NASA Langley Research Center
Hampton, VA 23681-2199

Paper 2000-1560

Flight Control using Distributed Shape-Change Effector Arrays

David L. Raney and Raymond C. Montgomery
Dynamics and Control Branch, MS 132

Michael A. Park and Lawrence L. Green
Multidisciplinary Optimization Branch, MS 159

41st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference & Exhibit
3-6 April 2000
Atlanta, Georgia

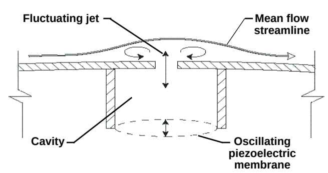
Motivation

- **A New Opportunity:**
  A host of **novel effector concepts** offer the potential to radically alter the fashion in which force and moments are generated for flight control

Physical Surface Distortions

- Inflatables
- Piezoelectrics
- Shape-Memory Alloys

Fluidic Effector Devices



This work focuses on developing the **flight control technologies** required to use such novel effectors in aerospace vehicle flight control systems

- **Potential Payoffs:**
  - **Systems Benefits**: Light-weight, reduced complexity, lower-cost alternatives to conventional effectors for control
  - **New Capabilities**: Mission-adaptative performance optimization and adaptive/ reconfigurable/ damage-tolerant flight control using distributed arrays of novel effectors and sensors

– Long Term Goal of Research –

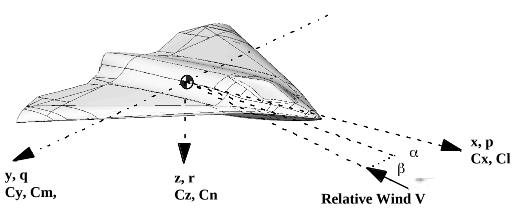
A design capability that incorporates distributed effector/sensor arrays into aircraft flight control to provide mission-adaptive performance optimization, reconfigurability and damage-tolerance for aerospace vehicles

– Scope of Presentation –

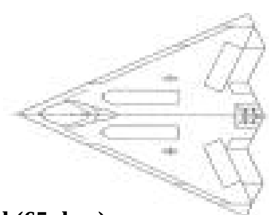
Methodology for design, analysis, and control of distributed shape-change device arrays with an application illustrating aircraft stabilization and maneuver control *(a first step)*

Example application: Lockheed-Martin's Innovative Control Effector (ICE) Configuration

LMTAS Innovative Control Effector (ICE) Configuration



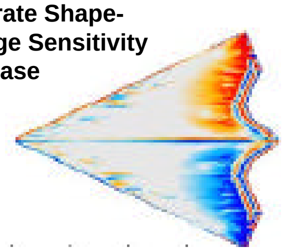
Wing Characteristics



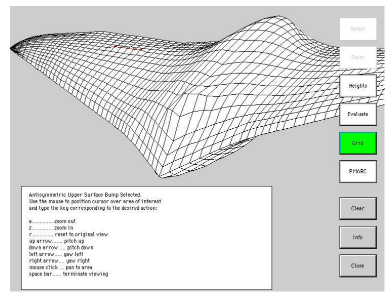
Area .... 75.12 m^2 (808.6 ft.^{2})
Span .... 11.43 m (37.5 ft.)
Aspect Ration ... 1.74
Leading Edge Sweep .. 1.134 rad (65 deg.)

Research Flowchart & Presentation Overview

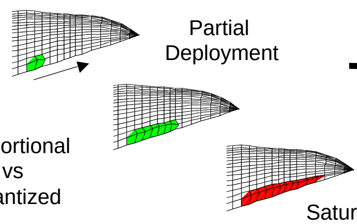
Generate Shape-Change Sensitivity Database



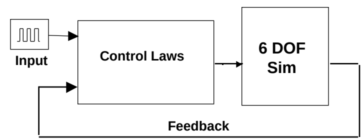
Preliminary Design – Select Location, Planform and Height of Effector Array



Deployment/Allocation Scheme



6 DOF Simulation



Generation of Shape-Change Sensitivity Data

PMARC - Panel Method from Ames Research Center, potential flow (Dale Ashby)

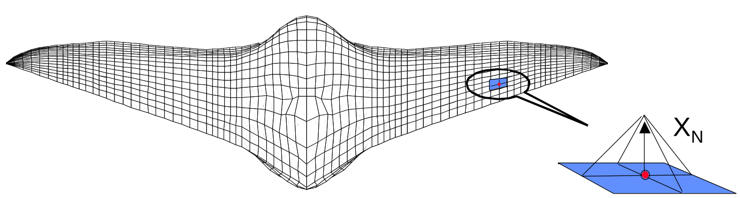
+

ADIFOR - Automatic Differentiation of Fortran (Argonne Labs, Rice Univ.)

