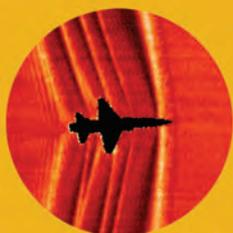




Armstrong Flight  
Research Center

# RESEARCH TECHNOLOGY & ENGINEERING

REPORT 2015







## From the Director: Research and Engineering Directorate

I am honored to endorse the 2015 Neil A. Armstrong Flight Research Center's Research, Technology, and Engineering Report. The talented researchers, engineers, and scientists at Armstrong are continuing a long, rich legacy of creating innovative approaches to solving some of the difficult problems and challenges facing NASA and the aerospace community.

Projects at NASA Armstrong advance technologies that will improve aerodynamic efficiency, increase fuel economy, reduce emissions and aircraft noise, and enable the integration of unmanned aircraft into the national airspace. The work represented in this report highlights the Center's agility to develop technologies supporting each of NASA's core missions and, more importantly, technologies that are preparing us for the future of aviation and space exploration.

We are excited about our role in NASA's mission to develop transformative aviation capabilities and open new markets for industry. One of our key strengths is the ability to rapidly move emerging techniques and technologies into flight evaluation so that we can quickly identify their strengths, shortcomings, and potential applications.

This report presents a brief summary of the technology work of the Center. It also contains contact information for the associated technologists responsible for the work. Don't hesitate to contact them for more information or for collaboration ideas.

### **Bradley C. Flick**

Director for Research and Engineering

## From the: Center Chief Technologist

I am delighted to present this report of accomplishments at NASA's Armstrong Flight Research Center. Our Center draws on a rich history of performance, safety, and technical capability spanning a wide variety of research areas involving aircraft, electronic sensors, instrumentation, environmental and earth science, celestial observations, and much more. Our dedicated innovators not only perform tasks necessary to safely and successfully accomplish Armstrong's flight research and test missions but also support NASA missions across the entire Agency.

I am especially pleased that our Center is supporting NASA's new strategic vision for its aeronautics programs by focusing aeronautics research in six thrust areas that are responsive to a growing demand for mobility, challenges to the sustainability of energy and the environment, and technology advances in information, communications and automation. This new vision, as articulated by NASA's Aeronautics Research Mission Directorate (ARMD) calls for NASA to develop transformative capabilities to enable the U.S. aviation industry to maintain and advance its global leadership.

Armstrong's talented researchers and engineers are involved in numerous projects that are part of the Agency's new strategy. We are developing and refining technologies for ultra-efficient aircraft, electric propulsion vehicles, a low-boom flight demonstrator, air launch systems, and experimental x-planes, to name a few. Additionally, with our unique location and airborne research laboratories, we are able to test and validate new research concepts.

Summaries of each project highlighting key results and benefits of the effort are provided in the following pages. Technology areas for the projects include electric propulsion, vehicle efficiency, supersonics, space and hypersonics, autonomous systems, flight and ground experimental test technologies, and much more. Additional technical information is available in the appendix, as well as contact information for the Principal Investigator of each project.

I am proud of the work we do here at Armstrong and am pleased to share these details with you. We welcome opportunities for partnership and collaboration, so please contact us to learn more about these cutting-edge innovations and how they might align with your needs.

**David Voracek**

Center Chief Technologist



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This Tecnam aircraft is part of an X-Plane demonstrator project. It will be modified to evaluate electric propulsion technologies.

# Electric Propulsion Technologies



The arrival of a unique experimental demonstrator at Armstrong in 2015 may herald a future in which many aircraft are powered by electric motors. Our researchers are collaborating on projects that are testing the premise that tighter propulsion-airframe integration, made possible with electric power, will deliver improved efficiency and safety as well as environmental and economic benefits.

These tests are precursors to development of a small X-Plane demonstrator proposed under NASA's Transformative Aeronautics Concepts program and are key elements of NASA's plan to help a significant portion of the aircraft industry transition to electrical propulsion within the next decade.



## Single Propulsor Test Stand

A modular test stand developed at Armstrong is helping researchers conduct extensive measurements for efficiency and performance of electric propulsion systems up to 100 kW in scale. The Airvolt test stand is helping engineers understand subsystem interactions as well as efficiencies of different batteries, motors, controllers, and propellers. The test stand offers opportunities to determine effective test techniques for this emerging technology. Its large suite of sensors gathers extensive data on torque, thrust, motor speed, vibration/acceleration, voltages and currents, temperatures, and more. This technology is allowing the aviation industry to test a wide range of electric propulsion systems to understand efficiencies and identify needed design improvements.

