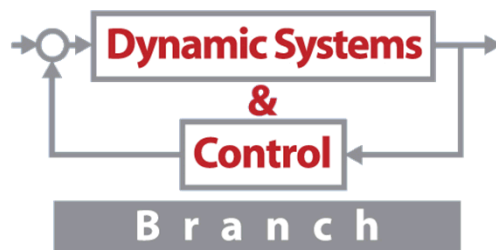


Flight Dynamics & Control at LaRC Update

ACGSC Meeting 116
October 14, 2015

Carey Buttrill



(D316)



(D317)



Abstract

An overview of Langley Research Center (LaRC), the Research Directorate, and the Flight Dynamics and Control (FDC) discipline is included in the appendix (back-up slides).

Recent activities of interest in the FDC area are described.

- Asteroid Redirect
- Uncertainty Quantification for Space Radiation
- Learn to Fly technology
- On-orbit Autonomous Assembly from Nanosatellites (OAAN)

Asteroid Redirect Mission: Dynamic Model and Simulation of the Landing System

Justin M Selfridge

PhD Candidate

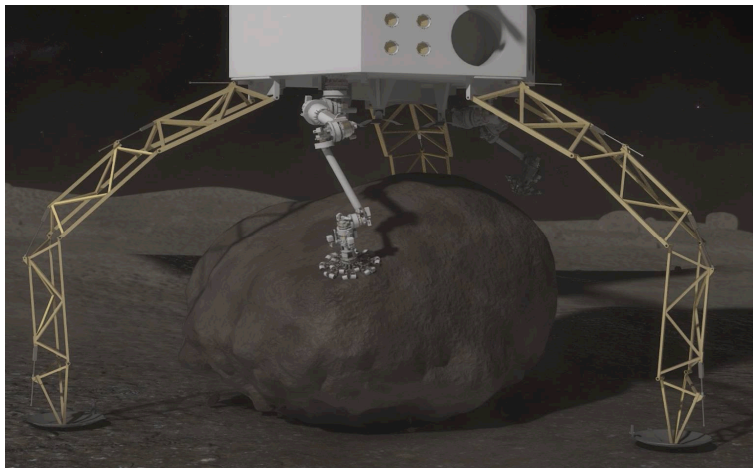
University of Virginia

Supporting:

Dynamics Systems and Controls Branch

NASA Langley Research Center

July - September 2015

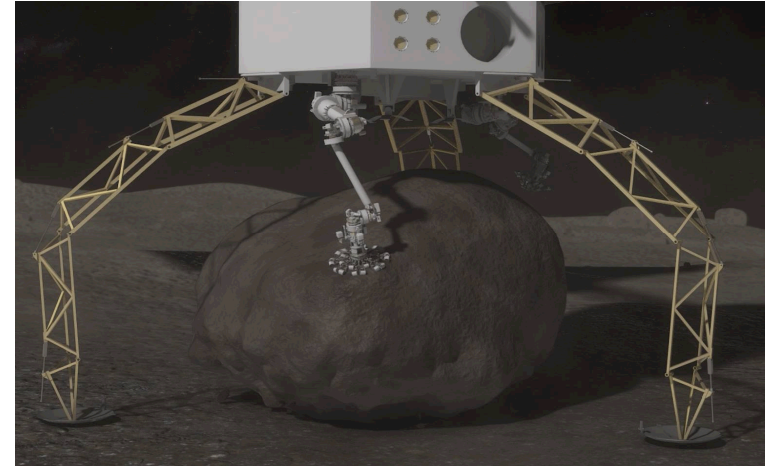


Mission Overview



- *Proposed missions:*

- Retrieve boulder
 - Identify a suitable sample target
 - Between 10 - 70 mT
 - About 2 - 4 meter diameter
 - Land (rendezvous) on near Earth asteroid (NEA) with legged landing system
 - Move boulder into lunar orbit
- Alter the trajectory of a large asteroid
 - About 450 meter diameter
 - Demonstrate measurable change in course



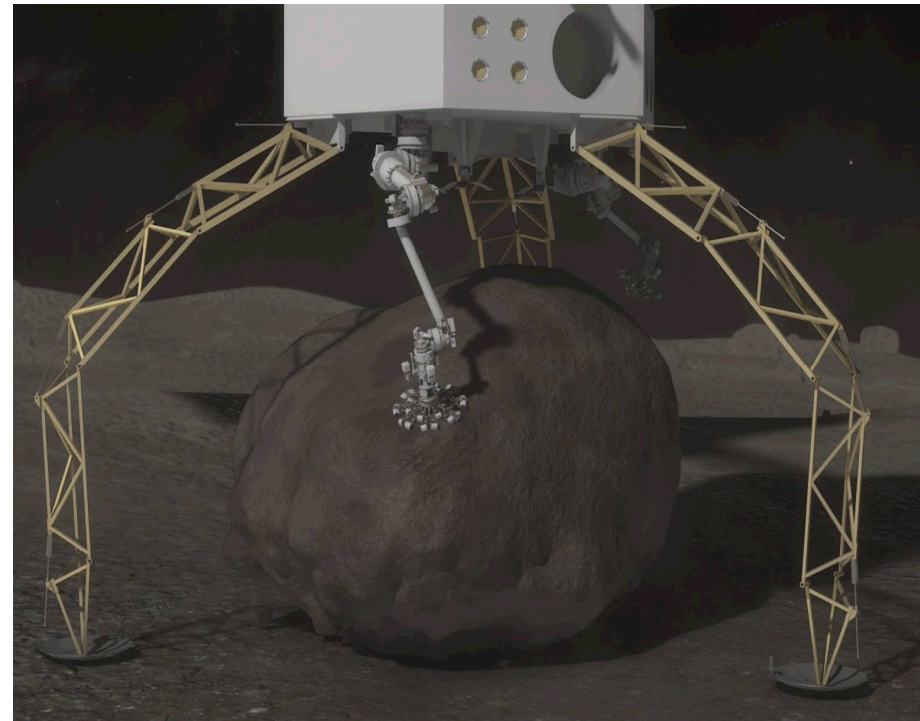
- *Dynamic Modeling and Control Challenges:*

- Inertias and center of gravity (CG) changes as legs move
- Vehicle rotates as legs move (reactionary forces on an unconstrained body)
- Requires precision landing over target boulder
- Gravity is small, but non-negligible
 - Contact must be soft, with no bounce
 - Solar arrays have flexibility which may provide noticeable rebound

Mission Challenges



- *Large solar arrays:*
 - Long moment arms are present
 - Deflections from bending act like a spring during landing and push off
- *Large body module:*
 - Leads to an upward CG position
 - Control is operating away from CG



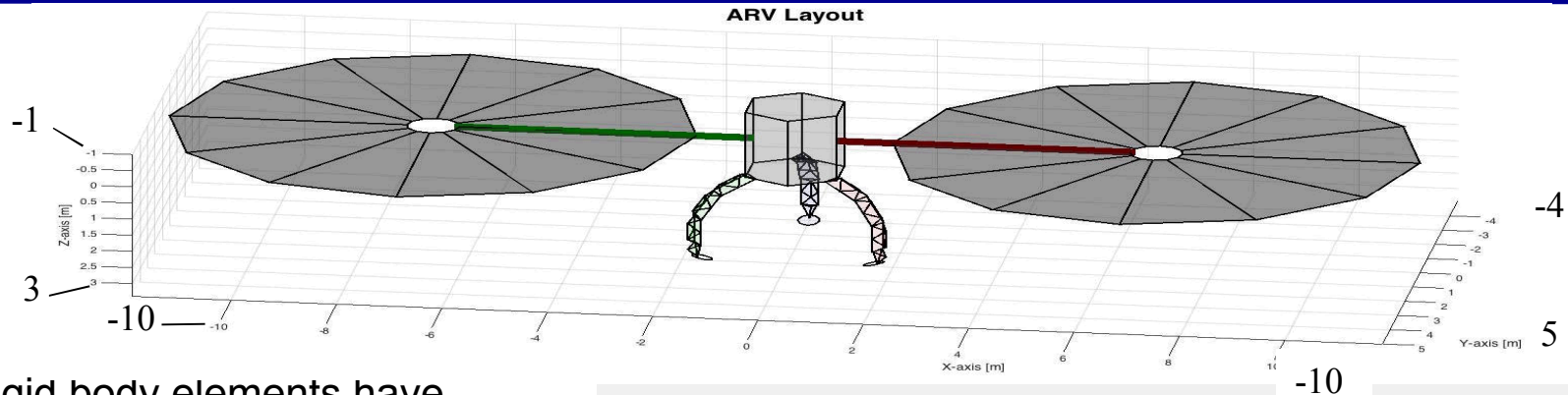
- *Small Clearance:*
 - Requires precise approach and attitude control for landing
 - Very little room to halt ARV
- *Irregular conditions*
 - Boulder shape and texture
 - Landing surface slope and terrain



