SLS
Space Launch System

Space Launch System Implementation of Adaptive Augmenting Control

John Wall
Dynamic Concepts, Inc.
(Jacobs ESSSA Group)

Jeb Orr, Ph.D.
The Charles Stark Draper Laboratory, Inc.
(Jacobs ESSSA Group)

Tannen VanZwieten, Ph.D.
NASA Marshall Space Flight Center
Control Systems Design and Analysis Branch (EV41)

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SLS Space Launch System

Introduction

NASA

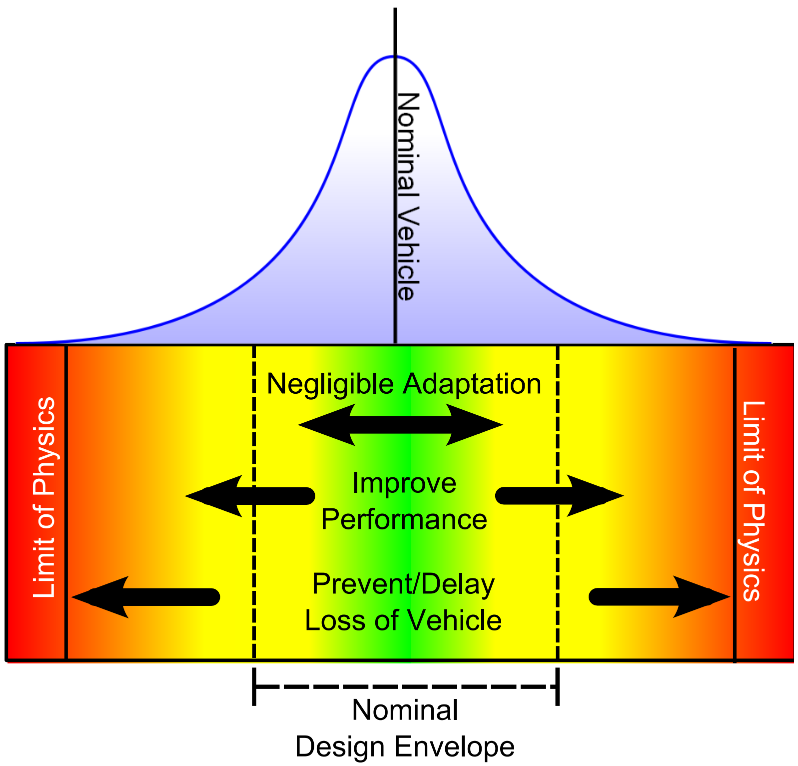
- **Adaptive Augmenting Control (AAC) has been developed for exploration class manned launch vehicles during the Constellation program [2]**
- **The AAC concept has been developed for NASA's Space Launch System family of launch vehicles and implemented as a baseline part of its full-scale flight control software**
- **SLS implementation of AAC has been dispersion tested in multiple simulation environments, flight tested using Dryden's specially outfitted F/A-18 test bed [3], and is fast approaching a CDR level of maturity**
- **Presentation will describe**
    - Basics of adaptive formulation
    - Changes to Original AAC for SLS
    - Application to SLS Control system
    - Simulation Results
        - Stressing Cases
        - Monte Carlo Analysis

Adaptive Augmenting Control Concept

- Extends performance and robustness of baseline gain-scheduled ("fixed gain") control system for the conditionally stable launch vehicle

- Augmentation uses sensed data to adjust the total loop gain on-line

- AAC summary-level design objectives:
  1. "Do no harm"; return to baseline control design when not needed
  2. Respond to error within ability of vehicle to track commands to increase performance
  3. Respond to undesirable parasitic dynamics (i.e., control-structure interaction) to regain stability



Original Adaptive Augmenting Control Law

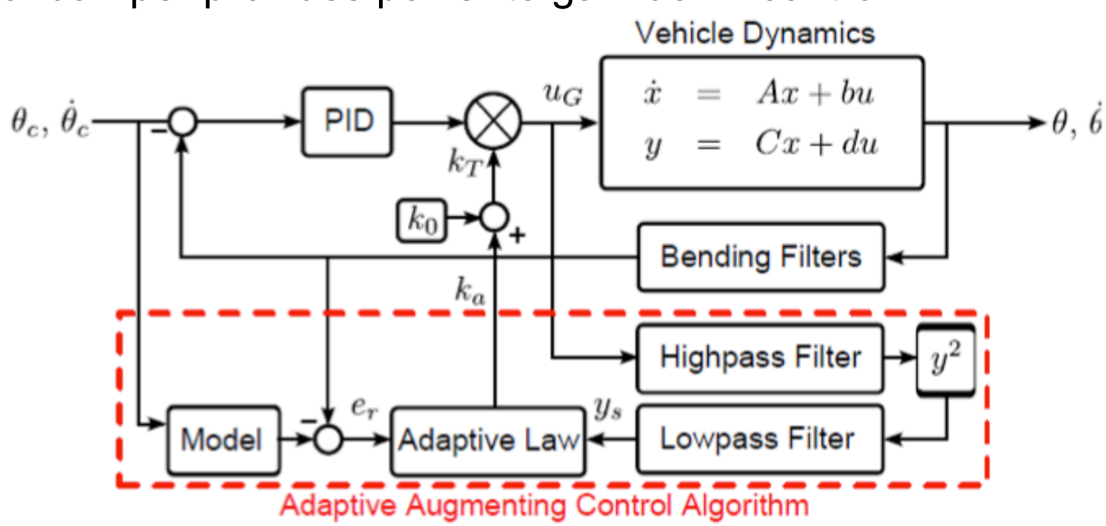
- **Original adaptive gain law [2] features three components corresponding to the three objectives**

