Flight and Propulsion Control Technology Development Plans under the new NASA Aeronautics Programs

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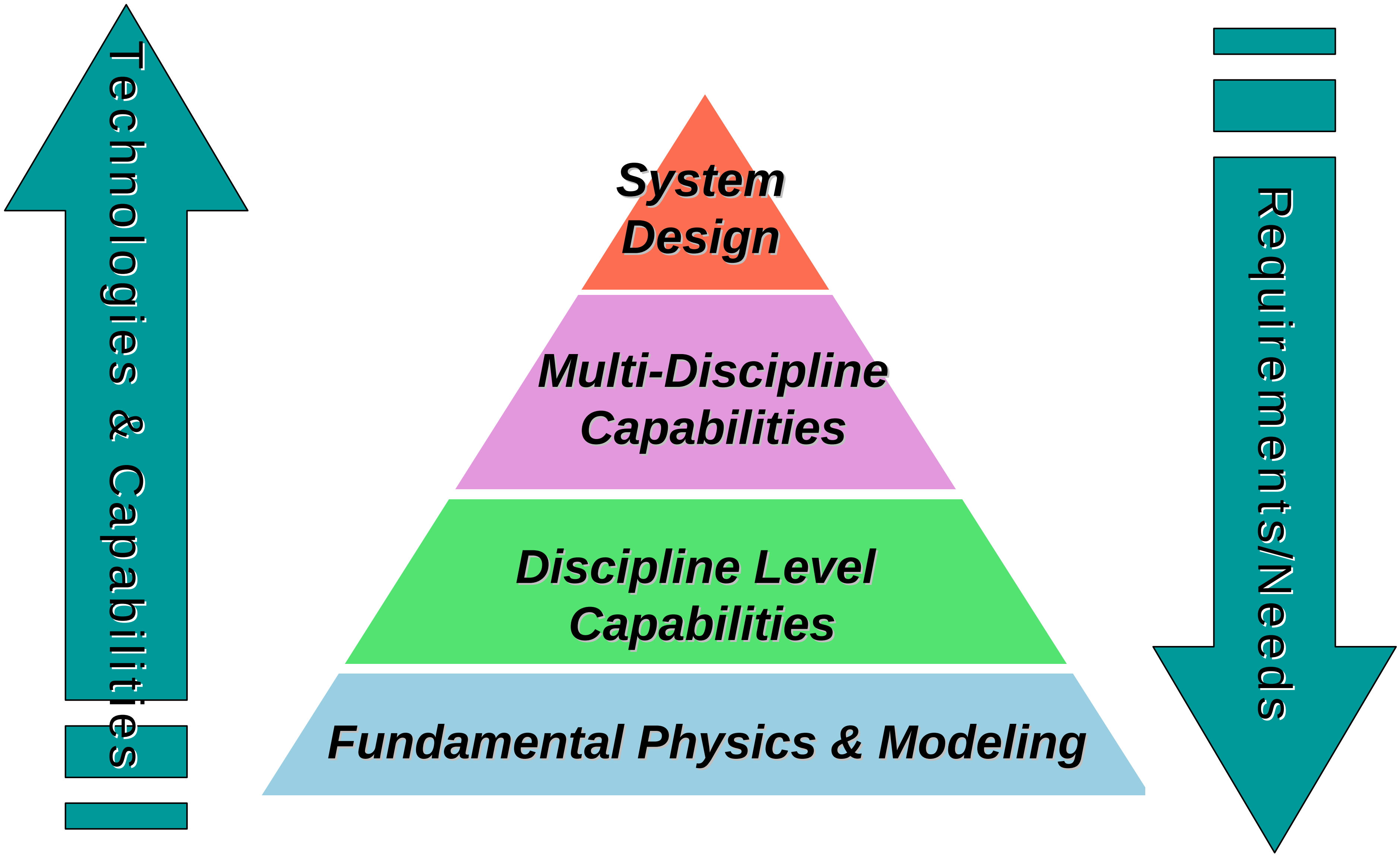
The Three Principles

- NASA is dedicated to the mastery and intellectual stewardship of the core competencies of Aeronautics for the Nation in all flight regimes
- Research will focus in areas that are appropriate to NASA's unique capabilities
- NASA will directly address the needs of the Next Generation Air Transportation System (NGATS) in partnership with the member agencies of the Joint Planning and Development Office (JPDO)

Research Philosophy



Impact on Partnerships

- NASA will take responsibility for the intellectual stewardship of the core competencies of Aeronautics for the Nation.
  - Ensures the availability of a world class resource (personnel, facilities, knowledge and expertise) ready to be drawn upon by our Government partners (e.g., DoD, FAA, JPDO) and by the private sector.
- University partnerships
  - We will integrate students and faculty as true partners in our research projects.
    - ■ Enables replenishment of workforce at both NASA and in industry.
  - Full and open competition for funds.
- Industry partnerships
  - We will shift from near-term, evolutionary procurements to long-term, intellectual partnerships.
    - ■ Ensures ability to provide long-term, stable investment in capabilities that will benefit all of industry.

