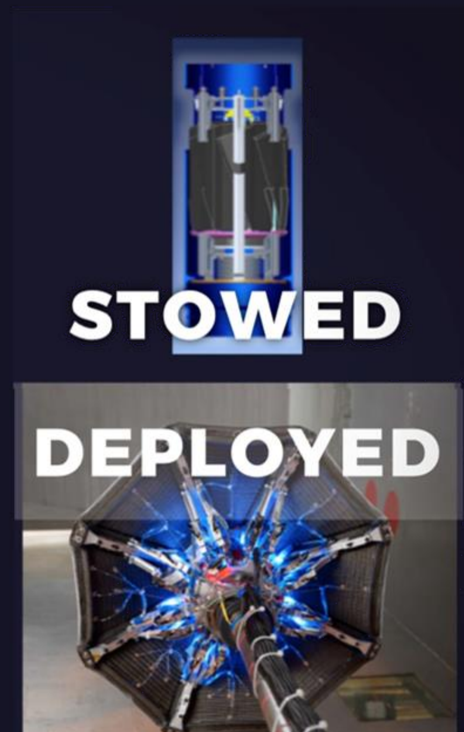
AFM-09/GNC-16
PTERODACTYL: CONTROL SYSTEM DESIGN FOR DEPLOYABLE ENTRY VEHICLES

Dr. Sarah D'Souza, Session Chair
Dr. Alan Cassell, Session Co-Chair
NASA Ames Research Center

AIAA SciTech 2020

MOTIVATION



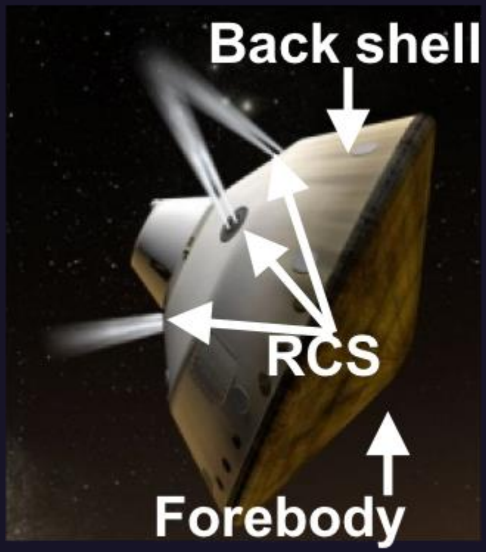
Deployable Entry Vehicles (DEV)

GUIDANCE & CONTROL MAKE DEV APPLICATIONS REALIZABLE!

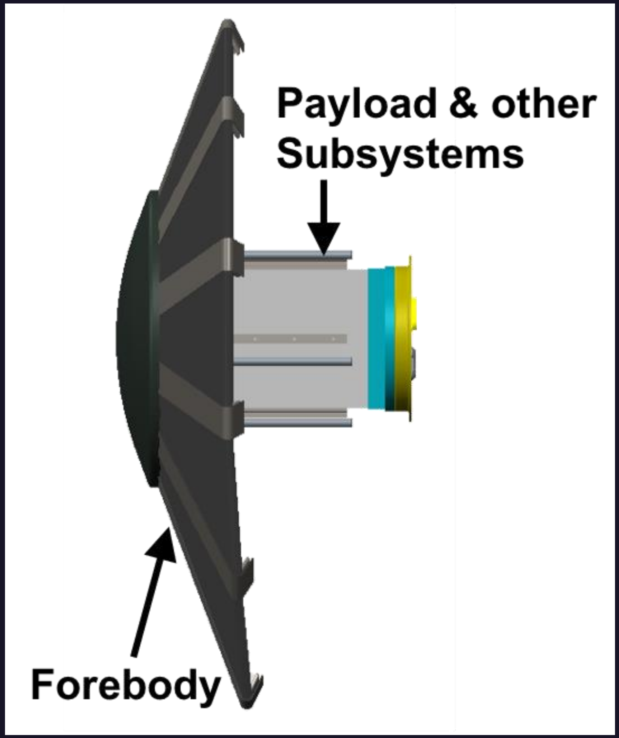
NASA's Space Technology Mission Directorate is funding Pterodactyl through the **Early Career Initiative (ECI) Award** to address the need for deployable entry vehicles that can land small and large mass payloads precisely

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?

ACKNOWLEDGEMENTS

NASA Core Team

Sarah D’Souza (Principal Investigator)
Antonella Alunni (Lead Systems Engineer)
Breanna Johnson (Guidance and Trajectory Design Lead)
Wendy Okolo (Control System Design Lead)
Ben Nikaido (Aerodynamics and Aeroheating Lead)
Bryan Yount (Mechanical Design and Structures Lead)
Benjamin Margolis (Controls Engineer)
Zane Hays (TPS System Modeling)

Mentors

Michelle Munk
NASA STMD Mentor and EDL Principal Technologist

Dave Kinney, Alan Cassell, and Ron Sostaric
NASA Mentors

Industry Partners

Kenneth Hibbard, Jeffrey Barton, Gabriel Lopez, Jeremy John, and Larry Wolfarth

Dr. Stephen Robinson
Brandon Reddish

SPECIAL SESSION AGENDA

#	Presentation Topic	Presentation Description
1	Mechanical Systems Design	Identify control effector mechanical design/integration
2	Aerodynamics & Aeroheating Modeling	Multi-flap modeling to generate database of forces and moments
3	Entry Guidance & Trajectory Design Development	Develop methodology for identifying σ and α/β control Design feasible trajectories for each control system
4	Control System Development and Comparison	Identify torque/control effector commands to track guidance commands
5	TPS Analysis	Estimation of TPS thickness and mass for Flap Control System (FCS)
6	Control System Trade Study	Compare three controls systems and identify system best suited for precision targeting

PTERODACTYL: MECHANICAL DESIGNS FOR INTEGRATED CONTROL DESIGN OF A MECHANICALLY DEPLOYABLE ENTRY VEHICLE

Bryan Yount, Alan Cassell, Sarah D'Souza

NASA Ames Research Center

OUTLINE

- Objectives & Approach
- Process & Methods
- Integrated Control Design
  - Baseline Vehicle
  - Flaps
  - Mass Movement
  - Reaction Control System
- Summary & Conclusions

CONTROL DESIGN OBJECTIVES

Determine a preliminary G&C design for multiple control configurations such that the final design is driven by:

guidance and control performance

AND

control system hardware integration/packaging

CONTROL DESIGN OBJECTIVES

Determine a preliminary G&C design for multiple control configurations such that the final design is driven by:

guidance and control performance

AND

control system hardware integration/packaging

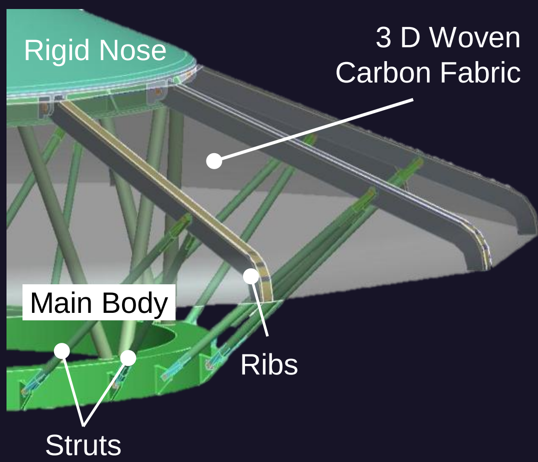
Conduct a trade study of three different deployable entry vehicle (DEV) control systems

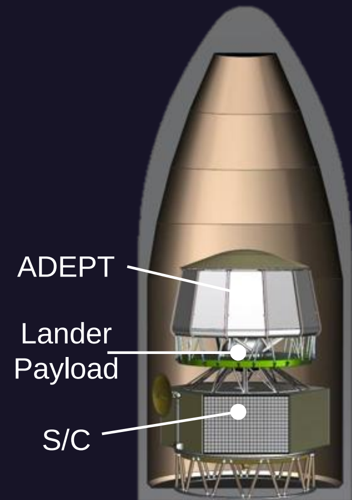
CONTROL SYSTEM DESIGN

- Start with a baseline vehicle configuration that has a specific L/D capability

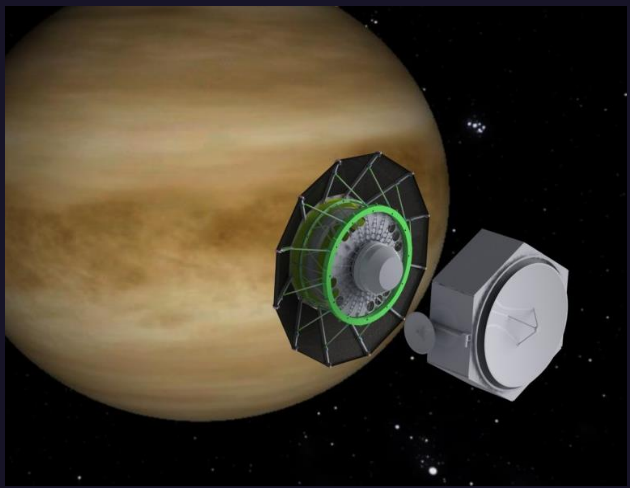
- Leverage the following:
  - Guidance algorithm that can find trajectories on the fly
  - Known vehicle subsystem configuration that enables packaging feasibility study for control system mechanical design