ADJIFOR - Adjoint Differentiation of Fortran (Carle & Fagan, Rice Univ.)

Applied to panel geometry grid of

ICE - Innovative Control Effector Configuration (Lockheed Martin)



$$\left[\frac{\partial C_l}{\partial X_N}\right] \quad \left[\frac{\partial C_m}{\partial X_N}\right] \quad \left[\frac{\partial C_n}{\partial X_N}\right]$$

Sensitivity Matrices:

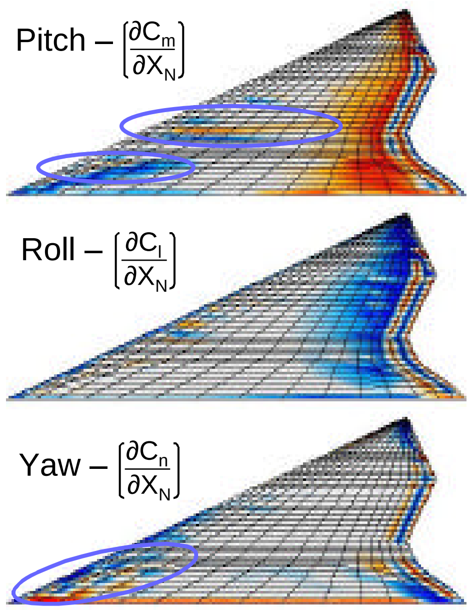
Roll, Pitch and Yaw moment derivatives with respect to displacement of gridpoint, N, normal to the surface (calculated for **each** of 2718 surface gridpoints)

Sensitivity Results

Pitch – $\left[\frac{\partial C_m}{\partial X_N}\right]$

Roll – $\left[\frac{\partial C_l}{\partial X_N}\right]$

Yaw – $\left[\frac{\partial C_n}{\partial X_N}\right]$



Color Map Scales Differ:

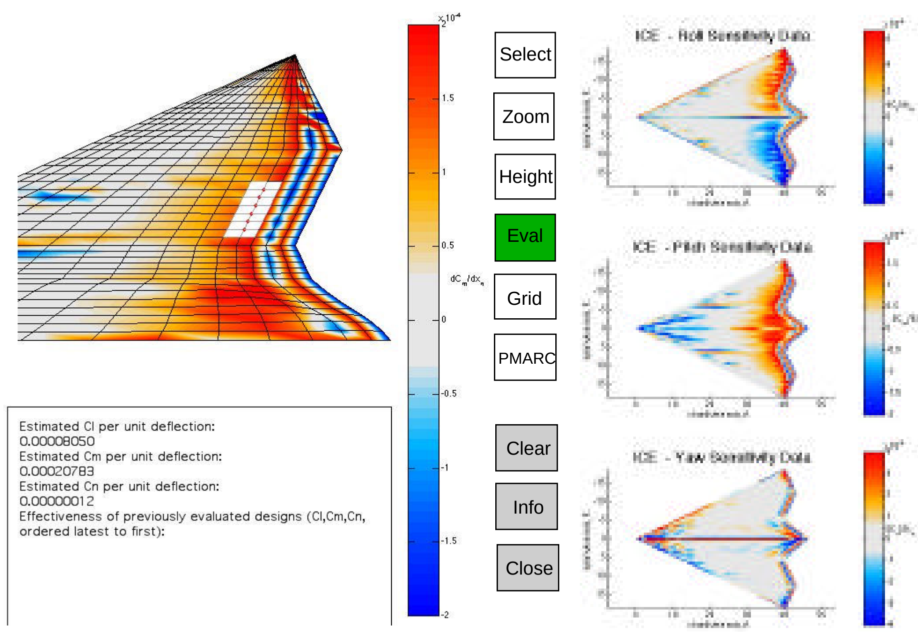
pitch	roll	yaw
2×10^{-4}	6×10^{-5}	4×10^{-5}
0	0	0
-2×10^{-4}	-6×10^{-5}	-4×10^{-5}

