Hypersonic Project
Guidance Navigation & Controls

Associate Principal Investigator

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Outline

- GNC Overview
  - Objectives
  - Focus
  - Road Map
- GNC integration with Vehicle Optimization
  - Motivation
  - Modeling and Analysis Tools
- Advanced Control Design
- Mode Transition (Turbine to ram/scramjet)
- TBCC inlet control design
  - Interactive Simulator
  - Wind tunnel test validation

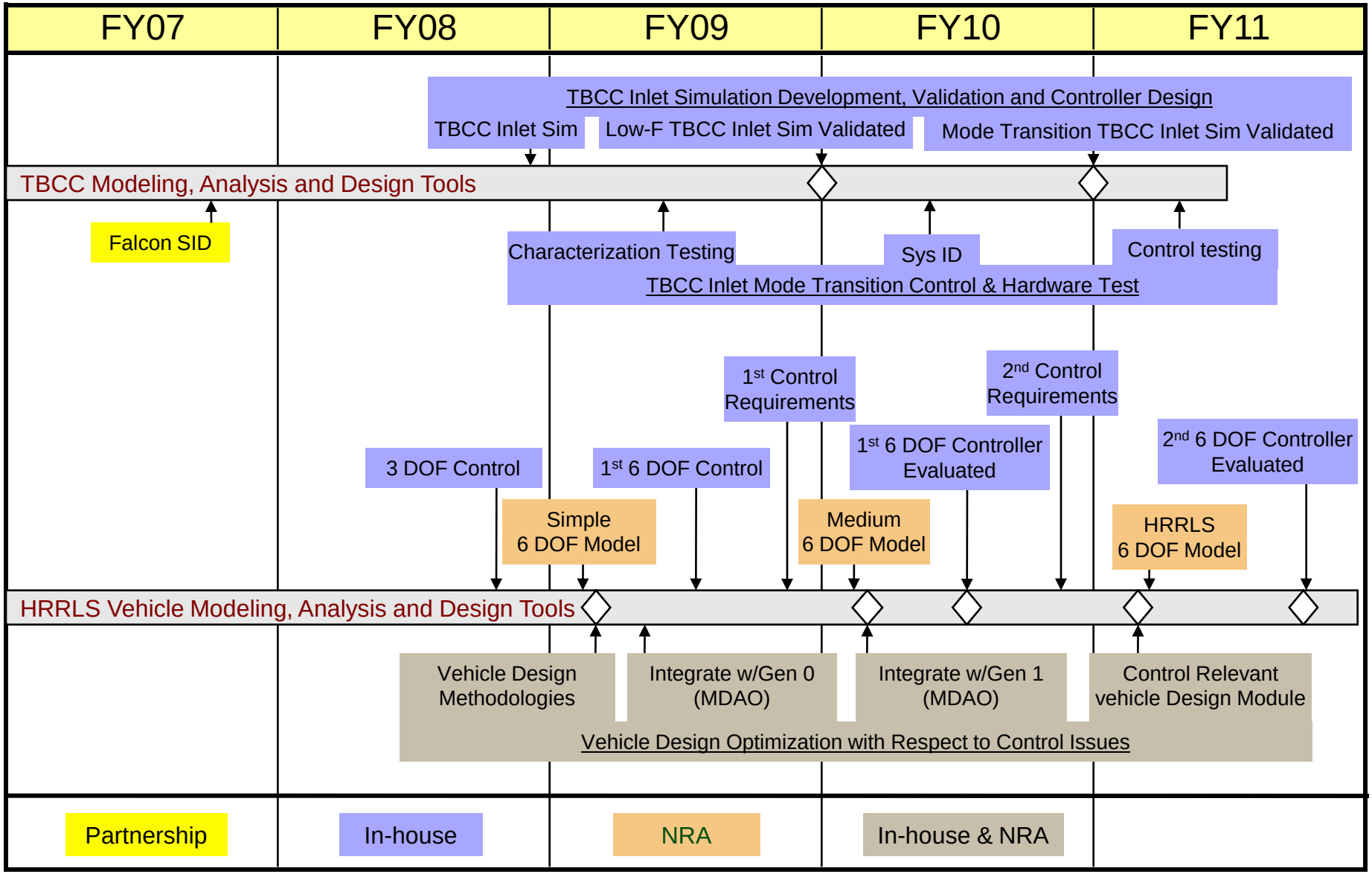
GNC Discipline Objective

- Develop models, analysis tools and design methodologies to enable the design of Highly Reliable Reusable Launch Systems (HRRLS)
  - which offer **robust dynamic performance** in the presence of **significant uncertainty**
  - by utilizing state-of-the-art control algorithms to coordinate available control actuators.
- Integrate control analysis and design tools into the overall vehicle conceptual design process.
  - Incorporate control system objectives (e.g. performance, robustness)
  - Utilize the NASA HRRLS TSTO (two-stage-to-orbit) reference vehicle as a test case.

