SLS
Space Launch System

Space Launch System Flight Control

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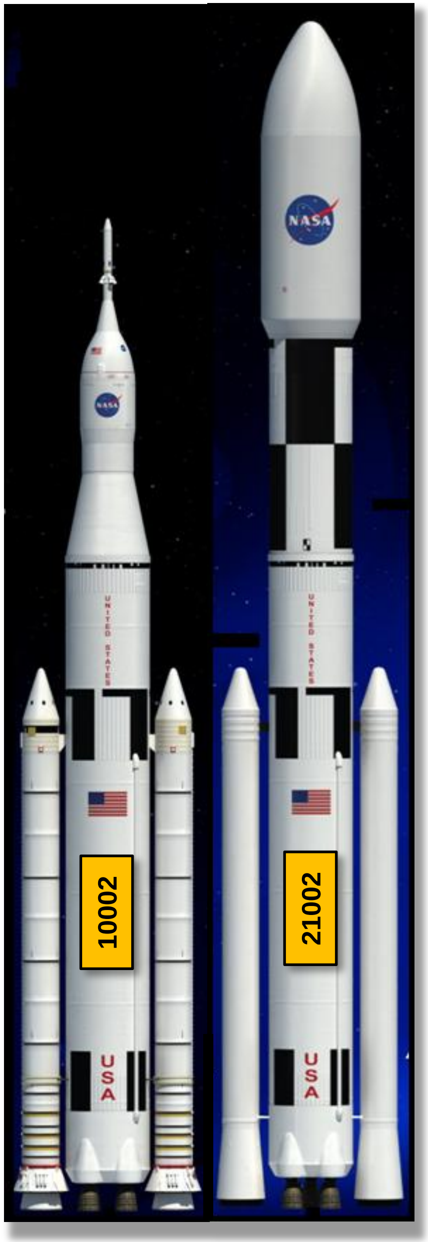
Introduction

- **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)

Vehicle	Booster	Core Stage	Upper Stage	Cargo
70t (10002) *Block I*	5 segment RSRMV	ET derived, 4x RS-25	ICPS, RL-10	MPCV (crew)
130t (21002) *Block II*	Advanced booster	ET derived, 4x RS-25	CPS, 2x J-2X	TBD

- **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



SLS Flight Control Challenges

- **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

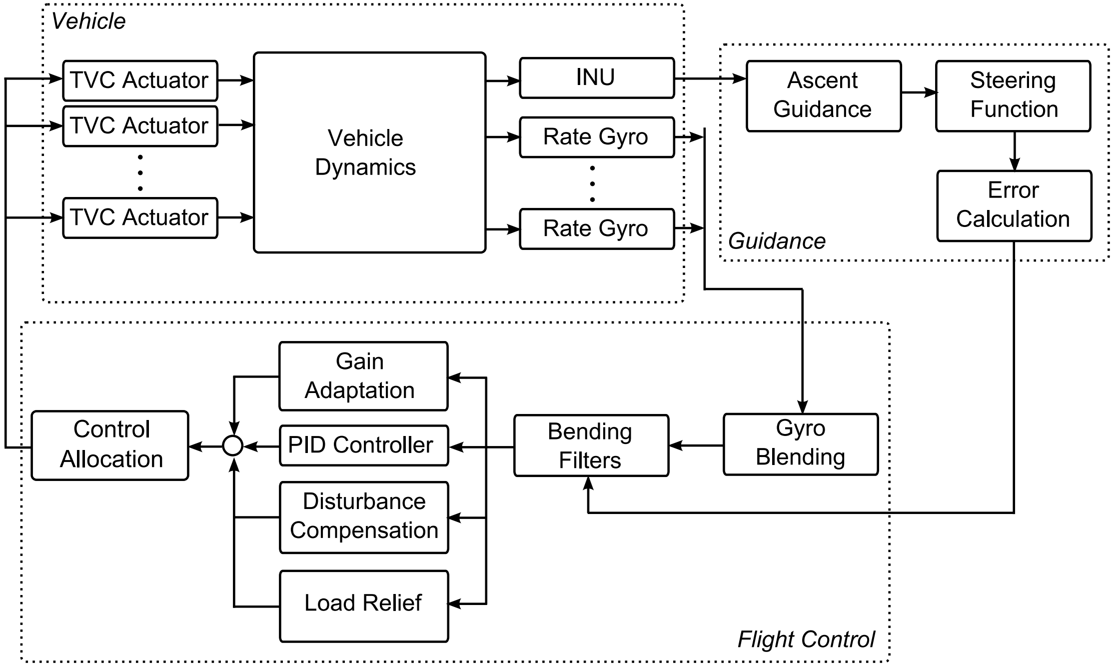
- **Rely on simple, proven, flight-tested algorithms and processes**
  - Classical PID control, gyro blending, linear bending filters, gain scheduling
  - Extensive frequency-domain and time-domain robustness
  - Algorithm and flight software commonality across all SLS platforms (common autopilot)

- **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

SLS FCS Architecture



- **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

Rate Gyro Blending

- **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

Minimize

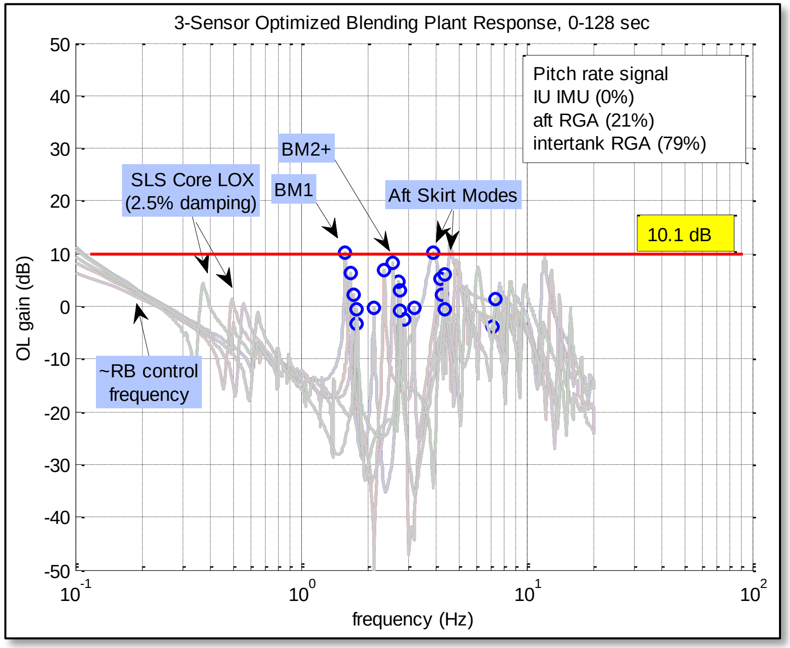
$$J(\alpha) = \sum_{t_k} \sup_{\omega} \left\{ \left| k_d^k \sum_{i=1}^{q} \alpha_i H^k_{\mathrm{rat},i}(j\omega) + k_p^k H^k_{\mathrm{att}}(j\omega) \right| \right\}$$

