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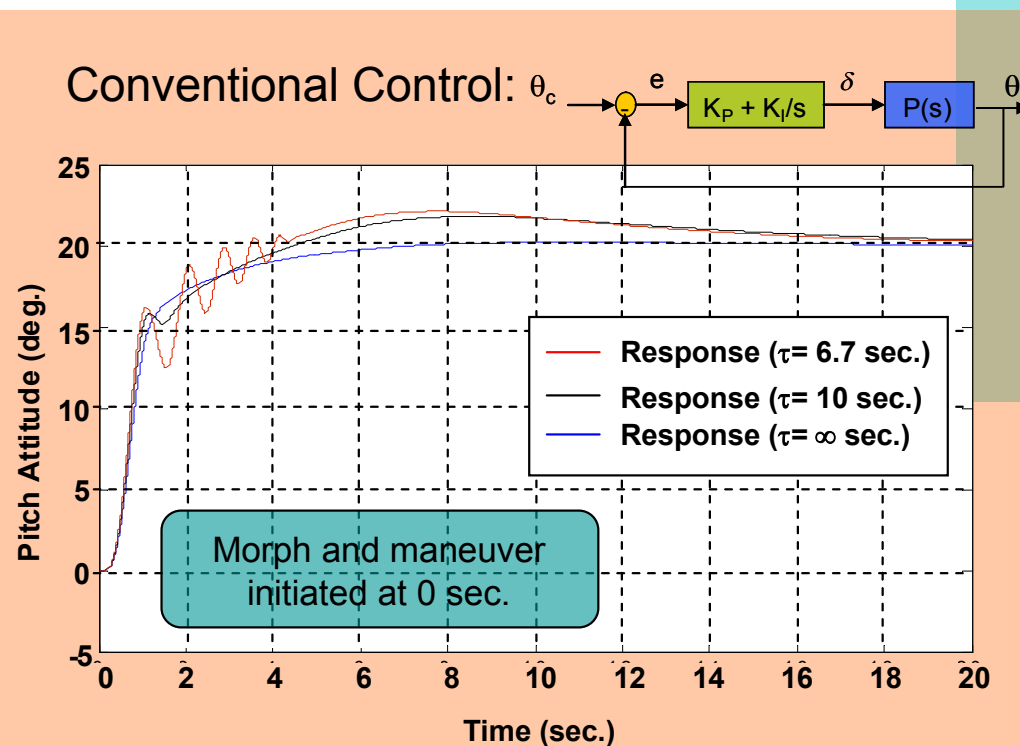
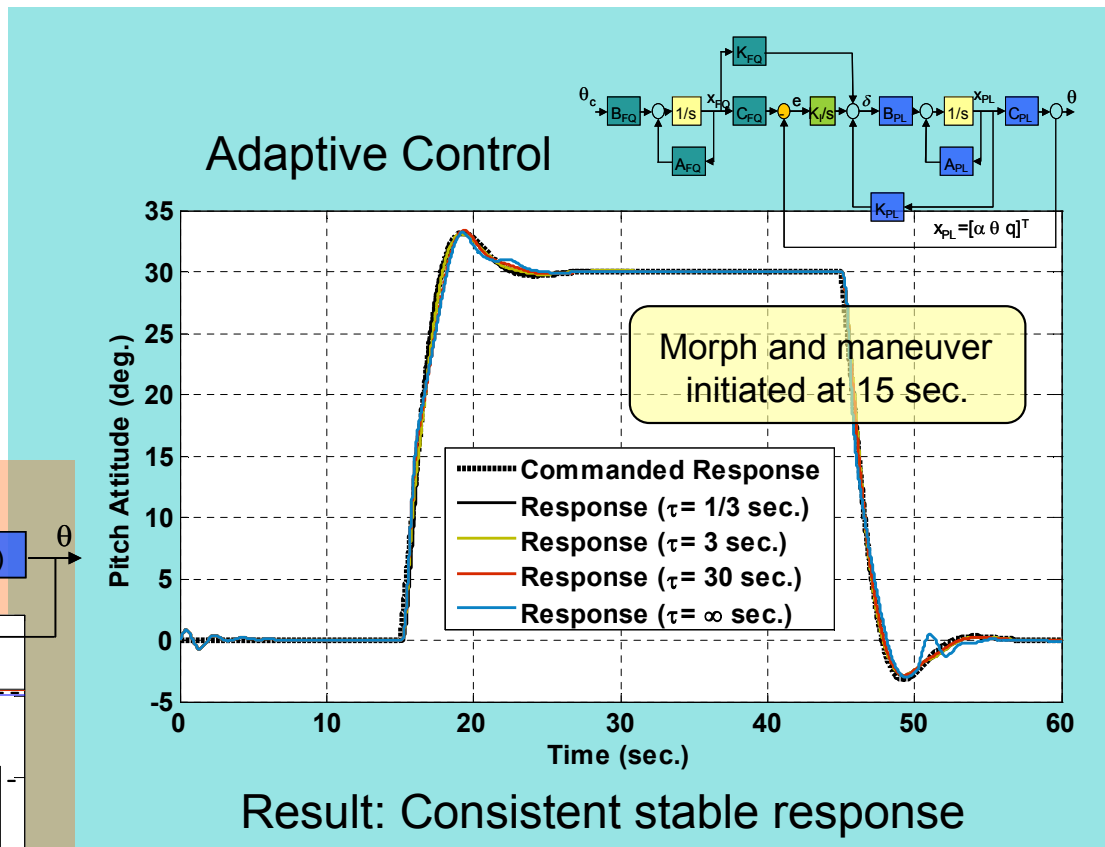
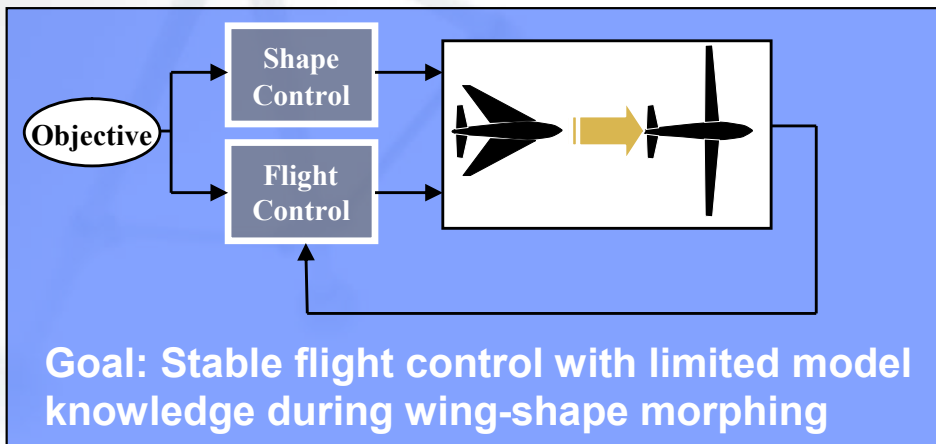
# Barron Associates, Inc. Selected Current Research

SAE International  
Aerospace Control & Guidance Systems Committee

Boulder, Co  
Feb 28, 2007

David G. Ward  
(434) 973-1215  
[ward@barron-associates.com](mailto:ward@barron-associates.com)

# Adaptive Control of Morphing Aircraft



## AF SBIR Phase II

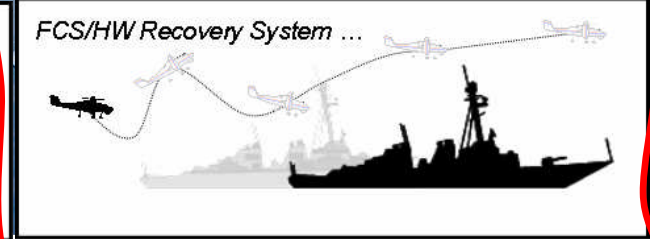
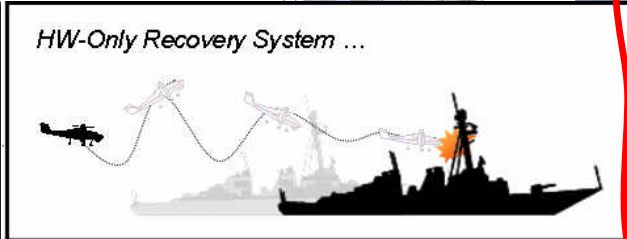
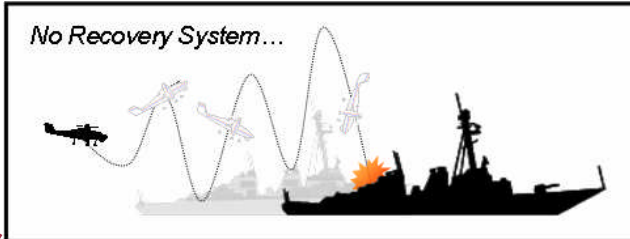
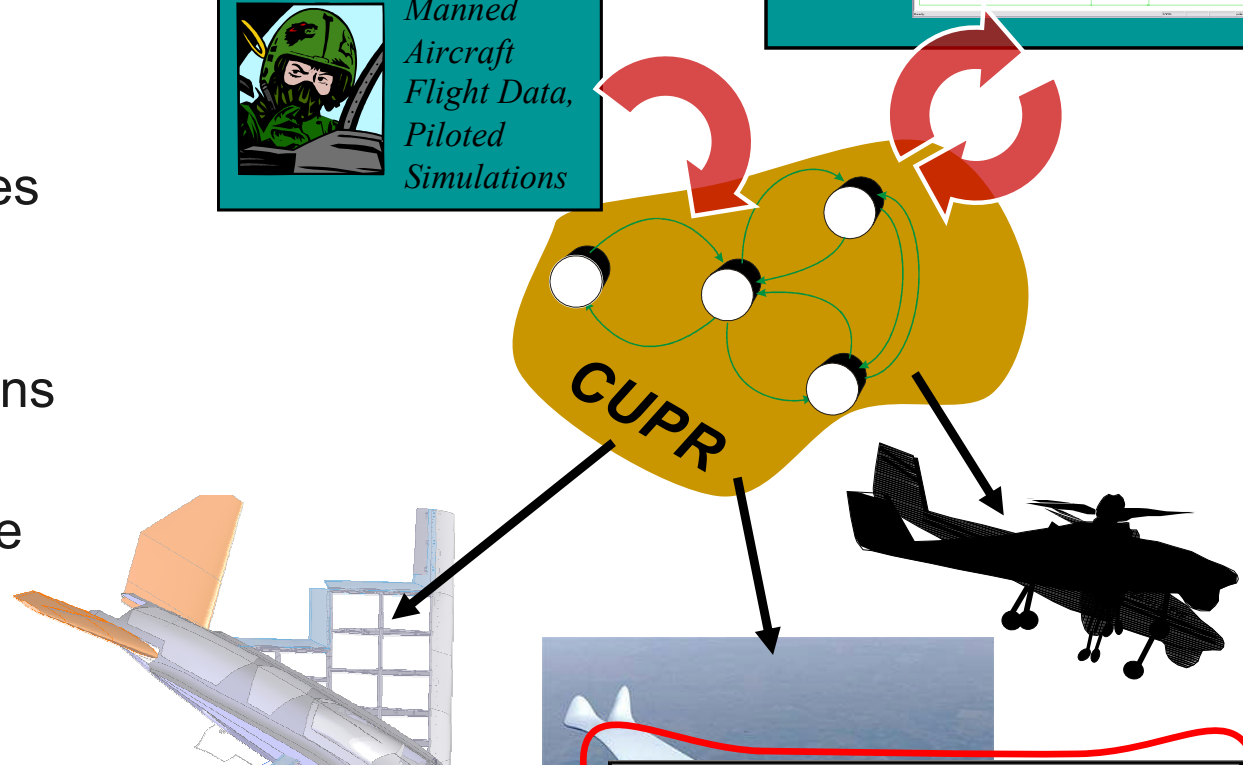
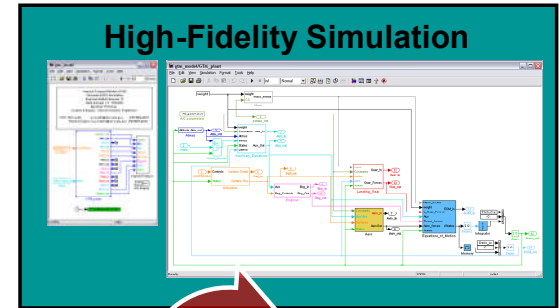
- With
  - NextGen / Northrop Grumman / VA Tech
- Bryan Cannon, COTR

## Demonstration Goal

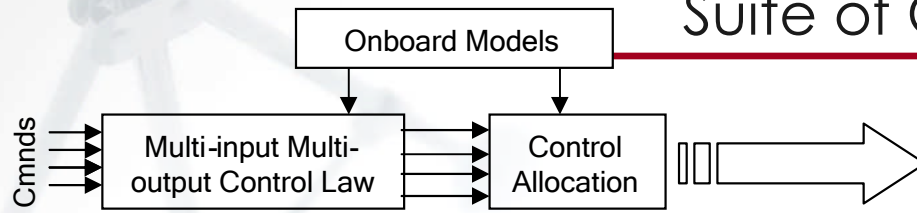
- Real-time wind-tunnel demonstration of stable morphing control using N-MAS wing

Develop a general-purpose automated-recovery system approach that

- learns appropriate recovery strategies
- adopts/encodes best-practices from the manned aircraft community
- avoids out-of-control conditions to the extent possible
- takes advantage of innovative actuation concepts

