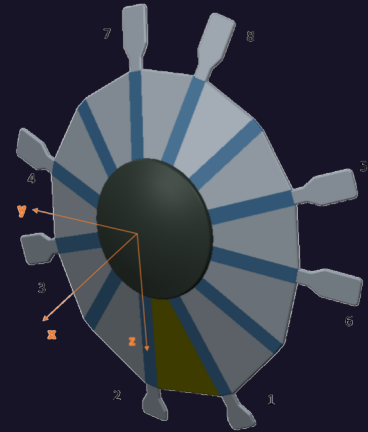
Roll, Pitch, & Yaw Moments

NEED AERODYNAMIC FORCES AND MOMENTS

AERODYNAMIC DATA

- Three force & moment coefficients:
 - C_D , C_S , C_L , and $C_{\mathcal{L}}$, $C_{\mathcal{M}}$, $C_{\mathcal{N}}$
- Dependent variables:
 - Mach M , Dynamic pressure q , angle of attack α , and sideslip β
 - Tab deflection angles δ_i for flap configuration only

$$C_{F/M} = f(M, q, \alpha, \beta, \delta_i)$$



USE AERO FORCES & MOMENTS TO CHARACTERIZE VEHICLE & DESIGN CONTROLLER

AERODYNAMIC DATA

- Aerodynamic forces and moment

$$F = \bar{q} S_A C_F$$
$$M = \bar{q} S_A \bar{c} C_M$$

- Aerodynamic coefficients

$$C_F = C_{F,PBV}(\alpha, \beta, M) + \Delta C_{F,FCS}(\delta_1, \dots, \delta_8)$$
$$C_M = C_{M,PBV}(\alpha, \beta, M) + \Delta C_{M,FCS}(\delta_1, \dots, \delta_8)$$

PBV Coefficients

0 for RCS and MMCS



LQR CONTROL DESIGN OVERVIEW

- Consider linear system $\dot{x} = Ax + Bu$
- Require feedback gain matrix K such that

$$u = -K(x - x_{des})$$

Desired states/control inputs

- Plant dynamics becomes

$$\dot{x} = \underbrace{(A - BK)}_{\text{Closed loop "A matrix"}}x + \underbrace{BK}_{\text{Closed loop "B matrix"}}x_{des}$$

Closed loop "A matrix"

Closed loop "B matrix"

- **Goal: Solve for K such that**
 - System is stabilized
 - u drives x to x_{des} while balancing objectives – small u and x goes to x_{des} "fast enough"
- Linear Quadratic Regulator (LQR) theory to solve



PTERODACTYL LQR DESIGN

- Require linear dynamics of the form

$$\Delta \dot{x}(t) = A_i \Delta x(t) + B_i \Delta u(t)$$

- Linearize system about a state, x_i^* and input, u_i^*

$$A_i = \left. \frac{\partial f}{\partial x} \right|_{x_i^*, u_i^*} \quad B = \left. \frac{\partial f}{\partial u} \right|_{x_i^*, u_i^*}$$

- By introducing

$$v(t) = [L(t) \quad D(t) \quad S(t) \quad \mathcal{L}(t) \quad \mathcal{M}(t) \quad \mathcal{N}(t)]^T$$

Ref: Evaluating & Augmenting Fuel-saving Benefits in Aircraft Formation Flight, Okolo 2015

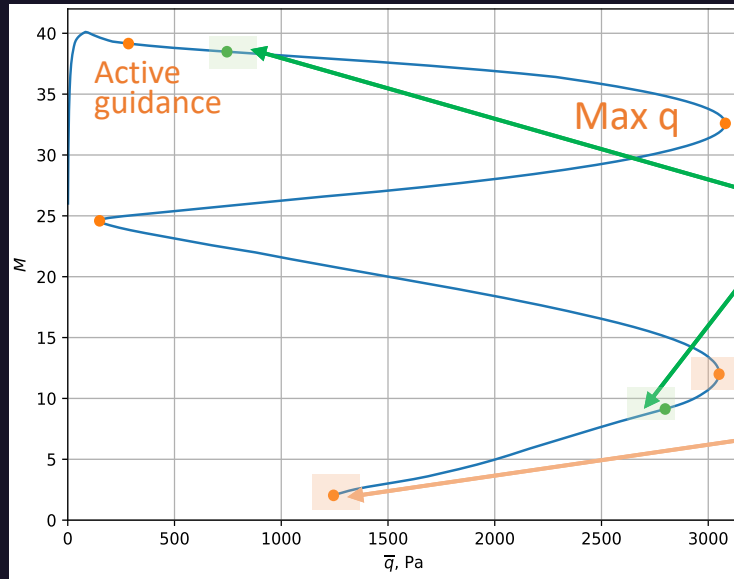
where

$$\begin{aligned} \Delta \dot{x} &= \tilde{A}_i \Delta x + \tilde{B}_i \Delta v \\ \Delta v &= F_i \Delta x + G_i \Delta u \end{aligned}$$

- This splits the linearization and provides two key benefits:
 - Aero database updates do not require a full linearization of the EOMs
 - Only need partial derivatives of the aero forces & moments w.r.t states & control input
 - Utilizing forces/moments as inputs allows us independently map control design to different control architectures with similar EOMs



PTERODACTYL LQR DESIGN



Linearization can be done about these points to obtain A & B matrices for LQR control design

Local min/max of dynamic pressure along trajectory for controller evaluation

Using linear system, we can design a feedback control system

$$\Delta u(t) = -K_i \Delta x(t)$$

where K_i is the matrix of control gains

that minimizes the performance index:

$$\int_0^\infty \Delta x^T(\tau) Q_i \Delta x(\tau) + \Delta u^T(\tau) R_i \Delta u(\tau) d\tau$$