NASA Aeronautics' Program Structure

- Aeronautics Research Mission Directorate
  http://aeronautics.nasa.gov/programs.htm
  - Fundamental Aeronautics Program
    - Hypersonics
    - Supersonics
    - Subsonic Fixed Wing
    - Subsonic Rotary Wing
  - Aviation Safety Program
    - Integrated Vehicle Health Management
    - Aging Aircraft
    - Integrated Flight Deck Technologies
    - Integrated Resilient Aircraft Control
  - Airspace Systems Program
    - Super-Density Surface Management
    - Next Generation Air Transportation System

Control Tasks Under Fundamental Aeronautics

Fundamental Aeronautics Program

Subsonic Fixed Wing

2.08 Controls and Dynamics
(Dan Vicroy, LaRC)

- Dynamic modeling and robust control of advanced configurations
- Performance Optimization Control
- Distributed Engine Control
- Advanced control for high lift configurations

Subsonic Rotary Wing

2.02 Flight Dynamics and Control
(Chad Frost, ARC)

- Integrated rotor and transmission control
- Individual blade control to improve HQ and agility
- Pilot performance modeling

Supersonics

2.02 Airframe & Propulsion Aero-Propulso-Servo Elasticity
(Bruce Jackson, Walt Silva, LaRC)

- Rapid dynamic model development
- Flexible mode control
- Integrated inlet/engine control
- Active Combustion Control (under different element)

Hypersonics

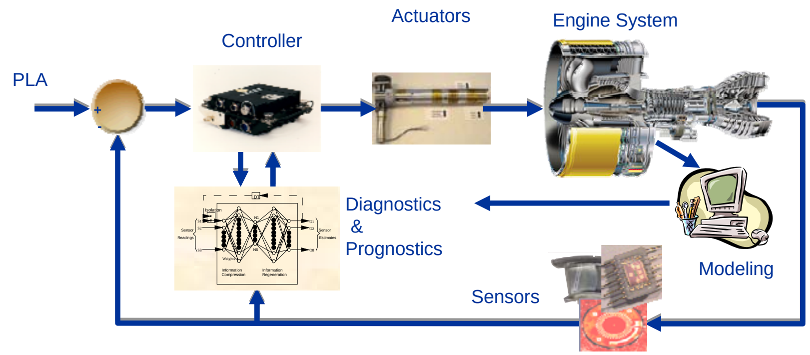
2.04 Advanced Control Methods
(Don Soloway, ARC)

- Guidance and control for multi-mission, multi-propulsion, multi-Mach
- Ground simulations and flight experiment test beds
- General application:
    - Capsule/Reentry Probe
    - Hypersonic Glider
    - Powered Glider

SFW.2.08 — Controls and Dynamics

Objective:

Enable improved aircraft performance by developing technologies for robust control of unconventional configurations and active control of components for improved propulsion efficiency and lower emissions.



An integrated system perspective is important when developing control system technologies – example engine control.

Approach:

Develop and validate multidisciplinary tools for unsteady, nonlinear flight dynamics, and robust and distributive control technologies.

Validation Strategy:

Apply Controls and Dynamics methods to benchmark models and simulations, and test from laboratory to flight:

- Model prediction within uncertainty bounds of test data
- Control approaches provide robustness against uncertainty
- Prototype components meet distributed control requirements

Focus:

Foundational and discipline level work in following areas:

- Dynamic modeling and robust control of configurations with distributed and unconventional control effectors
- Performance optimization control
- Distributed engine control
- Advanced control for high lift configurations

Highlights of Planned NASA In-House Research:

Foundational (Level 1):
- Assess aircraft performance optimization control technologies and establish baseline
- Develop methods for modeling control effectiveness of distributed effectors
- Define component requirements for distributed engine control

Discipline (Level 2):
- Assessment of dynamic modeling methods against existing test data
- Development of robust control approaches for distributed effectors
- Development of performance optimization control methods for unconventional configurations
- Development of advanced control for high lift configurations
- Development of preliminary distributed engine control components

Multi-Disciplinary and System Integration Work (Level 3 & 4):
- Evaluation of impact of robust control with advanced effectors on overall vehicle performance in flight tests in cooperation with industry partners.
- Quantify impact of distributed control on engine performance and emissions in a high fidelity simulation

NRA Investment (Level 1 & 2):

Potential Phase 1 Research in:
- Uncertainty modeling for robust control development
- Nonlinear control methods
- Test-beds for distributed control architecture and components

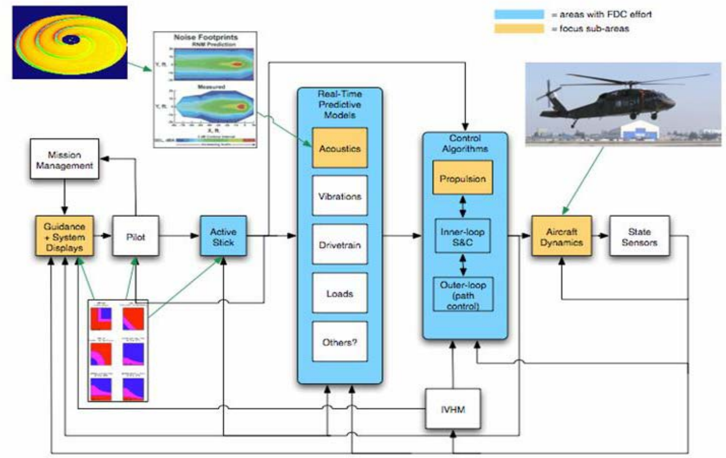
Highlights of Partnership Strategy (Level 3 & 4):

❑ DoD/DoE – leverage existing models, data, and identify validation opportunities
❑ NG, LM, Boeing and AFRL – identify dynamic modeling and advanced control validation opportunities on unconventional configurations such as BWB and AMC-X
❑ GE, P&W – identify opportunities for test of distributed engine control components

SRW.2.02 — Flight Dynamics and Control

Objective:

Enable Rotary-Wing aircraft developers to produce products that “Fly as Designed”, with Level 1 Handling Qualities across the flight envelope.



An integrated aircraft control architecture will incorporate predictive models from multiple disciplines.

Approach:

Develop and validate predictive design tools and multi-disciplinary guidance and control algorithms.

Validation Strategy:

Evaluate tools, models and techniques from the desktop, through piloted simulation, to flight test, and quantify:

- Model prediction within uncertainty bounds of test data
- Success of robust control methods
- Handling qualities achieved versus predicted

Focus:

Foundational and discipline level work in following areas:

- Synchronized control of multi-speed rotor, engine and transmission.
- Exploitation of on-blade and individual-blade control to improve HQ and agility.
- Pilot performance modeling.

