Path to First Flight of Adaptive Augmenting Control on NASA's Space Launch System for Artemis I

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ABSTRACT

This paper describes the development and implementation of the Adaptive Augmenting Control (AAC) system for NASA's Space Launch System (SLS), leading to its ground-breaking flight demonstration during the Artemis I launch on November 16, 2022. The paper documents the origin and evolution of the architecture, discusses analysis techniques employed, and provides an overview of the path that led to a successful transition of the technology from concept to flight. Attention is given to principles, studies and perspectives that shaped algorithm design and subsequent refinements which may be useful to flight controls practitioners of future space transportation systems. In its final test during the uncrewed first flight of NASA's SLS, AAC performed as intended throughout the launch phase and its response reflected a flight trajectory within the pre-flight expectations.

1 INTRODUCTION

NASA's Space Launch System (SLS) Flight Control System (FCS) design is largely based on a classical gain-scheduled control design that has heritage with the Saturn Program[1] and Ares I-X[2,3]. The design architecture consists of sensor blending, gain-scheduled proportional-integral-derivative control, bending filters, and a Disturbance Compensation Algorithm (DCA), Adaptive Augmenting Control (AAC), and optimal control allocation.[4,5,6,7] The adaptive component (AAC), which is the topic of this paper, modifies the attitude control system response to provide additional robustness should the ascending vehicle go outside its design envelope. In the presence of "expected" vehicle or environmental uncertainties, gain-scheduled autopilots for rockets can readily be optimized such that there is little motivation for on-line adaptation. However, a review of historical reusable launch vehicle data from 1990 to 2002 revealed that 41 percent of failures in subsystems other than GN&C might have been mitigated by advanced GN&C technologies.[8] Launch vehicle failures, which may have been prevented had an AAC-like feature been included in their control algorithm, include:

- 1994 loss of the first Pegasus XL due to poor aerodynamic modeling leading to inadequate flight control performance.
- 1995 loss of a Conestoga launch vehicle due to a modeling error of a bending mode frequency (see Figure 1). A full integrated vehicle ground vibration test (GVT) was not performed, and the vehicle was flown with limited control filter robustness to bending mode uncertainty. Control was lost after using up the limited supply of blow-down hydraulic fluid during a TVC limit cycle resulting from excessive coupling of the control system and bending.

- 1998 loss of the first Delta III due to a modeling error that led to excessive roll commands and depletion of TVC hydraulic fluid (see Figure 1).

The AAC was not designed to replace traditional gain-scheduled control designs, but rather to augment the classical design to increase robustness for off-nominal scenarios.

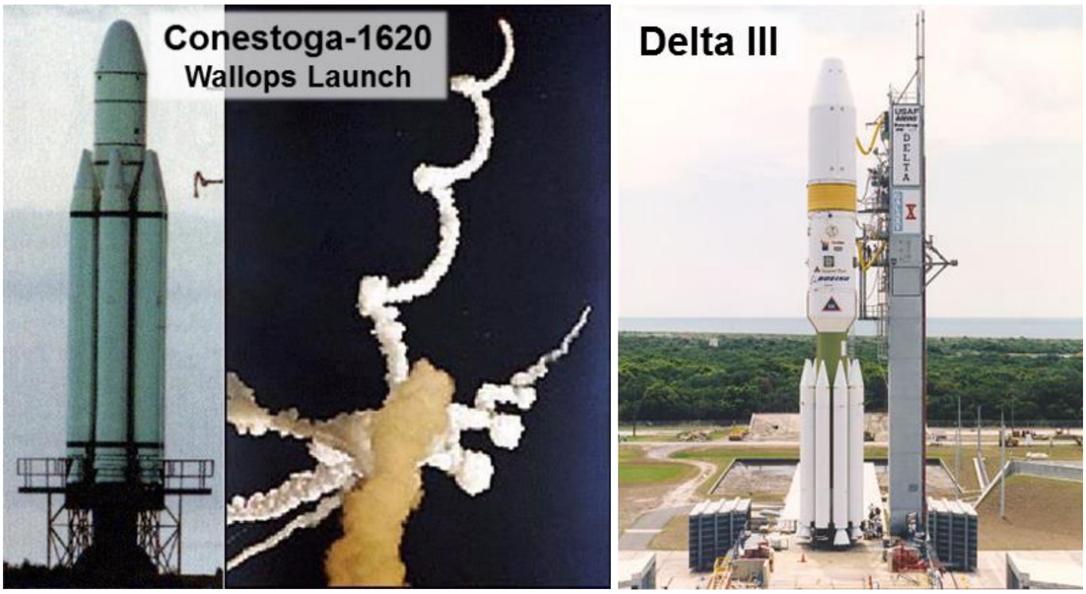

Figure 1. Conestoga-1620 Launch Vehicle (1995, left) and Delta III Launch Vehicle (1998)

The AAC algorithm was initially developed under the Constellation Program (CxP)[9], analyzed as a side-study for SLS Design Analysis Cycle (DAC)-1 (May 2012), and was subsequently baselined as part of the SLS FCS architecture in DAC-2 (November 2012). The functionally intuitive design was shown to minimally adapt within the design envelope, but significantly enhance robustness in off-nominal test cases. The post-Preliminary Design Review (PDR) version of the SLS FCS flight software prototype, including the AAC, was flight tested on a piloted F/A-18 at NASA Armstrong Flight Research Center.[10,11,12,13,14,15,16,17] The aircraft acted as a surrogate launch vehicle by mimicking the pitch attitude error dynamics of the massive, less responsive SLS for the completion of 100+ SLS-like boost phase trajectories[18] and closed-loop mitigation of an unstable F/A-18 structural mode.[15] Following the F/A-18 flight testing, a rigorous algorithm verification assessment was conducted,[37,19] the algorithm was exercised in the Marshall Space Flight Center (MSFC) System Integration Laboratory (SIL), and the technology was successfully demonstrated during the Artemis I launch on November 16, 2022.

This paper is intended to provide an overview of the vision for architecting the AAC algorithm and describe the key components of the algorithm design, maturation, and verification leading to its flight demonstration during the Artemis I first flight. The paper is organized chronologically, with Section 2 describing the early studies that established the vision for AAC followed by a description of the guiding principles in Section 3. Section 4 describes the evolution of the architecture, Section 5 describes the algorithm verification analyses that were conducted, and Section 6 provides an overview of the key events in the advancement of the Technology Readiness Level (TRL) with emphasis on the targeted F/A-18 flight testing that was conducted. The paper concludes with a discussion of the first flight (Section 7), overall timeline from development of the vision to first flight (Section 8), and concluding remarks (Section 9).

