



FROM DELTA-WING AIRCRAFT TO DEPLOYABLE SPACECRAFT: NOVEL CONTROL EFFECTORS FOR MOMENT TRIMMING & POSITION TRACKING

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SCENARIO

I saw a TV show once about Japan Airlines flight 123, in which the aft pressure bulkhead ruptured, disabling hydraulics and ripping off the vertical stabiliser. So the flight crashed after some time of flying with up-and-down oscillation.

Since then, I've also heard of two flights in which the aircraft lost control of flight control surfaces, but pilots guided their crippled plane into a landing using engine throttles only:

- [United Airlines flight 232](#)
- [2003 Baghdad DHL attempted shootdown incident](#), in which a cargo plane in Iraq was hit on a wing by a missile

In principle, could such a method have been used in Japan Airlines flight 123?

In principle, would it be possible to control such a plane by use of cooperating passengers moving around in the cabin, e.g. by instruction of a pilot, to shift the weight balance of the aircraft?

AIR & SPACE VEHICLES



Control Surfaces



Reaction Thrusters

APPLICATION: EXTENDED AIRCRAFT FORMATION FOR FUEL SAVINGS



MOTIVATION

A large commercial airplane is shown in flight, banking to the left. The aircraft has a white fuselage and a prominent red vertical stabilizer. It is flying above a thick layer of white clouds. In the background, a mountain range is visible under a dramatic sky with hues of orange, pink, and purple, suggesting a sunset or sunrise. The overall scene conveys a sense of global travel and the scale of the airline industry.

U.S. airlines: **\$4.62 billion** on fuel... in Jan. 2023

Global airline industry: **\$215 billion-dollar** fuel bill (estimated) in 2023

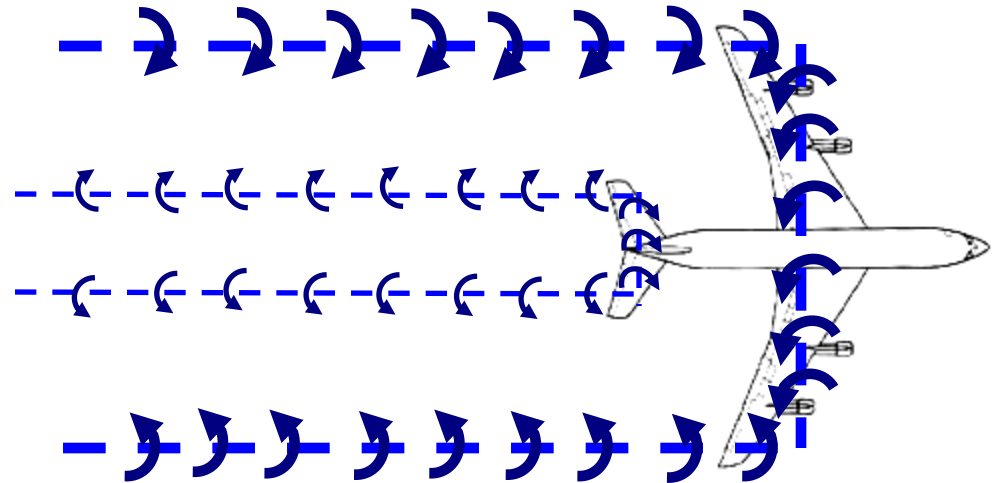
USAF: ~2 billion gallons annually. At \$2.82 per gal, this amounts to **\$5.64 billion** in FY23

IDEA: BIRD FLIGHT

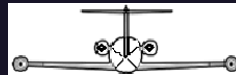
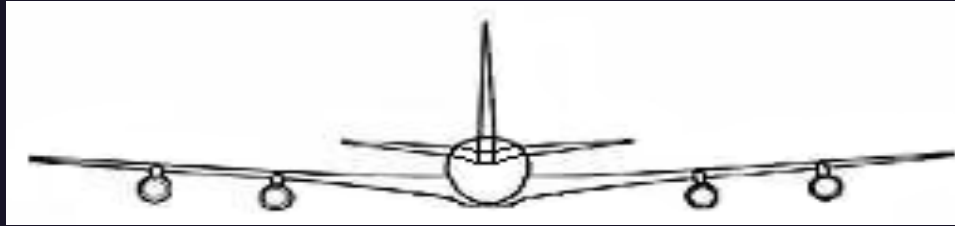


IDEA

Upwash leads to reduced drag benefits and significant fuel savings for trailing aircraft



