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

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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+
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
  - FRACSTAL-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
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
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
Sensitivity Studies

- Rapid model execution allows the calculation of novel metrics that characterize sensitivity to various dynamic model elements.
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
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
Reconfigurable Hardware-in-the-Loop Laboratory for Space Superiority Applications

- Small-scale hardware-in-the-loop laboratory for rapid prototyping and real-time 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)
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
VCSI is leading the team to build a Hover Test Vehicle (HTV) capable of testing lunar GN&C algorithms. The first project being supported is the International Lunar Network (ILN). It supports 10 seconds of mission flight time. It 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).
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