Highlights of Planned NASA In-House Research:

Foundational (Level 1):
- Development of multi-speed rotor/engine/transmission-shifting control
- Development of computational pilot performance models that include effects of noise and vibration

Discipline (Level 2):
- Development of design guidance for control mode transitions
- Development of control optimization strategies for IBC/OBC
- Development of super-integrated vehicle control architecture, incorporating models of acoustics, loads, and vehicle dynamics.

Multi-Disciplinary and System Integration Work (Level 3 & 4):
-Flight evaluation of super-integrated vehicle control system, utilizing multi-disciplinary predictive models.

NRA Investment (Level 1 & 2):

Potential Phase 1 Research in:
- Real-time tip-path-plane measurement
- Enhanced aeroservoelastic mode suppression

Highlights of Partnership Strategy (Level 3 & 4):

❑ DoD – leverage existing models, identify validation opportunities, conduct joint development of design tools
❑ Center for Rotorcraft Innovation (CRI, the Rotorcraft industry consortium) – identify pre-competitive opportunities of mutual interest

SUP 2.02. Aero-Propulso-ServoElasticity (APSE)

Objective:

Mitigate the undesirable effects on performance and flying characteristics of highly complex nonlinear aeroelastic/flight dynamics phenomena that simultaneously influence the airframe and propulsion control of unique structural configurations of supersonic aircraft

Semi span ASE model.

Approach:

- ASE/flight dynamic experimental validation data Collect high fidelity data on APSE effects using wind tunnel and flight experiments.
- ASE/flight dynamic analysis and design tool development. Assess effectiveness of current analysis tools; initiate development of improved analysis and design tools.
- APSE analysis and design tools. An initial APSE analysis tool set will be defined and integrated.

Validation Strategy:

Initial validation will be based on completion of tests of an existing semi-span model and on available flight databases. Validation of the APSE analysis tools will require development of a new wind tunnel model with some form of propulsion simulation. Flight data will be valuable for components of the model such as inlets and control surfaces. An industry partner will be sought to infuse configuration design realism into the model development.

SUP 2.02 APSE

Highlights of Planned NASA In-House Research:

Foundational (Level 1):

- Improve airframe non-linear aeroelastic/flight dynamic prediction (body freedom flutter)
- Improve computational efficiency in nonlinear aeroelastic analysis (airframe and engine) through Reduced-Order Modeling techniques
- Rapid flight dynamic model development and related rigid-body control strategies
- Rapid design level analysis and sensitivity analysis

Discipline (Level 2):

- ASE/flight dynamic and propulsion experimental validation data
- ASE/flight dynamic and propulsion analysis and design tool development
- APSE analysis and design tools

Multi-Disciplinary and System Integration Work (Level 3 & 4):

- Demonstration of applicability of design tools for safe, comfortable, and efficient supersonic flight

NRA Investment (Level 1 & 2):

Potential Phase 1 Research in:

- CFD-based aeroelastic methods development
- Advanced ASE control system design
- Aeroelastic shape sensitivity

Highlights of Partnership Strategy (Level 3 & 4):

- DoD computational research opportunities
- Collaborative work with Industry Consortia for supersonic biz jet

HYP.2.04 — Advanced Control Methods

Objective:

Develop next-generation guidance and control algorithms to address the multiple propulsion elements, wide Mach number variation, strong subsystem coupling, and grave modeling uncertainty associated with hypersonic flight; while returning the high performance efficiency necessary for these performance-limited systems.

Focus:

- Adaptive control
- Numerical optimal control
- Probabilistic modeling and control
- Modeling of system phenomena unique to hypersonic flight, e.g. aerothermoelastic behavior.
- Hierarchical control

Approach:

Develop technologies leading to design and analysis tools for trajectory design, and design of adaptive guidance and control laws, with particular emphasis on high L/D airbreathing and unpowered vehicles for flight in Earth's atmosphere, and heavy planetary probes with precise landing requirements. Tool development is supplemented by model development and participation in flight experiments.

Validation Strategy:

- Apply methods to benchmark systems and compare performance to predictions
- Share tools with potential users, e.g. at L4, and get user feedback.

Highlights of Planned NASA In-House Research:

Discipline (Level 2):
- Develop algorithms for trajectory shaping and control of future hypersonic vehicles, as well as hierarchical GN&C system architecture.
- Develop by 2009 improved ground simulation capability, with emphasis on simulating performance under various types of uncertainty, system-wide coupling, and associated model uncertainty.
- A Planetary Probe (HMMES-class) drag or roll modulation GN&C experiment will be conducted from the same vehicle. Using the proposed advanced control techniques, the expected >20% improvement in specific GN&C metrics (trajectory mid-point shaping, stability, targeting) can be attained.