Adaptation rate | Upper gain limitation | Error term | "Spectral damper" | Leakage

$$\dot{k}_a = \left(\frac{k_{max} - k_a}{k_{max}}\right) a e_r^2 - \alpha k_a y_s - \beta(k_T - 1) \qquad k_T = k_0 + k_a$$

2. Increase Tracking Performance | 3. Recover Instability | 1. Attract to Nominal

- **Total Gain resulting from adaptation applied to PID control signal**
  - AAC reference model provides error signal to gain up control
  - AAC spectral damper provides power to gain down control



SLS Adaptive Augmenting Control Law Updates

$$\dot{k}_a = \left(\frac{k_{max} - k_a}{k_{max}}\right) a e_r^2 - \alpha k_a y_s - \beta(k_T - 1) \qquad k_T = k_0 + k_a$$

- ♦ **SLS implementation carries three terms matching the original three objectives but with updates to the formulation**

Upper gain limitation **Lower gain limitation**

$$\dot{k}_T = p_{hi}(k_T) a e_r^2 - p_{lo}(k_T) \alpha y_s - \beta(k_T - 1)$$

2. Increase Tracking Performance **3. Recover Instability** **1. Attract to Nominal**

- ♦ **Right hand nonlinear dependencies on adaptation gain have been removed**
  - Provides for a more linear response of gain adaptation to inputs
- ♦ **Employed parameterized saturation functions to allow tunability of adaptation response to inputs**
  - Can yield a more rapid adaptation response than in the original formulation
  - SLS parameterized to effect a rapid, linear, response within 90% of allowable gain range
- ♦ **Adaptive law has been recast directly in terms of total gain**
  - Simplification of expression and flight code

Application to SLS Baseline Control Law

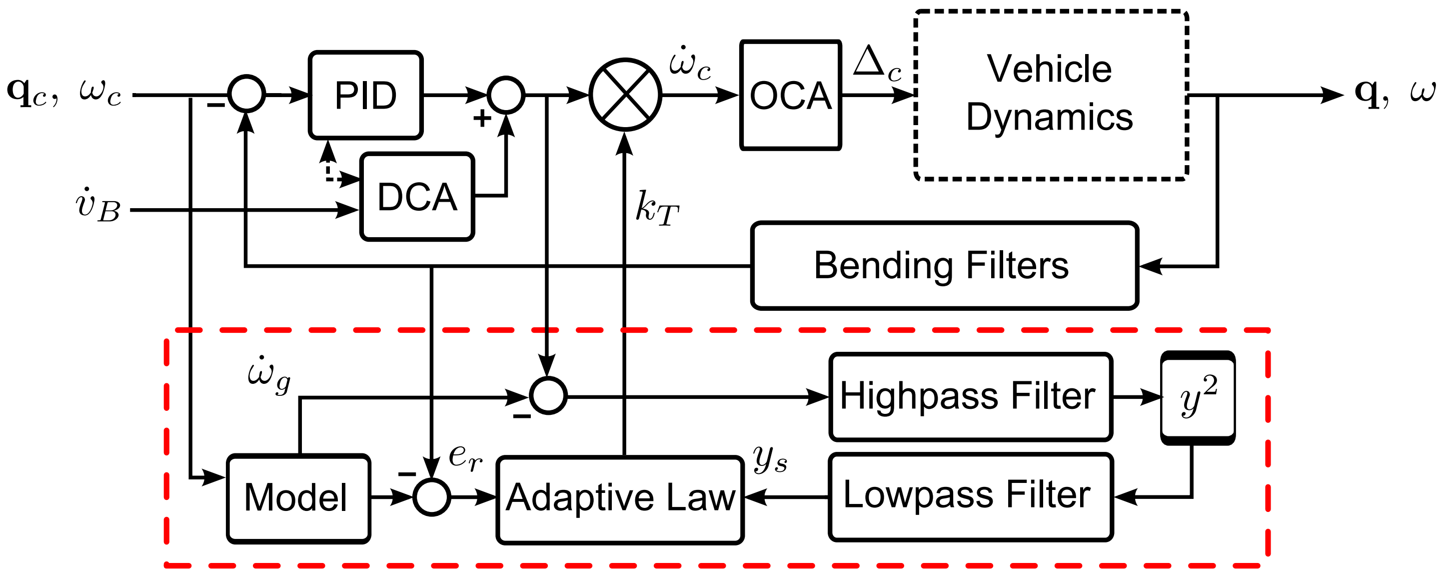
- **Baseline controller issues single angular acceleration command to the control allocator (OCA) per axis (pitch axis "q" shown)**