ADAPTIVE DEPLOYABLE ENTRY PLACEMENT TECHNOLOGY (ADEPT)





Stowed for launch

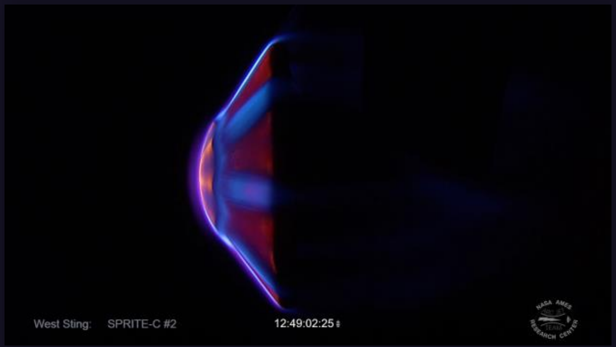


Deployed for entry

2 m Deployment Prototype Time Lapse Video

-Electrically driven actuators achieve high fabric pre-tension

System Level Aerothermal Testing

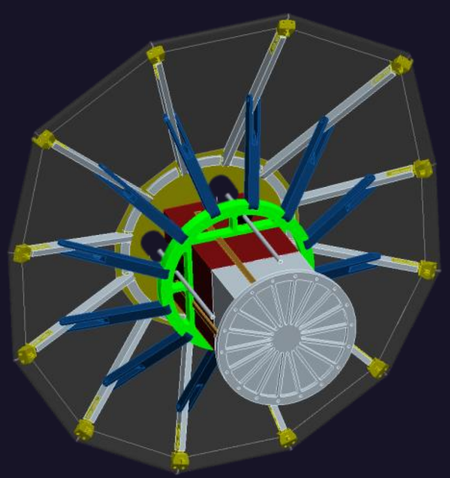


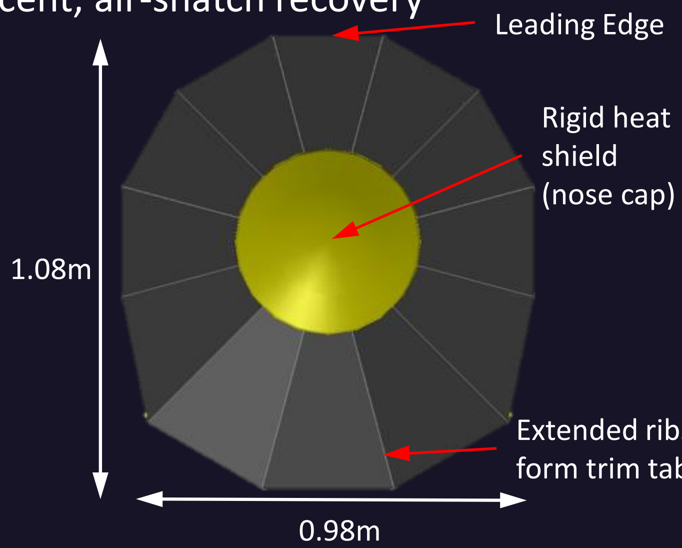
Highly capable flexible thermal protection system.
Fabric tested to 250 W/cm^2 (2100 °C).

LIFTING NANO-ADEPT (LNA)*

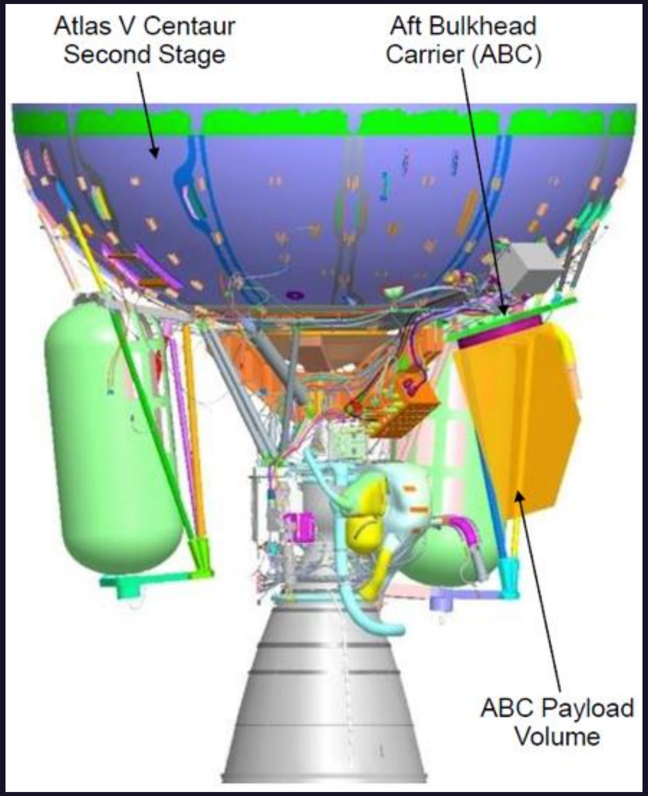
LNA Features

- LEO Secondary payload (ULA Centaur Upper Stage ABC)
  - 7.6 km/s entry from LEO (Mach 27 peak)
  - Aerothermal heating (>100 W/cm^2, ~3.5 kJ/cm^2 heat load)
- 1.0 m+ deployed diameter
- 12 ribs, 70 deg asymmetric shape to generate lift
- Carbon fabric flexible TPS, PICA nose TPS
- L/D = 0.19 (AoA = 11 deg), Guided hypersonic flight
- Electro-mechanical deployment system
- Parachute terminal descent, air-snatch recovery





LV Accommodation



*NASA Ames Center Innovation Fund (CIF) Design Study, 2016

GROUND RULES & ASSUMPTIONS

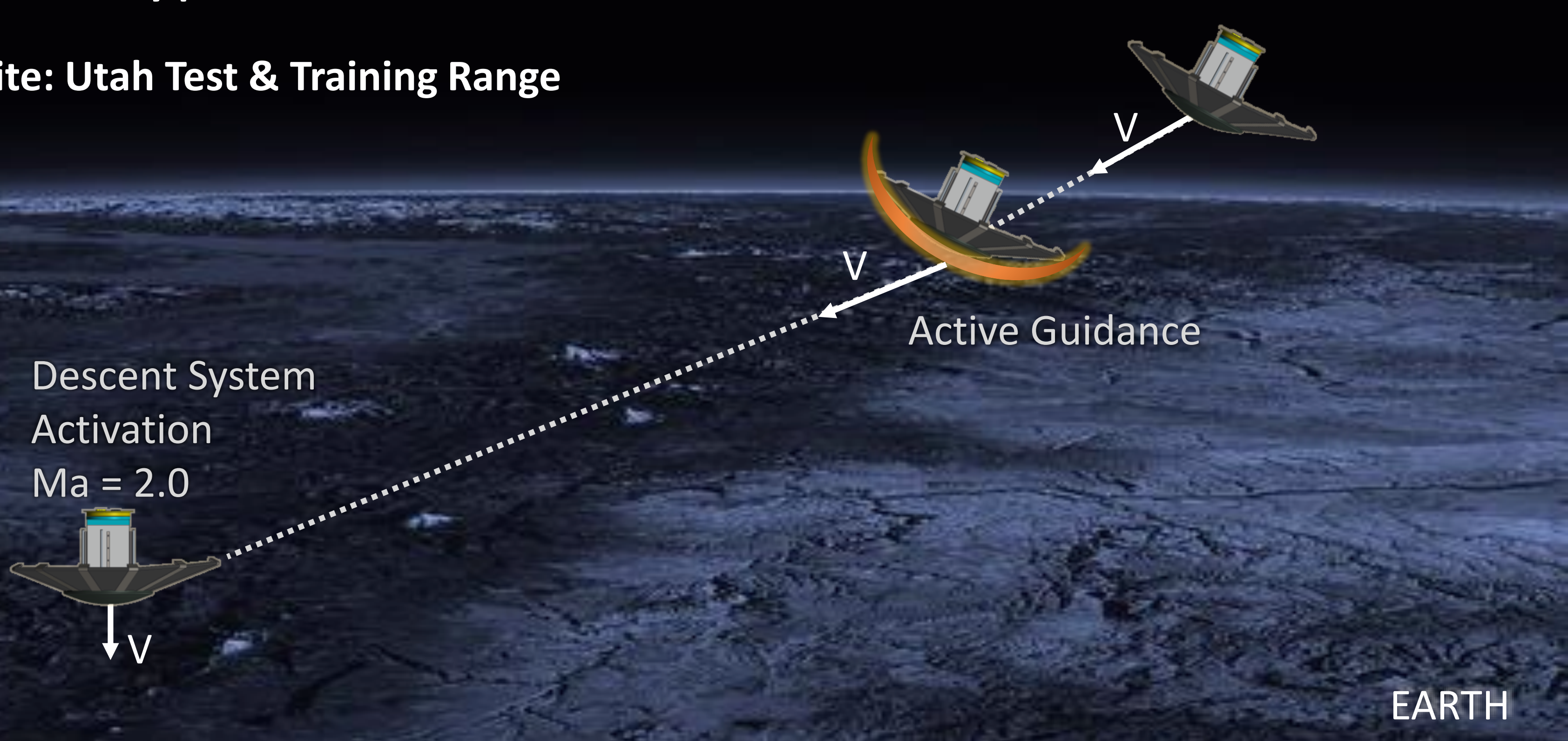
- The baseline aeroshell geometry is a constant for all control options
- Control systems should be compatible with the baseline vehicle configuration with only minor changes allowed
- Enclosed control components should fit within the 12 U payload enclosure
- The complete vehicle including control system should be compatible with the mass and volume constraints associated with the aft bulkhead carrier volume accommodation on the Centaur upper stage

