Hypersonic Vehicle (HSV) Modeling

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HSV Concentration

MACCCS Kickoff Meeting

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Team

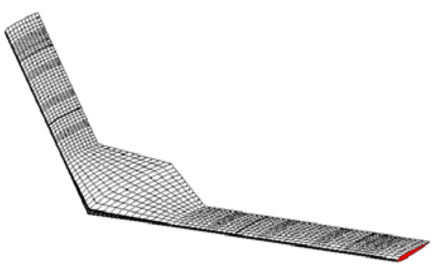
- U of M Faculty: Carlos Cesnik (PI), Jim Driscoll
- Current students: Nathan Falkiewicz, Torstens Skujins, Nathan Scholten, Sean Torrez, plus Post-doctoral fellow (TBD)
- AFRL collaborators: Mike Bolender, David Doman, Mike Oppenheimer

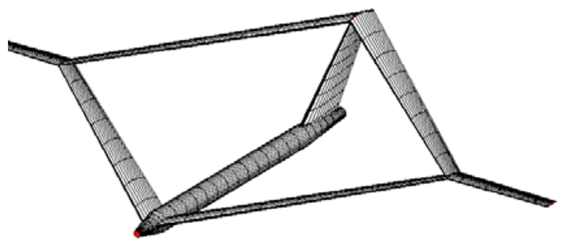
Overview

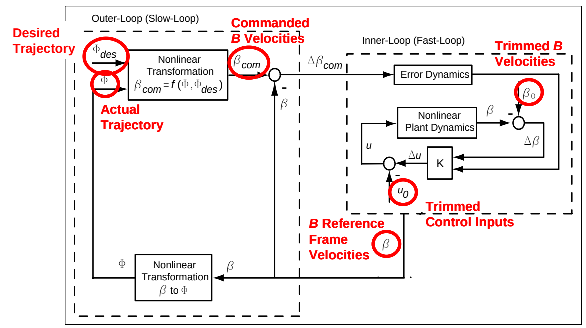
- Challenge: strong interactions among aerodynamics, elastic airframe and control effector deformations, heat transfer, and propulsion system (itself tightly integrated into the lifting body)
- Focus in two main areas:
  - development and validation of simple (low-order) control models that can characterize the main aerothermoservoelastic effects coupled with propulsion in a 6 DOF flight dynamics simulation of HSV; and
  - determination on how to appropriately modify vehicle configuration to improve its dynamic controllability without compromising vehicle performance.
- All done in close collaboration with AFRL/VACA researchers who will provide primarily the control design and modeling expertise as part of the Collaborative Center.

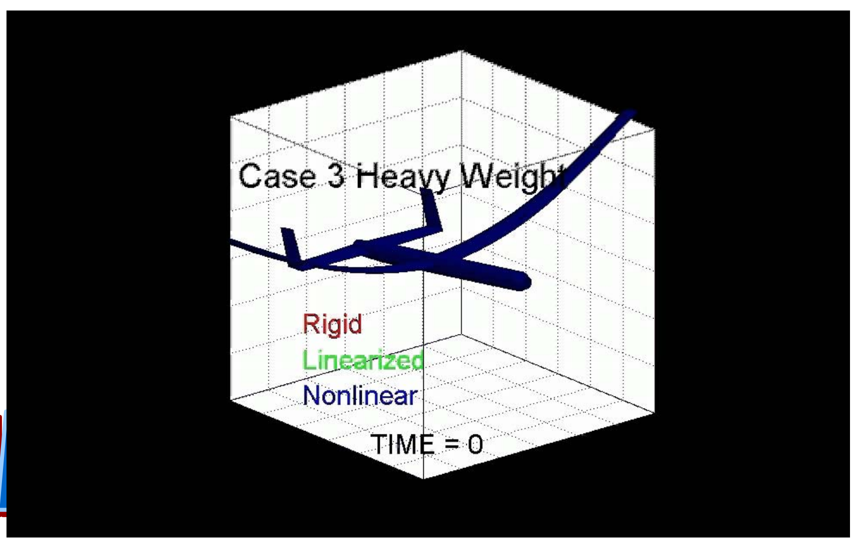
Sample Relevant Work at UM
Very Flexible HALE Aircraft (Sensorcraft-class)

