Space Launch System Flight Control

Jeb S. Orr (Draper Laboratory)

NASA Marshall Space Flight Center
Control Systems Design and Analysis Branch (EV41)

Aerospace Control and Guidance Systems Committee (ACGSC) Meeting 110
October 10-12, 2012
**Space Launch System (SLS)**
- NASA-developed launch vehicle for large-scale (exploration-class) crew and cargo access
- Shuttle-derived hardware and processes leveraging Constellation program development experience (tanks, engines, boosters)
- Primary development configurations are 70t crew (SLS-10002) and 130t cargo (SLS-21002)

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Booster</th>
<th>Core Stage</th>
<th>Upper Stage</th>
<th>Cargo</th>
</tr>
</thead>
<tbody>
<tr>
<td>70t (10002)</td>
<td>5 segment RSRMV</td>
<td>ET derived, 4x RS-25</td>
<td>ICPS, RL-10</td>
<td>MPCV (crew)</td>
</tr>
<tr>
<td>Block I</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>130t (21002)</td>
<td>Advanced booster</td>
<td>ET derived, 4x RS-25</td>
<td>CPS, 2x J-2X</td>
<td>TBD</td>
</tr>
<tr>
<td>Block II</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Program schedule**
- SRR/SDR Q2 FY12 completed
- PDR ~Q3 FY13
- CDR ~Q3 FY14
  - Abort system tests ~Q4 FY15
  - Exploration Mission (EM-1) (uncrewed, Block I) – ~Q1 FY18
  - Exploration Mission (EM-2) (crewed, Block I) – ~Q1 FY22
A new set of launch vehicle flight control design challenges

- Large, highly flexible vehicle structure with non-planar bending characteristics
- Complex TVC system with multiple fully actuated engines
- Massive propellant tanks with lightly damped lateral sloshing modes
- Uncertain payload envelope with parasitic dynamics (elastic, slosh)
- Highly optimized trajectories yielding widely varying operating conditions
- Aggressive robustness and redundancy requirements driven by human rating
Flight Control System Overview

סדרת קולרי

PID + linear bending filters is the architecture of choice
- Flight heritage, straightforward analysis, fundamentals understandable by non-controls engineers

Decoupled-axis duplicate pitch/yaw designs do not generalize
- MOI, control effectiveness varies with respect to body axis
- Aerodynamic cross-coupling may be significant

Value added by augmenting PID/filters with a disturbance compensation algorithm
- Acceleration feedback (in some form) provides control over translational state of the system, which may be desirable for several reasons (load relief, drift reduction, lateral maneuvers, tower clearance)
- Generalization of classical load relief (acceleration feedback) control
- Includes a component that estimates bias angular accelerations
  - Better performance can be obtained than with integral control alone with respect to the same stability margin constraints
General Architecture Considerations

♦ Use of multiple actuators necessitates an allocation algorithm
  • Allocate actuator deflection to minimize some weighted figure of merit like total deflection (steering losses, control authority) or actuator rate (capabilities)
  • Can handle actuator failures based on external notification

♦ Optimal allocation can be achieved with good accuracy based on combination of a priori data and flight-critical measurements
  • Multiple phases, throttled engines
    – Control effectiveness is a function of time, propellant remaining, throttle, altitude, etc
  • Transport delay and actuator dynamics are variable with allocation
    – Special feature of TVC & flex dynamics: mixing affects stability and loads!

♦ FCS design is more convenient in terms of angular acceleration than torque
  – Eliminates some units and scaling issues in design of interacting parts
  – Well-conditioned matrix manipulations for control allocation
Rely on simple, proven, flight-tested algorithms and processes
- Classical PID control, gyro blending, linear bending filters, gain scheduling
- Extensive frequency-domain and time-domain robustness
- Algorithm and flight software commonality across all SLS platforms (common autopilot)

Enhance algorithm capability when warranted with compact and verifiable methods
- On-line optimal linear control allocation
- High-performance acceleration based in-flight load relief capability
- Model reference gain adaptation with spectral feedback

Maximize robustness to failures
- Tolerate at least one engine failure at any point in the flight regime with negligible impact to flight control performance
- Demonstrate robustness to sensor failures and severe off-nominal conditions

