Advanced Aerospace Vehicle Stability Analysis and Control Design Using MATLAB & Simulink

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Huntsville, Alabama

From Science to Solutions

10-0789

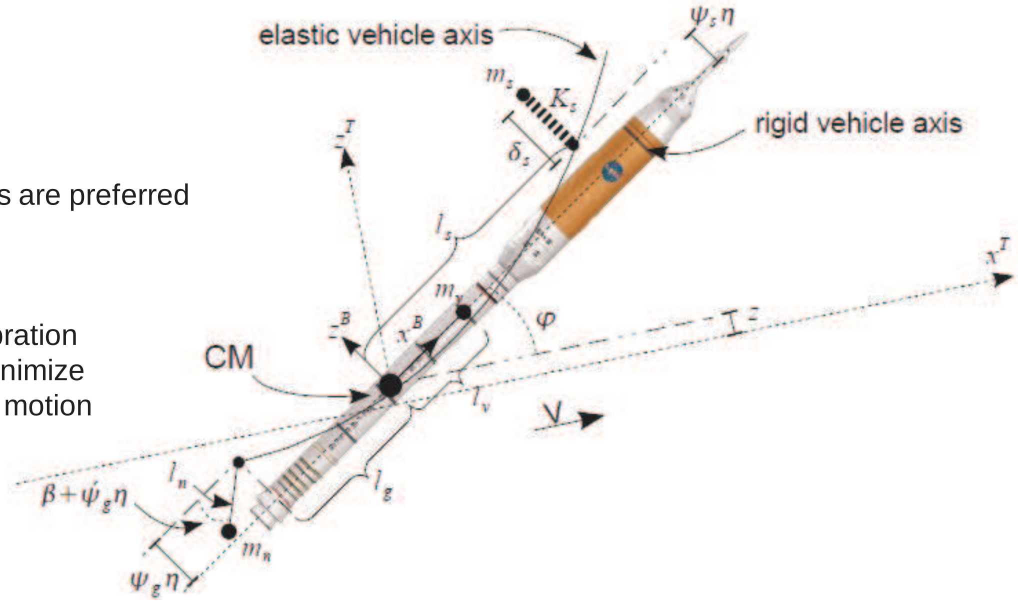
Agenda

- MATLAB/Simulink tools for Ares I GN&C
  - Challenges of scale and complexity in launch vehicle control systems
  - Overview of the Ares I and Ares I-X vehicles
  - How SAIC employs MATLAB and Simulink in supporting GN&C analysis and design for the Ares family
- Highlights of various SAIC design and analysis programs employing MATLAB/Simulink tools
  - Automated Rendezvous and Docking (AR&D) (SPARTAN)
  - Reconfigurable HWIL Laboratory for Space Superiority Applications
  - Joint Precision Approach and Landing System (JPALS)
  - Lunar Lander Test Bed (LLTB)
- Videos and bdStudio 3D animations

Challenges in Launch Vehicle GN&C

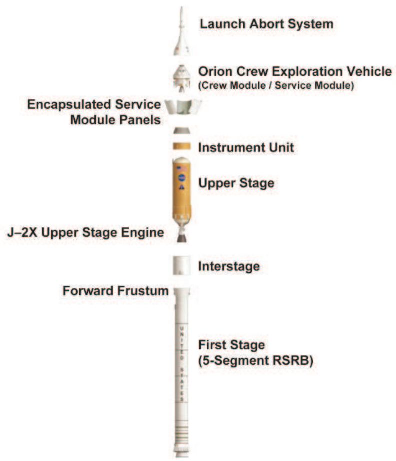
- The Difficult Problem of Dynamic Modeling
  - Nonlinear, coupled, flexible multi-body system with variable mass
  - Flexible body models can be very high order

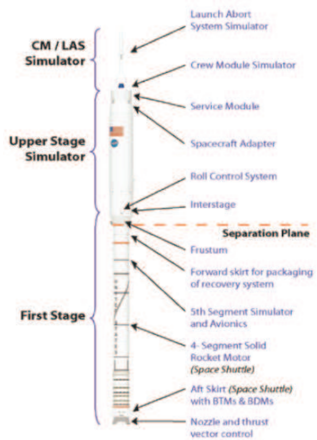
- Stability and Control Challenges
  - Limited controller architecture
    - Linear controllers prefaced with bending filters are preferred based on flight heritage
  - Highly flexible
    - Sensed angles and rates are corrupted by vibration
    - Structural oscillations must be mitigated to minimize bending loads, aerodynamics, and propellant motion
    - Conditionally stable in phase
  - Aerodynamically unstable
    - Conditionally stable in gain
  - Large uncertainties in key parameters
  - Considerable propellant slosh influence
  - Mode interactions (flex and slosh coupling, distributed aerodynamics, force following effects, etc)
  - All must be considered in control design and analysis