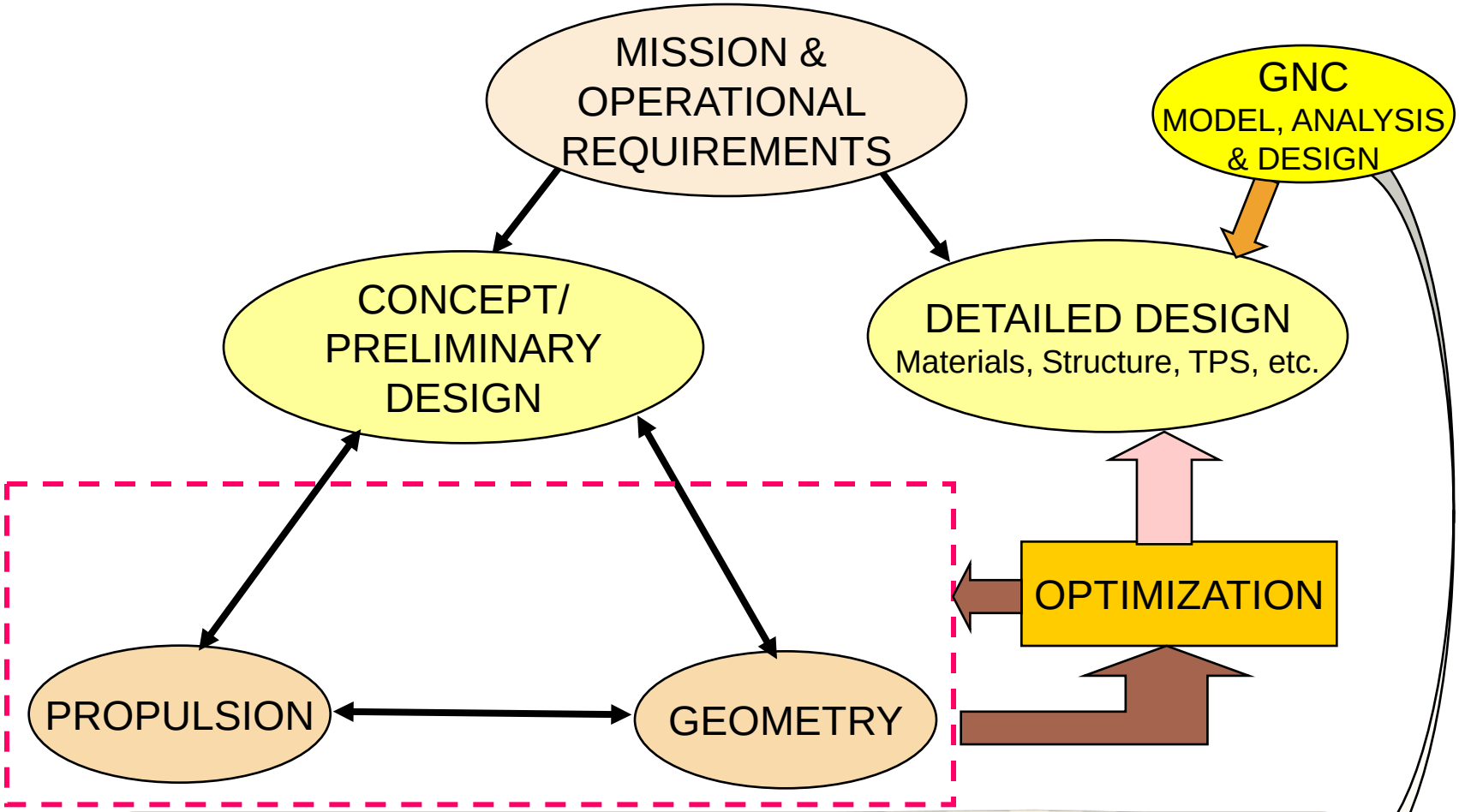
Hypersonic GNC Focus

- **Modeling**:
  - Develop adequate fidelity **6-DOF engineering models** for conceptual design that allow identification of critical control issues such as:
    - **Mode transition** from low-speed (turbine engine) to high speed (ram/scramjet) propulsion systems
    - Airframe-propulsion interactions
    - Aero-thermo-elastic interactions
    - Longitudinal-Lateral coupling in the presence of the above
- **Analysis:**
  - Determine **fundamental limitations** of vehicle dynamics to develop realistic control design criteria, such as,
    - Minimum time to double (how unstable is the vehicle)
    - Required **bandwidth** for command following
    - Required **control authority** for command following and disturbance attenuation
    - Minimum frequency for the first structural mode
- **Design**:
  - Control design
    - Robust dynamic performance in the presence of significant uncertainty
  - Vehicle Optimization
    - Impact conceptual vehicle design to minimize costly fixes later in design cycle.

GNC Road Map

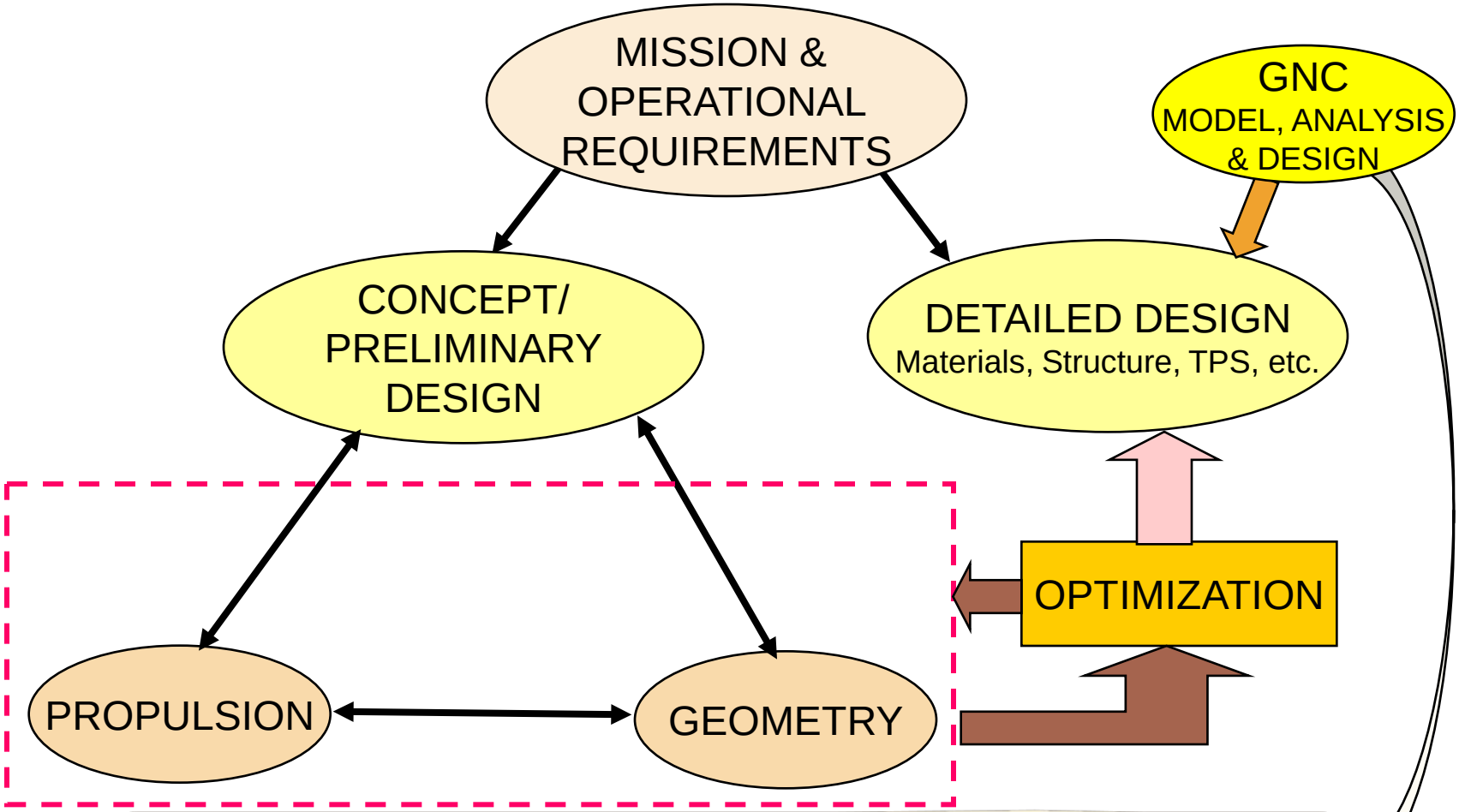

FY07
FY08
FY09
FY10
FY11
TBCC Inlet Simulation Development, Validation and Controller Design
TBCC Inlet Sim
Low-F TBCC Inlet Sim Validated
Mode Transition TBCC Inlet Sim Validated
TBCC Modeling, Analysis and Design Tools
Falcon SID
Characterization Testing
Sys ID
Control testing
TBCC Inlet Mode Transition Control & Hardware Test
1st Control Requirements
2nd Control Requirements
3 DOF Control
1st 6 DOF Control
1st 6 DOF Controller Evaluated
2nd 6 DOF Controller Evaluated
Simple 6 DOF Model
Medium 6 DOF Model
HRRLS 6 DOF Model
HRRLS Vehicle Modeling, Analysis and Design Tools
Vehicle Design Methodologies
Integrate w/Gen 0 (MDAO)
Integrate w/Gen 1 (MDAO)
Control Relevant vehicle Design Module
Vehicle Design Optimization with Respect to Control Issues
Partnership
In-house
NRA
In-house & NRA

Typical MDAO Process



Can the vehicle be stabilized?
Is there sufficient control authority/bandwidth to meet mission requirements?
Is there sufficient control authority to mitigate disturbances and uncertainties?
What is the minimum frequency the first structural mode can be?
What is the minimum sampling rate for the control system?

Typical MDAO Process



Can the vehicle be stabilized?

Is there … equirements?