Seamlessly integrate with the SLS Program to facilitate flight certification
- Shift toward TPM (Technical Performance Metric) reporting rather than classical stability margins and transient response characteristics only
- Opens the design space and burdens the flight control designer (rather than systems engineering) with assessing the quality of the design at the lowest possible level
**Integrated vehicle with control effectors and transducers**
- Vehicle controlled and parasitic dynamics (rigid body rotation and translation, propellant slosh, elasticity), hydraulic thrust vector control actuators, IMU + multiple rate gyros

**Guidance algorithms**
- Open loop boost pitch program, Shuttle-derived linear tangent law (PEG) guidance, intelligent vehicle steering

**Flight control algorithms**
1. Rate gyro blender
2. Bending filters
3. PID controller
4. Load relief and disturbance compensation
5. Gain adaptation law
6. Real-time fault-tolerant optimal control allocation (OCA) algorithm
Blending of multiple rate gyro signals is a well-known approach to mitigating excessive structural response.

- The positive and negative contributions of the modal elastic response at the sensor (mode slope or spatial shape function derivative) can be made to cancel at some nonzero positive weighting.

- This is an optimal zero placement problem.
- Practical blending must be robust to uncertainty in the structural dynamics.
- Location of sensors is a design variable.
- Numerical optimization is used to maximize robustness and preserve phase shape for certain modes (e.g. phase stable modes).

Design optimization methodology:

\[
J(\alpha) = \max_{\omega} \left\{ \frac{1}{2} \sum_{k} \alpha_k H_{\text{rat}}^k(j\omega) \right\}
\]

subject to

\[
0 \leq \alpha_i \leq 1,
\sum_{i=1}^{q} \alpha_i = 1
\]

where \( k \) is the number of model times, \( q \) is the number of sensors, and \( \alpha \in \mathbb{R}^q \).
Sensor Trade Studies

- Various RGA locations considered to maximize robustness
- Configuration 2 POD (Shuttle derived), configuration 3 baselined

Gain stable
Marginally gain stabilized
Gain stable
Not easily gain stabilized
Marginally gain stabilized
Autopilot bending filter design usually assumes 0.5%-1.0% structural damping for design.

Test data indicates lateral bending mode damping consistent with this assumption.

Ares I design: 0.5% (not dispersed)

Ares I-X design: 1.0% (dispersed ±0.5%)
- Tested at ~0.2% in VAB prior to flight

Filters are designed to either phase-stabilize or attenuate flexibility with sufficient margin (~6-10 dB)
In-Flight Load Relief (IFLR) and Disturbance Compensation Algorithms (DCA)

- **IFLR has been generalized into angular/translational state observers**
  - The algorithms are in essence smooth differentiators.
  - We take quantities we know (commanded angular and lateral acceleration, angular rates) …and estimate quantities we don’t know and can’t measure.
  - The concept of disturbance estimation and compensation is not new for launch vehicles – similar (linear) implementations were used on Ares, Shuttle, etc.

- **Translational DCA example: for LR feedback, we want \( \ddot{r}_B \), the acceleration at the CG**
  - The sensed acceleration, \( \ddot{r}_s \), neglecting high-order and elastic effects, is given by
    \[
    \ddot{r}_s = \ddot{r}_B + \dot{\omega} \times r_{BS} + \omega \times \omega \times r_{BS}
    \]
  - We want to extract the body acceleration. We can subtract the last term, but the second term requires a measurement of \( \dot{\omega} \) which we do not have.
  - A nonlinear observer is used to estimate \( \dot{\omega} \) from \( \omega \), and extract the CG acceleration:
In the absence of vehicle or environmental uncertainty, a fixed-gain controller is optimized prior to flight (no motivation for adaptation)

- Conservatism in launch vehicle design generally yields well-performing classical controllers
- There is no desire to improve on the well-tuned baseline control system design for nominal cases

Adaptive control provides additional robustness by using sensed data to adjust the gain on-line

AAC Objectives

- “Do no harm”
  - Maintain consistency with classical design approach
  - Protect nominal control gains
- Increase robustness; prevent / delay loss of vehicle (LOV)
Current architecture has heritage to flight-tested systems

- MH-90 (F-101) and MH-96 (X-20, X-15), ca. 1958-1967
- Based on a prescribed servo limit cycle amplitude (marginal servo poles)
- Saw numerous flight tests (>60) on X-15-3, improved performance and pilot opinion of handling qualities over wide-ranging flight envelope

- A similar concept is well-suited to a digital implementation
Launch vehicles are often conditionally stable due to competing objectives of unstable aerodynamics and parasitic internal dynamics. Because of uncertainty in models, we have to design with sufficient gain margins.