**Work to date:** The first application for Airvolt is to gather data from a Joby JM-1 motor to build a model that can be used for a hybrid electric hardware-in-the-loop simulation testbed. Accurate models are required in the simulation in order to reflect the true hardware configuration and provide an assessment tool for researchers.

**Looking ahead:** Another Airvolt application in the near future is to perform multiple ducted fan testing to support turbo-electric distributed propulsion research.

### Benefits

- ▶ **Highly efficient:** Offers high-speed sampling rates, up to 2.5 million samples per second per channel
- ▶ **Modular:** Allows researchers to test a variety of motors, controllers, batteries, and a wide range of parameters
- ▶ **Flexible:** Accommodates different motors, up to 100 kW, through the use of motor adapter plates

### Applications

- ▶ Characterize new electric propulsion technologies
- ▶ Refine simulation models
- ▶ Develop best practices for testing procedures through lessons learned

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## Leading-Edge Asynchronous Propeller Technology (LEAPTech)

Armstrong engineers collaborated with researchers at NASA's Langley Research Center and two California-based companies to develop an innovative approach to powering an aircraft with electricity rather than fossil-fuel propellant. Distributed electric propulsion technology is based on the premise that closely integrating the propulsion system with the airframe and distributing multiple motors across the wing will increase efficiency, lower operating costs, and increase safety. LEAPTech is a project that is investigating this technology through a series of ground tests to validate the tools used for designing a distributed propulsion wing. Small propellers with battery-powered motors are placed along the entire span of the research wing. Each motor/propeller can be operated independently at different speeds for optimized performance and lower acoustic noise.

**Work to date:** In summer 2015, the team conducted ground testing of the Hybrid-Electric Integrated Systems Testbed (HEIST) LEAPTech, a 31-foot carbon-composite wing that held 18 propellers and motors powered by lithium iron phosphate batteries. Researchers mounted the wing onto a specially modified truck and drove across a dry lakebed at up to 73 miles per hour, simulating takeoff and landing speeds. Results demonstrated that the distribution of power among the 18 motors creates more lift at lower speeds than traditional systems.

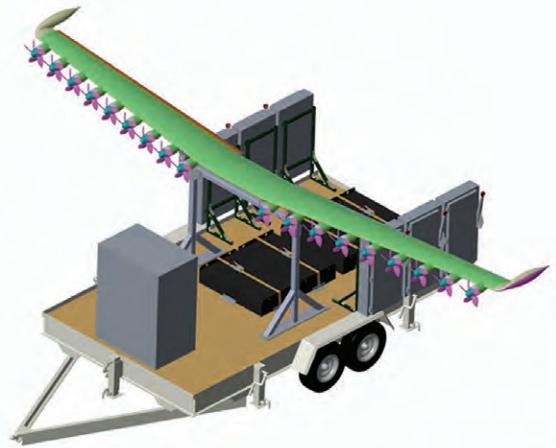
**Looking ahead:** The team is applying lessons learned in the LEAPTech effort to the Scalable Convergent Electric Propulsion Technology and Operations Research (SCEPTOR) Project. The ultimate goal is to develop an electric propulsion-powered aircraft that is quieter, more efficient, and more environmentally friendly than today's commuter aircraft.

**Partners:** Empirical Systems Aerospace, Joby Aviation, and NASA's Langley Research Center

### Benefits

- ▶ **High performance:** Offers 3.5 to 5 times more efficiency than equivalent general aviation aircraft and up to 45 percent lower total operating costs
- ▶ **Quieter:** Dramatically reduces aircraft noise
- ▶ **Environmentally friendly:** Produces zero emissions during flight

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## Hybrid-Electric Integrated Systems Testbed (HEIST) Ironbird

After HEIST LEAPTech testing is completed, the research wing will be removed from the truck and integrated with a piloted simulation to form the HEIST Ironbird. A primary focus is to study the system complexities of two power sources, one of which is a turbo-generator. Specifically, the team is developing a simulation that can be used to investigate flight control algorithms for managing this type of technology and to understand the unique power transition issues. This research effort is allowing the team to study integration and performance challenges to enable the design of more advanced electric propulsion system testbeds.

**Work to date:** Researchers are designing a research plan to test different types of hybrid electric propulsion technologies (e.g., batteries, turbo-generators) on an instrumented ironbird test wing. A small turbine generator will power the distributed electric propulsion system and be integrated with an Armstrong simulator to replicate system failures, control laws, and control systems.