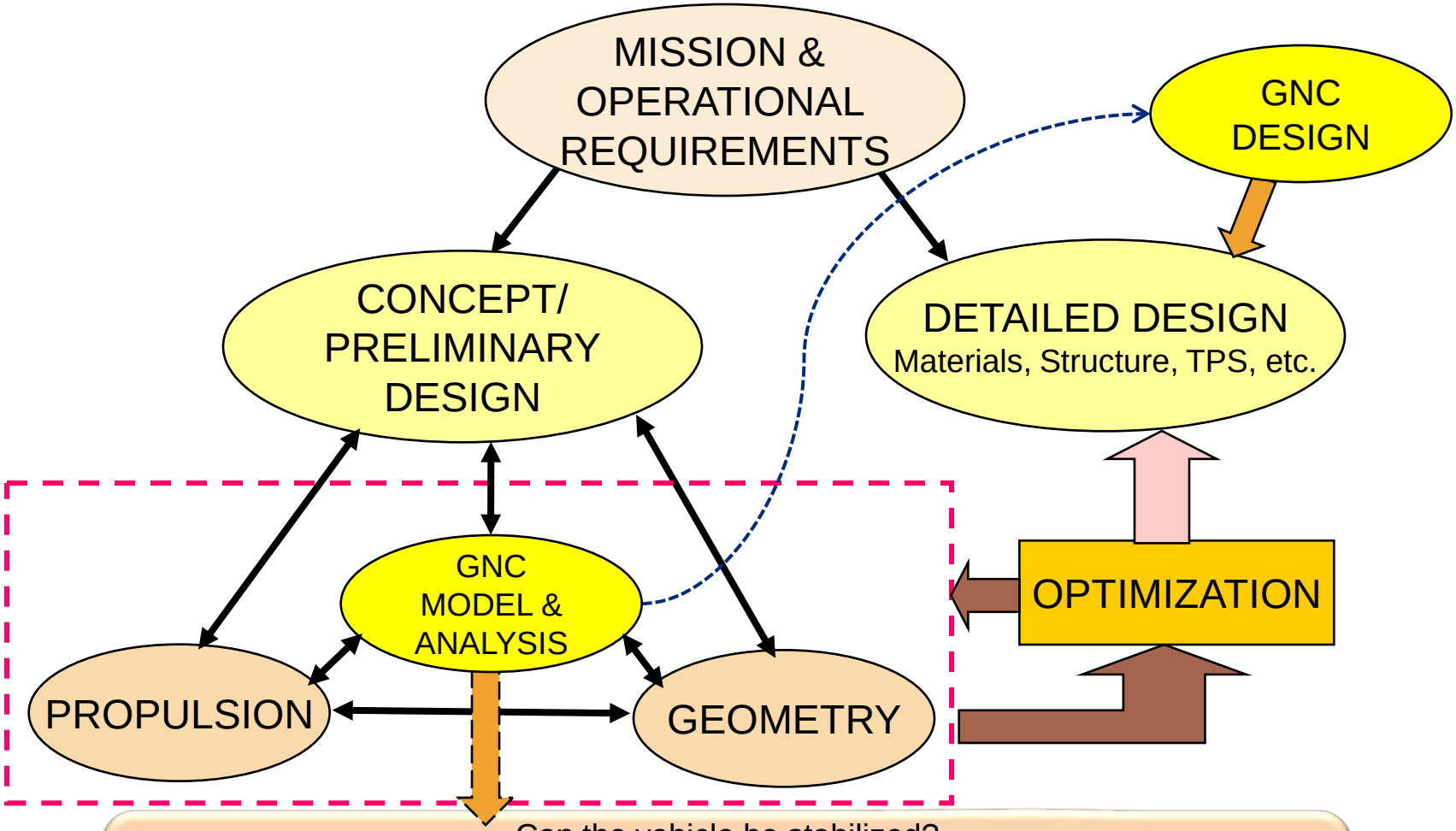
Is there … uncertainties?

W … an be?

What is the minimum sampling rate for the control system?

If we wait until the vehicle is designed, it may be to late to deal with negative answers to the control issue questions.

Role of GNC in MDAO Process



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Vehicle Modeling

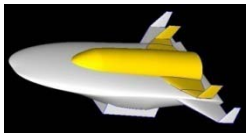
OBJECTIVES:

- **Develop adequate fidelity models for controller design and evaluation.**
- **Integrate control analysis and design tools into the vehicle conceptual design process.**

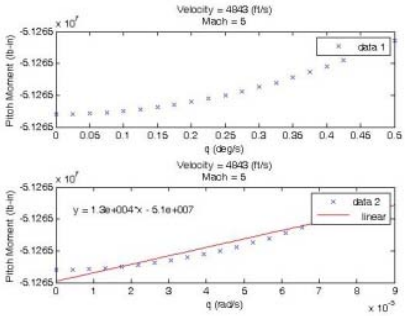
APPROACH:

- **Develop an environment to generate simplified integrated dynamic model of an air-breathing hypersonic vehicle.**
- **Develop control analysis tools to answer critical design questions.**
- **Validate against X43A flight data.**

Given a Geometry



Modeling Environment

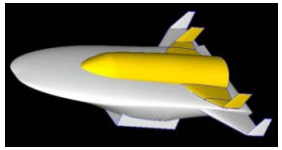


Control Design and
Control Evaluation
Dynamic Model

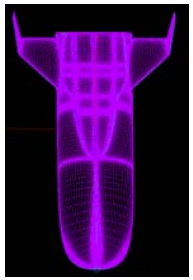
Can the vehicle be stabilized?
Is there sufficient control authority/bandwidth to meet mission requirements?
Is there sufficient control authority to mitigate disturbances and uncertainties?
What is the minimum frequency the first structural mode can be?
What is the minimum sampling rate for the control system?

Vehicle Modeling, Analysis and Control Design

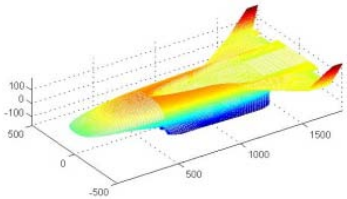
Given Geometry



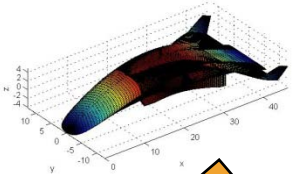
Mesh



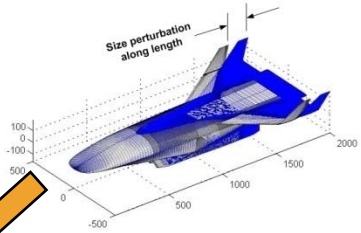
Add Surfaces



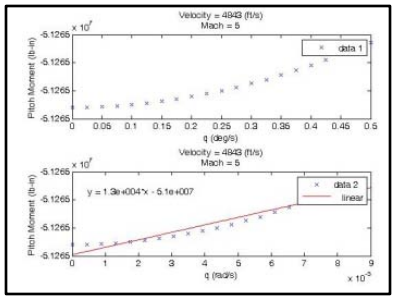
Modal Analysis



Perturb Model



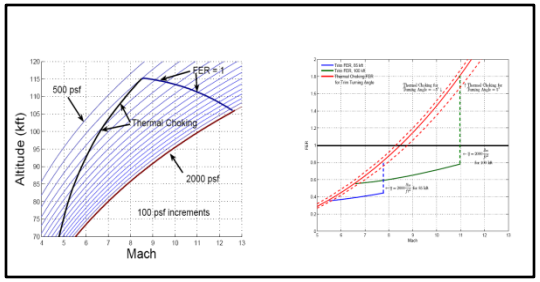
Validate Modeling Tool with X43A Flight Data



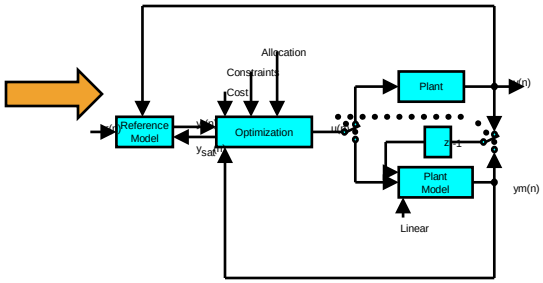
Generate:

Control Design and Evaluation Models

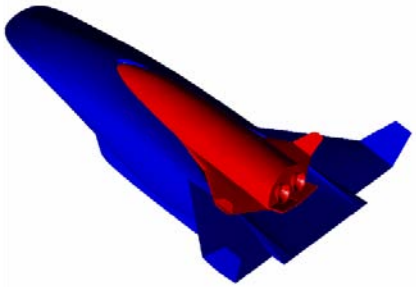
Sensitivity Data Base



Control Analysis



Controller Design



Feedback to Vehicle Design Process

Vehicle Modeling, Analysis and Control Design

- Tool suite aims at developing models with **6-DOF fully coupled longitudinal-lateral dynamics** to improve fidelity by capturing effects of coupled dynamics.
  - E.g. non-zero sideslip can affect pressure distribution on forebody, mass flow at engine inlet leading to change in engine performance at inlet and exhaust, and associated control requirements.
- Critical aspect in model development is to **balance fidelity with computational efficiency**.
- Main Idea - develop models with **adequate fidelity** to answer key questions:
  - what are **stability properties** of design in question?
  - which **parameters impact stability margins** most and by what amount?
  - how much **structural flexibility** can be tolerated?
  - what is **controller bandwidth** and is it sufficient to meet mission control objectives?
  - etc.
- Answers will **impact conceptual vehicle design** to **minimize costly fixes** later in design cycle!

Model types and Control Analysis

- **Types of models** to be generated:
  - Nonlinear Analytical, Linear Analytical
  - Nonlinear Hybrid, Linear Hybrid
  - Nonlinear and Linear Computational

- **Analytical models will be generated** (via symbolic solvers) for user-selected number of panels.
  - See functional relationship between different system parameters
  - Analytical models come at a price: some fidelity must be sacrificed

- Purely **computational (trajectory based) models will consist of force-moment databases** for a series of flight conditions.

- **Control analysis**:
  - conduct parametric equilibrium and dynamic trade studies
    - Interested in how
      - Trim values (L/D, static margins)
      - Stability
      - Frequency responses
      - Etc.

    depend on altitude, mach number, dynamic pressure, mass, cg location, flexibility, control effectors size/location, etc.

- **"Control-Relevant Modeling of Hypersonic Vehicles" – Submitted ACC 2009**

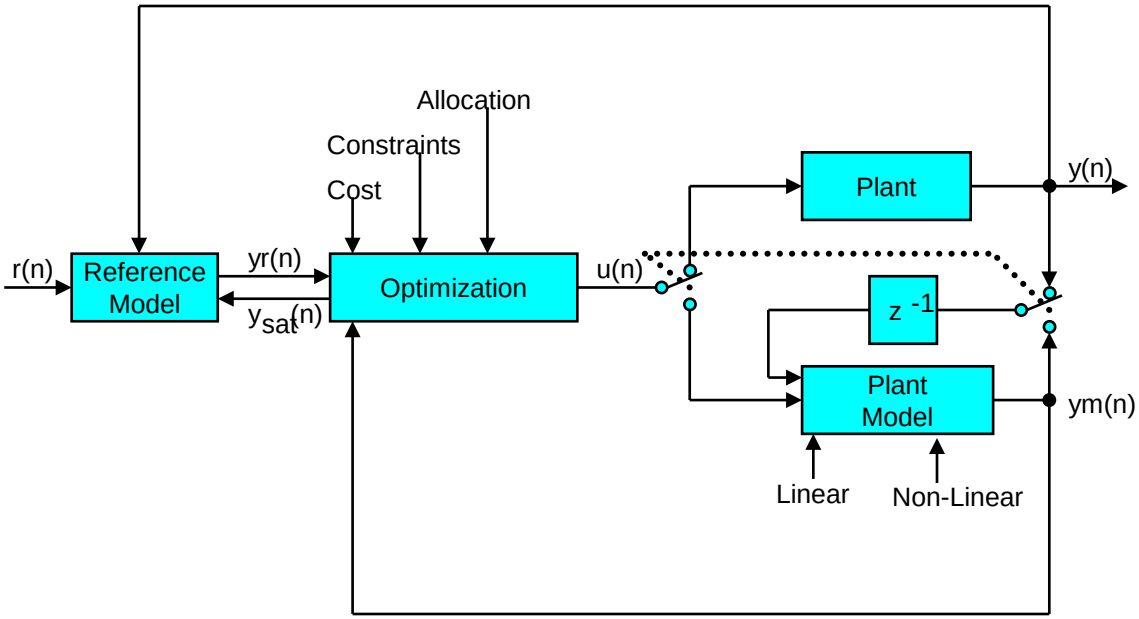
Advanced Control Design
Modified Generalized Predictive Control

OBJECTIVE:

Develop advanced robust control laws for a HRRLS vehicle over a large flight envelop in presence of significant uncertainty.

APPROACH:

Implement and evaluate suite of controllers on simple 3-DOF, 6-DOF, and HRRLS models.

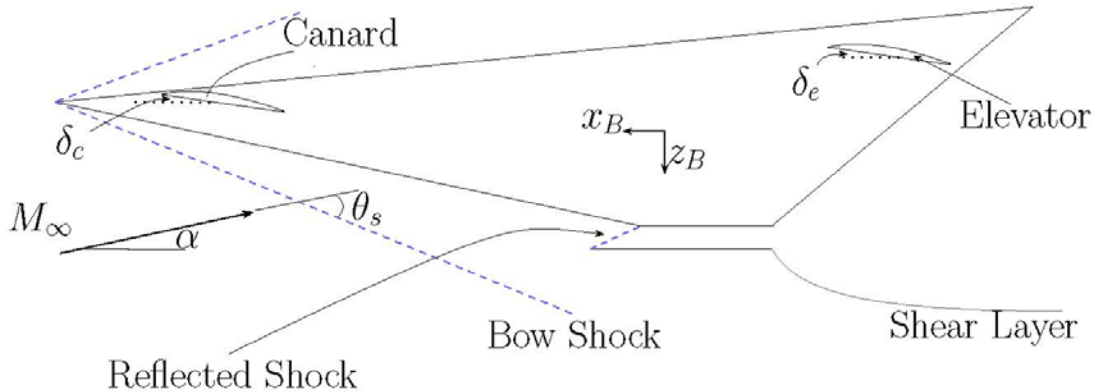


Modified Generalized Predictive Control Features:

- **Control non-minimum phase plants**
- Highly robust to modeling errors
- **Handles constraints**
- Control Reconfiguration
- Predictor model can be
  - **Linear**
  - Non-linear
  - Adaptive

AFRL Hypersonic Vehicle Model

Bolender et al (2004-2007)



Longitudinal Equations of Motion

$$\dot{V}_t = \frac{T\cos\alpha - D}{m} - g\sin(\theta - \alpha)$$

$$\dot{\alpha} = \frac{-L - T\sin\alpha}{mV_t} + Q + \frac{g}{V_t}\cos(\theta - \alpha)$$

$$\dot{Q} = \frac{M}{I_{yy}}$$

$$\dot{\theta} = Q$$

$$\dot{h} = V_t\sin(\theta - \alpha)$$

$$\ddot{\eta}_i = -2\zeta_i\omega_i\dot{\eta}_i - \omega_i^2\eta_i + N_i,\ i = 1, \ldots, n$$