2 EARLY STUDIES

During the Ares I Program, a technical risk was identified based on concerns that increased stack length, a large diameter upper stage, and control-structure interaction (i.e., vehicle structural modes in the control bandwidth) could introduce attitude flight control stability issues during ascent. The MSFC Ares I Guidance Navigation and Control (GN&C) team conducted a technical risk analysis, developed a risk mitigation approach involving detailed model validation through analysis and test, and proposed evaluating advanced technology to reduce potential impacts. Analyses demonstrated that established, traditional approaches to launch vehicle GN&C were sufficient to provide robust stability with adequate margins for Ares I ascent flight control.[20] The baseline ascent flight control design approach was to tune the compensator (loop shape) to achieve rigid body performance and stability, add baffles to enhance slosh stability, and augment the compensator with flex mode filters to gain and phase stabilize interacting structural modes.[21]

While the use of classical control design techniques and progressive test-based model validation was sufficient to demonstrate adequacy of the prior art for Ares I, the team asserted that further risk reduction could be achieved by *augmenting*, not replacing, the gain-scheduled control architecture with advanced control theory – namely, augmenting the classical control loops with an adaptive element to provide additional robustness against modeling errors and unforeseen in-flight dynamics. Thus began an effort across the broader launch vehicle GN&C community to leverage and apply this advanced, robust control technology to the Ares I GN&C design. This advanced technology employed control augmentation for unstable mode suppression with a primary focus on developing and maturing concepts for adaptive control system validation through demonstrable mathematical foundations (e.g., weight adaptation derived from a Lyapunov function to ensure bounded stability), high-fidelity Monte Carlo dispersion analysis, ground test, and research test flights.

Much emphasis was placed on Ares I adaptive flight control at the 2008 AIAA Guidance, Navigation and Control Conference and Exhibit (Honolulu, Hawaii, August 18-21, 2008). Sessions were held on Ares I GN&C and Modeling & Analysis as well as a focused session on "Adaptive and Nonlinear Control of Launch Vehicles."[22,23,24,25,26,27,28] A seminal event in the development and application of adaptive control for launch vehicles was the Adaptive Control for Human Launch Vehicles Workshop held in Denver, Colorado, immediately after the 2008 NASA Aviation Safety Program Technical Conference. Twenty-six experts gathered from NASA, AFRL, academia, and industry to lay the foundation for control system architectures and methods for flight validation. The novel and exceptionally impactful development and application of adaptive augmenting control for crewed launch vehicles continued under the team's efforts and progressed through research aircraft flight testing with AFRC, and is now baselined in the SLS, extending the safety and reliability of the exploration-class human-rated launch vehicle over the status quo.

3 GUIDING PRINCIPLES

The design architecture was formulated to leverage advanced control theory to *augment* rather than *replace* the traditional gain-scheduled design. Within this framework, the adaptive system was structured such that it would improve the baseline flight control system robustness, yet not unacceptably increase risk when the vehicle was operated within its nominal design envelope (Figure 2). Other key principles included maintaining a classical design architecture such that the adaptive system would only augment the control commands and return to the base controller when not needed. The architecture was designed with an ability to both increase performance (attitude error regulation) and decrease performance to avoid exciting parasitic dynamics such as vehicle flexibility and slosh. The system prescribed bounds on the adaptive gains in correlation to classical stability margins.[29,30] As the design matured, healthy tension emerged amongst the engineers who were seeking to achieve adequate adaptive system performance against the known launch vehicle failure modes while also adhering to well-known Lyapunov-based stability approaches. The team performed careful evaluation of each design component and articulated the associated benefits and drawbacks, departing from the well-studied Lyapunov approaches when necessary. The designers sought the simplest adaptive control law architecture that met the ascent launch vehicle-centric design objectives, and the introduction of additional complexity was thoroughly scrutinized for its efficacy to add robustness. Multiple stability analysis approaches were investigated, and the architecture was rigorously reviewed and evaluated using both high-fidelity simulations, a surrogate aircraft flight test campaign, and eventually the uncrewed first flight of the SLS.

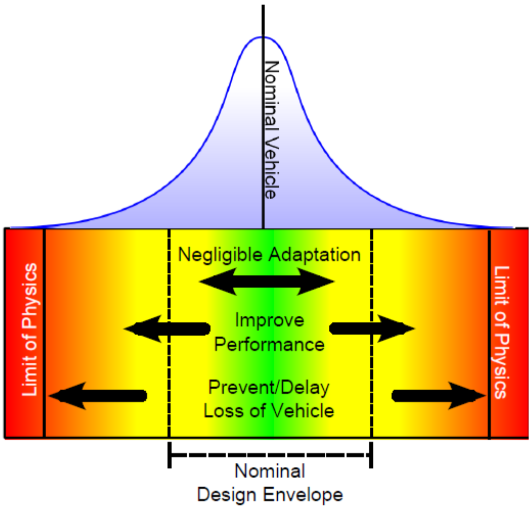

Figure 2. Driving Principle: Increase Robustness but "Do No Harm"

The following list summarizes the guiding principles as the adaptive control design evolved:

- Reduce risk by leveraging advanced control theory to augment (not replace) the fixed-gain control architecture.
- Embed the ability to both increase performance (error regulation) and decrease performance (increase robustness) to avoid exciting parasitic dynamics such as vehicle flexibility and slosh.
- Balance the classical and adaptive (Lyapunov) control perspectives with respect to system design, desired performance, and stability analysis.
- Retain stability margins with the no-failure design envelope (i.e., do not increase performance until a limit cycle is reached; employ adaptation only for off-nominal performance).
- Implement a prescribed bound on the adaptive gains that correlates to classical stability margins.
- Maintain ability to "turn it off" and/or remove AAC from the control algorithm, if merited.
- Maintain simplicity in algorithm design.

4 EVOLUTION OF THE ARCHITECTURE

This section describes the AAC algorithm architecture at key stages during the development and refinement process – the original vision for the architecture, AAC design implemented for early SLS design cycles and F/A-18 flight testing, and the final architecture as flown for Artemis I.

4.1 Design Vision for Adaptive Augmentation

An adaptive controller was proposed and discussed as an augmentation of the classical linear flight control architecture for Ares I at the "Adaptive Control for Human Launch Vehicles Workshop" led by MSFC in 2008. A block diagram depicting an initial vision for the architecture (Figure 3) was provided and the fundamental constraint emphasized that the augmenting control signal must be "small" in nominal conditions.

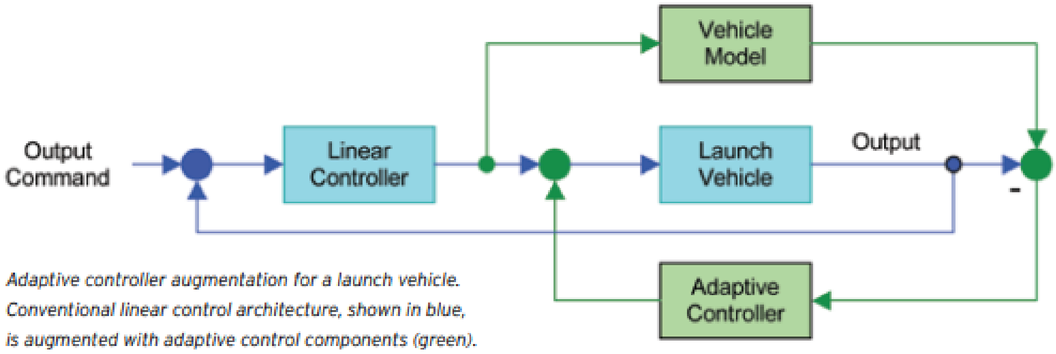

Figure 3. Concept for Augmenting a Linear Launch Vehicle Flight Control Algorithm[31]

Within the control augmentation architecture, a model reference adaptive control (MRAC) system and adaptive update law was designed with three primary objectives in mind:

1. Minimally adapt when the baseline control system is performing acceptably.
2. Increase performance and command tracking when extreme off-nominal conditions and disturbances produce large errors.
3. Decrease the system gain to prevent high-frequency content in the control loop from driving the system to instability.