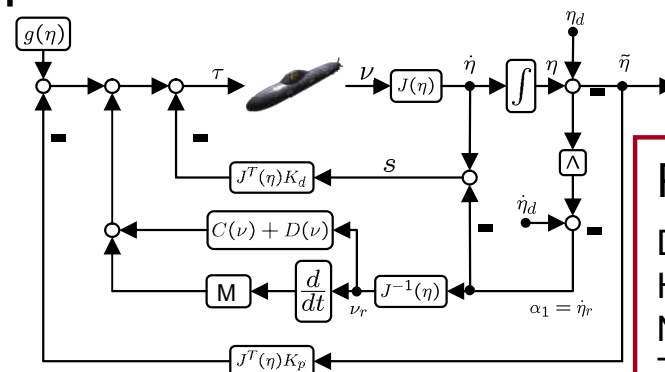
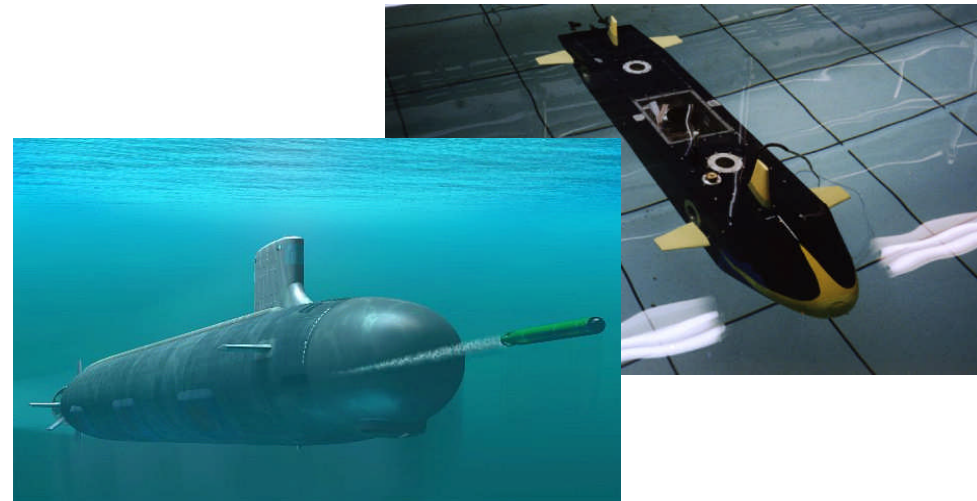
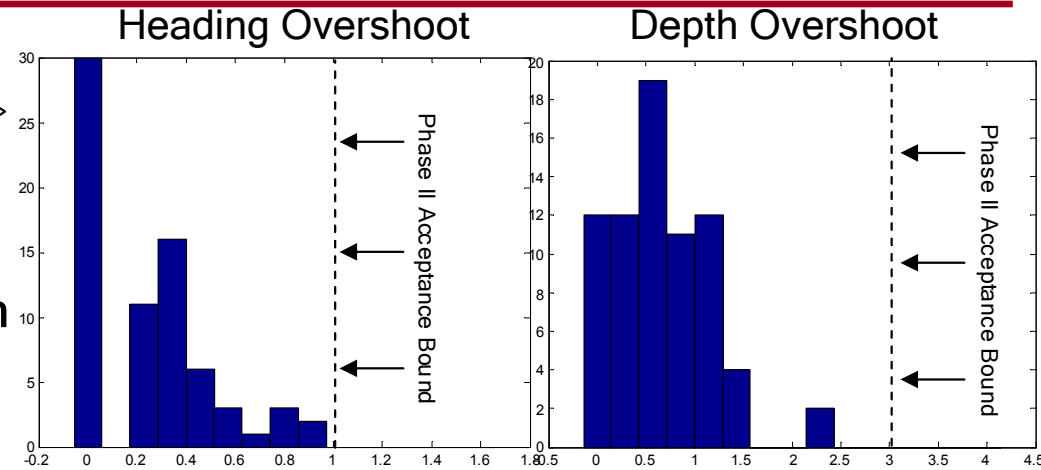


# Innovative Methods for Optimally Mixing a Diverse Suite of Control Effectors for Marine Vehicles



## Phase II Plan

- Formalize inner-loop control design methodology to be applicable to any vehicle with minimal reconfiguration and tuning - feedback linearization and backstepping
- Develop model based tuning approaches
- Develop methods to establish stability, robustness and performance characteristics of inner-loop approaches
- Develop state estimation approaches
- Develop outer-loop guidance design methodology that can be applied to a variety of vehicle platforms
- Develop path planning algorithm
- Apply design methodology to multiple vehicle models and evaluate performance



## Phase I Sponsor:

Dr. Edward Ammeen  
Head, Maneuvering and Control Division  
Naval Surface Warfare Center, Carderock  
Tel: (301) 227-5907



# NASA SBIR/STTR Technologies

## Damage Adaptation using Integrated Structural, Propulsion, and Aerodynamic Control



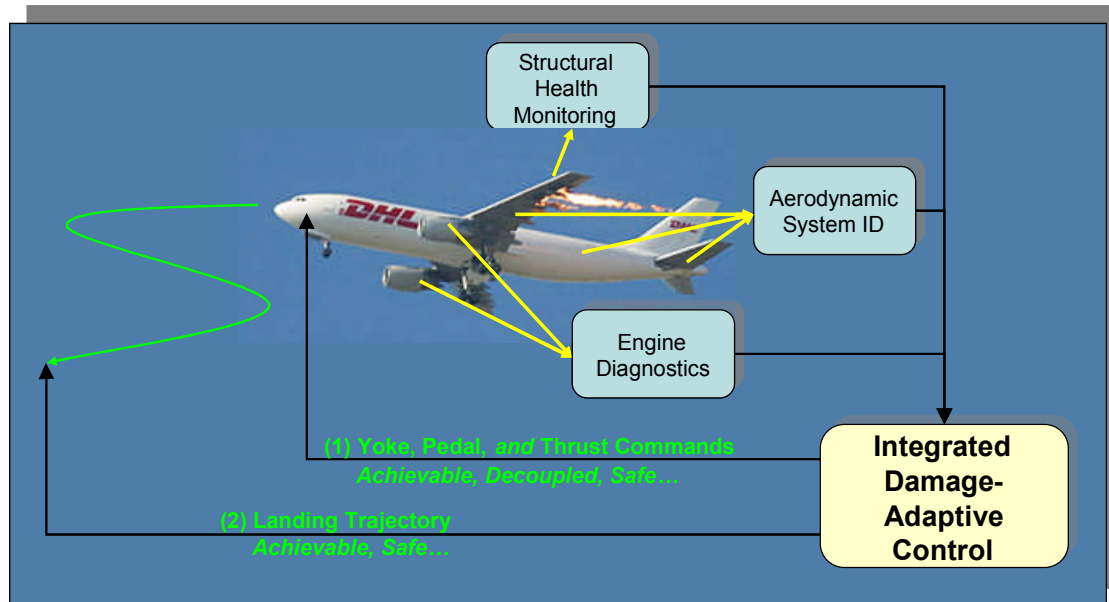
PI: D. Ward, Barron Associates, Charlottesville, VA

Topic A1.02 Integrated Resilient Aircraft Control -- Submittal No. A1.02-9516

### Identification and Significance of Innovation

#### Compensate for Simultaneous Effector, Airframe, and Propulsion Damage

- Built on flight-test-proven reconfigurable control algorithms
- Compute feasible control using aerodynamic and propulsive “effectors”
- Compute safe operating envelope in real-time using real-time structural health monitoring
  - No excessive loads on damaged components
  - No excitation of new structural modes
- Path-plan for safe landing
  - No unachievable trajectories or autopilot commands
  - No violation of structural limitations
- Can be implemented using V&V'able architectures



### Technical Objectives and Work Plan

#### Simulation Demonstration of Integrated Damage Adaptive Control System

#### Work Tasks

- Define demonstration problem (GTM / AirSTAR?)
- Integrate representative health-monitoring system
- Develop integrated damage-adaptive controller
- Integrate autopilot and path-planning approaches
- Simulation demonstration

### NASA and Non-NASA Applications

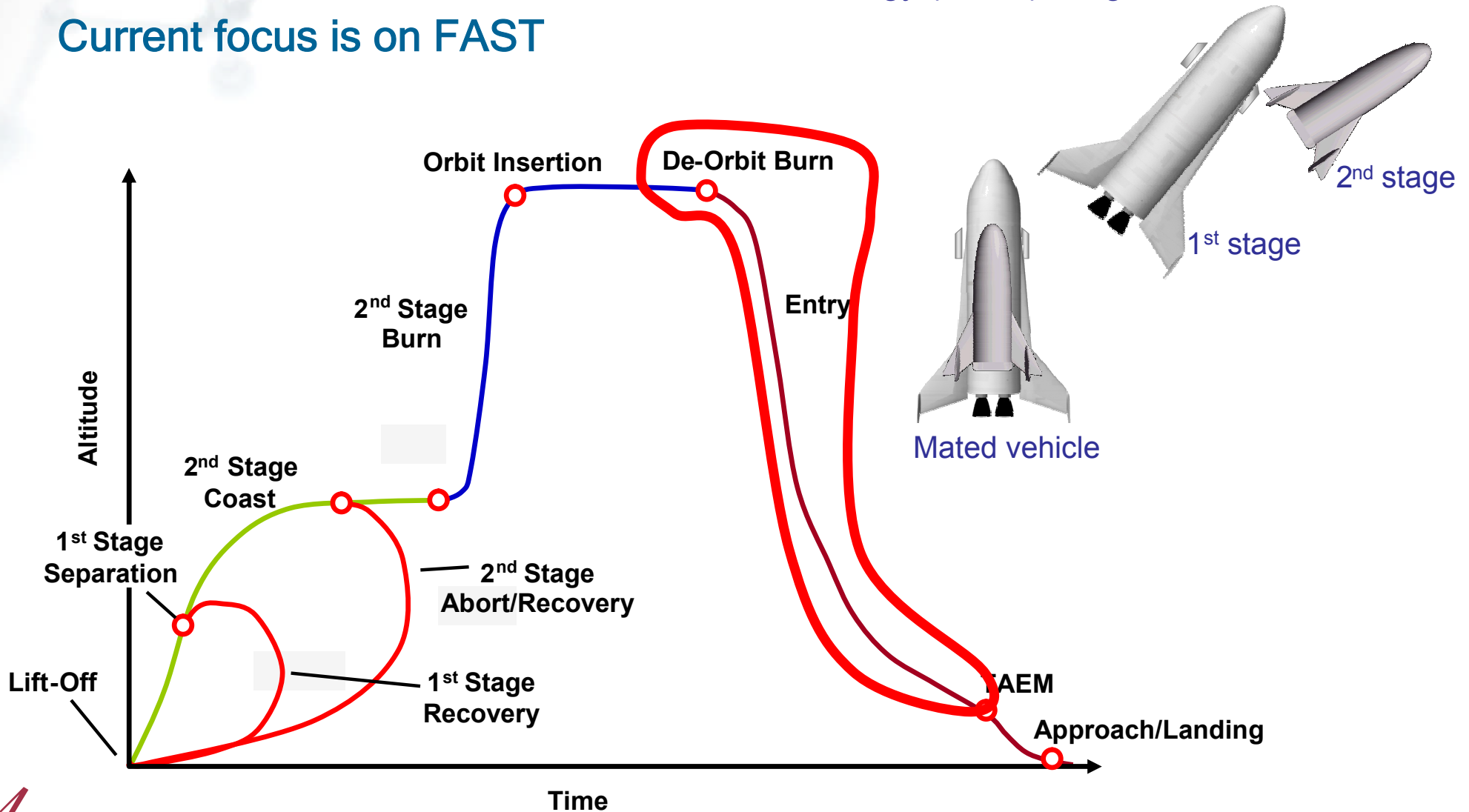
#### Civil Aviation, Military Aviation, Space, Life-Extending Control, ...

- Improved aircraft safety for civilian aviation
- Improved autonomous operations for space exploration in environments with massive uncertainties
- Improved autonomous operations for military vehicles (air, ground, surface, underwater, ...)
- Life-extending control
  - Use during normal conditions to reduce wear/fatigue on key structural components

# IAG&C Through RLV Flight Envelope

**Involved in all flight phases**  
**Current focus is on FAST**

Air Force's Fully Reusable Access to Space  
Technology (FAST) Program



# IAG&C for RLVs during Re-entry

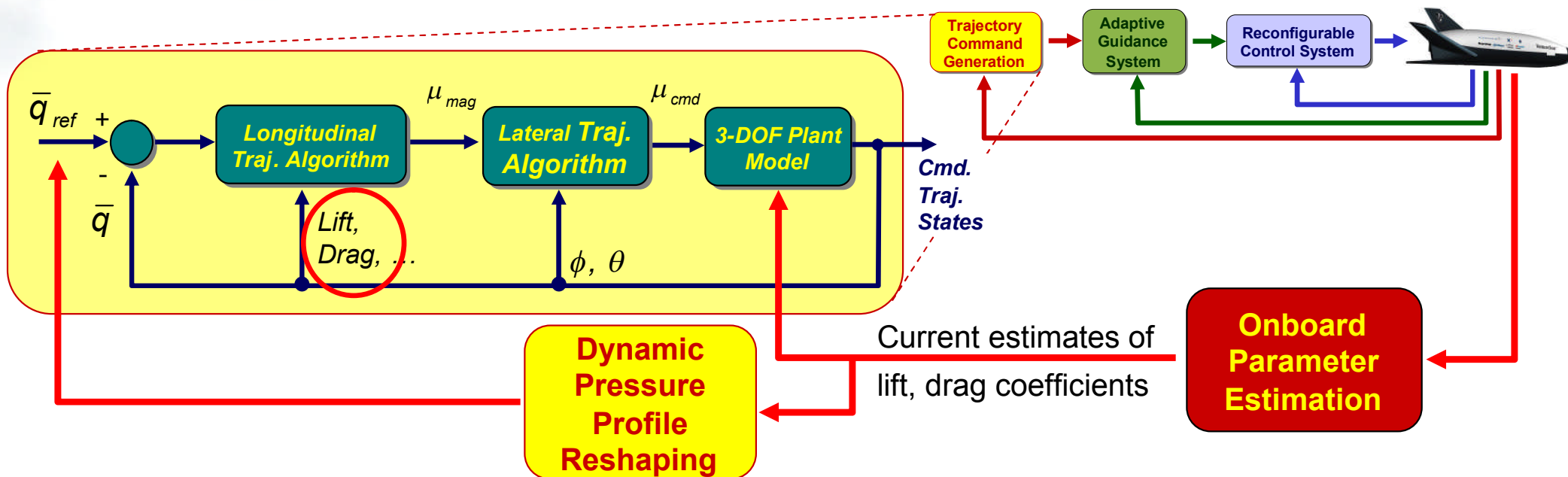
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## Goals/Objectives

- Adapt for effector failures
- Integrate with existing RCS systems
- Manage heating constraints, etc.