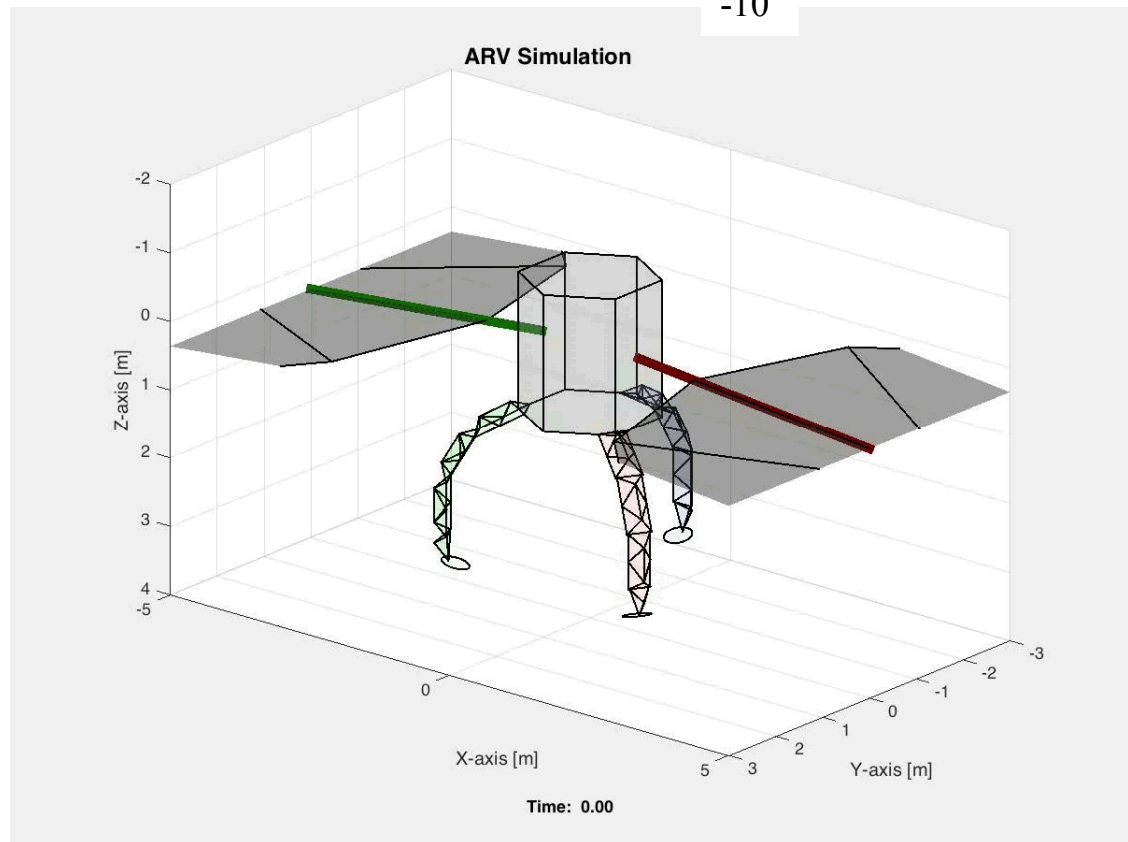
Problem Formulation

- The landing system must absorb energy during the landing. This is accomplished by coordinating the articulation of three legs, each with five rigid body elements.
- Upon landing, control of all the joints within the legs must coordinate with one another to properly influence the deceleration of the central vehicle body.
- The control system must also mitigate dynamics from non-rigid body elements, like the reactionary forces from flexibility within solar arrays.
- A high fidelity nonlinear dynamic model is needed to conduct controls analysis and to generate simulation results.

ARV Model and Simulation Development



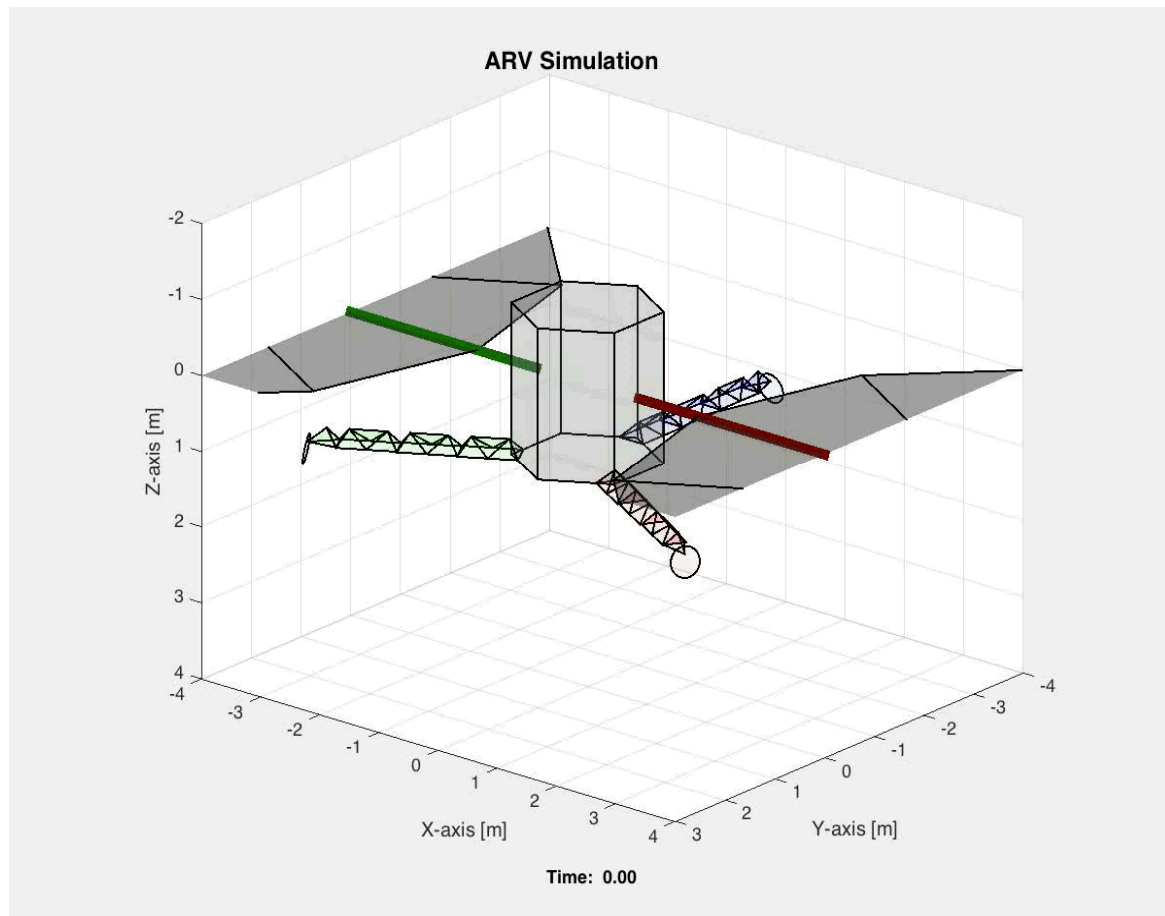
- All rigid body elements have been modeled
- Every element has a prescribed mass, moment of inertia, and CG location
- Connections are modeled as spherical socket joints
- Non hinged axes have restoring stiffness and damping
- Hinged axes have PID reference tracking control
- External forces and moments are included to model thrusters and disturbances

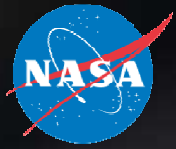


PID Reference Tracking Simulation



- *Demonstrates:*
 - Reference tracking within the hinge joint angles
 - Coupling between leg dynamics and body motion
 - CG location changes as legs articulate to new positions
- *Description:*
 - Five different leg poses
 - One second ramp to new position, and one second pause to observe transient
- *Notes:*
 - Exaggerated properties showcase the dynamics
 - Moderately damped joints
 - Smaller masses and moment inertias





Advanced Radiation Protection: Thick Galactic Cosmic Ray (GCR) Shielding Project

End of Year Continuation Review

Uncertainty Quantification

Presented by:
Ryan Norman and Sean Kenny
October 7, 2015



What Makes Uncertainty Quantification for GCR Particularly Challenging?

