NASA SPACE TECHNOLOGY MISSION DIRECTORATE

EARLY CAREER INITIATIVE

Pterodactyl

Integrated Control Design for Precision Targeting of Deployable Entry Vehicles

Dr. Sarah D’Souza, Principal Investigator
NASA Ames Research Center

PTERODACTYL TEAM

NASA Core Team

Dr. Sarah D'Souza (Principal Investigator)
Antonella Alunni (Lead Systems Engineer)
Breanna Johnson (Guidance and Trajectory Design Lead)
Dr. Wendy Okolo (Control System Design Lead)
Ben Nikaido (Aerodynamics and Aeroheating Lead, 18-19)
Veronica Hawke (Aerodynamics Lead, 20-21)
Bryan Yount (Mechanical Design and Structures Lead)
Dr. Benjamin Margolis (Controls Engineer)
Zane Hays (Aeroheating and TPS System Modeling)
Andrew Torricelli (TPS System Modeling)
Sander Visser (TPS System Modeling)

Advisors

Michelle Munk
NASA STMD Mentor and
EDL Principal Technologist

Dr. Dave Kinney, Dr. Alan Cassell, and Ron Sostaric
NASA Mentors

Industry Partners

Kenneth Hibbard, Jeffrey Barton, Dr. Gabriel Lopez, Jeremy John, Hyung Kang, Jeff Taylor, Matt Leibowitz, and Larry Wolfarth

Dr. Stephen Robinson
Brandon Reddish

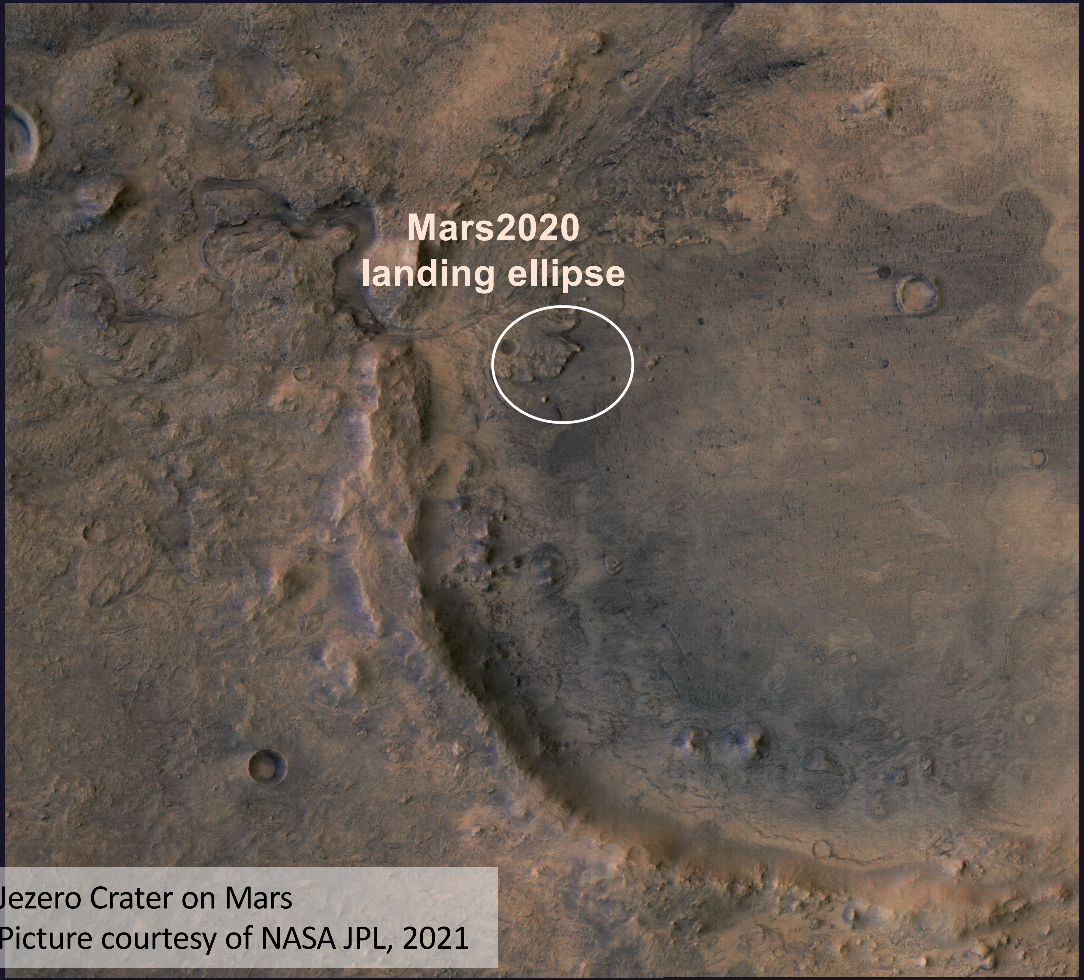
MOTIVATION

Demonstrate the capabilities required for human missions to Mars and other destinations.

Need to precisely land high masses on Mars very close to desired locations and assets.

EXPLORE MOON to MARS

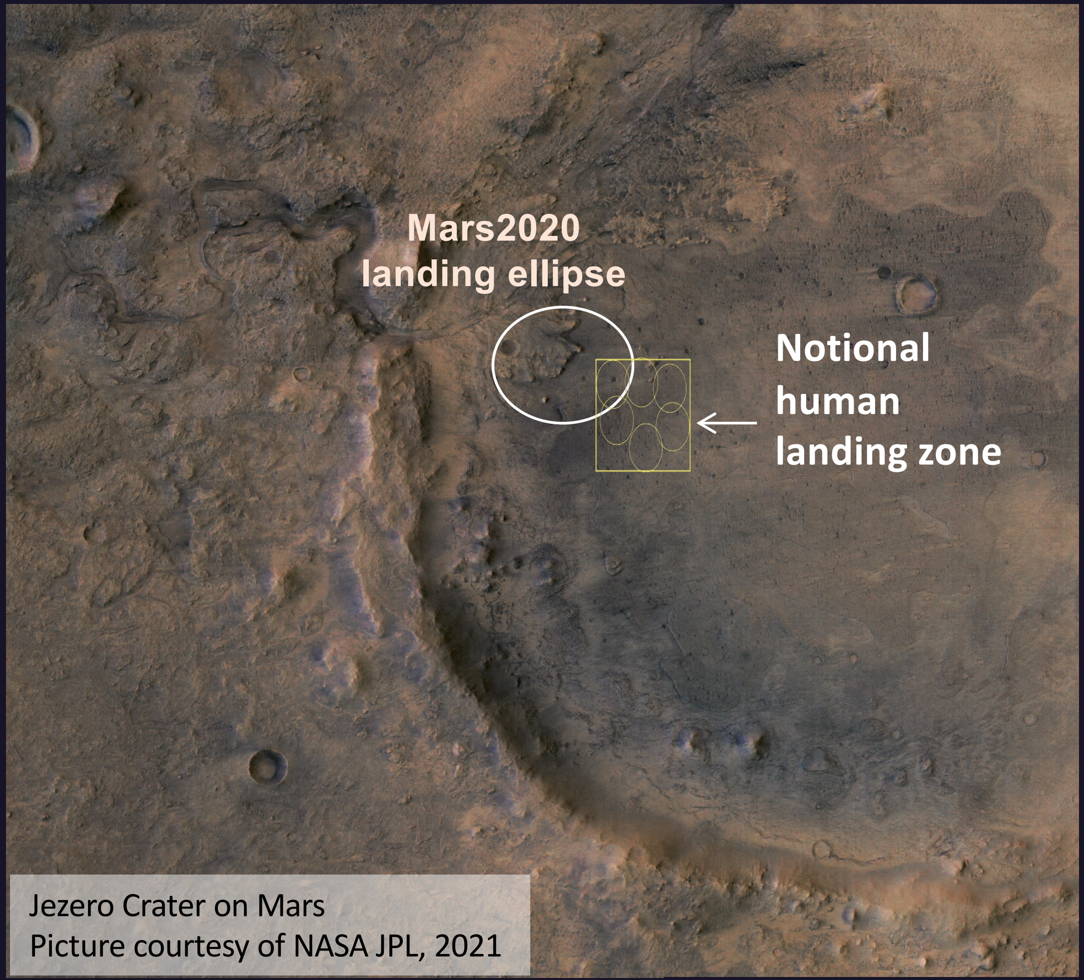
MOTIVATION (CONT'D)



Jezero Crater on Mars
Picture courtesy of NASA JPL, 2021

Past Mars robotic missions have demonstrated a capability to land up to 3.5 mT between 1km and 3km of the desired target site

MOTIVATION (CONT'D)



Jezero Crater on Mars
Picture courtesy of NASA JPL, 2021

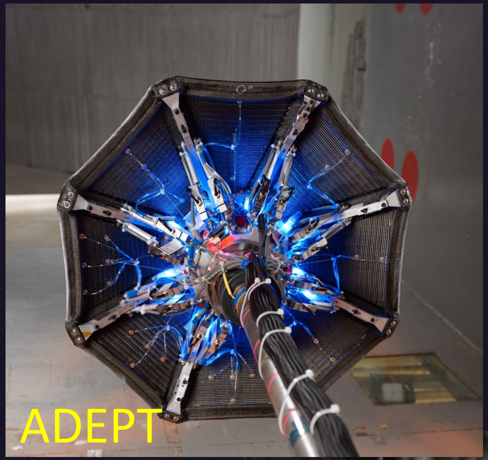
Future large mass missions to Mars will require autonomous targeting to land up to 25 mT and ensure human, science and life support assets are placed within 50m

MOTIVATION (CONT'D)

Deployable Entry Vehicles enable large mass missions to Mars because the aeroshell can stow to smaller diameters at launch for the equivalent payload of a larger diameter rigid aeroshell

NASA has invested and successfully developed flexible thermal protections systems for foldability DEVs