SWEET SPOT



Maximum Upwash
=>
Reduced Drag
@
Sweet Spot

0.9 m/s upwash

3.25 m/s downwash

W_z

W_y

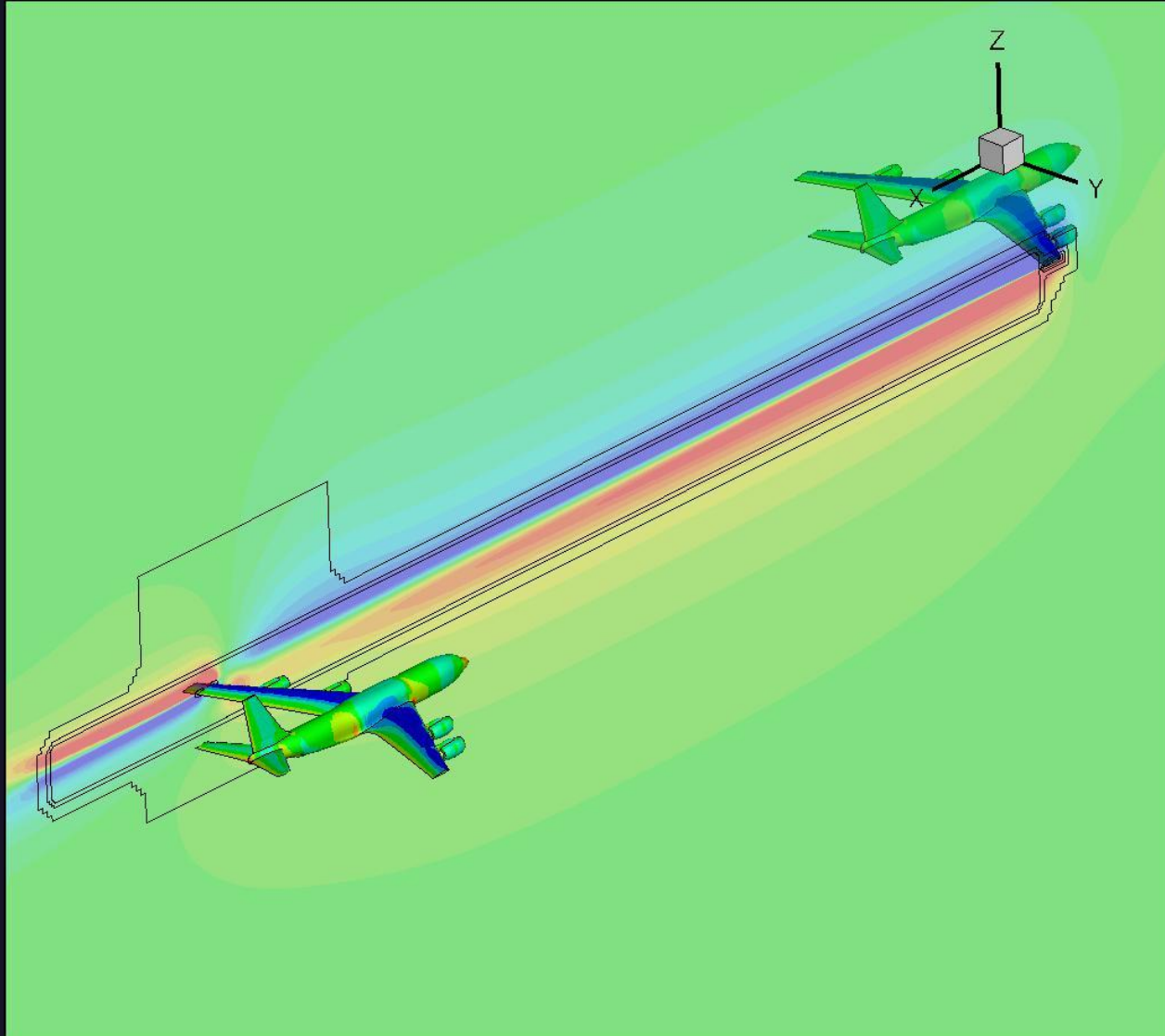
3 m/s sidewash

General Definition:
Sweet Spot is location
with maximum benefit
of formation flight