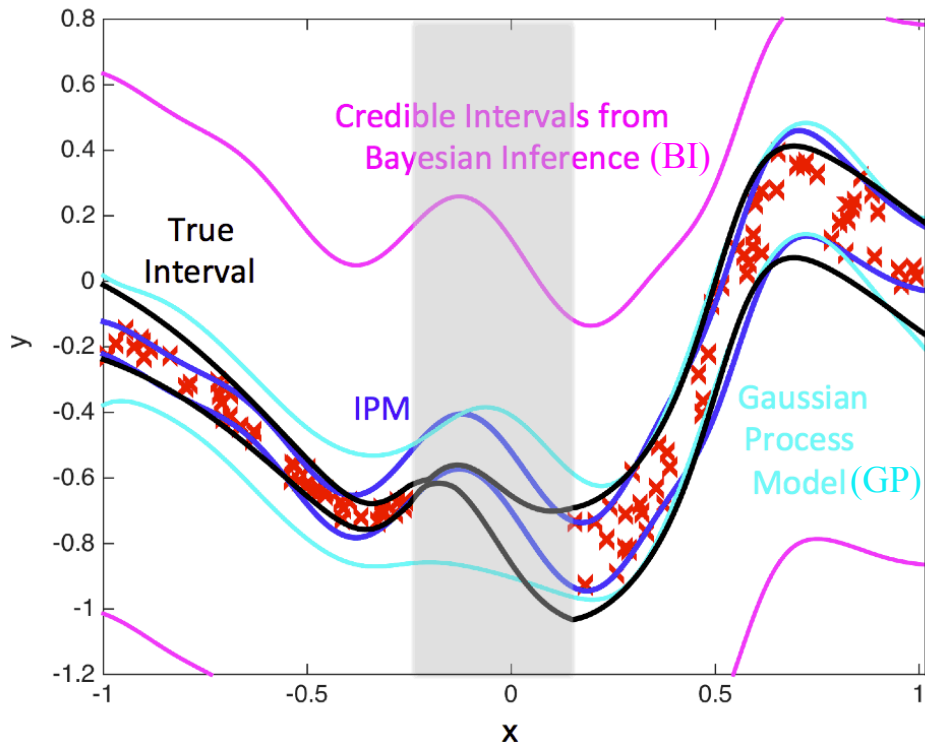
- Deliver mathematical model of radiation physics uncertainty that can be used to confidently extrapolate uncertainties from lab to space environment
 - **Extrapolation beyond validation data is very challenging**
- Develop models for prediction uncertainty based on comparison of measurements to Monte Carlo calculations
 - **Differing statistical fidelity between experiment and simulation**
- Enhance prediction uncertainty models for applications with HZETRN
 - **Increments calibrated to Monte Carlo codes and applied elsewhere**
- Use HZETRN to analyze Galactic Cosmic Ray (GCR) environment on humans
 - **Excessively large uncertainties will prevent making decisions**



- A comparative analysis among **Interval Predictor Models (IPMs)**, **Bayesian Inference (BI)** models, and **Gaussian Process (GP)** models was performed
- New UQ methods being developed for this project
- Based upon original IPM work: *Campi, M., et. al., Interval predictor models: Identification and reliability, Automatica, 2009*

Comparison with Other Methods

True Interval = 99.7% (3sigma) bounds



	Conservatism	Reliability	Computation
IPM	✓	✓	✓
GP	✗	N/A	✗ ✗
BI	✗ ✗ ✗	N/A	✗

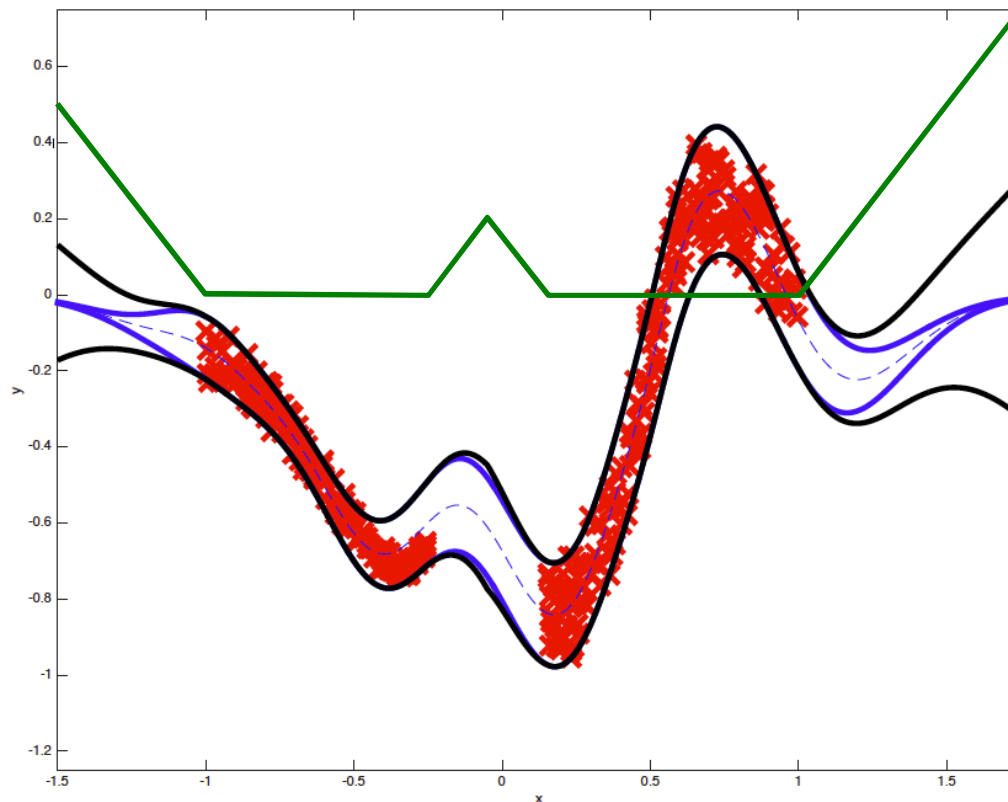
IPMs provide:

- tightest interval
- reliability guarantee
- computational advantage

Crespo L. G., Kenny, S. P.; and Giesy D.; A comparative analysis of metamodeling techniques using numerical experiments, AIAA Scitech, Jan 4-8, 2016

IPMs with Extrapolation & Data Gaps

- Strategies for shaping an IPM during extrapolation were developed
- Example: Blue is a data-based IPM, Green defines expert opinion trends, and Black is IPM combining data and expert opinion





Publications

• Journal Publications

- Crespo L. G, Kenny S. P., Giesy D. P.; Interval predictor models for linear parametric models, ASME Journal of Verification, Validation and Uncertainty Quantification, 2015. In review
- Crespo L. G, Kenny S. P., Giesy D. P.; Random Predictor Models for rigorous uncertainty quantification, International Journal for Uncertainty Quantification, 2015. Accepted

• Conference Publications

- Crespo L. G., Kenny, S. P.; and Giesy D; Norman R., Blattnig, S.; Interval Predictor Models with a Radial Basis Structure and their Application to Space radiation shielding, AIAA Scitech, Jan 4-8, 2016. Accepted
- Crespo L. G., Kenny, S. P.; and Giesy D; Mullins J, Hu, K.; A comparative analysis of metamodeling techniques using numerical experiments, AIAA Scitech, Jan 4-8, 2016. Accepted
- Crespo L. G, Kenny S. P., Giesy D. P.; Random predictor for rigorous uncertainty quantification: Part 1, ESREL Sept. 7-10, 2015, accepted
- Crespo L. G, Kenny S. P., Giesy D. P.; Random predictor for rigorous uncertainty quantification: Part 2, ESREL Sept. 7-10, 2015, accepted