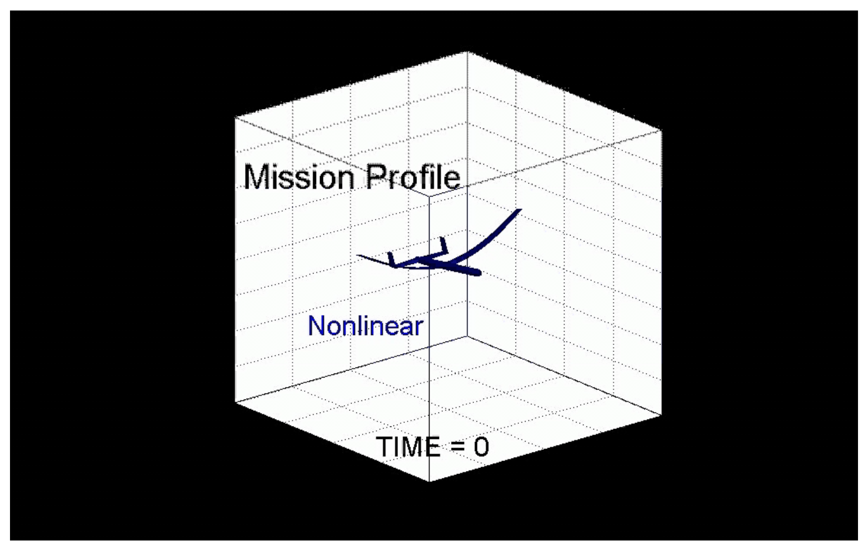
- **Aeroservoelastic formulations at different complexity levels**
  - **Target preliminary vehicle and control design and more detailed analysis**
  - **Able to simulate 6-DOF with fully flexible vehicle**
- **Numerically investigate aeroelastic response under nonlinear effects**
- **Model different vehicle configurations**