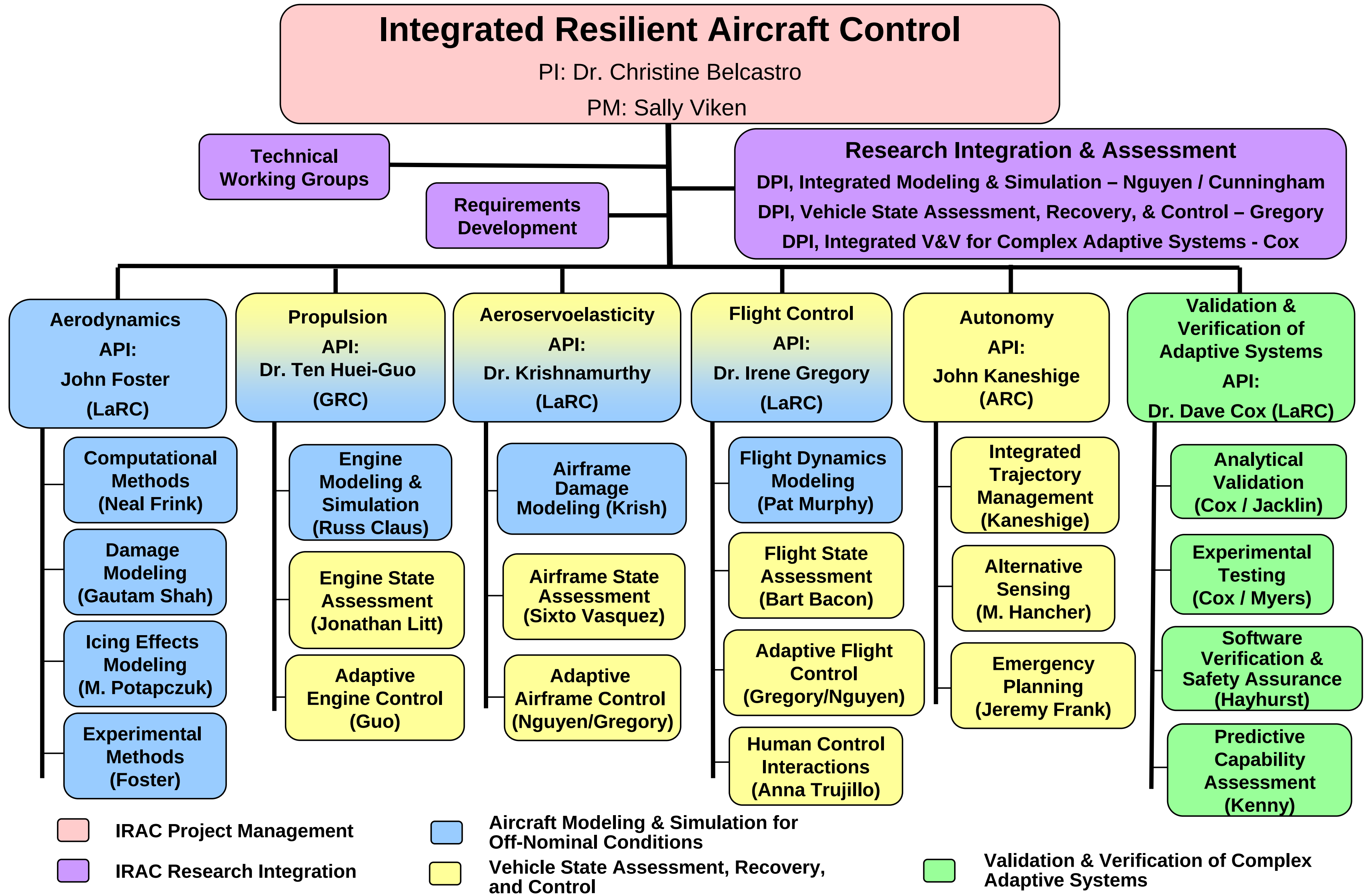
NRA Investment (Level 1 & 2):

Potential Phase 1 Research in:
- Adaptive, hierarchical control methods
- Enhanced aeroservoelastic mode suppression

Highlights of Partnership Strategy (Level 3 & 4):

❑ DoD – leverage existing (X-43A) and future (X-51 Phoenix) models, identify validation opportunities, conduct joint development of design tools

IRAC WBS and Research Elements



IRAC Aerodynamics

Integrated Resilient Aircraft Control

PI: Dr. Christine Belcastro,

PM: Sally Viken

Aerodynamics
API: John Foster (LaRC)

- Computational Methods (Frink)
  - Separated flow
  - Gridding methods
  - Aeroelastic interactions
  - Dynamic derivatives
- Damage Modeling (Shah)
  - Damaged airframe
  - Control surface failures
  - Load distribution
- Icing Effects Modeling (Potapczuk)
  - Hazard effects
  - Stability and control effects
  - Vehicle deformation
- Experimental Methods (Foster)
  - Wind tunnel dynamic rigs
  - Subscale flight vehicles
  - Full-scale flight testing

IRAC Aeroservoelasticity

Integrated Resilient Aircraft Control

PI: Dr. Christine Belcastro,

PM: Sally Viken

Aeroservoelasticity
API: Dr. T. Krishnamurthy
(LaRC)

Airframe Damage Modeling (Krishnamurthy)

- Damage Growth Analysis
- Inverse finite element method for damage estimation
- Equivalent plate analysis for frequency response
- Limit Load and residual life estimation

Airframe State Assessment (Sixto Vasquez)

- Design and develop sensing, monitoring, and diagnosis capability for anomaly detection and damage assessment
- Failure mode analysis-Airframe
- Life models

Adaptive Airframe Control (Nguyen/Gregory)

- Aeroelastic Coupling with control
- Control limits study/evaluation
- Flight simulator support

IRAC Propulsion

Integrated Resilient Aircraft Control

PI: Dr. Christine Belcastro, DPI: Dr. K. Krishnakumar

PM: Joseph Totah, DPM: Sally Viken

Propulsion (GRC)
API: Dr. Ten Huei-Guo)
APM: Susan Johnson

Engine Modeling & Simulation (Claus)

Engine Performance Study
- High inlet distortion
- Off-normal operation
- Fast response
- Operability

Engine State Assessment (Litt)

Engine Life Study
- Failure mode analysis
- Component life models
- Stochastic life models
- Remaining life prediction

Adaptive Engine Control (Guo)

Engine Adaptive Controls
- Control limits study/evaluation
- Control architectures
- Performance/Risk/Life trade-offs
- Propulsion system integration
- Flight simulator support
- TOC/PCA demo

IRAC Flight controls

Integrated Resilient Aircraft Control

PI: Dr. Christine Belcastro,

PM: Sally Viken

Flight Controls
API: Dr. Irene Gregory
(LaRC)