Learn To Fly Project



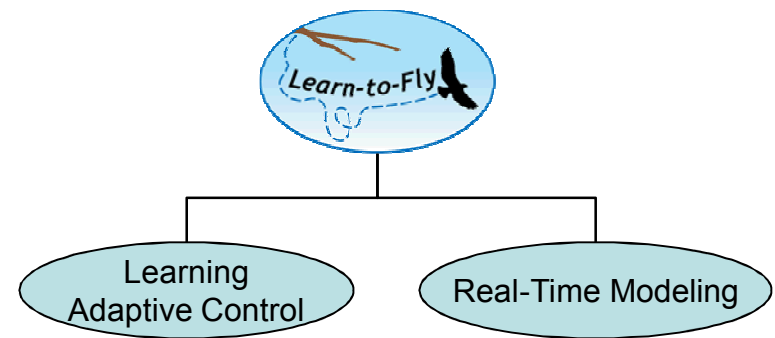
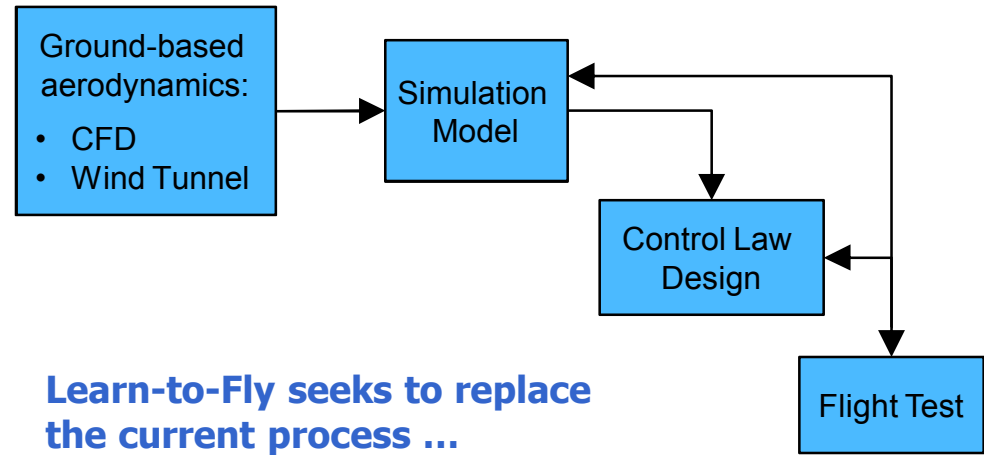
Jay Brandon - Lead



Learn To Fly Concept

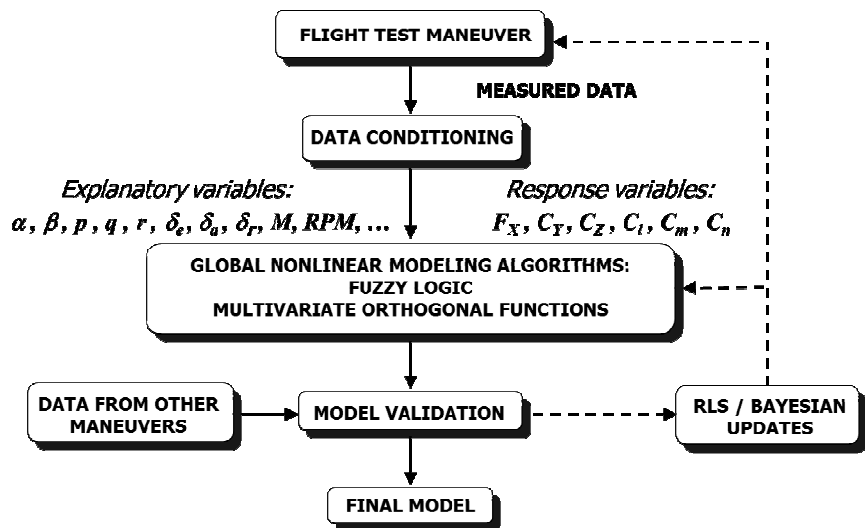
L2F: Merging real-time modeling, controls, and other disciplines with the goals of using self-learning to disrupt our current vehicle development paradigm

Enabling autonomous and other advanced vehicles...

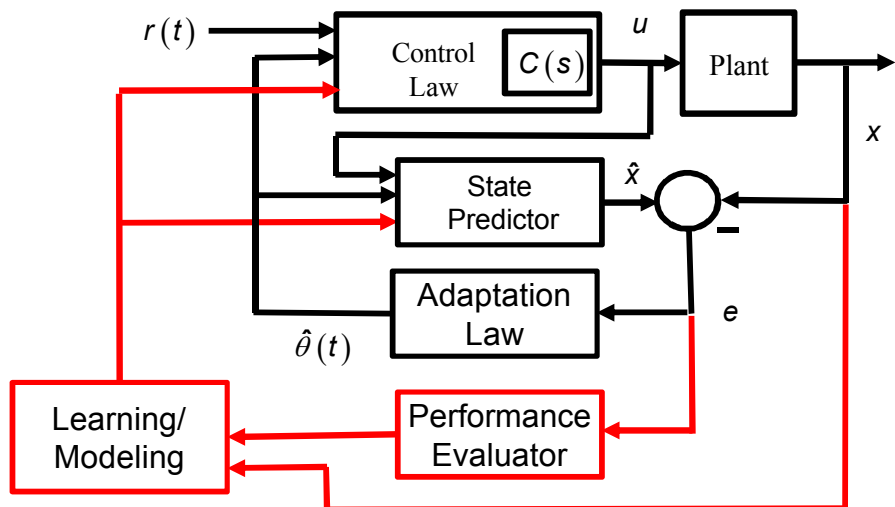


...with a new paradigm that enables N+3/N+4 and other advanced vehicles

Key Technologies



- Real-Time Modeling
 - Actual flight conditions
 - Interaction effects included
 - No model assumptions needed



- Learning/Adapting Controls
 - Adaptation for initial stability
 - Learning as conditions encountered