$$\dot{q}_c = \underbrace{k_T}_{\text{Total Gain}} \left(\underbrace{k_p\theta_e + k_d q_e + \int_{t_0}^{t_0+t} k_i \theta_e d\tau}_{\text{Proportional, Derivative, Integral Terms (PID)}} + \underbrace{\dot{q}_{DCA}}_{\text{Disturbance Compensation (DCA)}} \right) + \underbrace{\dot{q}_{PTI}}_{\text{Programmed Test Inputs (PTI)}}$$

- **Total gain is adjusted by adaptive law and applied to PID & DCA terms**
- **Application to DCA aids in two ways**
  - Objective 2: increases disturbance rejection performance, maintains PID/DCA gain ratios
  - Objective 3: allows adaptation decrease for parasitic dynamics in DCA loop
- **PTI is excluded from total gain**
  - Open loop table-lookup input for the purpose of flight test system identification
- **Angular acceleration command is the point at which SISO open loop (OL) response is constructed**
  - Total gain adjustments shifts the forward gain of the entire OL transfer function

SLS FCS with Adaptive Augmenting Control

- **Baseline Control System**
  - PID – (proportional, derivative, integral)
    - Quaternion and rate commands
  - Bending Filters – attenuates, phases parasitic dynamics (flex, slosh, actuator lag)
  - DCA (Disturbance Compensation Algorithm)
    - Rate and acceleration inputs
  - OCA (Optimal Control Allocator) – linear allocator based on weighted least-squares
- **Adaptive Augmenting Control**
  - Reference model
  - Spectral damper process (filters, rectification)
  - Adaptive Law



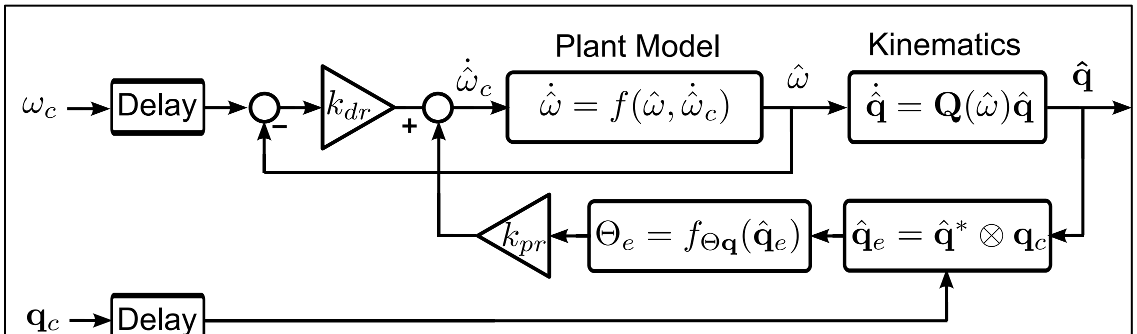
Adaptive Augmenting Control Algorithm

Multi-Axis Reference Model Mechanization

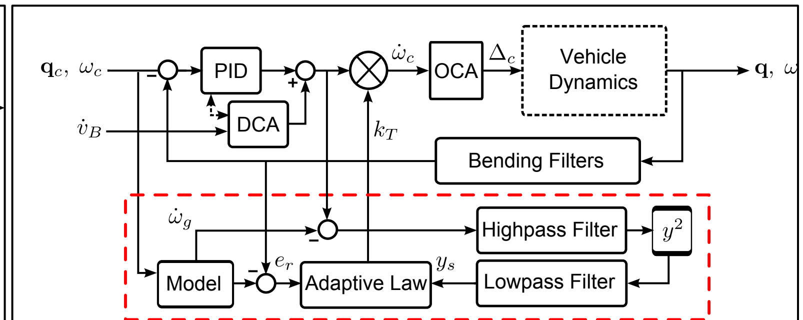
- **2nd order transfer function with input delay models nominal/baseline control response to guidance inputs**
  - Performs acceptably well compared to higher order systems
- **Each of the roll, pitch, and yaw control axes are sufficiently decoupled and parameterized independently**
  - Natural frequency, damping, and delay per axis
  - Parameters scheduled as a function of flight condition
- **Parallel roll, pitch, yaw rate transfer functions integrated in series with an outer loop quaternion mechanization**
  - Guidance inputs
    - Inertial to Body Quaternion Command, $\mathbf{q}_c$
    - Roll, Pitch, Yaw Rate Commands, ω_c
  - Output
    - Inertial to Body Quaternion Response, $\hat{\mathbf{q}}$
    - Roll, Pitch, Yaw Body Rate Response, $\hat{\omega}$

$$\dot{\hat{q}} = k_{pr}\left(\theta_c - \hat{\theta}\right) + k_{dr}\left(q_c - \hat{q}\right)$$

$$H_r(s) = e^{-s\tau}\frac{\omega_r^2 + 2\zeta_r\omega_r s}{s^2 + 2\zeta_r\omega_r s + \omega_r^2}$$