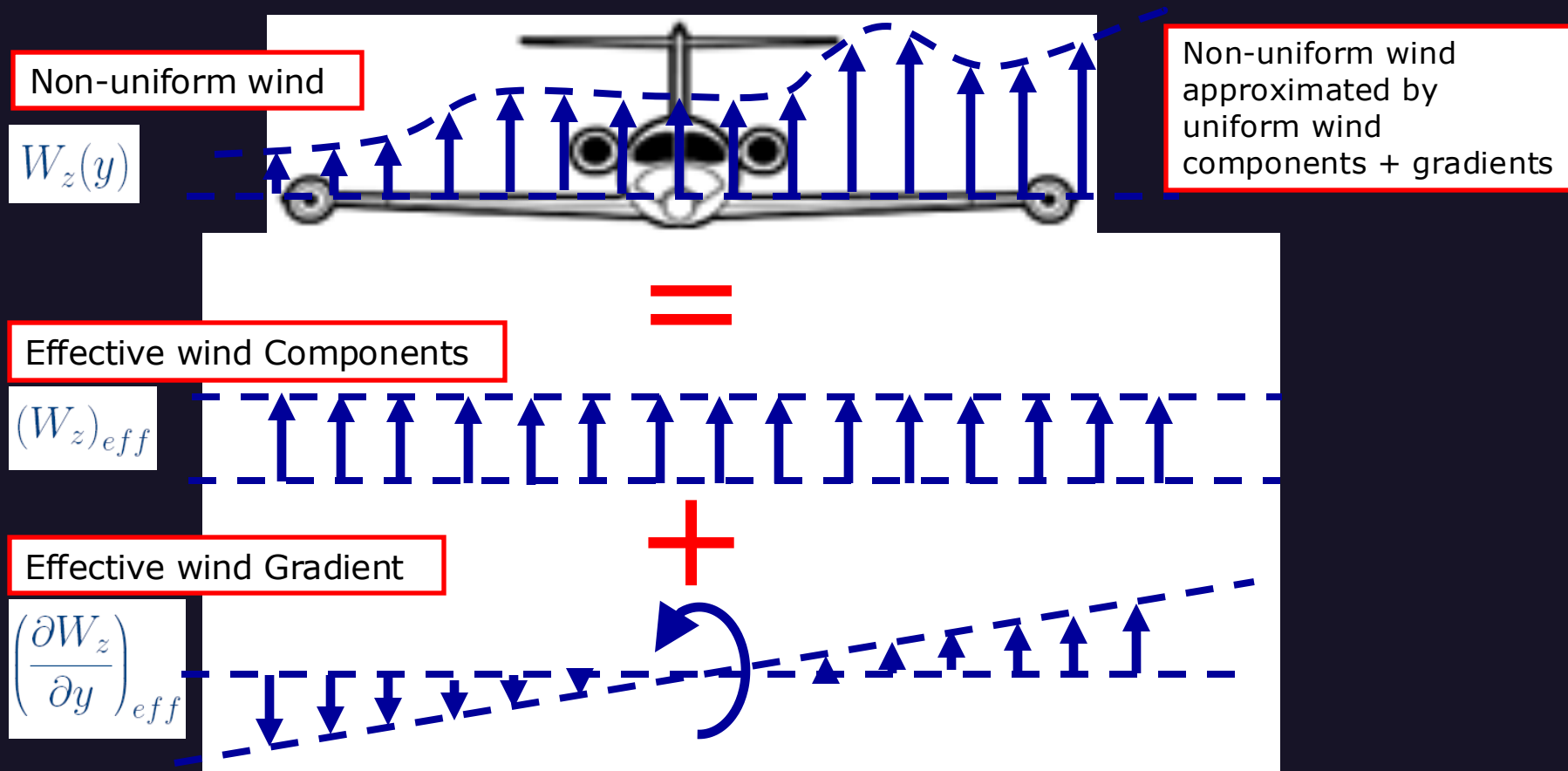
0.35 m/s forward-wash

W_x

CFD FORMATION VISUALIZATION



NON-UNIFORM WIND MODELING



¹Derivation of the dynamics equations of receiver aircraft in aerial refueling, J. Waishek, A. Dogan, W. Blake

²Flight control and simulation for aerial refueling, S. Sato, A. Dogan, W. Blake

³Flight data analysis and simulation of wind effects during aerial refueling, T. Lewis, A. Dogan, W. Blake

SIMULATION DEVELOPMENT

- Feedback controllers to control receiver position relative to tanker
- Outputs to be tracked: Relative Position
- Control Variables:
 - Control Effectors, Thrust and Differential Thrust
- MIMO State feedback optimal and integral control technique
- EOM linearized at 6 different nominal conditions
 - Tanker flying straight level at different airspeeds
 - Tanker turning right/left with specified turn rates at two different airspeeds
- Gain scheduling based on commanded speed and yaw rate

