REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
12/11/2011	Final	10/01/2010-09/20/2011

4. TITLE AND SUBTITLE
CONTROL-ORIENTED AEROELASTIC REDUCED-ORDER MODELING OF FIGHTERS

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-10-1-0539

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Stanford University
Stanford
CA 94305

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
875 North Randolph St.
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-OSR-VA-TR-2012-0805

12. DISTRIBUTION / AVAILABILITY STATEMENT
Public Release Unlimited

13. SUPPLEMENTARY NOTES

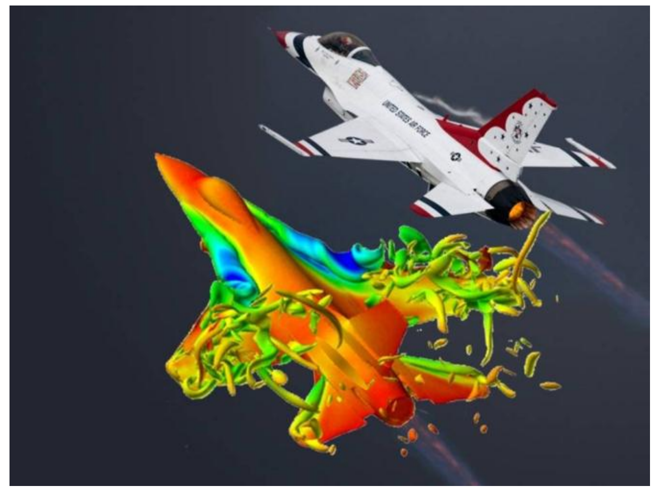
14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

CONTROL-ORIENTED AEROELASTIC REDUCED-ORDER MODELING OF FIGHTERS
FA9550-10-1-0539



Charbel Farhat and David Amsallem
Aeronautics and Astronautics
Stanford University

FSI: STATE OF THE ART

- Structural dynamics

  - multibody dynamics
  - geometrical nonlinearities (large displacements, rotations and strains)
  - material nonlinearities (nonlinear constitutive models)
  - crack propagation (failure)

- Computational fluid dynamics

  - shocks
  - turbulence

- Coupling

  - static (steady) and dynamic (unsteady)
  - eigen

IMPACT ON ENGINEERING

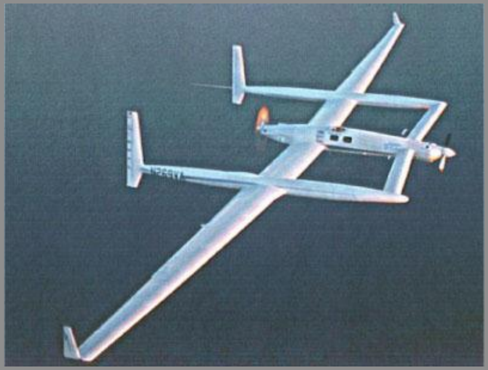
- Strong

  - analysis of carefully selected critical configurations

- Weak (or not as strong)

  - routine analysis
  - design (and test)
  - control

  } significant CPU time issues



" [*If I am not getting the NASTRAN answer after 4 hours on a Cray, then God is sending me the message I have the wrong design*] "

Burt Rutan, 1993

Manuel Balce Ceneta / AP

REDUCED ORDER MODEL (ROM)

- Model reduction (MOR)

  - build the lowest dimensional model that can capture the dominant behavior of the system of interest by projecting the high-fidelity model onto a well-chosen subspace

  → drastic CPU time reduction

- Complex, time-dependent problems (with a CFD component)

  o Perturbation problems (stability, trends, control, etc.)

  - linearized → linear ROMs

  o Response problems (behavior, performance, etc.)

  - nonlinear → (Newton) linearized → linear ROMs

MODEL REDUCTION

- What this is NOT about

  - building the simplest model
  - building a variable (or multi) fidelity model
  - adopting the coarsest mesh
  - substructuring
  - constructing a "surrogate" or "meta" model

LINEARIZED DYNAMICAL SYSTEMS

- External description (input-output map)

$$y = S(u) = h * u = \int_{-\infty}^{t} h(t - \tau)\, \mu(\tau)\, d\tau$$

- Internal description (model)

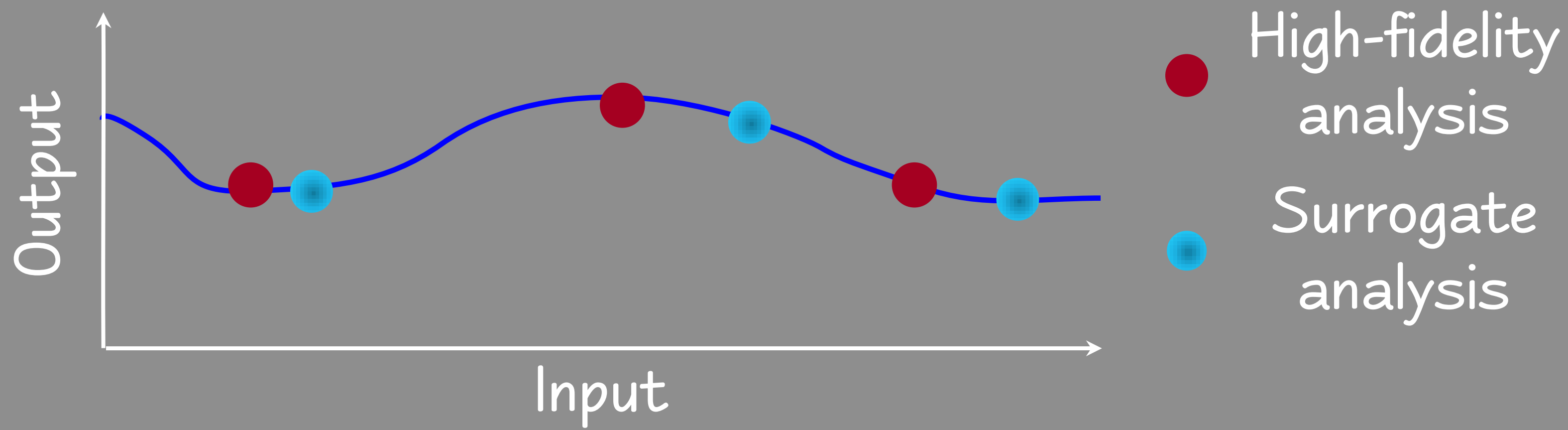
$$\dot{u} = A(\mu_1, \ldots, \mu_p) u + f$$

$$y = g(u, f, \mu_1, \ldots, \mu_p)$$

$$u(t_0) = u_0$$

SURROGATE MODEL

- External description



- meta-model, surrogate model, response surface, kriging
- lower-dimensionality is not guaranteed
- it is not a model of the system but of the output

MODEL REDUCTION

- Internal description

$$\dot{u} = A(\mu_1, \ldots, \mu_p)u + f \quad (\text{dimension} = N)$$

- Projection onto a subspace of dimension k << N

  - right Reduced-Order Basis (ROB) V_k, k << N

$$u \sim V_k y \longrightarrow V_k \dot{y} = A(\mu_1, \ldots, \mu_p)V_k y + f + r$$

  - left Reduced-Order Basis (ROB) U_k, k << N

$$\text{constraints} \longrightarrow \boxed{\dot{y} = U_k^T A(\mu_1, \ldots, \mu_p)V_k y + U_k^T f}$$

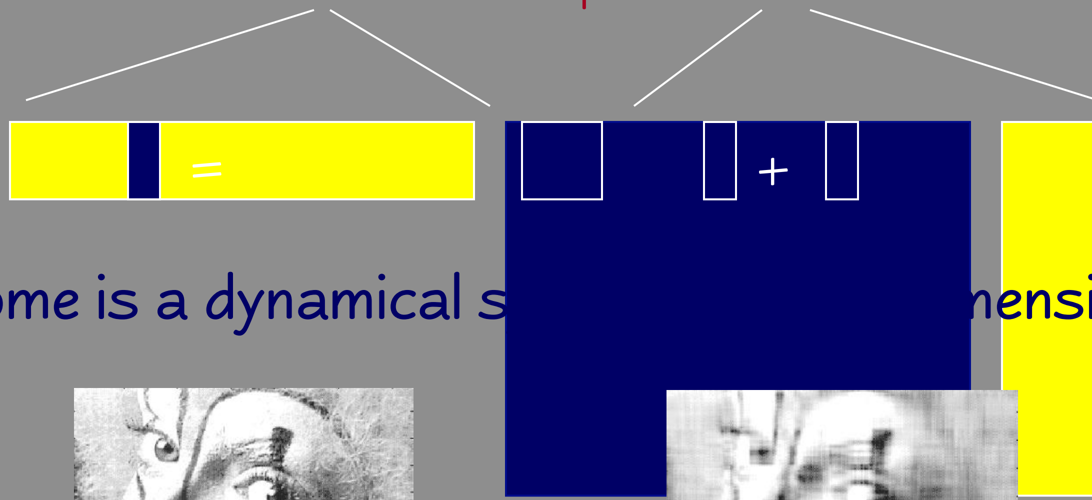
↓

parameterized linear(ized) Reduced-Order Model (ROM)