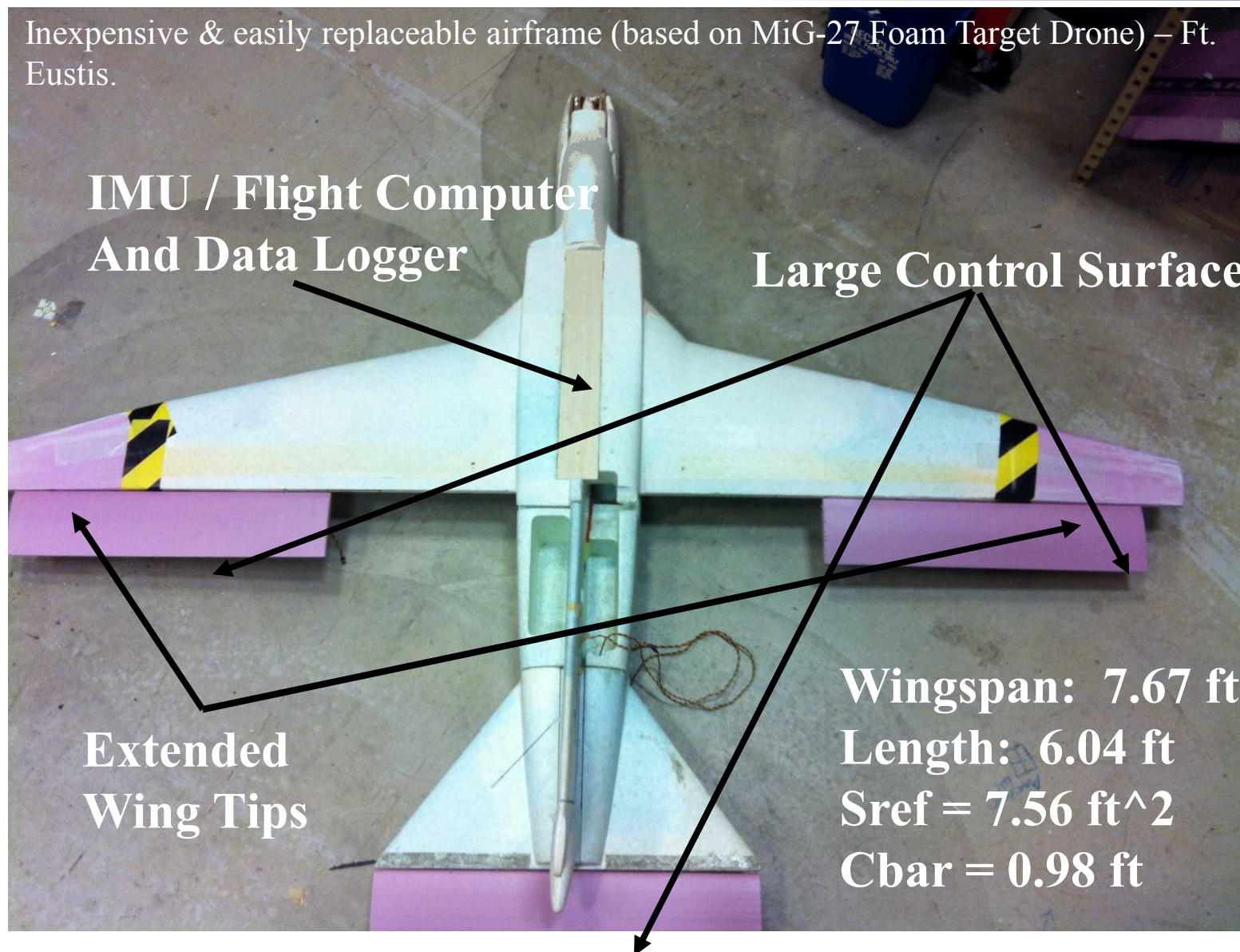


Project Overview

- Demonstrate Aspects of Self-Learning Airplane (ARMD CAS “Incubator” Project)
 - Jay Brandon, Gene Morelli, Sean Laughter, Bart Bacon, John Foster, Mark Croom, Ron Busan
- Drop Tests of Lightweight Foam Glider From Tethered Balloon (CAS project)
 - At LaRC “North 40”
 - Autonomous Navigation
 - Range Protection
 - Safety pilot with R/C
 - Lost-link failsafe
 - No Telemetry – all onboard instrumentation
 - Target Flight Week is Oct 26 - 30
- Development of rapid wind tunnel test methods (ARMD T³ project)
 - Fundamental tool/technique development
 - Allied with L2F self-learning airplane
 - Automated modeling and learning/adapting controls

Learn to Fly Foamie (#1)

Inexpensive & easily replaceable airframe (based on MiG-27 Foam Target Drone) – Ft. Eustis.

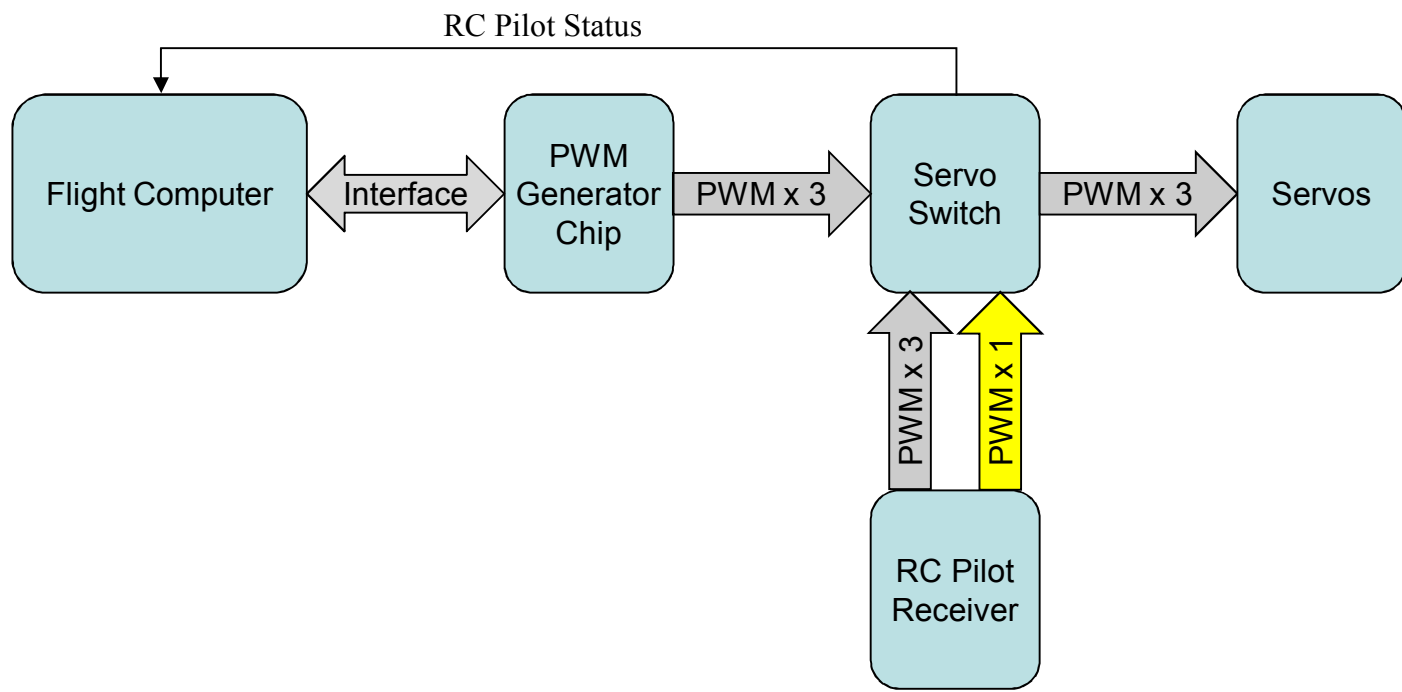




Safety / Reliability

- Control can be taken by safety pilot at any time
 - Already demonstrated it can be flown well by the safety pilot
- Lost-Link Failsafe
 - Lost link will result in controls hard-over, will put airplane in spin or tight spiral. Drift analysis shown in figure from simulation
 - Fail-safe controls verified prior to each operational day

Flight Computer & RC Pilot System



- Servo Switch external to flight computer and controlled by RC Pilot.
- Servo Switch does not latch, allows reversion back to flight computer control at RC Pilot discretion.
- Flight Computer CANNOT override lost-link failsafe.
- Lost-link failsafe controlled by RC Pilot receiver. In case of failsafe:
 - Servo Switch PWM command signal set to switch to RC Pilot
 - Servo commands set to failsafe positions

Tethered Drop Tests

- From 125' off JLG man-lift
- 10 successful flights
- All flown by Lou Glaab
- May/June 2015