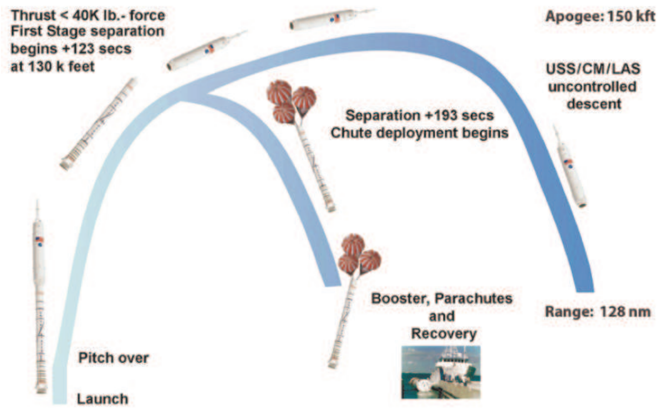


Ares I / I-X Overview

- Ares I
  - Two stage crew launch vehicle
    - Shuttle-derived 5-segment solid propellant booster
    - Saturn-derived upper stage powered by LOX/LH2 J-2X
  - 56,000 lbm payload capacity
  - >3M lbf thrust at liftoff
  - FS and US two-axis TVC control supplemented by roll control thrusters
  - ~10 minute ascent to LEO
- Ares I-X
  - First stage test vehicle with simulated upper stage
  - Slated to launch mid-year 2009
  - ~120 second flight to Mach 4+







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SAIC Launch Vehicle Simulation and Stability Analysis Tools

FRACTAL (Frequency Response Analysis and Comparison Tool Assuming Linearity) - Implemented using MATLAB and Control System Toolbox

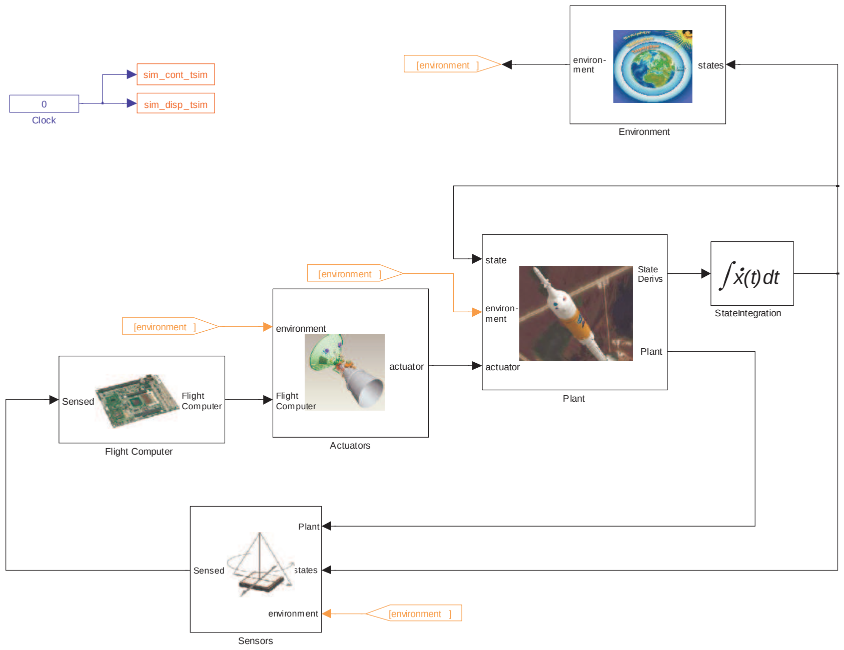
- Linearized planar frequency-domain simulation of LV dynamics based on Lagrangian formulation
  - Comprehensive simulation of dynamic coupling effects (30+ flexible modes, slosh, nozzle dynamics, high-fidelity actuators)
  - High-order (*n*>100) linear models
  - Linearized aerodynamics
  - Automated stability margin extraction
  - **Rapid turnaround** studies, **parametric optimization**, and **Monte Carlo analysis**
  - Closed-form analytically and numerically validated equations of motion based on heritage perturbation dynamics (Frosch and Vallely, Garner, Greensite)

SAVANT (Stability Aerospace Vehicle ANalysis Tool) - Implemented using MATLAB with Simulink and Simulink Control Design

- Nonlinear 6-DoF time-domain simulation of LV dynamics based on incremental Newton-Euler formulation
  - Flexible body dynamics
  - Propellant slosh
  - Closed loop guidance, nozzle inertia effects and high-fidelity actuators
  - High-fidelity distributed aero, winds, thrust, sensors, and environment models
  - Interfacing with legacy code via S-functions (FORTRAN, C)
  - **Monte Carlo analysis** and **numerical linearization** to compute frequency-domain stability margin criteria
  - Ongoing validation against similar 6-DoF tools