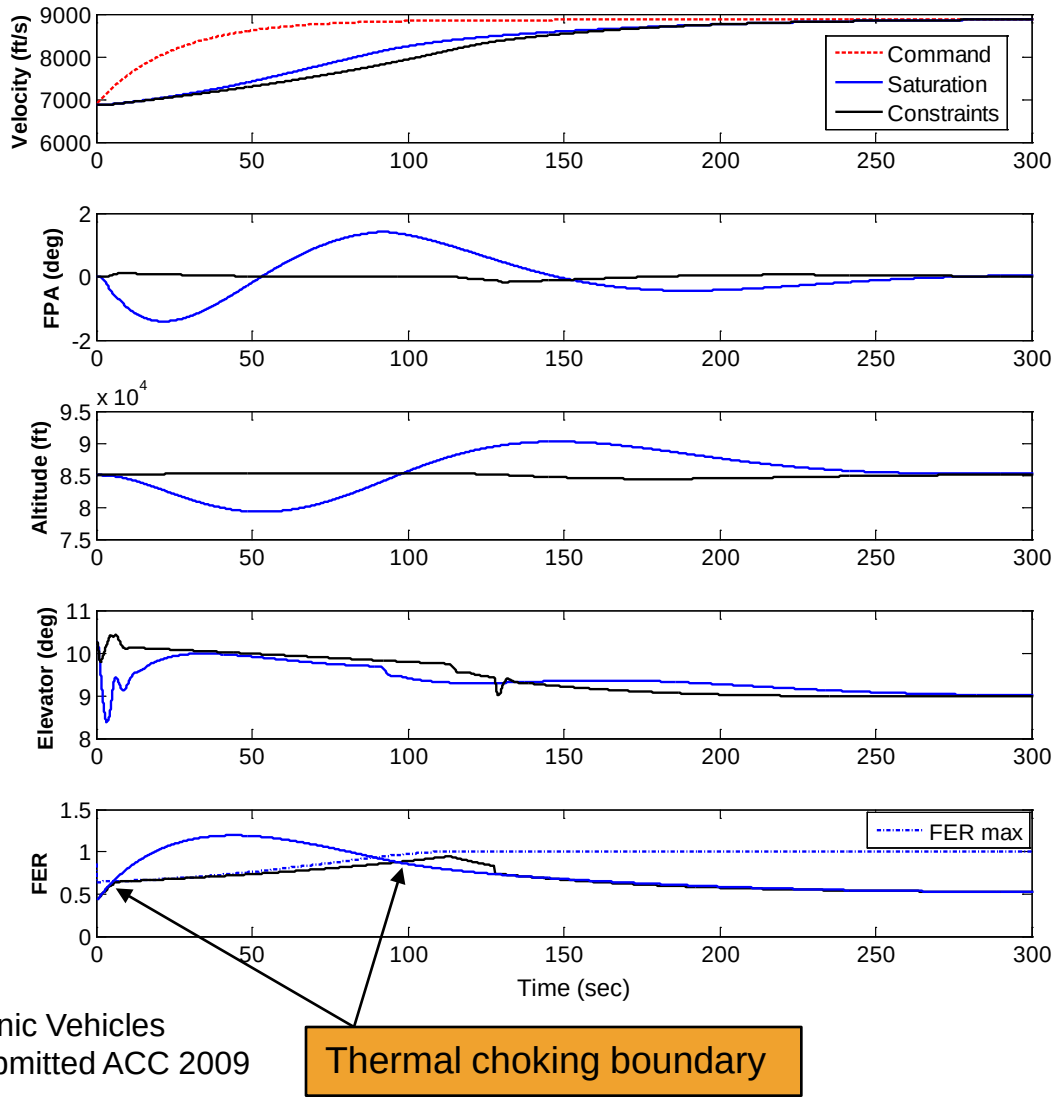
States		Controls	
V_t	Horizontal Velocity (ft/s)	δ_e	Elevator angle (deg)
α	Angle of Attack (deg)	δ_c	Canard angle (deg)
Q	Pitch rate (deg/sec)	Φ	Fuel Equivalence Ratio
h	Altitude (ft)		
Θ	Pitch Angle (deg)		
η	Generalized modal coordinate		
η_{dot}	Generalized modal coordinate velocity		

MGPC Control of a Hypersonic Vehicle with Dynamic Constraints on FER

- Controller Designs
  - Thermal Choking Boundary
    - Dynamic constraints or
    - Saturation
  - Decoupled control
  - Prediction Horizon 1 second
  - Control Horizon 0.08 seconds
  - Linearized model
    - 85000 ft
    - 7000 ft/sec
    - Level steady flight
    - Discretized at 0.02 seconds

- Fuel Equivalence Ratio (FER) maximum has upper bound that is min of 1 and thermal choking boundary for maximum efficiency

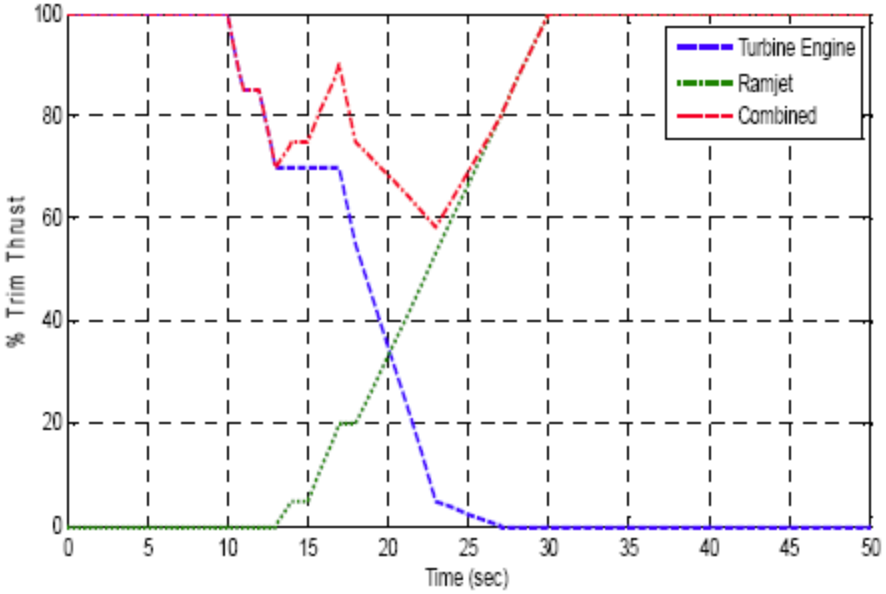
Response to velocity command of 2000 ft/sec

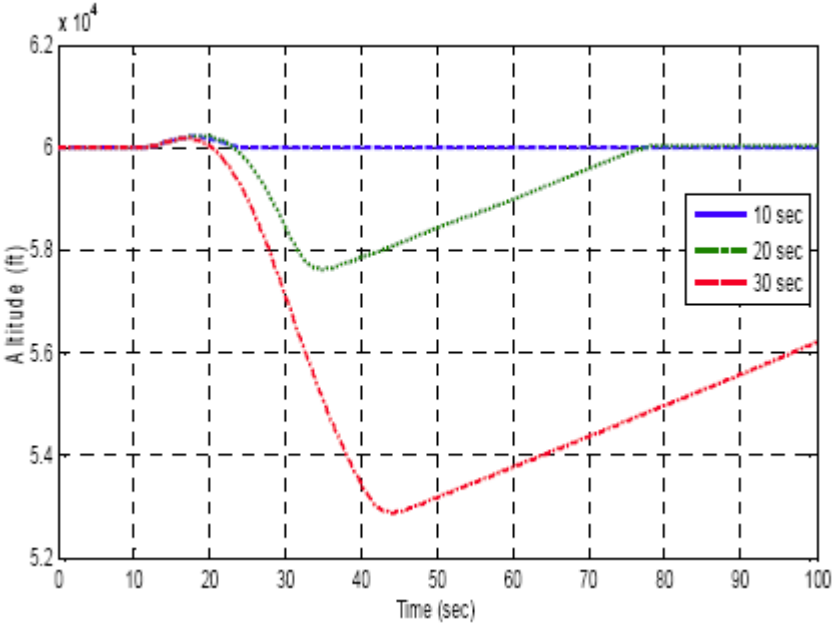


"Constraint Enforcement for Scramjet-Powered Hypersonic Vehicles with Significant Aero-Elastic-Propulsion Interactions" Submitted ACC 2009