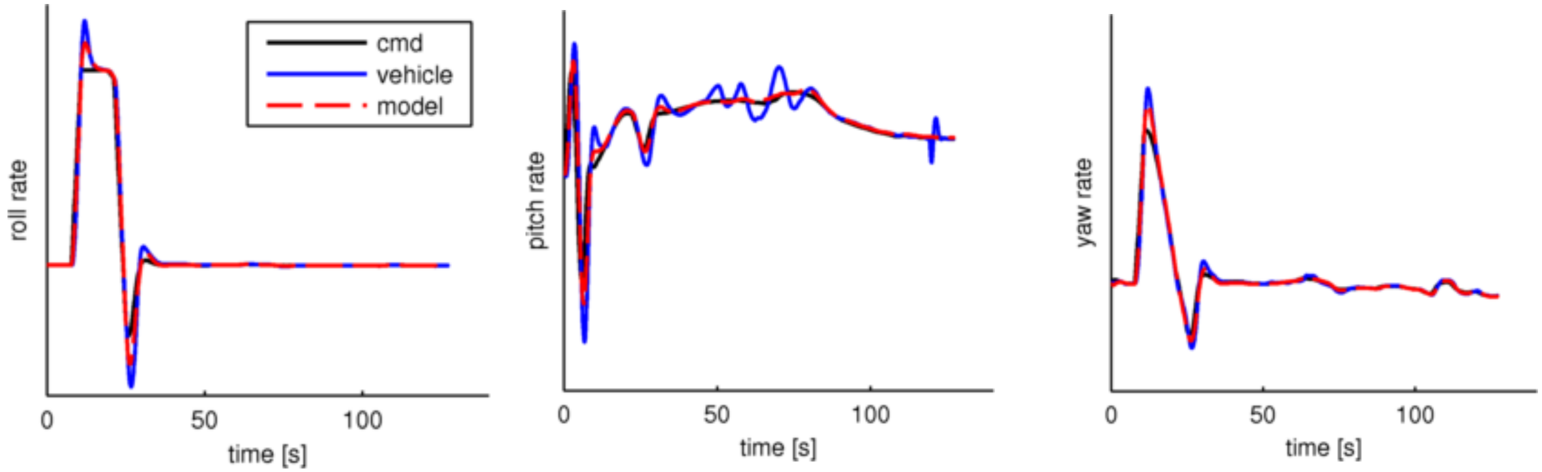
Reference Model



Total FCS

Reference Model Response and Error Signals

- **Reference model response compares well to actual system system**
  - Rate response for each axis shown on different scale
  - Roll shows largest commands during first half of boost phase trajectory
  - Pitch shows initial tower avoidance maneuver and day-of-launch wind adjustments
  - Yaw axis shows smallest command (cross-axis coupling during maneuvers)



- **Reference model response is compared to actual vehicle response to generate error signals indicating the extent to which rigid body control response has deviated from nominal/desired**

$$\dot{\gamma}_r = \hat{\omega} - \omega \qquad \gamma_r = \hat{\Theta} - \Theta$$

- **Rate errors and attitude errors are blended together for each axis to produce a single signal in each axis to effect an adaptation gain increase in the corresponding axis**

$$e_r = c\gamma_r + \dot{\gamma}_r$$

Spectral Damper, Updates to Original Formulation

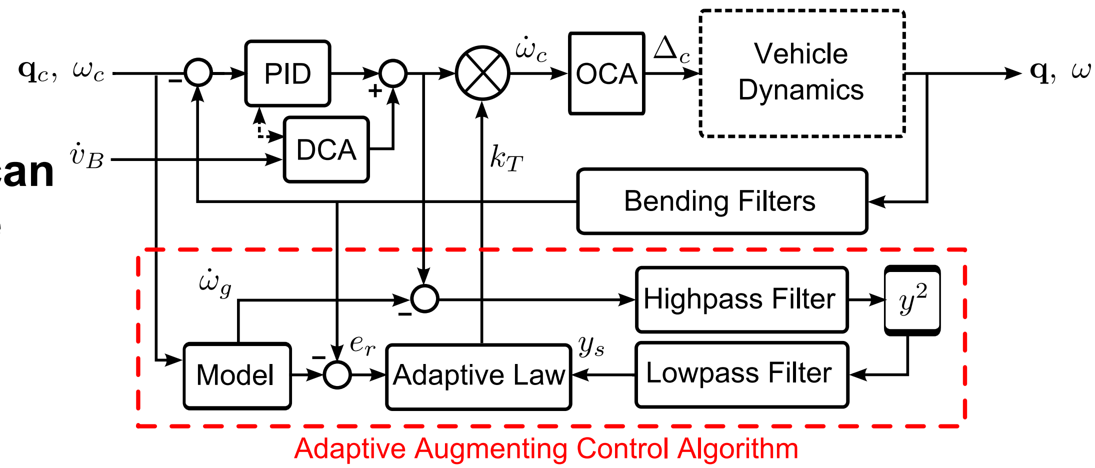
- **Spectral damper, consistent with the original formulation, provides an estimate of the power of undesirable frequency content in the feedback path**
- **Input signal is constructed from the angular acceleration control command**
  - Taken prior to application of total loop gain (avoids direct gain-induced transients)

