

50 Years Later, the X-15 Is Still a Platform for Knowledge

An adaptive flight control system currently baselined for use on NASA’s Space Launch System (SLS) borrows concepts from the design of the X-15, an experimental aircraft once operated by NASA and the U.S. Air Force. The manned hypersonic vehicle, which flew at speeds of up to Mach 6.7 and altitudes up to 350,000 feet, demonstrated new technologies including a “self-adaptive” control system. Though highly advanced for its time and successfully proven on previous flights, this control system contributed to a fatal X-15 accident in 1967. The initiating event for this accident was in essence an electrical anomaly, originating in an experiment payload, which coupled into the guidance, navigation, and control avionics creating a disastrous situation. And as is typically the case with accidents, additional compounding circumstances created a situation from which the pilot could not recover. *See “Testing the SLS Adaptive Augmenting Control” – page 9.*

Learning from a 1967 accident

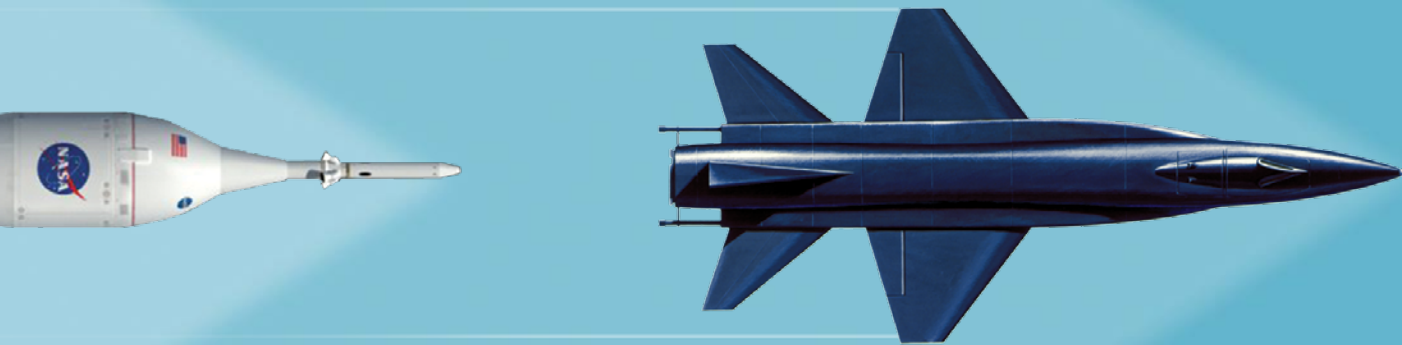
To more fully understand the role that the adaptive control system played in the accident, the NESC sponsored a comprehensive analysis of the X-15 mishap in parallel with the SLS adaptive control risk-reduction flight test effort that was conducted in 2013. The primary goal of the X-15 analysis was to evaluate the applicability of lessons learned not only to SLS but to other emerging aerospace systems. “New sub-orbital commercial concepts are proposing flight profiles similar to X-15 with fast reentries and high dynamic pressures, and will encounter similar flight control, system integration, and environmental challenges,” said Dr. Jeb Orr of Draper Laboratory and a member of the NESC Guidance, Navigation, and Control

Technical Discipline Team. “We need to understand to what extent lessons learned from the X-15 Program could be applied as risk mitigation to these emerging concepts.” The X-15 analysis taught us about engineering, human factors, and design shortfalls that unfortunately resulted in a major accident. The SLS adaptive control algorithm design approach mitigated these shortfalls, and the 2013 flight test campaign advanced the technical maturity and flight readiness of the algorithm.