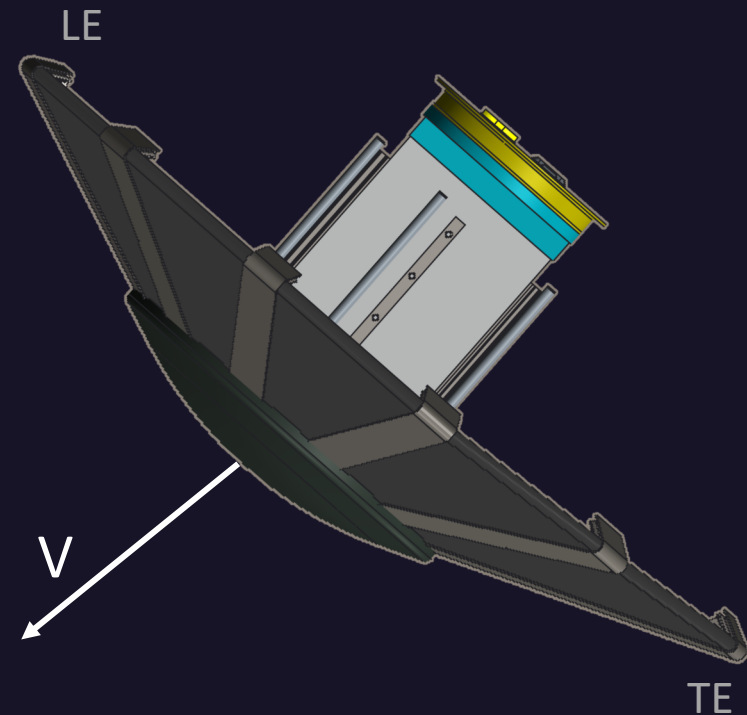
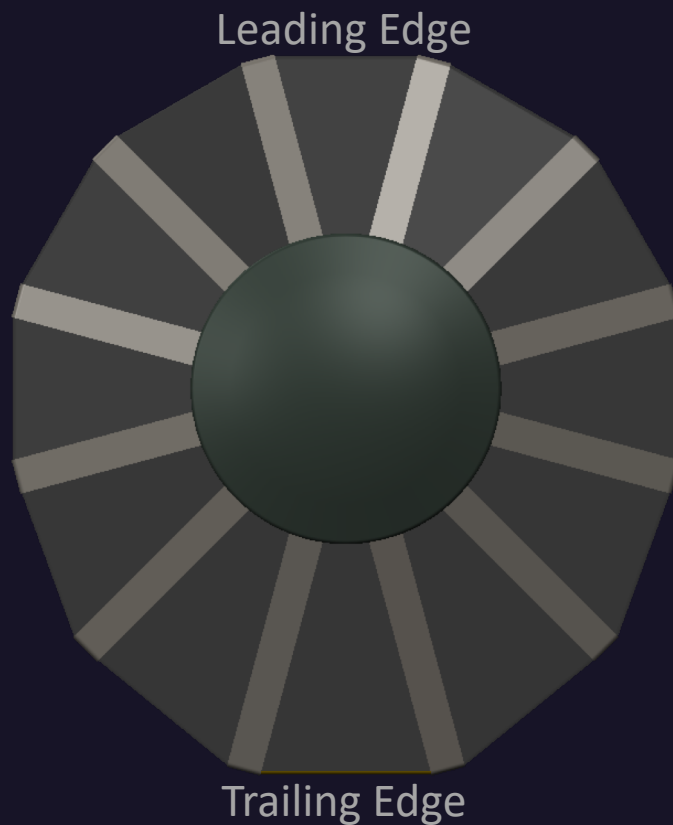
where Q_i and R_i are weighting matrices that determine state performance requirements and control surface use respectively

**CAN UTILIZE CONTROL
DESIGN FOR ALL THREE
CONFIGURATIONS...**

BUT FIRST...

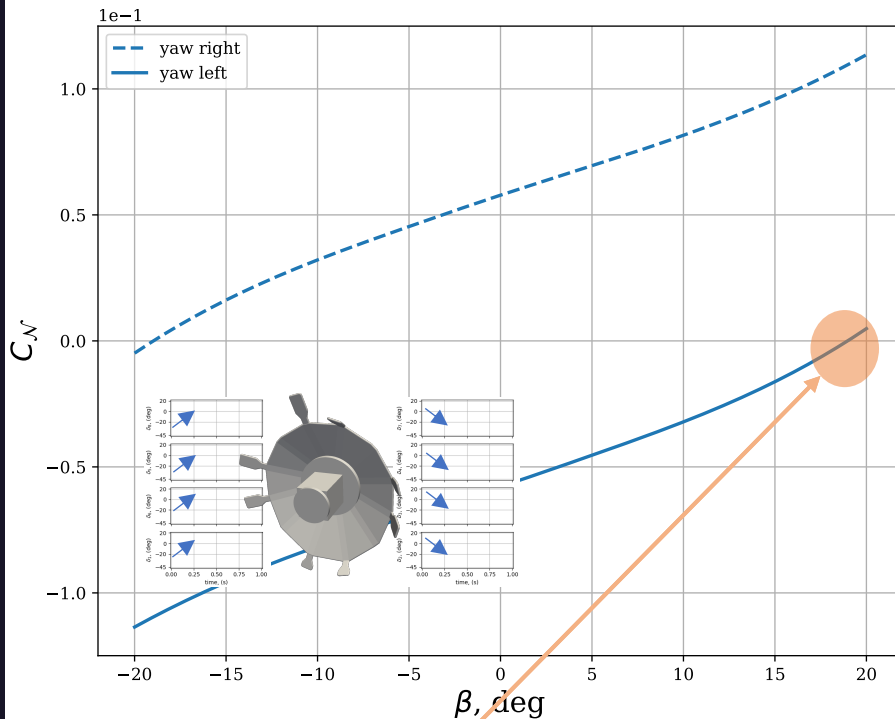


WHAT ARE THE LIMITS OF CONTROLLING THIS VEHICLE?