Mechanically Deployed

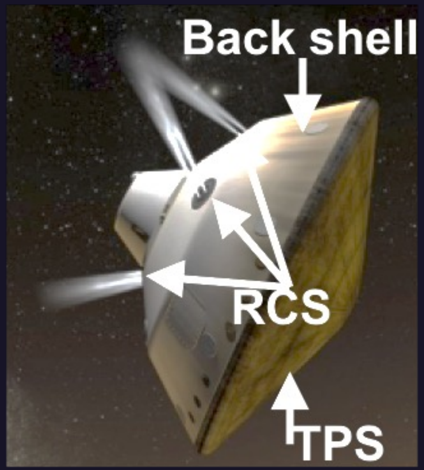


Inflatable

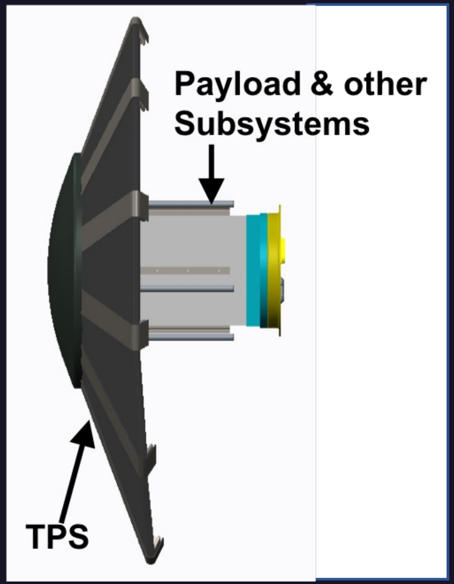
NEED Feasible guidance and control systems that achieve precision targeting

WHY IS THIS A CHALLENGE

Heritage Entry Vehicle with Reaction Control System (RCS)



DEVs have no back shell



GAP An integrated assessment of the theory and the control effector hardware for steering did not exist to close a design that achieved precision targeting for DEVs

RESEARCH GOAL

Pterodactyl was selected to address this gap in control system modeling and solutions for precision targeting of deployable entry vehicles (DEVs)

BRIEFING TOPICS

Demonstrate how Pterodactyl has **advanced the state of the art (SOA):**

1. **Tools/analysis** for Entry phase control system modeling for steering DEVs (mechanical and inflatable)

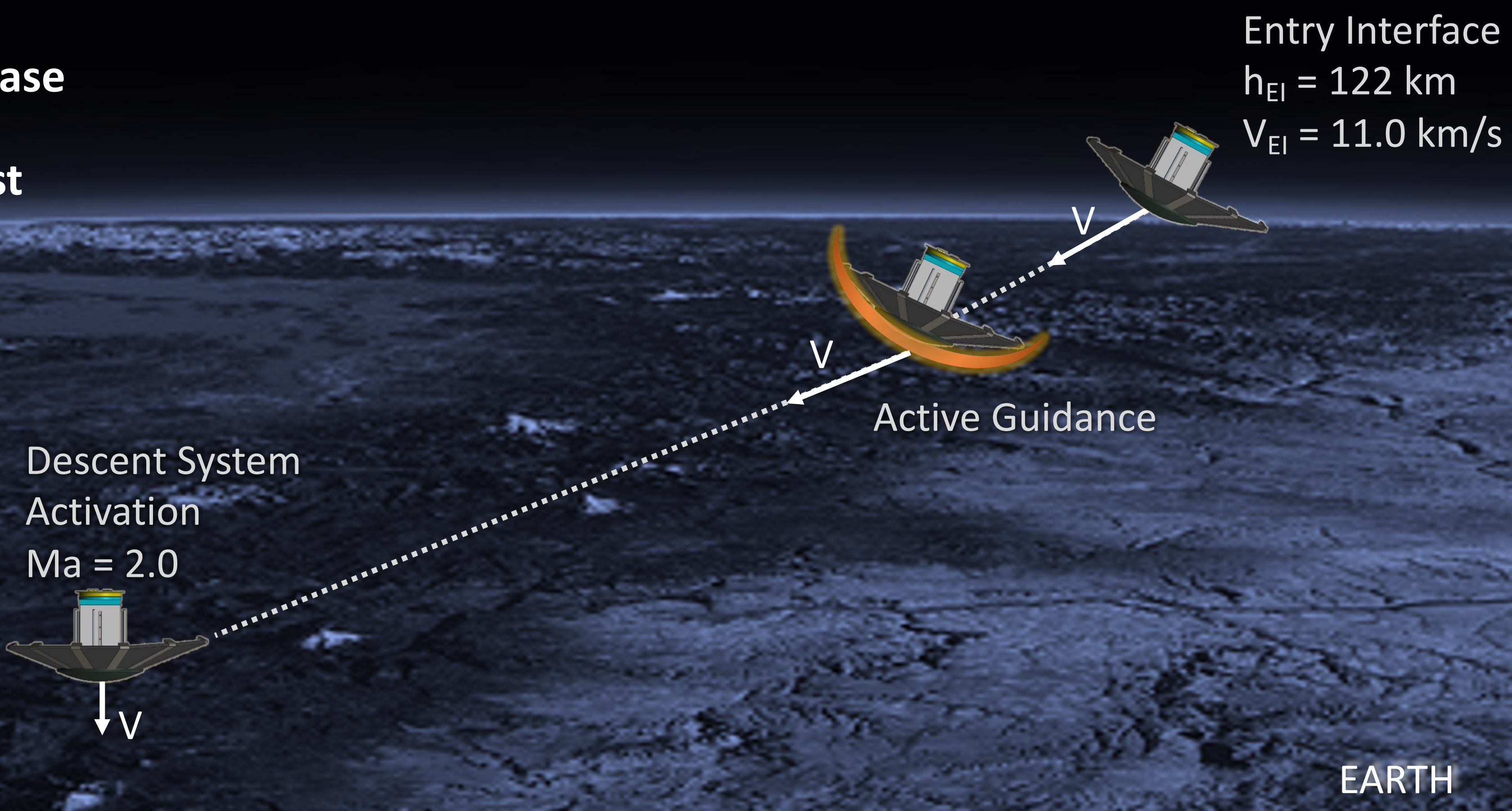
2. **Control Solutions** for steering DEVs, during the entry phase, that meets current targeting precision

BASELINE MISSIONS

Lunar Return mission

Focused on Entry phase

Target site - Utah Test and Training Range

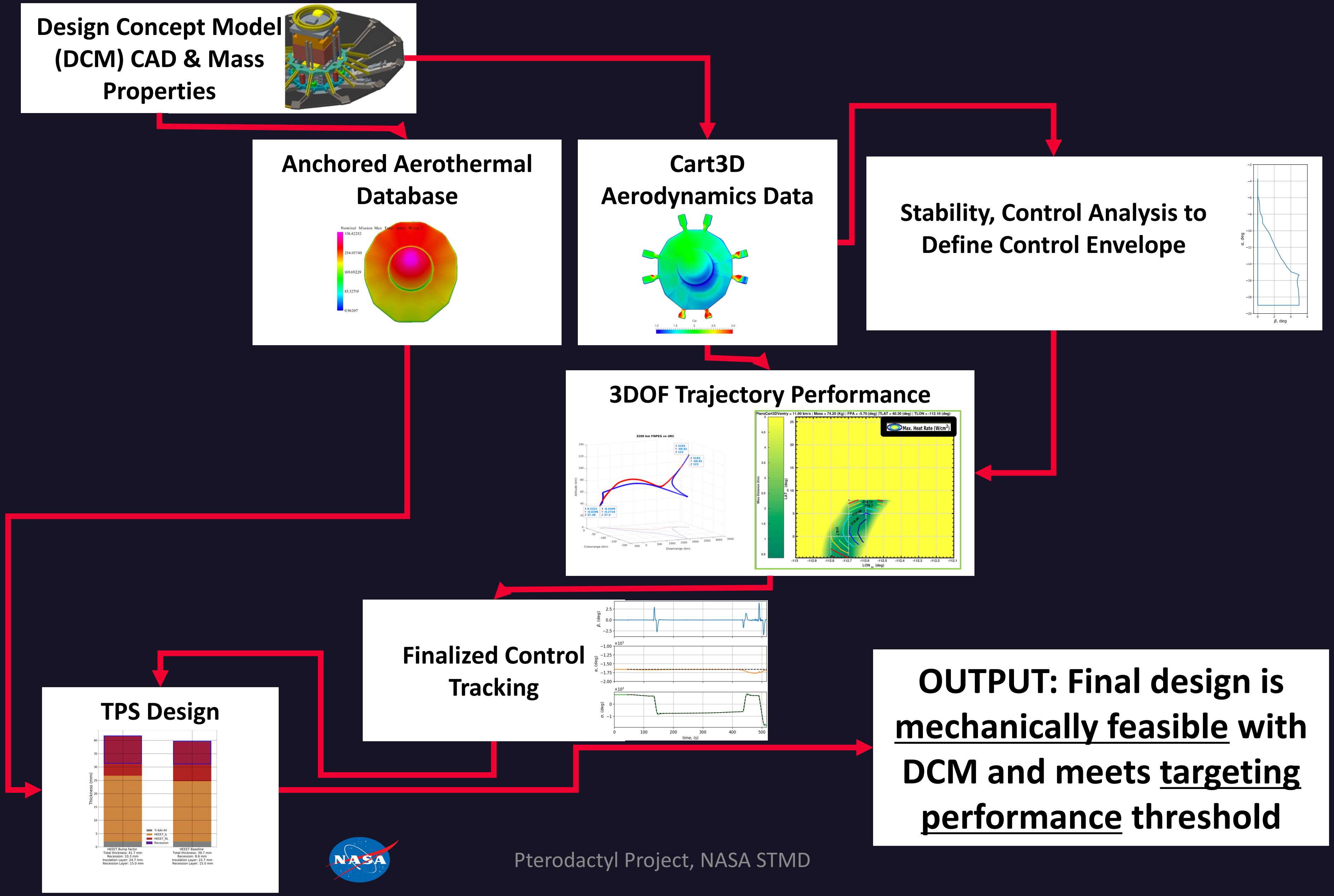


INNOVATIVE MODEL DEVELOPMENT

Developed models and simulations that enabled study of multiple different vehicle configurations