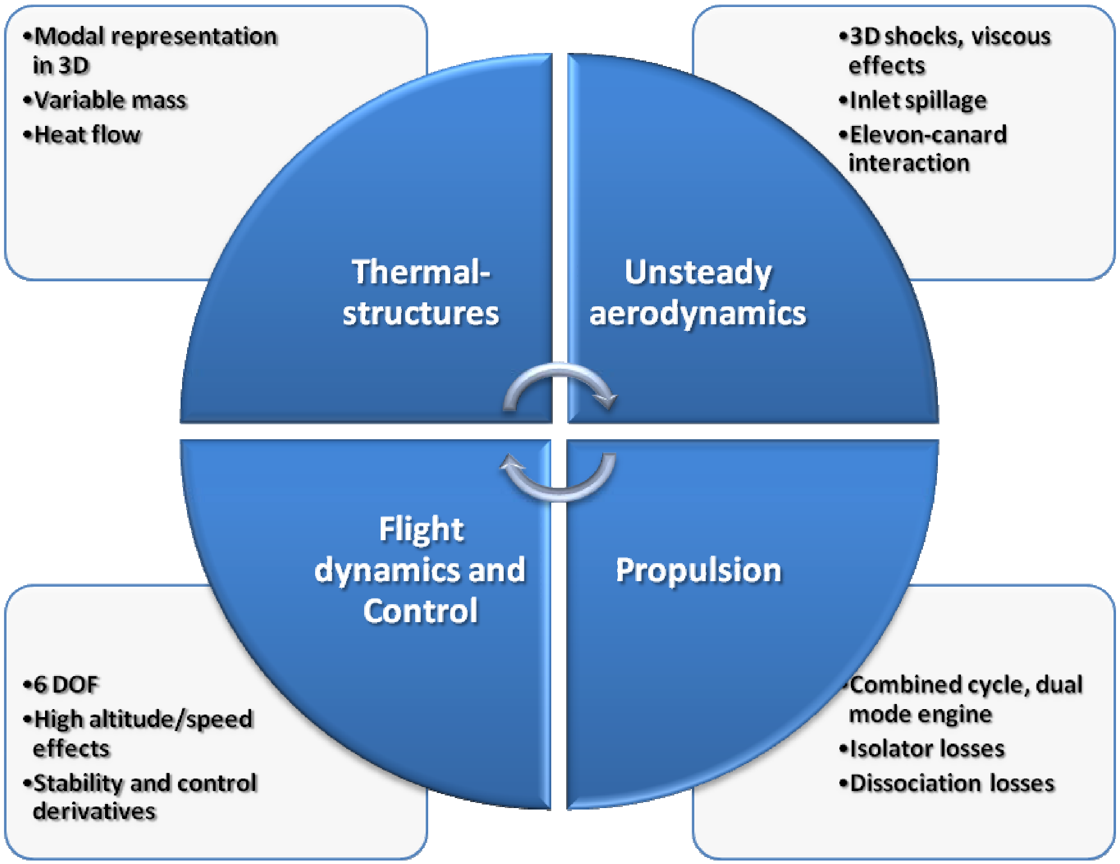






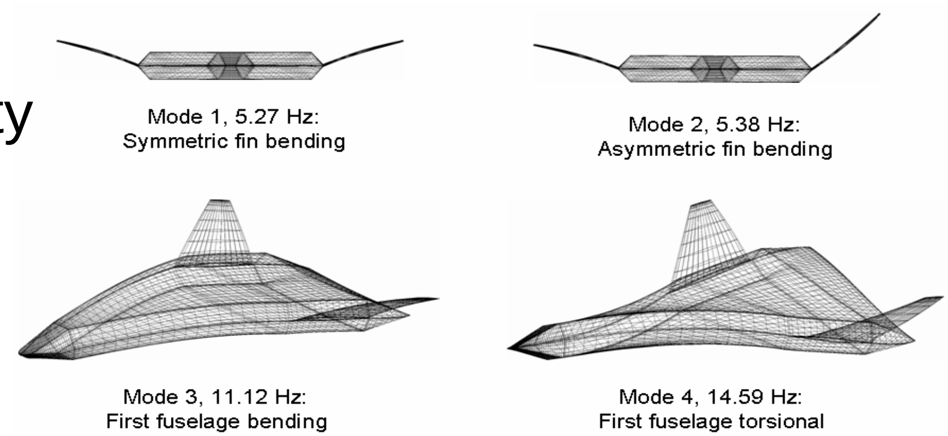
Disciplinary Components of HSV

- Four main component areas to be address in the study



Thermo-structural Dynamics Modeling

- Structures defined by flexibility and inertia effects
  – different options to characterize deformations

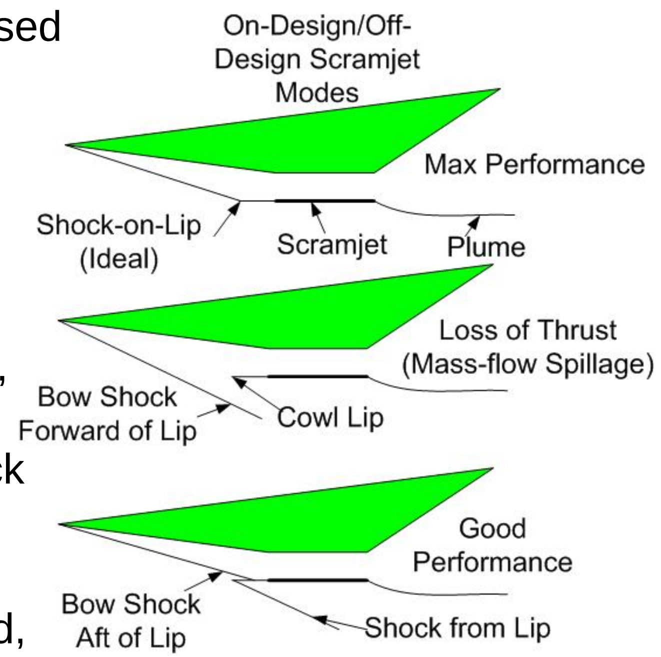


McNamara and Friedmann, 2006

- Heat issues:
  – thermo effects on the elastic characteristics of the vehicle
    - Dependent on the structural layout and material stacking sequence →need detailed model of the structure to assess impact on vehicle response
  – temperature gradients in the structure will impact
    - the reference vibration modes and static deflections of the control surfaces and possibly of the entire vehicle (mainly due to thermal stresses and material property degradation with temperature)
    - fuel temperature in the tanks (which can define optimum flight trajectories).

Unsteady Aerodynamics Modeling

- Complex environment of unsteady, viscous, non-equilibrium, reacting flow
- Current models limited to longitudinal dynamics
  - Stead state shock/expansion geometry determined based on the Oblique Shock Theory
  - Superimposed unsteady aero effects based on piston theory
- Several issues—AFRL has identified needed improvements in the following areas:
  - unsteady pressure over the entire wetted surface area, including lateral aerodynamics,
  - spillage effects caused by the location of the bow shock with respect to the inlet during vehicle bending,
  - coupling of the aerodynamics and the heat transfer,
  - control surface aerodynamics, including elevon, canard, and elevon-canard interactions,
  - viscous effects.



Propulsion Model

- Combined cycle engine as an integral part of the vehicle structure
- Model must contain (AFRL):
  - engine forces & moments related to bow shock/engine spillage, pressures on aft underbody
  - forces depend on fuel/air ratio, diffuser area ratio, cowl leading edge
- We will work with AFRL to improve modeling of:
  - inlet/isolator shock losses,
  - scramjet dissociation / frozen flow losses
  - real gas effects, finite-rate chemistry
  - how pressure varies with distance inside engine
  - thermal choking limitations to fuel-air ratio
  - RBCC (or TBCC) cycle analysis, ram-scram transition
  - boundary layer effects (effective duct shape change)