**Looking ahead:** Future plans include adding a flight control computer and flight research controller.

Dynamometers will be integrated into the ironbird to simulate aerodynamic loading. Various bus configurations will be tested to determine weight, size, electromagnetic interference (EMI), and thermal and energy transmission efficiency.

**Partner:** NASA's Glenn Research Center

### Benefits

- ▶ **Modular test environment:** Enables the use of a variety of power generation sources, bus wiring configurations, and models in various simulated flight conditions
- ▶ **Efficient test platform:** Allows researchers to test multiple flight control algorithms to evaluate effectiveness
- ▶ **Reduces risk:** Enables simulation of various scenarios involving active management of two types of power sources in a safe environment

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## Scalable Convergent Electric Propulsion Technology and Operations Research (SCEPTOR)

HEIST LEAPTech is a precursor to the SCEPTOR research effort, which is working to develop a small X-Plane demonstrator awarded under NASA's Transformative Aeronautics Concepts Program. The research involves removing the wing from an Italian-built Tecnam P2006T aircraft and replacing it with a high-performance, cruise-optimized experimental wing integrated with electric motors. Engineers will be able to compare the performance of the proposed experimental aircraft with the original configuration to demonstrate benefits of installing propellers at the wingtips to reduce vortex drag and the improved powertrain efficiency that electric systems provide in comparison to reciprocating engines. SCEPTOR is focusing on how distributed electric propulsion technologies can improve cruise efficiency at higher speeds.

**Work to date:** In September 2015, Armstrong pilots flew a Tecnam P2006T aircraft to collect data to compare to a modified aircraft that is under development. The project conducted a Preliminary Design Review in December 2015, and in January 2016, fabrication began on the new aircraft fuselage and wing.

**Looking ahead:** Currently under construction, the Tecnam is expected to be at Armstrong in 2017. Initial flights will use the original Tecnam wing with new electric motors in place of the stock reciprocating engines and powered by a custom battery pack. The team will then build and integrate a specially developed wing on that aircraft with electric motors for research flights.

**Collaborators:** NASA's Langley Research Center (research lead), Glenn Research Center, Empirical Systems Aerospace, Joby Aviation, Xperimental, Scaled Composites, Tecnam

### Benefits

- ▶ **Enables cleaner flight:** Electric propulsion provides 5- to 10-factor reduction in greenhouse gas emissions with current forms of electricity generation and essentially zero emissions with renewable-based electricity.
- ▶ **Reduces lead emissions:** Electric propulsion provides a technology path for small aircraft to eliminate 100 Low-Lead (100LL) avgas, which is the greatest contributor to current lead emissions.
- ▶ **Improves efficiency for commuter aircraft:** This research could lead to the development of an electric propulsion-powered commuter aircraft that is more efficient than today's models, while also being quieter and more environmentally friendly.
- ▶ **Reduces Total Cost of Ownership for small aircraft:** This project will demonstrate high performance electric motors, controllers and power delivery systems that are more reliable and easier to maintain than traditional hydrocarbon-based systems. These technologies will eventually allow aircraft to be built with reduced maintenance costs and improved reliability in flight.

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# Improving Aerospace Vehicle Efficiency



Increasing efficiency in aerospace vehicles is a key goal across the spectrum of NASA operations. Armstrong researchers are constantly striving to build efficiency into all phases of flight projects, through development, fabrication, and operations processes.

From a new wing design that could exponentially increase total aircraft efficiency to a novel method for validating design tools for large, flexible wings, our researchers are finding unique solutions that increase efficiency.



## PRANDTL Flying Wing

Armstrong researchers are experimenting with a new wing shape that could significantly increase aircraft efficiency. The team has built upon the research of German engineer Ludwig Prandtl to design and validate a scale model of a non-elliptical wing that reduces drag and increases efficiency. By allowing for longer wingspans, the new design produces 12 percent less drag than current solutions. In addition, the approach to handling adverse yaw employs fine wing adjustments rather than an aircraft's vertical tail. In a propeller application, efficiency could increase by 13 percent.

### Work to date:

- ▶ In 2013, the team developed, demonstrated, and validated a scale model of an improved PRANDTL-D wing. Initial results from a 4-month small-scale flight experiment unequivocally established proverse yaw. Since then, the team has flown more flights with up to 58 maneuvers. The most recent prototype glider weighs 26 pounds and has a 25-foot wingspan.
- ▶ In 2015, the team kicked off a special effort with summer interns to work on an autopiloted flying wing designed to land on Mars. The molds for the updated glider are done, and a high-altitude balloon launch is scheduled for March 2016.
- ▶ An effort is underway to publish a NASA Serial Report to document the work.