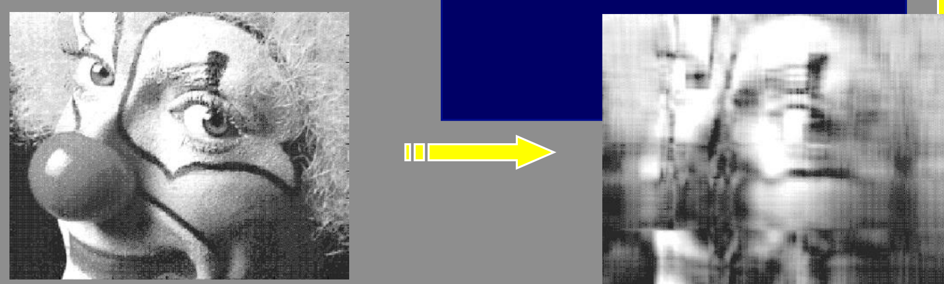
MODEL REDUCTION

$$\dot{u} = A(\mu_1, \ldots, \mu_p)\, u + f$$

$$\dot{y} = U_k^T A(\mu_1, \ldots, \mu_p)\, V_k\, y + U_k^T f$$



- The outcome is a dynamical s … nension



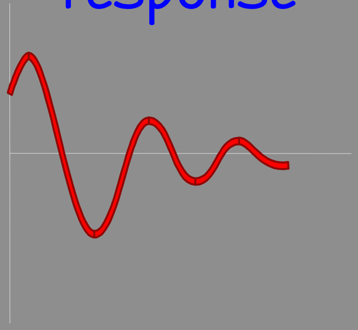
- Key issues
  - choice of the lower dimension k and the ROBs U_k and V_k
  - dependence of the resulting ROM on the parameters $\{\mu_i\}$

LINEAR(IZED) FLUID-STRUCTURE

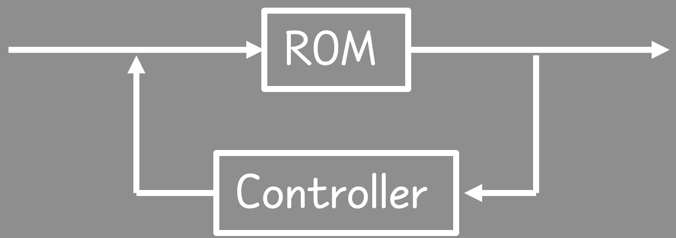
- General purpose linearized aeroelastic high-fidelity model (HFM)

$$\begin{pmatrix}\dot{w}\\ \ddot{u}\\ \dot{u}\end{pmatrix} = \underbrace{\begin{pmatrix} -H & -B & -C\\ M^{-1}P & 0 & -M^{-1}K\\ 0 & I & 0\end{pmatrix}}_{A(\mu);\quad \mu = (\mu_1, \dots \mu_q)} \begin{pmatrix} w\\ \dot{u}\\ u\end{pmatrix} + \begin{pmatrix}0\\ M^{-1}T_i^{T}\\ 0\end{pmatrix} F$$

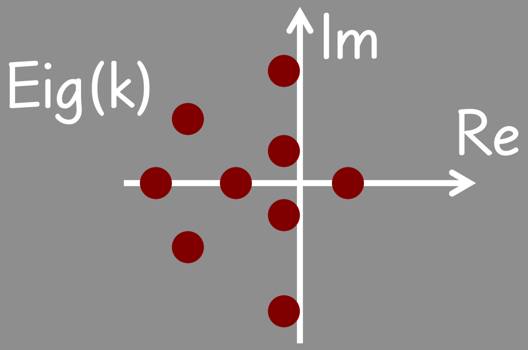
Aeroelastic response



Control



Flutter



MULTIDISCIPLINARY ROM

Fluid ROM

CFD-based HFM
Balanced POD-based ROBs
(with stability guarantee)

Structural ROM

FE-based HFM
Eigen-based ROB
(with truncation)

FLUID-STRUCTURE ROM

Fluid	Structure	Coupling
ROBs: $U_k, V_k \,/\, U_k^T V_k = I$	ROB: $X_m \quad (X_m^T M X_m = I)$	$B_r = U_k^T B X_m$
$w = V_k w_r$	$u = X_m u_m$	$C_r = U_k^T C X_m$
ROM: $H_r = U_k^T H V_k$	ROM: $\Omega_m^2 = X_m^T K X_m$	$P_r = X_m^T P V_k$

- General purpose aeroelastic ROM (flutter, response, control, …)

$$\begin{pmatrix} \dot{w}_r \\ \ddot{u}_m \\ \dot{u}_m \end{pmatrix} = \underbrace{\begin{pmatrix} -H_r & -B_r & -C_r \\ P_r & 0 & -\Omega_m^2 \\ 0 & I & 0 \end{pmatrix}}_{A_r(\mu);\quad \mu = (\mu_1, \ldots \mu_q)} \begin{pmatrix} w_r \\ \dot{u}_m \\ u_m \end{pmatrix} + \begin{pmatrix} 0 \\ X_m^T T_i^T F \\ 0 \end{pmatrix}$$

- aeroelastic response
- control, flutter
- aeroservoelastic analysis, …

OFFLINE FLUID SNAPSHOTS

- Natural mode shapes (ground vibrations) ($n_m = 9$ modes)

- Excitations in a sampled frequency range

$$0 < \kappa = \frac{\omega L_R}{v_R} \sim 1 \;\longrightarrow\; n_f = 5 \text{ frequencies}$$

- Responses of linearized flow (frequency domain)

$$(H + i\omega_q I)\, w_{jq} = -(C + i\omega_q B)\, u_j \qquad j = 1, \ldots, n_m, \quad q = 1, \ldots, n_f$$

w_{jq} → primal fluid snapshots W $\xrightarrow{\text{data compression}}$ V_k

$$(-H^T + i\omega_q I)\, w^*_{jq} = -P^T u_j \qquad j = 1, \ldots, n_m, \quad q = 1, \ldots, n_f$$

w^*_{jq} → dual fluid snapshots W^* $\xrightarrow{\text{data compression}}$ U_k

DATA COMPRESSION

- Modal superposition (Fourier decomposition)
  - limited range of applications
- Proper Orthogonal Decomposition (POD)
  - lacks stability
- Balanced Proper Orthogonal Decomposition (POD)
  - more robust than POD but still lacks stability

GUARANTEED STABILIZATION METHOD

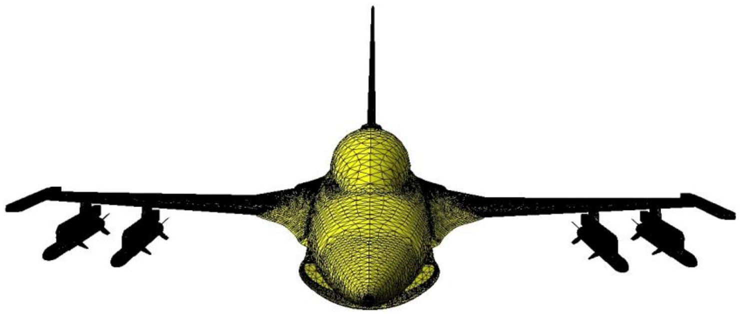
- ROM stabilization method (Amsallem and Farhat, 2011)