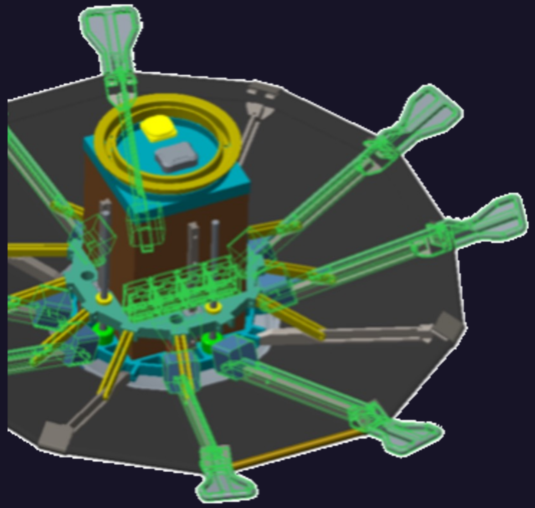
	Model	New Development
1	Mechanical Systems	Identified control effector mechanical design/integration
2	Aerodynamics & Aeroheating	Multi-control effector modeling to generate database of forces, moments, and heating environments with varying side slip and geometry
3	Entry Guidance & Trajectory Design Development	Developed methodology to generate α/β or σ guidance commands
4	Stability Analysis & Control Design	Developed novel control approach to identify torque/control effector commands and understand control system maneuverability
5	TPS Analysis	Increased fidelity to model control effector aeroheating environments and TPS thickness/mass for varying side slip and geometry

INTEGRATED CONTROL SYSTEM ANALYSIS PROCESS

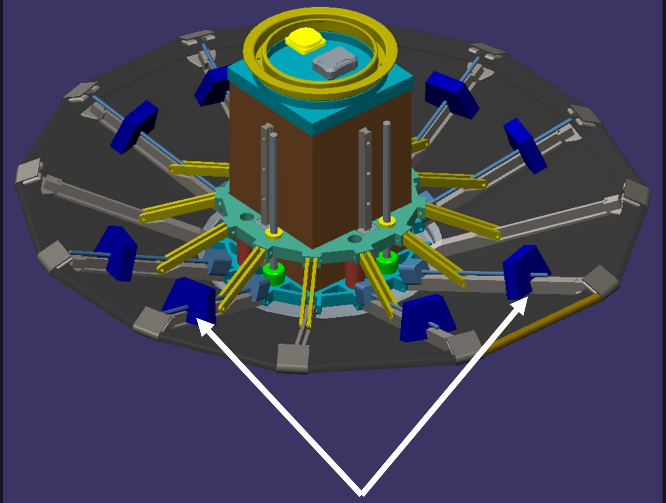


CONTROL SYSTEM TRADE STUDY

Flaps Control System

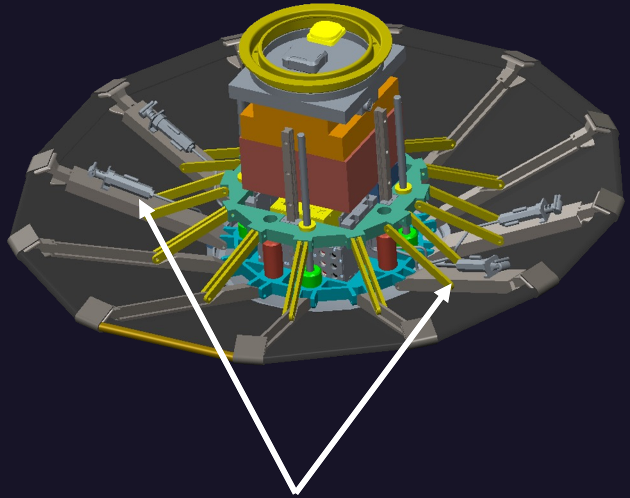


Mass Movement Control System



Independent
Moveable Masses

Reaction Control System



4 RCS Jets

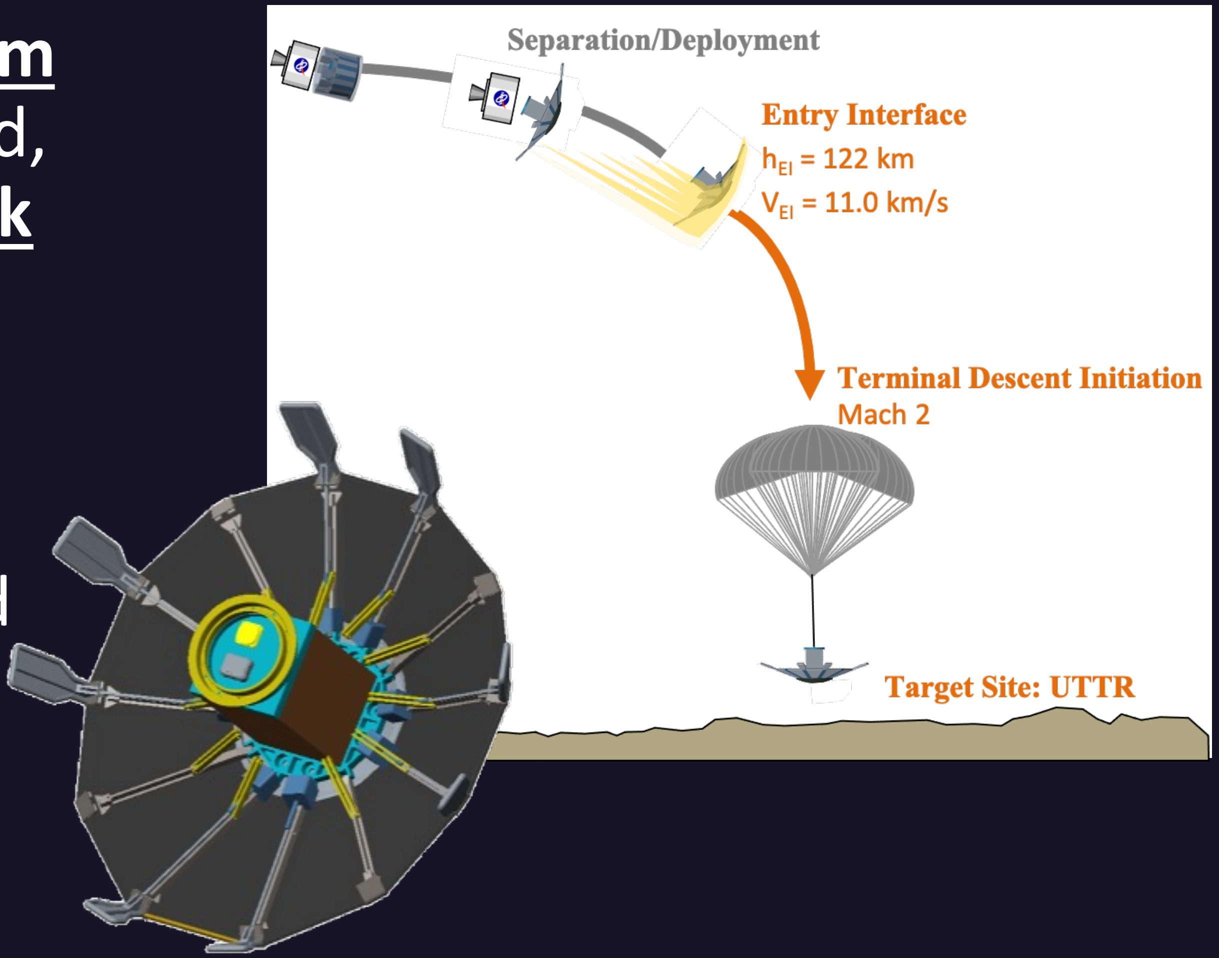
SYSTEM ANALYSIS POINT OF DEPARTURE

Established a feasible **flap control system** integrated with a mechanically deployed, **asymmetric** ADEPT DEV that tracks **bank guidance** commands