subject to

$$0 \leq \alpha_i \leq 1$$

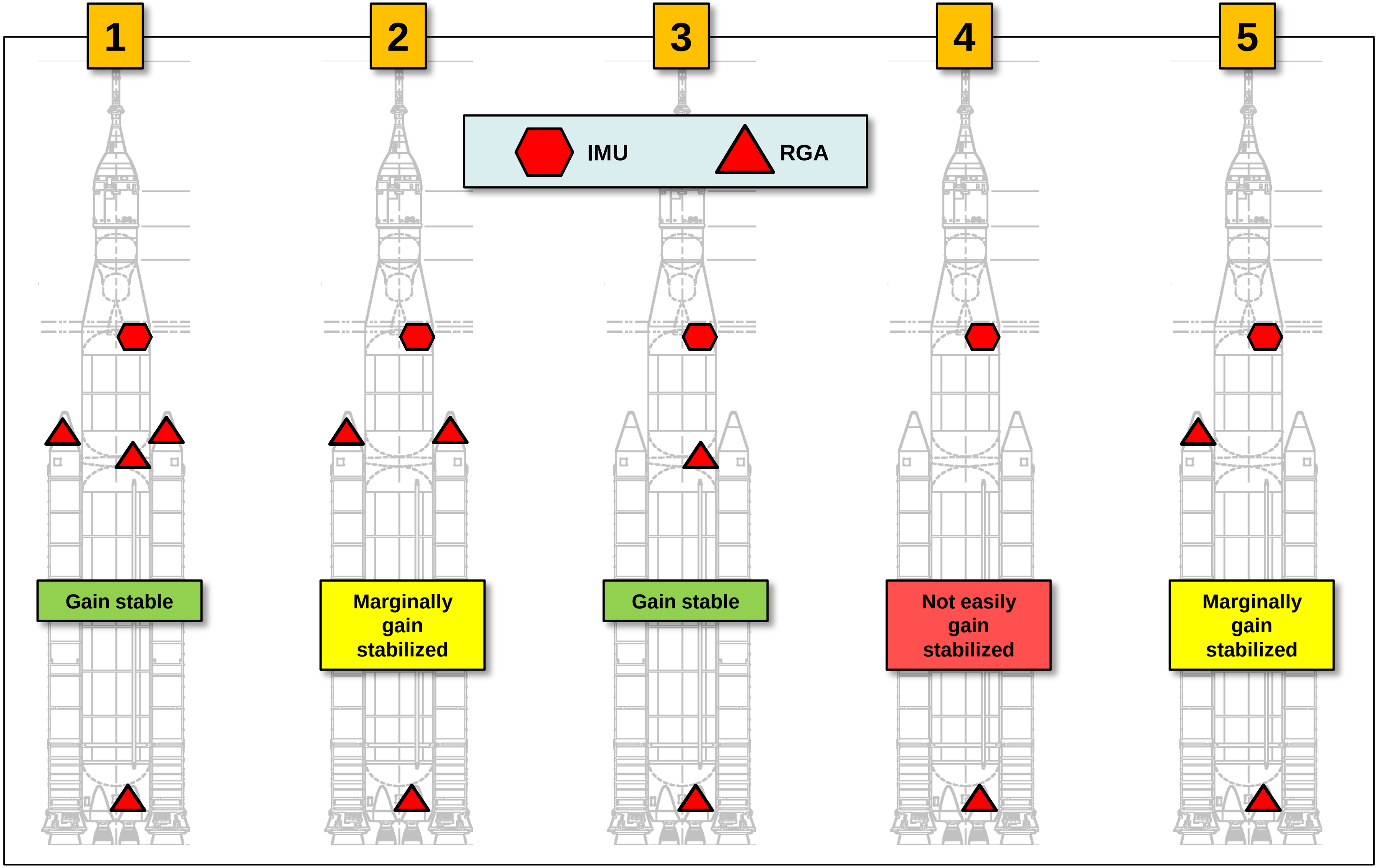
$$\sum_{i=1}^{q} \alpha_i = 1$$

where k is the number of model times, q is the number of sensors, and $\alpha \in \mathbb{R}^q$.