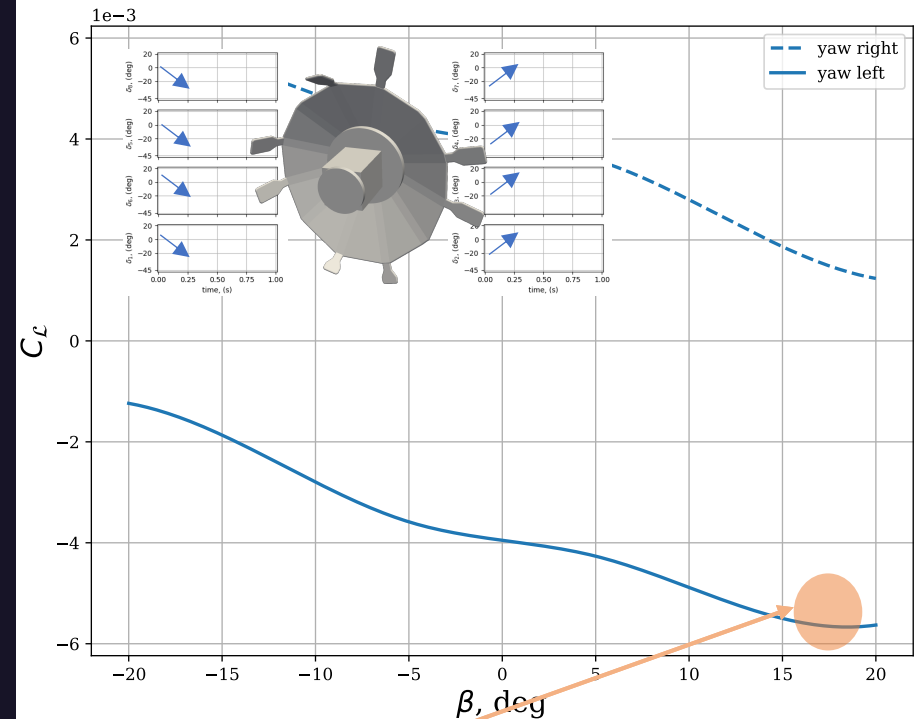
YAW AND ROLL MOMENT VS β

Yaw moment vs sideslip



Zero yaw at 18° sideslip in full yaw left configuration

Roll moment vs sideslip

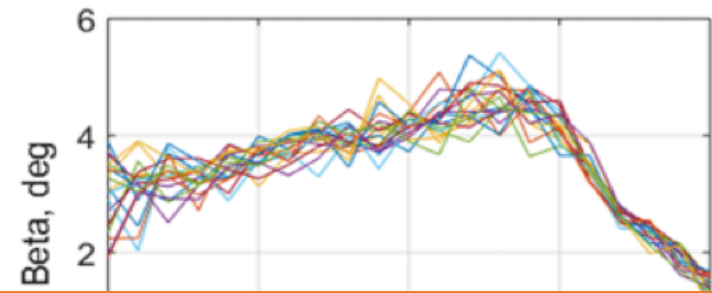
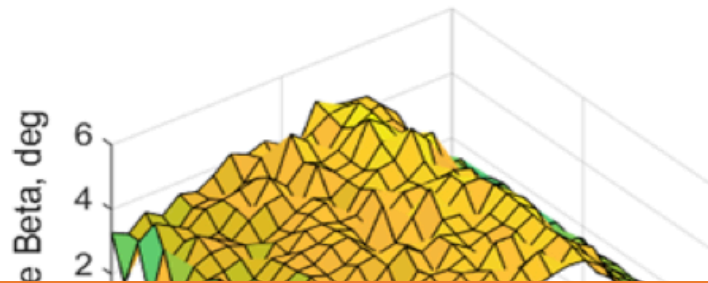


Non-zero roll at 18° sideslip in full yaw left configuration

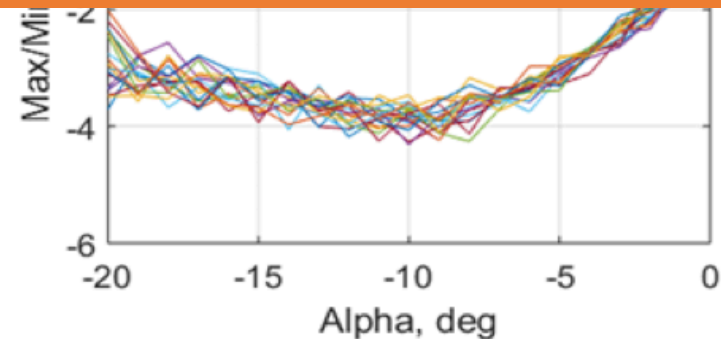
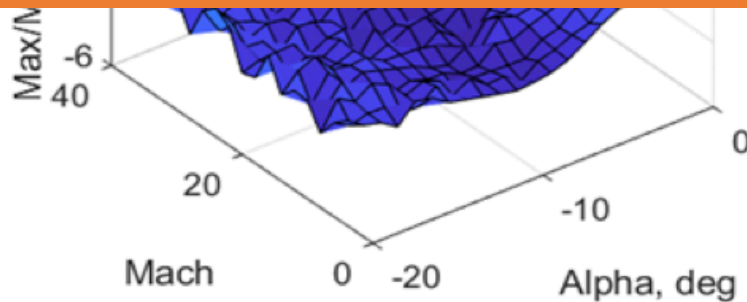
Yaw induces roll moment that vehicle needs to trim



VEHICLE CHARACTERIZATION - TRIMMABILITY



Side slip commands require constant reaction roll moments to trim induced roll.
Bank commands need roll moments only when roll is changing
→ roll moments not required at steady state roll.