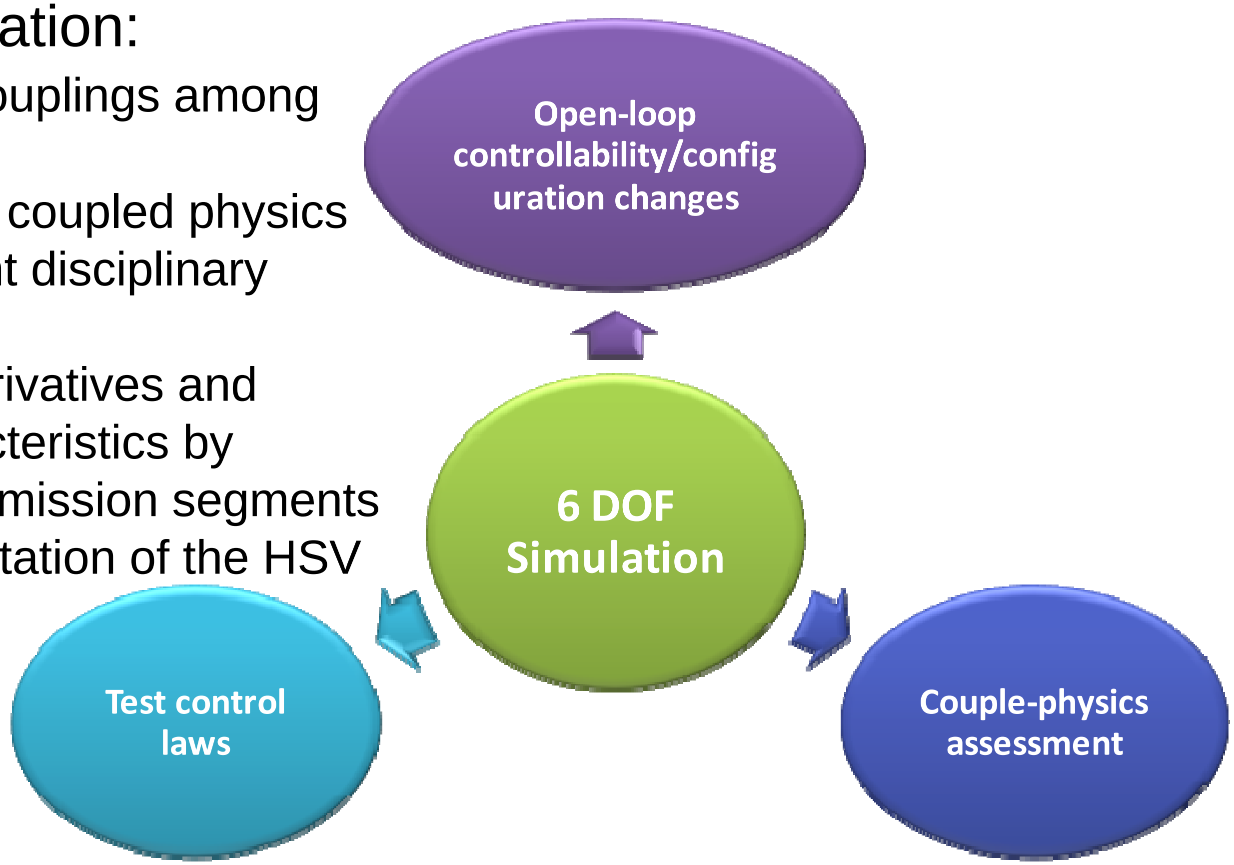
Driscoll will discuss more about it next

Flight Dynamics Model

- Free flight simulation of the flexible HSV is the ultimate goal
  - Lateral dynamics will bring new modes that may couple with the longitudinal ones (short-period mode; phugoid-like mode, although independent of speed; and a height mode, typically not seen in conventional subsonic vehicles)
- Development of the nonlinear rigid 6 DOF model based on AFRL's current planar (2D) formulation
- Solution of combined flight dynamics/aerothermoelasticity problem
  - numerical stability for long term simulations
  - integration of the disciplines and models

Vehicle Configuration and Sensitivities for Dynamic Controllability

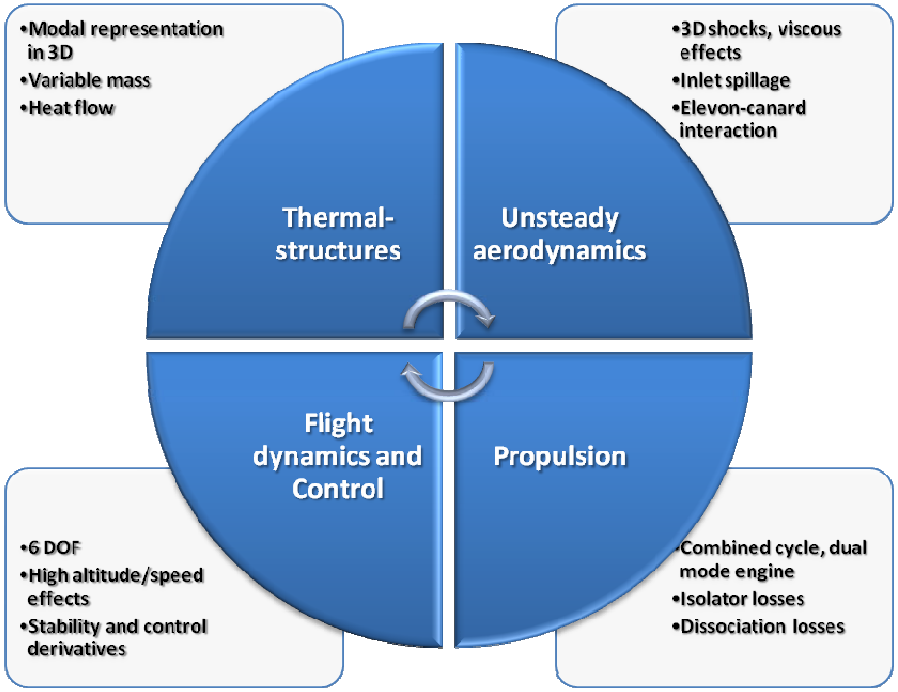
- Issue: *How to appropriately modify the vehicle's configuration to improve its dynamic controllability without compromising its performance*?
- Create 6 DOF Simulation:
  – Simulate open-loop couplings among different disciplines
  – Quantify the effects of coupled physics coming from the different disciplinary areas
  – Determine stability derivatives and overall root locus characteristics by linearization at different mission segments
  – Serve as the representation of the HSV for testing control laws