**Looking ahead:** The wind energy industry is open to new bladed designs that improve efficiency, and this market segment is large and growing. Discussions are underway with a market leader in the manufacturing of wind turbines.

### Benefits

- ▶ **Highly efficient:** Increases total aircraft efficiency by as much as 62 percent, including efficiency increases in drag reduction (12 percent) and when used in propulsion systems (13 percent)
- ▶ **Quieter:** Decreases noise
- ▶ **Faster:** Allows aircraft to fly faster

### Applications

- ▶ Aircraft
- ▶ Turbines
- ▶ Energy delivery systems

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## Adaptive Compliant Trailing Edge (ACTE) Flight Experiment

The ACTE experimental flight research project is a partnership between NASA and the U.S. Air Force Research Laboratory (AFRL) with the purpose of investigating whether advanced flexible trailing-edge wing flaps can be designed and integrated onto an aircraft. The eventual goal of the ACTE technology is improving aerodynamic efficiency and reducing noise associated with landings. The experiment involves replacing the conventional Fowler flaps of a Gulfstream III (G-III) research testbed aircraft with advanced, shape-changing ACTE flaps that form continuous bendable surfaces. The ACTE flaps are manufactured by FlexSys, Inc., and the primary goal of the experiment is to collect flight data about the integration and reliability of the flaps. This radically new morphing-wing technology has the potential to save millions of dollars annually in fuel costs and reduce drag and airframe weight.

**Work to date:** The G-III has been converted and instrumented into a test platform, and the first set of test flights was completed in April 2015. The test team met expectations by completing all primary and secondary objectives on schedule and within budget. Specific achievements include:

- ▶ Completed  $-2^{\circ}$  to  $30^{\circ}$  tests
- ▶ Collected structural and aerodynamic data
- ▶ Characterized the structural performance of the flap

**Looking ahead:** Testing will resume in summer 2016. Goals include:

- ▶ Extend Mach number to 0.85
- ▶ Fly the flaps in static twist configurations
- ▶ Gather engine performance data to estimate aircraft drag

### Benefits

- ▶ **Innovative:** Advances compliant structure technology for use in aircraft to significantly reduce drag, wing weight, and aircraft noise
- ▶ **Economical:** Reduces drag and increases fuel efficiency through the use of an advanced compliant structure

### Applications

- ▶ Aircraft control surfaces
- ▶ Helicopter blades and wind turbines

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## ACTE Flight Experiment to Leverage FOSS Technology

The ACTE experiment is a joint effort between NASA and AFRL to determine whether advanced flexible trailing-edge wing flaps can improve aerodynamic efficiency and reduce airport-area noise generated during takeoffs and landings. Armstrong's Fiber Optic Sensing System (FOSS) has long been used on this aircraft to collect strain sensing data. Researchers are now pursuing certification of the software so that it can be used in the control room to make real-time decisions on structural margins during flight tests.

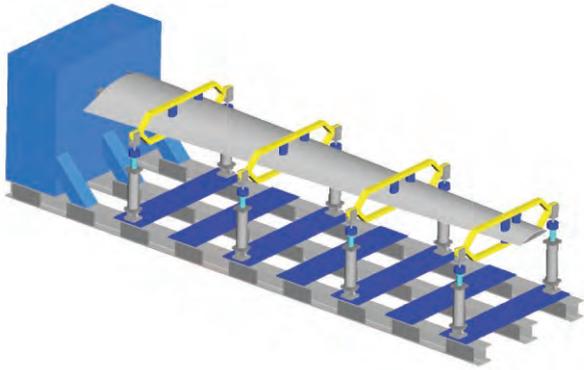


NASA aircraft technicians work on installation of test instrumentation for the ACTE flap on NASA's modified G-III testbed.

### Benefits

- ▶ Advances Class I software certification for use of FOSS in real-time flight critical applications

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## FOSS to Support Calibration Research Wing (CRew) Validation

NASA's CRew project is evaluating design and fabrication techniques for large composite wings with a high aspect ratio. The objective is to gather strain data on the wing in the laboratory and then use Armstrong's FOSS technology to validate predictions for strain, displacement, and twist. This information will ultimately help validate design tools for large, flexible wings. In the near term, and similar to the work performed on the X-56A Multi-Utility Technology Testbed (MUTT) project, FOSS is being used in the Flight Loads Laboratory to collect data on an instrumented wing.