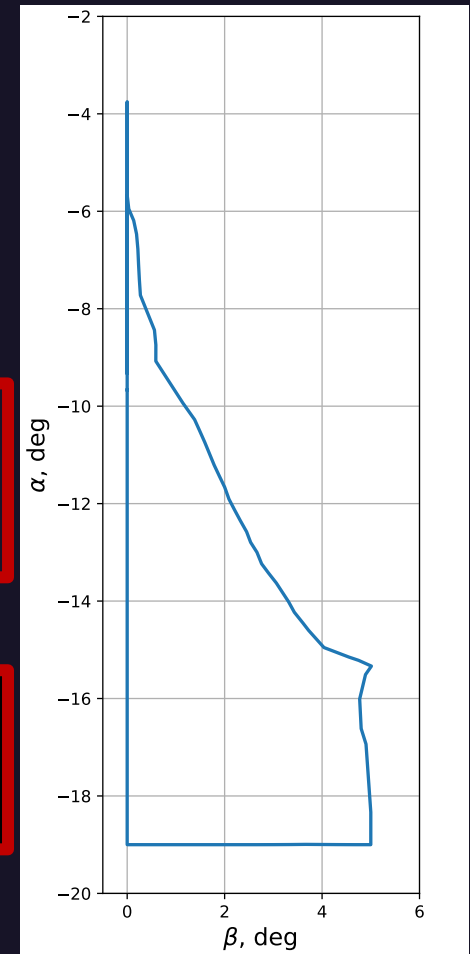
TRIMMABILITY CHARACTERIZATION

Stability & Control Characterization for Complex Control Systems

Provides control envelope for vehicle/control system configurations that are then provided to guidance for targeting performance assessment

MAJOR FINDING α and β have coupled operable ranges because the side slip commands require constant reaction roll moments to trim induced roll

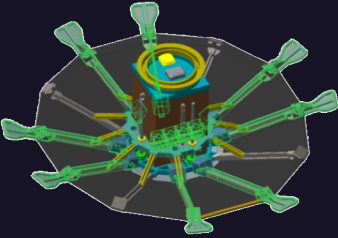
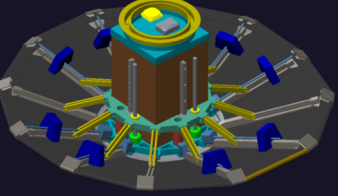
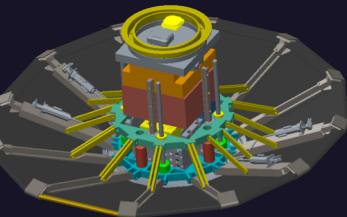
Determined that α/β is not possible for this vehicle/control configuration and mission



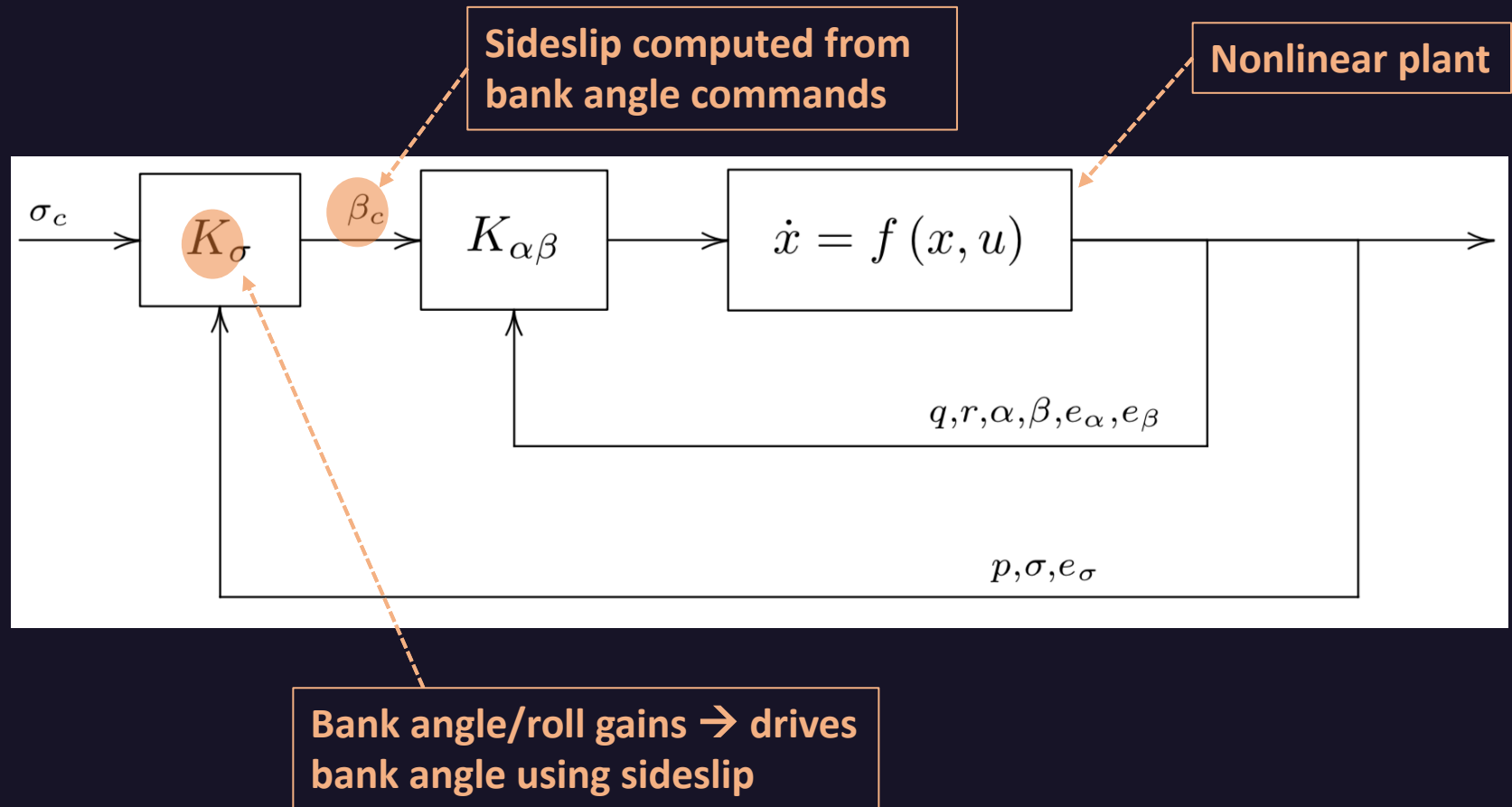
OPTIONS:
**(I) RE-DESIGN CONTROL HARDWARE
CONFIGURATION TO TRIM OUT ROLL OR,**
**(II) UTILIZE INDUCED ROLL FOR BANK ANGLE
GUIDANCE TRACKING – YAW TO BANK**