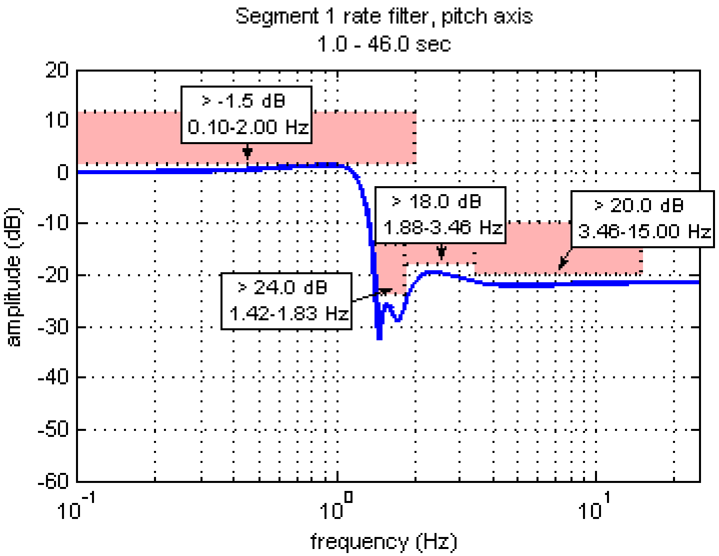
Sensor Trade Studies

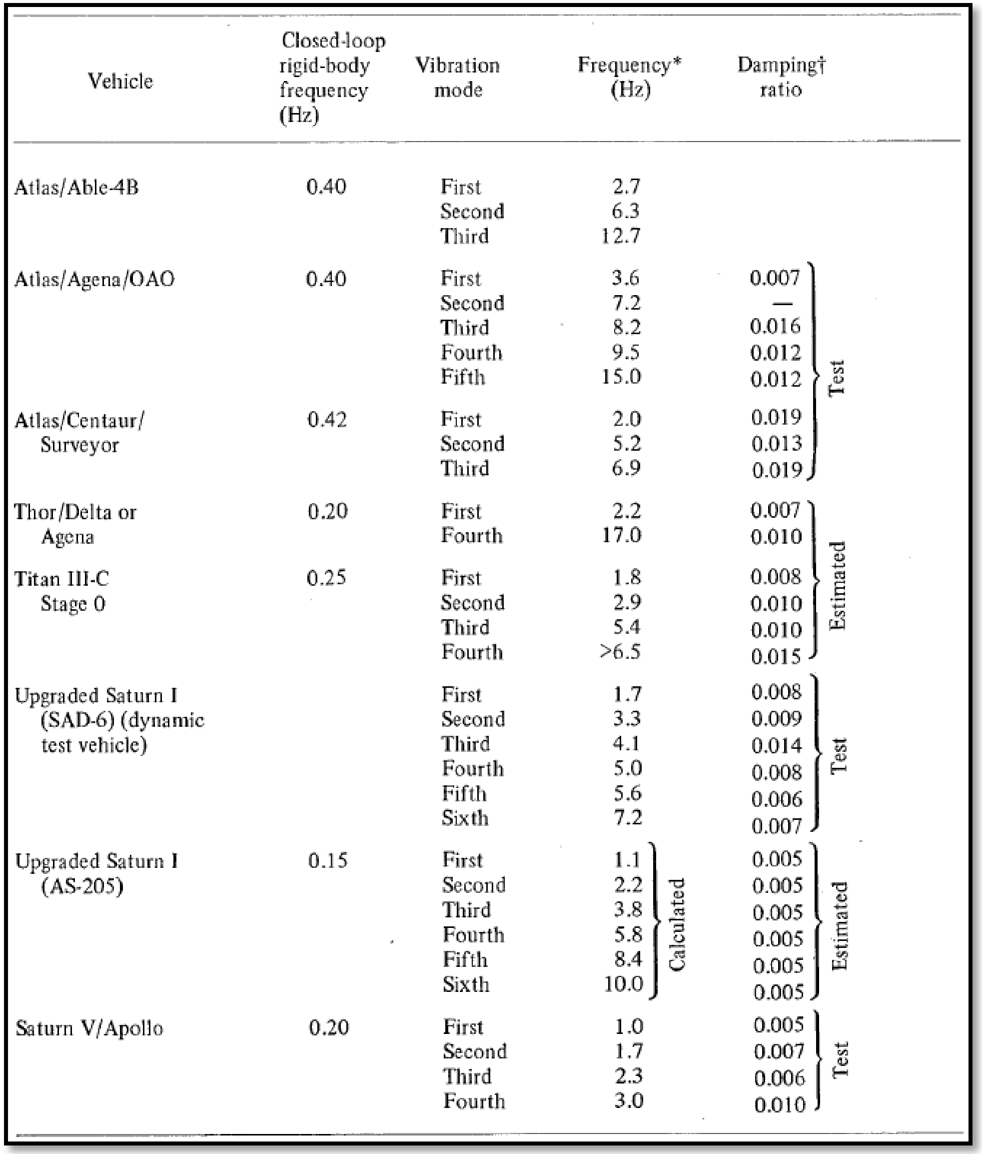
- Various RGA locations considered to maximize robustness
- Configuration 2 POD (Shuttle derived), configuration 3 baselined



Bending Filters

- 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)





Vehicle	Closed-loop rigid-body frequency (Hz)	Vibration mode	Frequency* (Hz)		Damping† ratio	
Atlas/Able-4B	0.40	First	2.7			
		Second	6.3			
		Third	12.7			
Atlas/Agena/OAO	0.40	First	3.6		0.007	Test
		Second	7.2		—	
		Third	8.2		0.016	
		Fourth	9.5		0.012	
		Fifth	15.0		0.012	
Atlas/Centaur/ Surveyor	0.42	First	2.0		0.019	
		Second	5.2		0.013	
		Third	6.9		0.019	
Thor/Delta or Agena	0.20	First	2.2		0.007	Estimated
		Fourth	17.0		0.010	
Titan III-C Stage 0	0.25	First	1.8		0.008	
		Second	2.9		0.010	
		Third	5.4		0.010	
		Fourth	>6.5		0.015	
Upgraded Saturn I (SAD-6) (dynamic test vehicle)		First	1.7		0.008	Test
		Second	3.3		0.009	
		Third	4.1		0.014	
		Fourth	5.0		0.008	
		Fifth	5.6		0.006	
		Sixth	7.2		0.007	
Upgraded Saturn I (AS-205)	0.15	First	1.1	Calculated	0.005	Estimated
		Second	2.2		0.005	
		Third	3.8		0.005	
		Fourth	5.8		0.005	
		Fifth	8.4		0.005	
		Sixth	10.0		0.005	
Saturn V/Apollo	0.20	First	1.0		0.005	Test
		Second	1.7		0.007	
		Third	2.3		0.006	
		Fourth	3.0		0.010	

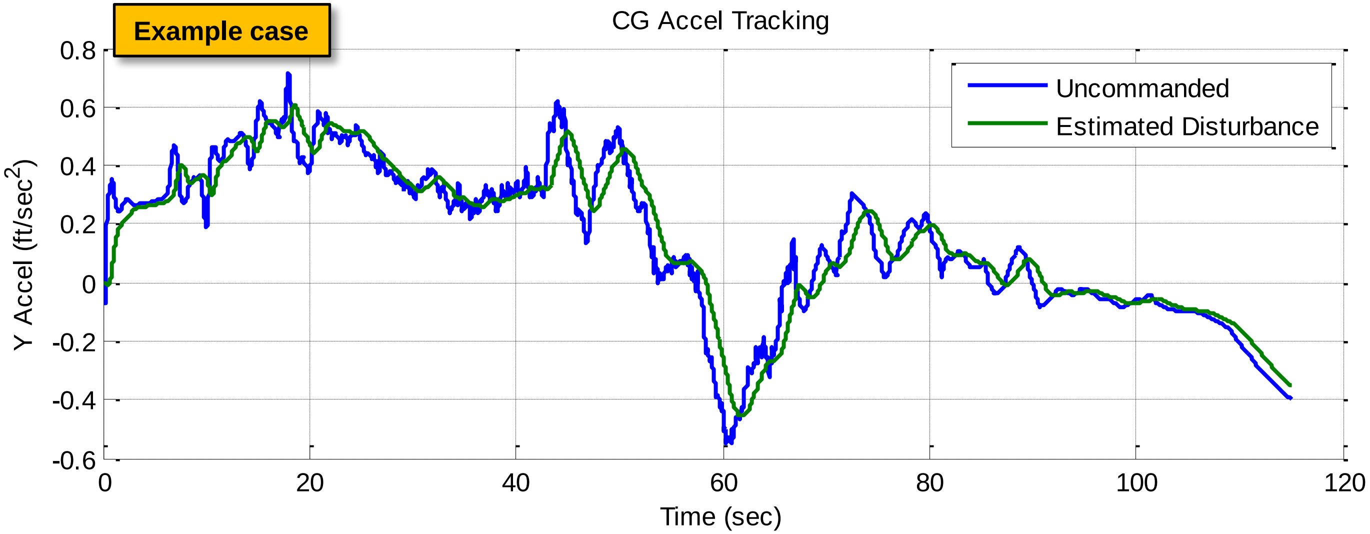
In-Flight Load Relief (IFLR) and Disturbance Compensation Algorithms (DCA)