The first objective was articulated at the workshop, the second objective is a typical goal for MRAC but complements the first goal by focusing on addressing extreme scenarios, and the third objective was added to address the possibility of having a closed loop instability due to launch vehicle flexibility, actuator nonlinearities, and/or slosh dynamics.

4.2 SLS AAC Architecture for First Two SLS Design Analysis Cycles

As with the original Ares I concept, the SLS AAC uses sensed data to adjust the controller responsiveness on-line (see Figure 4). It increases responsiveness when the SLS response is sluggish (i.e., it does not match the reference model), which typically occurs at a lower frequency than the rigid-body gain crossover. AAC decreases responsiveness when high-frequency content is observed in the control command, typically attributed to flexible motion, fuel slosh, or effects of actuator rate saturation, which occurs at a higher frequency than the rigid-body gain crossover.

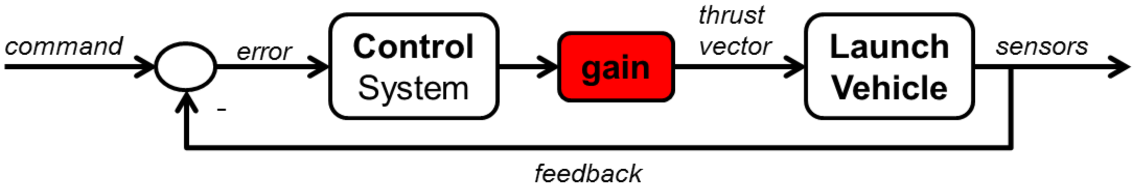

Figure 4. Simplified Vehicle-Control Interaction Diagram with Gain to be adjusted by AAC

Designers considered multiple options for addressing control-structure and control-slosh interaction component of the algorithm and converged on the inclusion of a "spectral damper" as inspired by the adaptive control schemes implemented in the early 1960s for the X-15 and X-20.[32,33] This gain adaptive approach was further supported by members of the MSFC-based Controls Working Group (CWG), who suggested that a multiplicative gain law would have the best traceability to classical gain margins, the Nyquist criterion, and an intuitive expectation of the desired change in system response. Multiplying the adaptive gain by the gain-scheduled control command rather than by the error signal was, in general, departure from traditional Lyapunov-derived adaptive architectures that augment the control command with additive terms. The resulting initial implementation is shown in Figure 5.[9] This architecture was carried as an optional control mode in SLS DAC-1,[1] where additional analyses with adaptive augmentation were performed in parallel to the baseline gain-scheduled control architecture. AAC was officially adopted during DAC-2 and enabled as part of the control baseline for the boost phase of flight (prior to separation of the SRBs). The DAC-2 adaptive augmentation consisted of a single adaptive gain driven by the update law[4]:

Upper gain limitation
"Spectral damper"

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

Adaptation rate
Error term
Leakage

The spectral damper output signal y_s, is formed from the controller gimbal command output u_G as

$$\begin{aligned} y_{HP} &= H_{HP}(s)u_G \\ y_s &= H_{LP}(s)y_{HP}^2 \end{aligned} \tag{2}$$

where H_{HP} is a linear high-pass filter and H_{LP} is a linear low-pass filter. The total loop gain is formed by the sum of a fixed minimum gain and the adaptive gain

$$k_T = k_0 + k_a \tag{3}$$

The adaptive update law included three terms, mapping to the three objectives of the algorithm introduced in the previous section: the error-driven "up gain," the spectral damper "down gain" that is driven by presence of high-frequency content in the control loop, and a leakage term that attracted the loop gain multiplier back toward unity. The adaptive gain can be viewed as a "knob" that tunes the controller on-line by increasing or decreasing the responsiveness when needed and gradually returning to the response of the gain-scheduled controller response with a multiplier of k_T = 1 when augmentation is no longer merited. The lower limit was defined by k_0, and the upper limit was defined as k_{max}. These were set to be 0.5 and 2.0 respectively, corresponding to ±6 decibel (dB) gain margin guideline.

[1] Delivery dates for DACs supporting Exploration Mission (EM)-1 were May 2012 (DAC-1), November 2012 (DAC-2), April 2013 (DAC-2R), April 2014 (DAC-3), and January 2015 (DAC-3R).

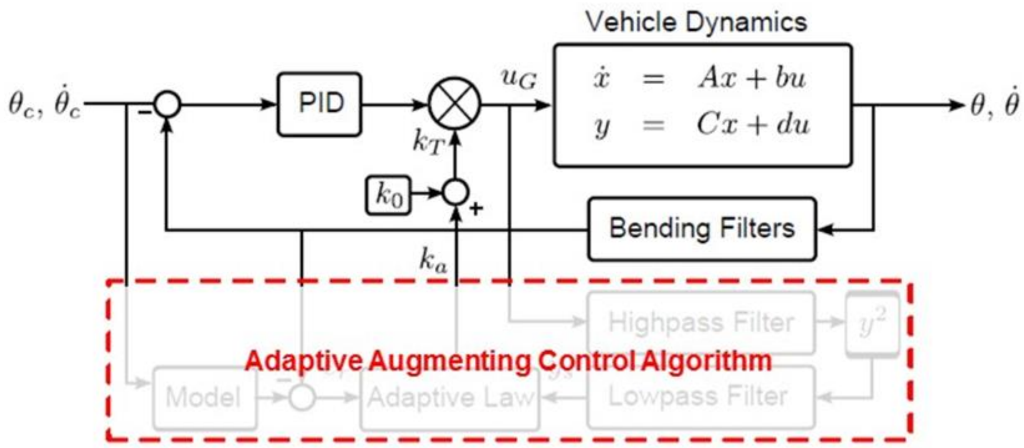

Figure 5. Basic AAC Architecture for SLS DAC-1 and -2

4.3 Architecture Flown on SLS for Artemis I

The architecture flown as part of the SLS FCS for Artemis I defined the adaptive gain as[34]

$$k_T = H_{AAC}(s)\,\mathrm{sat}_{k_{\min}}^{k_{\max}}\{K_e y_e - K_s y_s + 1\} \tag{4}$$

where $H_{AAC}(s)$ is a second-order low-pass filter and the term $sat_{k_{min}}^{k_{max}}\{\cdot\}$ provides user-prescribed limits of k_{min} and k_{max} on the adaptive input signal. Note that a second-order filter was implemented rather than a first-order filter for $H_{AAC}(s)$ to improve time response characteristics and provide attenuation of high frequency adaptation dynamics which is linked to limit cycling of the gains when the adaptation law is driven to its upper or lower limits. The multipliers K_e and K_s are constants, and y_e and y_s are given by

$$\begin{aligned} y_e &= H_{EF}(s)\,(H_{EW}(s)\dot{\omega}_{AAC})^2 \\ y_s &= H_{LP}(s)\,(H_{HP}(s)\dot{\omega}_{AAC})^2 \end{aligned} \tag{5}$$