**Work to date:** Current ground testing is focusing on load distribution and structural behavior of wings.

**Looking ahead:** In 2017, FOSS will be implemented on a new high-aspect-ratio wing, and researchers will perform loads testing using data collected from the FOSS work. The objective is to build on the knowledge gained from ground testing to develop an optimized wing for flight testing.



This unmanned sailplane shows off its graceful high-aspect-ratio wings.

### Benefits

- ▶ **Small and light:** Offers 100 times the number of measurements at 1/100 the total sensor weight
- ▶ **Improves safety:** Provides validated structural design data that enable future launch systems to be lighter and more structurally efficient
- ▶ **Multiple modalities:** Measures multiple parameters in real time

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## Real-Time Wing Deflection Measurement System

Measuring wing deflection and twist during flight is necessary to improve the design of next-generation aircraft wings. Innovators at Armstrong have developed a measurement system that uses photogrammetric methods to measure wing deflection and twist in real time with a high degree of availability and accuracy. The primary goal of this research is to test and improve the fidelity of current aerodynamic and structural models. A better understanding of wing dynamics and structural responses will enable more efficient and predictable wing designs. Real-time wing shape information can also be leveraged to implement active flutter control, apply adaptive control of aeroelastic structures, and even correct pilot-induced errors. An additional goal of the research is to evaluate using the Python open source programming language and the open source computer vision library OpenCV.

**Work to date:** The measurement system was developed for use on the Gulfstream III (G-III) Subsonic Research Aircraft Testbed (SCRAT) and deployed for the ACTE flight experiment. Post-flight data were evaluated after the system captured the G-III wing at 1 Hz through the ACTE flight tests. The system performed well and provided consistent results.

**Looking ahead:** The system will be upgraded with a new camera capable of capturing images at 25 Hz and a computer to process those images at a similar frame rate. Previous algorithms required a consistent target shape, but this constraint will be removed from future versions. The team is planning to test the new system during flight tests in summer 2016.

### Benefits

- ▶ **Flexible:** A better understanding of wing shape could be used to exploit other development technologies, such as structural model validation, adaptive control systems feedback, and health system monitoring.
- ▶ **Adaptable:** The system can be implemented by other flight test organizations to collect data to evaluate aerodynamic and structural wing models.

### Applications

- ▶ Wing deflection and twist measurements
- ▶ Flutter control
- ▶ Adaptive control of aeroelastic structures

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## Using Shape Memory Alloys (SMAs) to Morph Aircraft Structures

Armstrong innovators are part of a team that is investigating whether SMAs can be used to morph aircraft structures. SMAs are materials that can be deformed at low temperatures and recover their original shape upon heating. The biomedical industry has leveraged their elastic attributes for numerous medical devices, but they have only recently been utilized in aviation. NASA's Glenn Research Center is developing robust, high-temperature SMAs, and this research team is examining their potential use in aviation applications. If properly harnessed, these materials could become a lightweight, solid-state alternative to conventional actuators such as hydraulic, pneumatic, and motor-based systems.

**Work to date:** As part of this collaborative multi-Center research effort, Armstrong is performing tests with the subscale demonstration Prototype Test Evaluation Research Aircraft (PTERA). Goals are to (1) develop and vet an SMA actuator and control system that can be employed on larger systems, (2) experimentally determine aircraft flight response, and (3) validate analysis tools and develop larger actuators with quicker excitation methods. Aerodynamic analysis has quantified the flight handling response and benefit of the morphing structure. Upon completion of the subscale effort, the team is planning to use a NASA F-18 aircraft for full-scale demonstration of morphing structures.

The team is also working with actuator integration, using a proprietary material developed at Glenn.

**Looking ahead:** Planning is underway for flight tests in 2017. The team will also begin designing the initial groundwork for the full scale F-18 demonstration.

**Partners:** NASA's Glenn and Langley Research Centers; The Boeing Company; and Area-I, Inc.

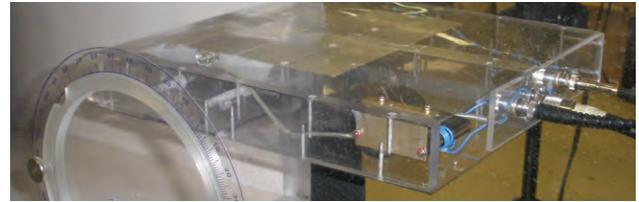
### Benefits

- ▶ **Adaptive:** Aids in the development of aero structures that will improve aircraft performance and fuel economy, due to small footprint but high energy density
- ▶ **Decreases maintenance:** Enables simpler designs that require fewer repairs