Flight Dynamics Modeling (Pat Murphy)

- Aircraft response in nonlinear unsteady regimes
- Integrated multidisciplinary and high-fidelity modeling
- Test techniques (ground & flight based), full-scale and sub-scale
- Real-time system identification for damage and aero hazards

Flight State Assessment (Bart Bacon)

Safety of Flight Analysis

- Onboard Modeling
- Achievable Dynamics
- Flt Envelope Prediction
- Controllability Prediction
- Icing Effects Detection
- Fault Detection Isolation

Adaptive Flight Control (Gregory/Nguyen)

Off-nominal conditions

- multi-objective & multi-constraint control
- integrated flight/propulsion control
- variable time scale & dynamic control effector response
- recovery from upset conditions
- mitigation of faults and failures
- composite adaptive control

Human Control Interactions (Anna Trujillo)

Upset, high stress conditions

- functional allocation
- situational awareness
- nondeterministic information
- operator as a sensor

IRAC Verification and Validation of Adaptive Systems

Integrated Resilient Aircraft Control

PI: Dr. Christine Belcastro,

PM: Sally Viken

Verification& Validation of Adaptive Systems
API: Dr. Dave Cox (LaRC)

- Analytical Validation (TBD)
  - *Robustness and stability of adaptive systems for non-linear, uncertain, and parameter dependent plants*
- Experimental Capability (Cox)
  - *Closed-loop subscale flight test capability for damage and upset flight conditions*
- Software Verification and Safety Assurance (Hayhurst)
  - *Correctness of implementation in complex and adaptive software systems*
- Predictive Capability Assessment (Kenny)
  - *Probabilistic techniques for uncertainty quantification and propagation in dynamic models*

Airborne Subscale Transport Aircraft Research (AirSTAR) Testbed

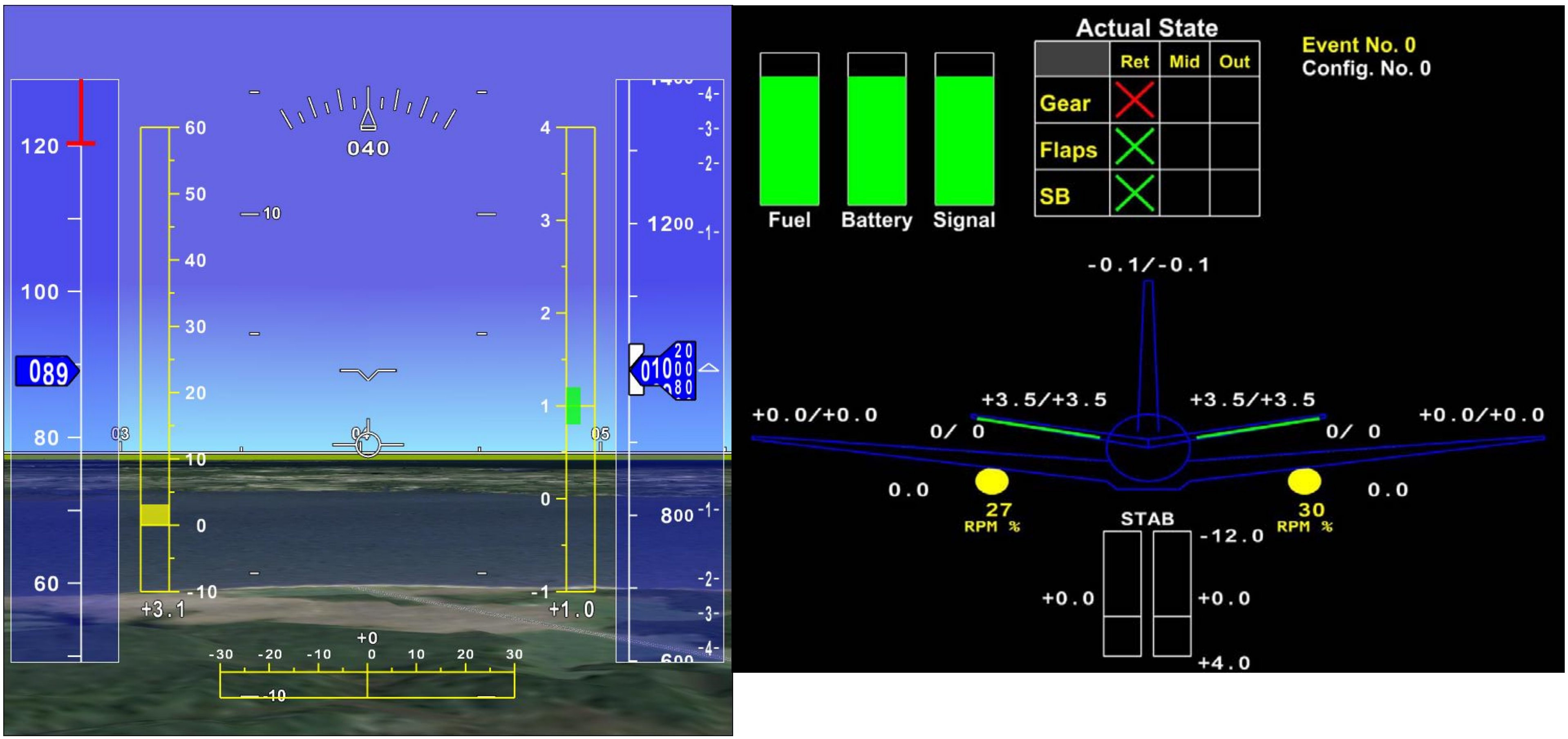
Aviation Safety: IVHM & IRAC | **Technology Verification & Validation**