MODIFIED CONTROL SYSTEM DESCRIPTIONS

	Control Variables	Control Effector Command	Challenge
Flaps 	σ <u>Coupled</u> down/cross range control	Flap Deflection Angle	Adequate fidelity to capture the aerodynamic flap increments for active control Capture adequate aeroheating for TPS sizing
Moving Masses 		Mass Movement Distance	Identifying achievable shift in the center of gravity Develop control algorithm that can identify feasible distance commands
RCS 		Jets on/off and duration	Identify thruster position off of the payload Feasibility to integrate thrusters, fuel lines, and fuel payload

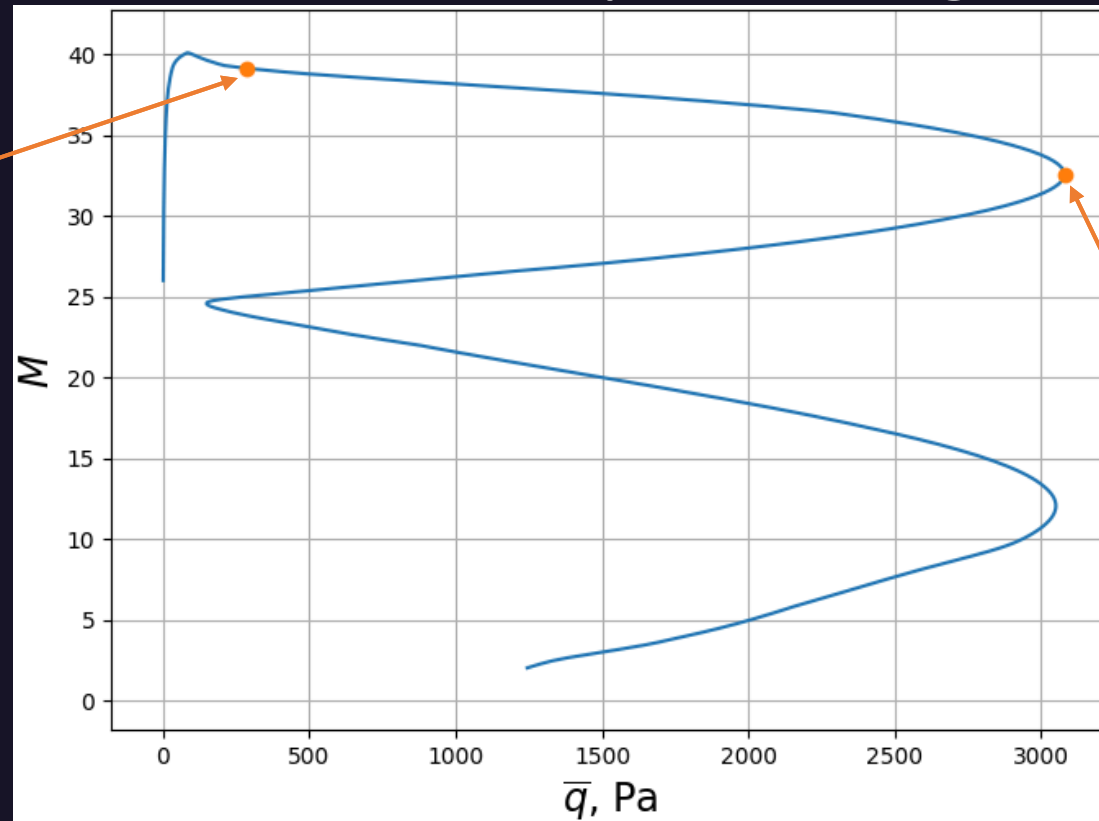
YAW-TO-BANK ARCHITECTURE



Block diagram for yaw to bank cascading control architecture

CONTROL COMPARISON METRIC

- Metric for control performance → bank angle acceleration
- Evaluate metric at two different points in flight envelope