- **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 ω, and extract the CG acceleration:



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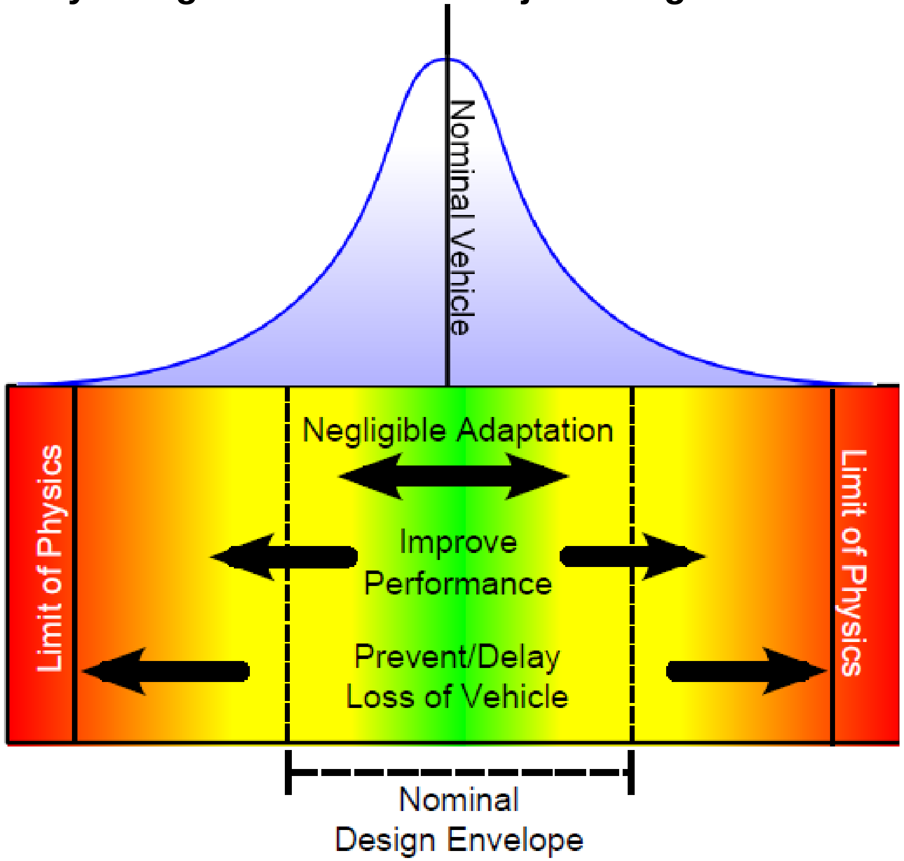
Adaptive Gain Augmentation

- **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

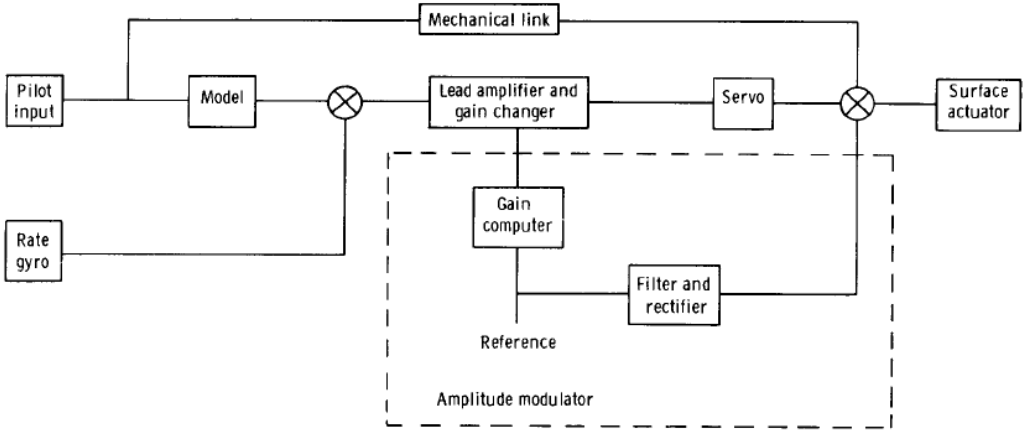
- “Do no harm”
  - Maintain consistency with classical design approach
  - Protect nominal control gains
- Increase robustness; prevent / delay loss of vehicle (LOV)