GTM-T1, T2

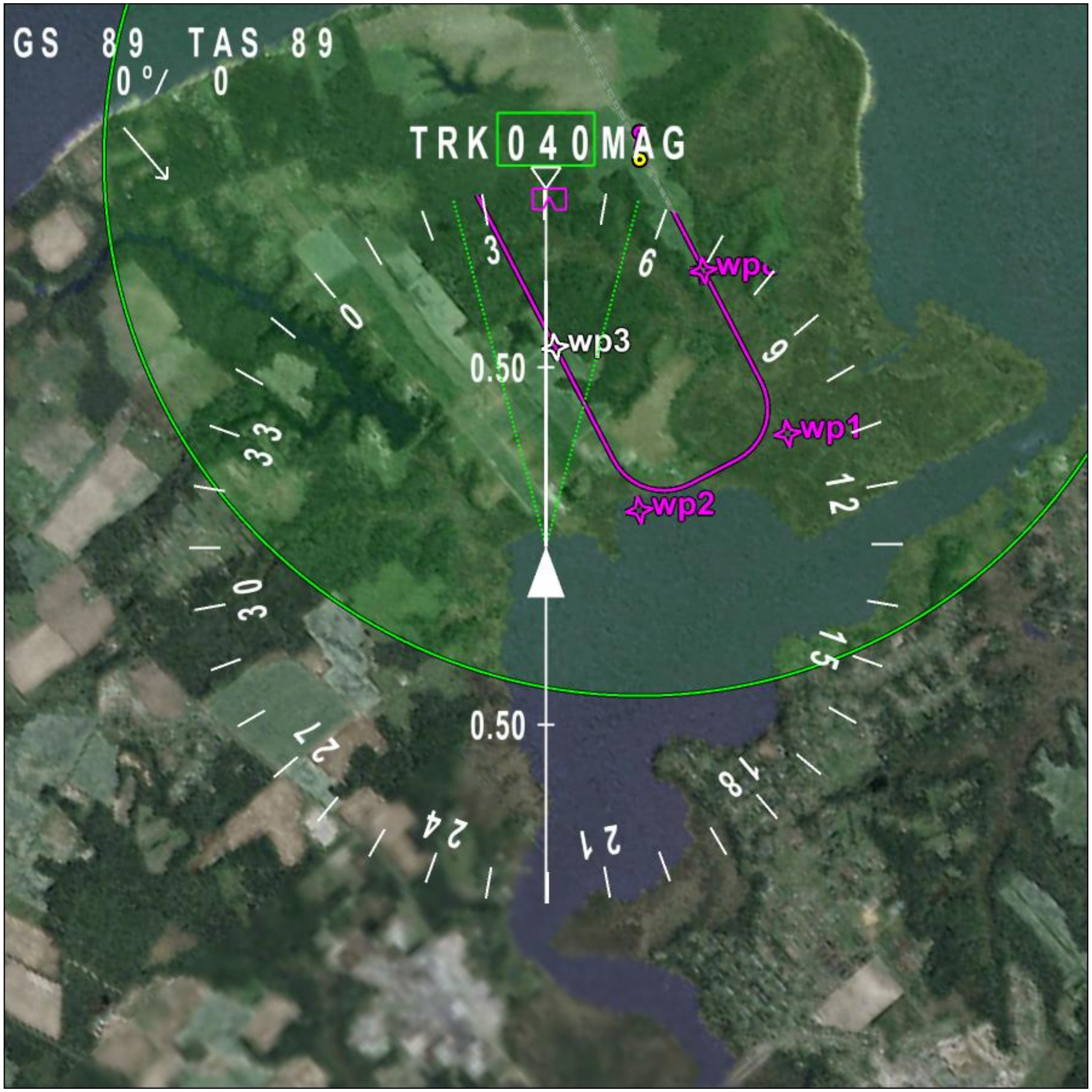

L1011-S1,S2

Subscale Vehicle Flight Testing under Abnormal Conditions

- Research pilot station display sample – HUD, vehicle state



Research Data Collection Flight Test



Flight test area
and
flight pattern

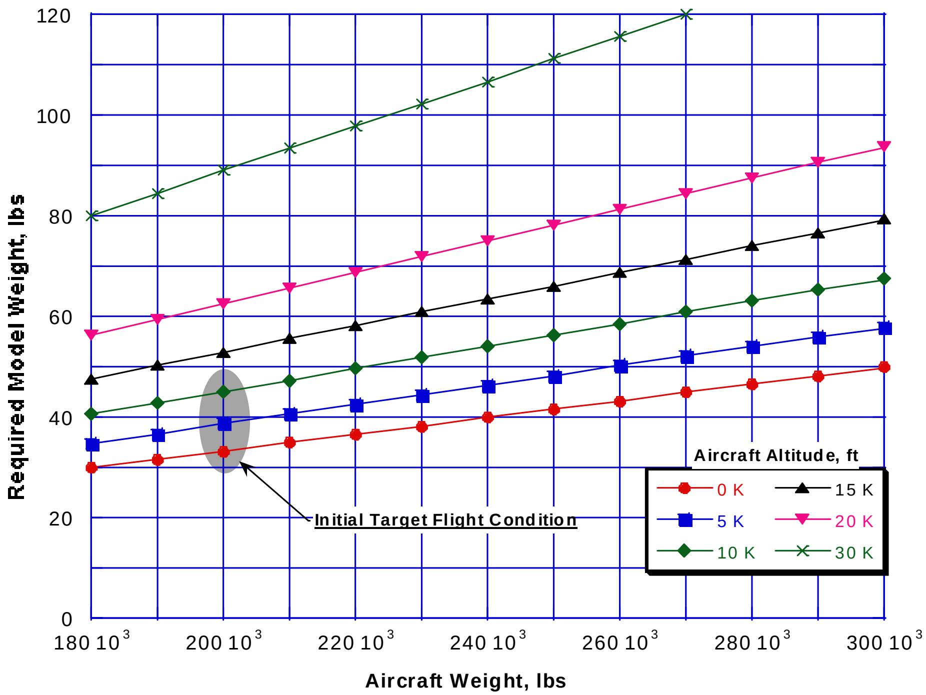
Thank you

Questions?