CONTROL CAPABILITY COMPARISON

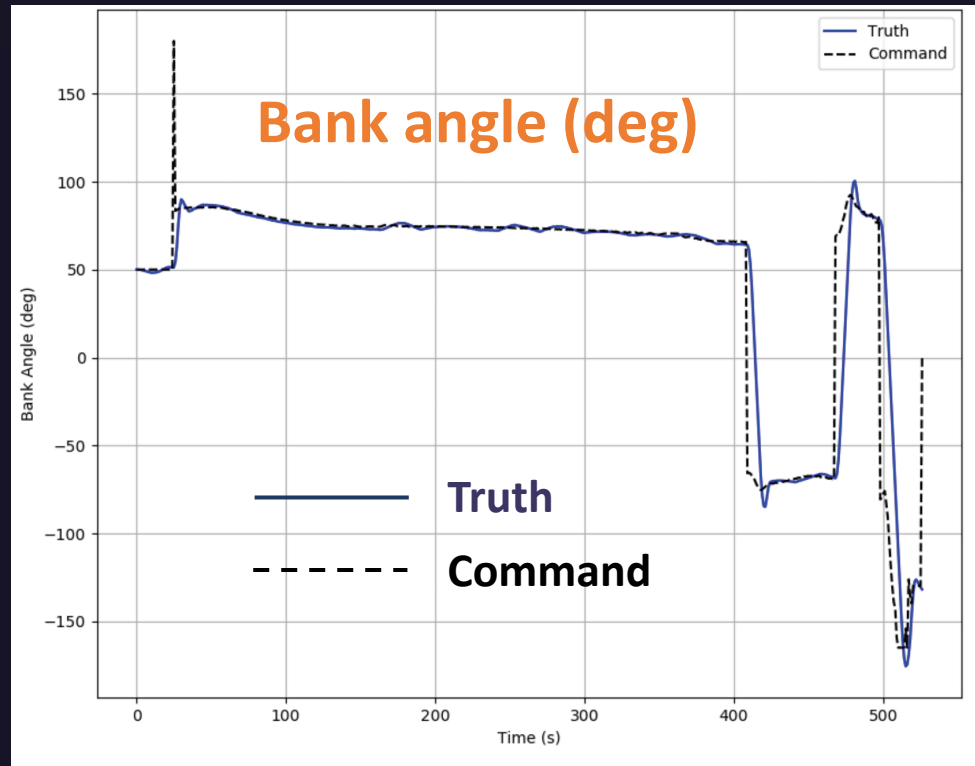
Control System		$\ddot{\sigma}$ (deg/s ²)
RCS		10.9
FCS	max $\bar{q}$	115
	G&C act	11.5
MMCS	max $\bar{q}$	13.8
	G&C act	1.48