Overview of Modeling Approach

- Two main thrusts for HSV modeling:
  - (Low-order) *control models*
  - (High-fidelity) *reference models*

along with a *control evaluation model*.



(Low-order) Control Models

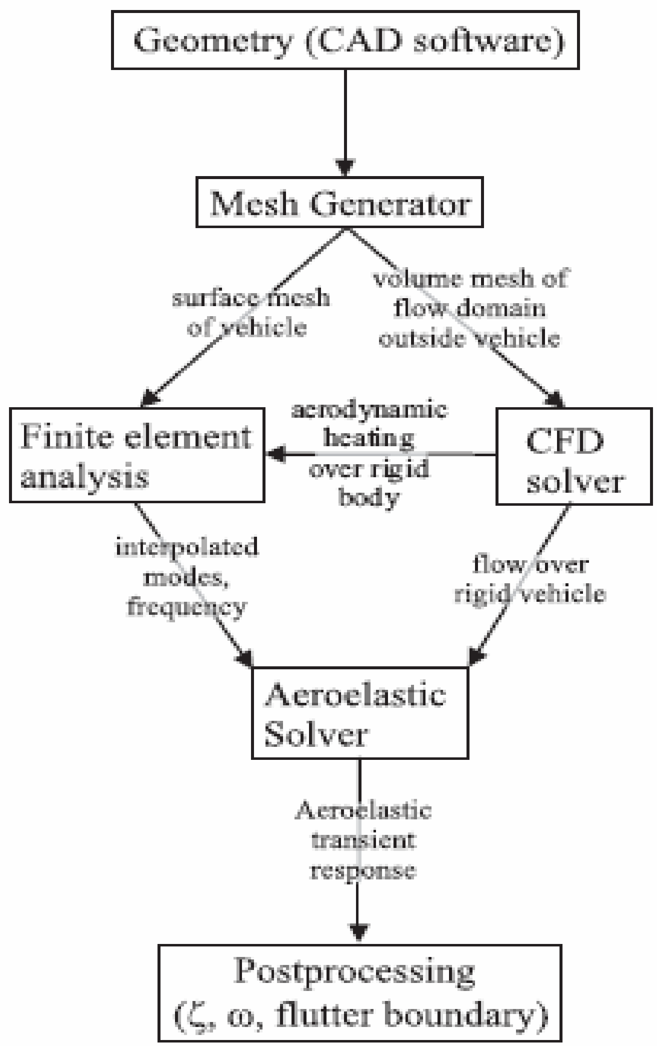
- Guiding principle: *represent the important physics that will drive the controllability of the HSV with the lowest number of states possible* (suitable for control studies)
- Approach: create *representative* low-order models for the thermo-structural dynamics, unsteady aerodynamics, engine dynamics, flight dynamics, and all their couplings from combination of:
  - (Direct) fundamental models
  - Reduced-Order Models (ROM) from high-fidelity models