**MODIFY & UTILIZE SIMULATION FOR AIRCRAFT
FORMATION FLIGHT STUDIES**

AIRCRAFT PAIRS

KC-135R – KC-135R

3.8 tanker wingspan behind



Large EQII – KC-135R

3.8 tanker wingspan behind



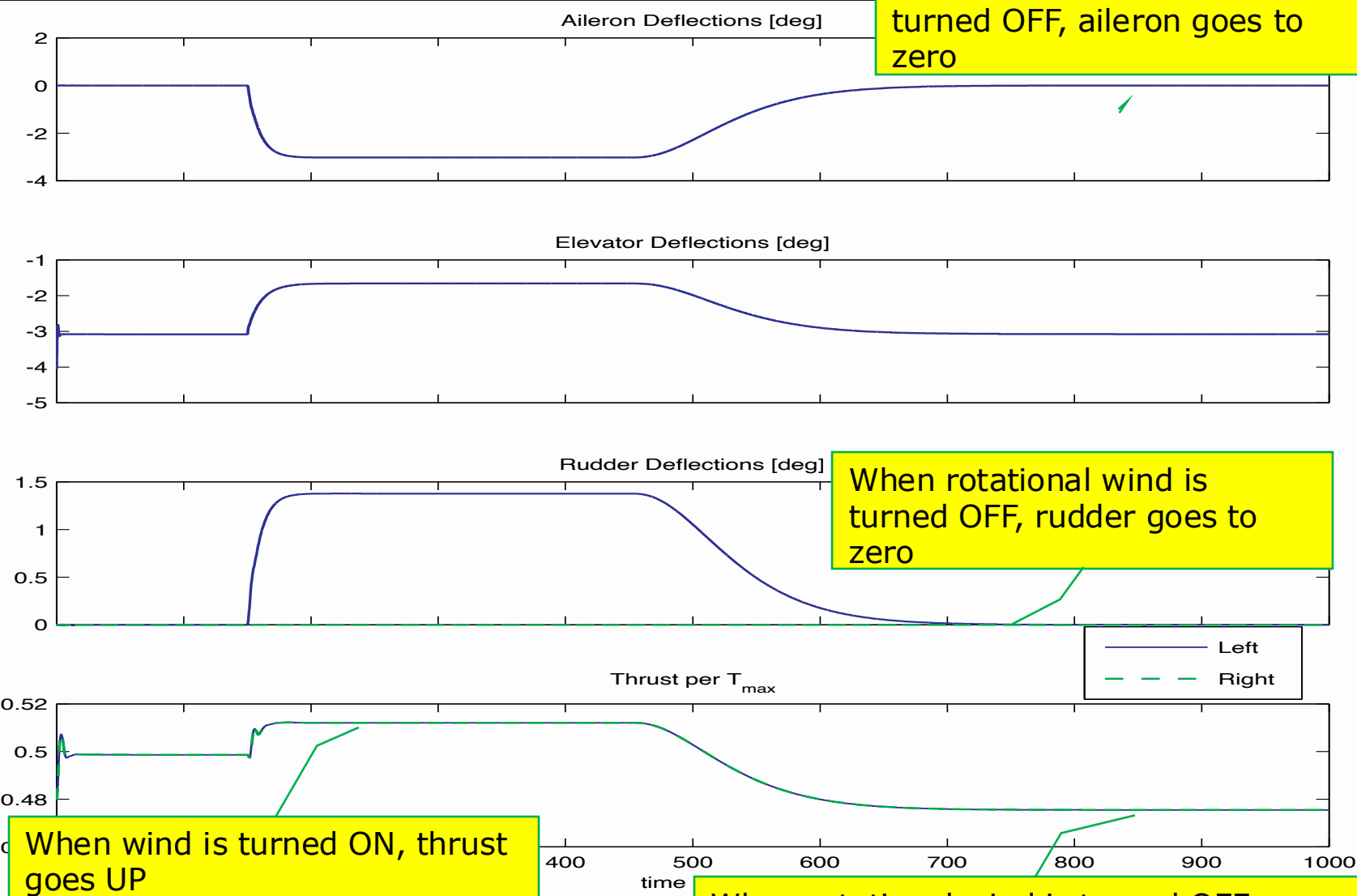
Small EQII – KC-135R

3.8 tanker wingspan behind



NON-UNIFORM WIND EFFECT

Control Variables



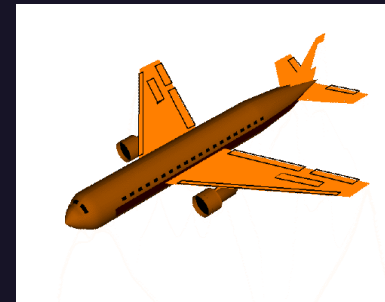
NON-UNIFORM WIND EFFECT ON CONTROL & THRUST

Thrust Comparison ($T/T_{\max}$)

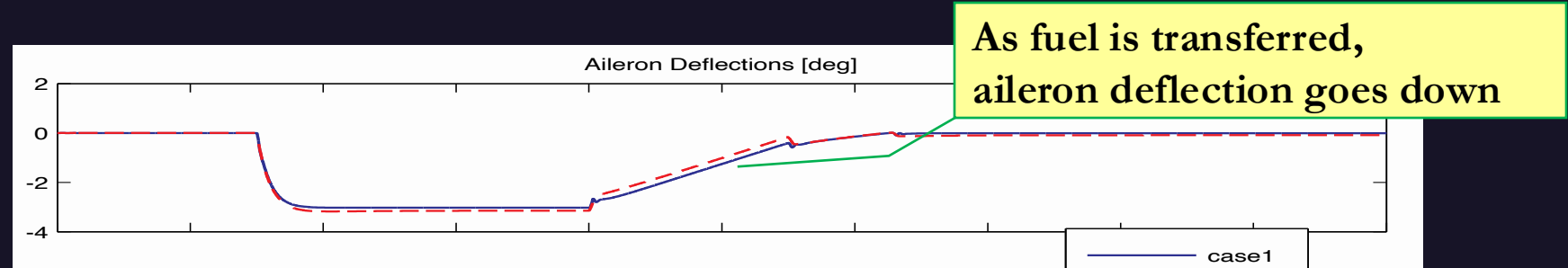
CASE	NO WIND	TRANSLATIONAL AND ROTATIONAL WIND	% REDUCTION	ONLY TRANSLATIONAL WIND	% REDUCTION	COST OF CONTROL EFFECTOR DEFLECTIONS
1	0.4986	0.5121	-2.71	0.4755	4.63	7.34%

7.34% thrust savings without using the rudder and aileron at the sweet spot with high L/D

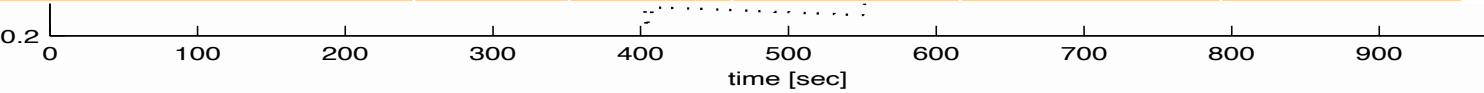
QUESTION: CAN WE (I) MOVE THE CM BY INTERNAL FUEL TRANSFER TO GENERATE ROLL MOMENT, & (II) GENERATE YAW MOMENT BY DIFFERENTIAL THRUSTING?



NON-UNIFORM WIND EFFECT ON CONTROL & THRUST



CASE	NO WIND	WITH WIND	% REDUCTION	AFTER FUEL TRANSFER	% REDUCTION	BENEFIT OF FUEL TRANSFER
1 RUDDER (NO DIFFERENTIAL THRUST)	0.4986	0.5121	-2.71	0.4756	4.61	7.32%
2 DIFFERENTIAL THRUST (REDUCED RUDDER)	2 X 0.4986	0.5832 + 0.4152	-0.12	0.5273 + 0.4045	6.56	6.68%
BENEFIT OF DIFFERENTIAL THRUST			2.99%		2.07%	



Max
Formation
Flight
Benefit

QUESTION: CAN WE (I) MOVE THE CM BY INTERNAL FUEL TRANSFER TO GENERATE ROLL MOMENT, & (II) GENERATE YAW MOMENT BY DIFFERENTIAL THRUSTING?

YES!