Exceptional control system capability

- Added trim augmentation, increased maneuverability

Notable available payload volume



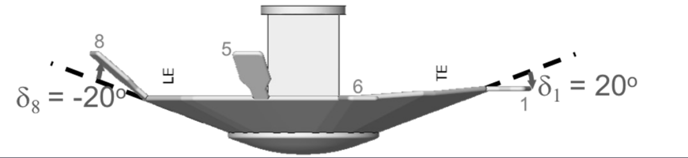
FLAP CONFIGURATION OVERVIEW

Longitudinal Control

Flaps 1, 2, 7, and 8

Lateral Control

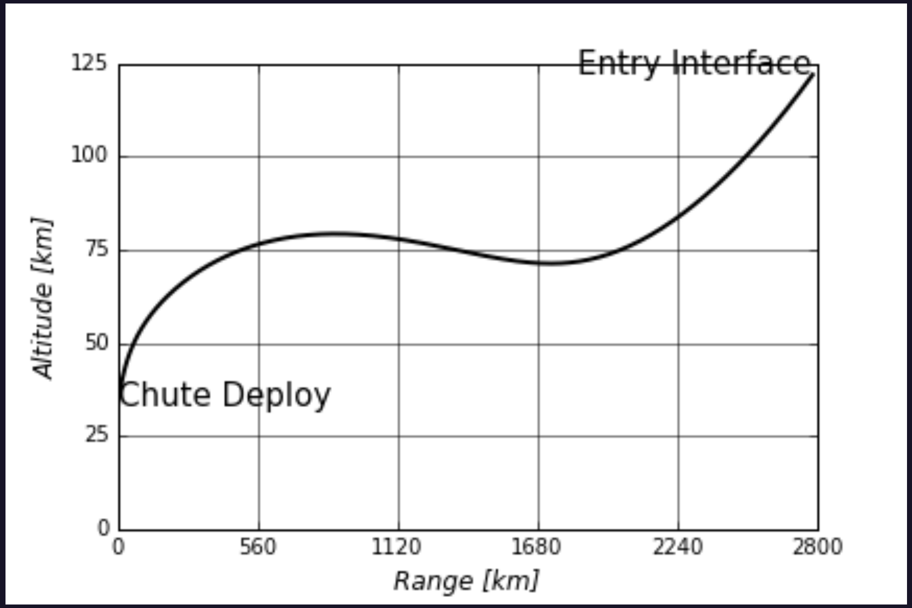
Flaps 3-6

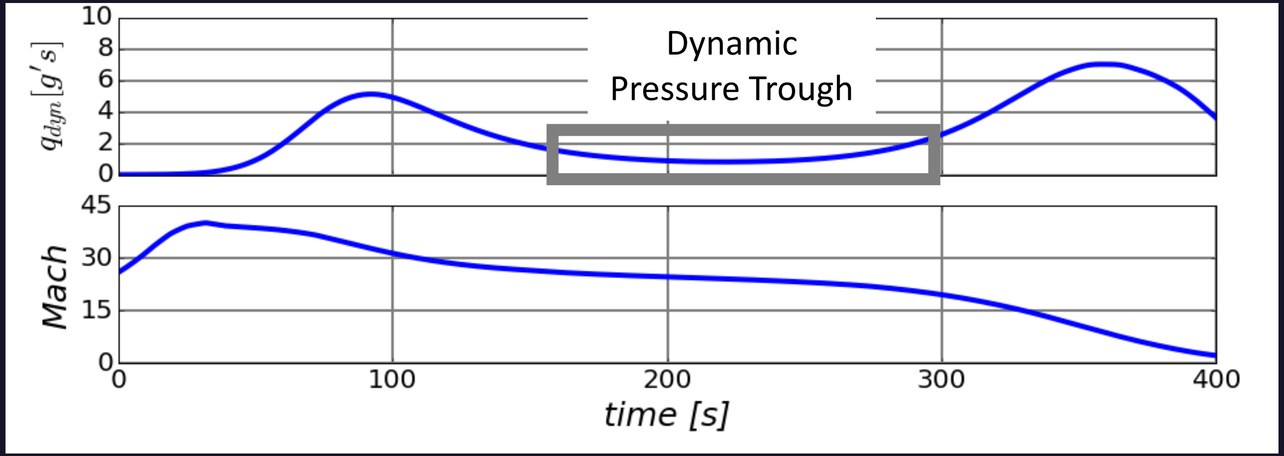


- **Flap deflection range: + 20° to - 45°**
- **Positive deflection pushes flap into the flow**
- **Negative deflection pulls flap out of the flow**

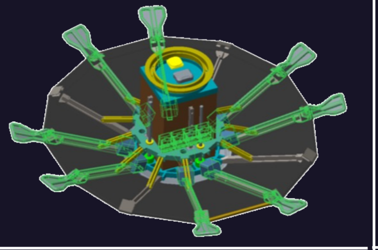
8 flaps to increase control authority, reduce of multi-axis coupling due to flap locations, & satisfy packaging/stowing constraints

BASELINE TRAJECTORY – GENRAL CHARACTERISITICS





FLAP CONTROL SYSTEM ANALYSIS

	Control Variables	Vehicle Parameters
Asymmetric 	σ <u>Coupled</u> down/cross range control	diameter = 1+ m mass = 75.7 kg
Symmetric 	α/β <u>Decoupled</u> down/cross range control	diameter = 2.86 mass = 703 kg
Symmetric, cg-offset 	σ <u>Coupled</u> down/cross range control	

Understand trade-offs between performance and mechanical complexity of flaps

BASELINE TRAJECTORY - SYMMETRIC

Key drivers for the achievable range:

1. Control envelope – Identifies how much α/β can be commanded with flaps and still maintain vehicle stability

2. 99%-tile Miss Distance – Conduct a Monte Carlo analysis to indicate whether the integrated system will meet targeting performance thresholds

3. Heating limits – Identifies if the resulting maximum heat rate is exceeded

4. Dynamic Pressure Trough – Identifies the minimum dynamic pressure between two peaks (trough) for a lofted entry

5. Cross range/attitude limits – Identifies whether guided α/β is flying the edges of the control envelope in order to achieve a significant cross range

BASELINE TRAJECTORY - SYMMETRIC

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Control envelope:
α-β = +/- 10 deg

BASELINE TRAJECTORY - SYMMETRIC

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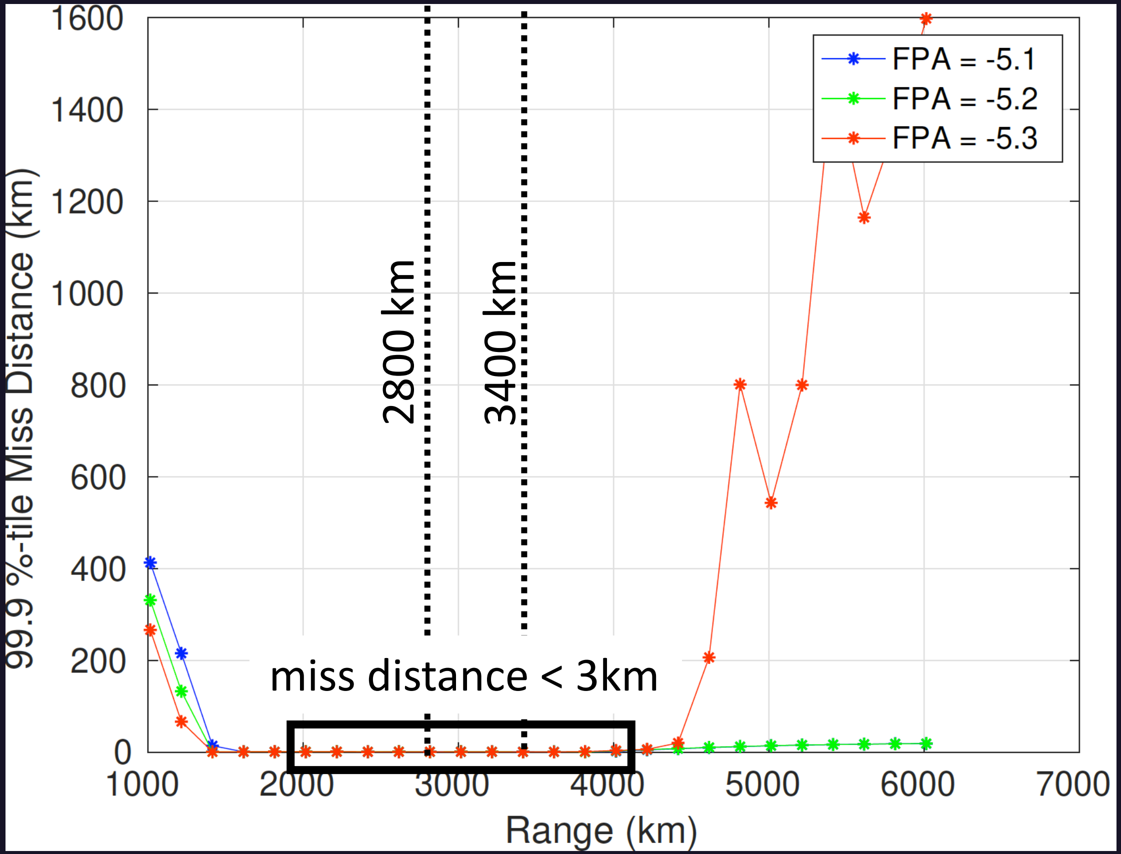

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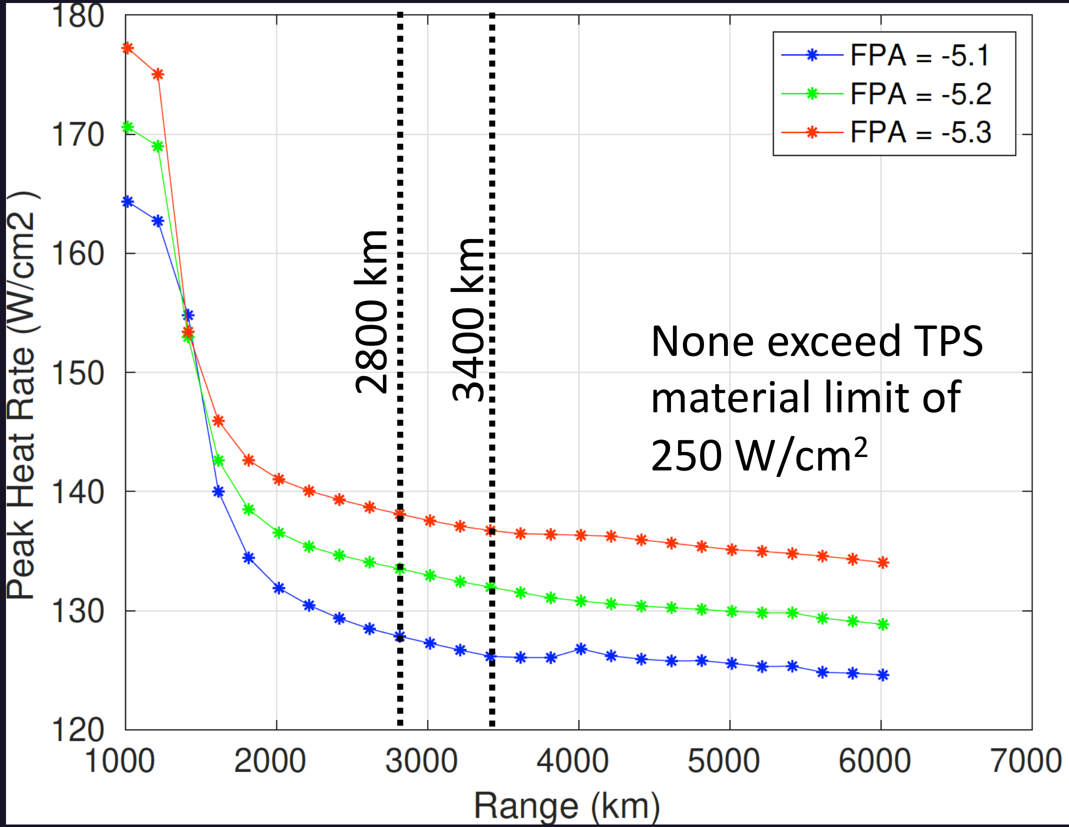