$$\dot{q}_c = \cancelto{1}{k_T}\left(k_p\theta_e + k_d q_e + \int_{t_0}^{t_0+t} k_i\theta_e\, d\tau + \dot{q}_{DCA}\right) + \cancelto{0}{\dot{q}_{PTI}}$$

  - Includes DCA to capture undesirable dynamics in its feedback paths
  - Subtracts a angular acceleration compensation term based upon the reference model dynamics to account for guidance-induced control commands

$$\dot{q}_g = \omega_r^2\left(\theta_c - \hat{\theta}\right) + 2\zeta_r\omega_r\left(q_c - \hat{q}\right)$$

- **Resultant signal is then band-passed, squared, and low-passed to provide a smooth positive signal used to effect an adaptation gain decrease**
- **Filter parameters selected to highlight frequency spectrum associated with dynamics which can be suppressed by a gain decrease**
  - propellant slosh
  - structural flexibility
  - actuator dynamics



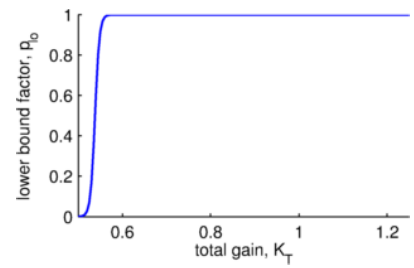
Limits Imposed on Adaptive Law

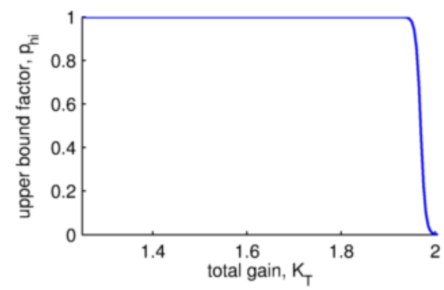
- **Saturation Functions Applied to Squared Error and Spectral Inputs**
  - Smooth saturation at ends of total gain range with tunable shape

$$\dot{k}_T = p_{hi}(k_T)ae_r^2 - p_{lo}(k_T)\alpha y_s - \beta(k_T - 1)$$

$$p_{hi}(k_T) = 1 - \left(1 + \exp\left[A\left(\frac{1}{A}\log\left(\frac{\epsilon k_{Tmax}}{1 - \epsilon k_{Tmax}}\right) + k_{Tmax} - k_T\right)\right]\right)^{-1}$$

$$p_{lo}(k_T) = \left(1 + \exp\left[A\left(\frac{1}{A}\log\left(\frac{1 - \epsilon k_{Tmax}}{\epsilon k_{Tmax}}\right) + k_{Tmin} - k_T\right)\right]\right)^{-1}$$





- **Explicit hard limits are additionally imposed on total gain**
  - 0.5 and 2.0 are current SLS total gain limits
  - correspond to -/+ 6 dB nominal gain margin design criteria

- **Adaptive rate limits imposed on squared error and spectral inputs**
  - Parameterized by the time for the term to effect a full scale gain change
  - Safeguards to preclude numerical problems due to large or spurious inputs

$$e_{lim}^2 = \left(\frac{k_{Tmax} - k_{Tmin}}{a\Delta t_{elim}}\right) \qquad y_{slim} = \left(\frac{k_{Tmax} - k_{Tmin}}{\alpha\Delta t_{sdlim}}\right)$$

- **Squared error and spectral signal are forced to be positive**
  - Spectral signal can be negative for low pass filters with complex poles