and then assess the validity of the models

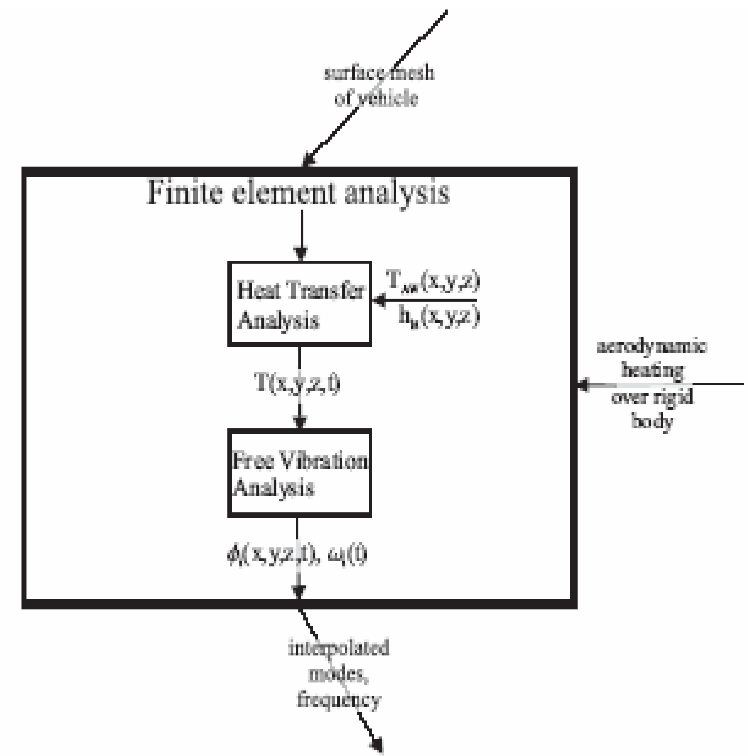
(High-fidelity) Reference Models

- High-fidelity computational models will be used to:
  - create the “truth” model for accuracy assessment of the control models
  - serve the basis for creating ROMs directly from its results
- Approach: codes (and models when available) will be used for this study and no code development effort is expected
  - MSC.Nastran for thermo-structural dynamics
  - FUN3D for unsteady aerodynamics
  - VULCAN for engine dynamics

Example: High-fidelity Aerothermoelastic Model



(a) Aerothermoelastic Solution Procedure.



(b) Finite Element Analysis.

McNamara and Friedmann, 2006

Example: ROM based on Volterra Series

- Impulse response method for (linear or nonlinear) time-invariant systems
- Successfully applied as Aerodynamic Impulse Response method for different flight regimes and different codes, including CFL3D (Silva, 1997, 2007; Guendal and Cesnik, 2001)
- Core of the process is based on discrete system identification

ID'ed Kernels

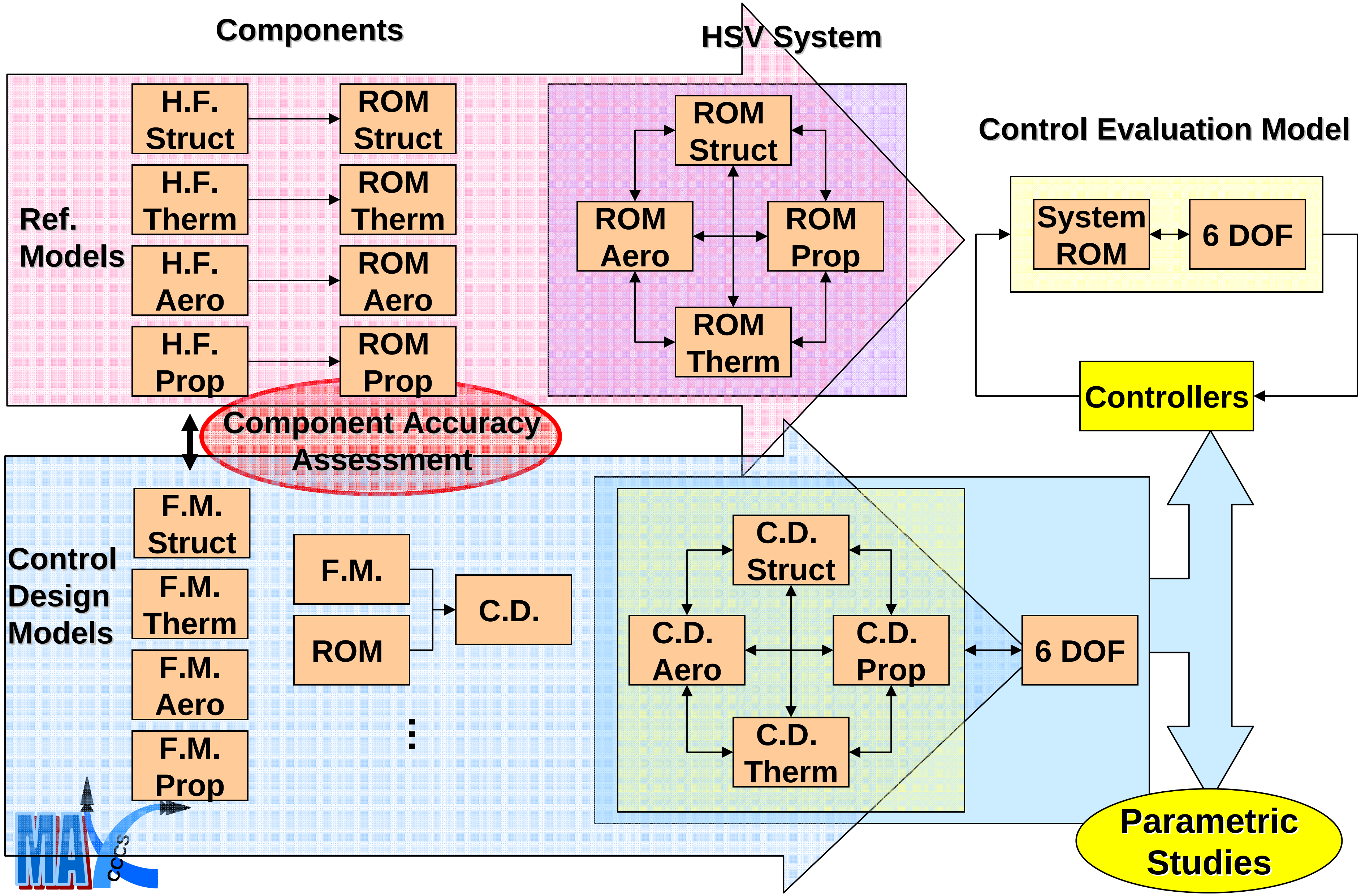
$$y(i) = h_0 + \sum_{k=0}^{N} h_1(k)\,u(i-k) + \sum_{k_1=0}^{N} \sum_{k_2=0}^{N} h_2(k_1,k_2)\,u(i-k_1)\,u(i-k_2)$$