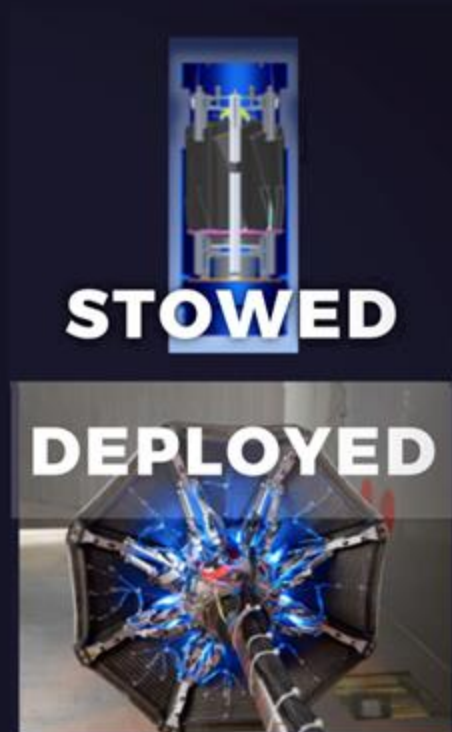
- Non-zero induced aero torques require drag-inducing control surface deflections → reduces expected formation benefit
- Use alternative trim mechanisms such as internal fuel transfer and differential thrusting to reduce the need for control effectors and obtain thrust/fuel savings

APPLICATION: DEPLOYABLE ENTRY VEHICLE



MOTIVATION

Deployable entry vehicles can land and return larger mass payloads



Deployable Entry Vehicles (DEV)



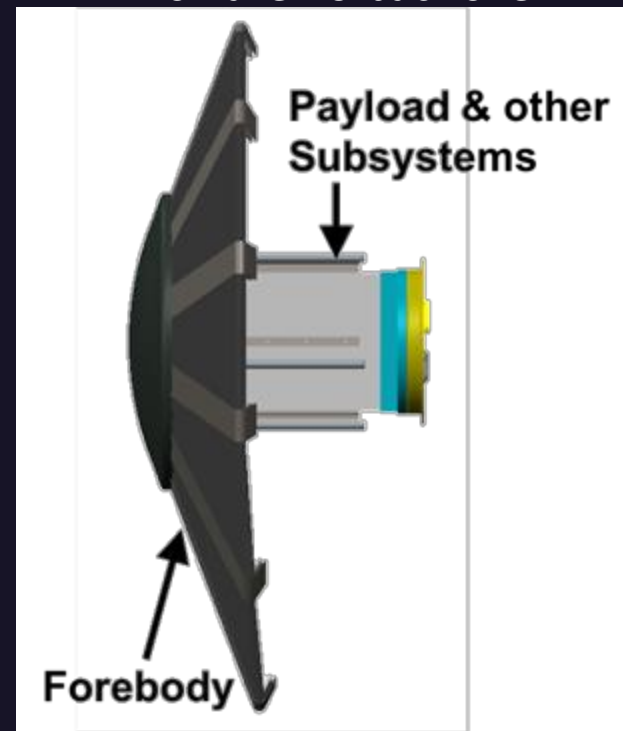
**GUIDANCE
& CONTROL
MAKE DEV
APPLICATIONS
REALIZABLE!**

CHALLENGE

Heritage Entry Vehicle with
Reaction Control System (RCS)



DEVs have no back shell



**QUESTION: CAN WE UTILIZE NOVEL CONTROL
TECHNIQUES TO GUIDE AND CONTROL A DEV
DURING ENTRY?**

PTERODACTYL BASELINE VEHICLE (PBV)

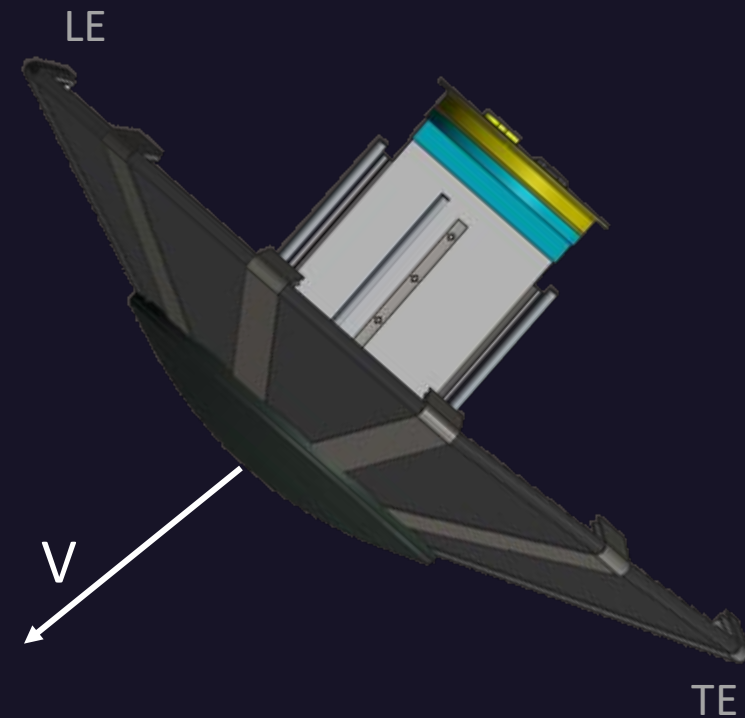
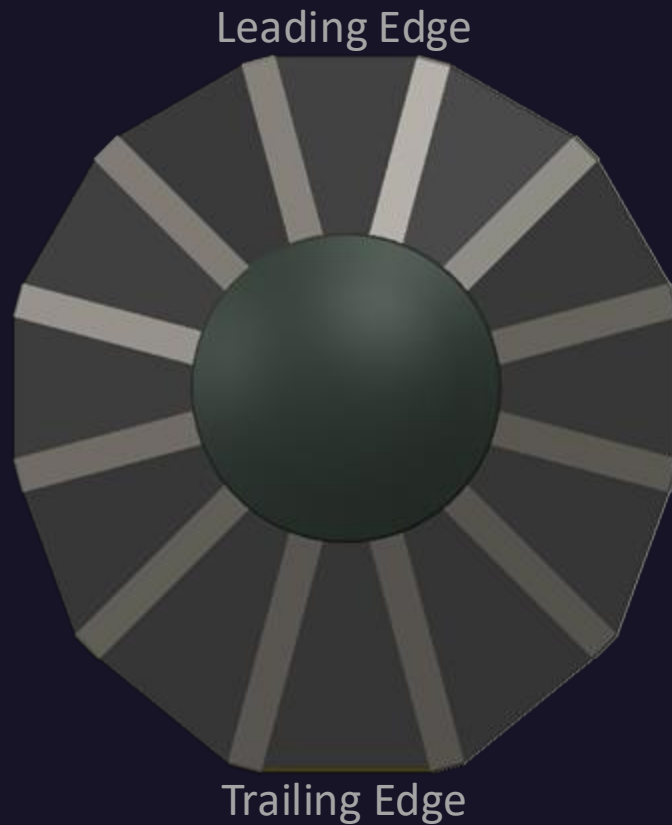
asymmetric