Test COTS equipment for use in its intended environment

Just before the 1967 accident, designers added a traverse probe experiment to the X-15 starboard wing pod to measure shock geometry. The experiment had flown previously on X-15 at lower altitudes without incident and was deemed acceptable for all flight environments. Unknown to designers, the probe’s commercial-off-the-shelf (COTS) motor contained a high voltage component, which at higher altitudes caused arcing and introduced electrical disturbances into safety-critical aircraft systems. This started a chain reaction that led to the eventual breakup of the aircraft. *See “COTS Components in Spacecraft Systems” – page 10.*

“A complacent culture develops that marginalizes risk,” said Orr. As the X-15 had been flying for several years, it was viewed more as an operational versus experimental platform. Numerous X-15 modifications were added without a clear understanding of potential subsystem interactions with avionics hardware. Without the original design specifications for the motor, designers did not know the motor would generate high voltages. “They



“If today’s designers relied only on simulation, they may not have found this case”

—Dr. Jeb Orr

had put the experiment on another aircraft and didn’t see any problems and assumed, without doing rigorous analysis of hardware design, that it would be okay in all flight environments.” See *“Protecting Against Failures from Nonessential Equipment”* – page 8.

For the X-15, the electronic hardware, combined with the pressure and temperature of the atmosphere at high altitude, led to the plane’s catastrophic electrical issues. Orr noted that ballistic space planes and crewed commercial concepts currently being developed are likely to spend more time in the same critical region as X-15 and experience the same types of environments.

Classical techniques can predict complex behavior

“There is a lot of insight to be gleaned from simple mathematical, rigorous analysis,” said Orr. To characterize the X-15’s flight control system, analysis techniques that were available during X-15’s operation were combined with new computer simulation tools to allow for quicker and more efficient evaluation of data.

Orr noted that today’s analysis methodology relies heavily on simulation, which has led to classical approaches falling out of favor. “Using approximation, or first order

principles, to understand system behavior is absolutely paramount,” said Orr. “Then it can be coupled with simulation to understand the underlying physics.” Orr also noted that describing function (DF) analysis was used to understand the X-15 flight control system’s limit cycle oscillation behavior, which prevented the aircraft’s pitch recovery. “If today’s designers relied only on simulation, they may not have found this case,” said Orr. “DF analysis is thought of as a lost art, though it’s an insightful technique.” See *“Describing Function”* – page 8.

Communication is key to situational awareness

During the X-15 flight, ground control staff did not communicate subsystem anomalies to the pilot, assuming the pilot had better situational awareness. In addition, not all flight data being telemetered was immediately available to ground control or required human analysis before recommendations could be made. This combination led to an overall lack of communication between the pilot and ground control, which contributed to confusion for the pilot, who also was receiving conflicting information from failing avionics systems. Orr noted that any anomaly of significance to aircraft safety should be relayed by ground control to the pilot or crew, even if it is redundant. This combination of events prevented the team from placing priority on restoring the X-15 to a safe state over the continuation of science objectives.

Design for the average human

“We need to design an interface for average humans, even if it is operated by astronauts,” said Orr. On the X-15, for example, the instrument panel had changed over time as

Continued on next page



The X-15 was a high-altitude hypersonic research vehicle, operated by NASA from 1959 to 1968, used to support development of new technologies including propulsion, instrumentation, structures, thermal protection systems, and flight controls.

X-15, 50 Years Later

Continued

switches and indicators were added or moved, eventually leaving all three X-15 aircraft with different instrument panels. In addition, each aircraft had slightly different emergency procedures depending on what equipment was installed. "That was fine in 99% of flights, but when things went wrong, it led to confusion. Astronauts are highly trained, but in times of high stress, they need a simple interface that gives them an unimpeded ability to maintain the safety of the spacecraft and its crew." In the case of the X-15 accident, a primary contributing factor was a lack of mode indication on a critical flight instrument, which had been uniquely modified to support a specific science objective.

The X-15 accident followed a familiar pattern where several unrelated, but concurrent failures came together to create an unrecoverable event. Several subsystem anomalies occurred, which were considered benign in their individual subsystems, such as the limit cycle oscillation in the X-15's flight control system. "But because it was coupled with other failures, it did cause an accident," said Orr. "If things don't behave as expected, you have to be willing to stand down and understand the risk and threat before continuing flight operations." □

Reference NASA/TM-2014-218538

Describing function

Describing function (DF) analysis is a classical technique to predict the behavior of certain types of nonlinear control systems. The technique was developed in the early twentieth century partly to provide an analytical method to supplement the limited computer capabilities of the time. Now, combining classical theory with modern numerical simulations, DF analysis has re-emerged as a mathematically rigorous and powerful tool for helping control engineers understand why and under what conditions nonlinear control systems oscillate in undesirable ways.