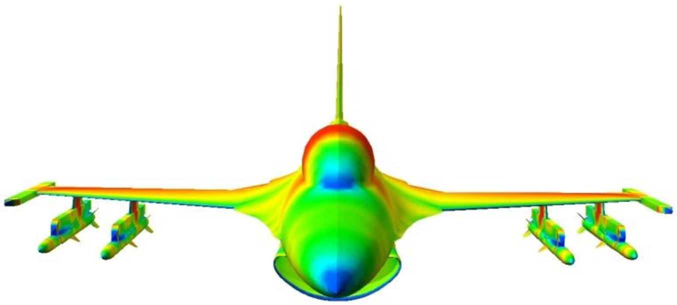
  - universal
  - non intrusive
  - computational complexity scales with the size of the ROM
  - preserves accuracy of original (unstable) ROM

F-16 BLOCK 40

- Higher-fidelity (higher-dimensional) models (HFM)

  - structure : FEM with 168,799 dofs
  - fluid : Euler CFD model with 403,919 grid points



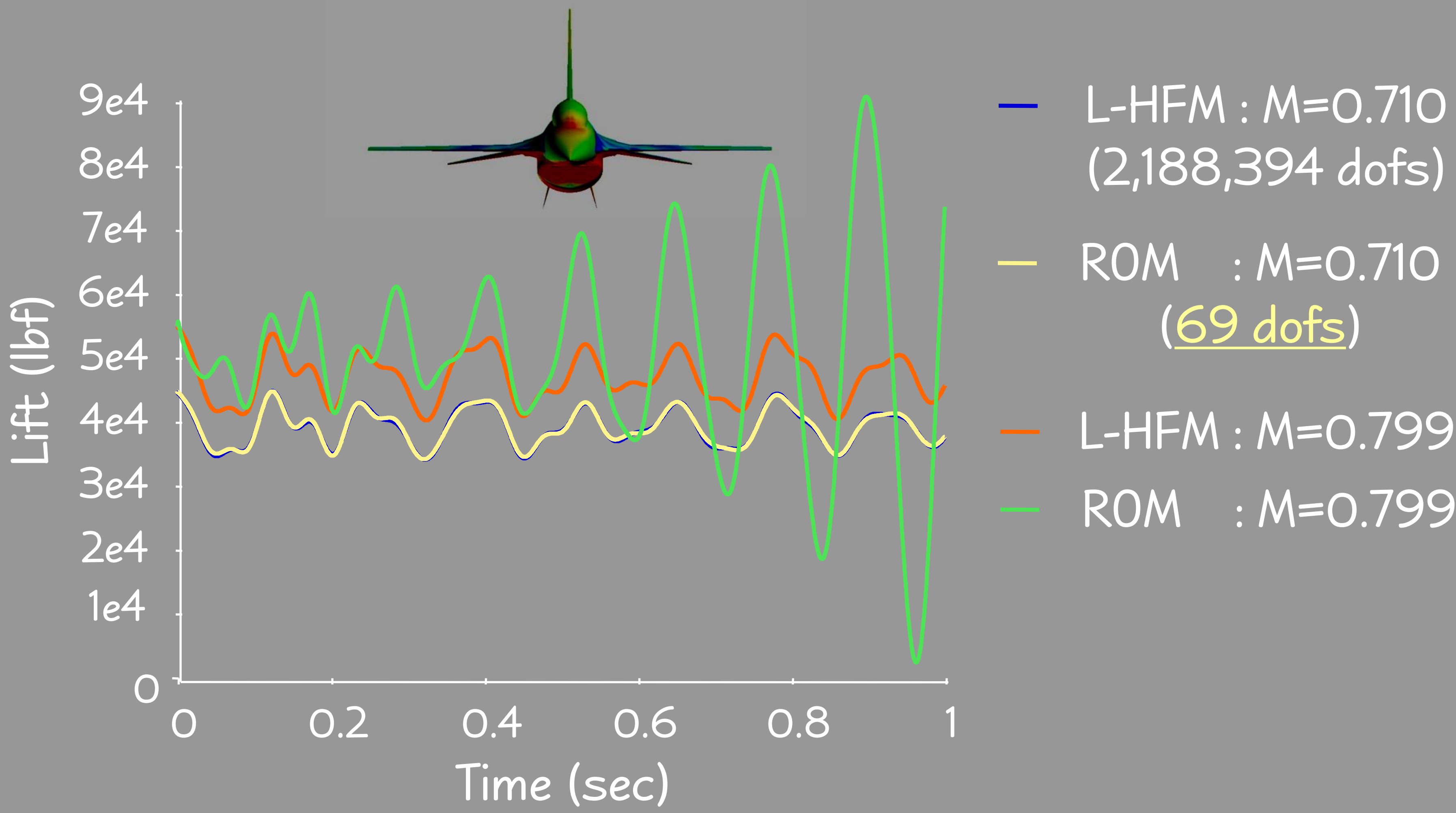


- ROMs

  - structure : projection on ROB consisting of first 9 natural mode shapes
  - fluid : projection on ROB of dimension 60 generated by POD using 99 snapshots (9 shapes x 5 ωs x 2 + 9 shapes at 0 Hz)

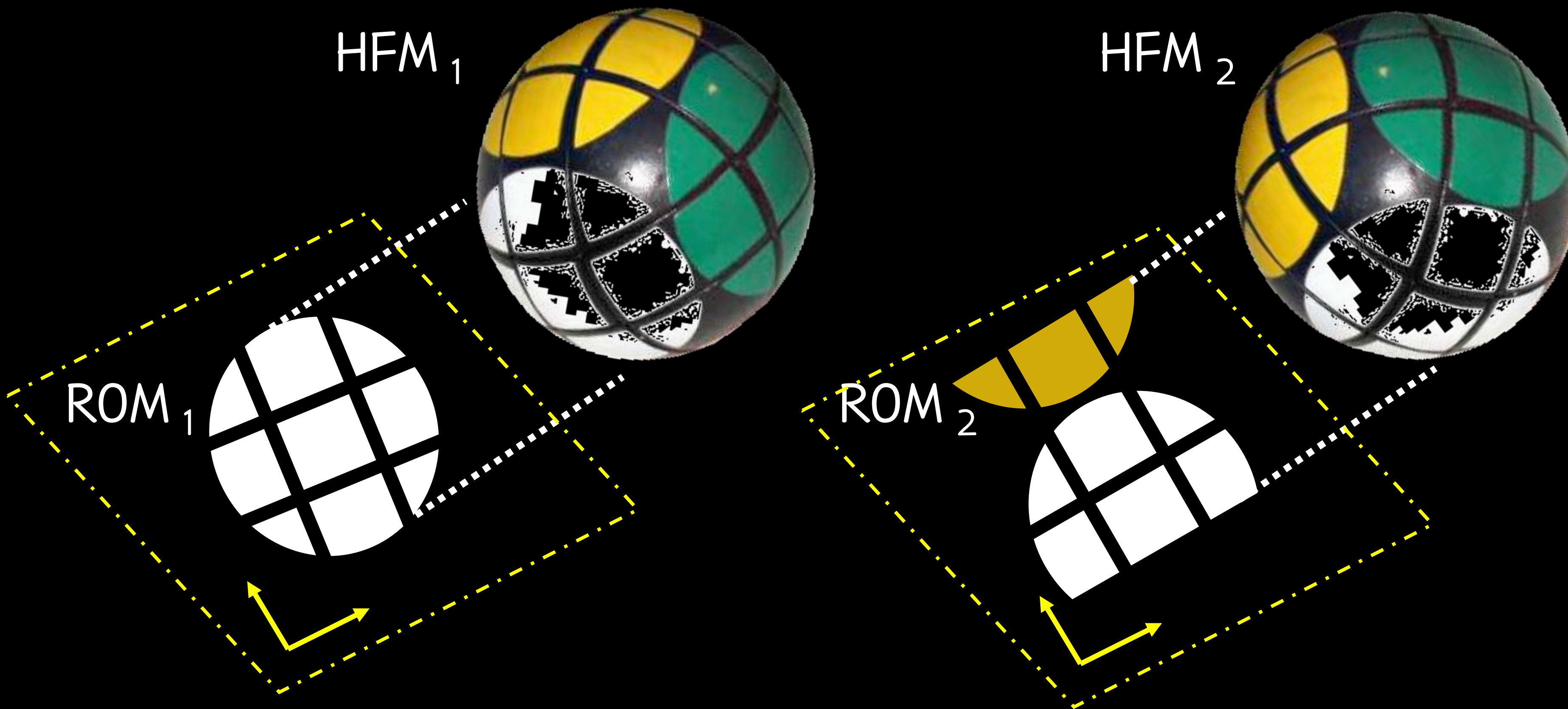
PARAMETER SENSITIVITY

POD-based fluid ROB (60) built at M = 0.710 (trimmed angle)