Simulation Results

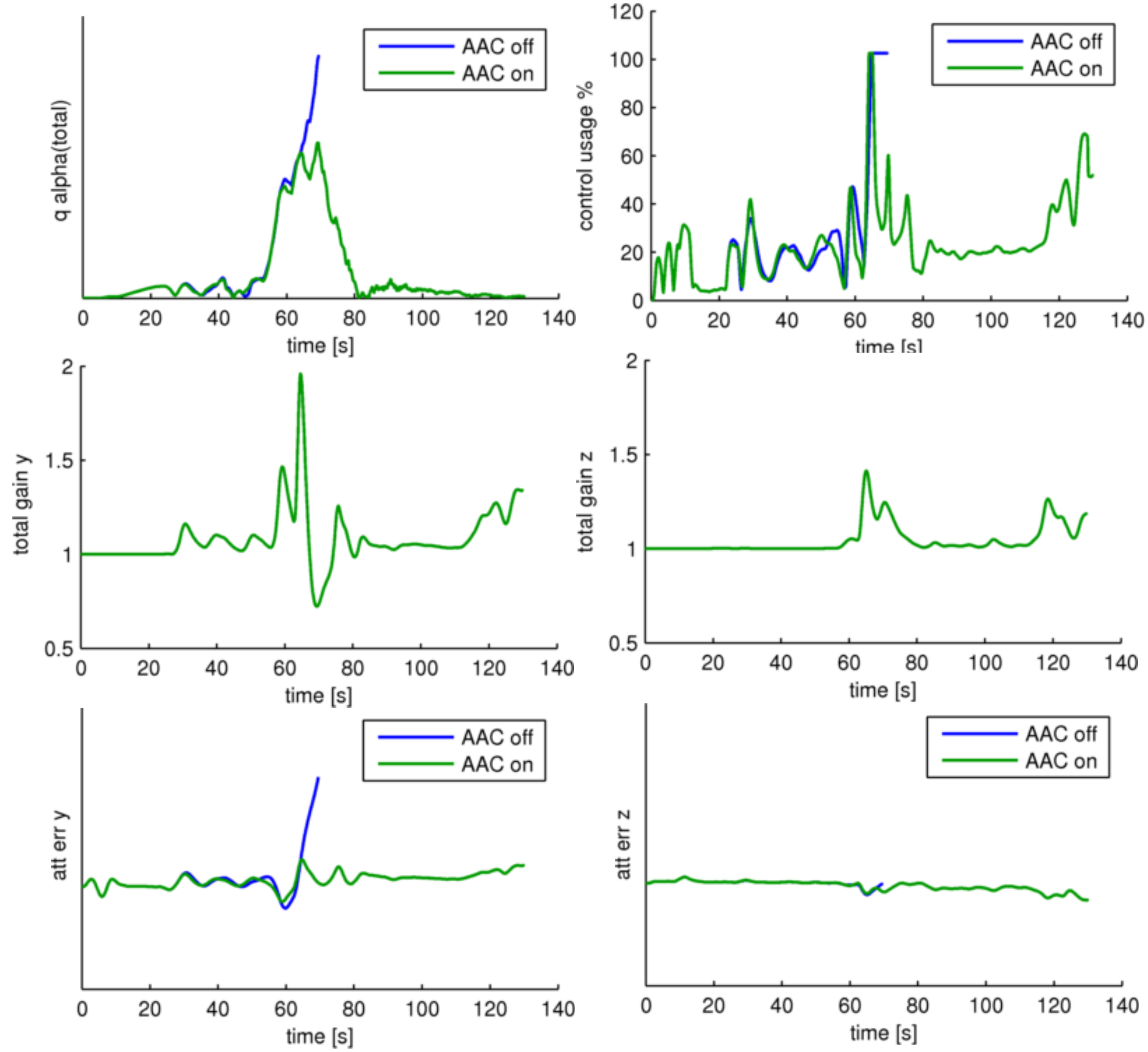
- **SLS AAC has been enabled for the boost phase of flight although plans exist to explore its extension through core stage flight**
- **The SLS FCS including AAC has been implemented in four main simulation tools:**
- **MAVERIC (Marshall Aerospace VEhicle Representation In C)**
  - MSFC developed 6-DOF time-domain simulation
  - Main ascent performance, guidance, navigation and control analysis tool
- **CLVTOPS (Crew Launch Vehicle Tree tOPology)**
  - Multi-body simulation built upon legacy TREETOPS tool
  - Employed for dispersed vehicle liftoff and staging separation clearance analysis
- **SAVANT (Stability Aerospace Vehicle ANalysis Tool)**
  - Simulink-based Verification and Validation Tool for SLS
- **STARS (Space Transportation Analysis and Research Simulation)**
  - NASA Langley developed, main simulation for Ares I-X
  - Simulink-based Verification and Validation Tool for SLS

- **Results using MAVERIC tool are shown in the following slides**
  - Stressing case demonstrating objectives 1 and 2
  - Stressing case demonstrating objectives 1 and 3
  - PDR Monte Carlo Analysis results