### Applications

- ▶ Commercial, military, and general aviation aircraft

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## Electromagnetic Flow Control to Enable Natural Laminar Flow Wings

A research team has developed a solid-state electromagnetic device that, when embedded along the leading edge of an aircraft wing, can disrupt laminar air flow on command. The methodology employs a combination of high-voltage alternating- and direct-current electric fields and high-strength magnets to generate crossflow. This crossflow either forms vortices or trips the flow to turbulent (depending on conditions), energizing the boundary layer to keep the flow attached and prevent stall. Presumed usage would be for an aircraft to activate the device at takeoff, turn the device off after gear-up and initial climb-out, then turn it back on for descent and landing. Using natural laminar flow principles in aircraft design can reduce fuel burn by 6 to 12 percent.

A new application has been proposed that could prove much more useful than the original incarnation. The swept wings used on commercial aircraft inherently generate crossflow similar to that generated by the proposed device, very quickly tripping the flow to turbulent. Therefore, the proposed device could be used to counter the crossflow on swept wings, delaying their transition to turbulent flow. This delay may be achievable either through actively countering the crossflow (although this may be too power intensive), or by finessing the flow in a similar manner to discrete roughness elements, with the forces tuned in real time by altering the electric field strength.

**Work to date:** The device has been tested on a flat plate in a wind tunnel. Analysis of these tests indicates significant amounts of crossflow are achievable.

**Looking ahead:** The research team is seeking funding to build and test a swept-wing article, either in a wind tunnel or on a flight test fixture. This new technology has application to both high-speed subsonic and supersonic flight conditions.

### Benefits

- ▶ **Efficient:** Enables fuel reduction
- ▶ **Simple:** Works with no moving parts, simplifying fabrication and maintenance
- ▶ **Improves safety:** Facilitates safer takeoffs and landings

### Applications

- ▶ Aircraft wings
- ▶ Heat transfer processes
- ▶ Industrial fluid processing

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## Convergent Aeronautics Solutions (CAS) X-Plane

Armstrong researchers are leading NASA's X-Plane effort to develop a cost-effective approach to design and build flight demonstration vehicles for NASA. These experimental aircraft—also known as X-Planes—will be used to test advanced technologies and revolutionary designs and to reduce the time it takes for technology to be adopted by industry and move into the marketplace. This research also is expected to provide technology that will reduce fuel use, emissions, and noise in next-generation aircraft.

The CAS project, which funds NASA researchers for short-duration (2-3 years) activities, is part of NASA's Transformative Aeronautics Concepts Program (TACP). TACP provides an environment for researchers to perform ground and small-scale

flight tests that allow them to drive rapid turnover into potential future concepts that can transform commercial aviation and unmanned aircraft systems (UAS).

**Work to date:** During the 18-month effort, the team chose one of the N+3 configurations to sharpen their pencils on a tailored system engineering requirements approach and interviewed affordable aircraft manufacturers on their development approaches and various cost drivers. The team is working to apply research methodology to develop basic manufacturing requirements that will be used to develop a series of X-Planes.

**Looking ahead:** In 2016, the team will finalize basic manufacturing requirements. In the longer term, this research will contribute to advancements in X-Plane technology.

**Partners:** NASA's Langley Research Center, Ames Research Center, and Glenn Research Center

### Benefits

- ▶ **Lowers costs:** Provides a cost-effective approach to accomplishing flight research with large-scale experimental aircraft to test solutions to technical challenges associated with ultra-efficient, future aircraft designs
- ▶ **Reduces development time:** Dramatically lessens the design-and-build phase for X-Planes and future aircraft designs with a concept-to-flight goal of less than 3 years

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NASA researchers observe one of the FT3 tests from the Research Ground Control Station at NASA Armstrong.

# Control of Flexible Structures



Armstrong engineers continue to pioneer new research in aircraft design and modeling. Researchers are experimenting with revolutionary hyperelastic wing control technologies that can reduce weight, improve aircraft aerodynamic efficiency, and suppress flutter. Other cutting-edge research involves techniques, models, and analysis tools for flutter suppression and gust-load alleviation.

Flight projects at Armstrong rely on advanced aircraft that can support research on lightweight structures and control technologies for future efficient, environmentally friendly transport aircraft. This work has applicability beyond flight safety and design optimization. Armstrong's research and development capabilities in this area also can be applied to other vehicles, such as supersonic transports, large space structures, and unpiloted aircraft.