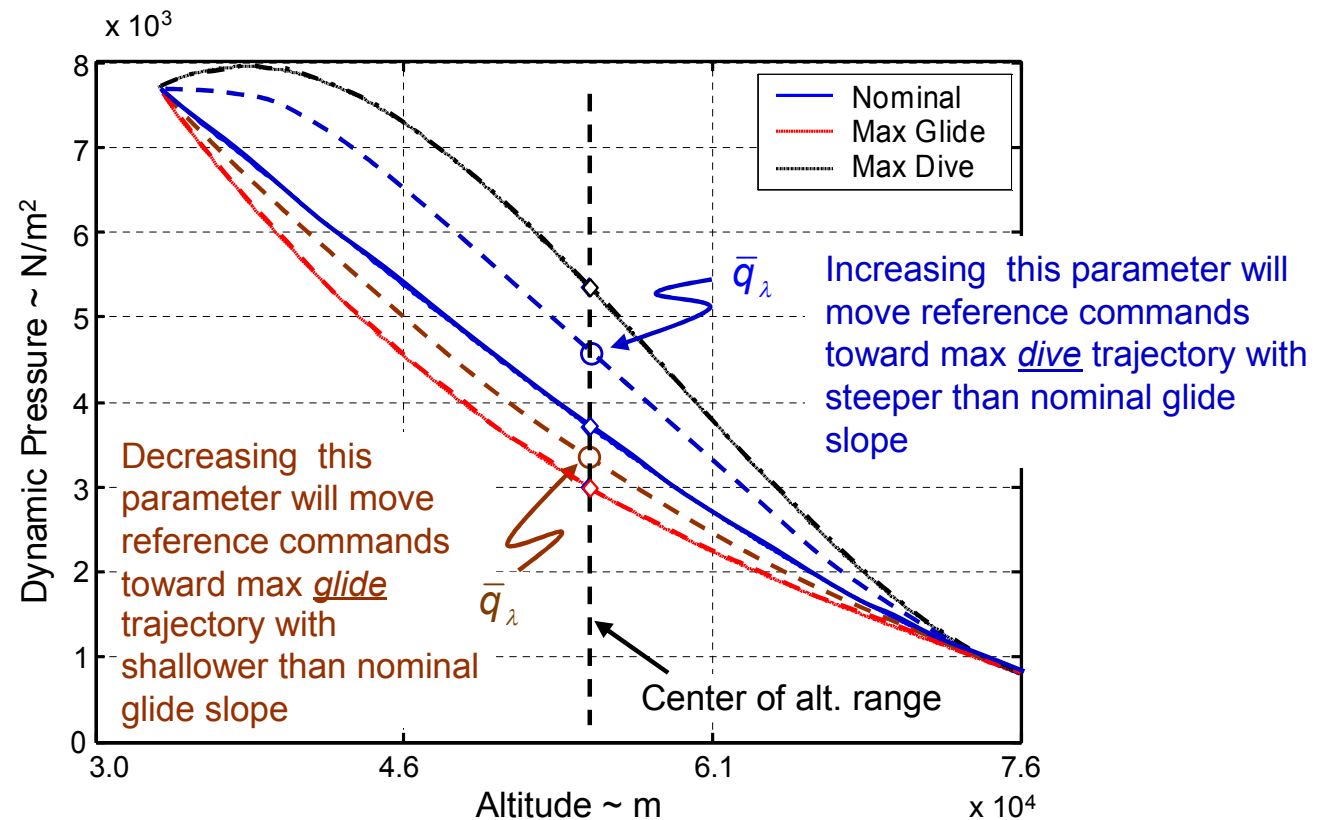


## Architecture for re-entry trajectory command generation



# Dynamic Pressure Profile Reshaping

## Commanded trajectory determined by reshaping dynamic pressure profile



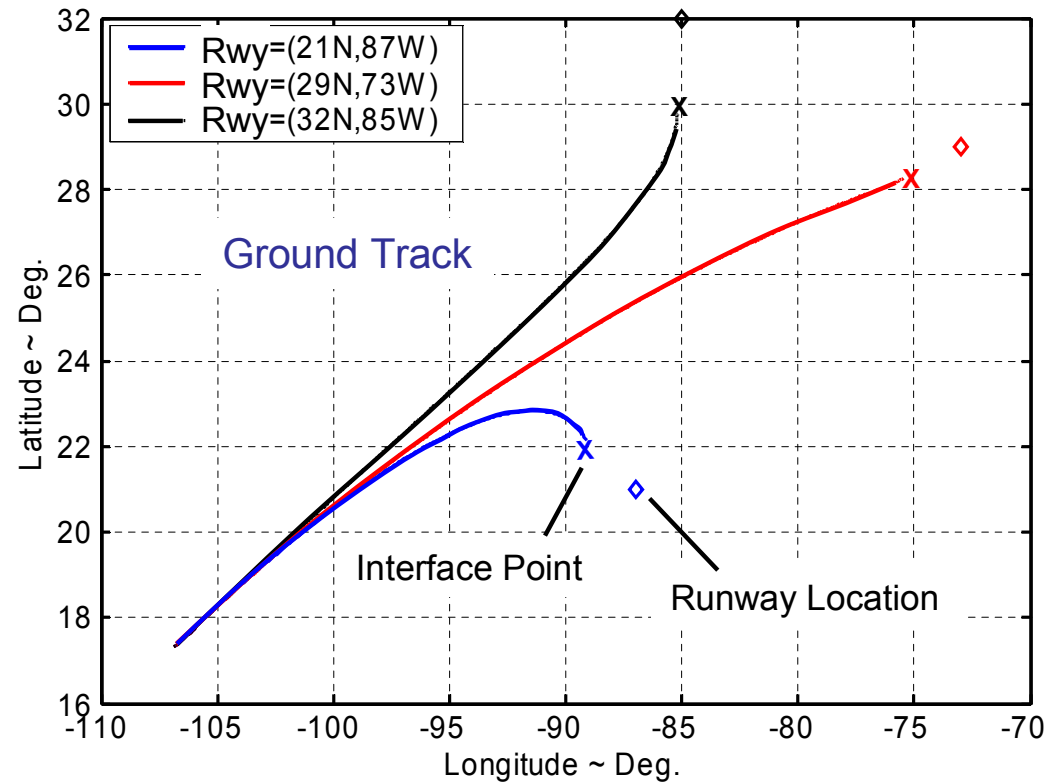
Max glide - longest achievable trajectory - limited by heat load constraint

Max dive - shortest achievable trajectory - limited by heat rate constraint

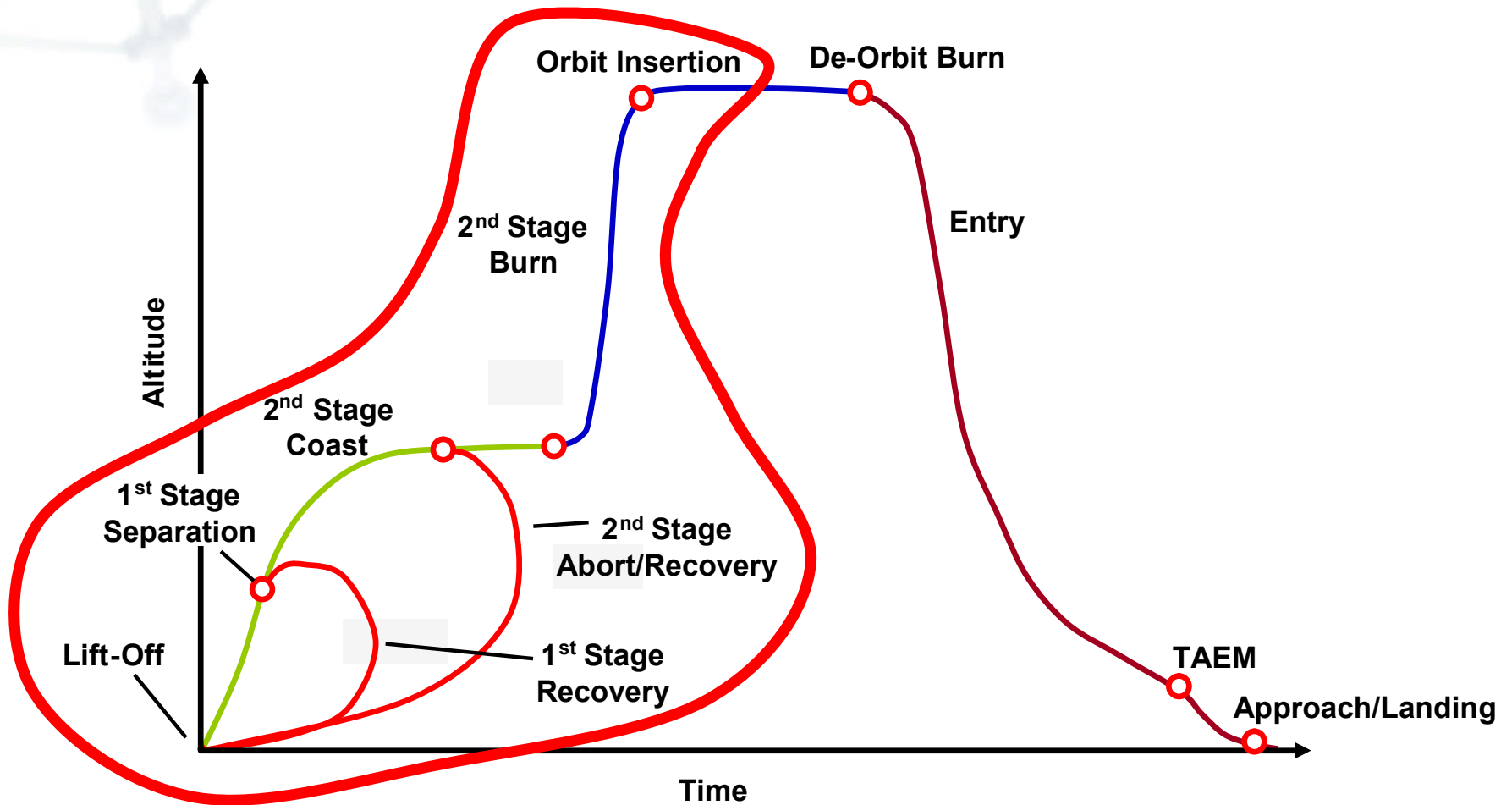
# Re-entry Trajectory Retargeting

## In-flight retargeting to alternate landing sites possible

- w/o extensive pre-mission planning



# IAG&C Through RLV Flight Envelope



## Develop guidance/path planning for:

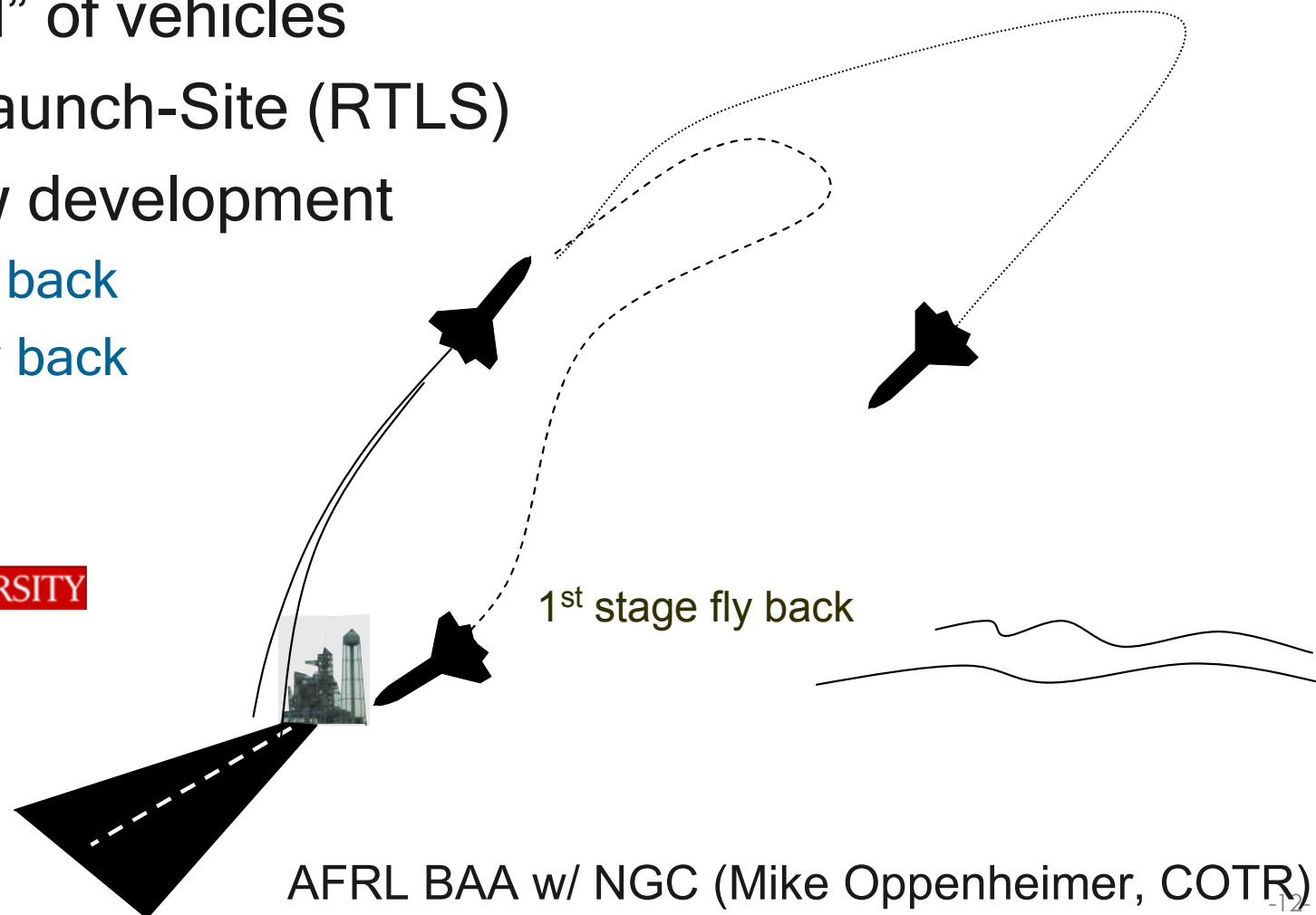
- Safe stage separation
- “Turn around” of vehicles
- Return-To-Launch-Site (RTLs)