The angular acceleration $\dot{\omega}_{AAC}$ is defined as

$$\dot{\omega}_{AAC} = \dot{\omega}_{PD} - \dot{\omega}_g \;, \tag{6}$$

where $\dot{\omega}_g$ is the angular acceleration from the reference model and $\dot{\omega}_{PD}$ is the angular acceleration from the proportional-derivative component of the controller. The associated block diagram is shown in Figure 6.

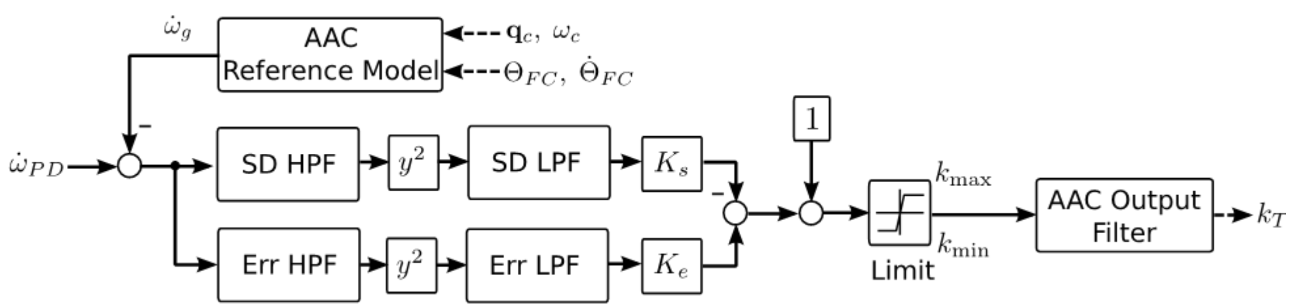

Figure 6. Block diagram of SLS AAC Architecture Flown on Artemis I

The function of the error (gain increase) and spectral damper (gain decrease) terms in equation (4) are shown in Figure 7. The error term (y_e) in equation (4) increases the response when there is reference model error. The spectral damper term (y_s) in equation (4) decreases the response driven by the spectral damper based on thrust vector activity in a specific frequency band (defined by the high-pass filter in the "SD HPF" block). The bias of 1 in equation (4) results in the unforced solution returning to the equilibrium state of unity gain. Note that the high pass (washout) filter in the error channel (denoted "Err HPF") is included to avoid saturation of "up gain" in the case of a large, constant input. It is defined such that the break frequency is well below the rigid-body (error) bandwidth and therefore it does not affect the AAC dynamics.

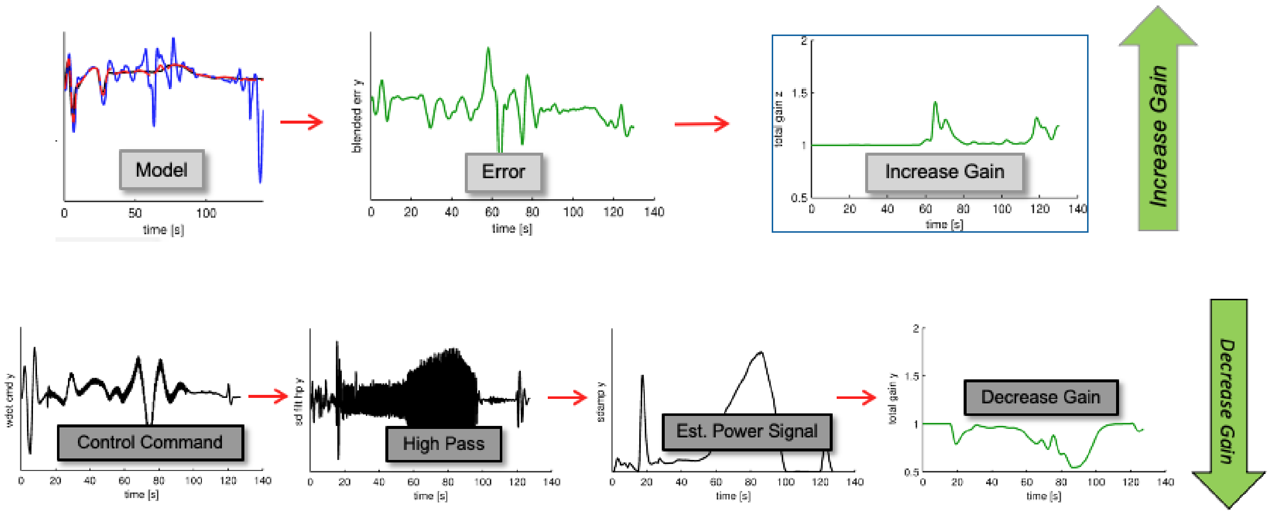

Figure 7. "Up Gain" (above) and "Down Gain" Components of SLS AAC[35]

As an alternate way of understanding the adaptive gain design, if the saturation constraints are removed and it is assumed that the filter on the output can be approximated as a first-order low-pass filter ($H_{AAC}(s) = \frac{1}{1+s/\omega_c}$) with cutoff frequency ω_c then equation (4) can be re-written as,

$$k_T = \frac{1}{1+s/\omega_c}(K_e y_e - K_s y_s + 1). \tag{7}$$

Then, multiplying across by the denominator of the filter and re-organizing the equation to have the $\dot{k}_T$ term on the left-hand side the following form is obtained,

$$\frac{1}{\omega_c}\dot{k}_T = K_e y_e - K_s y_s - (k_T - 1). \tag{8}$$

which resembles the early form of AAC provided in equation (1). The up-gain and leakage terms in this equation link to Lyapunov stability theory.[36, 37] The spectral damper down gain component and total system stability has been carefully considered in a thorough stability analysis treatment based on an extension of describing function techniques.[19,37]

5 ALGORITHM VERIFICATION

Control approaches that use real-time adaptation are potentially powerful tools to accommodate environmental or vehicle model uncertainties, including in-flight anomalies and failure scenarios, albeit with the risk of unanticipated or potentially unbounded emergent behaviours. Traditional barriers to capitalizing on the benefits of advanced control techniques that are particularly relevant for human-rated systems include algorithm and code complexity, predictability of the response, ability to reconcile the stability analysis in the context of classical gain and phase margin, and flight certification. In other words, "black box" approaches with numerous adaptive gains, complex nonlinearities, and limited correlations with classical stability margins would be difficult to justify from a risk perspective, even if performance exceeded that of the existing architecture. Thus, an algorithmically simple, predictable AAC design whose multiplicative form retained an ability to interpret results based on classical stability margins was an attractive option for SLS. The ability to perform adequate verification on the non-traditional flight control architecture with its inclusion of the AAC component is coupled with the design itself being developed with the end in mind – that it must be trusted to control a human-rated vehicle.