PTERODACTYL DESIGN REFERENCE MISSION

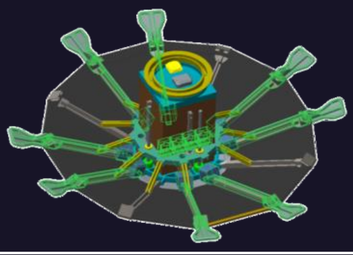
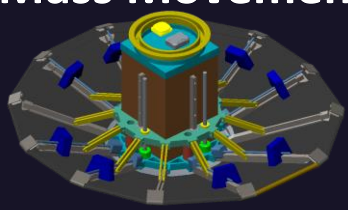
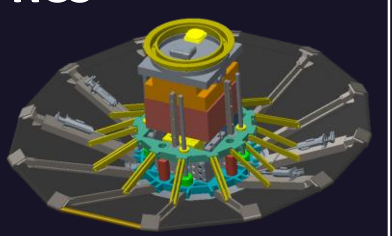
Lunar Return mission (Stress case for loads)

Focused on Entry phase

Target site: Utah Test & Training Range

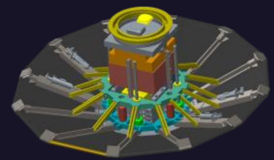


CONTROL SYSTEM CONFIGURATIONS

	Control Variables	Control Effector Command	Challenges
Flaps 	α/β Decoupled down/cross range control OR σ Coupled down/cross range control	Flap Deflection Angle	Adequate fidelity to capture the aerodynamic flap increments for active control Adequately analyze flap aeroheating for TPS sizing
Mass Movement 		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

DESIGN STARTING POINTS

Reaction Control Thrusters



Trajectory Performance Requirements for specific body rates

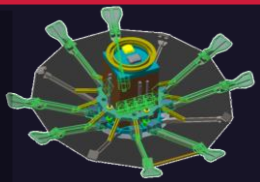
↓

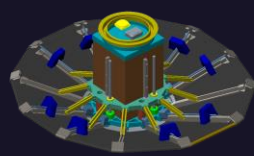
Find control system hardware that can achieve required torques

↓

Integrate that system into the hardware

Aero Effector Flaps





Moving Masses

Integrate maximum control capability that can be packaged into the hardware

↓

Trajectory analysis to determine torques and body rates

↓

Perform controls analysis to track guidance trajectory for required body rates

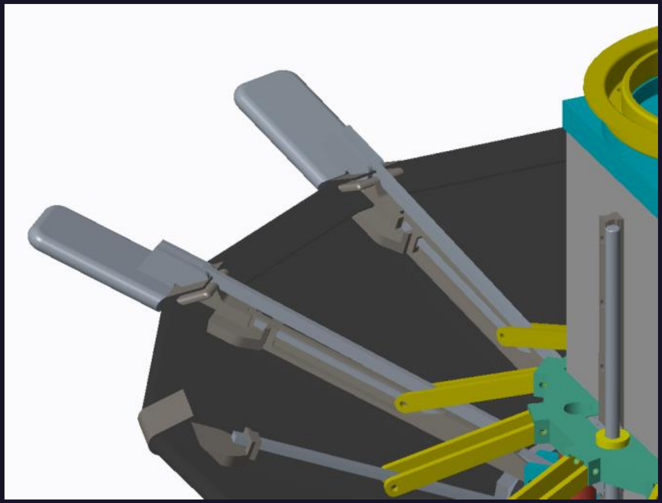
MECHANICAL DESIGN METHODS

3D Solid Modeling CAD (PTC Creo)

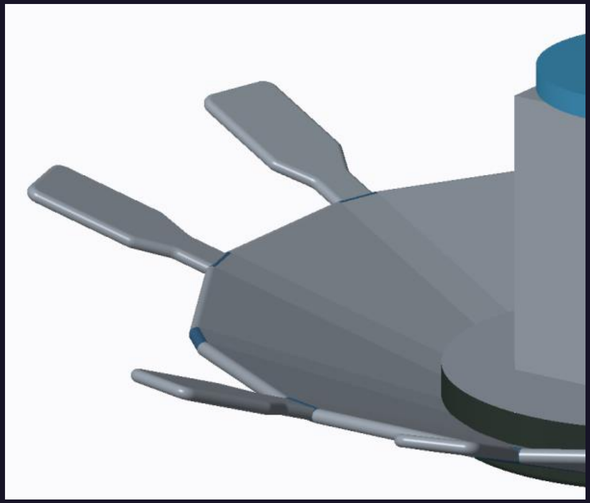
Models for analysis & trade study inputs:

1. Preliminary Concept (Visualization & Initial Feasibility)
2. Geometry Model for CFD (Simple & Clean for CFD gridding)
3. Design Concept Model (DCM) mid-fidelity design for trade study

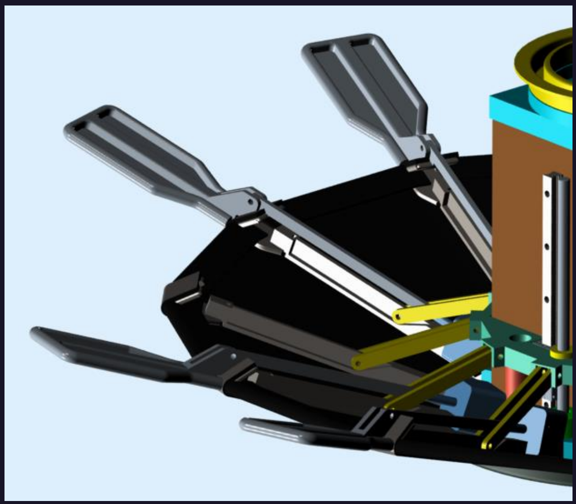
Preliminary Concept Model



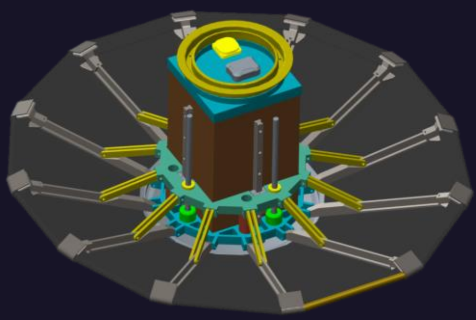
CFD Model



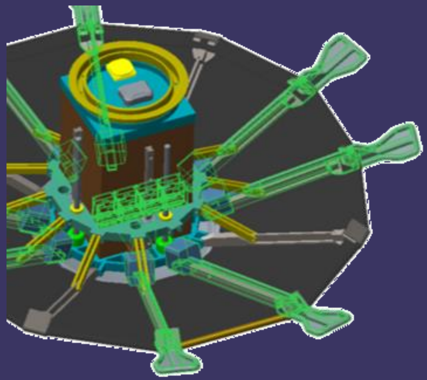
Design Concept Model



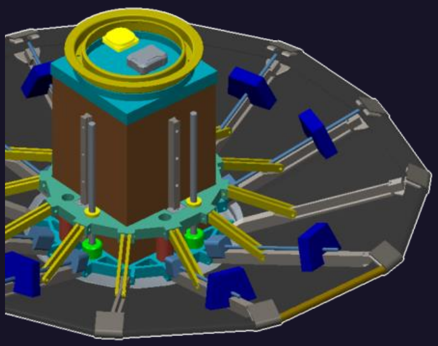
Baseline



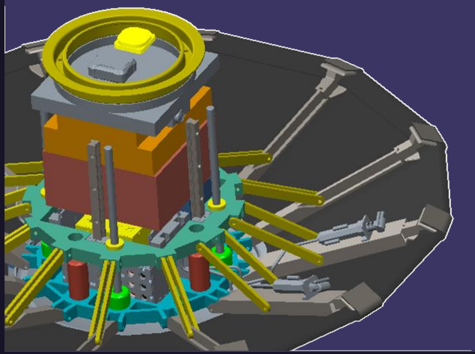
Flaps



Mass Movement



Reaction Control System (RCS)