Bank acceleration minimum for good performance: 5 deg/s²



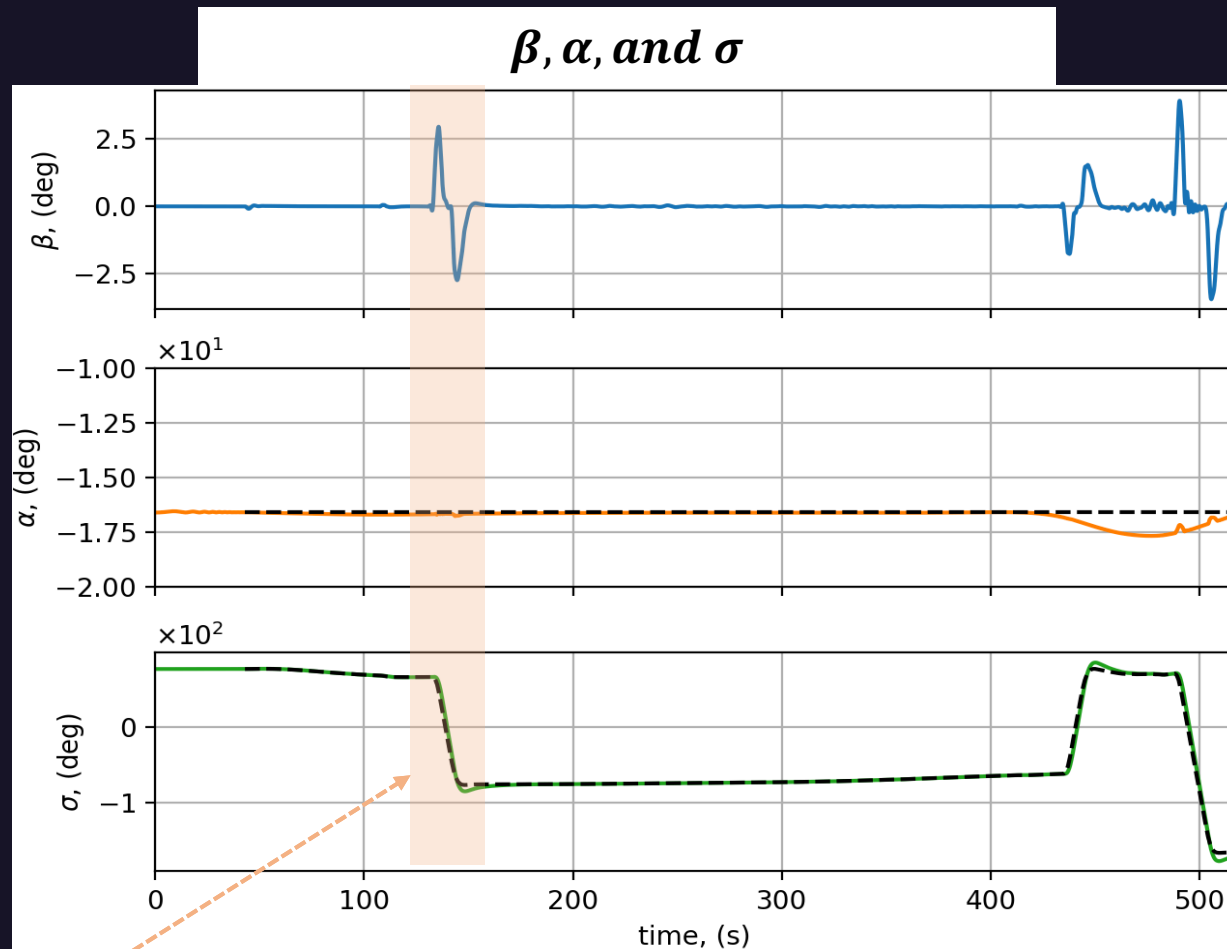
RCS – TRACKING

- Generalized jet selection algorithm takes inputs along with the control algorithm's desired torque to output ON/OFF commands
- Before flight, the jet selection tool is run to derive all torque combinations and pre-load into tables



FLAPS – TRACKING

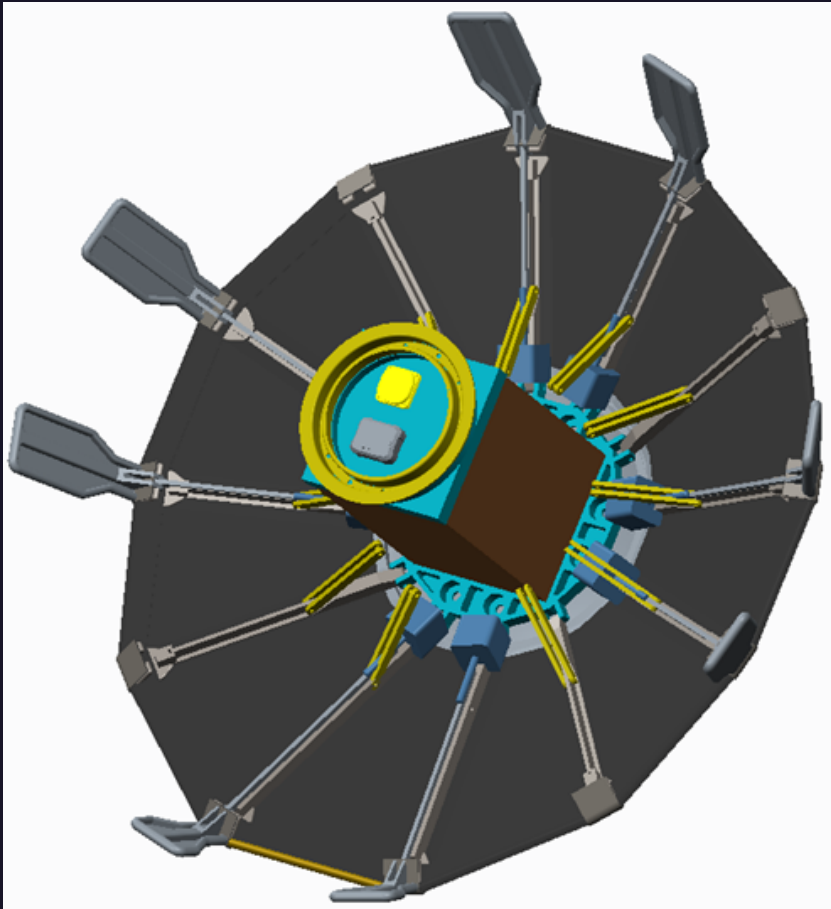
Tracking
bank angle
using sideslip
& holding
trim angle of
attack



Sideslip changes only to drive
bank and returns to 0



CONTROL SYSTEM SELECTION



Downselection: FCS

- Exceptional control system capability
- Notable available payload volume
- Added trim augmentation, increased maneuverability

SUMMARY

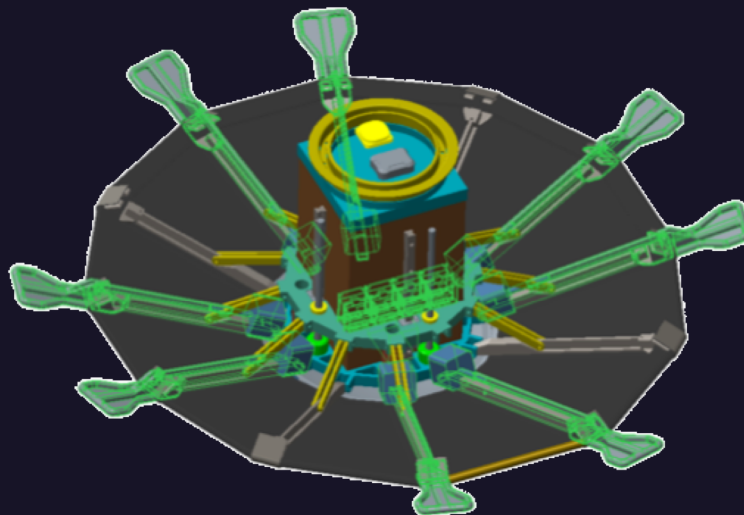
- Control architecture can handle alpha-beta or bank angle commands
- MIMO-LQR controller allows for over-actuated vehicle control
- Control design adaptable to other vehicles and actuator configurations
- Roll-yaw coupling renders alpha-beta control infeasible for *good* guidance with this vehicle, control designs, & mechanical limits
- Yaw to bank → attractive solution