The NASA Engineering and Safety Center (NESC) and the SLS Program performed a comprehensive assessment of the stability and robustness of AAC.[37] The standard launch vehicle flight control analyses performed for all SLS DACs are a combination of (1) frequency-domain stability analysis based on linear theory, and (2) high-fidelity Monte Carlo simulations in the time domain. Both analyses provide valuable information about the classical, gain-scheduled architecture but are not sufficiently comprehensive when applied to the nonlinear AAC algorithm. The frequency domain analysis provides the launch vehicle designer with confidence that there is adequate system margin, but it has shortcomings because it requires the linearization of the nonlinear AAC algorithm. The standard approach to Monte Carlo time domain simulation is of limited value because the core control algorithm (without AAC) can accommodate the dispersions and AAC is not substantially engaged. While these analyses confirmed that AAC does not introduce detrimental behaviour within the expected flight envelopes, they did not fully exercise the adaptive algorithm. As the SLS AAC algorithm was intentionally designed to augment (not replace) the existing classical architecture, it was deemed prudent to commission a comprehensive, multifaceted analysis of the stability of the FCS *with* AAC. In this spirit, the SLS Program augmented the standard analyses prior to this assessment by leveraging techniques based on describing functions (DFs) to provide insight into potentially undesirable dynamic interactions between competing elements of the AAC algorithm. The insights realized from the ongoing DF-based analysis in conjunction with the NESC/SLS study efforts led to several algorithmic enhancements and solidified the approach to adaptive parameter selection (gain tuning). The NESC/SLS assessment included the following analyses: Lyapunov-based stability analysis, classical stability analysis with static AAC gain variations, Generalized Gain Margins (GGMs) based on the Circle Criterion, Time-Domain Stability Margins (TDSMs), Monte Carlo simulations with expanded dispersions, and evaluation of stressing cases.[38,39] The extensive set of analyses that was completed by a team of engineers across a 2-year time-span are described in detail in NASA internal peer-reviewed documentation.[37] Several of the analyses focused on providing confidence that the AAC would *not harm* the system:

- **Classical stability metrics** were evaluated using a simplified model to assess the impact of scaling the FCS proportional and derivative gains between their minimum and maximum, mimicking the action of the AAC gain when at its limits.
- **GGMs** made use of a more complex Circle Criterion analysis to assess if nonlinear gain variations in the allowable range could drive the launch vehicle to instability. Saturation constraints define the allowable range to mitigate potential risk if the performance of AAC during flight is not as intended.
- **Monte Carlo simulations** were used to consider AAC's impact and the gain variation within nominal and expanded dispersion envelopes. Performance characteristics were not significantly impacted even under expanded dispersions. The only visible outcome from the adaptation was the AAC gain variations themselves, which are noted due to their impact on the standard frequency-domain stability assessments.

In addition to evaluating the stability risk introduced by the AAC, its ability to *enhance* stability was considered through the following analyses:

- **Nonlinear (Lyapunov) stability analysis,** which is the foundational theoretical tool for proving the stability of many adaptive control systems. Lyapunov stability analysis was applied to the error-driven ("up-gain") and leakage components of the AAC algorithm. A stability proof is documented for a modified version of the algorithm, and specific NESC recommendations[37] were incorporated into the design[19] to achieve Lyapunov-based stability of the up-gain and leakage portions of the adaptive control law.

- **Describing Function (DF) analysis** was used to address the characteristics of the "down gain" behavior,[19] as there was no known stability analysis technique that can be applied to the spectral damper component. This analysis led to the development of a frequency-domain description for the AAC's adaptation dynamics, called the *selectivity function,* which was directly employed when adjusting the AAC parameters for a desired response in terms of the modal characteristics of the vehicle dynamics. In addition, nonlinear analysis in the frequency domain supported the mitigation of "corner case" unintended behaviors that had occurred during time-domain analysis.
- **TDSMs** calculated using SLS' high-fidelity time-domain simulation with and without the AAC active, which showed an average of 5 dB added gain margin with the inclusion of AAC.
- **Stressing cases** completed in a high-fidelity SLS simulation environment were derived to target the inherent nonlinearity of the design and to quantify the efficacy of its robustness enhancing qualities. The stressing cases demonstrated that the AAC provides enhanced robustness and performance for the SLS flight control system in the presence of extreme off-nominal conditions. The stressing cases also illustrated the stability of the nonlinear adaptive system across a range of scenarios specifically targeted to break it.

The stability and robustness of AAC was assessed from both a "do no harm" perspective as well as a "do some good" perspective. The analyses completed resulted in several recommendations[37] regarding the design, parameter tuning, and completion of future analysis that were provided to and largely accepted and implemented by the SLS program[19]. Supplementary analysis tools were integrated into production SLS tools which includes a suite of stressing cases, Circle Criterion analyses, expanded Monte Carlo simulations, and time-domain stability margins (TDSMs) and maintained as standard analyses leading to the first flight. The verification activities also highlighted the coupled nature of design and verification activities, where a feedback mechanism should be in place to allow for design adjustments based on findings in the verification stage.

The verification activities confirmed the benefits of AAC.[37] Nonlinear stability analysis showed the error-driven and leakage components of the algorithm (two of three main elements) will adjust the FCS response in a manner that drives the system toward stability. Time-domain stability margins (TDSMs) were shown to nearly double with AAC in comparison with the gain-scheduled response. The simulated response to a diverse array of stressing cases consistently demonstrated that ACC enhances robustness, and performance-improvement objectives were met when operating well outside the design envelope.

6 ADVANCEMENT OF TECHNOLOGY READINESS THROUGH FLIGHT TESTING

Planned analyses as part of the standard launch vehicle practices included evaluation of the AAC algorithm using high-fidelity simulations (TRL-4) and software-in-the-loop testing in MSFC's SIL which advanced the AAC algorithm to TRL-8. This was augmented with a carefully designed suite of flight tests on an F/A-18[13,14,15,16,17] which advanced the AAC algorithm to TRL-6 and improved trust in the AAC component of the FCS prior to SIL testing and finalization of the GN&C design for the Artemis I mission. Before conducting the 2013 flight characterization experiment, AAC was the only part of the SLS autopilot that lacked a flight test (Figure 8). The flight tests conducted consisted of 95 SLS-like trajectories (Figures 9 and 10) during which the aircraft was controlled by the SLS FCS. A range of scenarios were designed to fully exercise the AAC algorithm, thereby ensuring its ability to achieve the expected performance improvements with no adverse impacts in nominal or near-nominal scenarios. Additional tests were conducted to explore interactions between SLS manual steering mode and AAC and demonstrate AAC's ability to mitigate a closed-loop control-structure instability of an unstable intentionally excited F/A-18 structural mode. These flight tests provided validation of the full-scale FCS algorithm (including AAC), characterization of the algorithm on a large-scale, manned flight test platform, and advancement of the technology readiness early in the program. AAC's final test was during the uncrewed first flight of SLS, where AAC performed as intended as part of the FCS throughout ascent. Key components of the AAC Technology Readiness Level (TRL) advancement are depicted in Figure 11 along with the software description for the associated TRL.