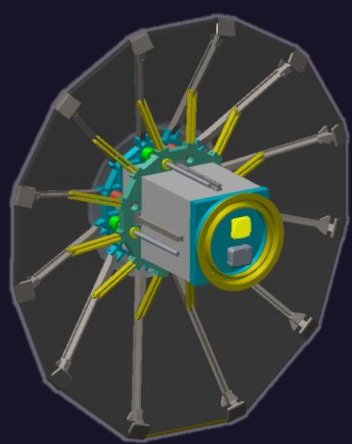


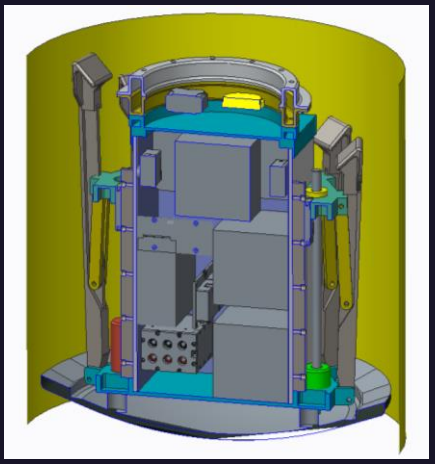
INTEGRATED CONTROL DESIGNS

PTERODACTYL BASELINE VEHICLE

Pterodactyl Baseline Vehicle (PBV):

- **LNA was originally configured for a LEO re-entry flight test mission as a secondary payload in the Aft Bulkhead Carrier (ABC) of the Atlas V Centaur upper stage.**
- **The baseline model was updated to reflect the mass required for the lunar return DRM**
  - Increased carbon fabric and nose cap TPS mass to reflect thickness needed for lunar return
  - Increased volume & mass allocation for a final descent system (3U)
  - Decreased the “science payload” allocation to 2U (for descent system)





➔ **Final Baseline model**

➔ **Mass: 59.4 kg** (w/o control system)

- **Payload Enclosure Volume Available: 40%**

ABC Limit Constraints:

Volume: .5m x .5m x .6m (L)

Mass: 77 kg

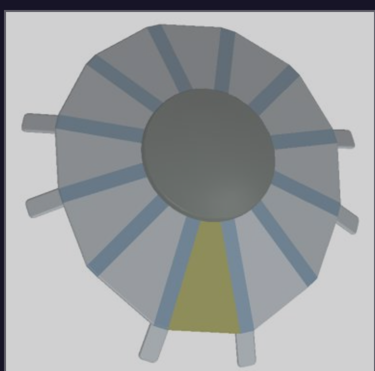
FLAPS

Flaps Option Development:

- Flaps for **α - β** trajectory was selected by team for development
- Preliminary Aero/CFD + Control Group evaluation iterated on several concepts to determine the best starting point for this analysis to identify the maximum control authority attainable for packaged design

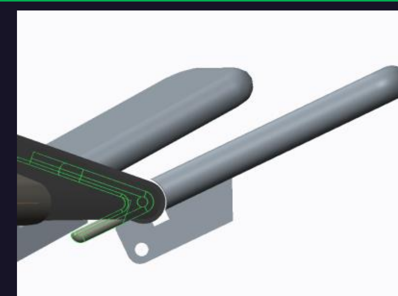
➔ **Aero group proposed a hinged flap that deploys at an angle into the flow**

✓ Preliminary Aero/CFD & Mechanical found hinged option to be feasible

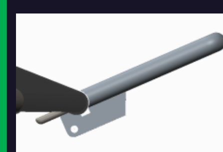


Initial Flap Control Concept

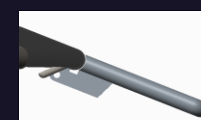
Flap – Linear Motion



Flaps – Hinged Into Flow



+20°

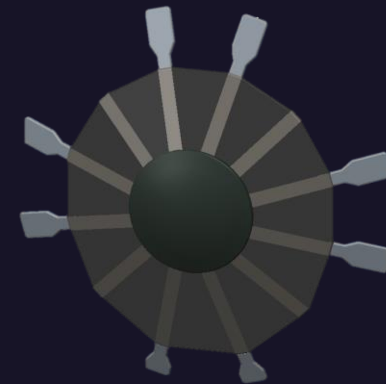


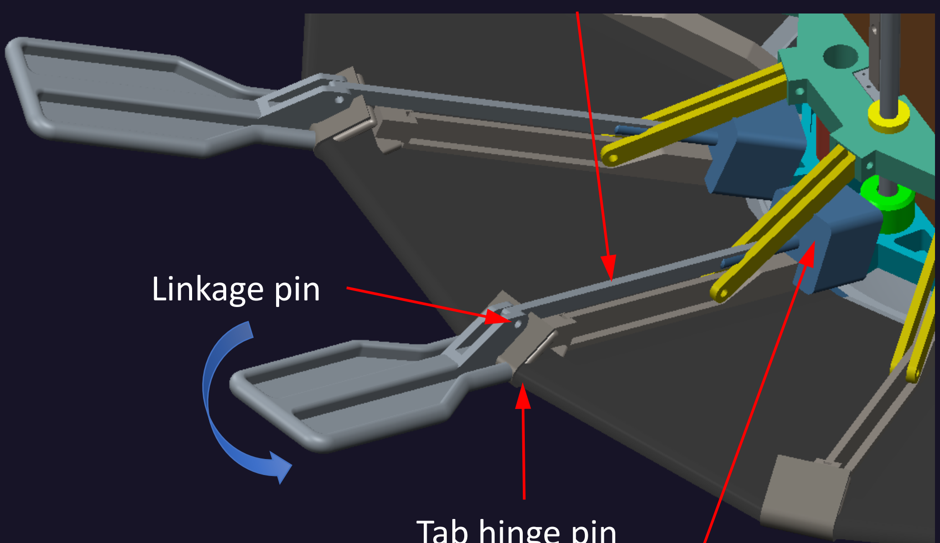
0°

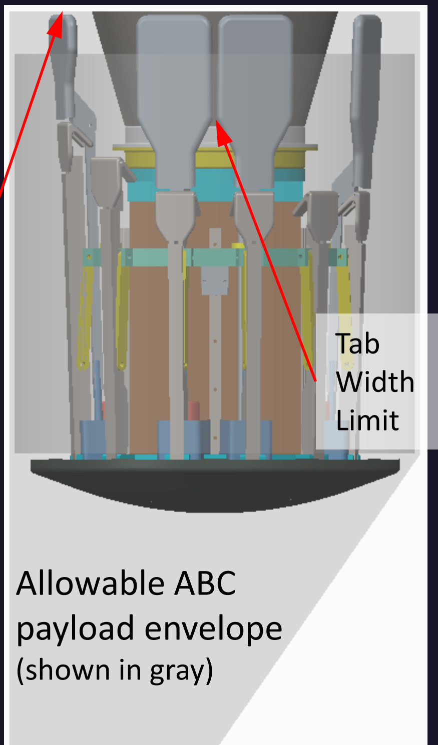
-45°

FLAPS (2/4)

- **Hinged flap option development went through several iterations**
- **Aero/Guidance/Control groups determined need for eight large tabs for α - β control** (pending anchored CFD results)
- **Mechanical group developed a max fit option (for ABC launch envelope)**
  Flared tab geometry per discussion with team
  - Uses maximum stowable flap size

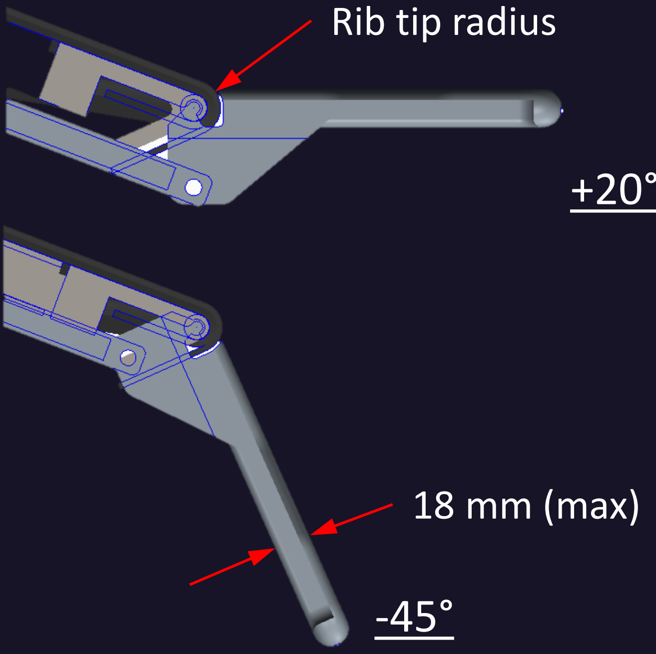






FLAPS (3/4)