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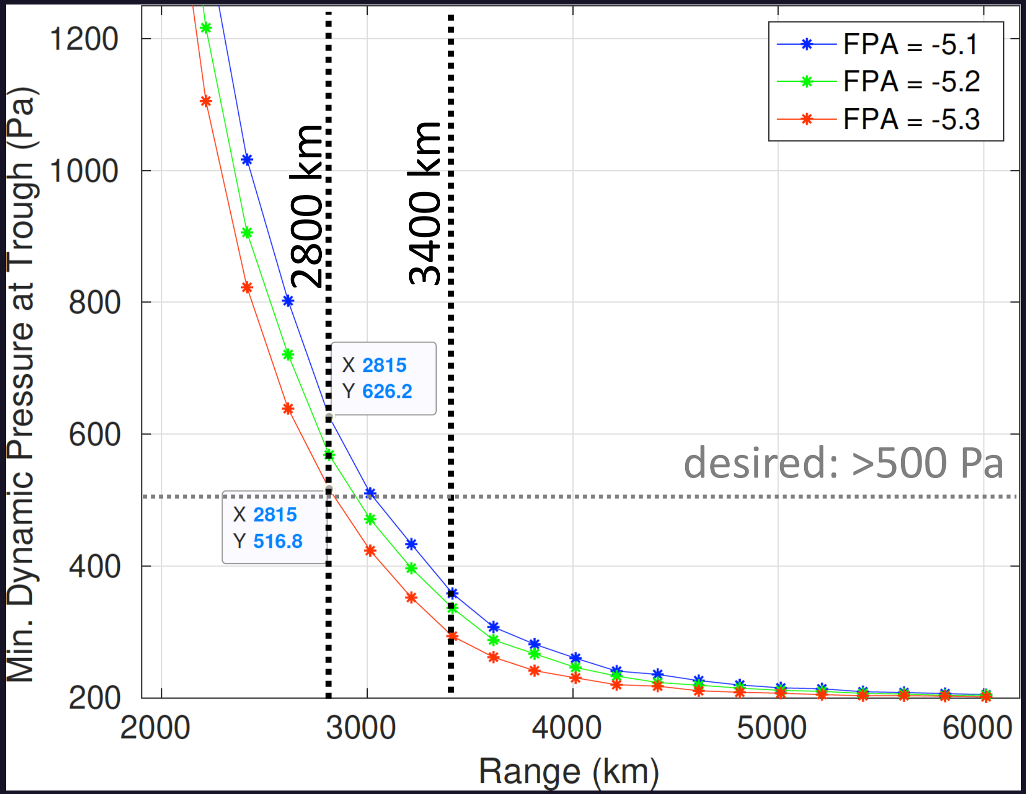

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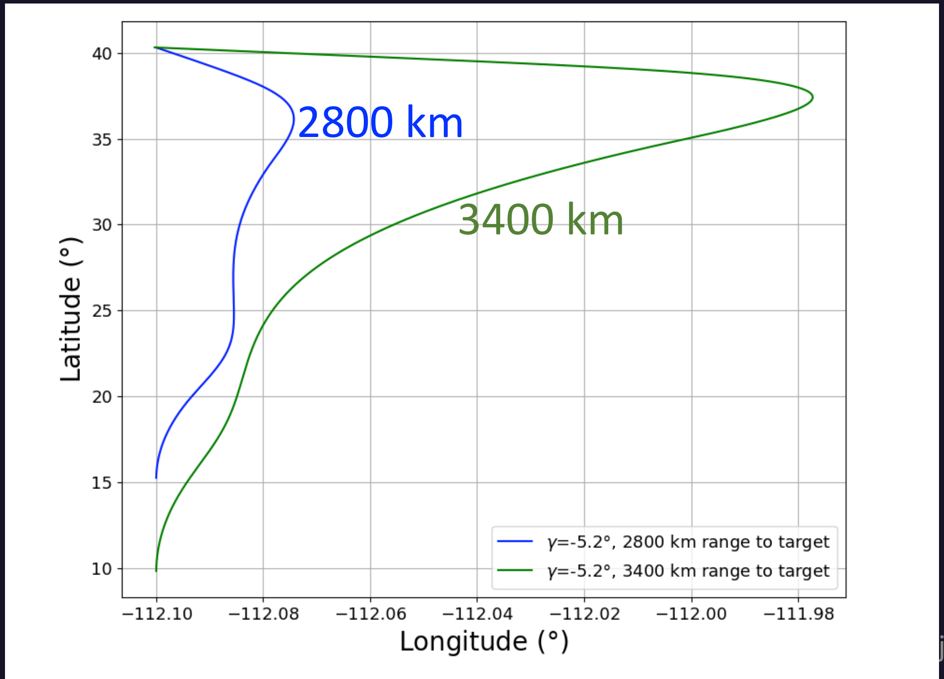
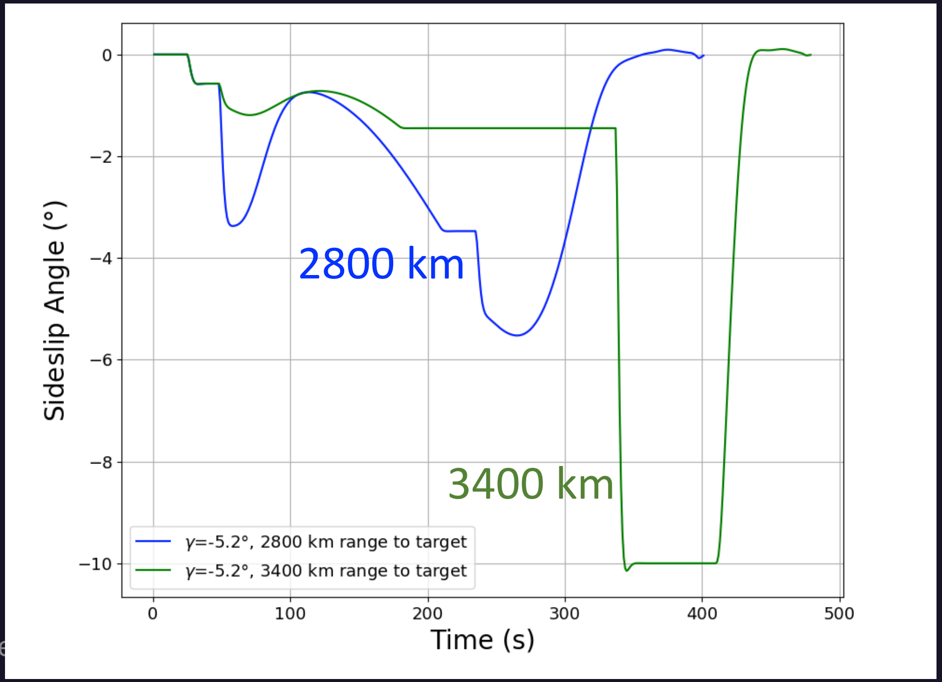




BASELINE TRAJECTORY - ASYMMETRIC

	Asymmetric σ-guidance	
Target Range [km]	***3400***	
	Mean	*99.9%-tile*
Miss Distance [km] < 3km	0.31	0.64
Peak Heat Rate [W/cm2] < 250	198	211
Peak G-load [g's] < 15g's	5.7	6.2

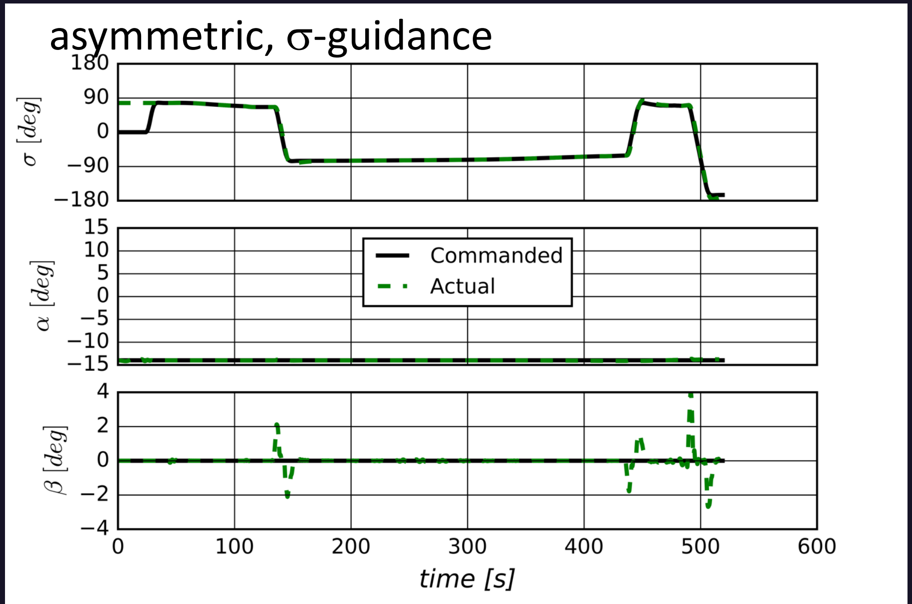
BASELINE TRAJECTORY - ASYMMETRIC

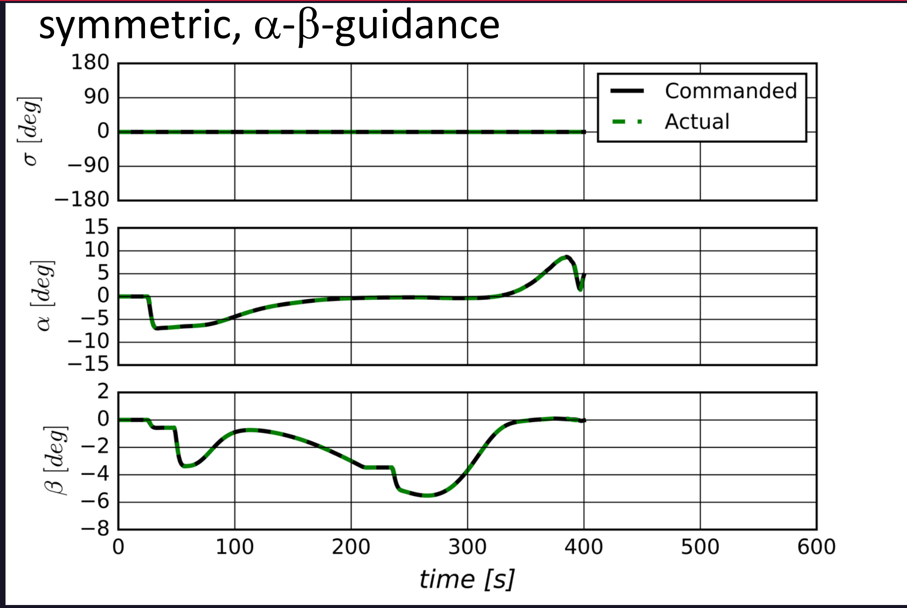
	Asymmetric σ-guidance		Symmetric α–β-guidance	Symmetric σ-guidance
Target Range [km]	***3400***		***2800***	
	Mean	*99.9%-tile*		
Miss Distance [km] < 3km	0.31	0.64		
Peak Heat Rate [W/cm2] < 250	198	211		
Peak G-load [g's] < 15g's	5.7	6.2		