ANALOGY

Configuration 1 | Configuration 2

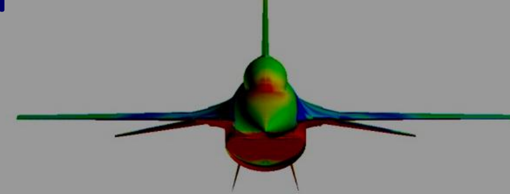


Reduced-order basis V_{k_1}

Reduced-order basis $V_{k_2} = V_{k_1}$

TURNAROUND TIME

- F-16 Block 40 — 1 operating point — 2^{nd}-order discretization
  64-processor Linux cluster

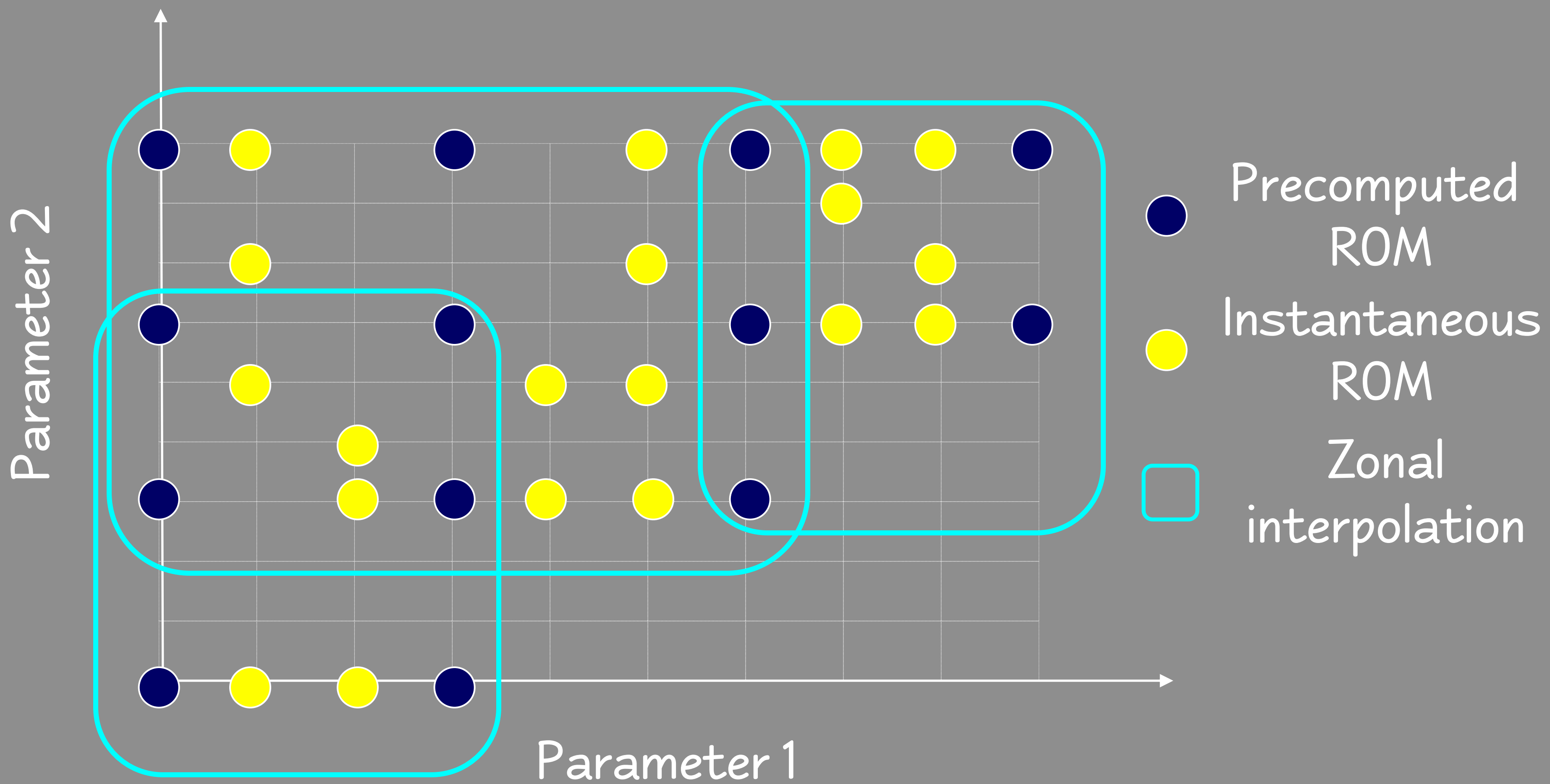


Construction and processing of aeroelastic ROM in [0, 1.0] s

steady-state computation	6 minutes
ration of 99 fluid snapshots and based fluid ROB	50 minutes
truction of fluid ROM	0.25 minute
Processing aeroelastic ROM	0.10 minute
l CPU time	57.25 minute