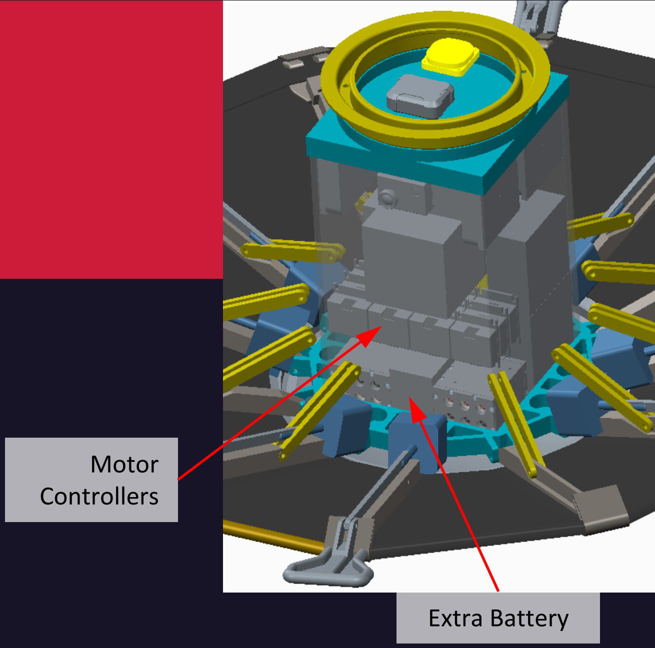
- **Flap components sized for CFD Aero Loads:**
  - Flap structures & linkages sized to support max flap pressure loads
  - Actuators sized to drive flaps at max pressure load
  - Extra battery capacity added to provide flap actuation power
- **Flap range of motion & thickness:**
  - Flap rotates around rib tip radius
  - + deflection limit at +20 degrees to prevent flap from hitting upper aeroshell surface
  - Retraction limited at -45 degrees to prevent flap bracket & linkage from hitting rib
  - Flap thickness < rib tip diameter to allow rotation (18 mm for current rib tip design)
- **Flap thickness after TPS sizing:**
  - *More on this in the TPS Analysis presentation*



FLAPS (4/4)

- **Flaps control system components:**

<u>Flap Control Components</u>	<u>Components in Payload Enclosure:</u>
Flaps (Structure)	Batteries for Control Actuators
Flaps <u>TPS</u> ➔ (Separate Presentation)	Flap Actuator Motor Controllers
Modified Ribs & Rib Tips for Flaps	Control System Cable/Harness
Flap Control Linkages	
Flap Actuators	
Additional Fasteners	



- The flaps after TPS sizing are thicker than the current rib tip can accommodate, but the carbon fabric TPS & nose cap TPS also have thickness issues
- The flap <u>mass</u> is updated to reflect the required TPS for lunar entry

➢ ***Implementation will be a challenge as flaps are exposed to plasma while moving***

➔ **Flap Concept Model**

- **Mass: 74.2 kg** (as estimated for G&C) ➔ ***<u>Updated to 75.7kg after TPS sizing</u>***
- **Payload Enclosure Volume Available: 33% | Integration Score: 1/5**
- Flap Performance Data: Range: -45° to +20° | Rate: 47°/s | Accel: 1000°/s^2

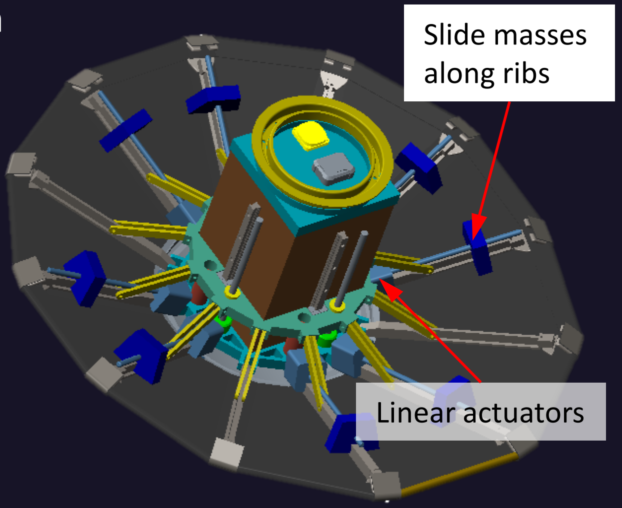
MASS MOVEMENT

Mass Movement Option Development:

- Mass movement for **α - β** trajectory was selected by team as an alternate control system option

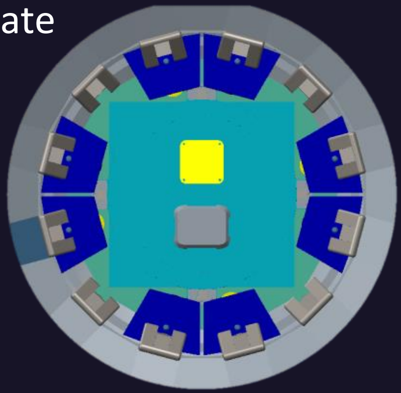
- Concept employs sliding mass blocks along ribs to provide maximum motion and large mass offsets from central axis
  - To maintain ~symmetry, 8 mass blocks arranged in pairs: LE Ribs (2), TE Ribs (2), Lateral Ribs +Y (2), -Y (2)

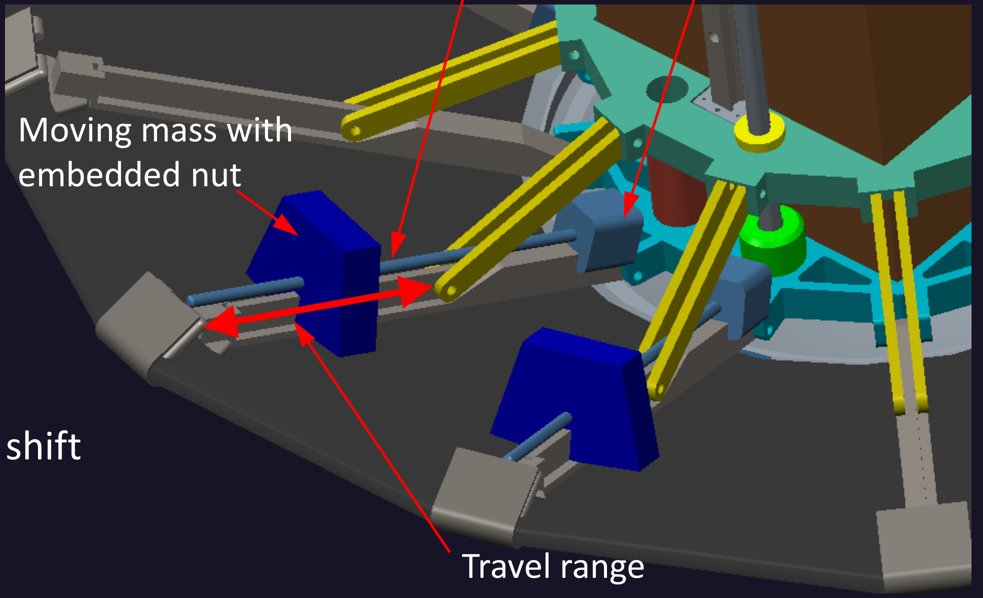
- Uses Pterodactyl Baseline Aero data



MASS MOVEMENT (2/2)

- Determined range of motion along ribs
- Actuation similar to flaps
- Size limited by stowed state
  - Adjacent masses, payload enclosure, deploy ring





- Very large masses needed to provide 10mm c.g. shift

➔ **A <u>max fit</u> moving mass config was created**

➔ **Mass: 80.1 kg (>ABC max allowable of 77 kg)**

- **Volume Remaining: 34% | Integration: 3/5**
- Performance: Moving masses: 2 kg each
  - Travel range: +/- 69 mm from nominal
    (+/-112 mm on T.E. ribs)
    - Provides +/-9mm Zcg shift & +/-7mm Ycg shift
  - Mass actuation rate 80 mm/sec
  - Mass acceleration rate 1600 mm/s^2
- Updated offset calcs show only ~ +/-4° of AoA and Side Slip Control

<u>Components Added or Modified for Moving Mass Cfg.</u>

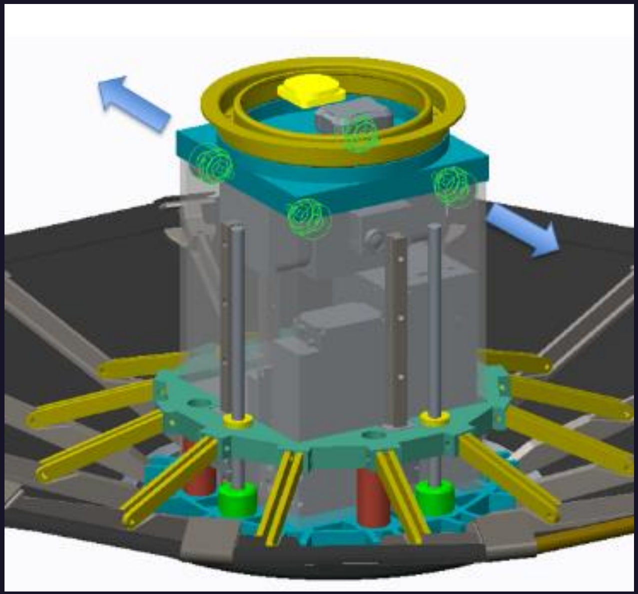
Mass Move Components	Components in Payload Enclosure:
Mass Blocks (w/nut)	Batteries for Control Actuators
Mass Actuators	Actuator Motor Controllers
Additional Fasteners	Control System Cable/Harness