guidance law development

- 1<sup>st</sup> stage fly back
- 2<sup>nd</sup> stage fly back

Working w/ Ping Lu

IOWA STATE UNIVERSITY



## Develop guidance/path planning for:

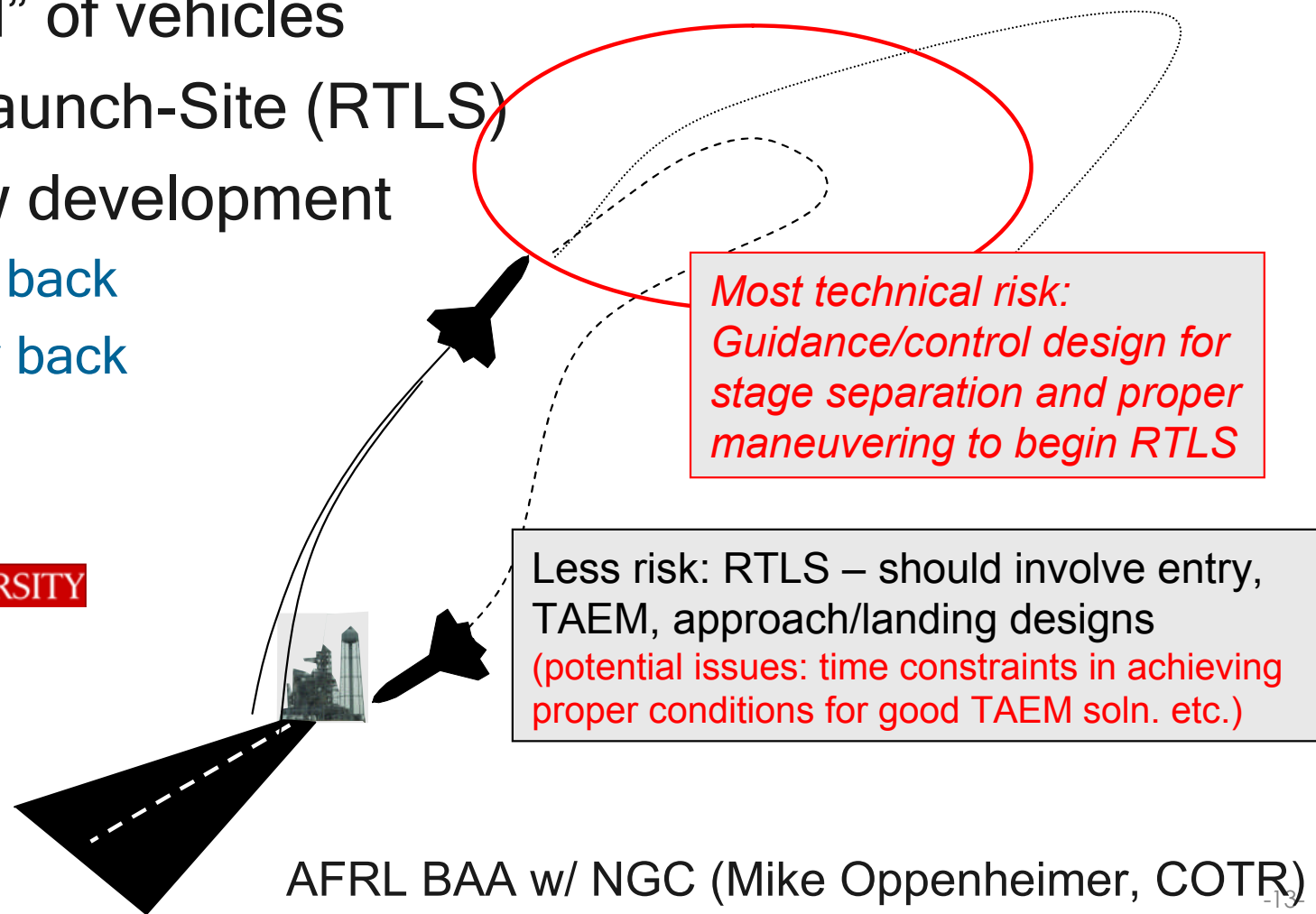
- Safe stage separation
- “Turn around” of vehicles
- Return-To-Launch-Site (RTLs)

guidance law development

- 1<sup>st</sup> stage fly back
- 2<sup>nd</sup> stage fly back

Working w/ Ping Lu

IOWA STATE UNIVERSITY



*Most technical risk:  
Guidance/control design for  
stage separation and proper  
maneuvering to begin RTLs*

Less risk: RTLs – should involve entry,  
TAEM, approach/landing designs  
*(potential issues: time constraints in achieving  
proper conditions for good TAEM soln. etc.)*

## P. Lu's Approach at TRL 1

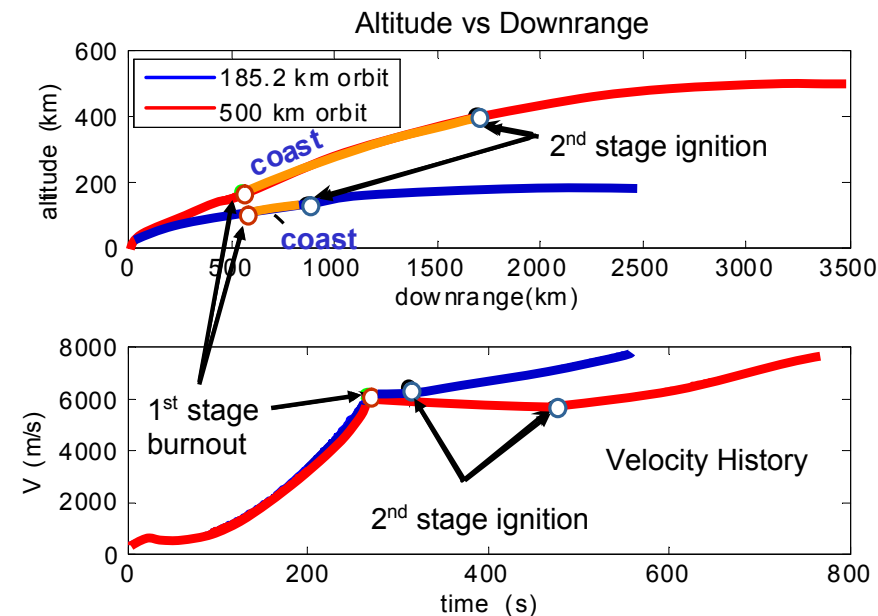
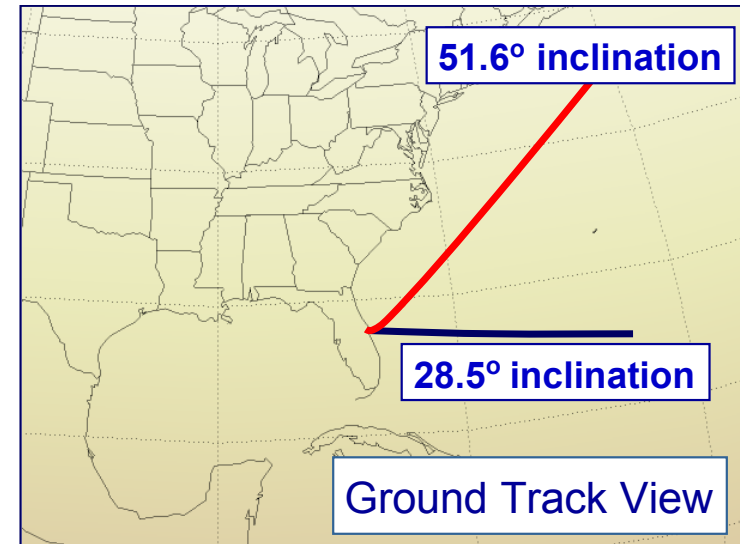
### Progress to Date (TRL approaching 2)

- Code completely reconstructed to allow integration into Northrop's simulation environment
- Convergence issues addressed
- Numerous Monte Carlo experiments successfully completed
  - Engine performance variations/wind profile dispersions

### Near Term Plans

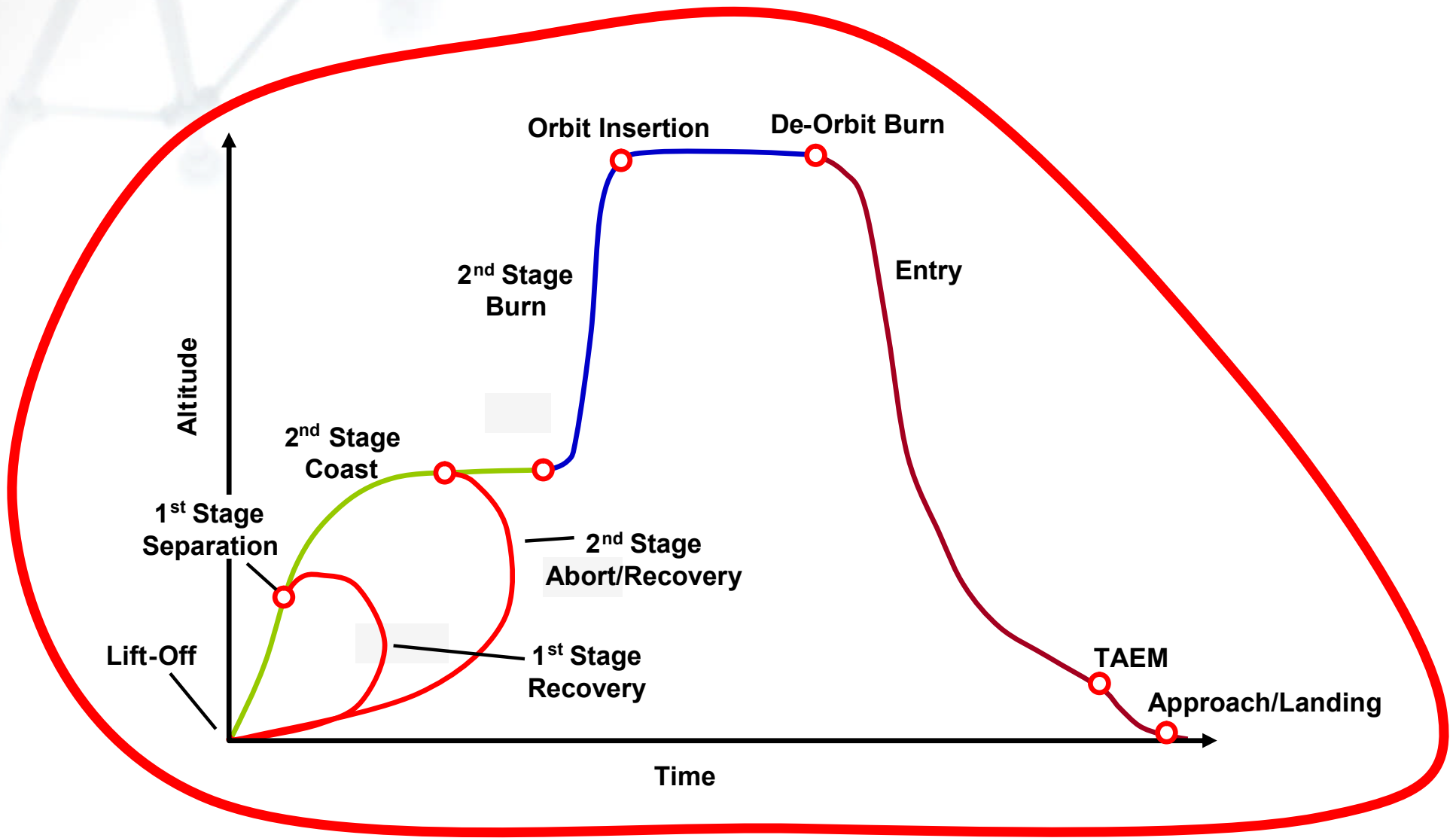
- Working on autonomous decision making
  - Coasting - vs - no-coasting option (key attribute under abort scenarios - especially for engine-out cases)
- Developing adaptive elements

## Sample 3-DOF Results:



Launch Profiles for Various Coast Times

# IAG&C Through RLV Flight Envelope



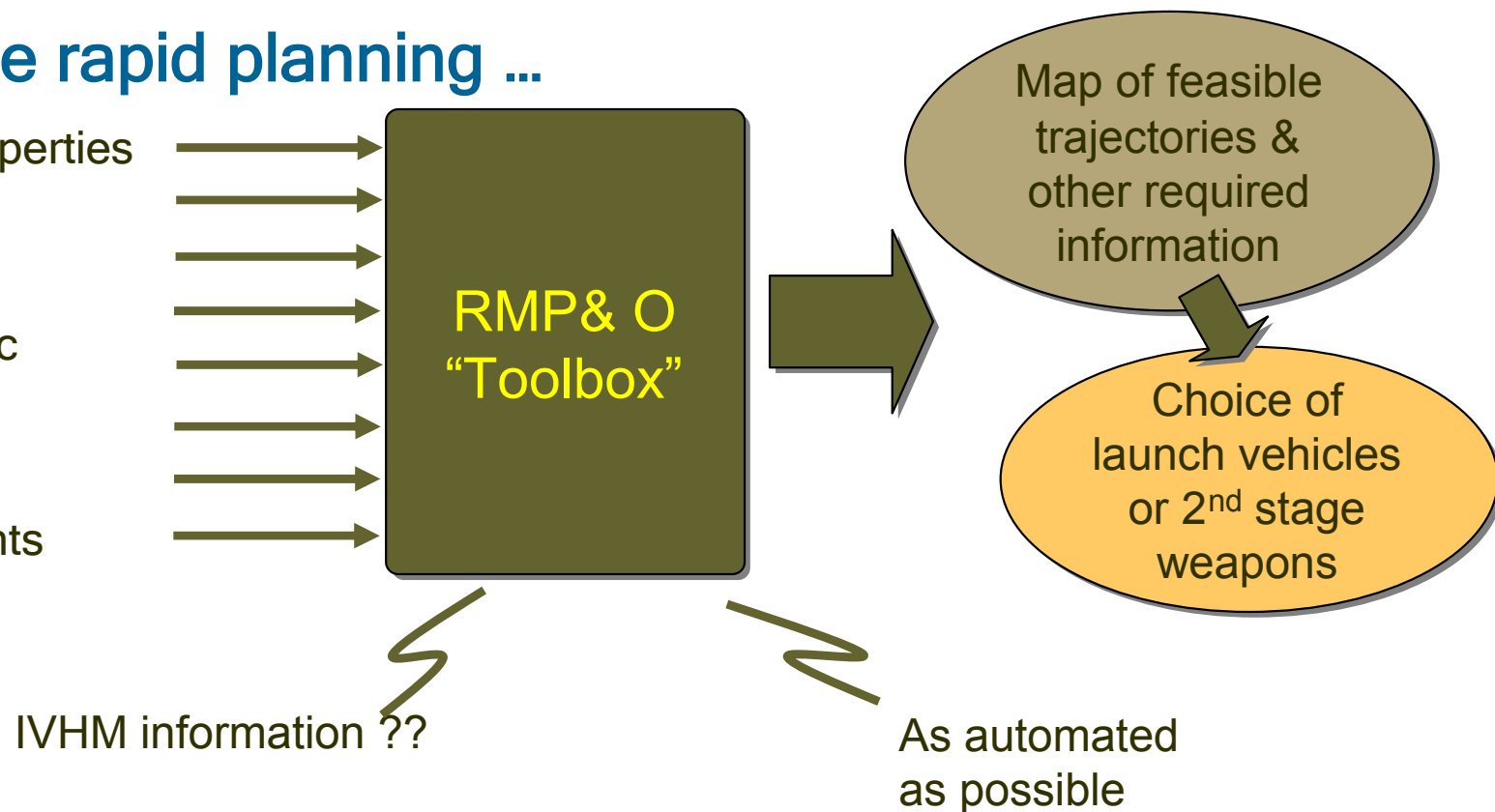
# Rapid Mission Planning and Optimization