Stability Analysis Capabilities

- Generation of accurate, high-fidelity trajectory data using SAVANT
  - Used for input to stability analysis tools, or directly linearized
  - Can be interfaced to visualization tools (bdStudio) for high-quality visualization
  - Support for real-time interfacing (manual steering, HWIL, etc.)
- Verification of robust stability margins
  - Monte Carlo approach - over one million cases considered for a typical analysis
  - Automatic margin extraction and case tracking (seven catalogued frequency response characteristics)
- Parametric optimization, sensitivity studies, FCS design and analysis
  - Pure m-code model enables rapid calculation of the linearized plant dynamics
  - Allows use of the model to optimize frequency response with respect to various vehicle parameters
  - FRACTAL-AST (Automated Slosh Tool) optimizes slosh damping parameters to meet specified response
- Sensitivity analysis
- FCS tweaking capability provided to a human-in-the-loop via MATLAB GUI interface to plant dynamics model



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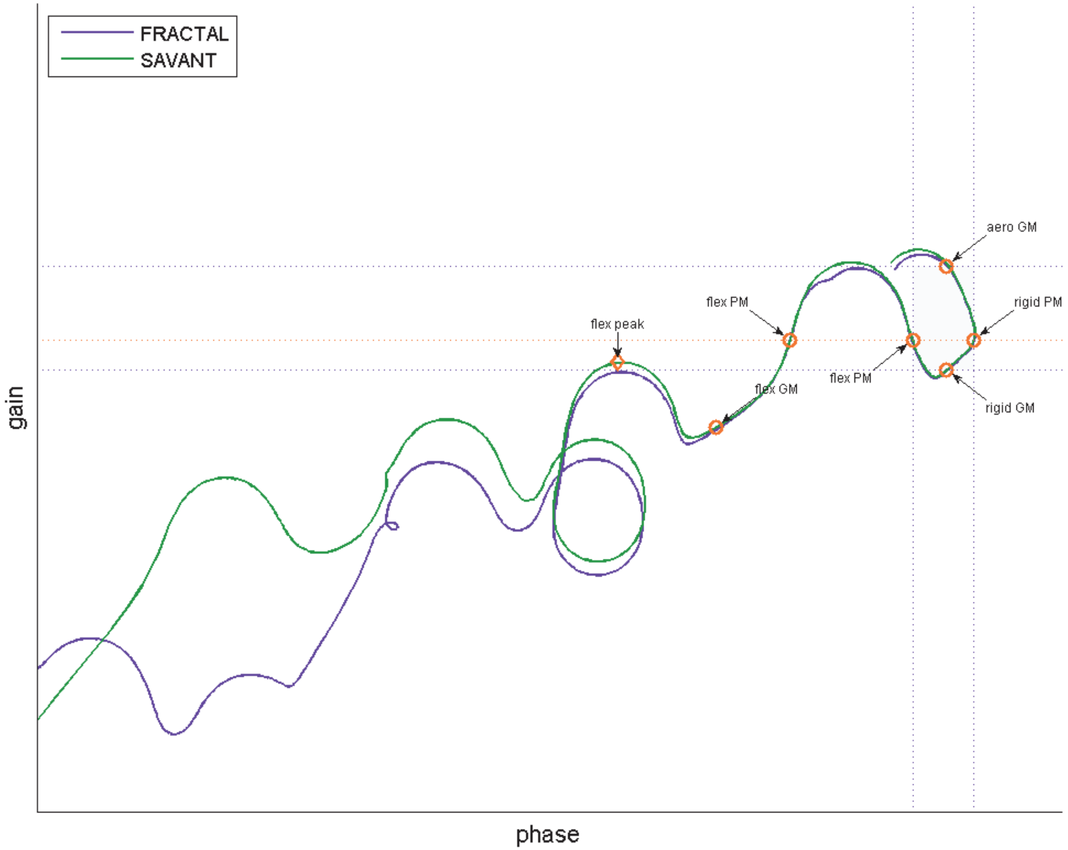
FRACTAL/SAVANT Tool Validation

- Numerical linearizations (SAVANT) validated against classical perturbation dynamics (FRACTAL)
- Automated plotting and margin cataloging tools (developed with Control System Toolbox) automatically tabulate stability margins and other performance criteria