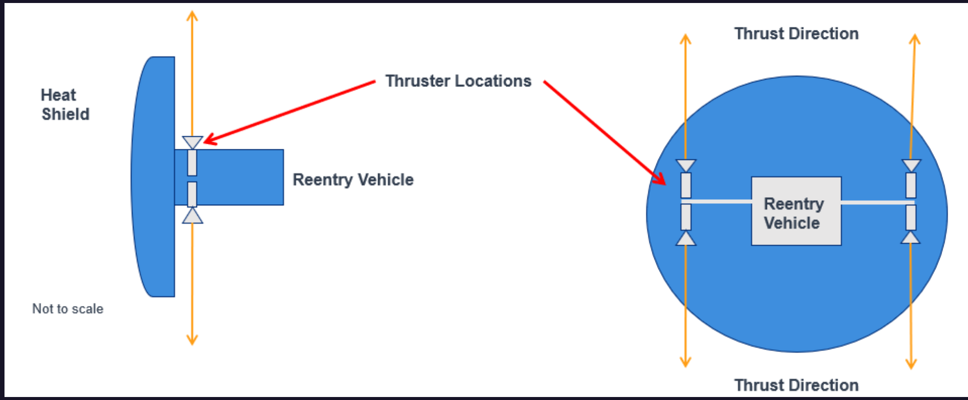
REACTION CONTROL SYSTEM (RCS)

RCS Development:

- Roll thrusters for Bank Angle Control similar to LNA study
  - Initial Pterodactyl RCS concept scaled from LNA LEO mission
    - Baseline aero
    - Cold gas thrusters
    - Thrusters mounted to aft enclosure
  - Revised for a Lunar return trajectory
  - Mass increased per Lunar baseline
    - RCS capacity increased

- APL performed an RCS sizing study for the Pterodactyl DRM
  - ➔Found the body mounted cold gas thruster concept to be lacking
    - Inadequate control torque
    - Inadequate I_{sp} from the available propellant volume
  - ➔Recommended locating thrusters at a larger reaction radius
  - ➔Recommended Hydrazine or Green Prop to provide adequate Impulse



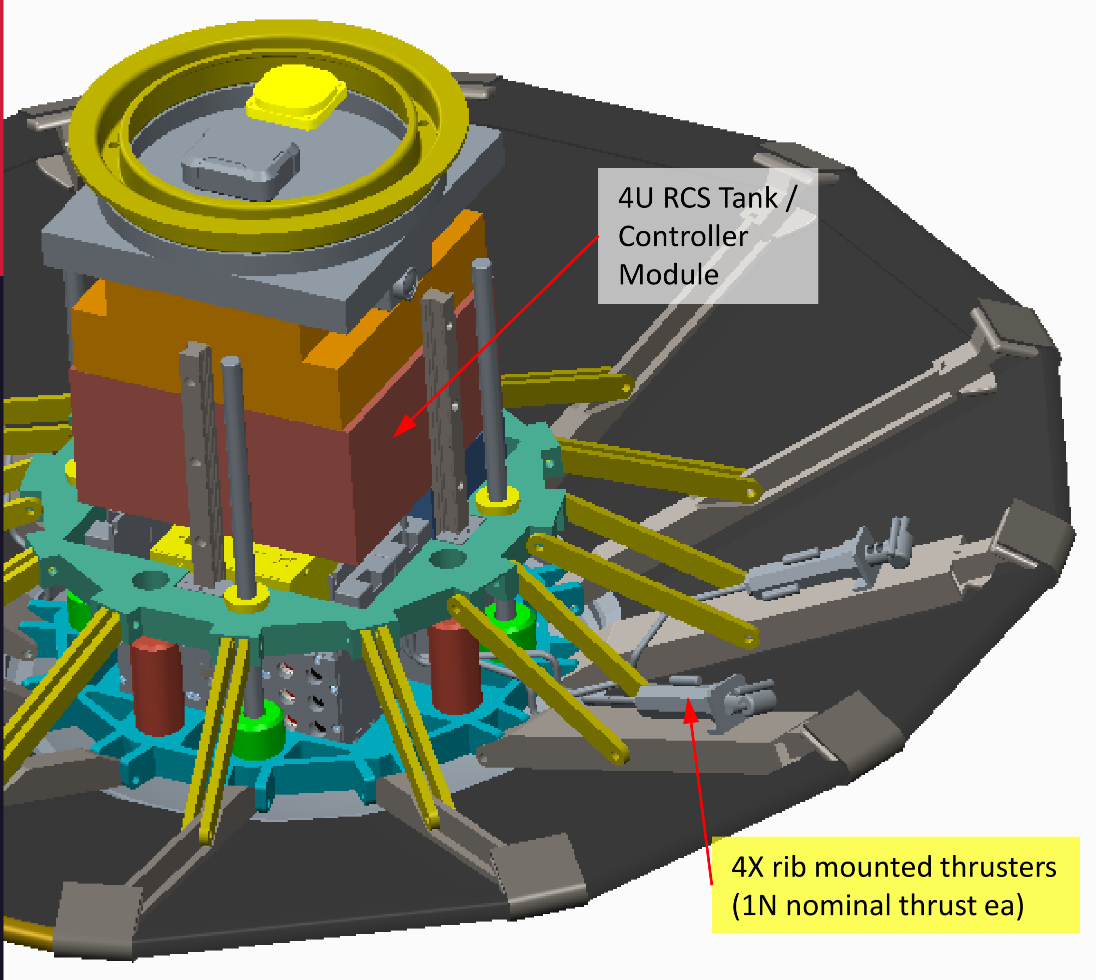


RCS (2/2)

- **RCS design concept updated to reflect APL's study results**
  - Hydrazine system (or green propellant)
  - 1N thrusters mounted on lateral ribs
  - Thrust reaction radius: 0.39m
  - Act as opposing pairs
  - Full 4U storage & distribution unit
  - Propellant mass per study
  - Updated battery estimate
    - Pumps, valves, catalyst & line heaters
- ➢ Payload enclosure nearly full
  - Less than desired 25% volume remaining
- ➢ Rib mounted thrusters require:
  - Widened / modified ribs
  - Minor mods to deployment geometry
  - Flexible or hinged propellant lines
  - Cable routing

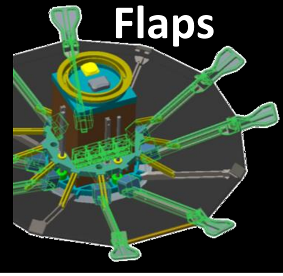
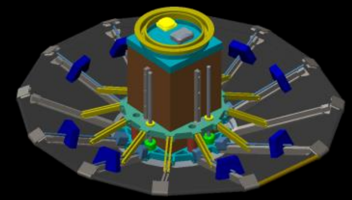
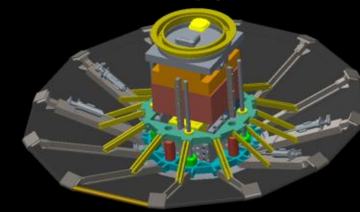
➔Resulting RCS Configuration

- **Mass: 69.1 kg**
- **Payload Volume Remaining: 17%**
- **Ease of Integration Score: 2/5**
- Performance data:
  - Thrusters: 1.0N each (2 pairs)
  - Reaction radius: 0.39 m



RCS Components on ADEPT	RCS Components in Enclosure:
Valve/Thruster Modules (Rib Mtg)	Batteries for RCS Components
Flex Lines	4U Prop Storage / Control Unit
Widened Ribs for Thrusters	Propellant Mass Allocation
	Cable & Plumbing Allocation

MECHANICAL SYSTEMS RESULTS SUMMARY

	Flaps	Mass Movement	RCS
			
Control System Mass Fraction (Baseline Mass: 59.4 kg)	Total Mass: 75.7* kg C/S Mass: 16.3 kg	Total Mass: 81.0 kg C/S Mass: 21.6 kg	Total Mass: 69.1 kg C/S Mass: 9.7 kg
Packaging / Stowage Efficiency	Payload Volume Remaining: **33%** Ease of Integration Score: **1/5**	Payload Volume Remaining: **34%** Ease of Integration Score: **3/5**	Payload Volume Remaining: **17%** Ease of Integration Score: **2/5**

CONCLUSIONS

- Developed designs for 3 control system options. Key products included:
  - Concept models for design evaluation
  - Simplified models for CFD analysis (aerodynamics database and aerothermal environments)
  - Design concept models used to analyze required torques and body rates. These models also informed mass properties and packaging metrics.

- Each control system design appears to be feasible, but each approach has pros/cons that are evaluated within the trade study framework.

- Advancements in deployable entry vehicle control system development are anticipated to enhance NASA's ability to achieve precision landing for Science and Exploration mission applications.