## Rapid, reliable response

- Mission ready within 2 hours, 24 hours a day, 7 days a week

## Tool to enable rapid planning ...

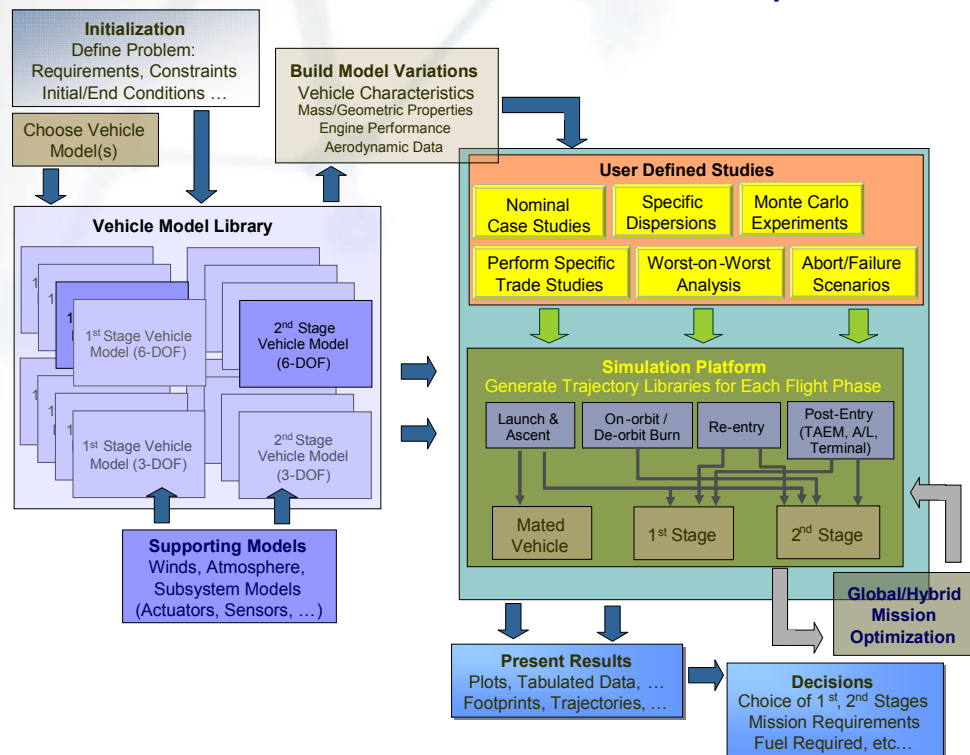
- Vehicle specific properties
- Mission specific parameters
- Current atmospheric conditions
- Other launch conditions/constraints



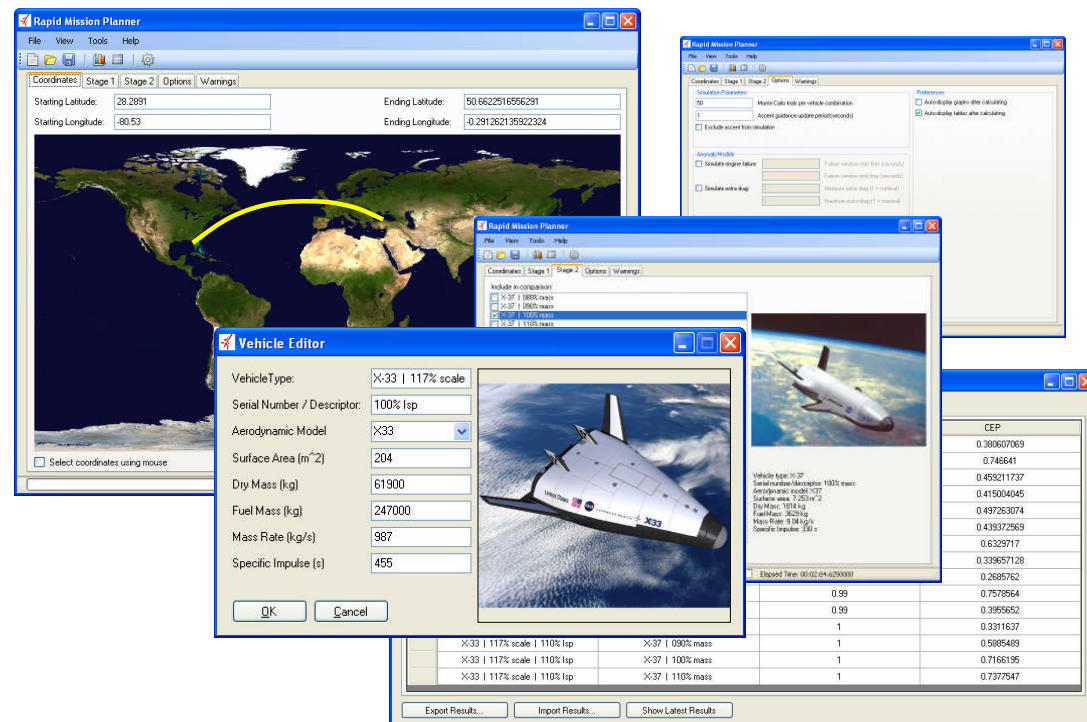
## Main Efforts Proposed:

- Fully develop rapid mission planning software toolbox: *“The Mission Planner”* shall be completed to a high TRL to be used by AF & industry
  - “Real-world” demonstration of the Mission Planner: a complete mission plan shall be completed
  - “FAST launch vehicle” simulation model developed for demonstrations
- **Primary Features of the Mission Planner:**
  - Employ trajectory generation algorithms developed in past AF IAG&C programs: very fast optimization routines designed for in-flight use - for full mission:
  - Ascent / On-orbit / Entry / TAEM / A&L
- **Built-in analysis capabilities:**
  - choice of model fidelity & vehicle characteristics
  - Monte Carlo/dispersion analyses & trade studies
  - Fault/failure modes analysis
  - Hybrid / mission optimization

## Software toolbox architecture development



## Graphical User Interfaces Constructed



# Preliminary Experiments Conducted

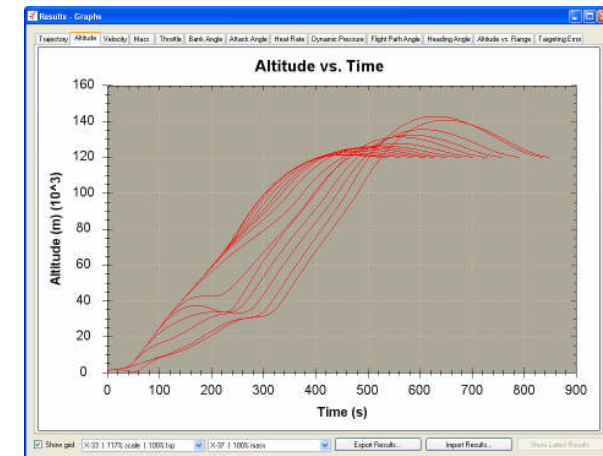
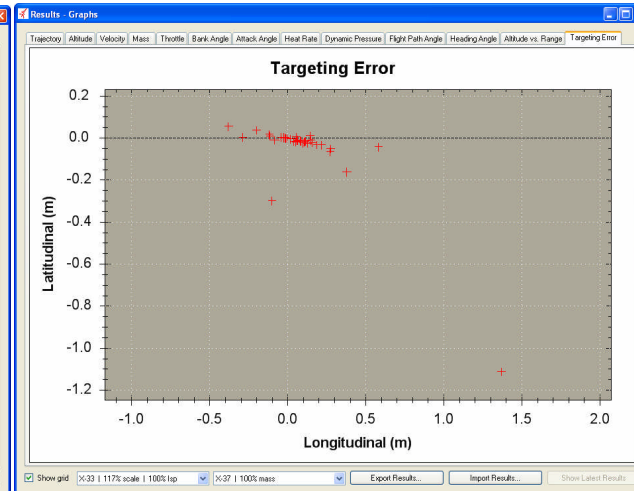
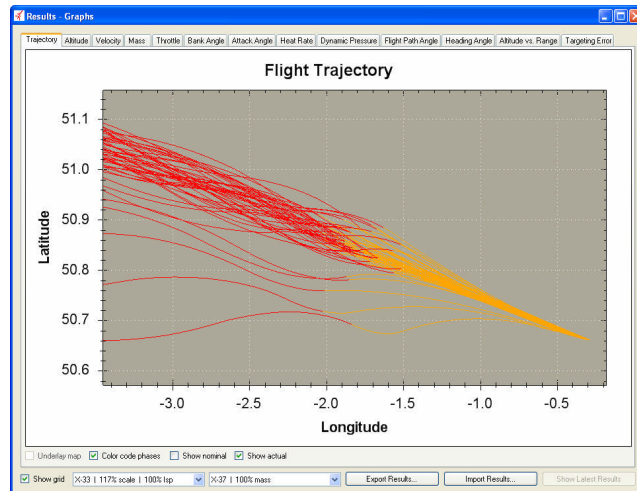
## ■ Nominal ascent & descent studies

- Mission Trade Studies
- Engine performance tradeoffs for ascent
- Mass tradeoffs for reentry & terminal guidance

| Mission Summary | Ascent Phase                 | Orbital Phase | Entry Phase      | Terminal Phase |                |             |
|-----------------|------------------------------|---------------|------------------|----------------|----------------|-------------|
|                 | Stage1                       |               | Stage2           |                | MissionSuccess | CEP         |
|                 | X-33   117% scale   090% lsp |               | X-37   120% mass |                | 1              | 0.214935526 |
|                 | X-33   117% scale   090% lsp |               | X-37   110% mass |                | 1              | 0.14203839  |
|                 | X-33   117% scale   090% lsp |               | X-37   100% mass |                | 1              | 0.130533951 |
|                 | X-33   117% scale   095% lsp |               | X-37   120% mass |                | 1              | 0.150378853 |
|                 | X-33   117% scale   095% lsp |               | X-37   110% mass |                | 1              | 0.137470379 |
|                 | X-33   117% scale   095% lsp |               | X-37   100% mass |                | 1              | 0.157083422 |
|                 | X-33   117% scale   100% lsp |               | X-37   120% mass |                | 1              | 0.181699246 |
|                 | X-33   117% scale   100% lsp |               | X-37   110% mass |                | 1              | 0.17434068  |
|                 | X-33   117% scale   100% lsp |               | X-37   100% mass |                | 1              | 0.150030613 |

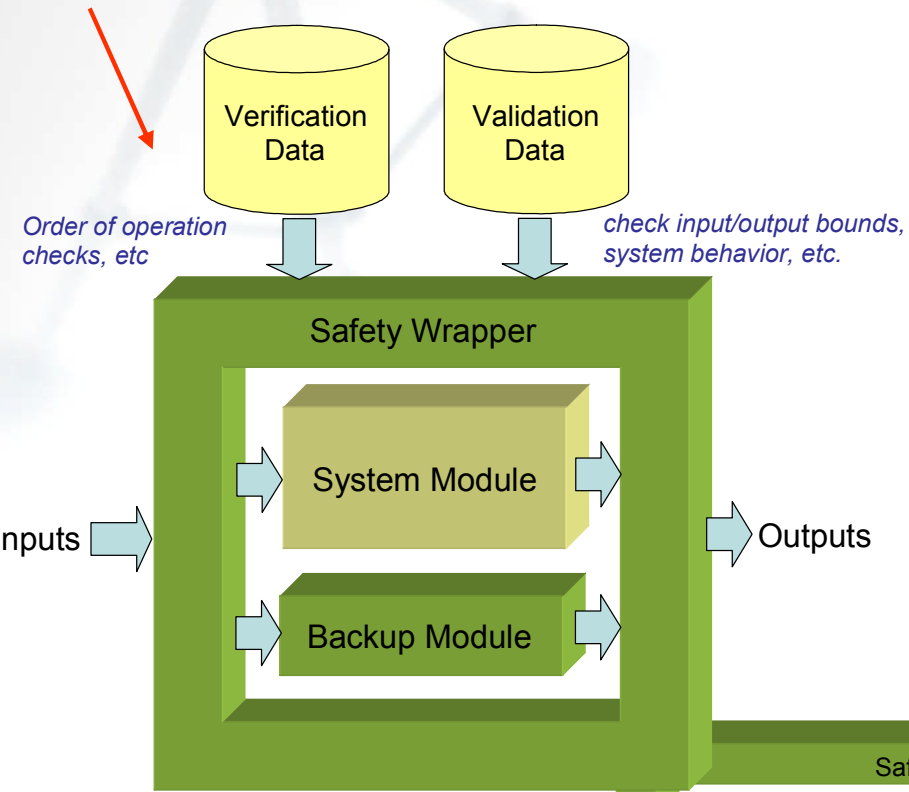
## ■ Anomaly Studies

- Engine failure during 1st stage burn
- Effects of mass-to-orbit margin studied
- Drag anomalies during reentry & terminal guidance