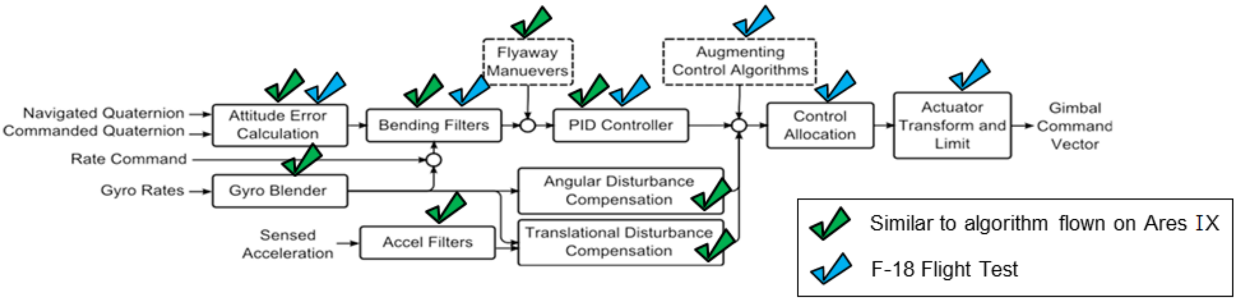

Figure 8. Flight Testing of the SLS Autopilot Flight Software Prototype

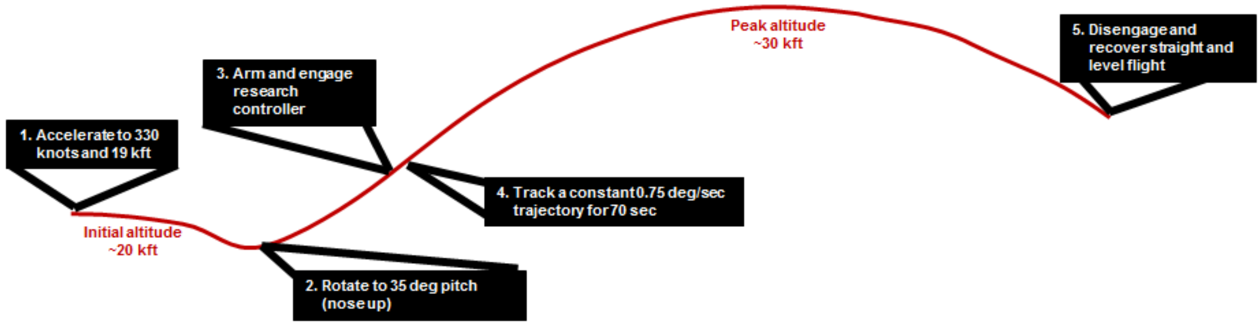

Figure 9. Prescribed F/A-18 Trajectory for the Flight Experiment

Figure 10. Photographs Taken during the Flight Experiment Depicting the Trajectory Flown Repeatedly by the F/A-18

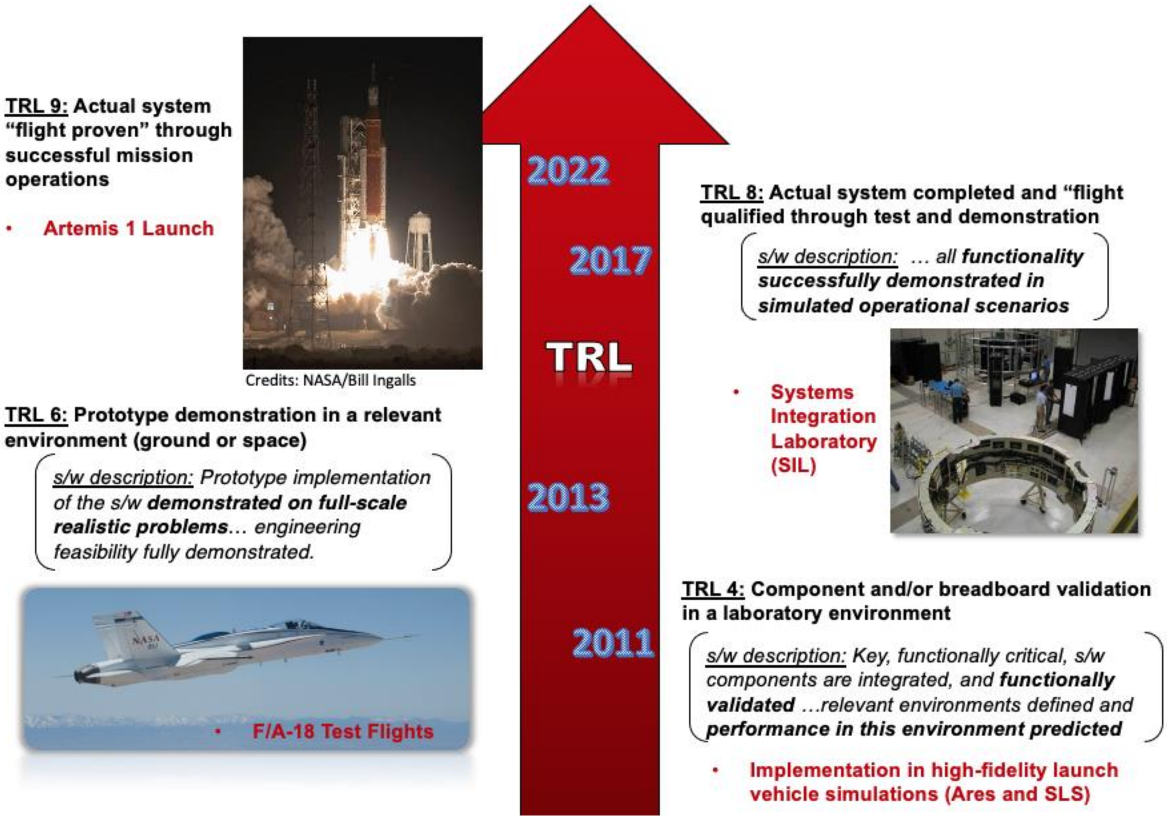

Figure 11. AAC Technology Readiness Level (TRL) Advancement

7 SLS FIRST FLIGHT (ARTEMIS I)

SLS launched on the Artemis I flight test on Wednesday, November 16, 2022 from Launch Complex 39B at NASA's Kennedy Space Center in Florida at 1:47 a.m. EST (Figure 12). The SLS AAC was an active part of the FCS until Main Engine Cutoff (MECO) was reached. During this uncrewed first flight of SLS, AAC performed as intended throughout the launch phase and its response reflected a flight trajectory within the pre-flight expectations.