Regions of alternating sign due to modeling near trailing edge

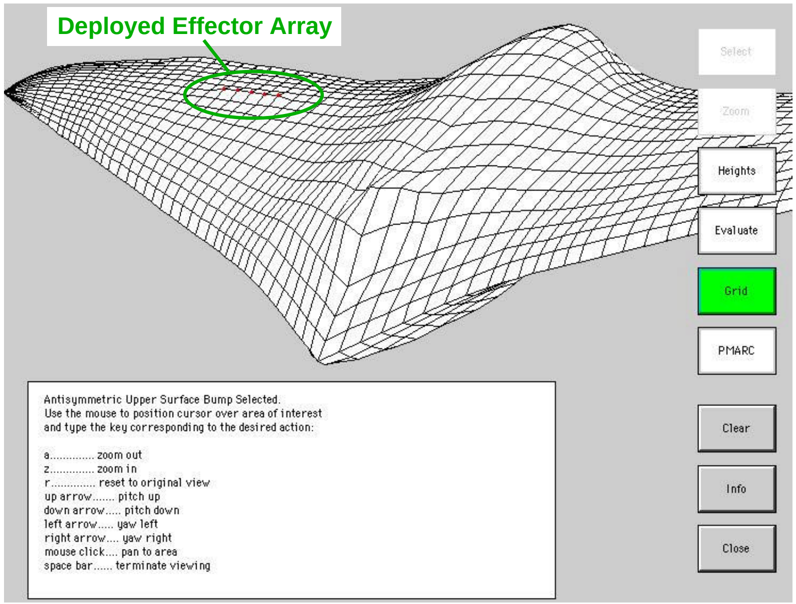
Streaked regions, , are likely to shift with flight condition & alpha