FRACTAL Ares IX Stability Result



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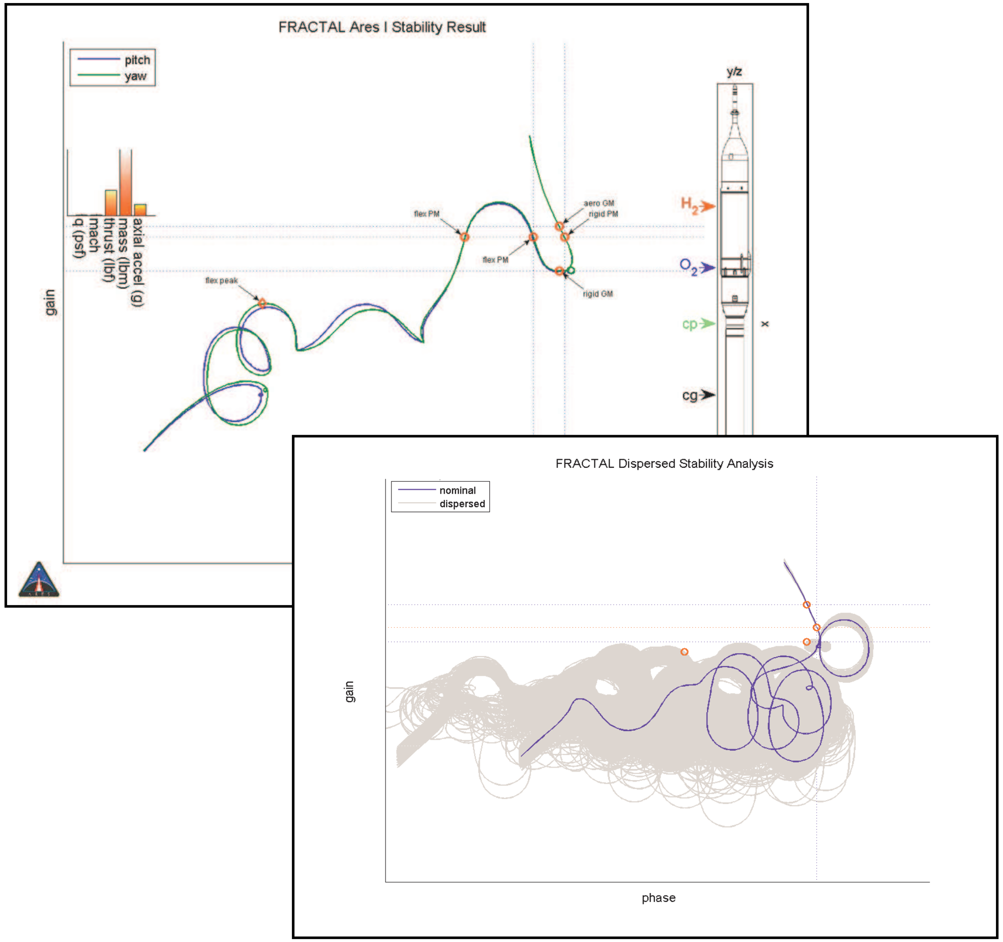
High-Resolution Stability Margin Assessment and Monte Carlo Analysis

- Animations of time-varying stability results facilitated by rapid model execution
- Vehicle stability is analyzed at quasi-steady-state intervals as small as 0.2 sec

- Over one million dispersed cases among eight trajectories considered in Monte Carlo analysis
- About 24 hour runtime on a COTS 8-core PC running MATLAB x64
- Past programs had no high-fidelity rapid turnaround capabilities due to processing and tool limitations



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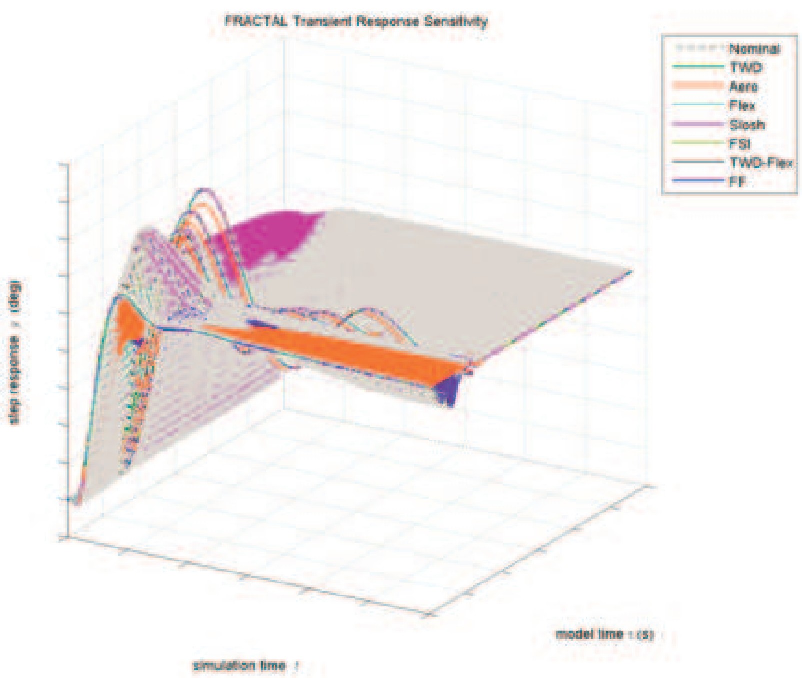
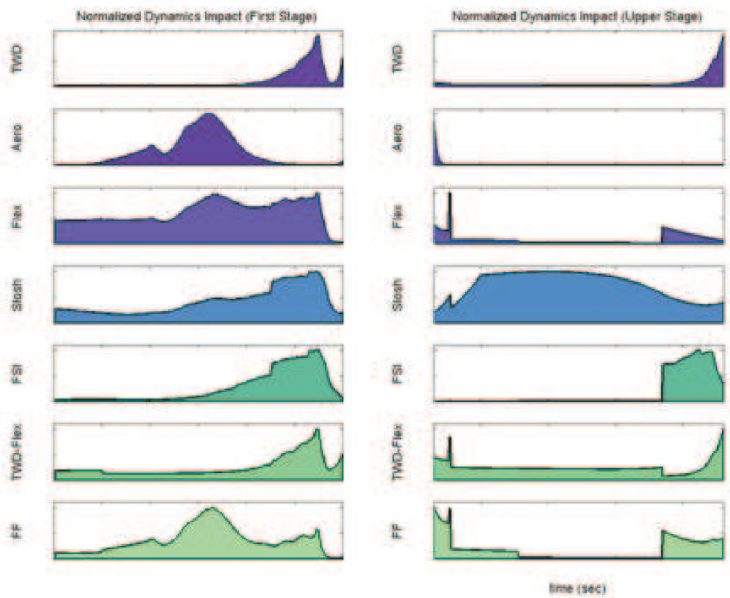
Sensitivity Studies