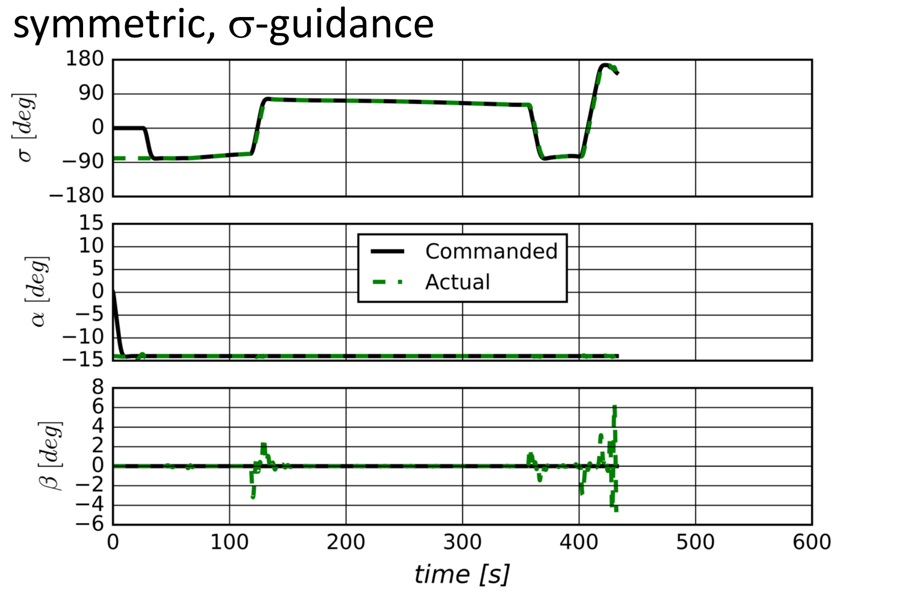
BASELINE TRAJECTORY - ALL

	Asymmetric σ-guidance		Symmetric α–β-guidance		Symmetric σ-guidance	
Target Range [km]	***3400***		***2800***			
	Mean	*99.9%-tile*	*Mean*	*99.9%-tile*	*Mean*	*99.9%-tile*
Miss Distance [km] < 3km	0.31	0.64	0.35	0.79	0.52	1.36
Peak Heat Rate [W/cm2] < 250	198	211	207	223	201	215
Peak G-load [g's] < 15g's	5.7	6.2	6.5	7.2	5.6	6.2

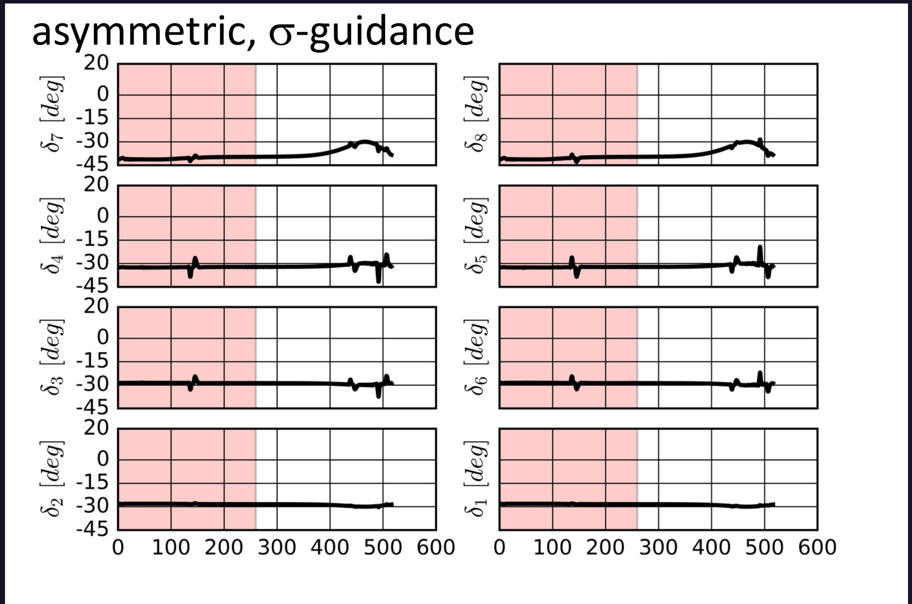
GUIDANCE COMMANDS - ALL

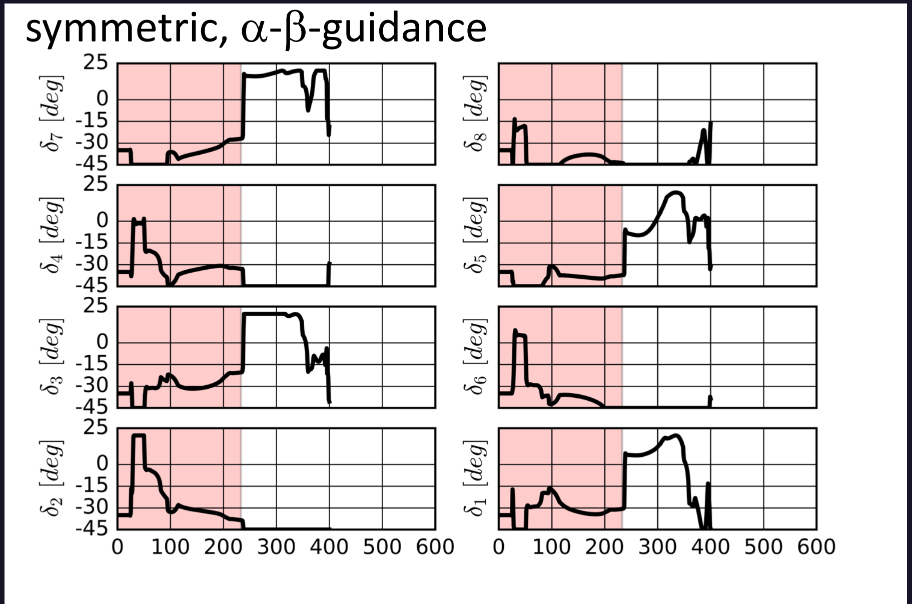






FLAP USAGE


asymmetric, σ-guidance
δ7 [deg]
δ8 [deg]
δ4 [deg]
δ5 [deg]
δ3 [deg]
δ6 [deg]
δ2 [deg]
δ1 [deg]
20
0
-15
-30
-45
0 100 200 300 400 500 600