Overlapping regions of high effectiveness → coupled moment generators

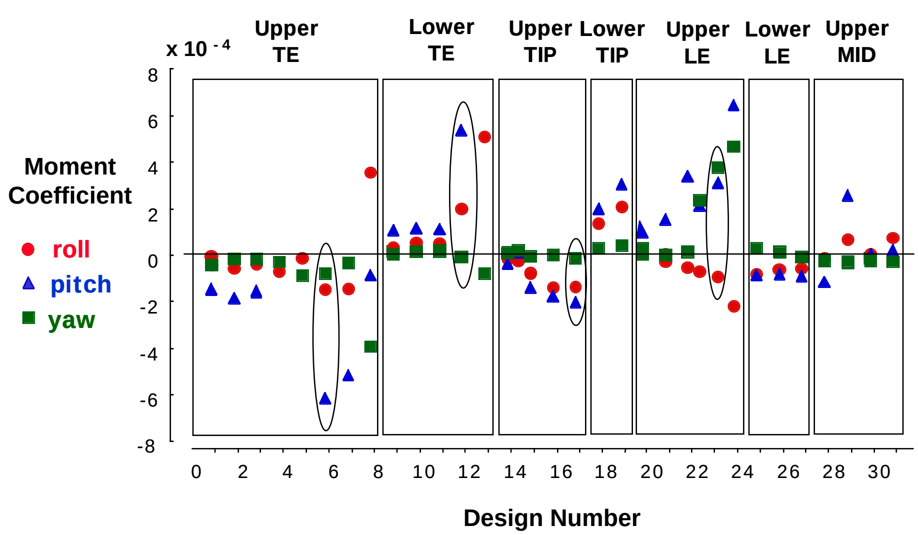
Effector Array Design Tool



Shape-Change Array Design Example

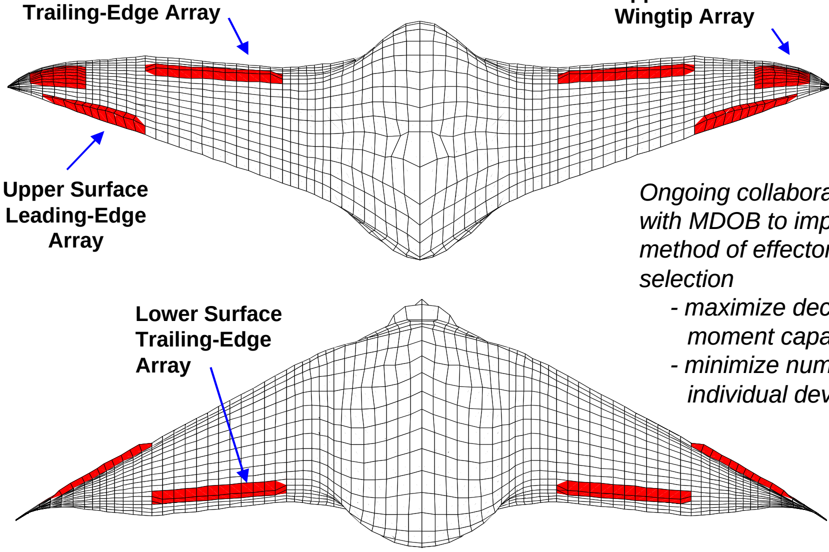


Shape-Change Effector Array Design Study



• Generally, low-authority coupled moment producers

Selected Suite of Shape-Change Effector Arrays



Ongoing collaboration with MDOB to improve method of effector suite selection

- *maximize decoupled moment capability*
- *minimize number of individual devices*

• 4 arrays, 82 devices per wing: A total of 164 individual devices

Allocation and Deployment Scheme

Allocation:

Pseudoinverse with provision for one-sided effectors

$$\Phi = \mathbf{B^T\,[B\;B^T\,]^{-1}}$$

Allocation to generate desired moment vector

$$\delta^{+/-} = \Phi\, M_{cmd}$$

Reflection of $\delta < 0$

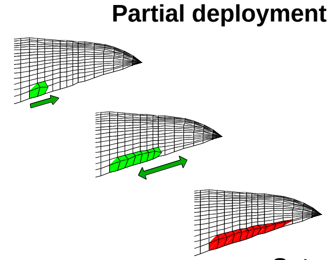
$$\delta^{+}_{LAT} = f_{LAT}(\delta^{+/-})$$

Correction for pitch error

$$\delta^{+}_{LON} = f_{LON}(\delta^{+}_{LAT}\,, C_{M\ err}\,)$$

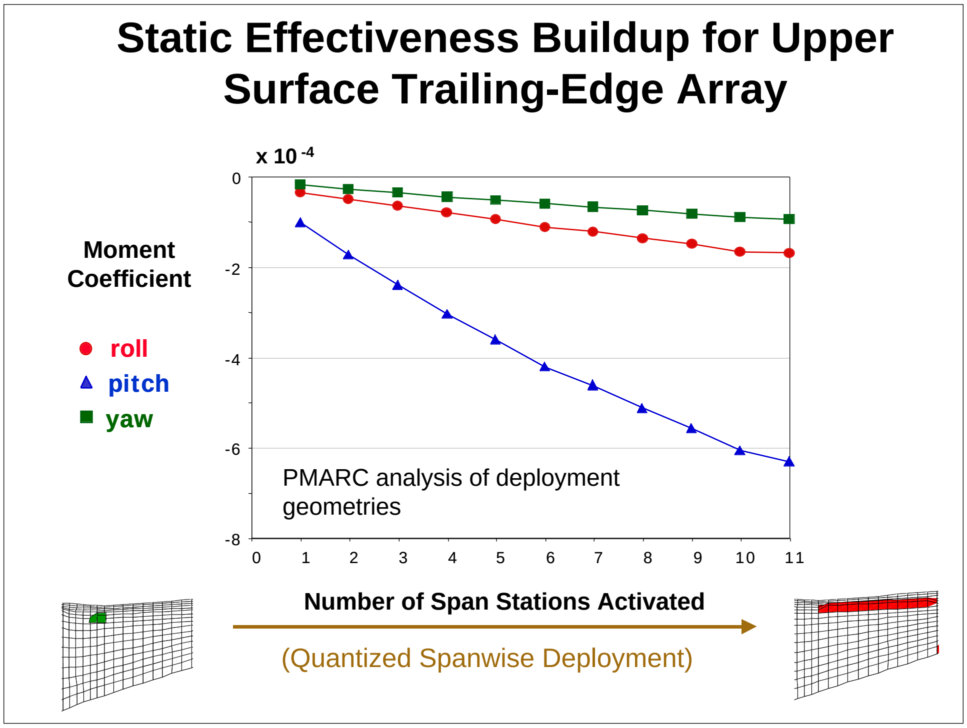
Deployment Scheme:

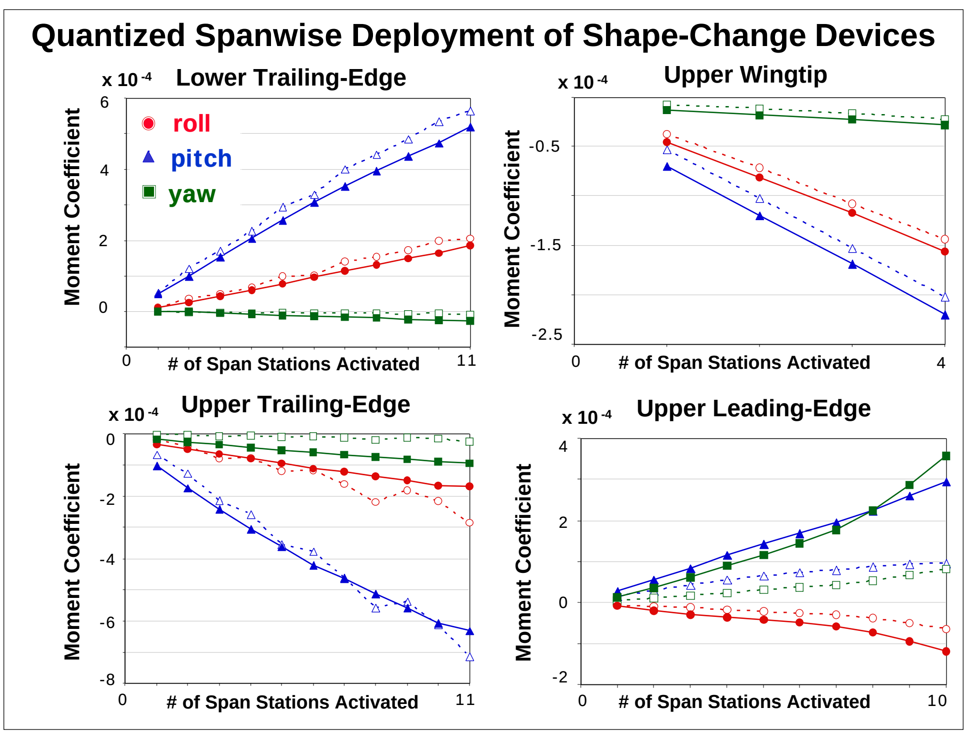
Quantized spanwise progression



Devices activate ***inboard to outboard*** *as* ***more*** *control is required*

Control vector, δ, has many components ⇒ Opportunities to exploit extra degrees of freedom in future research


Static Effectiveness Buildup for Upper Surface Trailing-Edge Array
x 10 -4
Moment Coefficient
roll
pitch
yaw
0
-2
-4
-6
-8
0 1 2 3 4 5 6 7 8 9 10 11
PMARC analysis of deployment geometries
Number of Span Stations Activated
(Quantized Spanwise Deployment)


Quantized Spanwise Deployment of Shape-Change Devices
Lower Trailing-Edge
x 10 -4
Moment Coefficient
roll
pitch
yaw
6
4
2
0
0
# of Span Stations Activated
11
Upper Wingtip
x 10 -4
Moment Coefficient
-0.5
-1.5
-2.5
0
# of Span Stations Activated
4
Upper Trailing-Edge
x 10 -4
Moment Coefficient
0
-2
-4
-6
-8
0
# of Span Stations Activated
11
Upper Leading-Edge
x 10 -4
Moment Coefficient
4
2
0
-2
0
# of Span Stations Activated
10