Figure 12. SLS Launch (Artemis I) on Wednesday, November 16, 2022 from Launch Complex 39B at NASA's Kennedy Space Center in Florida at 1:47 a.m. EST Image Credit: NASA/Bill Ingalls

Figures 13-15 depict the flight response of the AAC adaptation gain (blue) as compared to the pre-flight nominal simulation (dashed black) and the 99.865% at 50% confidence level statistical enclosure from pre-flight Monte Carlo simulations (solid gray). Generally, the AAC response during flight was well behaved with an adaptation of the FCS loop gain within 10% of unity gain (i.e, minimal adaptation). The exception to the 10% rule was in the yaw axis during booster tailoff (T+110s to T+130s) where thrust imbalances and variations in the actual versus predicted booster thrust trace was expected to drive an AAC response. Even considering this, the AAC response at this sensitive timeframe was shown to be well within pre-flight Monte Carlo bounds.

Along with other telemetry points in the roll channel, such as attitude and rate error, AAC showed more activity in the roll axis in Core Stage flight as compared to pre-flight simulations. Detailed post-flight analysis suggests this is due to friction effects in the Core Stage TVC gimbal bearings.[40] Greater roll activity (not reflected in the pre-flight in the figures below) in the attitude and AAC response was observed when using pre-flight models including the effects of Core Stage gimbal friction.

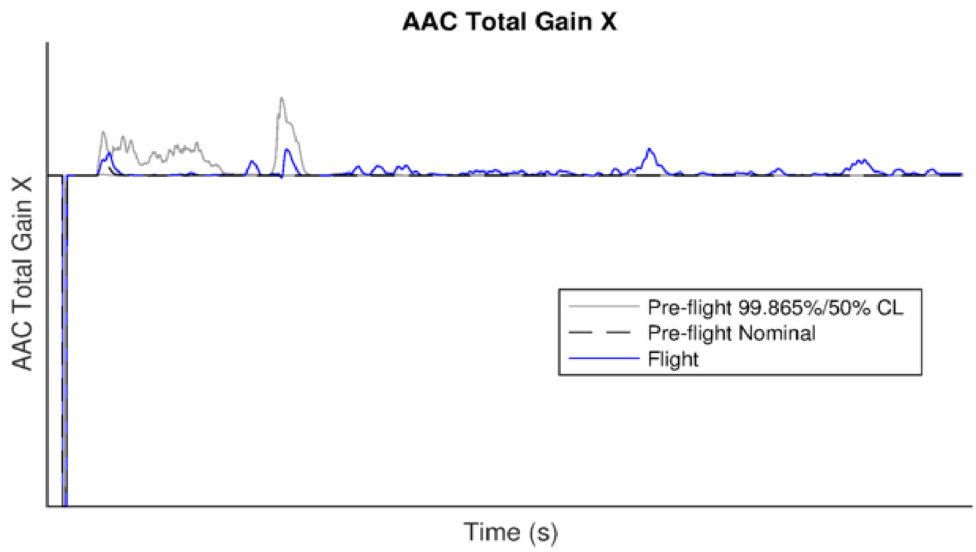

Figure 13. Gain Adaptation in X-axis during Artemis I Flight from Liftoff to MECO

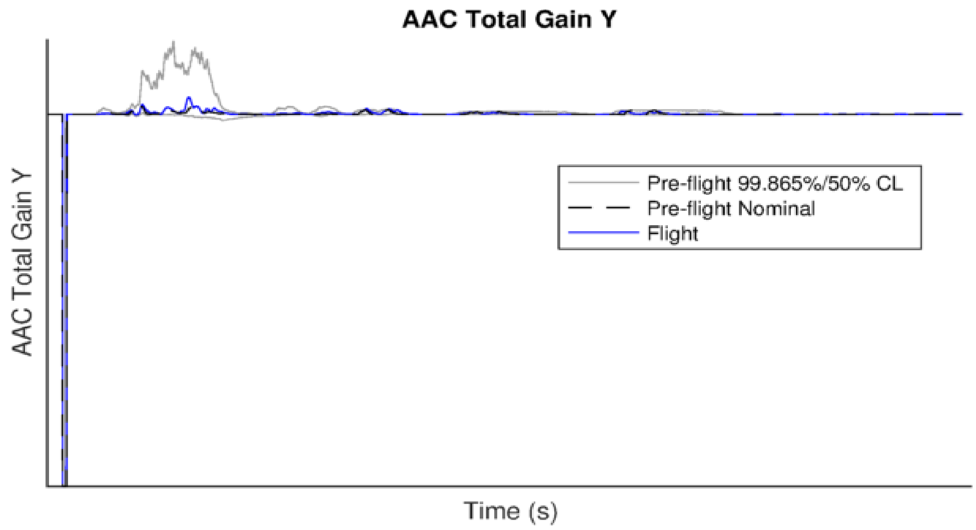

Figure 14. Gain Adaptation along Y-axis during Artemis I Flight from Liftoff to MECO

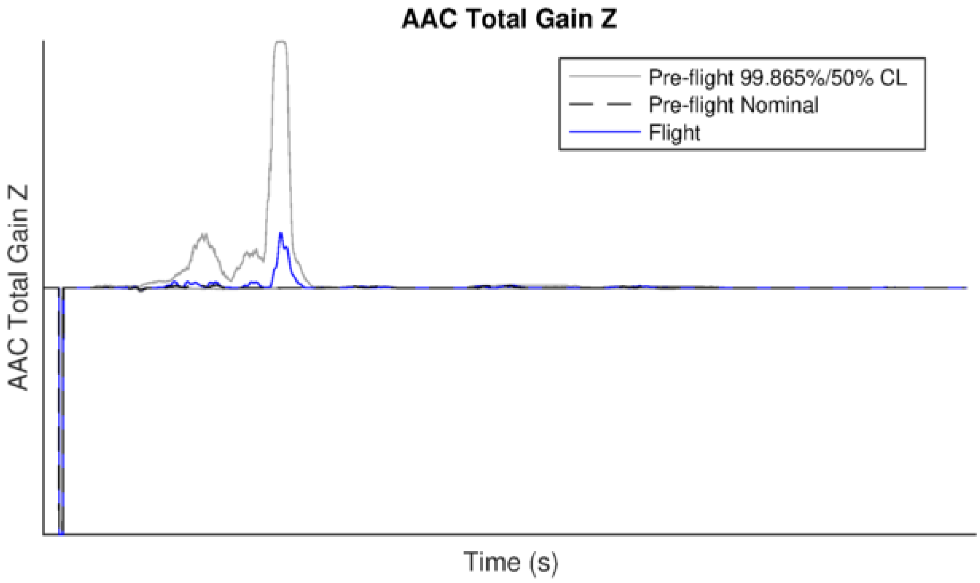

Figure 15. Gain Adaptation along Z-axis during Artemis I Flight from Liftoff to MECO