response

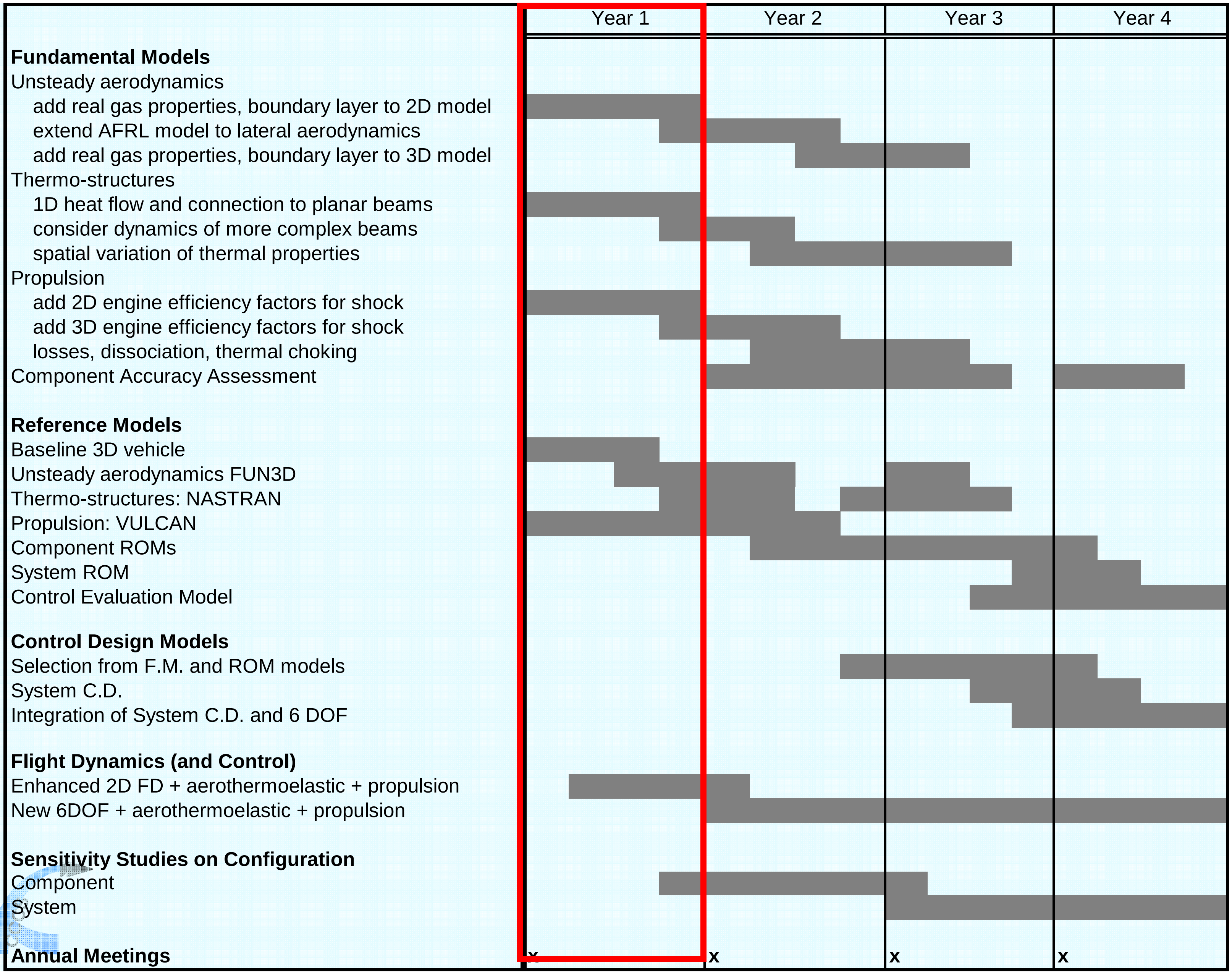
excitation

- Applicability to the other disciplines and to the combined coupled problem will be investigated