Protecting against failures from nonessential equipment

NASA spacecraft and commercial aircraft designers now go to great lengths to protect flight-critical systems from potential hazards generated by "nonessential" systems such as experiments flying on the International Space Station or in-flight entertainment systems in commercial aircraft. Engineers also went to great lengths to protect flight-critical avionics in the Space Shuttles from problems with experiments that operated in the orbiter's payload bay.



Test trajectories flown repeatedly by NASA's F/A-18 while testing the SLS AAC.

Testing the SLS Adaptive Augmenting Control

In 2013, a partnership of NASA organizations including MSFC, AFRC, NESC, and the Science and Technology Mission Directorate Game Changing Technology Office, conducted a series of F/A-18 research flights to test Space Launch System (SLS) prototype software, including the previously untested adaptive augmenting control (AAC) component.

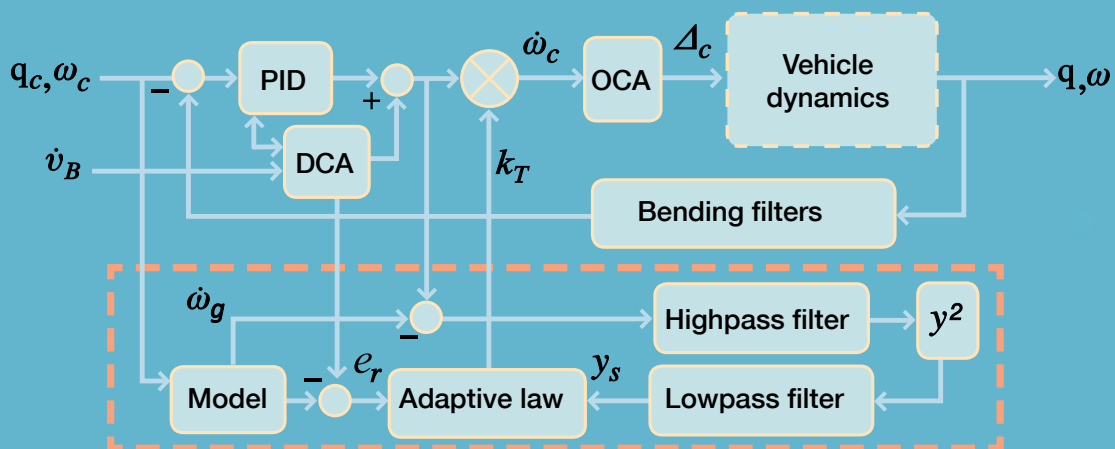
Because SLS will deliver more payload to orbit and produce more thrust than any other vehicle, past or present, it opens the way to new frontiers of space exploration as it carries the Orion Multi-Purpose Crew Vehicle, equipment, and experiments into new territories. The addition of AAC to SLS offers significant benefits to the total attitude control architecture by providing the fixed gain control architecture with additional robustness. AAC increases flight control system (FCS) performance when excessive tracking error is present and decreases responsiveness to undesirable frequency content. It expands the envelope under which the FCS is capable of safely flying the vehicle, maximizing vehicle survivability and crew safety.

If there were no vehicle or environmental uncertainty, a fixed-gain controller could be optimized prior to flight

with no need for adaptation; however, a review of historical reusable launch vehicle data from 1990 to 2002 revealed that over 40% of failures resulting from other malfunctions might have been mitigated by advanced guidance, navigation, and control technologies. Thus, an algorithmically simple, predictable AAC design with direct ties to classical stability margins was implemented for SLS. It was initially formulated and tested during the former Constellation Program, then refined as part of the baseline autopilot design and flight software prototype for SLS.

During flight testing on the F/A-18 Full-Scale Advanced Systems Testbed aircraft at AFRC, the aircraft completed a series of trajectories during multiple sorties with the SLS FCS enabled. The aircraft's pitch rate was matched to the SLS and matching attitude errors for various nominal and extreme SLS scenarios were incorporated through the use of a nonlinear dynamic inversion controller. The emphasis of the 100-plus SLS-like trajectories was on fully verifying and developing confidence in the AAC algorithm in preparation for the first uncrewed launch of SLS. □

Reference NASA/TM-2014-218528



Simplified block diagram of the SLS flight control system.