- Rapid model execution allows the calculation of novel metrics that characterize sensitivity to various dynamic model elements





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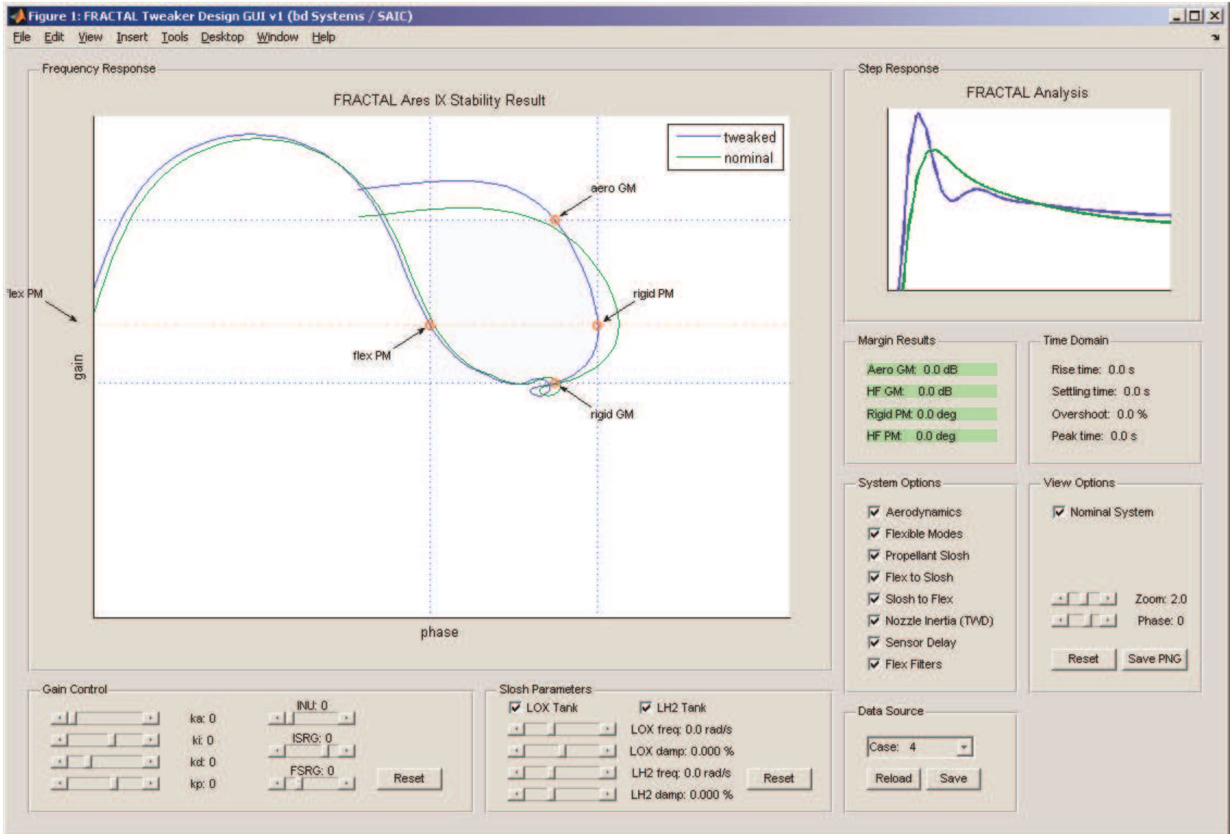
GUI Design Tools