Mode Transition

- **Why?**
  - **Turbine Based Combined Cycle (TBCC) systems are a means to accelerate a reusable hypersonic vehicle from takeoff to staging and return to land**
- **What?**
  - **The transition from a low-speed system (turbine engine) to a high-speed system (ram/scramjet)**
- **When?**
  - **Between Mach 3 and 4**
  - **Significant design consequences to transition MN**
- **What's the problem?**
  - **Need seamless transition of propulsive forces/moments**
  - **Both turbine engine and ram/scramjet will be operating at their operability margins**
  - **Common inlet**
  - **Upsets could be catastrophic!!**





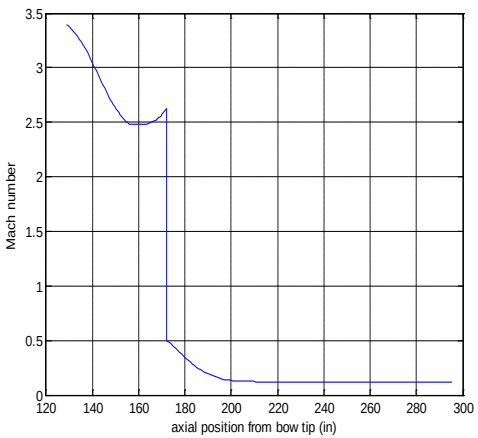
TBCC Inlet Control Simulator

OBJECTIVE:

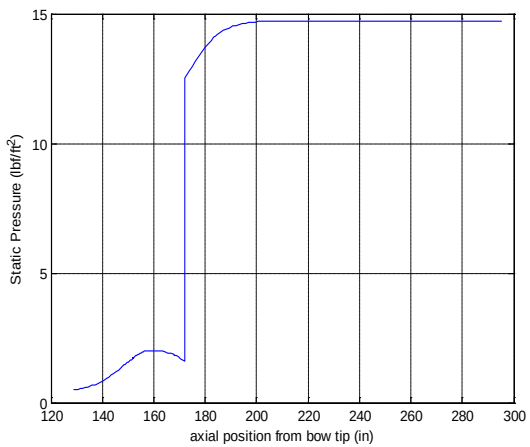
Design and develop tools and procedures that lead to controllers for hypersonic vehicle propulsion systems.

APPROACH:

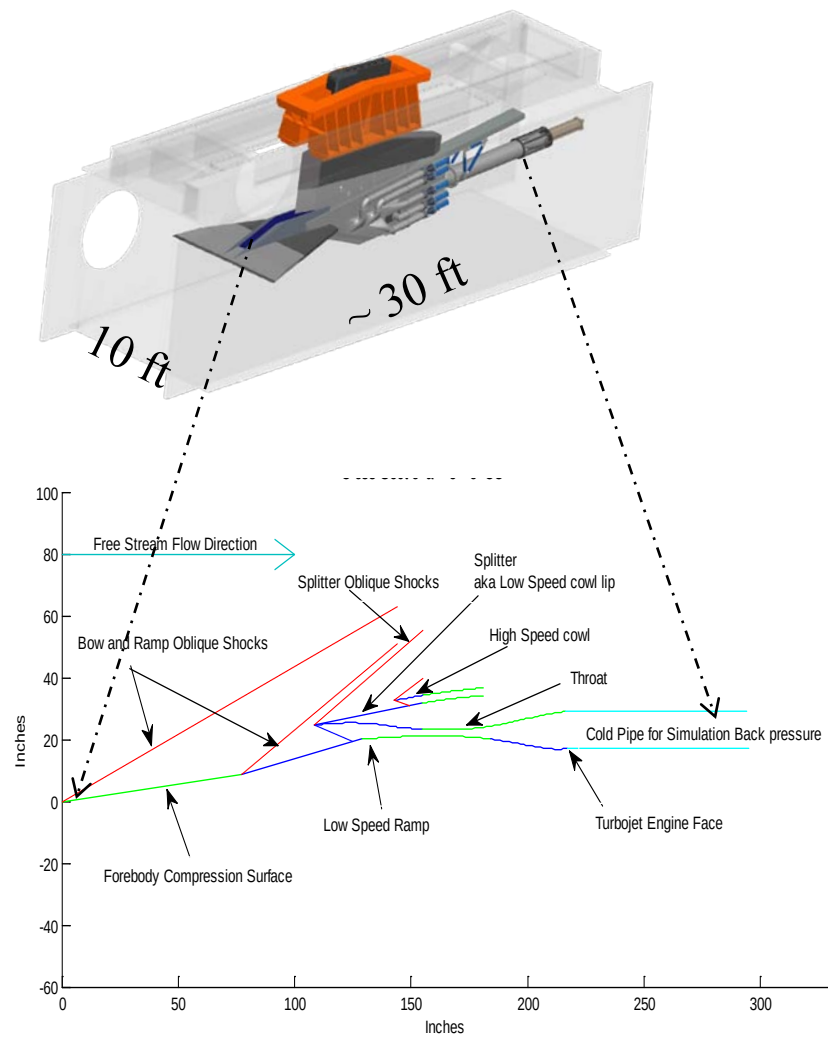
- **Develop a simplified integrated dynamic analytical model of an air-breathing hypersonic propulsion system.**
- **Modeling activity leverages the ability of LAPIN, MOC, and generic representations of aero-servo interactions.**
- **Validate against CFD and experimental data.**