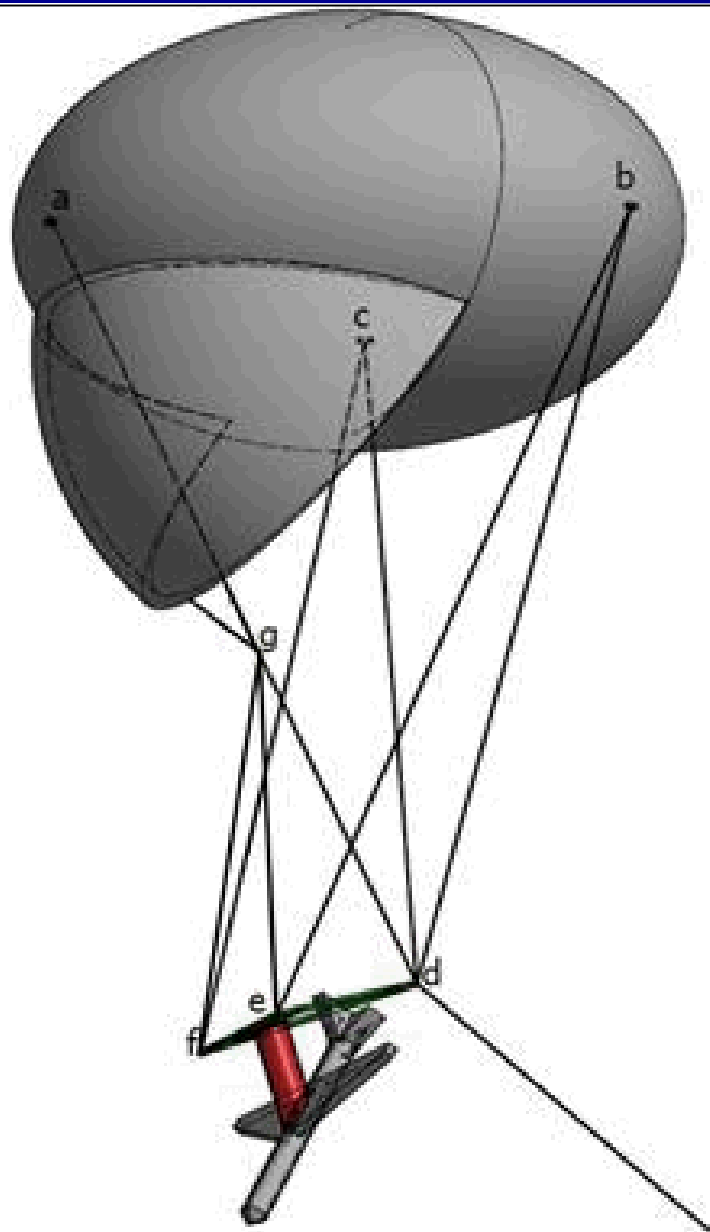
Balloon Inflation Test

- Developed and checked out balloon inflation, operation, and deflation
- Evaluated support trailer
- Evaluated dynamics during model drop
- 40 lbs lifting capability
- 5 Students - Summer

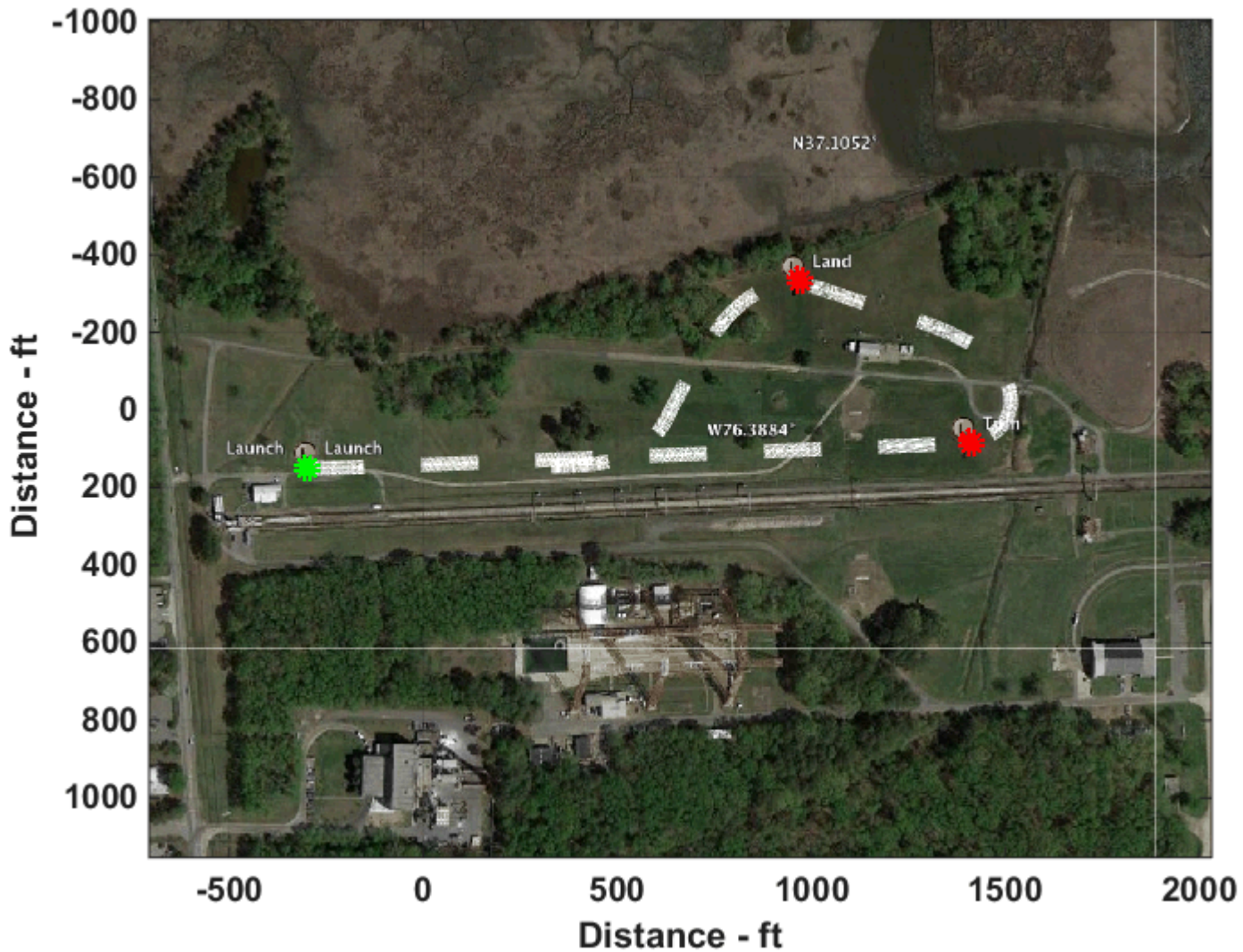


Flight Operations

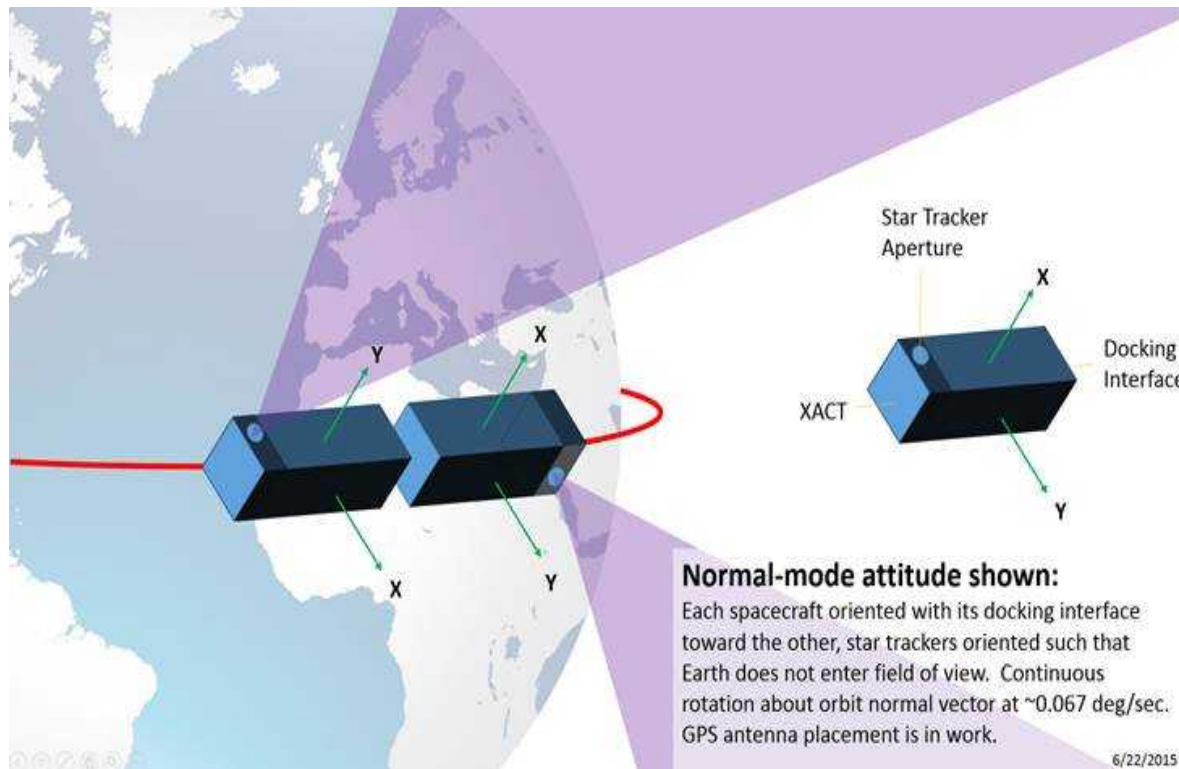
- Autonomous Flight
 - No telemetry
 - GPS waypoint navigation
- Safety Pilot
 - R/C system to take control to keep model in range, if needed
 - Might perform landings