- FRACTAL *Tweaker*
- GUI interface to full plant dynamics
- Real-time analysis of the impact of various modeling elements, gain changes, sensor blending, changes in propellant characteristics
- Provides real-time Nichols, transient response data, stability margins, and so on
- Used for “what-if” analysis and minor tuning of control system



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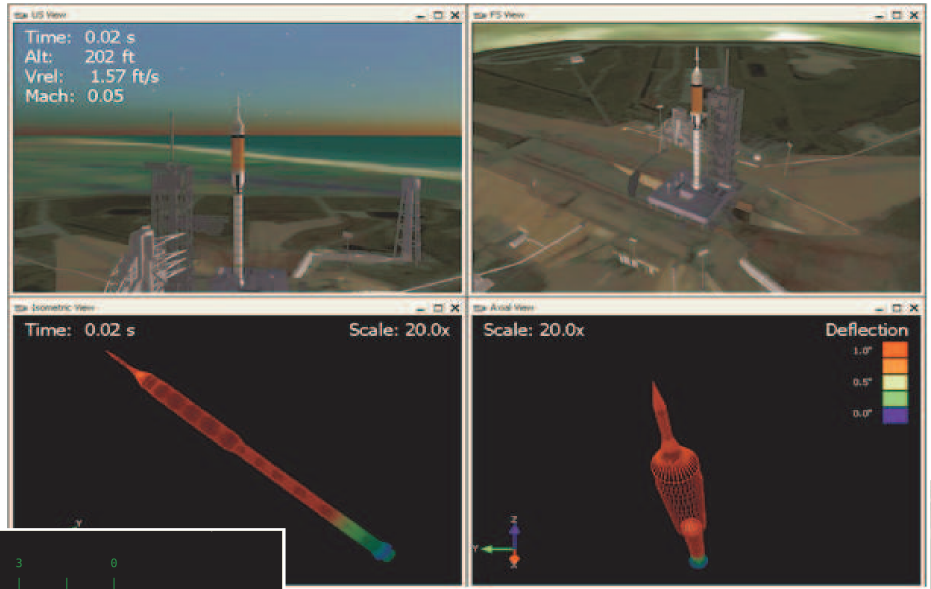
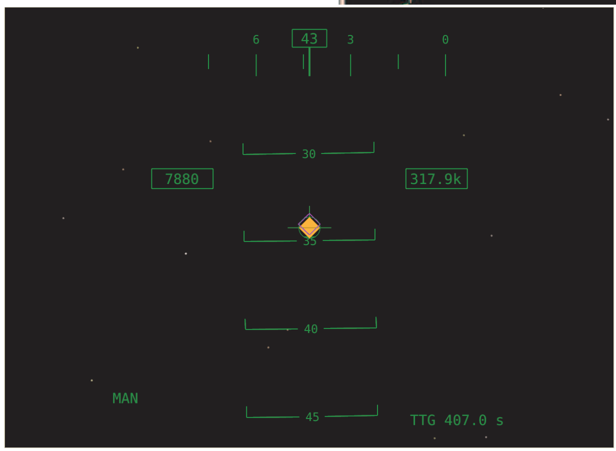
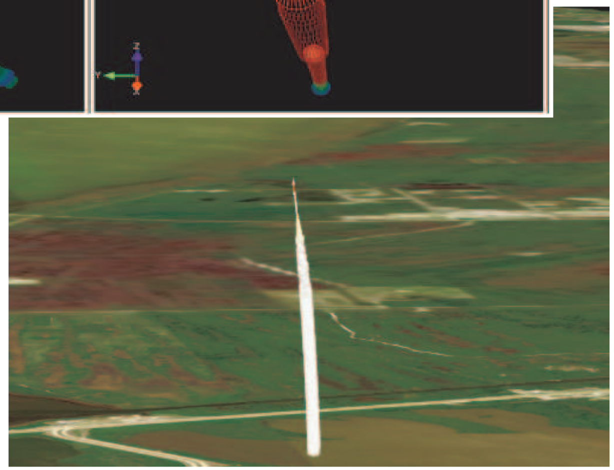
Graphics Interfacing – bdStudio Visualization Tool

- bdStudio provides post-processing and data visualization using an in-house visualization toolbox
- Rigid and Flex Body displays with data-driven special effects (RCS thruster firings, actuator deflections, etc.)
- Real-time interfacing via S-functions
- Real-time joystick input to Simulink models used for human-in-the-loop simulations