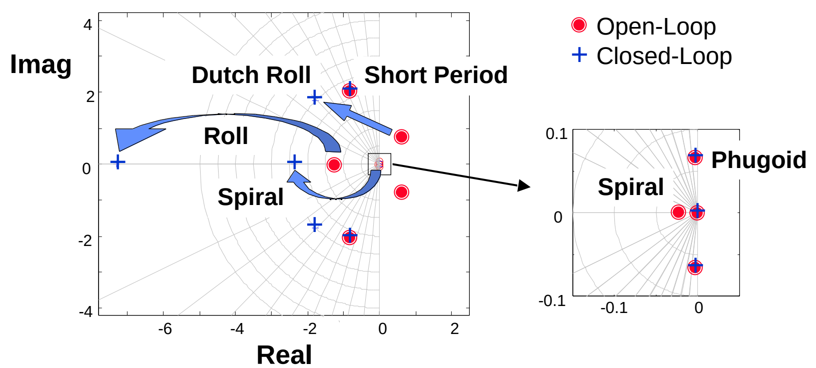
Lateral/Directional Control Design

- Bank-angle command architecture

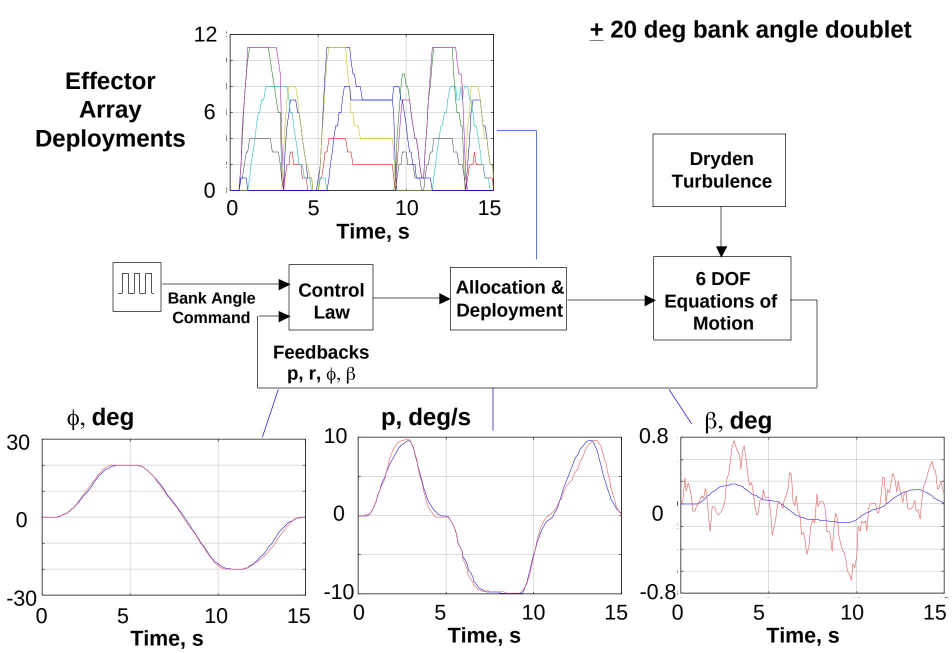
$$\mathbf{M}_{cmd} = \begin{Bmatrix} C_l \\ C_m \\ C_n \end{Bmatrix}_{cmd} = \mathbf{[K]} \begin{Bmatrix} \beta \\ p \\ r \\ \varphi \end{Bmatrix}$$

with yaw-rate washout for steady turns & roll-rate command limited to 10 deg/s

- Gain matrix, **K**, via pole-placement – stabilize lateral dynamics & improve settling time for gust response; track bank angle commands

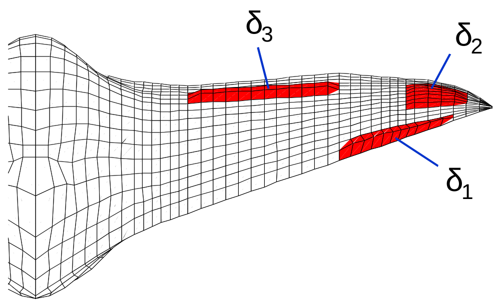


ICE Simulation Results: Mach 0.6, 15,000 ft



Modeling Caveats

- Potential flow (PMARC)
- Control deployments do not induce separation
- Static control effectiveness predictions
- No actuator deployment dynamics
- Effector array interactions are not considered (δ_1 does not change the effectiveness of δ_2 or δ_3)



Future Research

- Control using large distributed sensor/effector networks
  - Unconstrained device distribution and deployment
  - Deal with nonlinear device interactions
  - Exploit unconventional aspects of device arrays (highly distributed discrete effectors) for adaptive control/ adaptive performance optimization
- Design Tools: Adapt for use with other novel effector concepts (collaboration with MDOB)
- Experiments: Use novel effectors for control in dynamic test articles (collaboration with FMCB)
  - Active Separation Control
  - Forebody Vortex Control
  - Mild Maneuvering
  - Fluidic Thrust Vectoring