AirSTAR Generic Transport Model (GTM)

Aviation Safety: IVHM & IRAC | **Technology Verification & Validation**

5.5% Dynamically Scaled Transport Model Aircraft




GTM-T1


GTM-T2

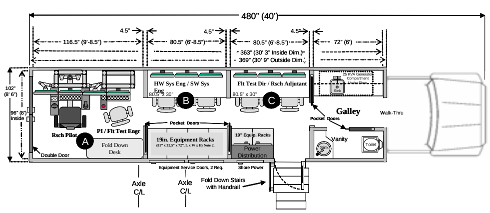
Selected scaled parameters of a 5.5% model

	Length	Wingspan	Weight	Roll inertia	Airspeed	Altitude
Full Scale Transport	145.5 ft	124 ft	200,000 lbs	$2.64e^6$ sl-ft^2	320 mph	13000 ft
5.5% Model	96 in	82 in	49.6 lbs	1.33 sl-ft^2	75 mph	1000 ft

Subscale Vehicle Flight Testing under Abnormal Conditions

Aviation Safety: IVHM & IRAC — **Technology Verification & Validation**

Airborne Subscale Transport Aircraft Research (AirSTAR) Testbed



Approach:

- Phased Transport Aircraft Build-Up & Pilot Training
  - » COTS Jet Trainers
  - » Non-Dynamically Scaled Aircraft
  - » Dynamically Scaled Aircraft
- Remote Control via Telemetry
  - » Piloted
  - » Research Algorithms
- Simulation-to-Flight Testing
  - » Pilot Training
  - » Algorithm Implementation & Verification/Validation

Status & Plans:

- Dynamically Scaled Aircraft: FY02-04
- Subscale Vehicle Simulation: FY03
- Ground/Pilot Station & Ops: FY04-06
- Validation Testing: FY07-11

Benefits / Payoffs

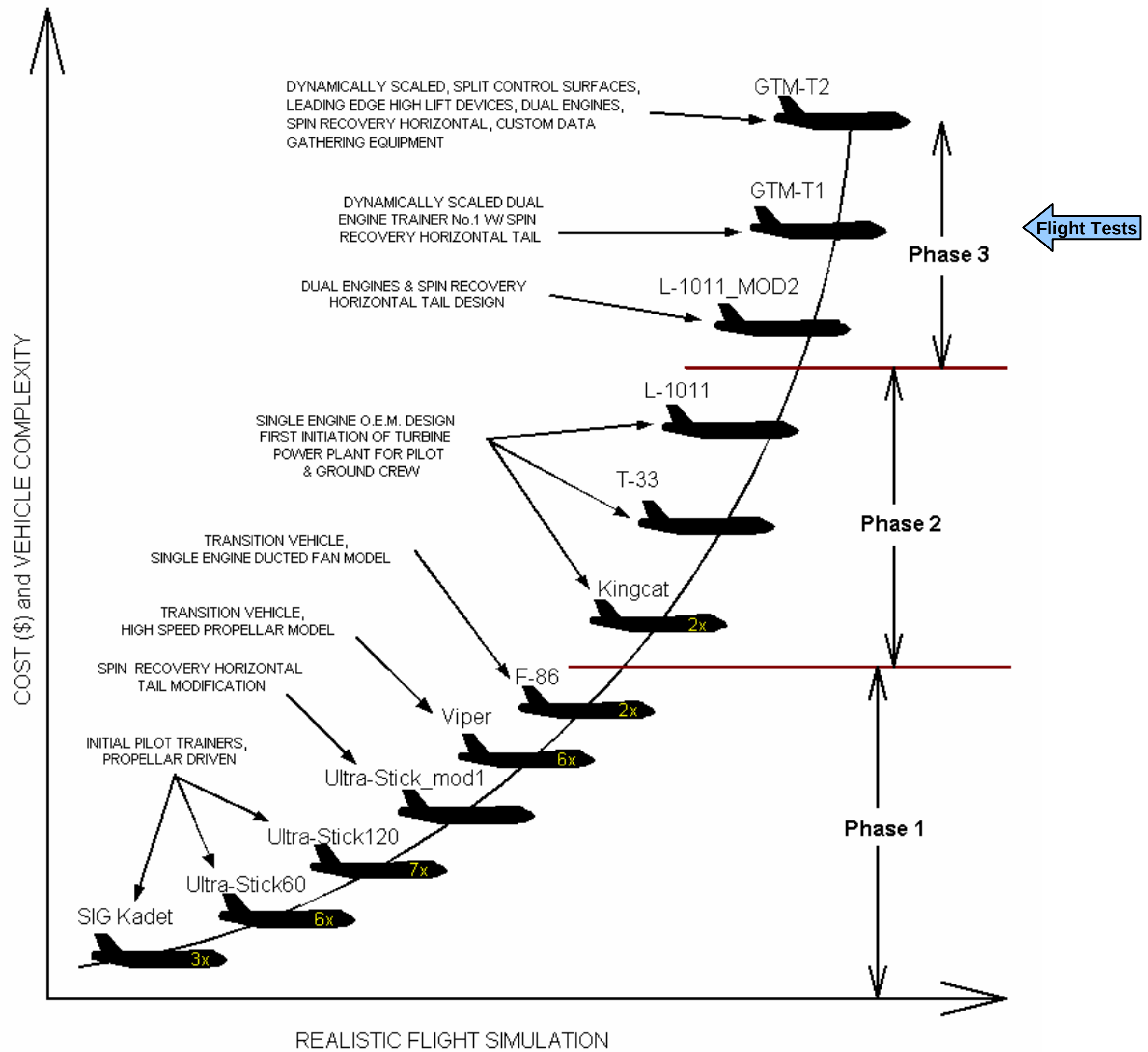
- In-Flight Validation of Models & Safety/Security Enhancement Systems Involving High-Risk Conditions
  - » Flight Outside of Normal Operational Envelope
  - » Failures / Damage
- In-Flight Testing of Integrated Systems
  - » Vehicle Health Management
  - » Control Upset Prevention & Recovery
  - » Damage Adaptive Control Systems