History

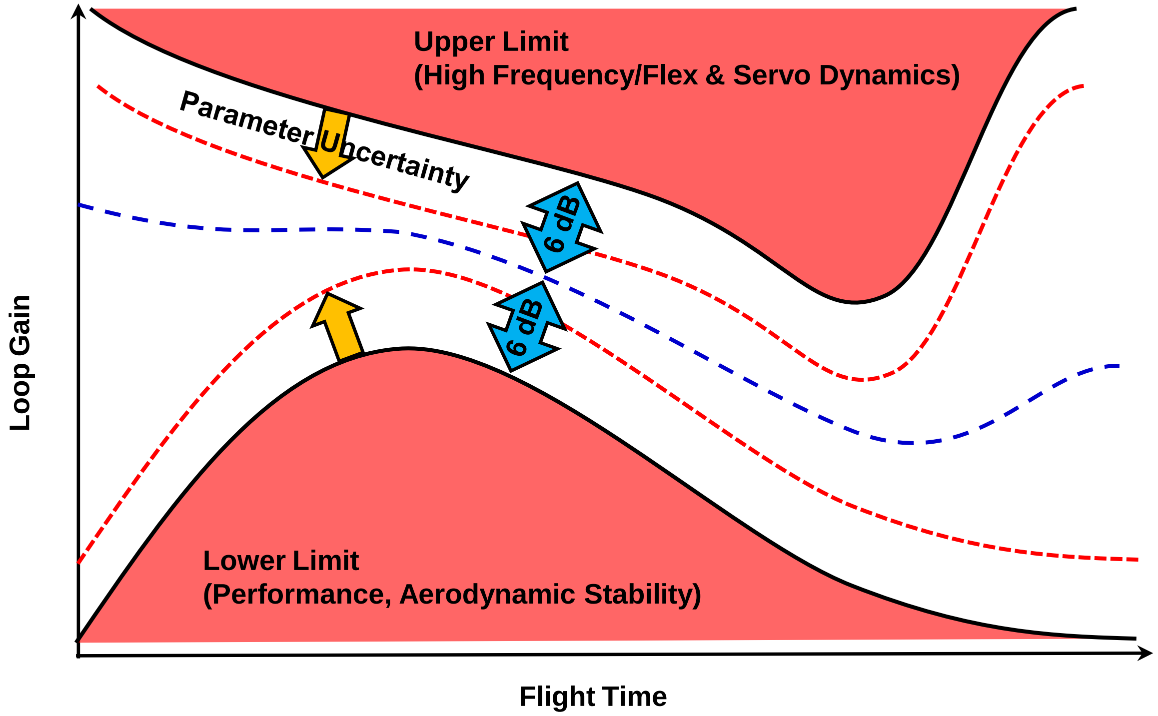
- **Current architecture has heritage to flight-tested systems**
  - MH-90 (F-101) and MH-96 (X-20, X-15), ca. 1958-1967
  - Based on a prescribed servo limit cycle amplitude (marginal servo poles)
  - Saw numerous flight tests (>60) on X-15-3, improved performance and pilot opinion of handling qualities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

  - A similar concept is well-suited to a digital implementation



Adaptive Gain Modulation

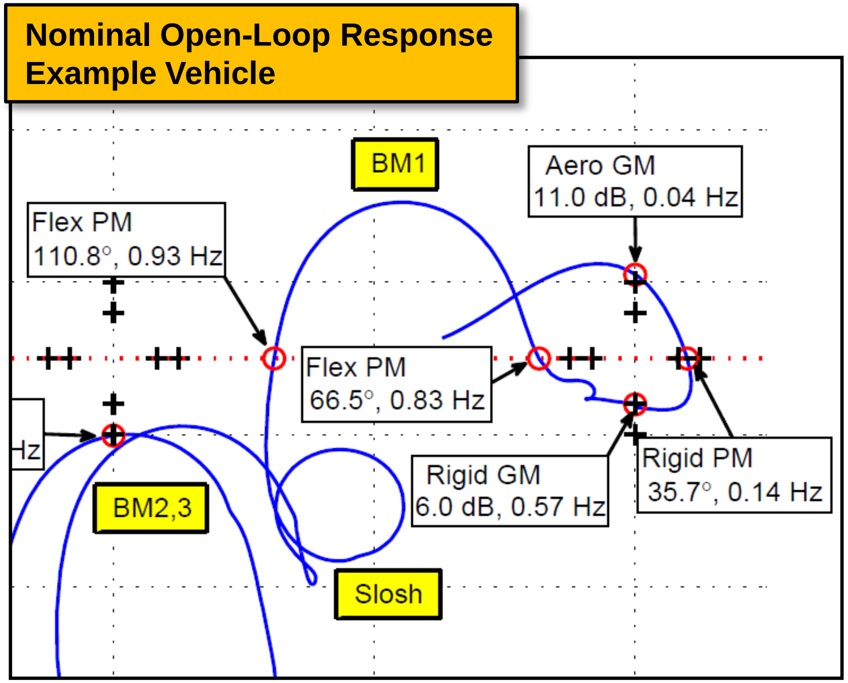
- Launch vehicles are often conditionally stable due to competing objectives of *unstable aerodynamics* and *parasitic internal dynamics*
- Because of uncertainty in models, we have to design with sufficient *gain margins*



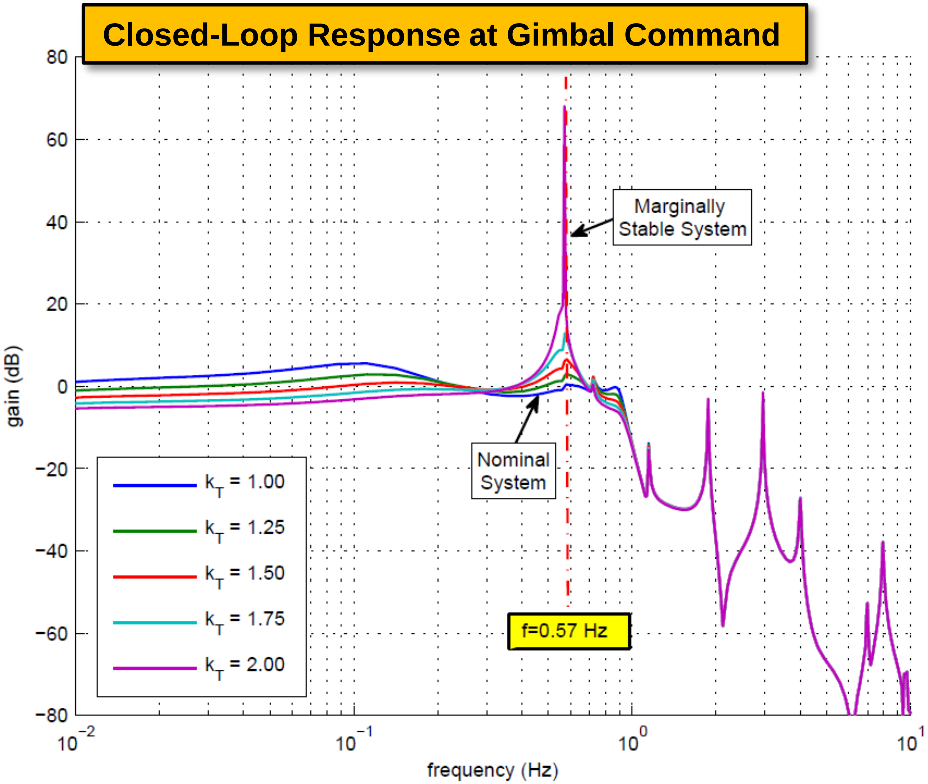
- *Adaptive gain augmentation senses off-nominal upper and lower limits in real time*