Adaptive gain augmentation senses off-nominal upper and lower limits in real time.

Adaptive Gain Modulation
High-frequency closed-loop spectrum under high forward loop gain can be readily deduced from the open-loop frequency response

- Correlation allows design of spectral damper filters
- Used directly to determine high-pass cutoff frequency specification

**Nominal Open-Loop Response Example Vehicle**

- Flex PM 110.8°, 0.93 Hz
- BM1
- Aero GM 11.0 dB, 0.04 Hz
- BM2,3
- Flex PM 66.5°, 0.83 Hz
- Rigid GM 6.0 dB, 0.57 Hz
- Rigid PM 35.7°, 0.14 Hz
- Slosh

**Closed-Loop Response at Gimbal Command**

- Marginally Stable System
- Nominal System
- $f=0.57$ Hz
Assume a well-tuned classical controller for the nominal system

- The forward loop gain $k_T$ is augmented by a signal $k_a$
  - The total gain is formed from a fixed minimum gain and the augmenting gain:
    \[ k_T = k_0 + k_a \]

- Multiplicative augmentation is easy to assess in terms of gain margin
- The update law for the augmenting signal depends on the command, sensed attitude and rate, and the baseline controller output
Baseline controller induces structural resonance
- Bending parameters are well-outside 3-sigma bounds for robust design
- Adaptive controller reduces gain to bring bending to stable limit cycle
- System slowly recovers lost performance as BM1 shifts up in frequency during flight

Example: Recovery From Unstable Bending

**Example Vehicle**
Multi-actuated thrust vector controlled systems are well-posed for control allocation
- Redundant control authority in three axes with two or more nozzles
- Some configurations may have nine or more nozzles, each with two degrees of freedom

Solutions to the constrained allocation problem exist and can be implemented online
- In the face of constraints, we must solve an LQ or LP using an iterative algorithm
- May not yield a moment collinear with command
- Other constrained solutions include daisy chaining, etc.
- A nonlinear solution: does not directly admit linear stability analysis

The constrained thrust vector control allocation problem differs from the aircraft problem
- Each control input has two degrees of freedom
- Saturation constraints are insufficient to represent the constraint boundary. Coupled constraints apply to two degrees of freedom each
- Due to significant servoelastic coupling, the choice of effector mixing at a given flight condition affects the stability of the closed-loop structural-dynamic system
- Linear allocators are preferred to enable linear stability analysis of the short period dynamics for flight certification
- A linear allocator can be computed online based on optimal parameterization (e.g., a weighting matrix)
Candidate Allocator Approaches

- **On-line Optimization**
  - LQ/LP
  - Must consider convergence, stability analysis, computational expense

- **Generalized Inverse Matrix Lookup**
  - Interpolation of matrix do not give exact results
  - Requires substantial data storage for sufficient resolution

- **Fixed polarity allocator with Vehicle/Engine Properties Scaling**
  - Shuttle-like approach
  - Does not maximize the attainable moment
  - Can adjust to guidance throttling

- **Fixed Allocator (Polarity Matrix)**
  - Gains contain engine & vehicle properties
  - Does not maximize the attainable moment
  - Steering loss & local thrust structure loads

- **Weighted Least Squares Cyclic Computation**
  - The best solution for launch vehicle application
  - Reconfigurable In-flight to anomalies for which the system is prepared (engine out)
  - Can adjust to guidance throttling
  - Can maintain high allocation efficiency for many geometries
Saturn V Allocator

- Saturn vehicles used a polarity table that approximated the least-squares solution.
- The push-pull arrangement of the actuators allowed nozzle motion tangent to the radius vector to the CM in the case of a roll command.
- Least-squares allocators usually effect tangent motion to the virtual radius vector in the angular acceleration frame.
- In body frame with a symmetric vehicle, circular constraints, and equal thrust engines, this behavior is almost optimal.
We compute a moment effectiveness matrix as a function of time

\[ M = \begin{bmatrix} -F_1 r_1^x u_1^x & -F_2 r_2^x u_2^x & \ldots & -F_k r_k^x u_k^x \end{bmatrix} \begin{bmatrix} T^{BG} \end{bmatrix} \]