Military/Aerospace/High Reliability

NASA wisdom is based on broad and deep knowledge of these parts that has enabled reliable use for decades.

Extensively documented experience (good and bad) collected and shared about parts that have evolved steadily.

Data generated over more than 40 years analyzed and reported to provide extensive information.

NASA has ready access to mandated data, common to all suppliers.

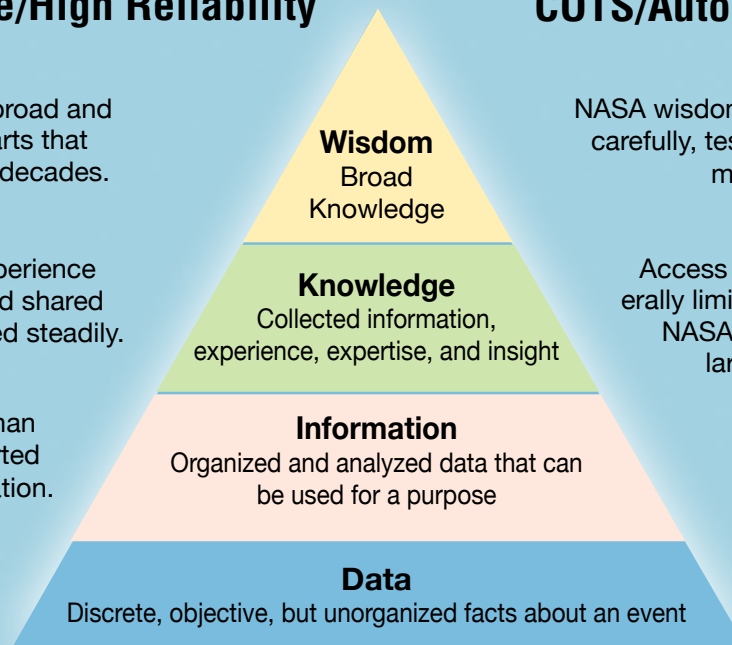
COTS/Automotive/COTS Plus

NASA wisdom says: use these parts very carefully, test extensively, and gather as much knowledge as possible.

Access to detailed information generally limited to important customers. NASA has limited experience with large-scale use of these parts.

Market-focused reports available. NASA must generate own information.

Manufacturers supply extensive data aimed at their target market.



COTS Components in Spacecraft Systems: Understanding the Risk

NASA's Commercial Crew Program (CCP) is stimulating efforts within the private sector to develop and demonstrate safe, reliable, and cost-effective space transportation capabilities to the International Space Station. One initiative involved investigating the possible use of commercial grade electronic parts in launch vehicle and spacecraft designs. The CCP was interested in data that would help frame the technical, cost, and schedule risk trades associated with the use of electrical, electronic, and electromechanical (EEE) parts of a lower grade than traditionally used in most NASA safety-critical applications.

The fundamental question

The fundamental question is "Can commercial-off-the-shelf EEE parts with limited screening be used in crewed flight hardware systems?" The terms "commercial-off-the-shelf parts," or "COTS," and "screening" are broadly defined and not applied consistently. Automotive, commercial aviation, medical, and safety conscious consumer electronics industries engage in assurance processes within their supply chain to establish a basis for the quality and reliability of the EEE parts used in their products before assembling them into critical applications. These assurance processes, with inspections and tests possibly performed on a sample

basis depending on criticality, are intended to identify defects and abnormalities that serve as warning signs of a potential for premature failure, reduced performance, and safety.

Parts screening approaches

There is a wide spectrum of approaches to parts screening. At one end of the spectrum, EEE parts used in critical space systems in general are subjected to 100% parts-level inspections and testing to provide high assurance of quality and reliability. At the other end of the spectrum are commercial catalog parts that have not been subjected to any testing other than those established by the manufacturer. An NESC team analyzed two COTS parts screening approaches: one that employs only card-level testing coupled with box-level and system-level testing versus the traditional approach of screening at the parts level prior to card, box and system-level testing. The team concluded that there are fundamental concerns with replacing parts-level screening and qualification with card and box-level or system-level testing only.