# Generic Run-Time V&V Safety Wrappers

## Generic individual safety wrapper for one system module



## AF SBIR Phase II

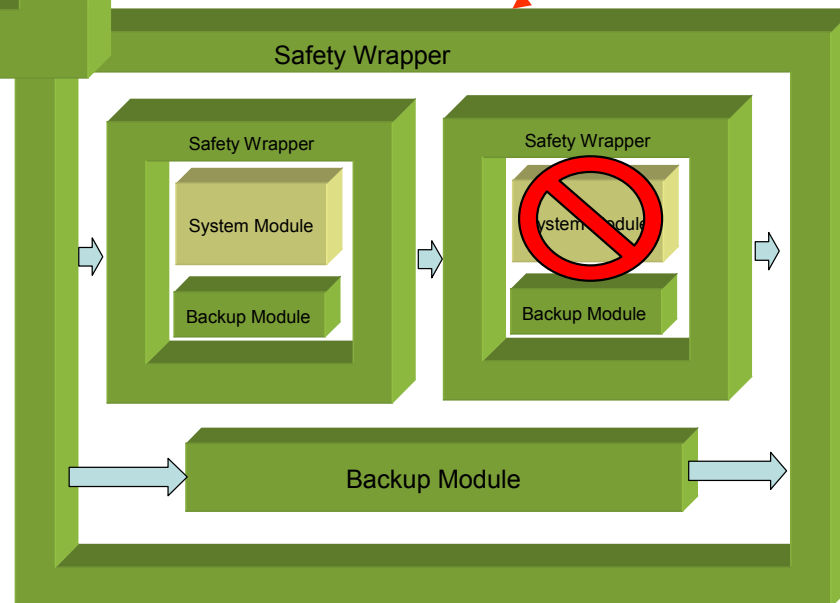
- With Lockheed Martin
- Wendy Chou, COTR

## Demonstration Goal

- Real-time HIL demonstration of V&V of intelligent UAV mission planning and control software

Safety wrapper for overall system comprised of a multitude of subcomponent safety wrappers

Incremental degradation:  
shut down only those sub-components not working, allowing other advanced components to continue operation



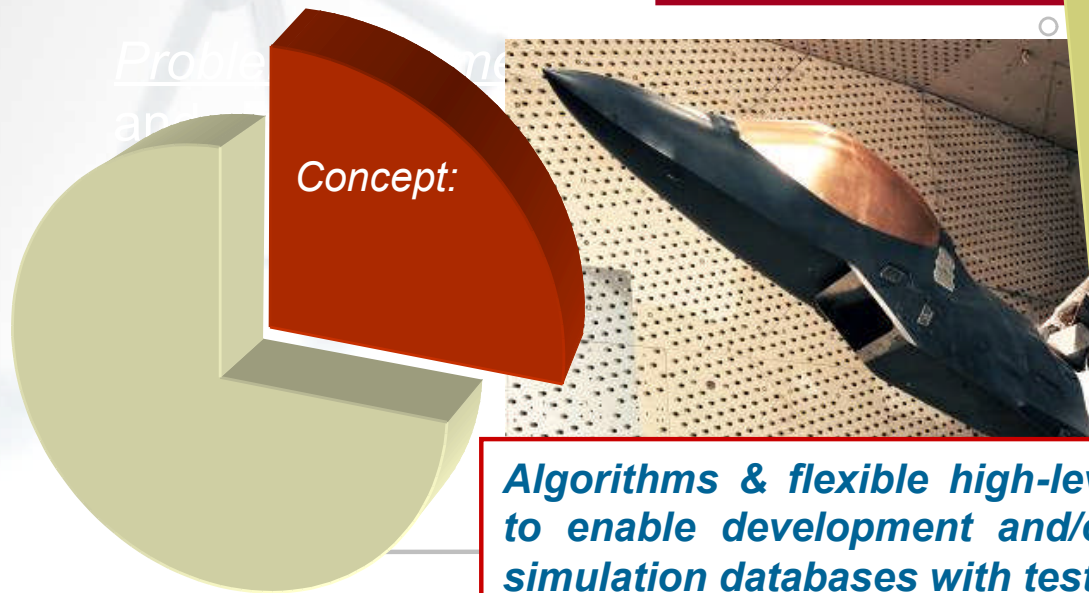
Failure Classes that can be Accommodated

System (Aircraft)

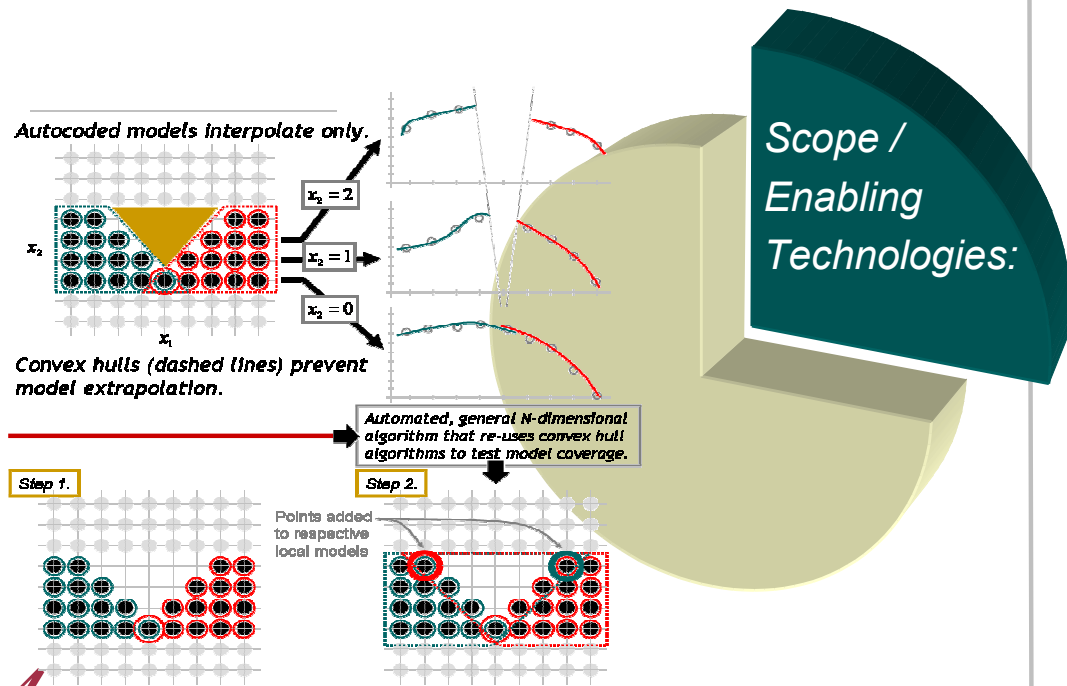
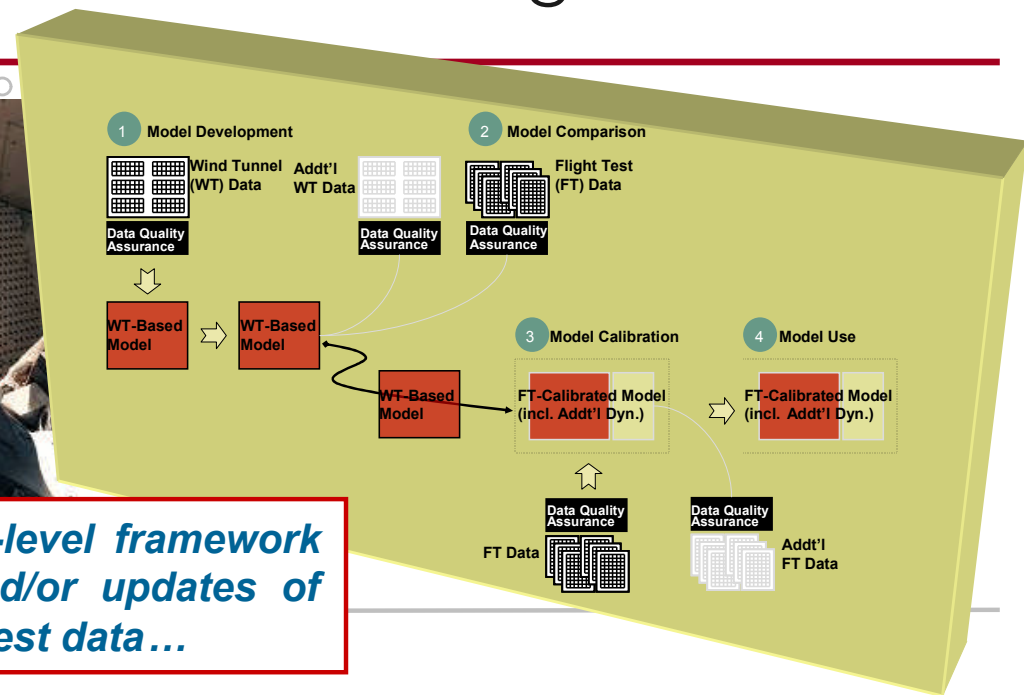
SW Implementation

SW Design

# AUSPEX Modeling Environment



**Algorithms & flexible high-level framework to enable development and/or updates of simulation databases with test data ...**



## Model Development:

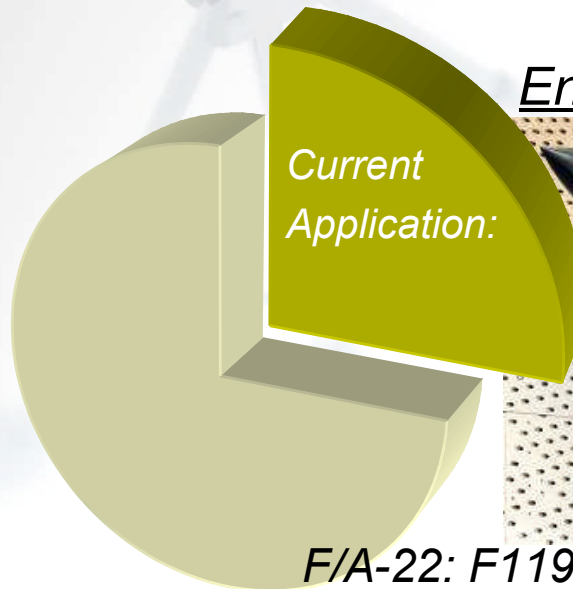
Automated local modeling / data partitioning  
 Structure learning polynomials and hybrid (empirical-CFD-first principles) models

## Model Calibration:

Parameter estimation to update model parameters to match test data

## Model Updating:

Hypersurface blending to merge local model results with existing databases

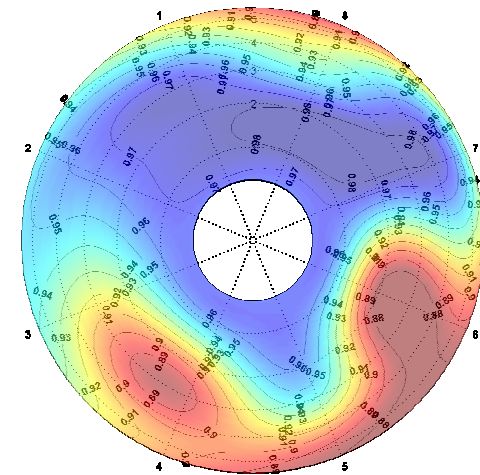


## Engine Inlet Modeling ...

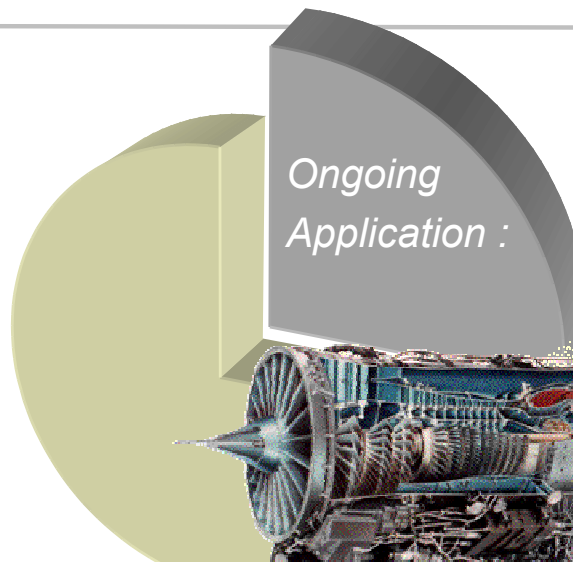
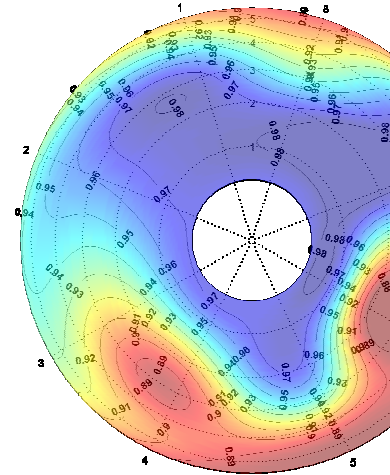


*F/A-22: F119 Engine Inlet (Barron)*  
*F-35: F135 Engine Inlet (AEDC)*

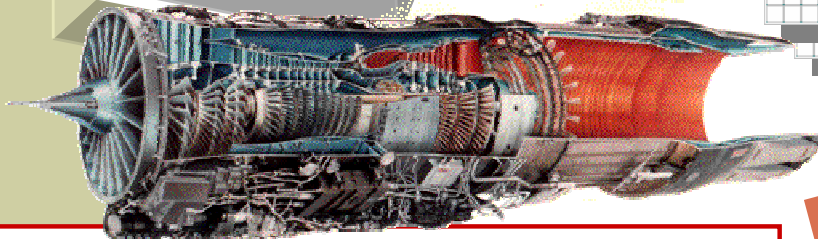
**EMPIRICAL MODEL (CALIB.)**  
 Recovery = 0.940