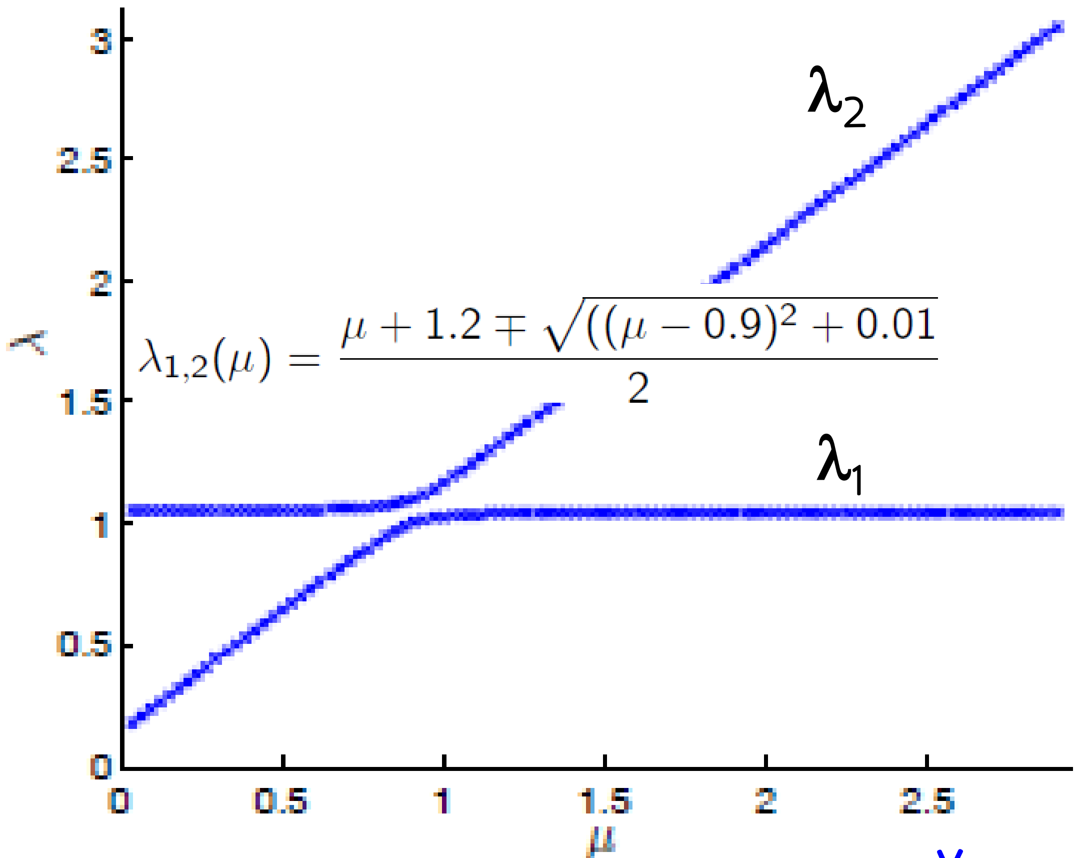
APPROACH

- Database of fixed-size stable ROMs

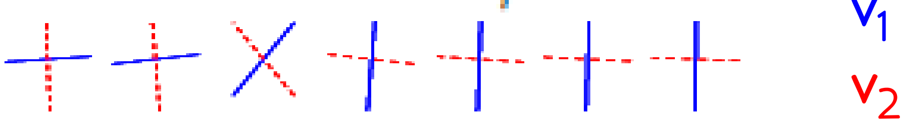


CONSISTENCY

Eigenvalues



Eigenvectors

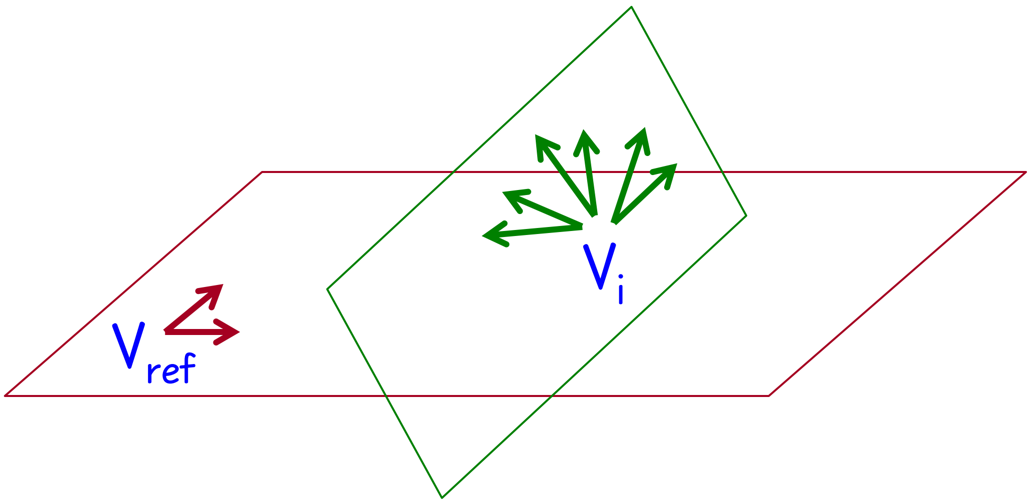


→ precomputed ROMs are not necessarily computed in a consistent set of generalized coordinates

ROM TRANSFORMATION

- Congruence transformations

  - reference ROB: $V_{ref} = V_k(\mu_{ref})$
  - $V_i \longleftarrow V_i Q_i \qquad Q_i = \arg \min_{Q \in O(k)} \| V_i Q - V_{ref} \|_F$

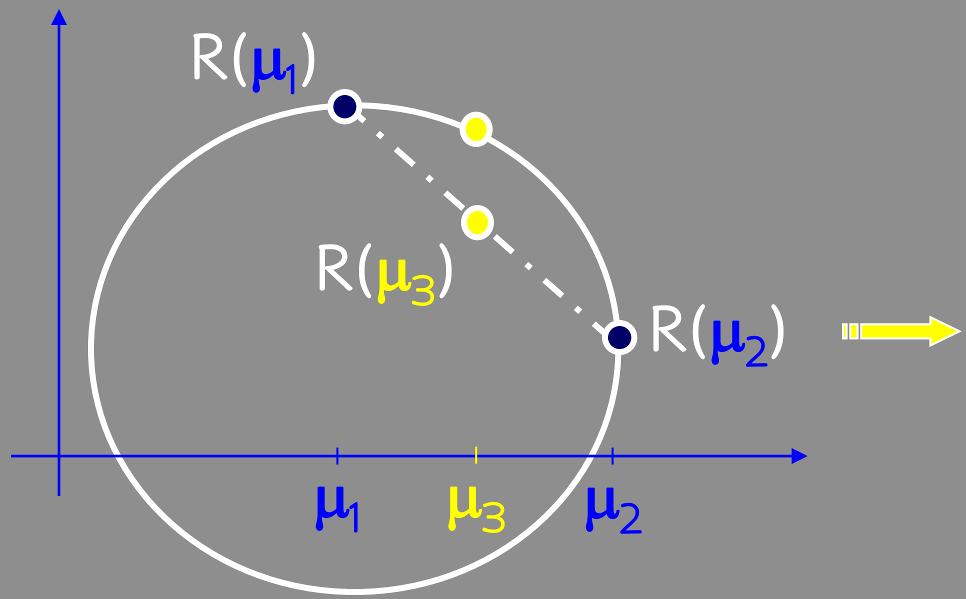


- Orthogonal Procrustes problem

  - SVD: $V_i^T V_{ref} = U_i \Sigma_i Z_i^T$

    $\Longrightarrow Q_i = U_i Z_i^T$

QUOTIENT AND EMBEDDED MANIFOLDS



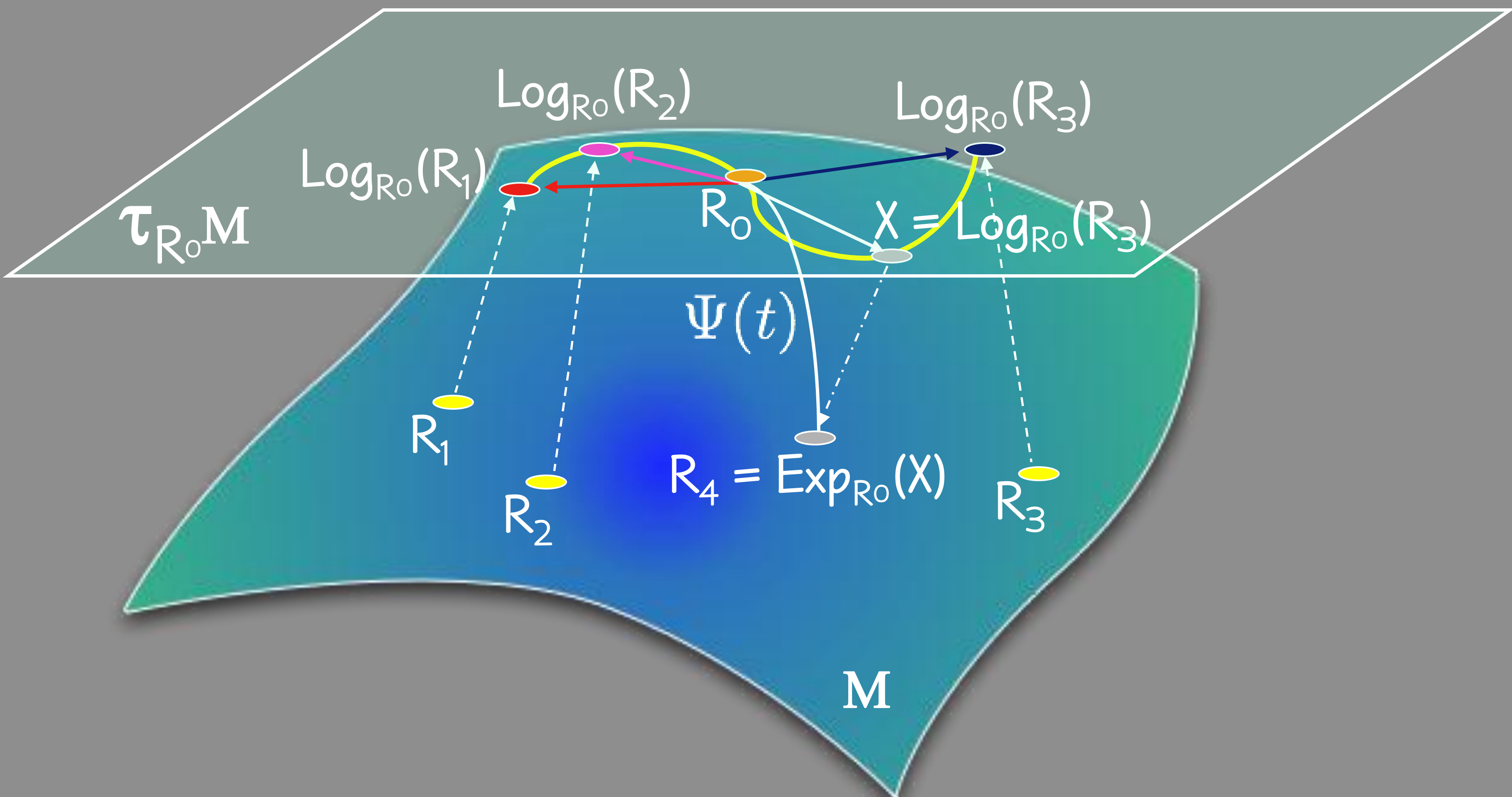
- standard interpolation of a ROM does not produce a ROM
- interpolation must be carried out on a manifold characterizing the ROM

- Manifolds of interest (quotient = blue, embedded = yellow)

  - span(V_k) belongs to the Grassmann manifold G(k,N)
  - $A_r(\mu) = V_k^T A(\mu) V_k$ belongs to
    * manifold of invertible matrices GL(k) [fluid]
    * manifold of (reduced-order) symmetric positive definite matrices SPD(k) [structure]