Example Simulated Trajectory



On-Orbit Autonomous Assembly of Nanosatellites

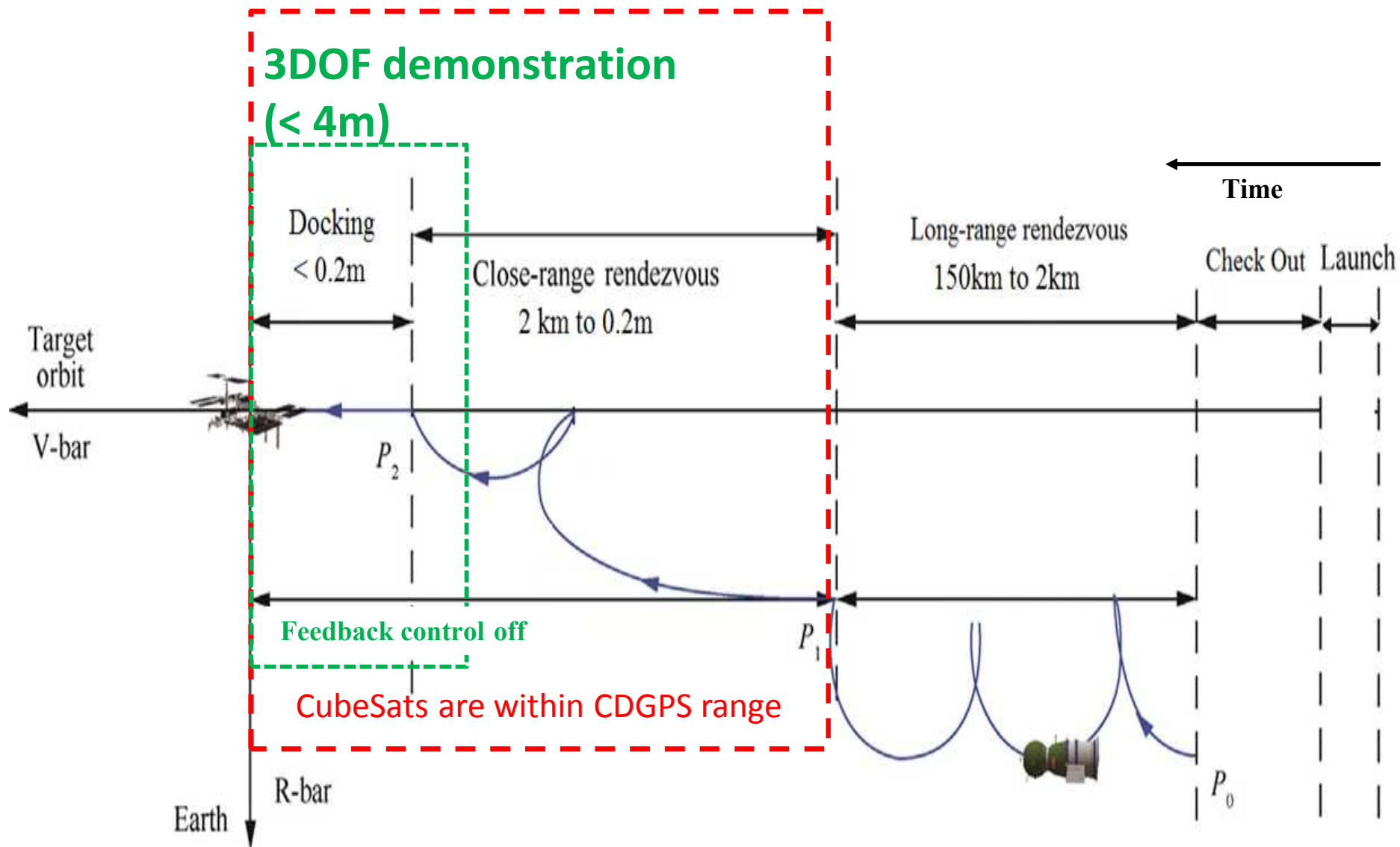


Jing Pei (Vehicle Analysis Branch, LaRC)



- On-Orbit Autonomous Assembly of Nanosatellites (OAAN) is a proposal that was selected by STMD as part of the Early Career Initiative (ECI) program
- Innovative part of this project is the **development of an autonomous low-powered magnetic docking subsystem** that would provide a collision free basin of attraction when docking two CubeSats in space
 - Eliminates the need for high precision GN&C features or human in the loop
 - Magnetic docking subsystem automatically align the two CubeSats
- Two year guaranteed funding period
 - At the end of the two year, the team shall demonstrate proof of concept in a 3-DOF environment.
 - If successful, funding would continue and the team will have the opportunity to perform the experiment in-space (need to apply for a launch opportunity)
- Team consist of 7 early career engineers at LaRC and Cornell University as the external partner (PI: Mason Peck and 2 graduate students)
- GN&C Team: Jing Pei (Vehicle Analysis Branch, LaRC) and Ryan Elandt (Cornell university)

Concept of Operation Schematic (On Orbit/In-space)