Spectral Damper Concept

- **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



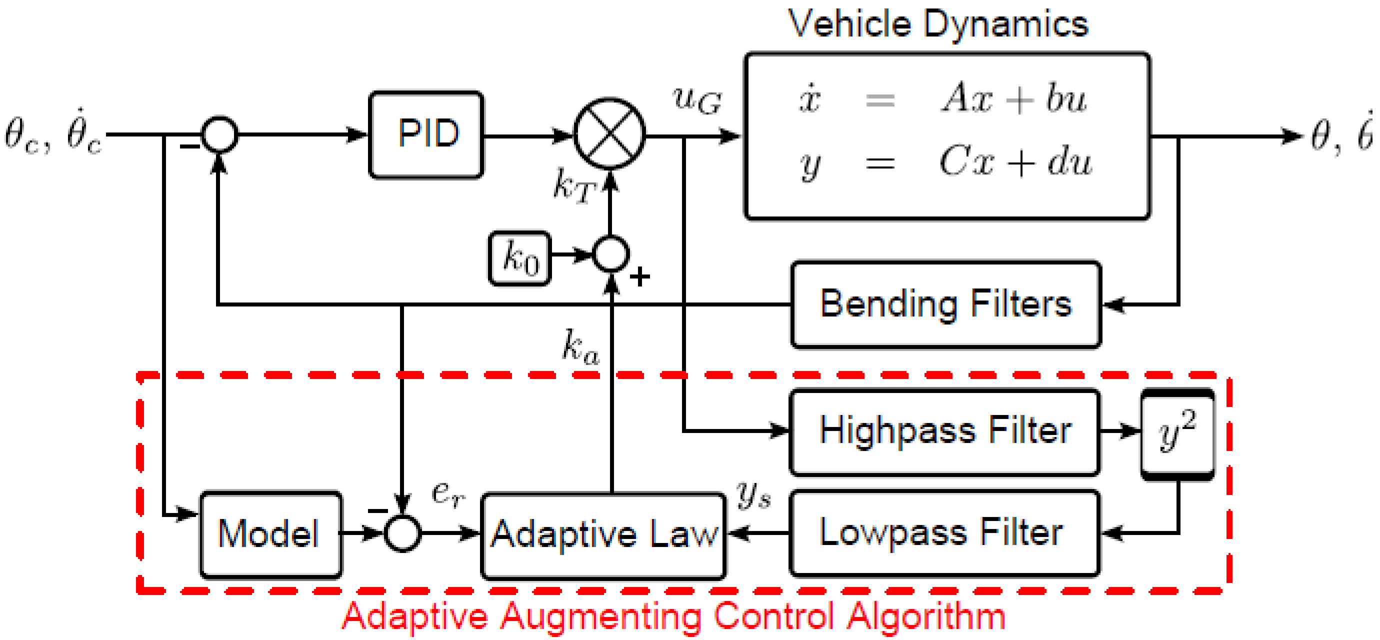
Closed-Loop Response at Gimbal Command

Adaptive Augmenting Concept

- **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;

$$k_T = k_0 + k_a$$

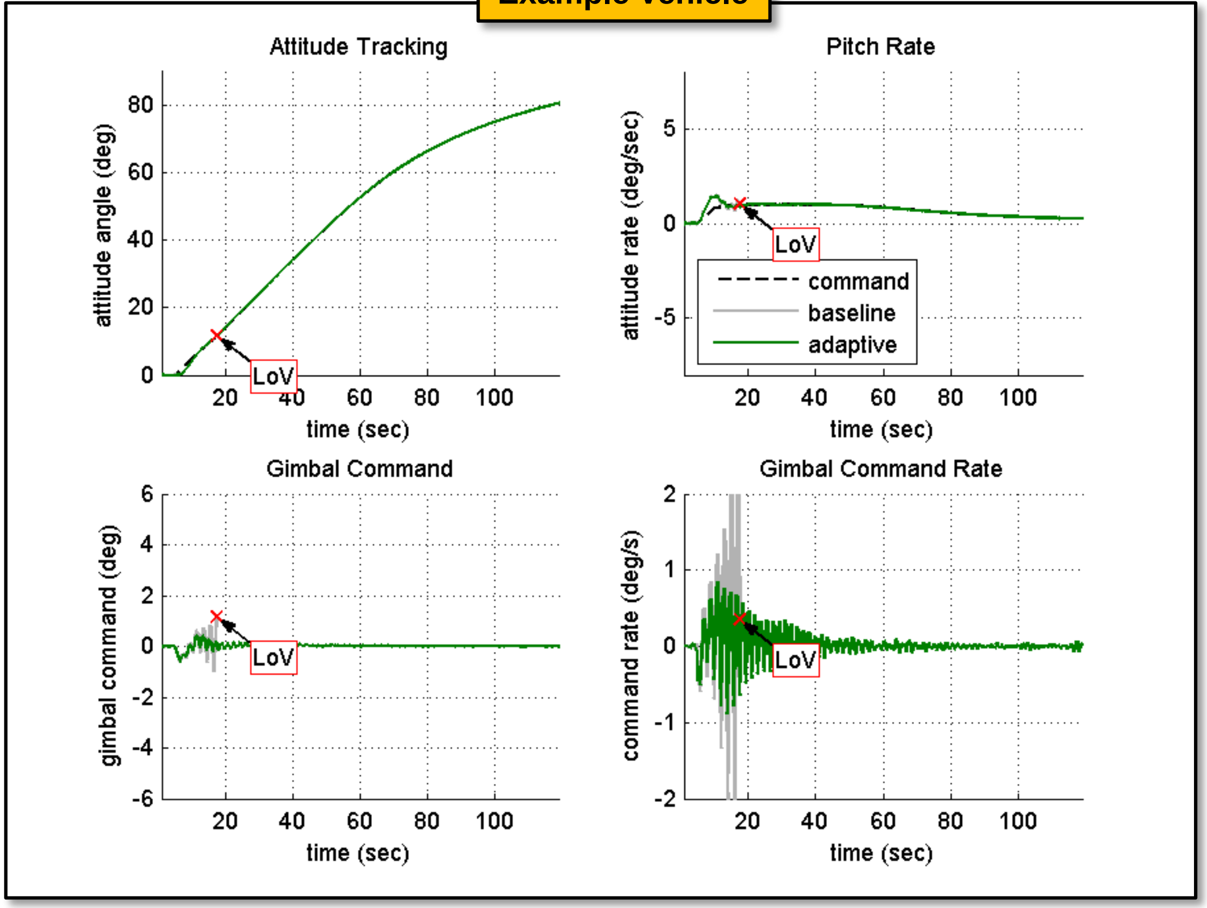
  - Multiplicative augmentation is easy to assess in terms of gain margin
  - The update law for the augmenting signal depends on the command, sensed attitude and rate, and the baseline controller output