Stressing Case for Objective 2

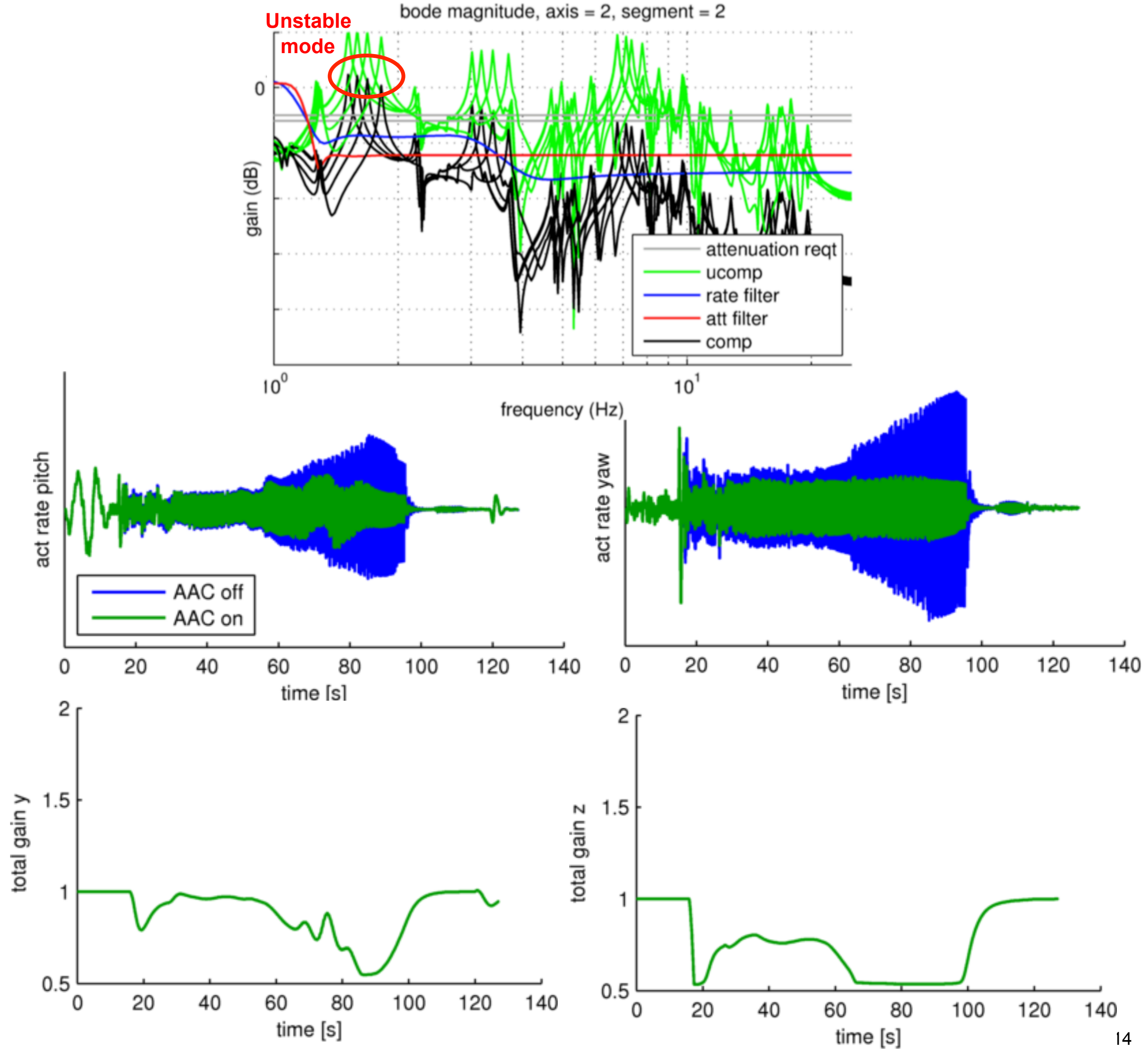
- **Example case: increased aerodynamic instability, severe winds, and a single-engine dual actuator hardover occurring during maximum dynamic pressure**

- **Extreme scenario with AAC off results in a violation of the rigid body load indicator (dynamic-pressure * total angle of attack) limit**
  - Plot terminates
- **AAC gains up the system at the onset of the disturbances**
  - Greatly improves attitude tracking
  - Load indicator stays well below limit
  - Control effort only temporarily saturates
- **AAC gain returns to nominal unity value after disturbances subside (objective 1)**