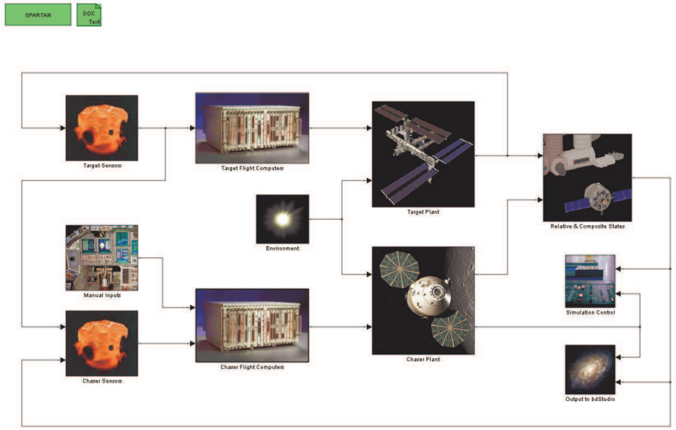
Highlights of Other SAIC Programs

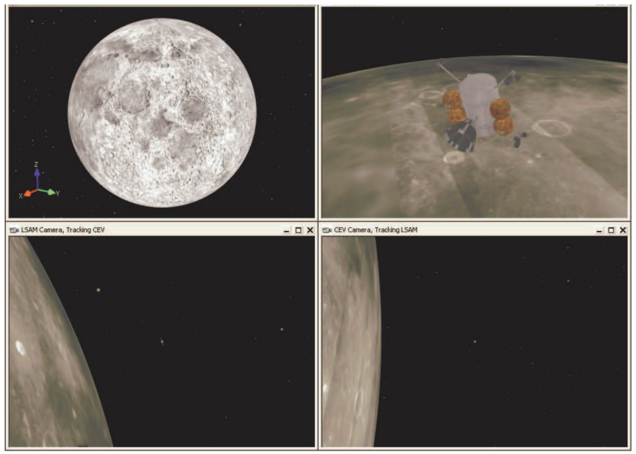
- Automated Rendezvous and Docking (AR&D) Simulation (SPARTAN)
- Reconfigurable Hardware-in-the-Loop Laboratory for Space Superiority Applications (HWIL-SSA)
- Joint Precision Approach and Landing System (JPALS)
- Lunar Lander Test Bed (LLTB) Simulation and Control Design

Automated Rendezvous and Docking (AR&D) Simulation (SPARTAN)

- SPARTAN -
  Simulation Package for Autonomous Rendezvous Test and Analysis
- High-fidelity, on-orbit simulation
- Tracks multiple 6DOF vehicles
- Tests AR&D sensors and GN&C requirements and algorithms
- Supports Earth and Lunar AR&D scenarios

- Tests sensor requirements
- Long-range, through proximity ops and docking
- Evaluates Kalman filter algorithms
- Easily support all constellation missions
- Supports Monte Carlo analysis
- Supports real-time mission computer code generation
- Supports closed-loop applications with synthetic scene generation
- Supports real-time HWIL testing





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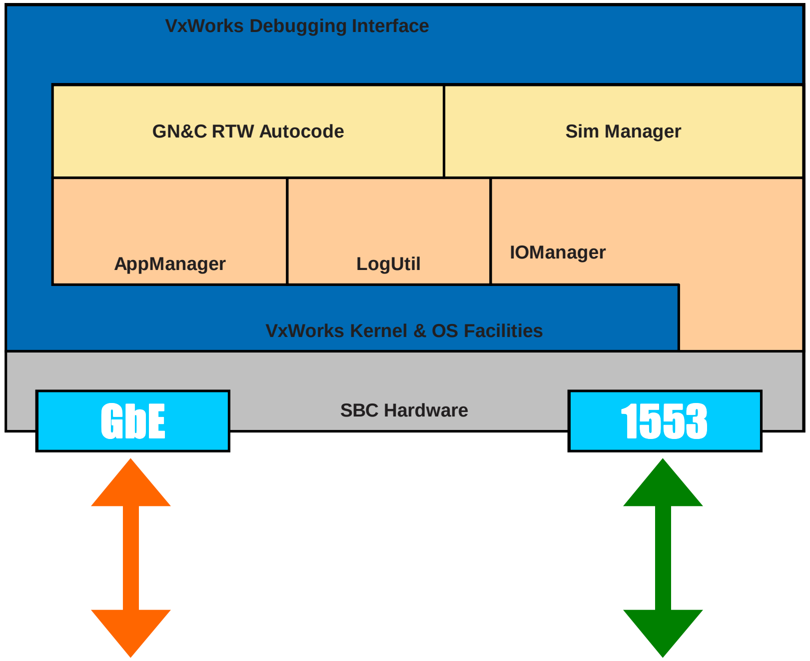
Reconfigurable Hardware-in-the-Loop Laboratory for Space Superiority Applications