Example: Recovery From Unstable Bending

- **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 Vehicle



Optimal Control Allocation

- **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

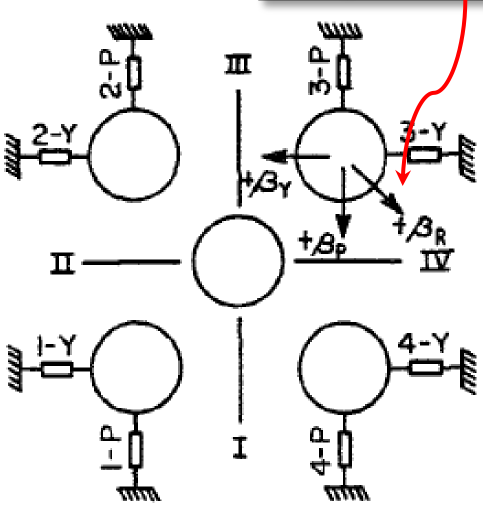
- **On-line Optimization**
  - LQ/LP
  - Must consider convergence, stability analysis, computational expense
- **Generalized Inverse Matrix Lookup**
  - Interpolation of matrix do not give exact results
  - Requires substantial data storage for sufficient resolution
- **Fixed polarity allocator with 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

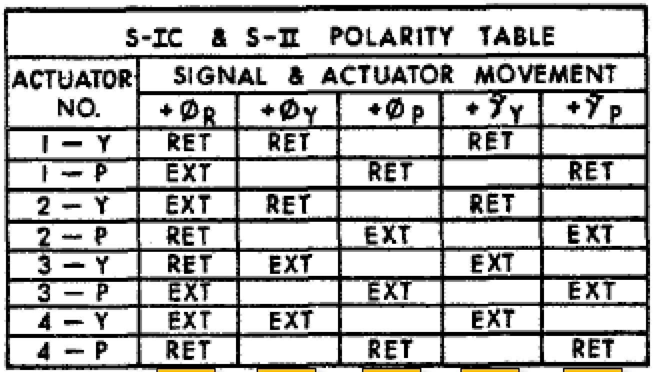
Saturn V Allocator

- 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

Tangent roll deflection



S-IC & S-II ACTUATOR LAYOUTS



S-IC & S-II POLARITY TABLE

ACTUATOR NO.	SIGNAL & ACTUATOR MOVEMENT				
	$+\phi_R$	$+\phi_Y$	$+\phi_P$	$+\ddot{\gamma}_Y$	$+\ddot{\gamma}_P$
1 – Y	RET	RET		RET	
1 – P	EXT		RET		RET
2 – Y	EXT	RET		RET	
2 – P	RET		EXT		EXT
3 – Y	RET	EXT		EXT	
3 – P	EXT		EXT		EXT
4 – Y	EXT	EXT		EXT	
4 – P	RET		RET		RET

-roll

-yaw

-pitch

+yacc

-zacc

WLS Control Allocator Formulation

- **We compute a moment effectiveness matrix as a function of time**

$$M = \begin{bmatrix} -F_1 r_1^\times u_1^\times & -F_2 r_2^\times u_2^\times & \dots & -F_k r_k^\times u_k^\times \end{bmatrix} \begin{bmatrix} T^{BG} \end{bmatrix}$$

- **In terms of angular acceleration, it becomes**

$$B = \begin{bmatrix} B_1 & B_2 & \dots & B_k \end{bmatrix}$$

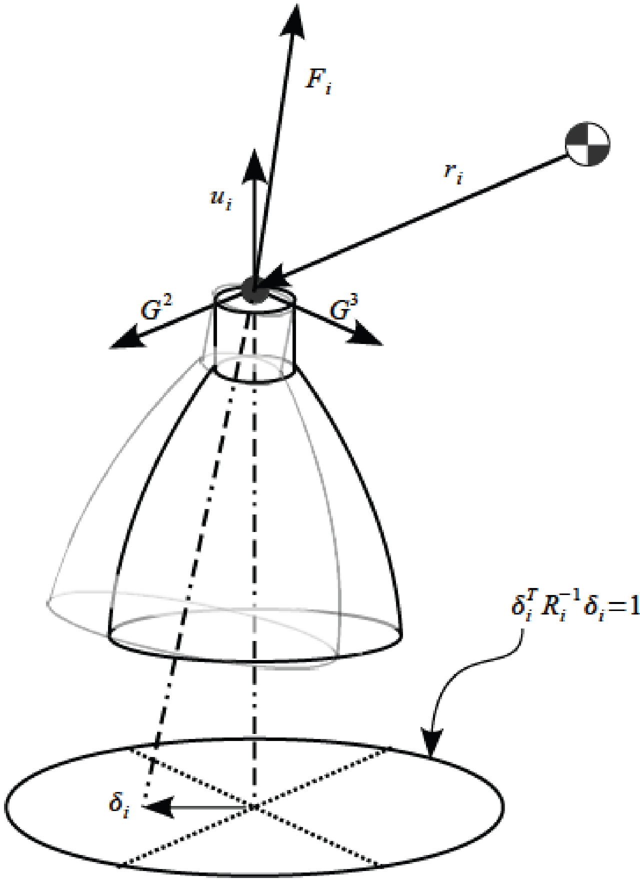
- **We minimize** $H = \frac{1}{2}\Delta^T R \Delta + \lambda^T(\dot{\omega}_c - B\Delta)$

  with $\Delta = \begin{bmatrix} \delta_1^T & \delta_2^T & \dots & \delta_k^T \end{bmatrix}^T$