## X-56A Multi-Utility Technology Testbed (MUTT)

Longer and more flexible wings are considered crucial to the design of future long-range, fuel-efficient aircraft. Because these wings are more susceptible to flutter and the stress of atmospheric turbulence, NASA is investigating key technologies for active flutter suppression and gust-load alleviation. The goal of the X-56A MUTT project is to advance aeroservoelastic technology through flight research using a low-cost, modular, remotely piloted experimental aircraft. The aircraft is being tested using flight profiles where flutter occurs in order to demonstrate that onboard instrumentation not only can accurately predict and sense the onset of wing flutter but also can be used by the control system to actively suppress aeroelastic instabilities.

**Work to date:** The project marked a milestone in August 2015, when Armstrong researchers completed a series of performance envelope expansion flights. These flights showed that control and operation of the vehicle has been successfully transitioned from the Lockheed Martin contractor to the NASA test team.

**Looking ahead:** Goals for 2016 test flights include (1) maturing flutter-suppression technologies, (2) reducing structural weight to improve fuel efficiency, and (3) increasing aspect ratio by 30 to 40 percent to reduce aerodynamic drag.

**Partner:** U.S. Air Force Research Laboratory

### Benefits

- ▶ **Advanced:** Enables construction of longer, lighter, more flexible wings for a variety of crewed and remotely piloted aircraft
- ▶ **Configurable:** Enables a vast array of future research activities for wing sets, tail sections, sensors, and control surfaces

### Applications

- ▶ Lightweight commercial aircraft
- ▶ High-altitude surveillance platforms
- ▶ Low-boom supersonic transport vehicles

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## Robust Virtual Deformation Control of the X-56A Model

An Armstrong research team has developed a virtual deformation controller designed to actively suppress flutter on the X-56A experimental aircraft by changing wing shape. A remotely piloted aircraft with a stiff body and flexible detachable wings, the X-56A was developed for the sole purpose of testing various active flutter-suppression technologies. As part of its sensor array, the aircraft wings will be instrumented with fiber optic sensors that can measure strain at thousands of locations. The controller will use these sensors in an adaptive feedback system to automatically manipulate the trailing edge control surfaces and body flaps to suppress flutter. A robust modal filter solution for wing damage assessment and robust flight control adaptively finds strain anomalies in the structure and reports them to the control system. This technology will contribute to the development of robust controllers that can safely extend the envelope of commercial aircraft.



**Work to date:** The team has validated the controller for both flutter suppression and shape control in simulations using X-56A models that contain all six rigid-body degrees of freedom, flexible modes, 10 control surfaces, and actuators. Simulations have shown that the shape controller can affect the global angle of attack and achieve drag changes. The fiber optic sensors have been installed on the flexible wings of the X-56A.

**Looking ahead:** The fiber optic sensors will be calibrated for static loads and ground vibration testing. Additional steps include linear analysis on validated flex-wing models, non-linear simulations, and in-flight controls feedback.

**Partner:** U.S. Air Force Research Laboratory

### Benefits

- ▶ **More design freedom:** Allows designers to consider lighter/larger wing profiles
- ▶ **Safer flight:** Reduces likelihood of losing control

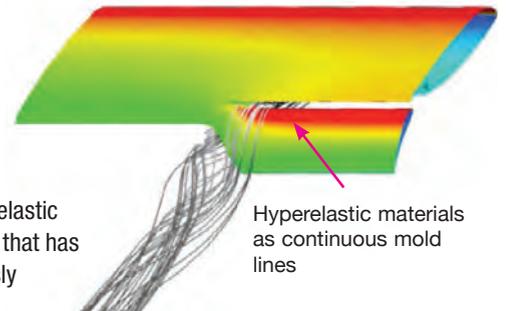
### Applications

- ▶ Aircraft design and aeroservoelastic tailoring
- ▶ Active flutter suppression
- ▶ Loads and health monitoring

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## Fundamental Research into Hyperelastic Materials for Flight Applications

This research effort seeks to fill in knowledge gaps that currently exist in the fundamental understanding of hyperelastic materials, including their response under static and dynamic loading, and to explore their potential for application to structures in flight. Hyperelastic materials have been proposed as a continuous mold line—enabling technology for future generations of aircraft design. However, the data required to prove their flight-worthiness and practical application are not readily available. The outcome of this research effort is contributing to component data currently lacking and providing insight into the behavior of hyperelastic materials in flight that has not been previously explored.



### Work to date:

Three project tasks were developed to gather biaxial strain data, evaluate concentration factors, and validate analytical mode shapes and frequencies for test coupons of hyperelastic materials under a range of stretch ratios. The three areas investigated were approached via three subtasks: biaxial testing, stress concentration studies, and dynamic testing.