ACKNOWLEDGEMENTS

NASA Core Team

Sarah D'Souza (Principal Investigator)
Antonella Alunni (Lead Systems Engineer)
Breanna Johnson (Guidance and Trajectory Design Lead)
Wendy Okolo (Control System Design Lead)
Ben Nikaido (Aerodynamics and Aeroheating Lead)
Bryan Yount (Mechanical Design and Structures Lead)
Benjamin Margolis (Controls Engineer)
Zane Hays (TPS System Modeling)

Mentors

Michelle Munk
NASA STMD Mentor and EDL Principal Technologist

Dave Kinney, Alan Cassell, and Ron Sostaric
NASA Mentors

Industry Partners

Kenneth Hibbard, Jeffrey Barton, Gabriel Lopez, Jeremy John, and Larry Wolfarth

Dr. Stephen Robinson
Brandon Reddish

MECHANICAL SYSTEMS BACKUP

KE L DESIGN OUTPUTS

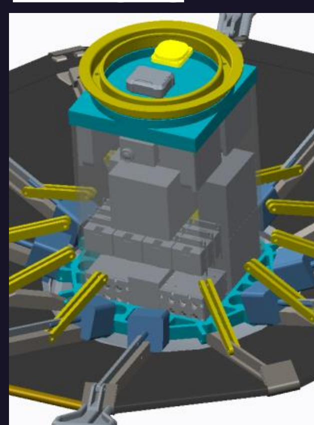
Mass		74.2 kg			
MGA Factor		1.15			
CG X, Y, Z		-1.5979E-01	0.0000E+00	8.7317E-03	m
Inertia Matrix about C.G.	Ixx, Ixy, Ixz	6.2327E+00	0.0000E+00	3.4740E-02	kg*m^2
(Body Ref CS-2 orient)	Iyx, Iyy, Iyz	0.0000E+00	3.8652E+00	0.0000E+00	kg*m^2
	Izx, Izy, Izz	3.4740E-02	0.0000E+00	3.7379E+00	kg*m^2

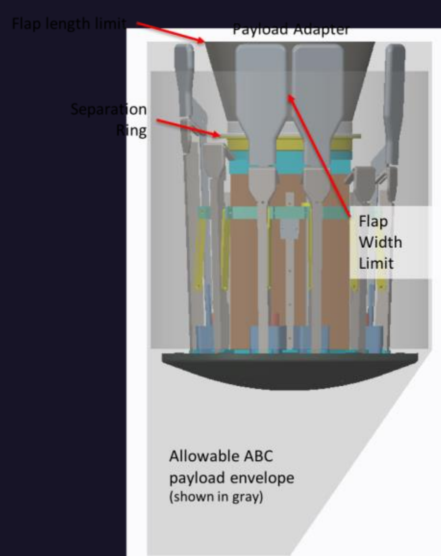
Design Concept Models (DCM) in CAD for evaluation:

- Mass Estimates → FOM #2 ***AND*** as input for G&C performance calculations
- Packaging & fit evaluation → FOM #3
- Component performance estimates for team to evaluate overall performance
- INTEGRATION COMPLEXITY VERBIAGE for trade study input
- REMOVE FOM REFERENCES

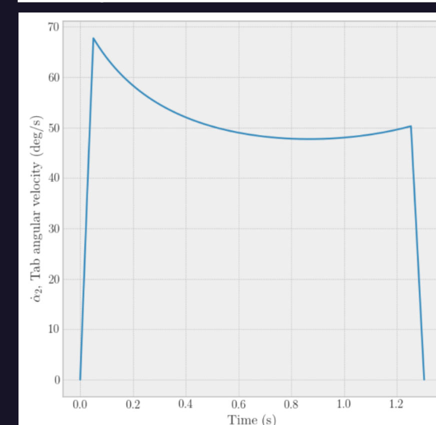
Mass Properties

Packaging





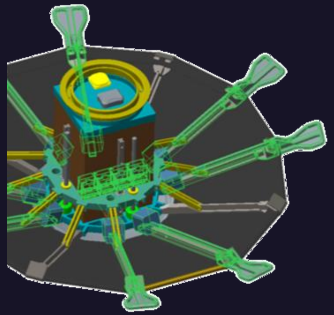
Component Performance



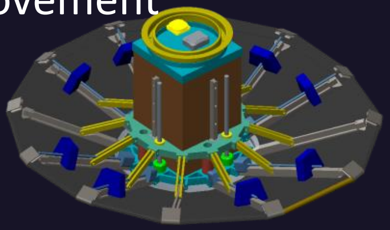
FOM 2: CONTROL SYSTEM MASS FRACTION
PERFORMANCE AND EFFECTIVENESS

System mass fraction equal to the mass of the control system to the total mass of the system

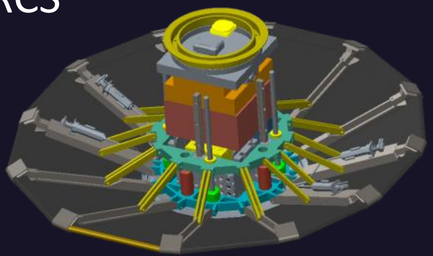
Flaps



Mass Movement



RCS



	Total Mass	Control System Mass	Mass Fraction
Flaps [a]	75.7	16.3	.27
Mass Movement	81.0 [b]	21.6	.36
RCS	69.1	9.7	.16

C.S. Mass Fraction = C.S. Mass / Baseline Mass
(Baseline Mass = 59.4 kg)

a) Values include TPS mass update. G&C used 74.2 kg estimate.
b) Slightly exceeds ABC payload mass limit of 77 kg

FOM 2: CONTROL SYSTEM MASS FRACTION
(PERFORMANCE AND EFFECTIVENESS) EVALUATION METHOD

FOM #2 considers the mass of each control system

- **Design Concept Model is used to generate a MASS ESTIMATE**
  - For simplicity, all estimates use a blanket 15% MGA
- **Baseline configuration is used as the entry system mass w/o control system**
- **Control system mass is calculated as:**
  - $\text{C.S.Mass}_{(\text{Option N})} = \text{Total\_Mass}_{(\text{Option N})} - \text{Mass}_{(\text{Baseline})}$
- ***Control System Mass Fraction*** **is calculated as:**
  - $\text{C.S.Mass\_Fraction}_{(\text{Option N})} = \text{C.S.Mass}_{(\text{Option N})} / \text{Mass}_{(\text{Baseline})}$
  - **Results are reported as decimal fractions**
  - **Lower values are better**
  - **Final Results will be presented in a later section…**

Configuration: LNA-P DCM08 (Top Level)		8/29/2018
LNA-PT DCM08 Top Level MEL	**Est. Subsystem mass (lb)**	**Est. Subsystem mass (kg)**
Nose Cap	10.35	4.69
Rib Pivot Plate	4.56	2.07
Ribs (12)	15.92	7.22
Rib Tips (12)	9.27	4.20
Deployment Ring	2.88	1.31
Struts (12 pairs)	1.95	0.88
Actuation (Motor|Gearbox|Leadscrew)	6.81	3.09
Linear Guides	4.75	2.15
Carbon Fabric Skirt (18 layer)	14.22	6.45
Payload Enclosure Structure	8.21	3.72
Payload Enclosure Contents (incl. harness)	28.17	12.78
Aft Deck	2.62	1.19
Lightband Separation Ring	0.78	0.35
Fastener Mass Allocation	3.31	1.50
LNA-PT Total Mass: (CBE)	**113.8**	**51.6**
LNA-PT Total Mass: (w/ 15% MGA)	**130.9**	**59.4**

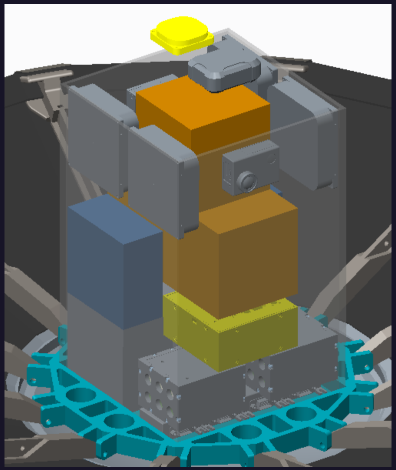
FOM 3: PACKAGING & STOWAGE EFFICIENCY
(PERFORMANCE AND EFFECTIVENESS)
EVALUATION METHOD

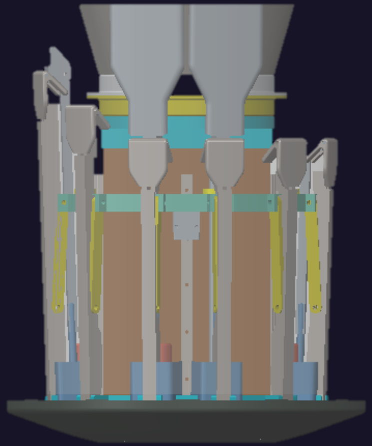
FOM #3 considers the fit & ease of integration of each control system

- **Packaging & Stowage Efficiency is evaluated in two ways**
  1. Volume remaining within the Pterodactyl payload enclosure
     - Payload enclosure (empty) is 12U: 12,000 cm^3
     - Available volume is evaluated (in CAD) for each DCM
     - Baseline has 40% available volume remaining

     ➔ % volume remaining after adding control components is reported as FOM 3.1
       - * 25% remaining is desirable for assembly & cabling
  2. Ease of integration of control components with deployable aeroshell
     - Based on engineering judgement considering:
       - Fit when stowed, compatibility with structure & deployment, added complexity, & modifications required to baseline

     ➔ Qualitative score from 1-5 based on above criteria is reported as FOM 3.2
     (1:Major Issues, 2:Challenging, 3:Moderate, 4:Fairly Easy, 5:Very Easy)