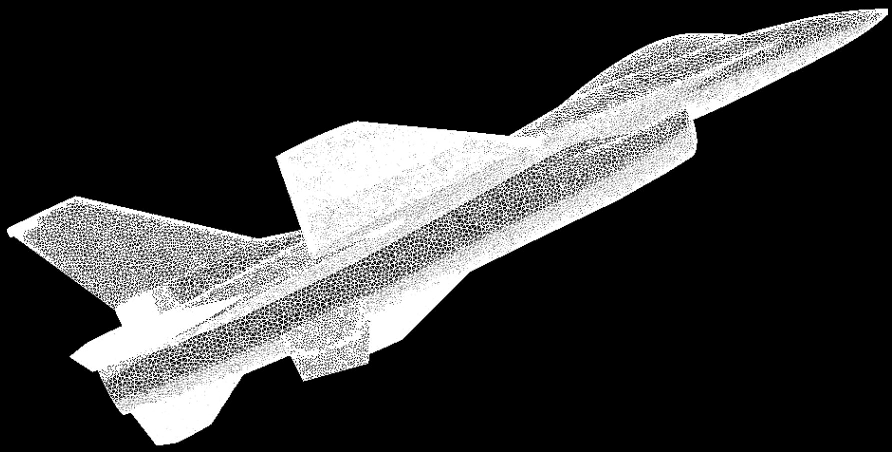
ONLINE INTERPOLATION ON A MANIFOLD

- Given a p-parameter system, the appropriate Riemannian manifold, and its logarithmic and exponential maps

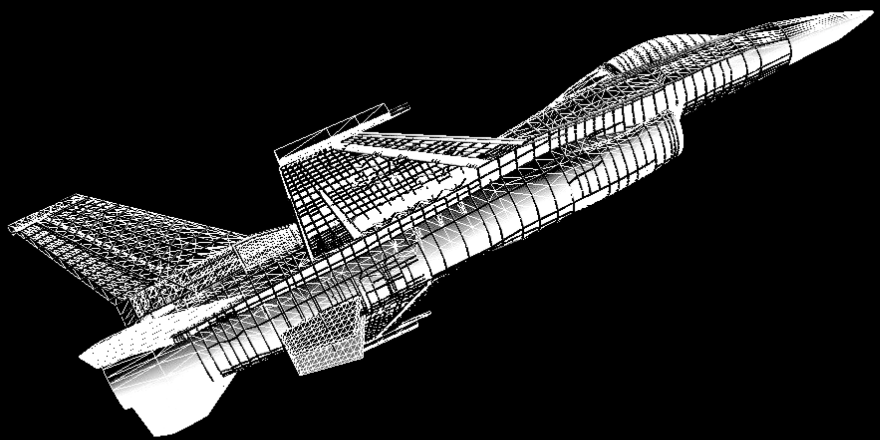


SHOWCASE APPLICATION

- F-16 Block 40



CFD model

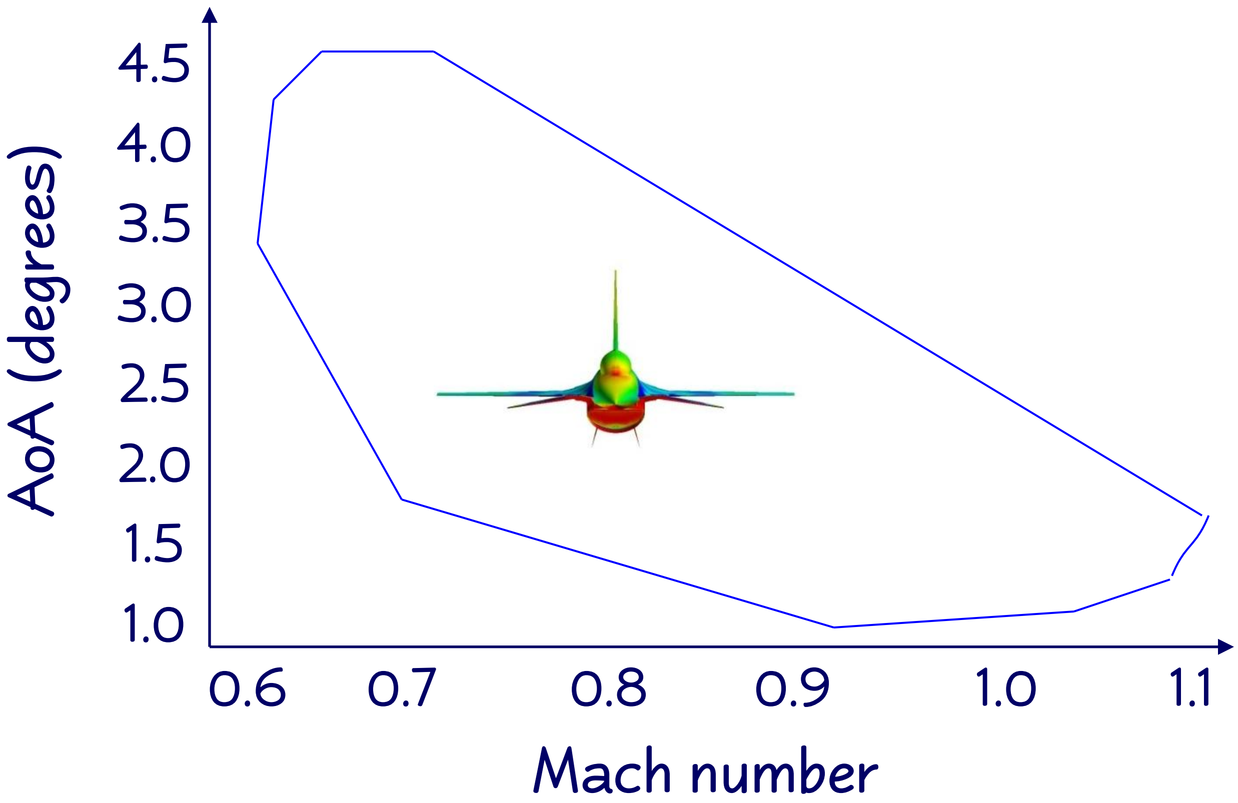


FEM structural model

- Assisting flight test

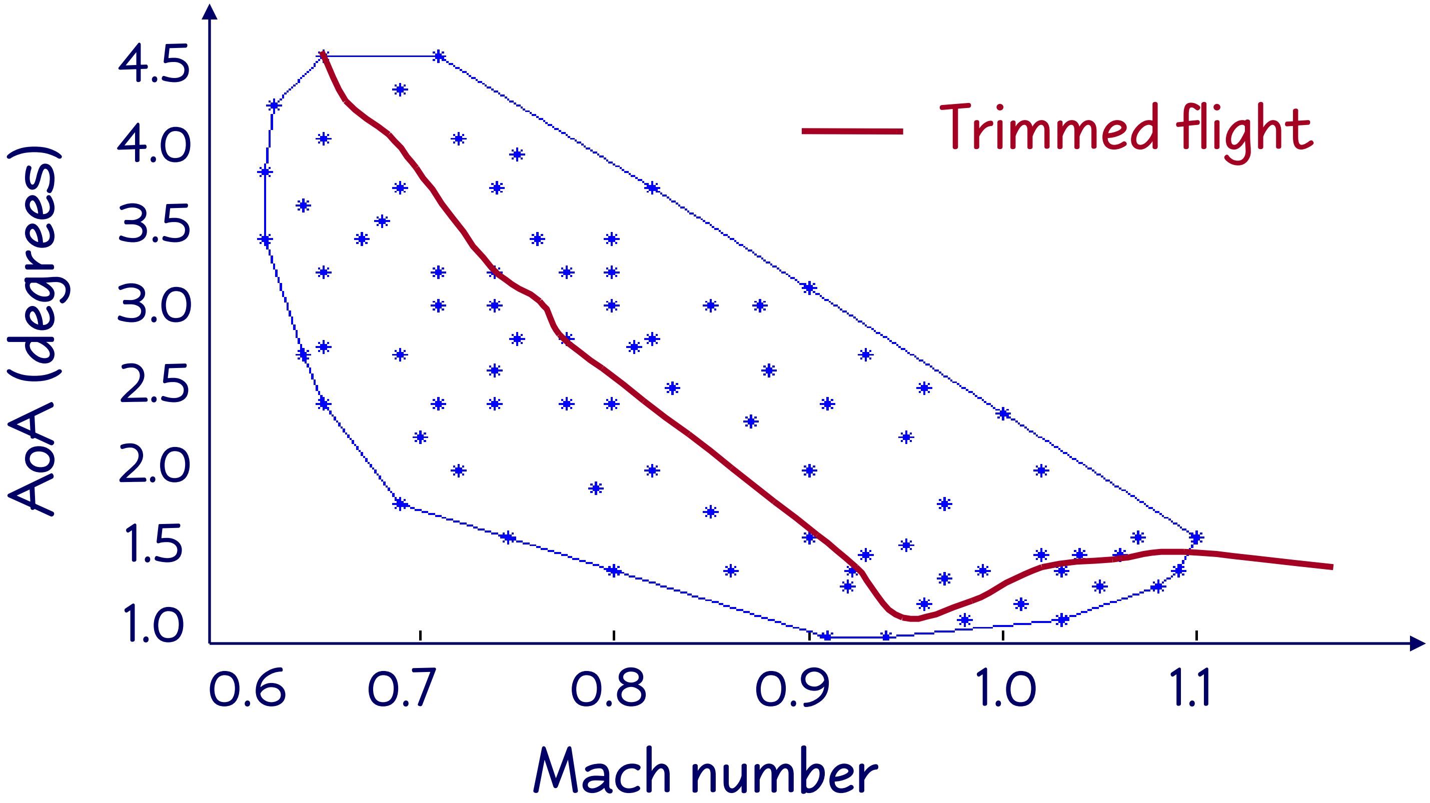
  - single aircraft configuration ⟶ single structural ROM
  - hundreds of flight conditions ⟶ database of fluid ROBs