diameter = 1+ m

mass = 59.4 kg

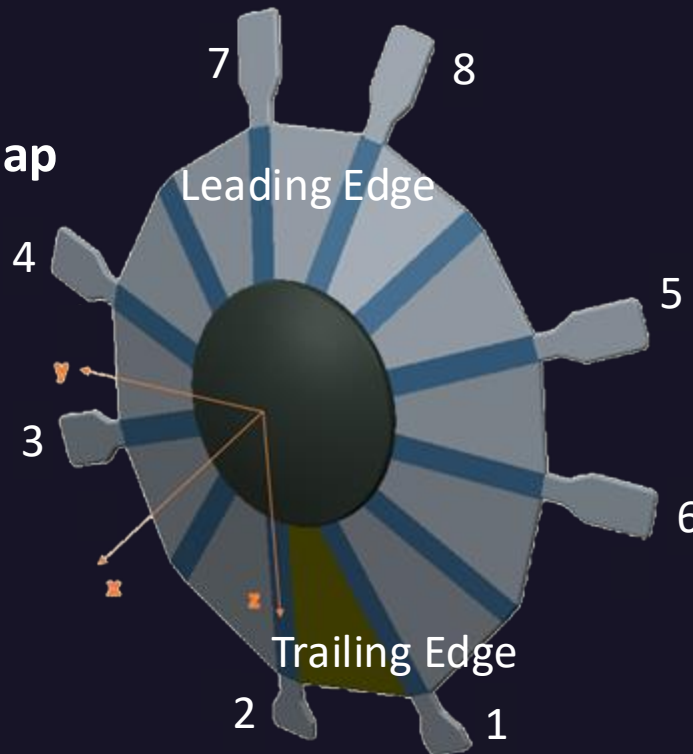
$L/D_{\text{trim}} = 0.2$

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



PBV WITH FCS

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



Constraints

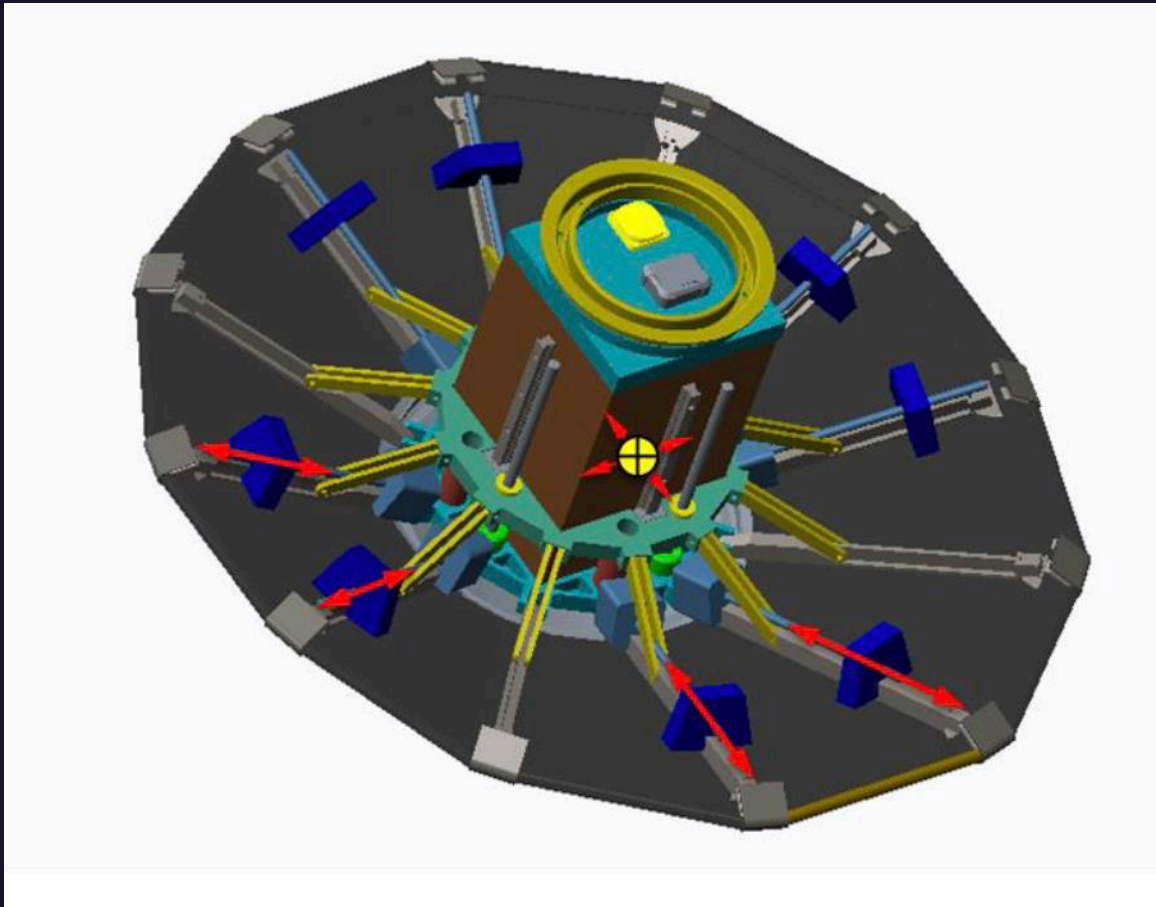
Fixed aeroshell and subsystems

Flap hardware integration with ribs not gore

Result → 8 flaps to increase control authority, reduce multi-axis coupling, & satisfy packaging/stowing constraints