- **Yielding the standard (WLS) structured generalized inverse**

$$P(W) = W B^T (B W B^T)^{-1}$$

  - 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

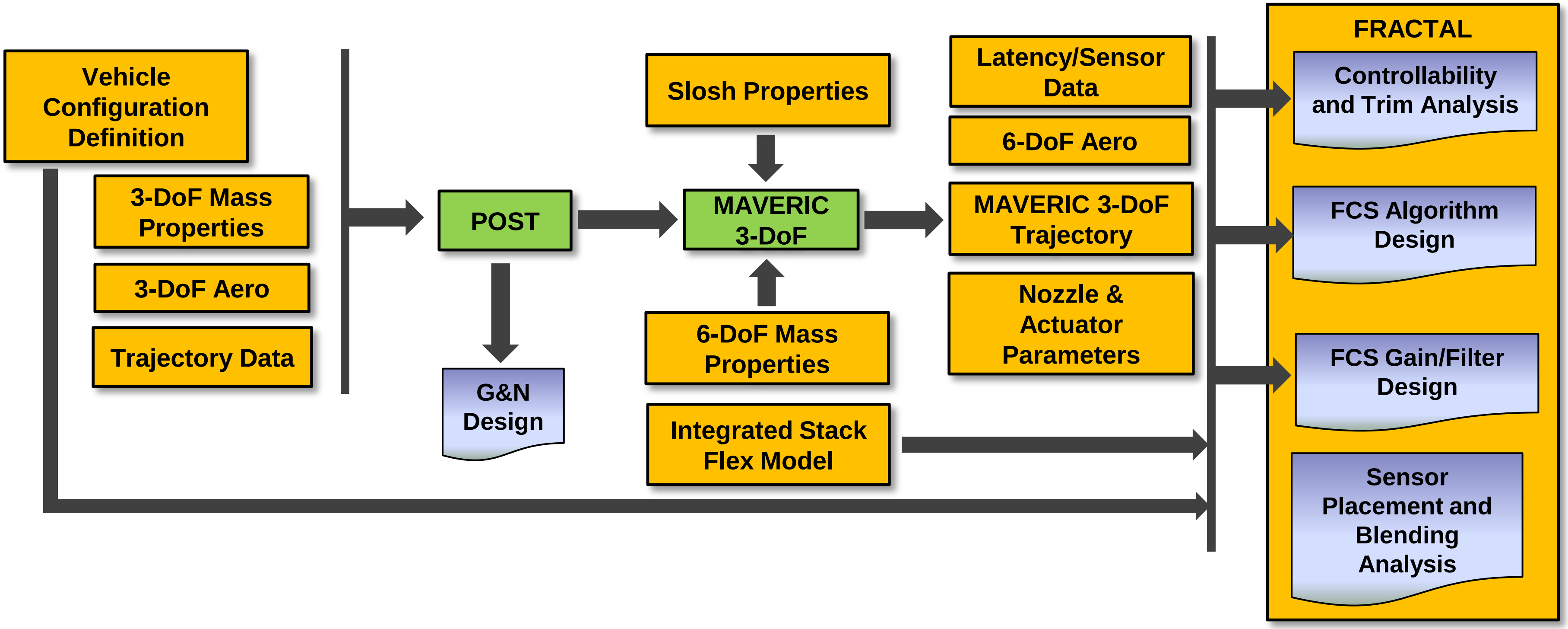


Primary Design Tools and Processes

◆ **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



Vehicle Configuration Definition

3-DoF Mass Properties

3-DoF Aero

Trajectory Data

POST

G&N Design

Slosh Properties

MAVERIC 3-DoF

6-DoF Mass Properties

Integrated Stack Flex Model

Latency/Sensor Data

6-DoF Aero

MAVERIC 3-DoF Trajectory

Nozzle & Actuator Parameters

FRACTAL

Controllability and Trim Analysis

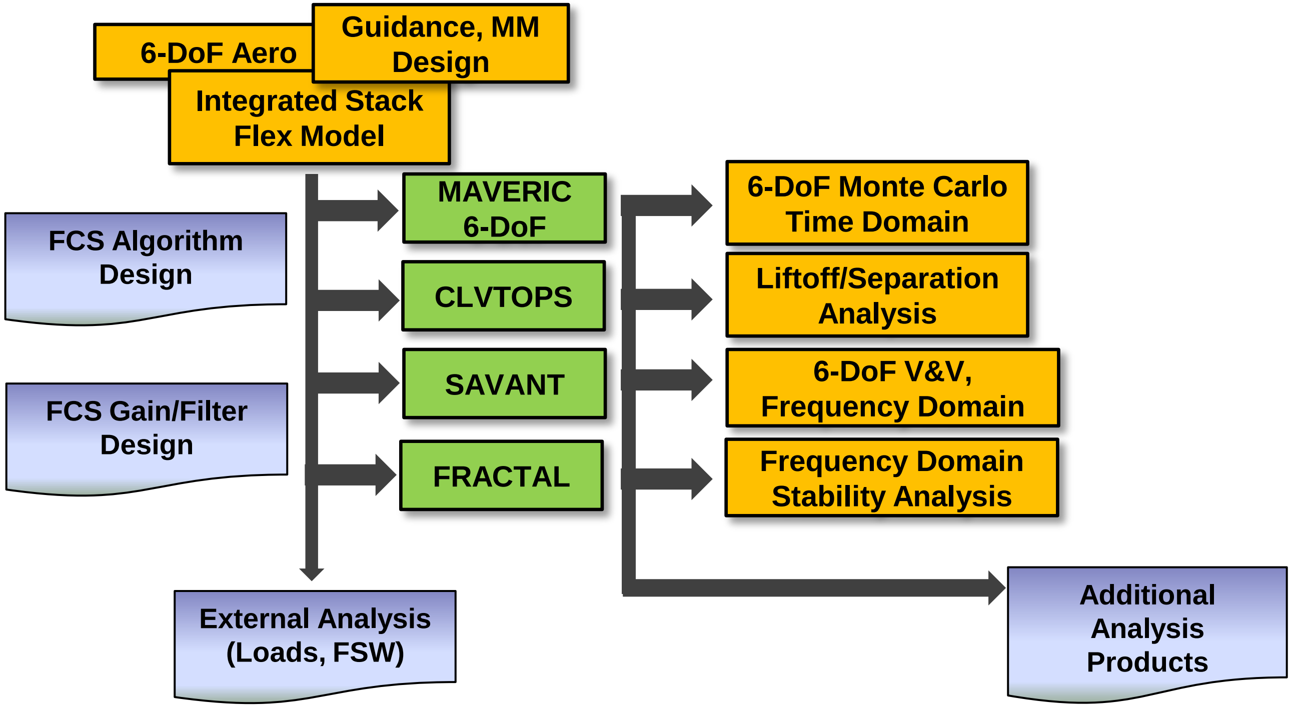
FCS Algorithm Design

FCS Gain/Filter Design

Sensor Placement and Blending Analysis

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



Summary

- **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**

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