**CONTROL CAPABILITY ESTIMATE FOR YAW TO BANK →
ACHIEVABLE BANK ACCELERATION WITH SIDESLIP ANGLE
DEPENDENCY**



CONCLUSION

- Yaw-to-bank leverages roll-yaw coupling to achieve increased maneuverability compared to heritage RCS
- FCS has the highest bank maneuverability of the three control architectures
- Control system recommendation → FCS



KEY TECHNICAL CONTRIBUTIONS

First of its kind study that closes a DEV control system design with hardware feasibility and guidance & control performance (July 2019)

IMPACT Enables further application of inflatable/mechanical DEVs for science missions and high mass to Mars



KEY TECHNICAL CONTRIBUTIONS

First of its kind study that closes a DEV control system design with hardware feasibility and guidance & control performance

Toolset that can be **applied to any vehicle/control system** configuration (July 2019)

IMPACT Pterodactyl can retire risk by addressing integrated assessment hardware and G&C at an early conceptual phase in both conventional and non-traditional entry system technologies



KEY TECHNICAL CONTRIBUTIONS

First of its kind study that closes a DEV control system design with hardware feasibility and guidance & control performance

Toolset that can be **applied to any vehicle/control system** configuration

Closed a **NOVEL** control solution that makes asymmetric vehicle configurations controllable (formerly not controllable, July 2019)

IMPACT Demonstrates feasibility for vehicles not previously considered for non-traditional entry vehicles that better serve mission needs versus traditional symmetric designs



KEY TECHNICAL CONTRIBUTIONS

Identified a **100% non-propulsive** entry control system (June 2020)

IMPACT Enables significant **mass, volume** and operational **cost savings**



KEY TECHNICAL CONTRIBUTIONS

Identified a **100% non-propulsive** entry control system (June 2020)

Built 6DOF Simulation Testbed with core Flight Software capability and developed Technology Maturation plan (June 2020)

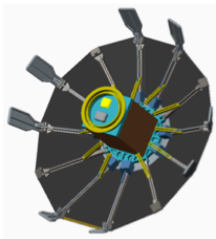
IMPACT Provides foundation to understand challenges, risks, costs for future flight projects



NEXT STEPS

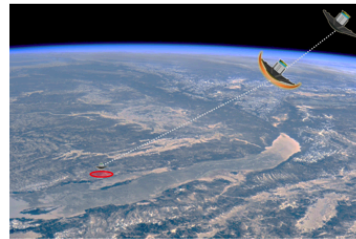
- Investigate option 1: Redesign flap control architecture to enable alpha-beta tracking
- Obtain follow-on funding for hardware prototyping, demonstrator, and sub-orbital test flight

Leverage Pterodactyl guidance & control technology advancements and personnel experience to drive development of precision landing of payloads



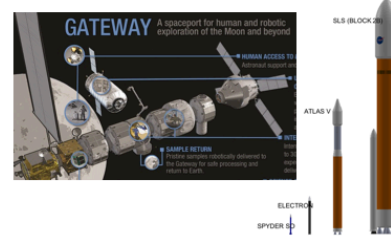
Pterodactyl Early Career Initiative

Developing design tools and guidance & control system for precision targeting



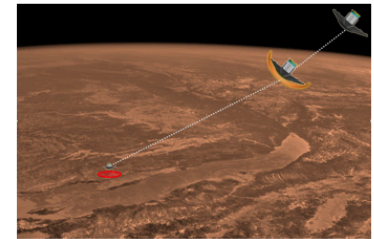
STF21 Proposal

Develop sub-orbital flight test vehicle to demonstrate operational capability of precision landing



Lunar Advancement

Develop Lunar Return flight test vehicle to spur on-demand sample return capability



Mars Advancement

Feed forward technology developments to precision landing of heavy payloads to Mars



REFERENCES

Yount, B. C., Cassell, A. M., and D'Souza, S. N., "Pterodactyl: Mechanical Designs for Integrated Control Design of a Mechanically Deployed Entry Vehicle (DEV)," AIAA SciTech 2020 Forum, AIAA, Orlando, FL, 2020.

Nikaido, B. E., D'Souza, S. N., Hays, Z. B., and Reddish, B. J., "Pterodactyl: Aerodynamic and Aeroheating Database Development for Integrated Control Design of a Mechanically Deployed Entry Vehicle," AIAA SciTech 2020 Forum, AIAA, Orlando, FL, 2020.

Johnson, B. J., Rocca-Bejar, D., Lu, P., Nikaido, B. E., Yount, B. C., D'Souza, S. N., and Hays, Z. B., "Pterodactyl: Development and Performance of Guidance Algorithms for a Mechanically Deployed Entry Vehicle," AIAA SciTech 2020 Forum, AIAA, Orlando, FL, 2020.

Okolo, W. A., Margolis, B. W., D'Souza, S. N., and Barton, J. D., "Pterodactyl: Development and Comparison of Control Architectures for a Mechanically Deployed Entry Vehicle," AIAA SciTech 2020 Forum, AIAA, Orlando, FL, 2020.

Hays, Z. B., Yount, B. C., Nikaido, B. E., Tran, J., D'Souza, S. N., Kinney, D. J., and McGuire, M. K., "Pterodactyl: Thermal Protection System for Integrated Control Design of a Mechanically Deployed Entry Vehicle," AIAA SciTech 2020 Forum, AIAA, Orlando, FL, 2020.

Alunni, A.I., D'Souza, S.N., Yount, B.C., Okolo, W.A., Nikaido, B.E., Margolis, B.W., Johnson, B.J., Barton, J.D., Lopez, G., Wolfarth, L. S., and Hays, Z. B., "Pterodactyl: Trade Study for an Integrated Control System Design of a Mechanically Deployable Entry Vehicle," AIAA SciTech 2020 Forum, AIAA, Orlando, FL, 2020.



QUESTIONS



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