8 TIMELINE

The key milestones in the development, verification, and validation of the AAC are as follows:

- **2005-2009:** Vision for architecting an adaptive augmentation of a baseline controller established during the Constellation Program.
- **2008:** Augmentation of linear flight control architecture proposed at "Adaptive Control for Human Launch Vehicles Workshop" hosted by MSFC.
- **2008-2010**: Robust Augmenting Control for Enhanced Safety (RACES) Project included university grants and in-house strategizing for formulation and implementation of an adaptive augmentation to the baseline FCS design for the Ares I vehicle. This included early design and testing of algorithm using high-fidelity simulations, leading to the development of the Adaptive Augmenting Controller (AAC).
- **2011**: AAC algorithm developed and presented to the internal MSFC controls working group.
- **2012**: AAC analysis on high fidelity models completed as a side-study for SLS Design Analysis Cycle (DAC)-1. Initial design architecture published externally.[9]
- **2012**: AAC incorporated and maintained as part of the SLS FCS architecture since DAC-2 (November 2022). Monte Carlo analysis inclusive of AAC conducted for each subsequent analysis cycle.
- **2013**: Flight testing stressing cases developed to evaluate algorithm robustness. SLS AAC algorithm flight tested on an F/A-18 with cross-agency support from MSFC, AFRC, and the NESC.[14] AAC baselined as part of the SLS FCS.
- **2014:** Describing function analysis techniques applied which provided a means to quantify robustness to limit cycle phenomena, optimally select parameters, and provided insight into fundamental dynamic behaviour.
- **2015**: Vehicle Critical Design Review (CDR) completed, including a large set of analyses with matured AAC algorithm and flight models.
- **8/2014-8/2016**: SLS-NESC Assessment titled "Stability of the SLS Flight Control System with Adaptive Augmentation" which included a comprehensive set of AAC algorithm verification analyses.[37] This resulted in algorithm updates to improve nonlinear (Lyapunov) stability characteristics and the development of tools that were included in future analysis cycles.

- **2016**: First vehicle Verification Analysis Cycle (VAC) completed. SLS-NESC Assessment recommended algorithm modifications incorporated and pertinent analyses re-performed to demonstrate flight readiness. Performed code and algorithm peer reviews and finalized SLS FCS flight software for Artemis I.
- **2017 - 2022:** Vehicle parameters updated/finalized and key analyses repeated as vehicle models were updated.
- **2019:** Software-in-the-loop testing completed in MSFC's SIL.
- **2022**: SLS AAC algorithm launches on the unmanned Artemis I mission on November 16, 2022.

The timeline for AAC concept development, design, V&V and first flight is provided in Figure 16. The initial AAC design took approximately 2 years, followed by ~1 year of flight testing (2013) and ~2 years of rigorous V&V which resulted in algorithm modifications, and ~6 years of additional V&V in alignment with standard SLSP analysis cycles. It was important that verification activities and targeted flight testing occurred early in the Program. This increased trust in the algorithm and resulted in recommended design modifications that were provided with sufficient time in the schedule for them to be integrated.

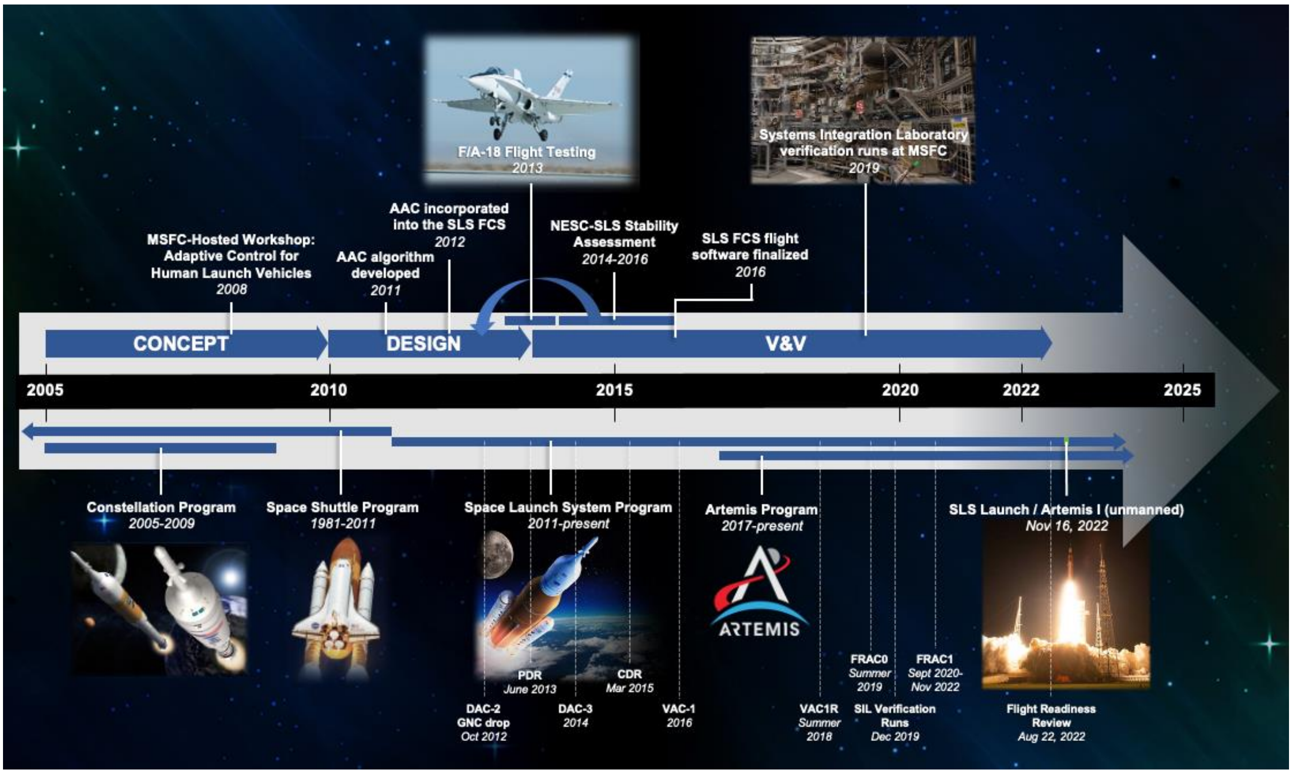

Figure 16. Timeline for SLSP AAC Algorithm Conceptualization, Design, V&V and First Unmanned Flight Test

9 CONCLUSIONS

This paper provided an overview of the path to first flight of the SLS AAC algorithm, including the vision for augmenting the existing flight control architecture, discussion of the principles which guided the design, description of the architecture evolution, algorithm V&V, key milestones in the development and TRL advancement, and description of the first flight as part of the Artemis I mission. In its final test during the uncrewed first flight of SLS, AAC performed as intended throughout the launch phase and its response reflected a flight trajectory within the pre-flight expectations.

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