FLIGHT ENVELOPPE



ROM DATABASE

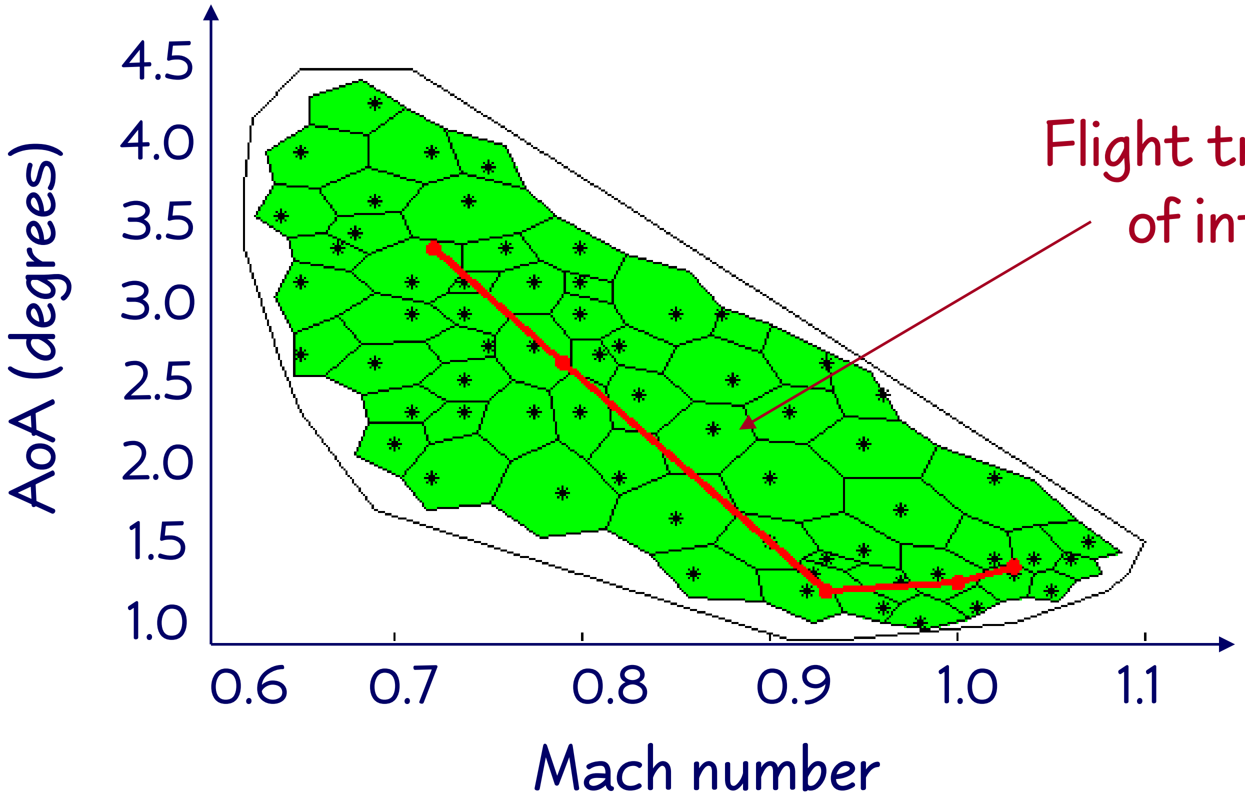
- 83 pairs of flight conditions (operating points)
  - 70.6 hours CPU on a 64-processor Linux cluster



ON-DEMAND PREDICTIONS

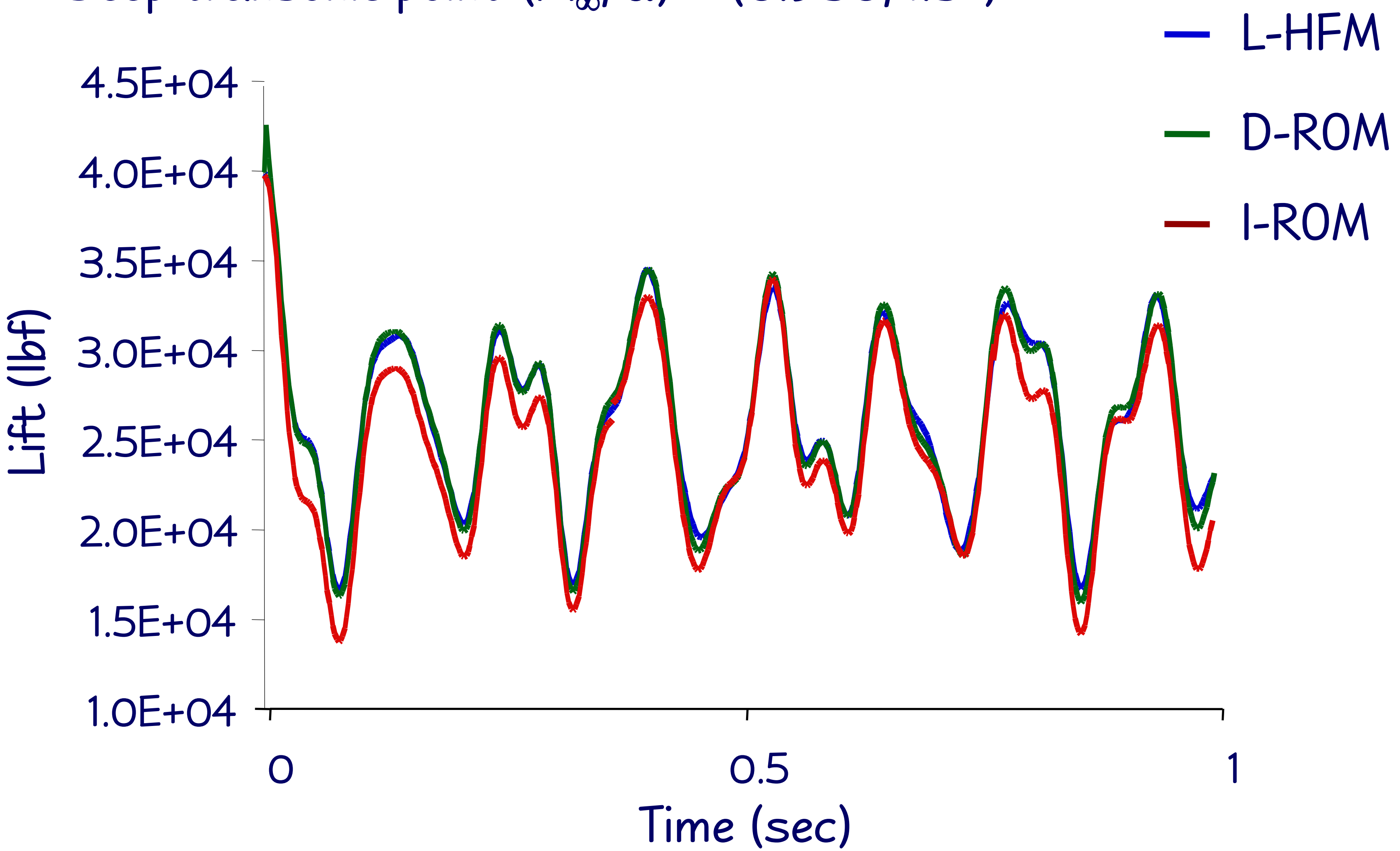
- Fast responses to 5 queries

  - possible scenarios: flight test, flutter clearance, optimization
  - interpolation of fluid ROMs



