Space Launch System
Flight Control

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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)

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<tr>
<th>Vehicle</th>
<th>Booster</th>
<th>Core Stage</th>
<th>Upper Stage</th>
<th>Cargo</th>
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<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>
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<td>Block I</td>
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<td>130t (21002)</td>
<td>Advanced booster</td>
<td>ET derived, 4x RS-25</td>
<td>CPS, 2x J-2X</td>
<td>TBD</td>
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<td>Block II</td>
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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

- **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
Flight Control Design Paradigms

♦ 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)
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:

![Graph](image.png)
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.*
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
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
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 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

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

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

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

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

![Diagram showing the relationship between various design tools and processes.]
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

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