Proposed Modeling Approach



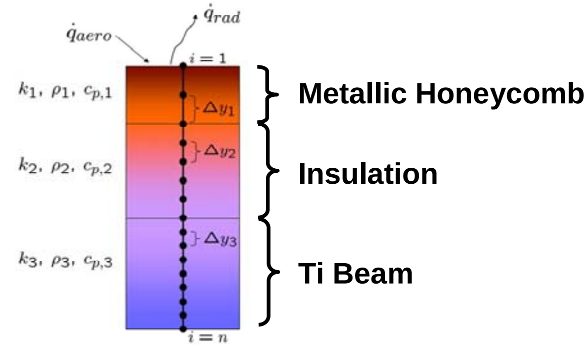
Schedule

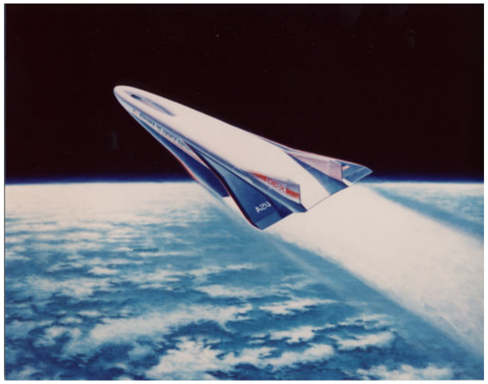


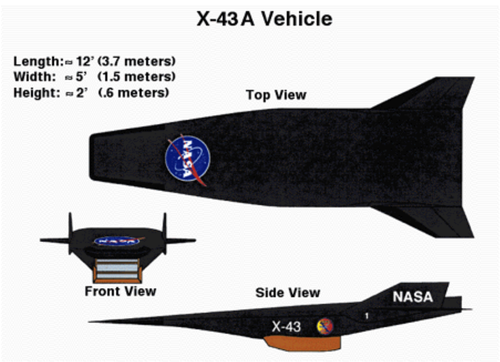
Year 1
Year 2
Year 3
Year 4
Fundamental Models
Unsteady aerodynamics
add real gas properties, boundary layer to 2D model
extend AFRL model to lateral aerodynamics
add real gas properties, boundary layer to 3D model
Thermo-structures
1D heat flow and connection to planar beams
consider dynamics of more complex beams
spatial variation of thermal properties
Propulsion
add 2D engine efficiency factors for shock
add 3D engine efficiency factors for shock
losses, dissociation, thermal choking
Component Accuracy Assessment
Reference Models
Baseline 3D vehicle
Unsteady aerodynamics FUN3D
Thermo-structures: NASTRAN
Propulsion: VULCAN
Component ROMs
System ROM
Control Evaluation Model
Control Design Models
Selection from F.M. and ROM models
System C.D.
Integration of System C.D. and 6 DOF
Flight Dynamics (and Control)
Enhanced 2D FD + aerothermoelastic + propulsion
New 6DOF + aerothermoelastic + propulsion
Sensitivity Studies on Configuration
Component
System
Annual Meetings
x
x
x
x

First Year Activities

- Fundamental model development
  - extend AFRL's piston theory-based aero model to include B.L.'s displacement thickness effects
  - model elevator-canard interaction (started over the summer, Skujins and Oppenheimer)
  - model 1D thermo-structural response to extract parameter corrections for HSV structure
  - add realistic efficiency factors to propulsion model
- Reference models
  - setup codes and input files for reference case
  - define fundamental information flow between components and define key I/O for ROM generation
  - create baseline structural layout for 1D thermo analysis
  - run 2-D propulsion model to identify critical issues
- Select baseline vehicle
  - stretched X-43A (to 100-ft length) with NASP-based interior structural layout (info needs to be accessible)



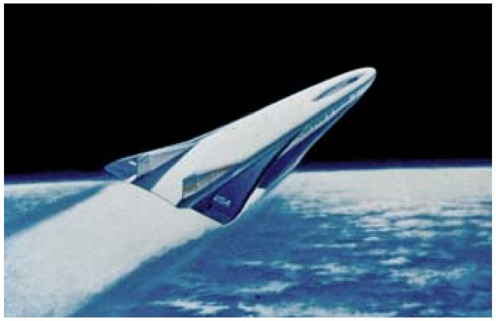




Initial Task Assignments

- Graduate students:
  - Torstens Skujins (MS/PhD): unsteady aerodynamics modeling (canard-elevon interaction, steady CFD coupled with piston theory, boundary layer effects) and flight dynamics
  - Nate Falkiewicz (MS/PhD): thermo-structural modeling (1D heat flow through the thickness and its connection with structural dynamics model parameters, FEM modeling of representative structure)
  - Nate Scholten (MS): High-fidelity aerodynamics and propulsion modeling
  - Sean Torrez (MS/PhD): propulsion modeling (1D efficiency factor corrections, engine cycle code reference modeling)
  - TBD: Aerothermoelastic ROM generation and system integration for controls applications
- Post-doctoral fellow (TBD):
  - Baseline 3D vehicle definition
  - H.F. code and input setup

Concluding Remarks



- Highly coupled multidisciplinary problem modeling effort for control design and simulation
- Several specific challenges lay ahead—group is highly motivated and bring disciplinary expertise and prior experience in similar issues
- Good start with student summer activity (Torstens Skujins) at AFRL—more is expected in the following summers
- Initial activities will focus on extending current 2D AFRL models for potentially important effects
- New initiatives in high-fidelity modeling will provide reference cases for error assessment and initial validation of the models