Control of the Flexible Ares I-X Launch Vehicle

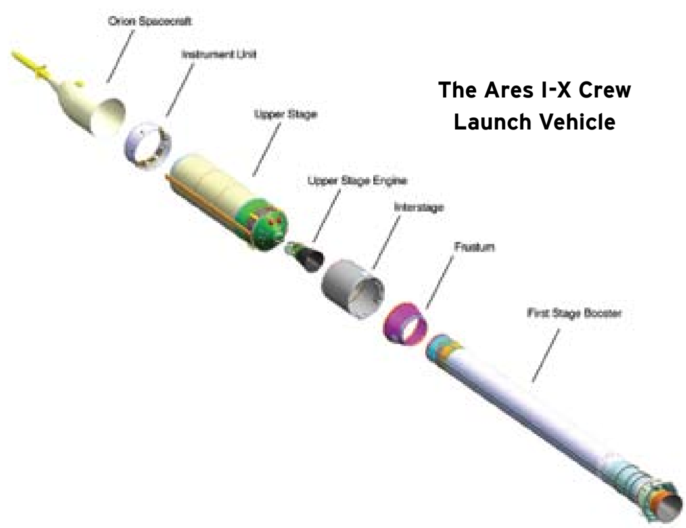
Ares I-X Flight Test Launch, October 28, 2009. Photo courtesy of NASA.

The Ares I-X flight test launch was the first flight test of an experimental launch vehicle as part of the NASA Constellation Program. The Ares I Launch Vehicle is planned as the crew launch vehicle replacement for the Space Shuttle, which is scheduled for retirement in 2011.

The Ares I-X configuration resembles the Saturn V vehicle but differs in ways that are significant from a flight control perspective. The first stage is a single, recoverable solid rocket booster derived from the Shuttle program. The first and upper stages are separated by a frustum and an interstage that houses the roll control system and avionics. A single liquid propellant engine powers the upper stage, and the upper stage reaction control system is located on the aft end of that stage. A redundant inertial navigation unit (RINU) and flight computers used for guidance, navigation, and control are located in the instrument unit at the top of the upper stage.

Challenges of Flexible Launch Vehicle Control

The ascent flight control system (AFCS) design for a flexible launch vehicle such as the Ares I-X is challenging due to the wide range of dynamic interactions between the vehicle and its environment, as well as varying mass properties, aerodynamic loads. and propulsion system characteristics that must be accommodated to maintain adequate margins on stability and performance. Launch vehicles are typically aerodynamically unstable due to the center of pressure being located above the center of mass. Ares I-X had an atypically large negative static margin due to the mass distribution in the first stage and the larger diameter upper stage. The low-frequency unstable aerodynamics were readily compensated by the relatively high-bandwidth first stage thrust vectoring. Due to the separation of control effectors (thrust vectoring) and flight control sensors (typically in the upper stage), control of the first bending mode was non-minimum phase, as is typical of flexible launch vehicles. These challenges are compounded by uncertainties in aerodynamics, ascent wind profiles, and the variability of vehicle mass properties and structural dynamics as propellant is consumed during flight. Lessons learned on the Ares I-X will lead to better design practices for the next generation of human-rated and heavy lift launch vehicles.



The Ares I-X Crew Launch Vehicle

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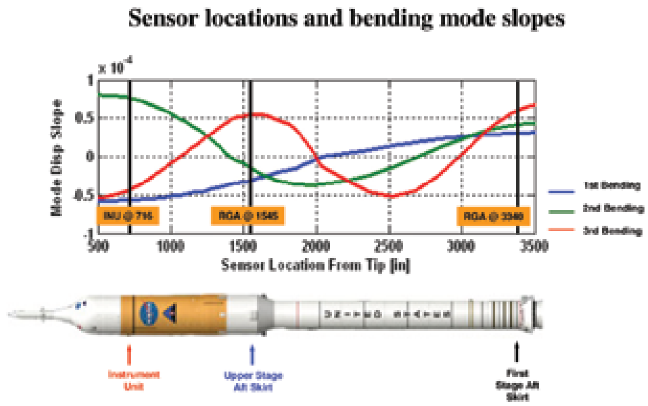
AFCS Design Process

The Ares I-X AFCS design approach begins with PID control designs for rigid-body performance in pitch and yaw and a phase plane control design for roll control. Multiple rate sensors are located along the structure to allow for blending of the sensed rotational rate. The need to increase robustness to force and torque disturbances such as those caused by wind and thrust vector misalignment led to the development of an anti-drift channel option for the autopilot. Unique to the Ares I-X flight test was the introduction of "parameter identification" maneuvers during ascent flight. Flight test instrumentation measured the dynamic response of the vehicle to these programmed torque commands, and post-flight data analysis was conducted to validate vehicle parameters obtained from test and analysis.

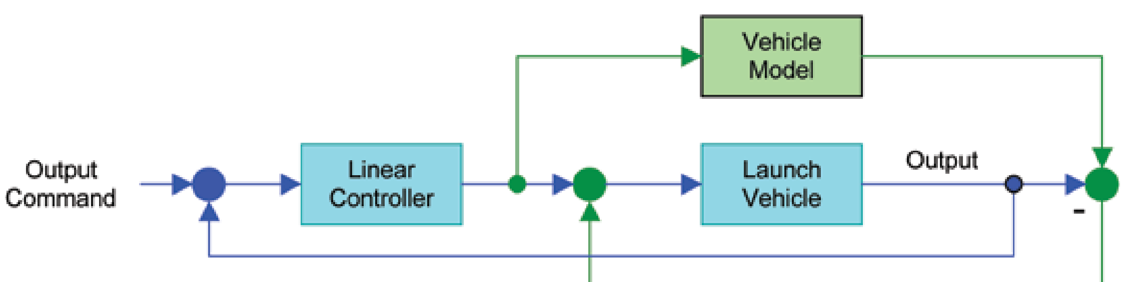


Adaptive Control: A Promising Future Trend in Launch Vehicle Control

Design and analysis of the Ares I-X AFCS indicates that classical control is sufficient to meet stability and performance requirements. Yet adaptive control concepts used in conjunction with classical approaches afford the opportunity to improve performance with increased robustness and crew safety.

Recent trends in adaptive control augmentation of existing controllers leverage the wealth of engineering heritage and experience in the development of classical control of launch vehicles while allowing for adaptation to recover and enhance stability and performance in the event of off-nominal vehicle response (see figure below). Having shown promise in missile and aircraft flight tests, these methods are showing preliminary benefits in design and analysis for the next generation of flexible launch vehicles as well.

Implementation of adaptive control for future launch vehicles will require technical and cultural transitions whereby new suites of tools for analysis and proof of stability and performance will gain confidence with program managers. Early progress is being made through theoretical developments that bridge the gap between classical and adaptive control. These developments are demonstrating analogs to traditional gain and phase margins using Monte Carlo-based gain-margin assessment and metrics such as time-delay margins. As these new "acceptance paradigms" mature and gain validity through practice, the next generations of aerospace vehicles will be safer and more capable than is possible with today's technology.



Adaptive controller augmentation for a launch vehicle. Conventional linear control architecture, shown in blue, is augmented with adaptive control components (green).

For further information: C. Hall, et al., Ares I flight control system overview, AIAA-2008-6287; M. Whorton, C. Hall, and S. Cook, Ascent flight control and structural interaction for the Ares-I crew launch vehicle, AIAA-2007-1780.