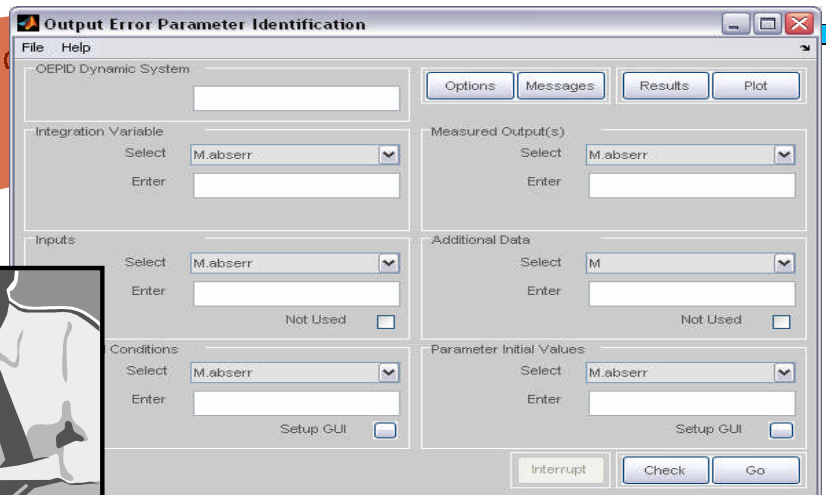
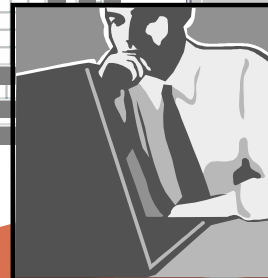
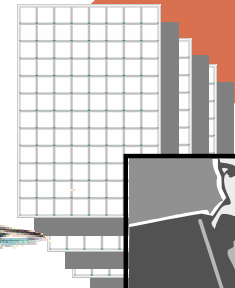
**FLIGHT TEST**  
 Recovery = 0.940



## Engine Model Calibration...

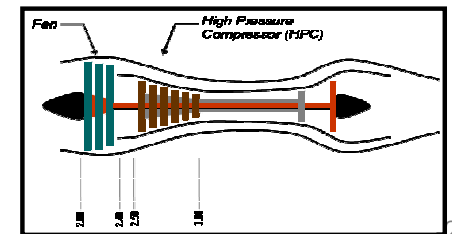


Test Data



**Interactive analysis / data comparison**  
**Output-error tuning of thrust deck free parameters to match test data**

Contractor High-Fidelity Transient Thrust Deck



## Control-law Automated Evaluation through Simulation-based and Analytic Routines

### Identification & Significance of Innovation

#### V&V Major Barrier to Advanced Control Laws

- many advanced control approaches work well in tests
- certifying for fleet vehicles very difficult

#### Automated Test is Key Technology

- V&V is expensive and time consuming
- Automated test key to making V&V manageable

### Approach

#### Combine Analysis and Simulation-based Test

- use worst-case analysis tools to gain insight
- select simulation-based test conditions based on results

#### Provide Uncertainty Tools for Simulink

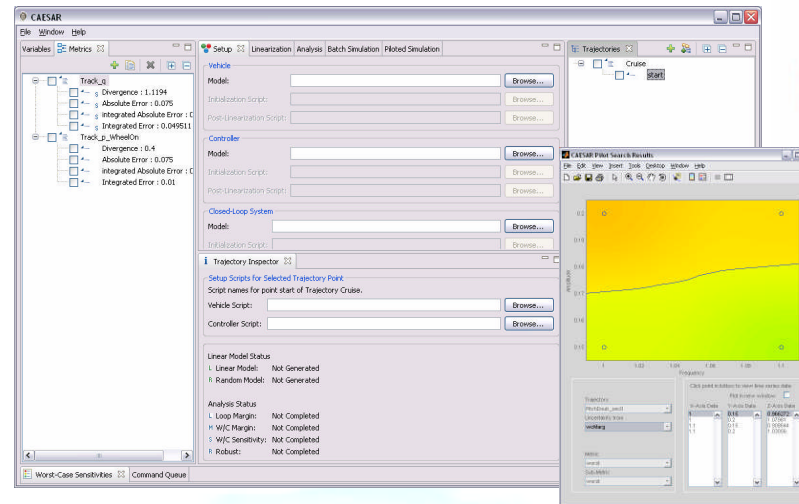
- uncertainty blocks for non-linear Simulink models
- linearization capability for uncertain Simulink models

#### Design general SW framework

- facilitate design, analysis, V&V of control systems
- permit performance validation for arbitrary systems

#### Open-Architecture MATLAB Implementation

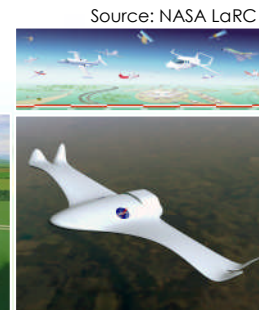
- plug in user analysis and app-specific performance SW
- body of advanced algorithms and toolboxes in MATLAB



### NASA Applications

#### Design, Analyze, & Validate Technologies for...

- AvSP/SAAP
- VSP/AuRA
- SATS
- ARES (Mars Airplane)



Source: NASA LaRC

### Non-NASA Applications

#### Design, Analyze, & Validate Technologies for...

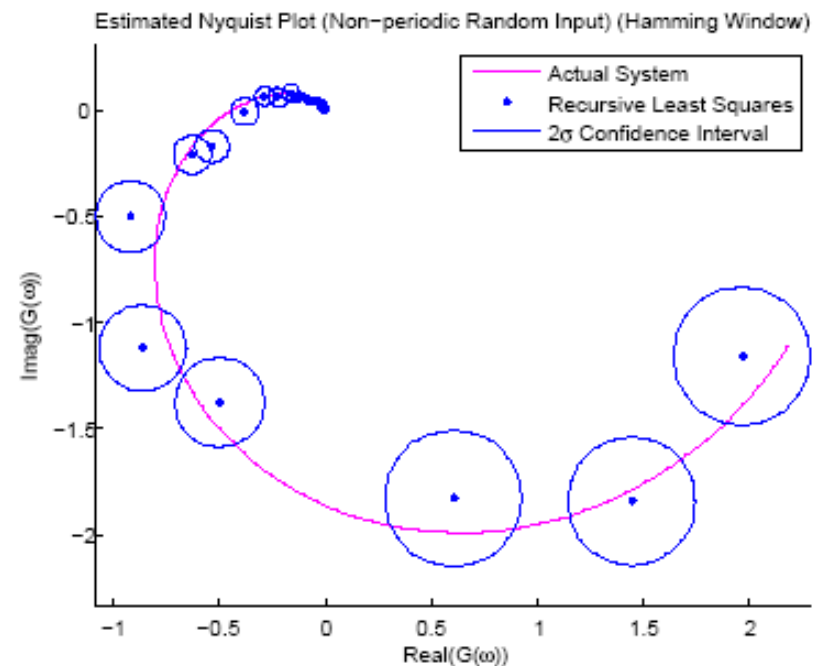
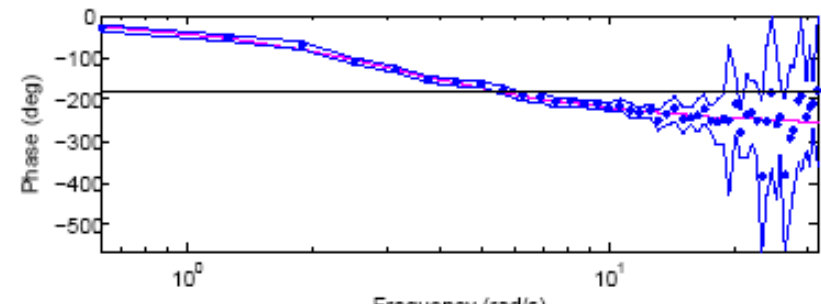
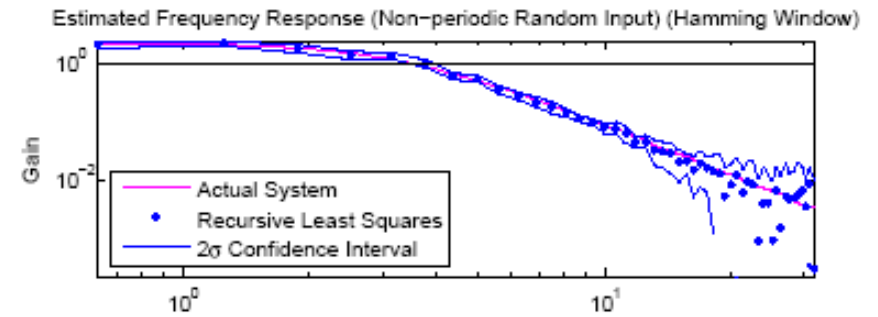
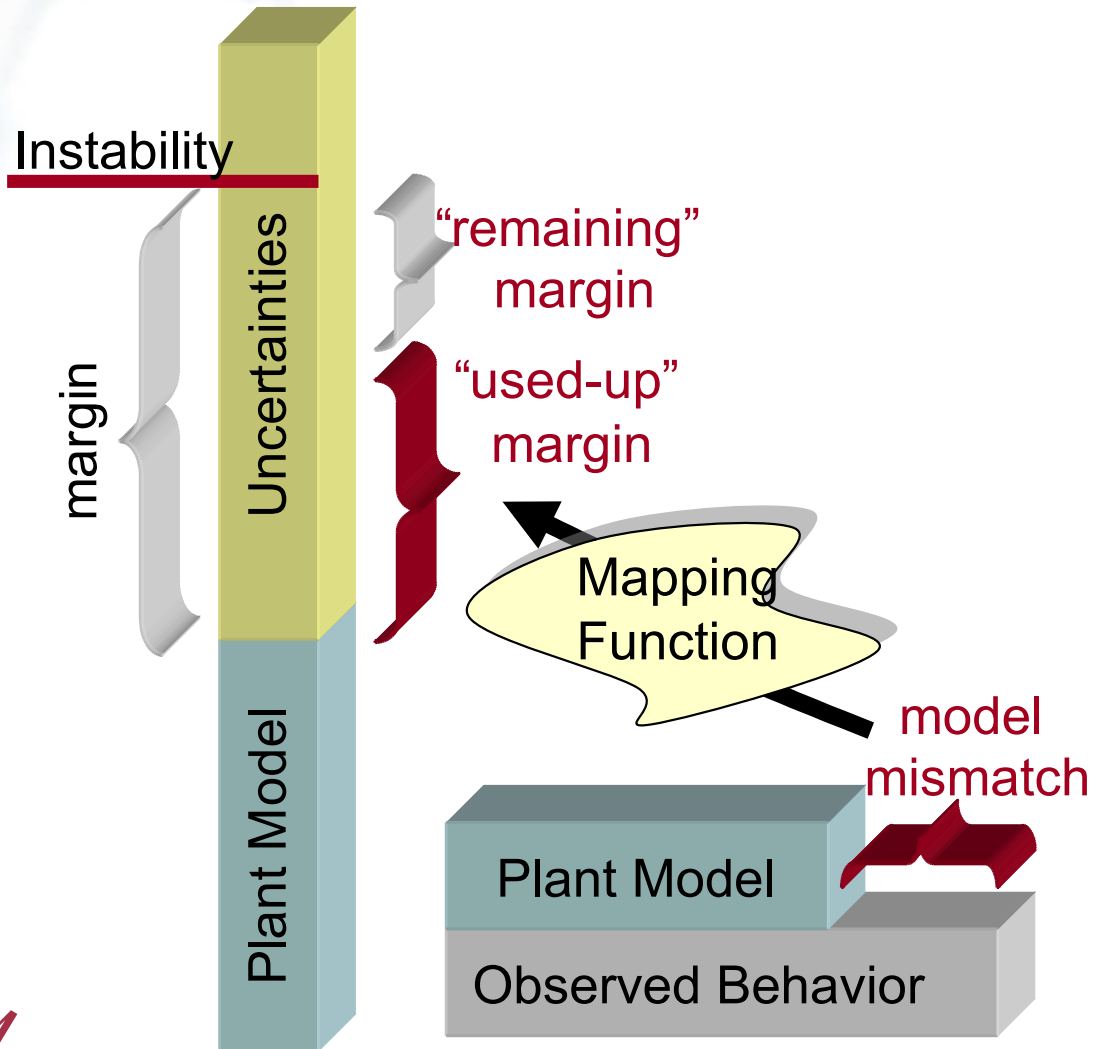
- commercial, & GA aircraft safety
- military aircraft survivability & performance
- UAV autonomy
- adaptable robots, power systems, etc.



# Real-time Observation-based Margin Estimation

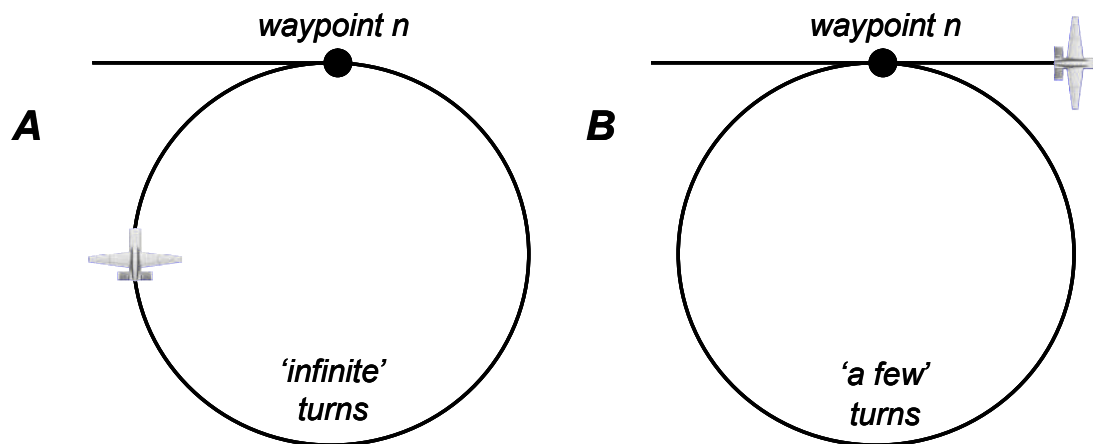
## Estimate transfer functions during flight test

- Compute confidence intervals for estimates
- Incorporate additional data as test progresses
- Compare to off-line worst-case margin estimates