- Small-scale hardware-in-the-loop laboratory for rapid prototyping and realtime GN&C algorithm evaluation
- Test and integration of avionics busses (MIL-STD-1553)
- Execution of RTW-generated autocode in a VxWorks environment using a custom OS framework
- Easy integration with MATLAB/Simulink and RTW means rapid development cycles for testing new vehicle configurations and GN&C algorithms
- Used to demonstrate capability of in-house rendezvous, docking, circumnavigation, stationkeeping, and image processing algorithms
- Complex multirate Simulink spacecraft dynamics and GN&C running real-time on COTS x86 hardware and flight-like PPC SBCs
- Simulink-based dynamics simulation based on the SPARTAN Core Dynamics Engine (CDE)



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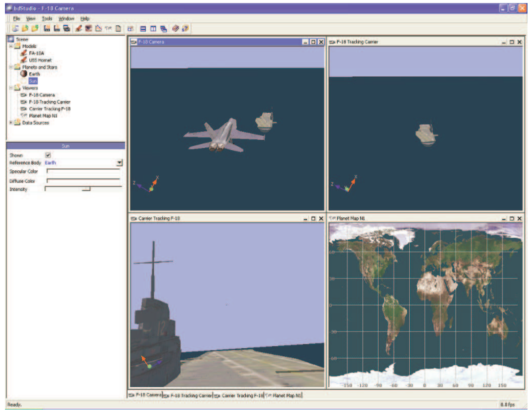
Joint Strike Fighter (F-35)
Joint Precision Approach and Landing System (JPALS)

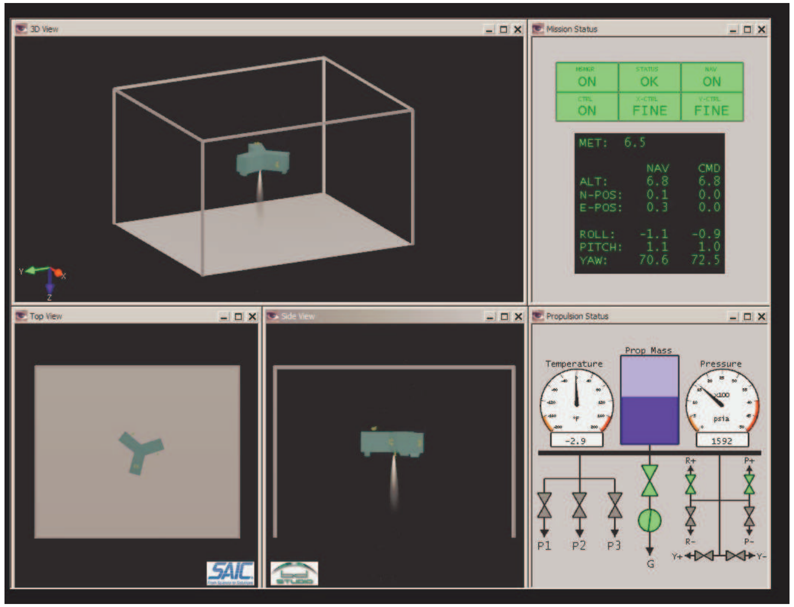
Program Goal - Autonomously land the F-35 Joint Strike Fighter on US and UK Aircraft Carriers

- Our customer is Lockheed Martin supporting US Air Force and US Navy
- Helping with autonomous guidance and relative Kalman Filter algorithm development
- SAIC HSV is developing the JSIM integrated simulation testbed for JSF and Aircraft Carrier in MATLAB/Simulink
- Integrating 6-DoF models for aircraft carrier and JSF with capabilities for variable sea state and wind conditions
- Using high-fidelity vendor models to simulate INS and GPS sensors at different locations on both vehicles as well as simulating the broadcast link



Lunar Lander Test Bed (LLTB) Simulation and Control Design

- VCSI is leading the team to build a Hover Test Vehicle (HTV) capable of testing lunar GN&C algorithms
- First project being supported is the International Lunar Network (ILN)
- Supports 10 seconds of mission flight time
- Uses cold-gas (compressed air) thrusters
- SAIC is the lead for the vehicle flight software and avionics integration
- Using Matlab/Simulink to develop and refine GN&C algorithms in a high-fidelity 6DOF environment
- Algorithms will be auto-coded to C using Real-Time Workshop and embedded on flight real-time OS (VxWorks)



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Summary

- Flexibility in MATLAB/Simulink tools enable rapid development of scalable, interoperable high-fidelity simulations
  - Control System Toolbox supports rapid development of complex linear launch vehicle dynamics models with over 100 states
  - Simulink Control Design used for numerical linearization of a nonlinear 6-DoF time-domain simulation that compares exceptionally well with classical perturbation dynamics
  - Accessible APIs assist in interfacing legacy code and creating GUI tools for a rich user experience

- SAIC leverages MATLAB/Simulink expertise to provide unprecedented fidelity in launch vehicle stability analysis and control design, enhancing overall program safety

- SAIC employs MATLAB/Simulink across multiple disciplines including aerodynamics, avionics, structural dynamics, on-orbit GN&C, real-time HWIL, and more

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