Assembling COTS EEE parts on circuit boards for space applications without proper parts-level qualification or additional screening could result in assembling good parts along with any weak parts (parts containing

latent defects and infant mortals and/or parts not suitable for the application) into flight hardware, with the questionable assumption that board-, box-, and system-level testing can effectively identify parts that might fail during the anticipated mission lifetime. Proper parts-level qualification is essential to: 1) ensure the part technology, design, and construction is capable of predictable and required performance in the space environment and 2) identify parts that function properly in terrestrial applications but may not perform safely in the more extreme space radiation, vacuum, vibration, and thermal environments found in spaceflight applications. Card-level, box-level, and system-level testing cannot replicate accelerated failure factors that voltage, current, and temperature stresses can provide during parts-level screening prior to installation on a circuit board.

Commercial parts use at NASA

NASA has successfully used commercial parts in spacecraft for specific and sometimes mission-critical applications throughout the Agency's history. This has been achieved by careful selection, qualification, and screening. The level of screening required for commercial parts to ensure they will work successfully is highly dependent on the mission, intended application, environment, mission duration, and part technology. The level of screening is quite well characterized in existing NASA parts documents such as EEE-INST-002. NASA flies non-MIL (non-military) grade parts when the required functionality and/or performance is not available in MIL parts. If a MIL part can be used, they are preferred.

Initial qualitative analysis indicates significant differences in reliability and safety can result between screened MIL parts and unscreened commercial parts. Parts quality, architecture (including the selection of like or diverse backup systems), and mission duration are inseparable variables that must be traded in a mission design. One system architecture could use lower grade parts for short-duration missions (a few minutes to a few days) and possibly exhibit acceptable analytical system reliability. That same architecture may not provide the analytical reliability required for long-duration missions (a few weeks to many months) when using lower grade parts. Parts quality dominates system reliability in long-duration missions where environmental effects like space radiation and single event upsets are more likely to occur. A system design for long-duration missions is an example where NASA would typically employ in critical applications high reliability space-qualified military grade parts or use highly screened and qualified COTS parts.

Alternative approaches

Any alternative approach for the use of COTS EEE parts in critical applications other than those that have proven successful, such as described in EEEINST-002

Important definitions

COTS: An assembly or part designed for commercial applications for which the item manufacturer or vendor solely establishes and controls the specifications for performance, configuration, and reliability (including design, materials, processes, and testing) without additional requirements imposed by users and external organizations. For example, this would include any type of assembly or part from a catalog without any additional parts-level testing after delivery of the part from the manufacturer.

COTS Plus: A COTS part supported by test data available to end users establishing random failure rate assumptions, performance consistent with the manufacturers data sheet and methods to exclude infant mortal parts, parts with latent defects, weak parts, or counterfeit parts. For example, automotive electronics council-certified or compliant automotive parts are one type of COTS Plus.

Parts Qualification: Sample-based mechanical, electrical, and environmental tests at the piece parts level intended to verify that materials, design, performance, and long-term reliability of parts on the same production line are consistent with the specification and intended application until a major process change.

Parts Screening: A series of tests and inspections at the piece parts level intended to remove nonconforming and/or infant mortal parts (parts with defects that are likely to result in early and/or cluster failures) and thus increase confidence in the reliability of the parts selected for use.

or similar NASA documents, requires a firm basis for substantiation. Any approach based on architecturally similar redundancy and card-level, box-level, and system-level testing alone is not sufficient to enable widespread use of unscreened parts acquired from commercial catalog distributors in critical applications. To reduce the likelihood that parts failures result in unacceptable mission risk, standard practice dictates designers to: 1) develop and implement a systems engineering-oriented mission assurance program to address EEE parts derating, qualification, traceability, and counterfeit control, and demonstrate how it mitigates the risks associated with EEE parts applications, and 2) provide data supporting the effectiveness of the proposed screening approach, ensuring part failure rates are adequately bounded. □