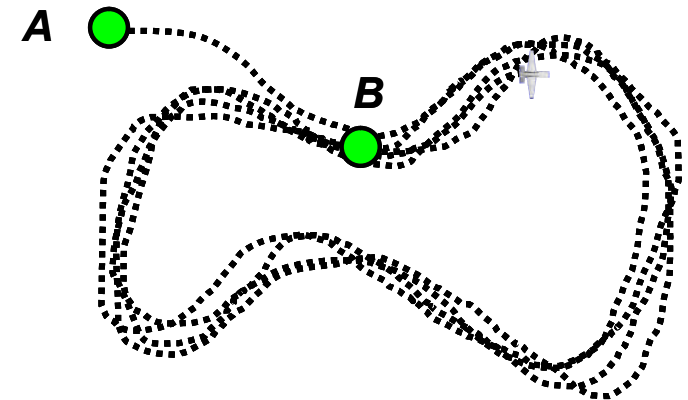


## ■ Demonstration of several run-time V&V monitors

- Shut down effector blender - revert to classical control assignment
- Shut down dynamic inversion - revert to classical P-I-D controller
- Command hedging - reduce desired dynamics to FQ Level II or III
- Shut down complex logic in outer-loop guidance - command return to base waypoint following



Check for breakdown in waypoint following  
Command trajectory back to base



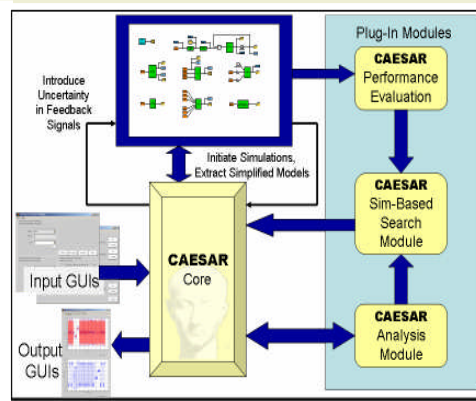
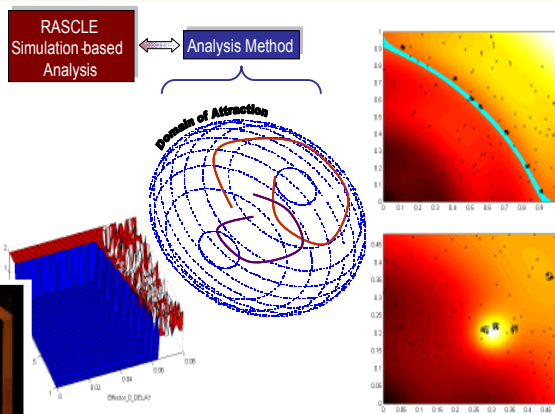
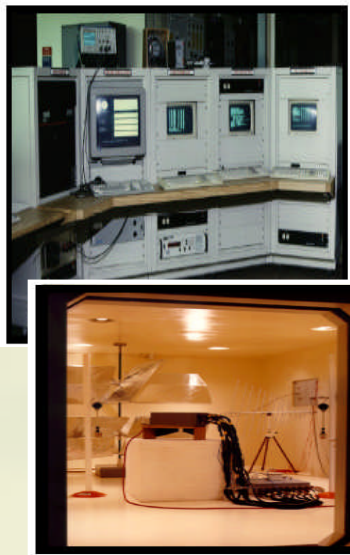
## Phase II Enhancements

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- Automatic generation of Simulink (autocodable) monitors
- Develop sets of monitors for a variety of *critical parameters*
- Automatically generate parameters/bounds required by monitors
- Monitoring for triplex architectures
- Guaranteed bounds for on-board neural networks

# Analysis Methods, Software Tools, and Novel System Designs

## V&V Through the Control Law Life Cycle

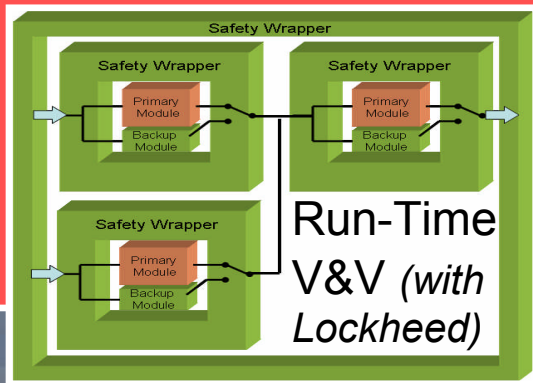


Flight Testing

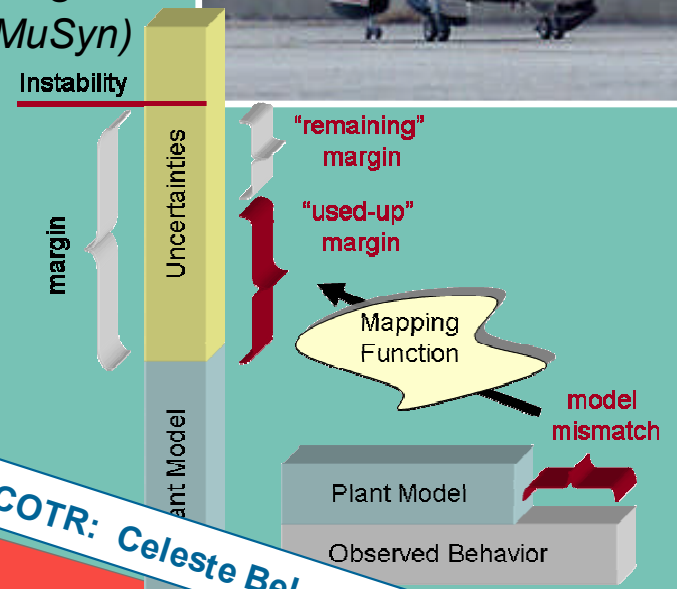
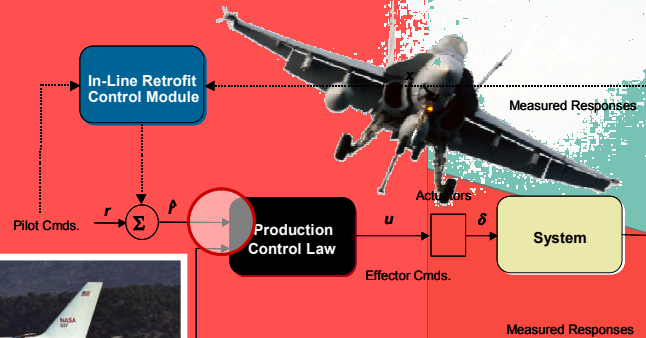
Automated Off-Line Test Of Stability, Robustness, and Performance (with MuSyn)

Real-Time Monitoring of Safety Margins (with MuSyn)

COTR: Christine Belcastro, NASA Langley



Retrofit Flight Controls



COTR: Celeste Belcastro, NASA Langley

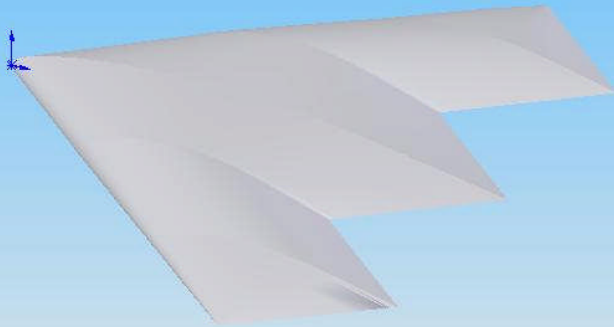


Production Vehicles - DACS

With U. of Virginia (Gang Tao, Ph.D.)  
And U. of Wyoming (Douglas Smith, Ph.D.)

# Adaptive Control of Synthetic Jet Arrays with Unknown Nonlinearities

## Phase II Wind Tunnel Model Design



**Long-Term PAYOFF:** Closed-loop flight control without mechanical control surfaces, plus expanded flight envelopes

### OBJECTIVES

- Design, implement, and test adaptive control algorithms to achieve closed-loop flight control objectives using synthetic jet actuators for virtual surface shaping
- Demonstrate closed-loop control performance using an innovative, tailless wind tunnel model with integrated synthetic jet actuators

### APPROACH/TECHNICAL CHALLENGES

- The control inputs for synthetic jet actuators to achieve a desired aerodynamic effect have been shown to be complex
- The control algorithms are based on the adaptive inverse technique developed specifically to compensate for sensor and actuator nonlinearities that are imperfectly known

### ACCOMPLISHMENTS/RESULTS

- Designed, fabricated, and tested synthetic jet actuators and wind tunnel model
- Designed and implemented a real-time control and data acquisition system
- Wind tunnel tests over a wide range of conditions

### FUNDING (\$K)—Show all funding contributing to this project

|             | <u>FY05</u> | <u>FY06</u> | <u>FY07</u> | <u>FY08</u> | <u>FY09</u> |
|-------------|-------------|-------------|-------------|-------------|-------------|
| AFOSR Funds | 100         | 375         | 375         |             |             |

### TRANSITIONS

- Deb, Tao, Burkholder, Smith, "An adaptive inverse control scheme for a synthetic jet actuator," *Proc. 2005 ACC*
- Deb, Tao, Burkholder, Smith, "Adaptive compensation of nonlinearities in syn. jet actuators," *AIAA GNC 2006*
- Deb, Tao, Burkholder, Smith, "Adaptive compensation control of synthetic jet actuator arrays for airfoil virtual shaping," to appear *AIAA Journal of Aircraft*

### STUDENTS, POST-DOCS

Dipankar Deb (U. of Virginia); Patrick Shea (U. of Wyoming)

### LABORATORY POINT OF CONTACT

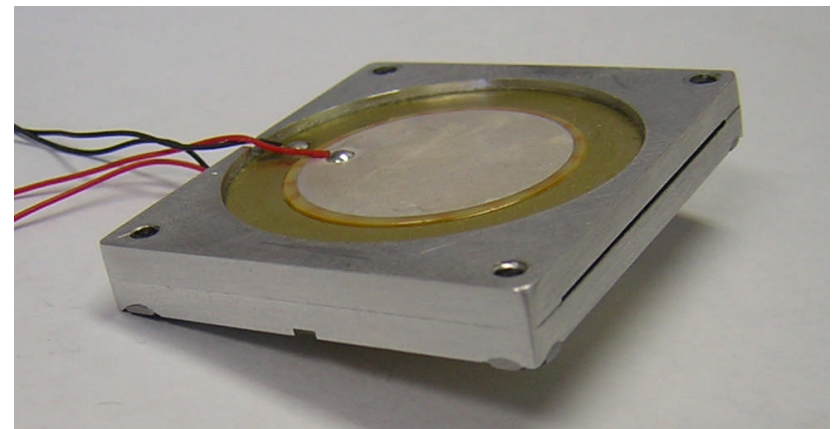
Dr. James Myatt, AFRL/VACA, WPAFB, OH

# INNOVATIVE WIND TUNNEL MODEL WITH INTEGRATED SYNTHETIC JET ACTUATORS AND REAL-TIME CONTROL SYSTEM

- Real-time adaptive control and data acquisition system implemented using xPC Target RTOS from Mathworks
- Algorithms implemented and tested in Matlab/ Simulink can be rapidly deployed in hardware
- Parametric models suitable for control algorithm design were developed for synthetic jet actuators operating at high angles of attack to delay flow separation



- Tailless aircraft model with distributed synthetic jet actuators and pressure ports
- Wind tunnel testing is being conducted over a wide range of operating conditions



**Synthetic Jet Actuator**

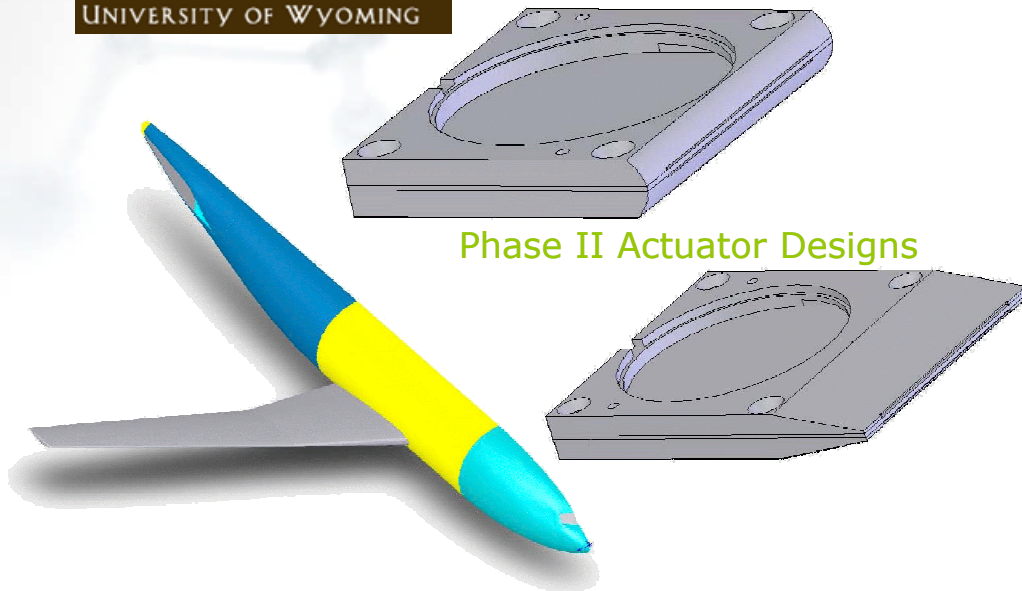
# NASA SBIR/STTR Technologies

## Active Flow Control with Adaptive Design Techniques for Improved Aircraft Safety

PI: Jason Burkholder / Barron Associates, Inc. – Charlottesville, VA



**Proposal**  
**T2.02-9831**



Phase II Actuator Designs

### Significance of Opportunity

- Potential for low-cost safety improvements for commercial transport aircraft
  - Innovative synthetic jet actuators strategically-located on airfoil could delay stall and provide “back-up” control power
  - Adaptive control is required due to complex, nonlinear actuator dynamics

### Phase I Results

- Designed and implemented adaptive control laws - verified performance analytically and in simulation
- Designed wind tunnel model, novel actuators, and comprehensive Phase II test plan

### Phase II Wind Tunnel Model Design

### Phase II Work Tasks

- Develop fully functional AIFAC tool (Adaptive Inverse For Actuator Compensation)
- Fabricate wind tunnel models and synthetic jet actuators - optimize actuator layout
- Implement real-time adaptive control system and demonstrate in closed-loop wind tunnel tests
- Quantify safety improvements and develop V&V Plan to facilitate future flight tests

### Applications

- AirSTAR Testbed for AvSP/SAAP
  - Complex damage-adaptive FDI & control
  - Operation near edge of flight envelope
- NASA Intelligent Flight Control System (IFCS)
- Commercial and military aircraft - especially tailless “stealth” aircraft

### Contacts

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