symmetric, α-β-guidance
δ7 [deg]
δ8 [deg]
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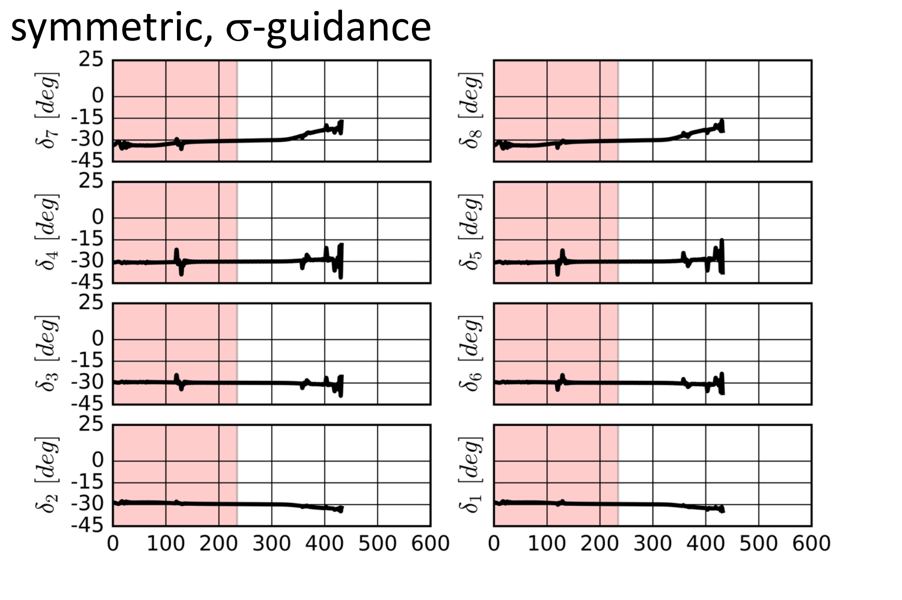
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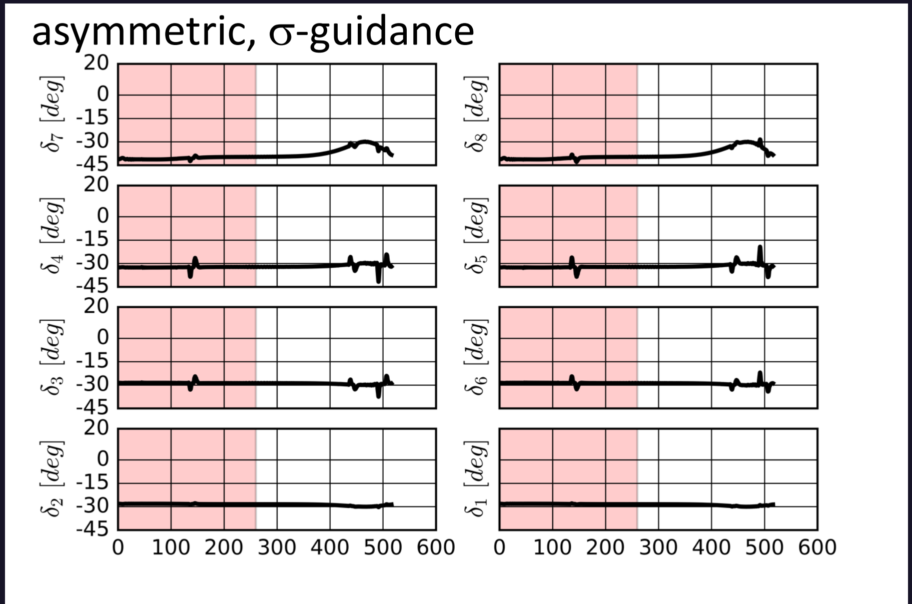
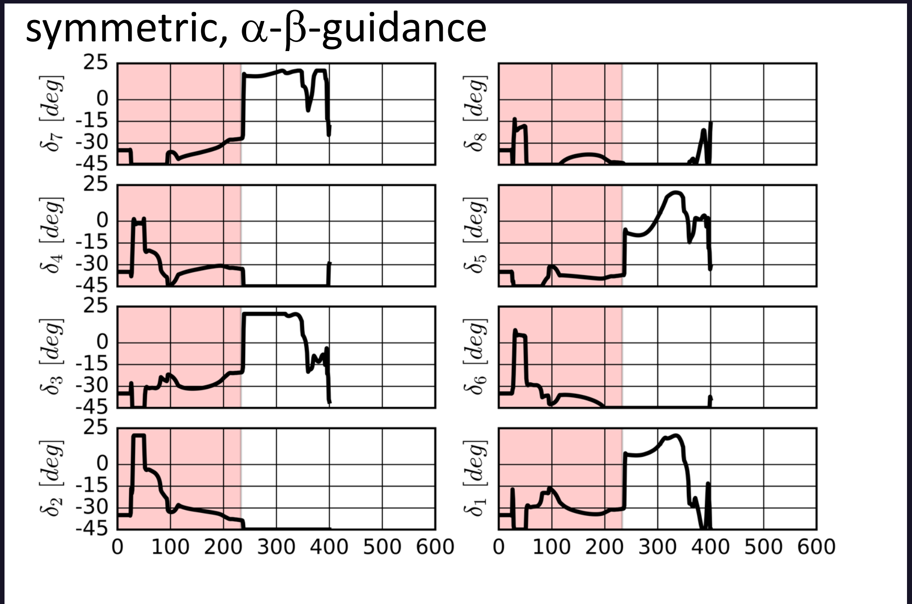
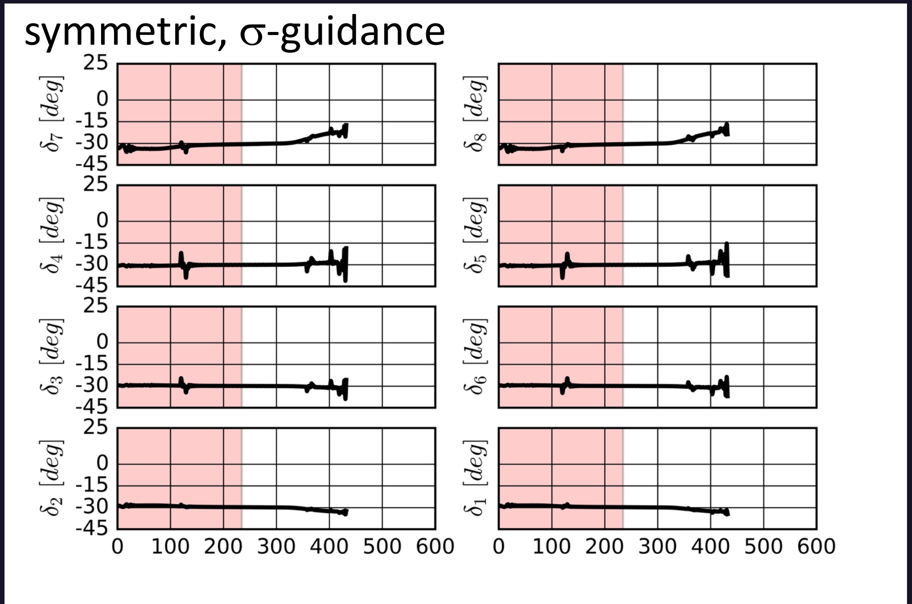






Tracking an alpha-beta guidance requires larger deflections and more activity from the flaps

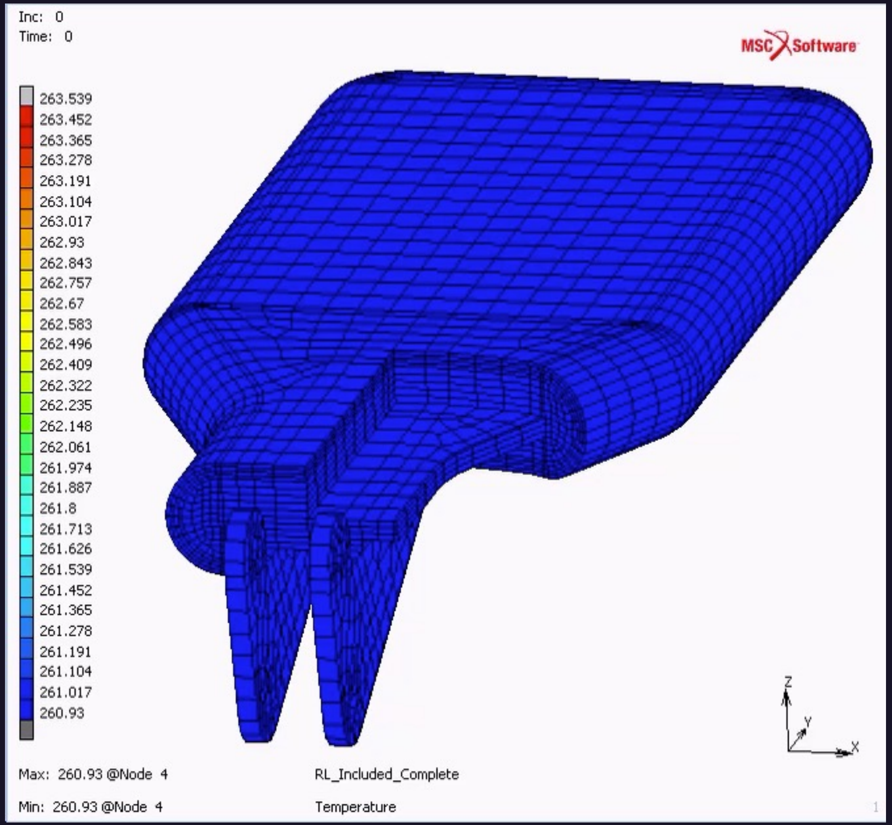
Tracking bank guidance requires fewer flaps, reducing complexity and saving mass

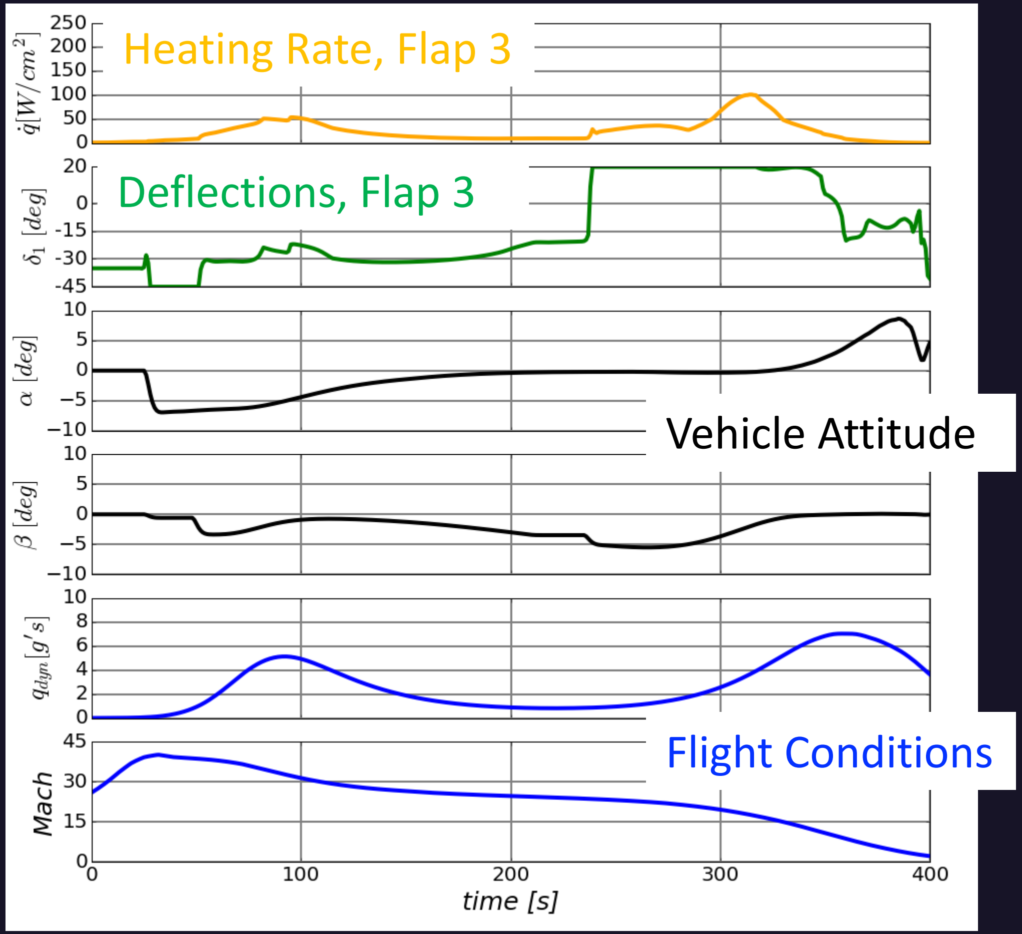
Flap TPS & Heating analysis

FLAP HEATING – 3D EFFECTS

Symmetric, α-β-guidance

3D Temperature for Flap 3





MAJOR FINDINGS

- Potential mass saving for TPS for a symmetric vehicle with reduced angle of attack and more flap area
- TPS thickness does not exceed the shoulder radius
- Application of a bank guidance may lead to a control system that is less mechanically complex and minimizes control system mass
- All configurations have feasible control system solutions, but vary in complexity
- Symmetric aeroshell enabled success with both guidance methods, as opposed to the asymmetric aeroshell, which was only able to perform bank tracking