DELIVERED ACCURACY

- Deep transonic point $(M_\infty, \alpha) = (0.930, 1.3°)$



TURNAROUND TIME

- F-16 Block 40 — 1 operation point — 1-processor (desktop)

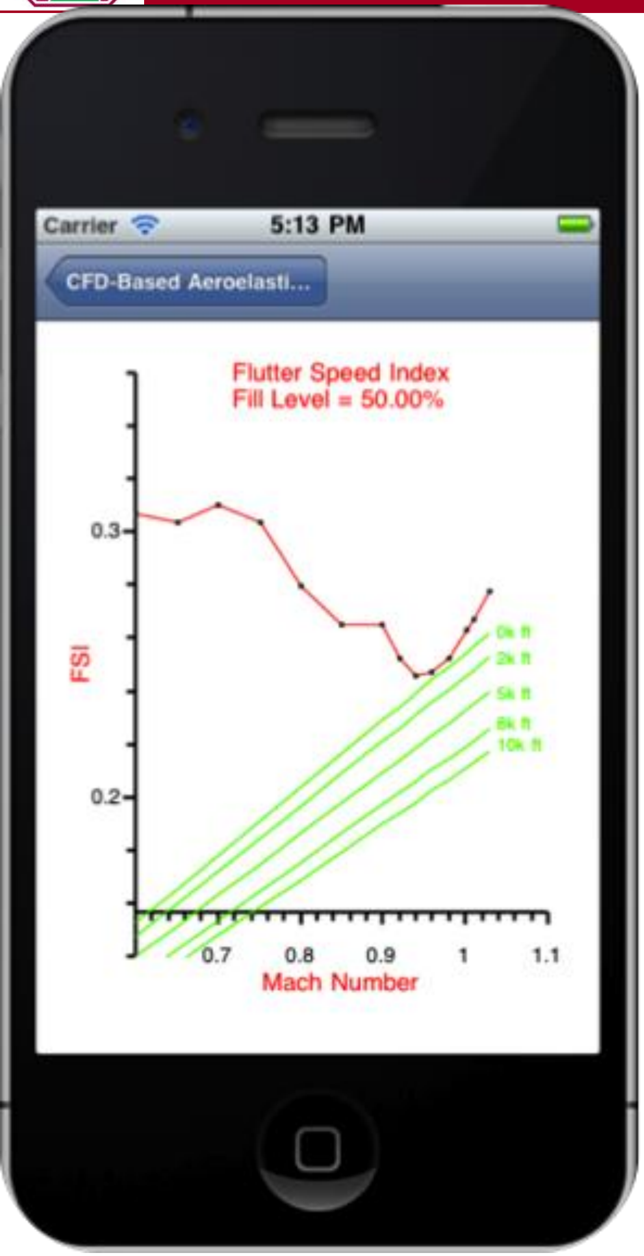
CPU time for interpolating and processing
1 CFD-based aeroelastic ROM

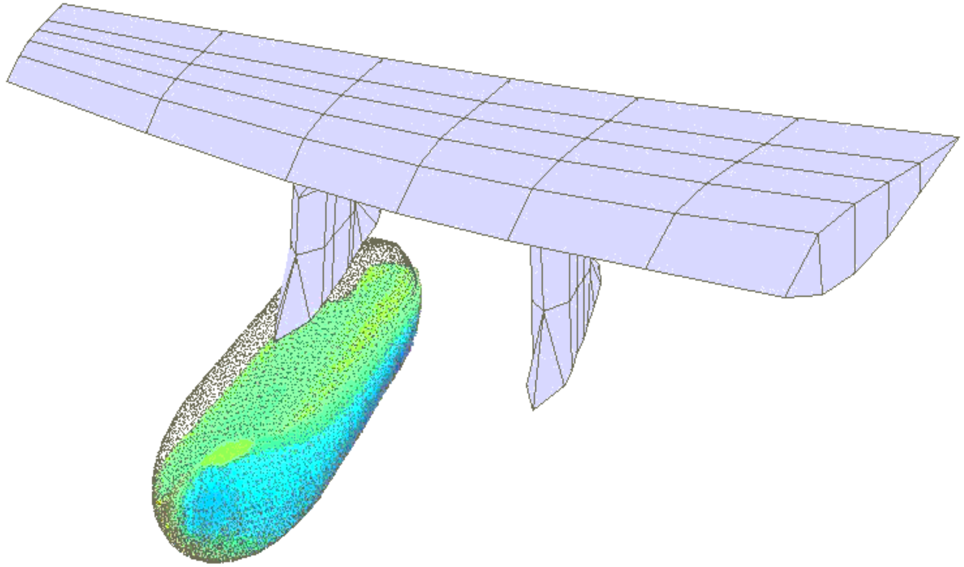
Fluid ROM interpolation (5 points)	0.2 second
Aeroelastic ROM processing (FD)	0.3 second
Total CPU time	0.5 second

→ real-time, parameterized, CFD-based flutter analysis

IMPLEMENTATION ON MOBILE DEVICES

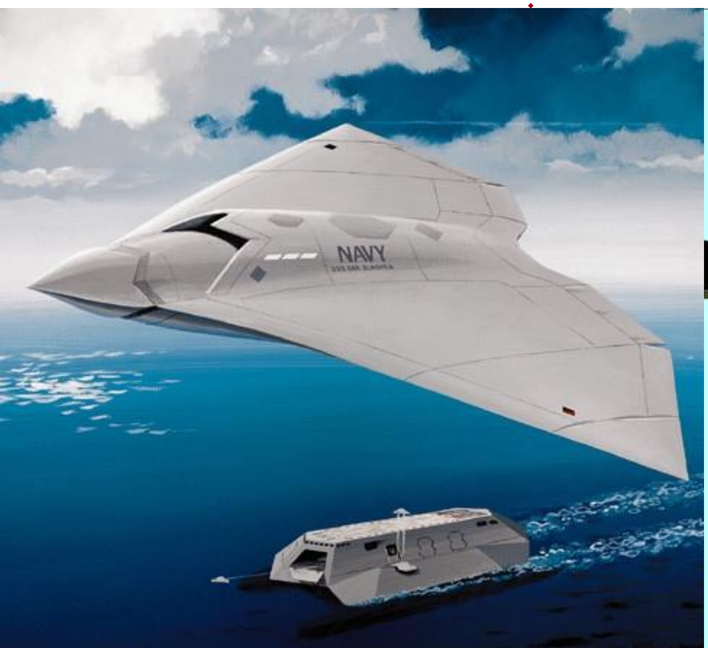
IMPLEMENTATION ON MOBILE DEVICES

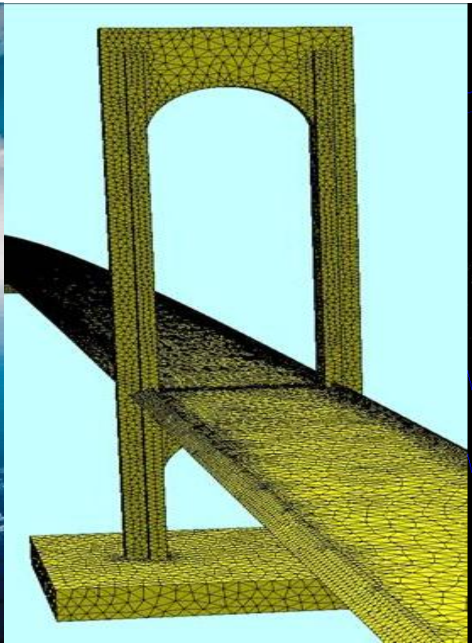




VISION

ROM inside






Courtesy of Charlie Taylor

ACKNOWLEDGEMENTS

- US Air Force Office of Scientific Research, T&E Program