PBV WITH MMCS

- 8 sliding masses
- Shifted longitudinally & laterally to control angle of attack and sideslip



Constraints

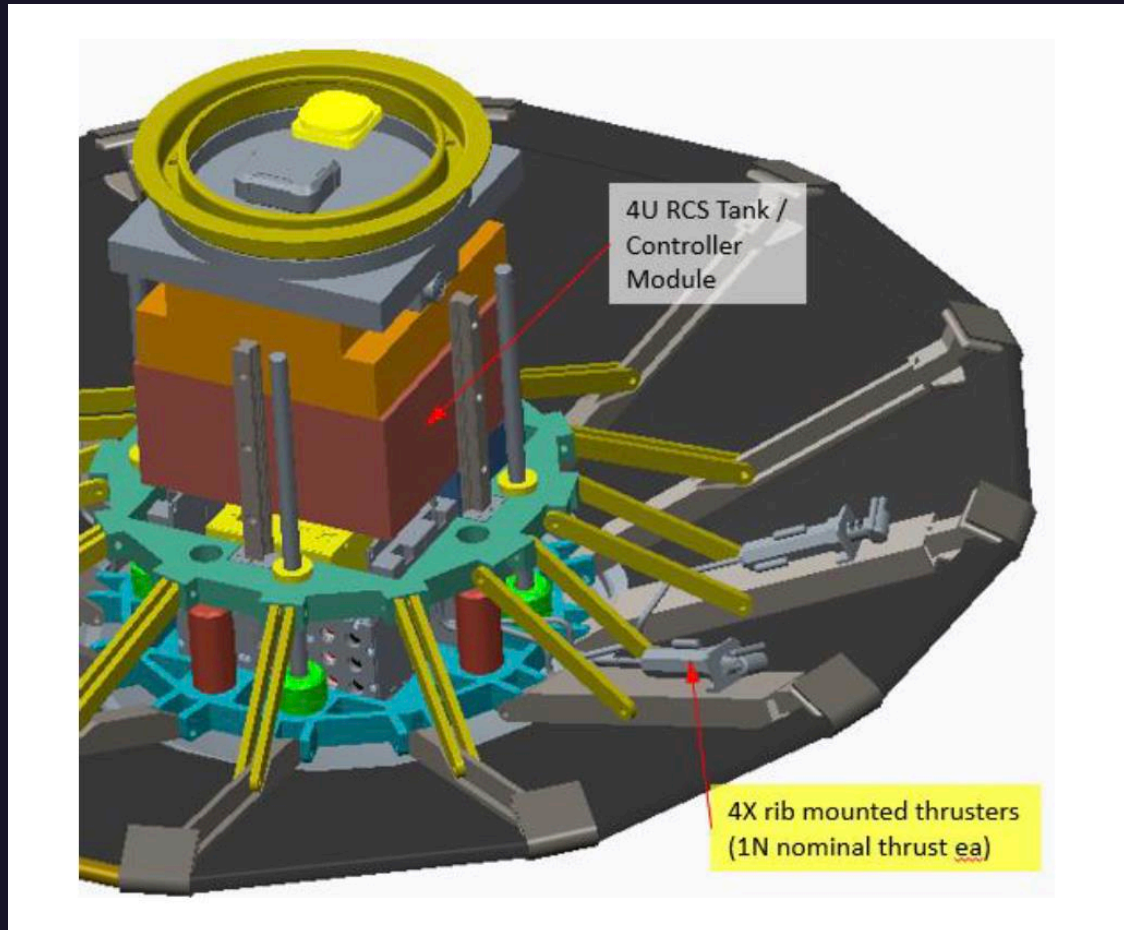
Fixed aeroshell and subsystems

Moving masses integration with ribs not gore

Result → 8 masses grouped in pairs to maintain balance due to vehicle layout

PBV WITH RCS

- Thruster capabilities: 1.0N
- Fired in pairs to roll the vehicle in different directions