PTERODACTYL PROJECT STATISITICS

Technical Impact

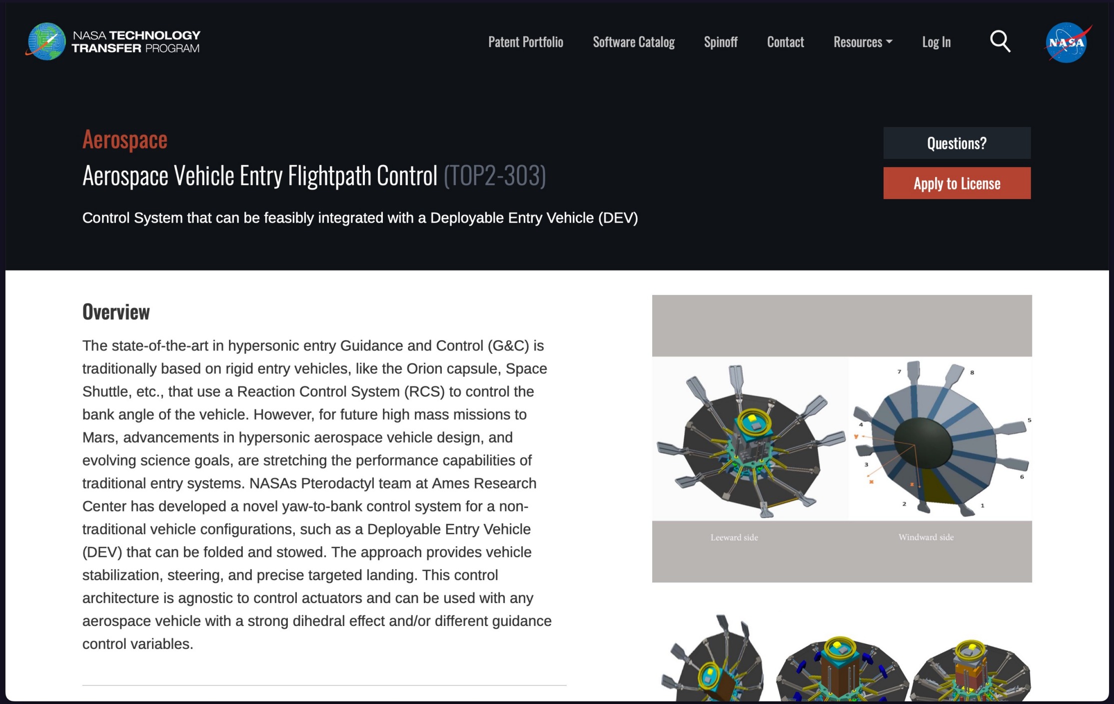
- Developed new, innovative models, with appropriate fidelity, to design appropriate G&C systems for DEVs
- Developed modern day control to steer vehicle to a precise target
- Ames Tech Transfer Approved Provisional Patent Application Submission
  (U.S. Provisional Appl. No. 63/039,453)
- Published **19 papers/presentations at 8 conferences**

  Submitted white paper to Planetary Science Decadal Survey entitled "**Maximizing Planetary Science Return by Advancing Non-Propulsive Control Systems**

  AIAA SciTech 2021 Special Session – ***EDL Guidance, Navigation, and Control***

  AIAA SciTech 2020 Special Session - ***Pterodactyl: Control System Design for Deployable Entry Vehicles***

  International Planetary Probe Workshop – 2018, 2019




Pterodactyl Weekly Tag-Up
Leave
Nikaido, Ben (CIV)
Johnson, Breanna J (JSC-EG511)
Hays, Zane (ARC-AA)[SCIENCE & TECH...
Visser, Sander J. (ARC-TSM)[Analytical ...
Okolo, Wendy A. (ARC-TI)
Dsouza, Sarah N. (ARC-TSS)
Kenneth E. Hibbard
Jeffrey Barton
Harbert, Gregory J. (ARC-AT)[WYLE LA...
Hawke, Veronica M (ARC-AA)[SCIENCE...
Alunni, Antonella I. (ARC-TSS)
Margolis, Benjamin W. (ARC-AA)
QUESTIONS?
Okolo, Wendy A. (ARC-TI)
ML
Matt Leibowitz (Guest)
KH
Kenneth E. Hibbard
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Hays, Zane (ARC-AA)[...
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Torricelli, Andrew (AR...
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Yount, Bryan C. (ARC-...

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  - AIAA SciTech 2020 Special Session - ***Pterodactyl: Control System Design for Deployable Entry Vehicles***
  - **International Planetary Probe Workshop – 2018, 2019**

Personnel Impact

- In a short time, grew disparate discipline engineers to be **versatile and productive members of the EDL, GNC, and CFD technical communities**. Available to make strident contributions to NASA's mission in the near and far term.
- **26 Awards and Recognitions**

POTENTIAL GROWTH AREAS

NON-PROPULSIVE CONTROL SYSTEM SCALABILITY, TRADE STUDY

Identify non-propulsive control system, via a trade study, that is the most mass efficient and has the highest targeting performance for a future, high-priority mission to a specific planet. ESTIMATED COST/TIME: ≤$5 MILLION/≤3 YEARS

NON-PROPULSIVE CONTROL SYSTEM RISK REDUCTION

Conduct robust analyses and experimental work that identify the performance and reliability of control system components.

- Modeling and simulation of aeroheating
- Wind tunnel testing of control surfaces or shape morphing systems
- Arc-jet testing of TPS for protecting control surfaces

ESTIMATED COST/TIME: ≤$5 MILLION/≤5 YEARS

EARTH ENTRY TECHNOLOGY DEMONSTRATOR

Develop a flight test article for a 1m vehicle, performing a guided entry from low Earth orbit, that proves the functionality of the controls system to meet precision targeting requirements in a relevant aerodynamic loading and heating environment, raising the TRL to 6.

ESTIMATED COST/TIME: ≤$40 MILLION/≤5 YEARS

Individual and team publications (2018– PRESENT) – Pterodactyl and other work

1. D'Souza, S., Smith, B., Okolo, W., Johnson, B., and Nikaido, B., "Pterodactyl: Integrated Control Design for Precision Targeting of Deployable Entry Vehicles", 15th International Planetary Probe Workshop, Boulder, CO, 2018.
2. Smith, B., D'Souza, S., Okolo, W., Johnson, B., and Nikaido, B., "Pterodactyl: Integrated Control Design for Precision Targeting of Deployable Entry Vehicles", Exploration Science Forum, NASA Ames Research Center (https://nesf2018.arc.nasa.gov/program).
3. D'Souza,S.N.,Okolo,W.A.,Nikaido,B.E.,Yount,B.C.,Tran,J.,Margolis,B.W.,Smith,B.,Cassell,A.M.,Johnson,B.J., Hibbard, K., Barton, J. D., and Hays, Z. B., "Developing an Entry Guidance and Control Design Capability Using Flaps for the Lifting Nano-ADEPT," AIAA Aviation 2019 Forum, AIAA, Dallas, TX, 2019.
4. Margolis, B. W., Okolo, W. A., Nikaido, B. E., Barton, J. D., and D'Souza, S. N., "Control and Simulation of a Deployable Entry Vehicle with Aerodynamic Control Surfaces," Astrodynamics Specialist Conference, 2019.
5. Margolis, B. W., Okolo, W. A., and D'Souza, S. N., "Control Design & Sensitivity Analysis for a Deployable Entry Vehicle with Aerodynamic Control Surfaces," International Astronautical Congress, 2019.
6. Johnson, B., "Pterodactyl: An Uncoupled Range Control Approach To Fully Numerical Predictor-corrector Entry Guidance", 16th International Planetary Probe Workshop, Oxford, UK, 2019.
7. Okolo, W., "Stability Analysis & Control Design For A Deployable Entry Vehicle With Aerodynamic Control Surfaces", 16th International Planetary Probe Workshop, Oxford, UK, 2019.

Invited Presentations –

- NESC Joint TDT Meeting – Flight Mechanics, Aerosciences, Guidance, Navigation, and Control
- NASA Entry, Descent, and Landing Technical Interchange Meeting
- NASA Ames Research and Technology Showcase

AIAA SciTech 2020 Special Session - ***Pterodactyl: Control System Design for Deployable Entry Vehicles***

8. 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.
9. 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.
10. 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.
11. 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.
12. 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.
13. 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.

AWARDS and RECOGNITION – individual and team achievements on Pterodactyl and other involvement (2018 – Present)

NASA Internal

NASA Director's Management Group Achievement award (Pterodactyl Civil Servant Team)
NASA Performance Award (B. Yount)
NASA Time-off Award for Orion BFS Controls (B. Johnson)
NASA Outstanding Achievement Award (D. Rocca Bejar)
NASA Ames Honor Award - Student Achievement (B. Margolis)
NASA Ames Early Career Researcher Award (W. Okolo)
NASA Honor Award - Group Achievement (S. D'Souza, W. Okolo)
NASA ARMD Superior Accomplishment Award (S. D'Souza)
NASA Ames Superior Accomplishment Award (W. Okolo)
NASA Administrator Visit Demonstration Team Award (S. D'Souza)
NASA in Silicon Valley: The Artemis Generation: NASA's Journey Forward to the Moon (W. Okolo)
NASA in Silicon Valley - Wonder Women of NASA (S. D'Souza)
NASA Ames Honor Award (W. Okolo)
NASA Ames Exploration Technology Directorate Spotlight Award (W. Okolo)
NASA Ames Office of the Center Director Spotlight Award (W. Okolo)

External Organizations

AIAA Best Paper Nomination – Pterodactyl Special Session (A. Alunni)
IPPW 2019 Student travel award (B. Margolis)
IAC 2019 Student travel award (B. Margolis)
University of Texas at Arlington Distinguished Recent Graduate Award (W. Okolo)
Women in Aerospace Award for Initiative, Inspiration, & Impact (W. Okolo)
Black Engineer of the Year Award (BEYA) for Most Promising Engineer in Government (W. Okolo)
Elected Vice Chair – AIAA Atmospheric Flight Mechanics Technical Committee (S. D'Souza)
Ames Research and Technology Council (S. D'Souza)
Georgia Tech's National, Virtual Women in Engineering Panel (S. D'Souza, B. Johnson)
NSTRF and ECF Panel Reviewer (B. Johnson)