Objective: Develop Subscale Vehicle Flight Test Capability for Evaluation & Validation of AvSP Technologies

- Flight Validation of Vehicle Dynamics Modeling for Upset and Damage Conditions
- Failure/Damage Detection & Accommodation
- Upset Recovery

AirSTAR Pilot Training

Phased Risk Reduction Approach

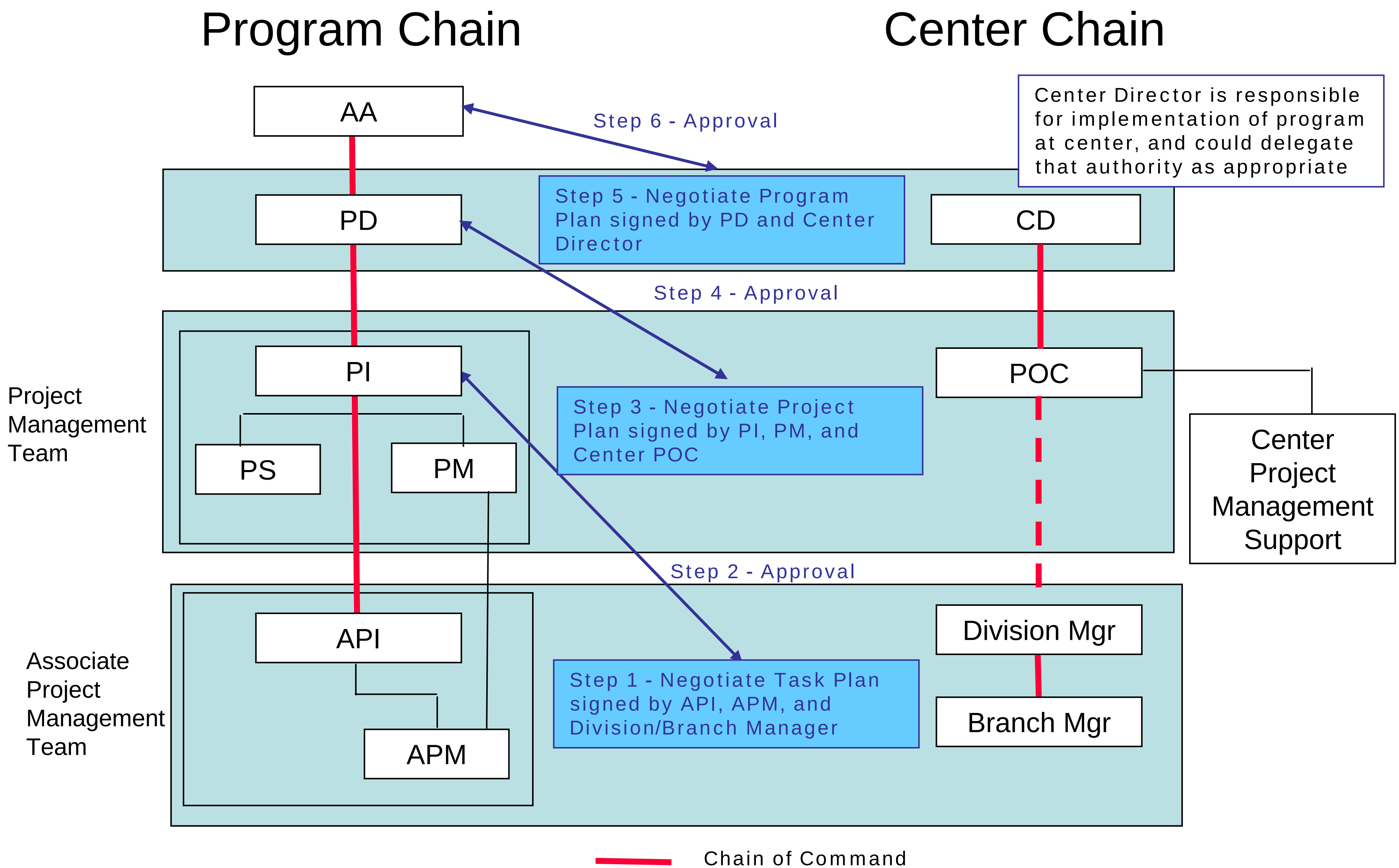


AirSTAR Development Schedule

Aviation Safety: IVHM & IRAC — ***Technology Verification & Validation***

SMITHFIELD		WALLOPS ISLAND		
PHASE I **May 2005**	**PHASE II** **May 2006**	**PHASE III** **Sept 2006**	**PHASE IV** **March 2007**	**PHASE V** **Nov 2007**
				
AIR - Dynamically Scaled Vehicle	- Dynamically Scaled Vehicle - Data System	- Dynamically Scaled Vehicle - Data System	- Dynamically Scaled Vehicle - Data System	- Dynamically Scaled Vehicle - Data System - Autopilot
				
GROUND - Safety Pilot	- Safety Pilot	- Safety Pilot - Mobile Operations Station	- Safety Pilot - Mobile Operations Station - Research Pilot (visible range)	- Safety Pilot - Mobile Operations Station - Research Pilot - Video Tracking (beyond visible range)

ARMD Program Management Structure and Working Relationships with Performing Centers



Airframe Damage Assessment