Axial Mach Number

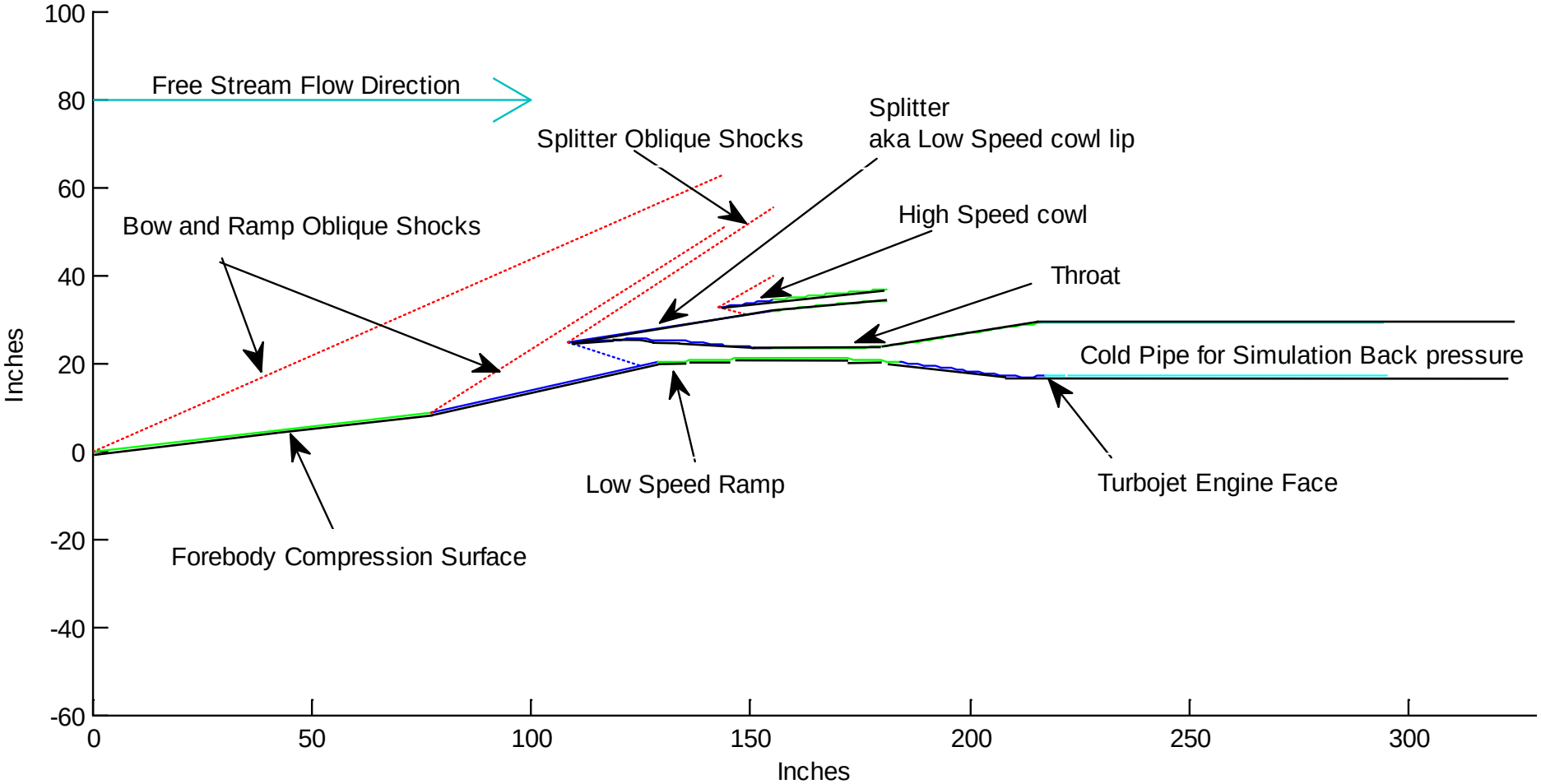


Static Pressure



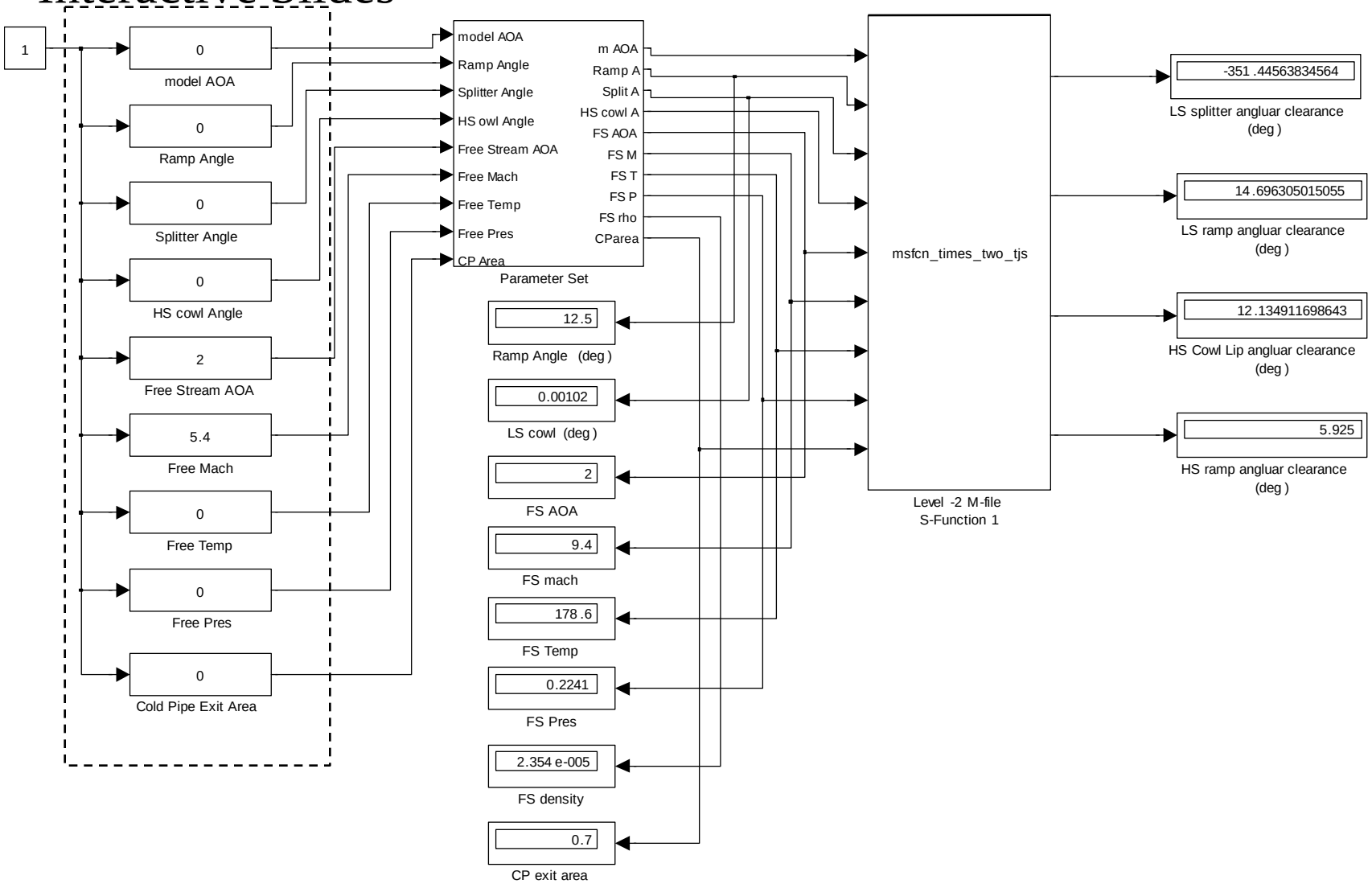
Interactive TBCC Simulator

Interactive TBCC Simulator



Simulink Block Diagram of Interactive Simulator

Interactive Slides



Simulink Block Diagram of Interactive Simulator

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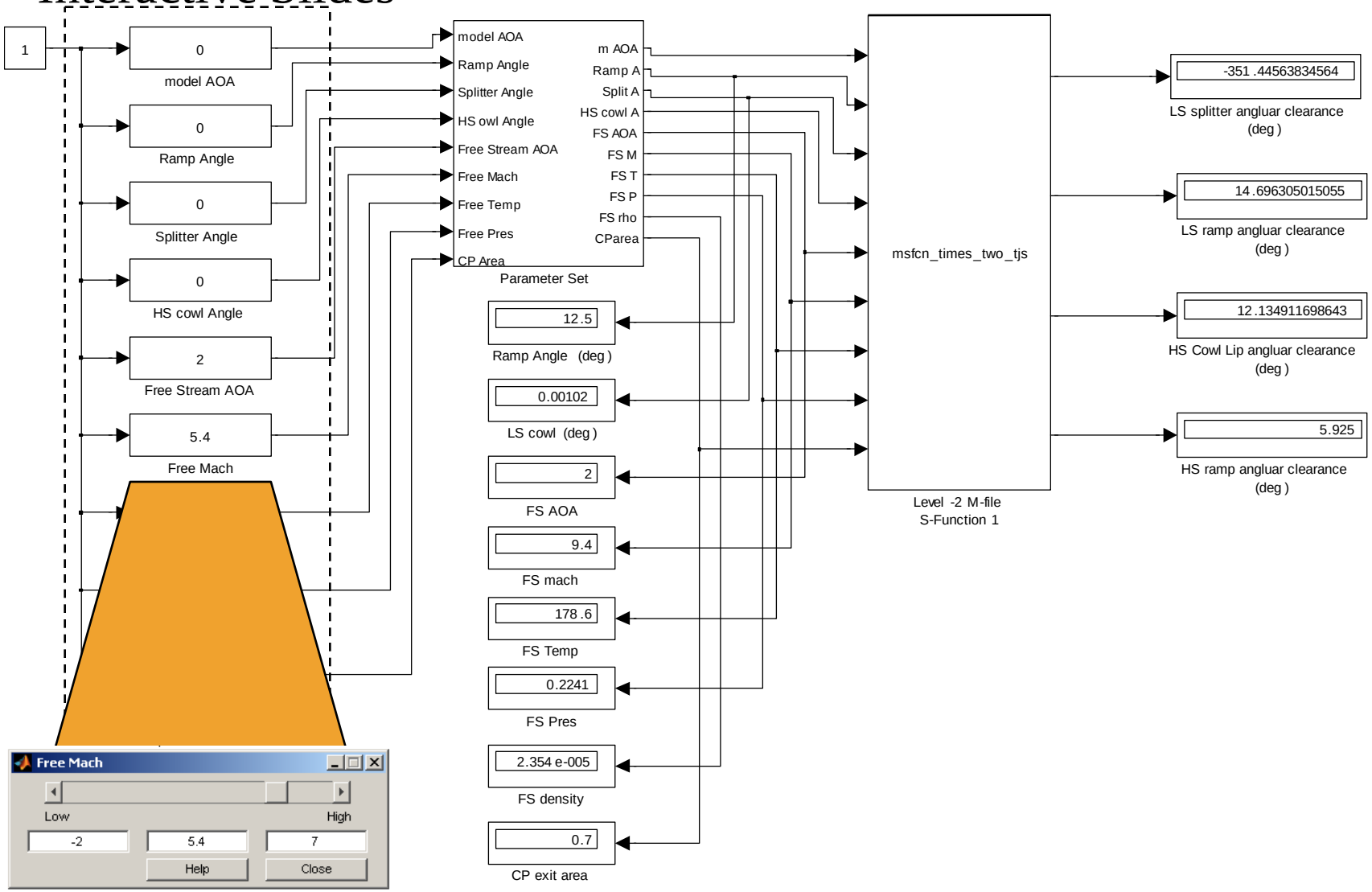

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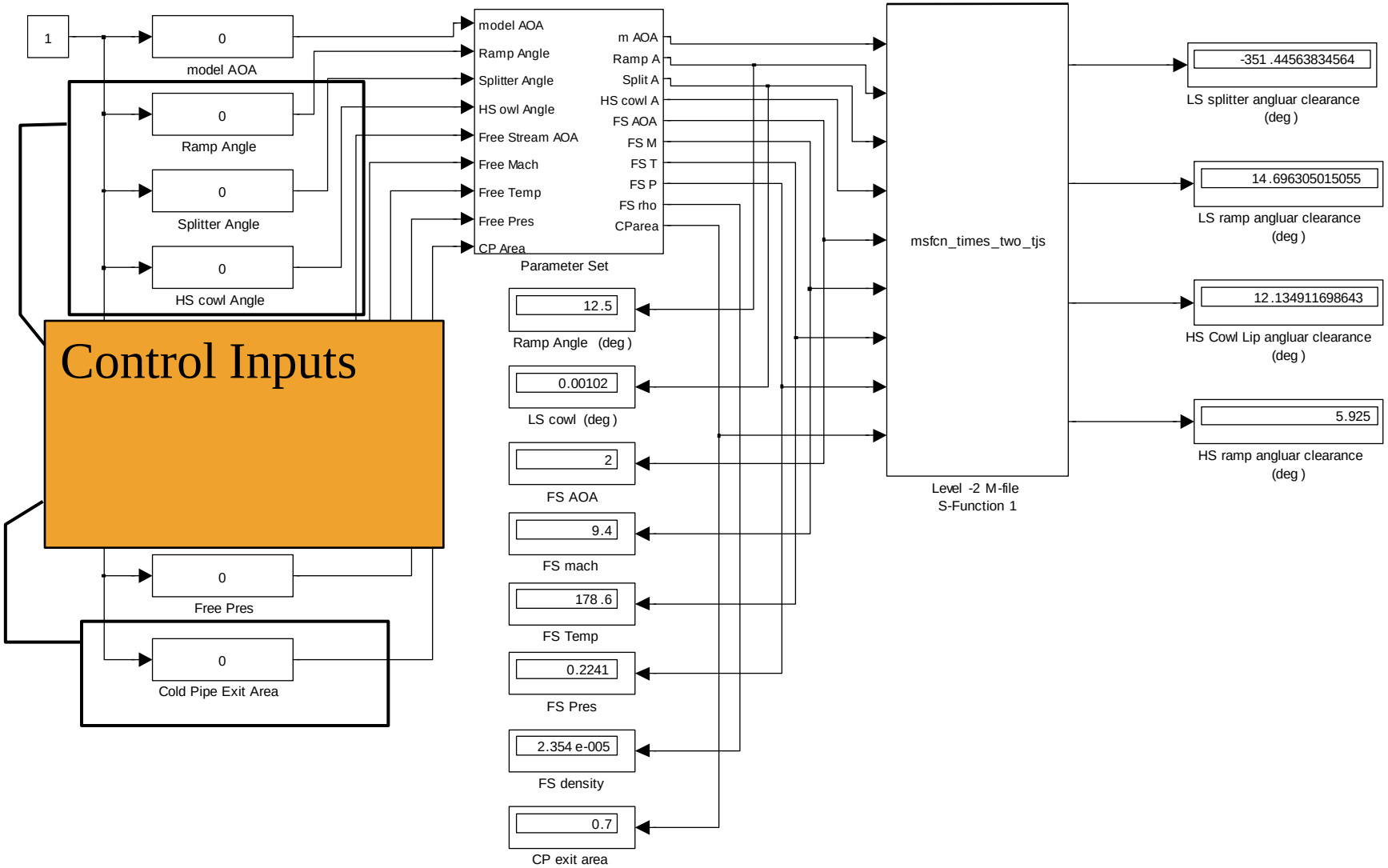

Test Schedule

- Parametric Inlet Characterization Testing (April 2009):
  - Bleed vs Pressure recovery trades,
  - Bleed vs Engine inlet distortion trades,
  - Inlet unstart and recovery,
  - Inlet Mode Transition,
  - CFD assessment to predict above.

- System Identification (3 weeks in FY10):
  - Extract mathematical models describing a linear relationship between actuator movement and static pressure measurements.

- Control testing (3 weeks in FY11), and
  - Test advanced control concepts on the inlet system configured with a cold pipe that simulates a turbine engine.
  - Demonstrate normal shock control
  - Demonstrate a controlled transition from one flow path to the other
- Inlet, Turbine Engine, and Nozzle Integration (6 weeks in FY11 and FY12).
  - Demonstrate an advanced controller for the propulsion system
  - Demonstrate normal shock control
  - Demonstrate a controlled transition from one flow path to the other

Summary

- Developed a program to impact conceptual vehicle design to minimize costly fixes later in design cycle.
- Investigating Mode transition issues and trade offs.
- Validating approaches with experimental data.