Stressing Case for Objective 3

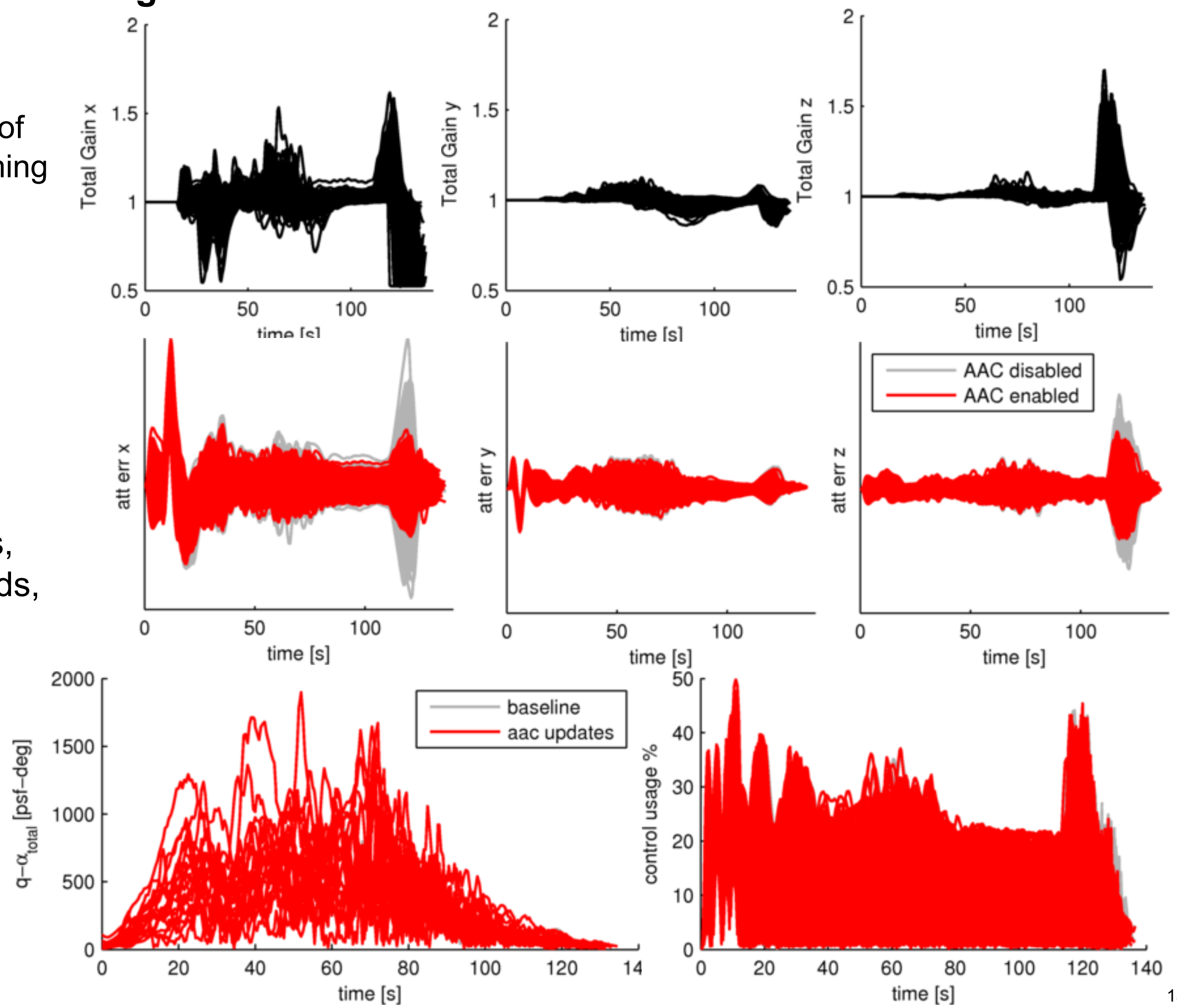
- Example case: primary structural mode undergoes simulated instability during region of flight where gain of mode is higher than necessary attenuation provided by control filters
- Extreme scenario with AAC off results in divergent behavior in the actuator rates
- AAC gains down the system at the onset of the instability
  - Suppresses modal response to a limit cycle of non-destructive magnitude
- AAC gain returns to nominal unity value after instability ceases to persist (objective 1)



Monte Carlo Simulation Results

- Example Monte Carlo simulation from liftoff to booster separation (2000 runs)
- Dispersions include but not limited to mass properties, structural dynamics, sensor noise, aerodynamics, winds, thrust misalignment

- **Total gain in pitch shows minimal adaptation**
  - Small deviation towards end of flight due to booster tailoff timing variations
- **Yaw shows adaptation in booster tail-off region**
  - Corresponding to highly dispersed booster thrust imbalance
- **Roll shows the most adaptation**
  - Large guidance commands, excursions due to high winds, booster tailoff, and conservative booster slag model
- **Overall, minimal effect on load indicators and control usage despite vehicle and environment design dispersions (objective 1)**



Questions?

References

- [1] J. Orr, J. Wall, T. VanZwieten, and C. Hall, "Space Launch System Ascent Flight Control Design," in *AAS Guidance, Navigation, and Control Conference, Breckenridge, CO*, 2014.
- [2] J.Orr and T.VanZwieten, "Robust, Practical Adaptive Control for Launch Vehicles," in *AIAA Guidance, Navigation, and Control Conference, Minneapolis, MN, AIAA-2012-4549*, August 2012.
- [3] T. VanZwieten, E. Gilligan, J. Wall, and J. Orr, "Adaptive Augmenting Control Flight Characterization Experiment on an F/A-18," in *AAS Guidance, Navigation, and Control Conference, Breckenridge, CO*, 2014.
- [4] J. Orr, "Optimal Recursive Digital Filters for Active Bending Stabilization," in *AAS Guidance, Naviga- tion, and Control Conference, Breckenridge, CO*, 2013.
- [5] J. Hanson and C. Hall, "Learning About Ares I from Monte Carlo Simulation," in *AIAA Guidance, Navigation, and Control Conference, Honolulu, HI, AIAA-2008-6622*, 2008.