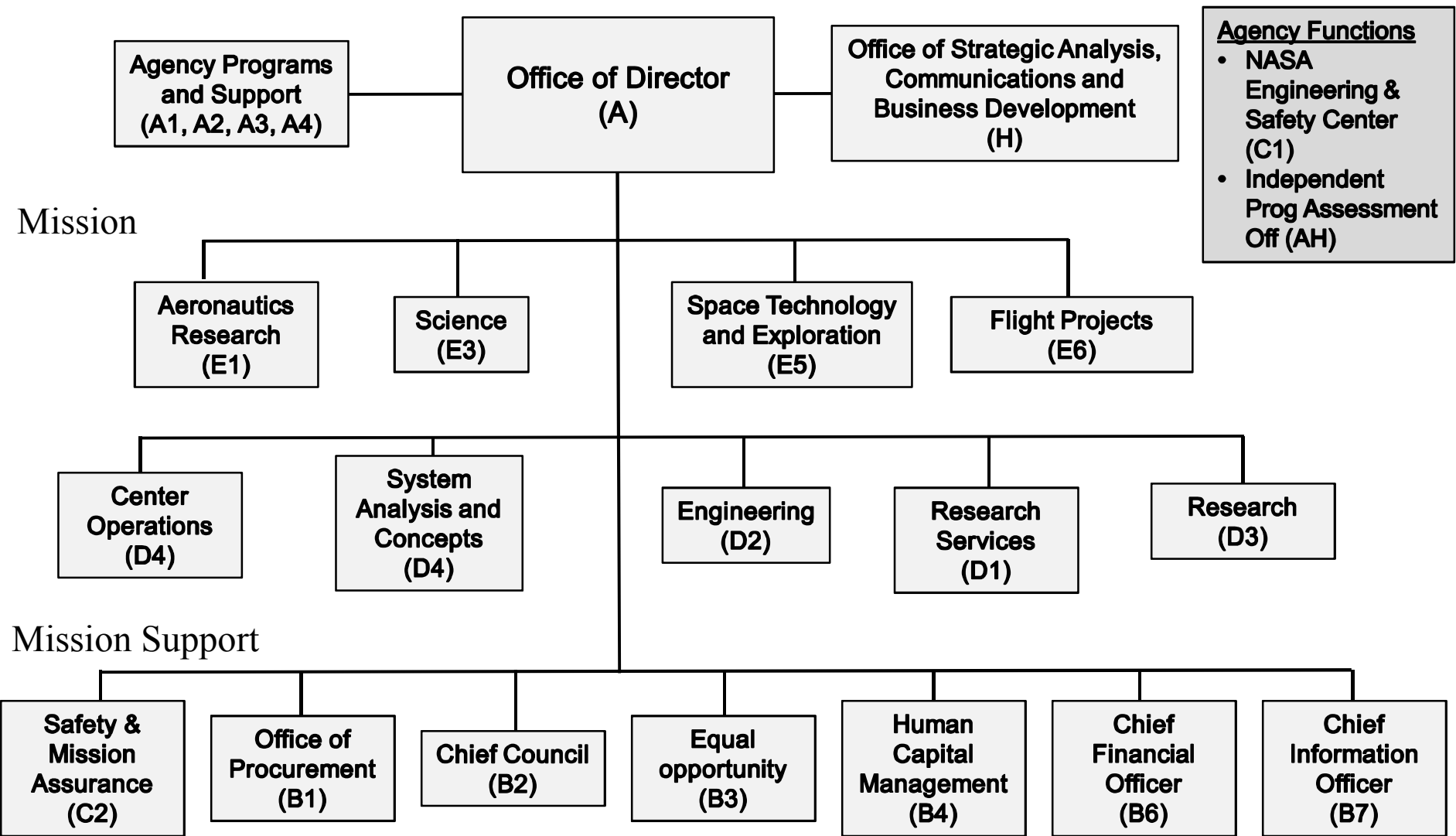




Background



NASA Langley Org Chart





Safety

Sr. Safety Eng.
Safety Eng.

RESEARCH DIRECTORATE (D3)

Director

Deputy Director

Deputy Director for Program Development
Director for Facilities & Laboratories Ops.
Assoc. Director for Resource Management
Director for Program Development
Associate Director for Facilities Operations
Assoc. Director for Laboratories Ops.
Executive Secretary

Chief Engineers (CE) & Tech Leads

CE for Testing Technologies
CE for Test Ops Excellence
CE for Hypersonics
CE for Aerodynamics
CE for Materials & Structures
CE for Acoustics
CE for Airborne Systems
CE for Measurement Sciences
Agency NDE Specialist
Lead for Business Partnership
Senior Project Portfolio Manager
Fac. & Lab Investments Mgr.

Resource Management Team

ATP Business Mgr.
Business Mgr.
Program Analyst (3)
Sr. Adm. Officer
Adm. Officer (3)
TEAMS II Center Mgr.
NIA COR
SMAAART COR
IT Manager
Program Specialist

**D301 Configuration
Aerodynamics Branch**

**D302 Computational
Aero-Sciences Branch**

**D303 Flow Physics
and Control Br**

**D304 Advanced
Sensing & Optical
Measurement Branch**

**D305
Aerothermodynamics Br**

**D306 Hypersonic
Airbreathing
Propulsion Branch**

**D307 Advanced
Materials &
Processing Branch**

**D308 Aeroelasticity
Branch**

**D309 Durability,
Damage Tolerance, &
Reliability Branch**

**D312 Structural
Mechanics &
Concepts Branch**

**D313 Nondestructive
Evaluation Sciences
Branch**

**D314 Aeroacoustics
Branch**

**D316 Dynamic
Systems & Control
Branch**

**D317 Flight
Dynamics Branch**

**D318 Crew Systems &
Aviation Operations
Branch**

**D319
Electromagnetics &
Sensors Branch**

**D320 Safety-Critical
Avionics Systems
Branch**

**D321 Structural
Acoustics Branch**

**D322 Structural
Dynamics Branch**

**D325 Materials
Experiments Br**

**D326 Structures
Experiments Br**

**D327
Subsonic/Transonic
Testing Branch**

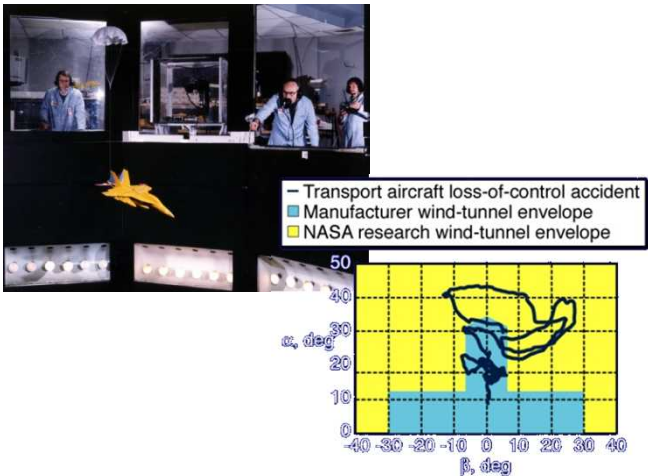
**D328
Supersonic/Hypersoni
c Testing Branch**

**D329 Structures
Testing Branch**

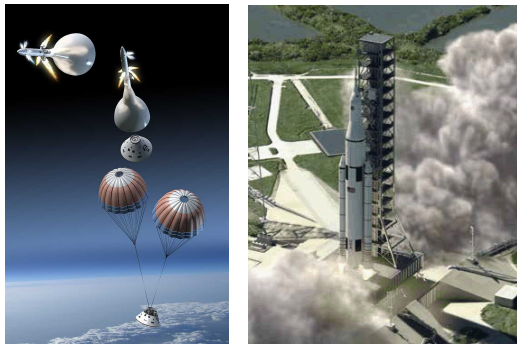
**D330 Technologies
Application Branch**

**D331 Revolutionary
Aviation Technologies
Branch**

Flight Dynamics and Controls in RD at Langley



Control Upset Characterization and Prediction

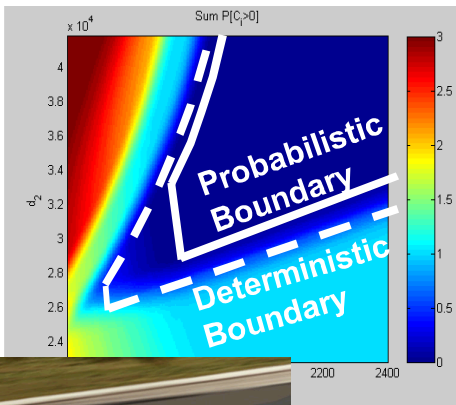


Entry and Launch Vehicle Flight Dynamics and Control

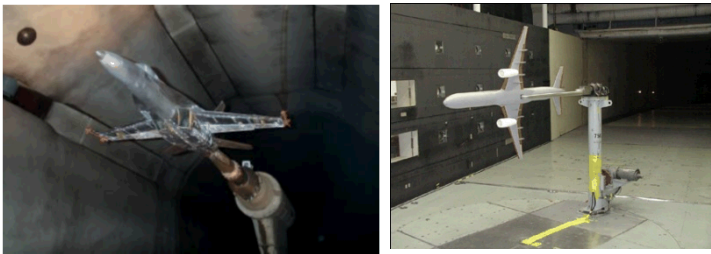


Trajectory Analysis And Control

Uncertainty Quantification



Robust, Adaptive Control



Static and Dynamic Stability & Control



Flying / Handling Qualities



OAAN GNC Activities

- High Priority
 - Designing the translational GN&C algorithms along with an novel magnetic docking subsystem that guarantees a collision free basin of attraction during the final few meters
 - Extensive testing of the navigation hardware which relies on [Carrier Differential Phase GPS](#) that provides relative position measurements between the two CubeSats
 - Extensive simulation results indicate that the concept works as expected under uncertainties
 - Fully integrating a COTS Attitude Determination and Control package
 - OAAN team is preparing for a demonstration of this concept in a 3 DOF environment
- Lower Priority
 - Demonstrate the novel magnetic docking subsystem in-space (ultimate goal)
 - Develop GN&C algorithm that perform robust rendezvous between two CubeSats given a wide range of initial conditions (ie. the CubeSats could be as far as 150km apart in the relative $\mathbf{v}$ -bar direction)
 - GN&C team is currently performing trade studies on two main far field rendezvous approaches: 1) optimized impulse burn approach based on solving Lambert's problem, 2) Continuous feedback control scheme based on the propagated orbital dynamics states