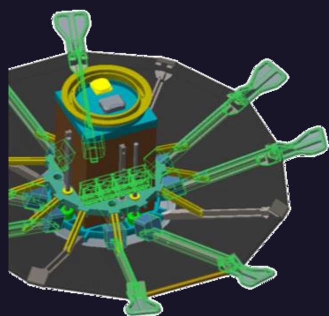


- **Large volume remaining and high ease of integration scores are preferred**
- **Volume and ease scores will be combined for final FOM evaluation**
- **Final Results will be presented in a later section…**

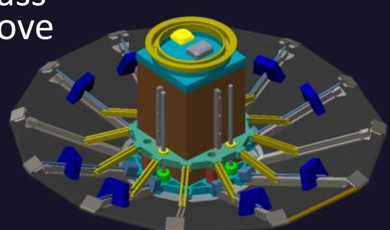
FOM 3: PACKAGING/STOWAGE EFFICIENCY
PERFORMANCE AND EFFECTIVENESS

Stowed system volume remaining in Pterodactyl enclosure

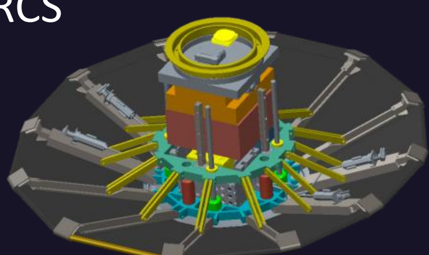
Flaps



Mass Move



RCS



	Payload Volume Remaining	Integration Score (n/5)
Flaps	33%	1
Mass Movement	34%	3
RCS	17% [c]	2

(Integration Scoring: 1:Major Issues, 2:Challenging, 3:Moderate, 4:Fairly Easy, 5:Very Easy)

Notes:

- Baseline has 40% payload volume remaining
- Integrating active flaps in hot flow will be a major TPS challenge
- Mass movement is most straightforward to integrate, but still presents some actuator packaging challenges

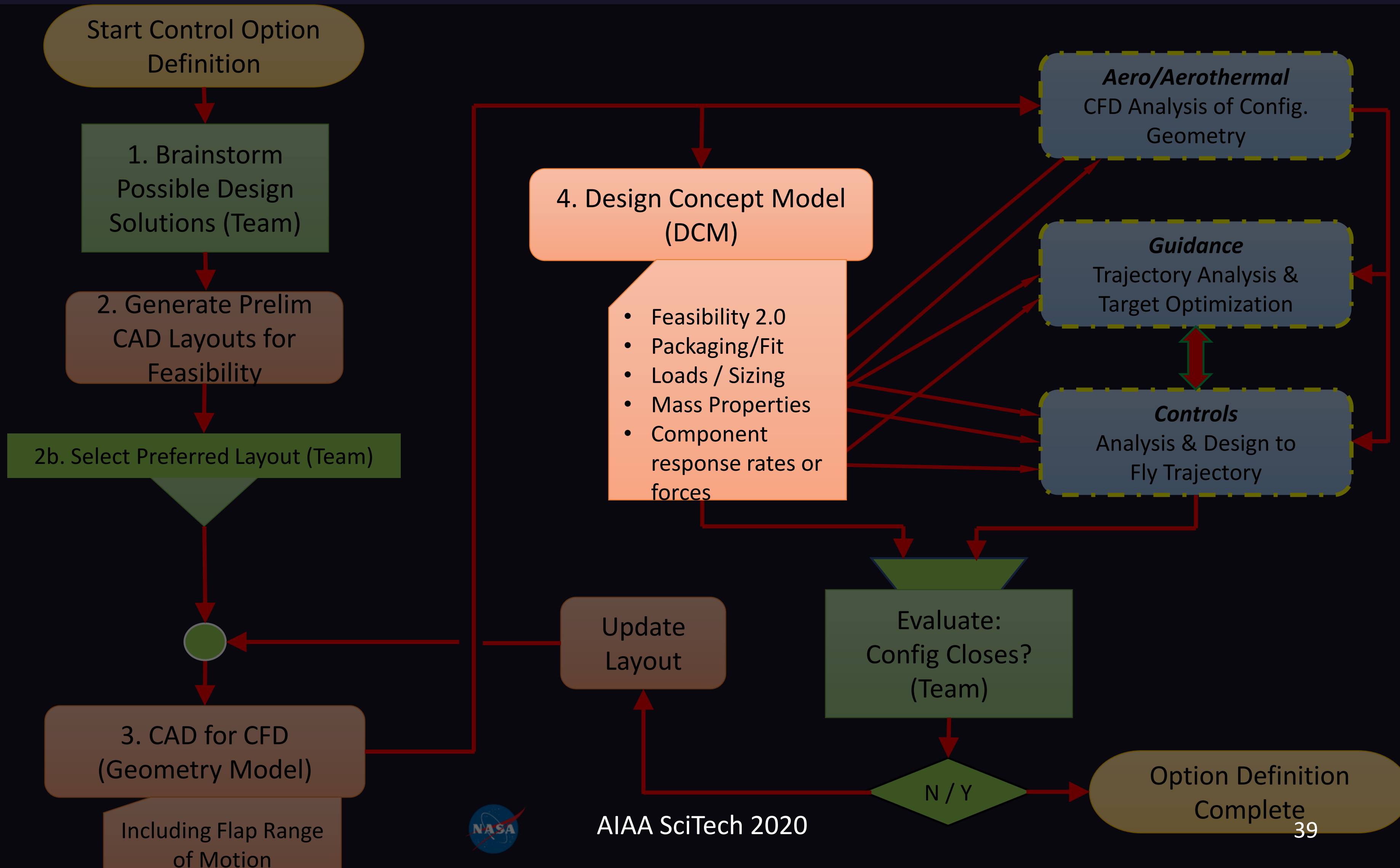
c) Volume remaining is less than the 25% desired for component packaging

COMPONENT PERFORMANCE
(→ GUIDANCE & CONTROLS TEAMS FOR ANALYSIS)

Control System Component Performance Information

- **Design process includes estimating control system component level performance** (i.e. initial component sizing / specifications to effect vehicle control – *hopefully / iterate*)
- **Info provided to G&C teams as inputs for vehicle level control evaluation**
- **Examples:**
  - **Flaps:** Range of motion (deg), flap angle change rate (deg/sec), flap angular acceleration (deg/sec^2)
  - **Mass Movement:** Amount of moving mass (kg), range of motion (m), positioning rate (m/sec), acceleration (m/sec^2)
  - **RCS:** Thruster force (N), [also thrust vector for Torque], minimum impulse bit (N*s), total impulse (N*s)

MECHANICAL GROUP: PROCESS

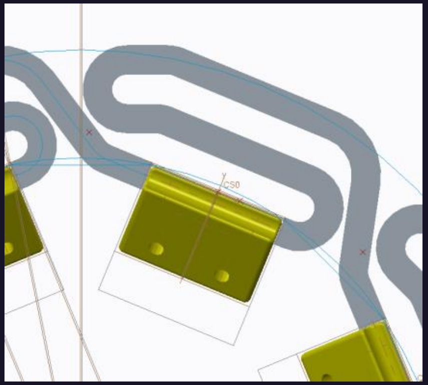


BASELINE RESET

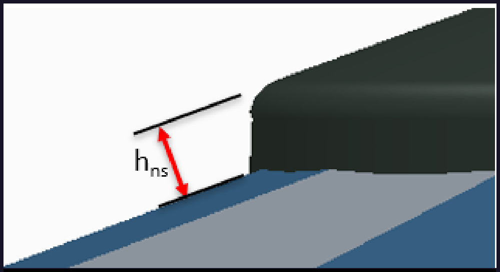
- **Initial baseline model was sized for a LEO re-entry, but then a lunar return DRM was selected for the control system study**
- Implications filtered in as more analyses were completed
  - Higher peak heat flux and total heat load
  - Model updated with higher mass
  - Trajectory updated: reduced peak flux, but even higher heat load

➢ ***<u>Result: Total heat load 4X initial baseline assumption</u>***

- ***4X increase in ADEPT carbon fabric TPS layers needed***
  - 18 total layers can't be folded/packaged on a 1m ADEPT
  - ➢ ***<u>ADEPT scaling rules implies the vehicle will need to be scaled up to accommodate 18 layers of fabric</u>***
- ***Thicker nose cap TPS also required***
  - A large step-down from nose cap to deployable aeroshell is aerodynamically undesirable
  - ADEPT recommended max step-down height of 1.6% of vehicle diameter exceeded



Fabric Bend Radius Allowance



Nose Cap Step-Down

SCALING DECISION

- **1m diameter baseline vehicle design doesn't accommodate the required TPS thickness for the lunar DRM**
  - ADEPT fabric bend radius rules not met
  - ADEPT nose cap step-down rules not met

- **ADEPT scaling rules of thumb suggest that the TPS thicknesses CAN be accommodated on a vehicle with a larger diameter**
- **Project is too far along for a complete restart on a vehicle design**

➢ ***Project Decision: <u>analyze the 1m diameter vehicle</u> for control system performance <u>using the correct mass</u> with TPS sized for the lunar return DRM & defer the ADEPT-related thickness rules***
  - Carbon fabric & nose cap TPS thickness not expected to affect controls study
  - If an actual ADEPT-based lunar return vehicle is designed ➔ 2.5m diameter