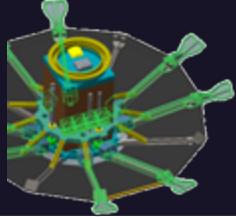
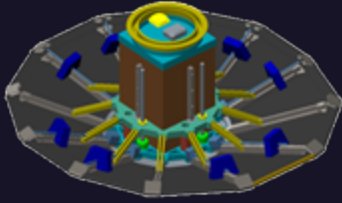
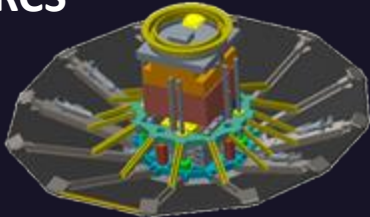
Constraints

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Flap hardware integration with ribs not gore

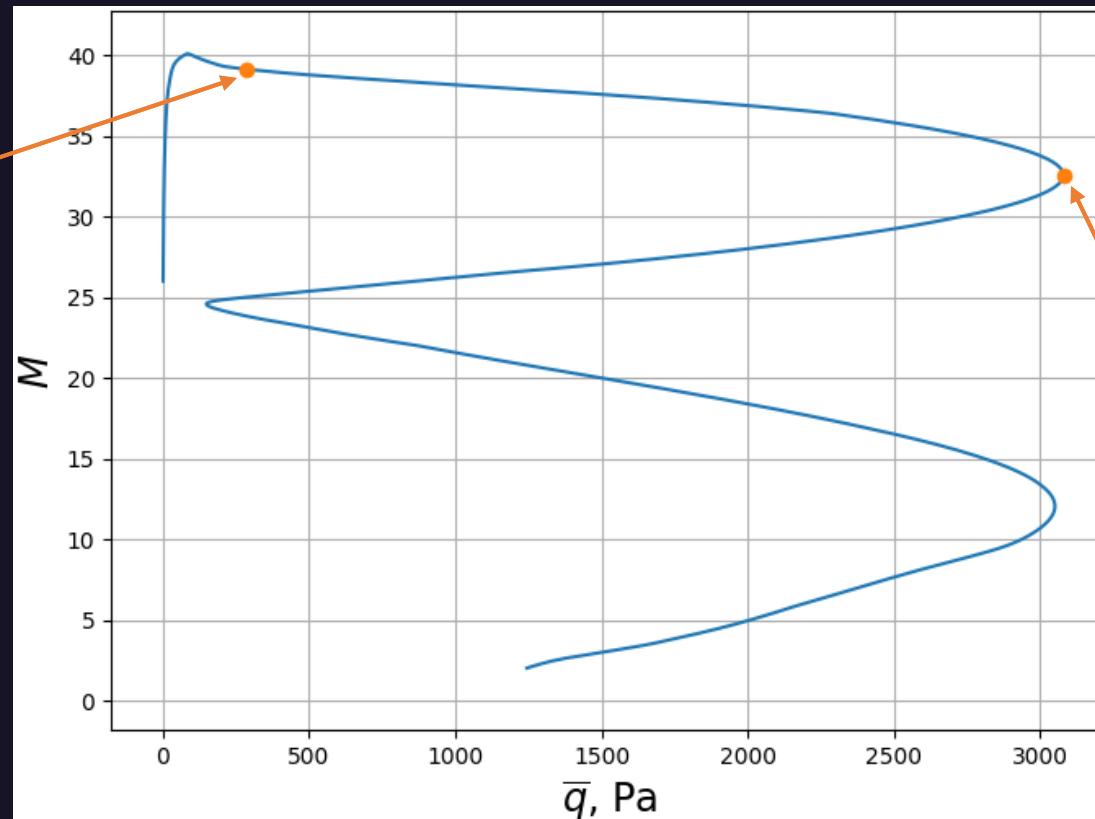
Result → Four 1.0N thrusters mounted on the backside

CONTROL SYSTEM CONFIGURATIONS

Configuration	Control Outputs	Requirements
Flaps 	Flap Deflection Angle	Map flap deflections (in/out of the flow)
Moving masses 	Mass movement distance	Determine mass displacement along rib
RCS 	Moments/torques required	Map thruster selection & duration

CONTROL ARCHITECTURE COMPARISON

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



CONTROL ARCHITECTURE 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

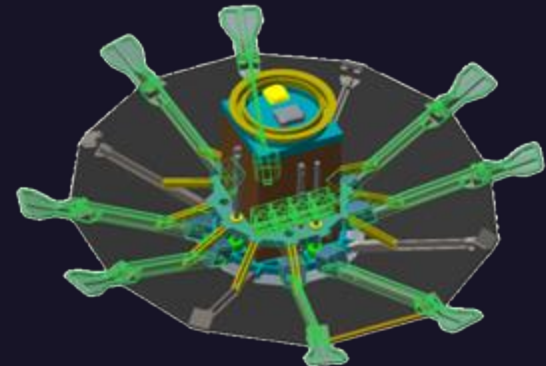
Thus, FCS is most attractive for maneuverability

FCS provides highest bank angle accelerations

QUESTION: CAN WE UTILIZE NOVEL CONTROL TECHNIQUES TO GUIDE AND CONTROL A DEV DURING ENTRY?

YES!

- FCS has the highest bank maneuverability of the three control architectures
- Control system recommendation → FCS



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