In terms of angular acceleration, it becomes

\[ B = \begin{bmatrix} B_1 & B_2 & \ldots & B_k \end{bmatrix} \]

We minimize

\[ H = \frac{1}{2} \Delta^T R \Delta + \lambda^T (\omega_c - B \Delta) \]

with

\[ \Delta = \begin{bmatrix} \delta_1^T & \delta_2^T & \ldots & \delta_k^T \end{bmatrix}^T \]

Yielding the standard (WLS) structured generalized inverse

\[ P(W) = WB^T (BW B^T)^{-1} \]

- The weight matrix can be determined online based on knowledge of the constraint boundaries and control effectiveness, such as engine out and guidance throttling.
- The problem can be expressed in a coordinate system where the matrix computations are sparse; scalar math can be used for high-efficiency computation.
- Constraints can be satisfied using special features of the ellipsoidal topology of the constraint boundaries.
Primary Design Tools and Processes

- **POST [Program for Optimizing Simulated Trajectories] (LaRC / MSFC)**
  - 3-DoF trajectory optimization, guidance design, performance analysis

- **MAVERIC [Marshall Aerospace VEhicle Representation in C] (MSFC)**
  - 3-DoF / 6-DoF flight mechanics simulation with high-fidelity elastic, slosh, actuator, atmospheric models

- **FRACTAL [Frequency Response Analysis and Comparison Tool Assuming Linearity] (MSFC)**
  - High-fidelity 6+-DoF perturbation analysis engine with parametric optimization capability
Supporting Design Tools and Processes

- **CLVTOPS** *(TREETOPS-derived)* (MSFC)
  - Multiple flexible body dynamic simulation, separation analysis, liftoff clearance analysis

- **SAVANT** *(Stability Aerospace Vehicle ANalysis Tool)* (MSFC)
  - 6+-DoF *Simulink*-based flight mechanics simulation supporting numerical linear stability analysis

- **FRACTAL** *(Frequency Response Analysis and Comparison Tool Assuming Linearity)* (MSFC)
  - Large scale Monte Carlo frequency domain analysis

---

A flowchart diagram illustrating the relationships between various tools and processes:

- **Integrated Flex Model**
  - **6-DoF Aero**
  - **Guidance, MM Design**

- **FCS Algorithm Design**
  - **FCS Gain/Filter Design**

- **External Analysis (Loads, FSW)**

- **MAVERIC** (6-DoF)

- **CLVTOPS**

- **SAVANT**

- **FRACTAL**

- **6-DoF Monte Carlo Time Domain**

- **Liftoff/Separation Analysis**

- **6-DoF V&V, Frequency Domain**

- **Frequency Domain Stability Analysis**

- **Additional Analysis Products**
- NASA and contractor teammates have developed a robust, scalable architecture for SLS flight control
- A careful balance of modern and heritage design principles maximizes performance and overall mission capability

### MSFC EV41 SLS Flight Control Team

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Alaniz</td>
<td>J. Bush</td>
<td>J. Compton</td>
<td>S. Douglas</td>
<td>S. Derry</td>
</tr>
<tr>
<td>(Draper)</td>
<td>(TriVector)</td>
<td>(DCI)</td>
<td>(MSFC)</td>
<td>(LaRC)</td>
</tr>
<tr>
<td>E. Gilligan</td>
<td>C. E. Hall</td>
<td>R. A. Hall</td>
<td>M. Hannan</td>
<td>B. Hipp</td>
</tr>
<tr>
<td>(MSFC)</td>
<td>(MSFC)</td>
<td>(CRM Solutions)</td>
<td>(MSFC)</td>
<td>(MSFC)</td>
</tr>
<tr>
<td>S. Hough</td>
<td>M. Johnson</td>
<td>K. Black</td>
<td>J. Orr</td>
<td>J. Jang</td>
</tr>
<tr>
<td>(DCI)</td>
<td>(SAIC)</td>
<td>(CRM Solutions)</td>
<td>(Draper)</td>
<td>(Draper)</td>
</tr>
<tr>
<td>J. Powers</td>
<td>J. Pei</td>
<td>T. VanZwieten</td>
<td>J. Wall</td>
<td>J. Zhou</td>
</tr>
<tr>
<td>(MSFC)</td>
<td>(LaRC)</td>
<td>(MSFC)</td>
<td>(DCI)</td>
<td>(LaRC)</td>
</tr>
</tbody>
</table>