**Looking ahead:** An effort is underway to design a small flight test project that will subject panels of hyperelastic material to transonic and supersonic flight conditions. The objective is to further understand the behavior of hyperelastic materials in flight applications, particularly panel flutter and panel-type responses. The general concept involves installing hyperelastic panels on the flight test fixture of NASA's F-15 supersonic flight testbed. NASA's Langley Research Center and Ames Research Center are potential partners for this effort.

### Benefits

- ▶ **Innovative:** Increases the reliability of hyperelastic materials in flight applications
- ▶ **High performance:** Improves aerodynamic capabilities and enables morphing structural technologies by sealing structural gaps

### Applications

- ▶ Aircraft/Spacecraft control surfaces
- ▶ Motor vehicles, trains, and ships
- ▶ Industrial engines (e.g., vibration damping)

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# Inverse Finite Element Method (iFEM) Investigation for Aerospace Structures

This research project is evaluating an innovative technique that uses experimental strain sensors to measure structural deformations and full-field strains in aerospace structures. An iFEM analysis reconstructs a deformed structural shape based on the experimental strain measurement data or strains simulated by FEM analysis to represent the *in situ* strain measurements. Mapping the iFEM displacement solution onto a full FEM model without the applied loading allows the complete fields of displacement, strain, and stress to be reconstructed to a high degree of accuracy. The innovation improves safety by enabling more efficient health monitoring of control surfaces and flexible structures. This project supports work on multiple flight research projects at Armstrong.

**Work to date:** The team has completed and validated a FEM code utilizing a three-node flat shell element.

**Looking ahead:** Future plans involve developing and validating the algorithm on a full-size flight test article.

**Partner:** NASA's Langley Research Center

## Benefits

- ▶ **Accurate:** Enables accurate full-field structural shape and strain measurement
- ▶ **Economical:** Uses a minimal number of sensors to recreate the full-field structural deformations and strains

## Applications

- ▶ Aircraft wing flaps
- ▶ Helicopter blades
- ▶ Wind turbines
- ▶ Motor vehicles
- ▶ Trains
- ▶ Ships and submersibles

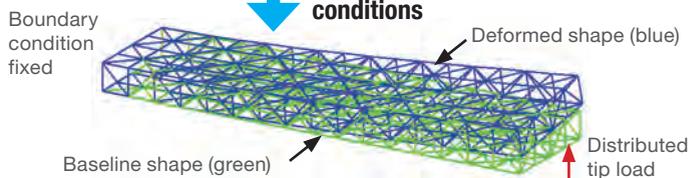
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## Aerospace structure

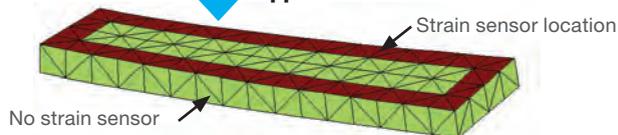


Installed strain sensors

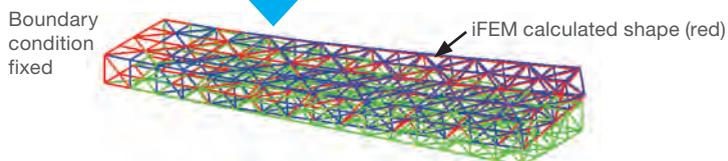
## Wing box FEM model of structure with representative boundary conditions



## Experimental or FEM strains applied to model



## iFEM formulation



The cockpit of NASA's SOFIA 747SP



University of Minnesota UAV Laboratories photo

## Lightweight Adaptive Aeroelastic Wing

This research effort is integrating multidisciplinary tools, techniques, technology, and processes to develop a performance adaptive aeroelastic wing that can continuously optimize its shape for current flight conditions and aircraft configuration. For example, this approach could maximize lift for takeoff and minimize fuel consumption at cruise altitude. The wing structure will leverage curvilinear spars and ribs (SpaRibs) and be designed with minimal weight to handle static loading. The design will include distributed control effectors and a large distributed sensor network, enabling innovative control solutions for flutter suppression. In addition, alleviation of gust and turbulence loading will further decrease the structural weight. Outer-loop control laws will optimally alter the wing shape and load distribution at varying conditions across the flight envelope, adaptively minimizing drag and providing high lift for takeoff and landing. Flight testing on Armstrong's X-56A aircraft is planned over the course of the 5-year program.

**Work to date:** This research is advancing the state of the art for adaptive wings, which allow for reduced weight, higher aspect ratio, and shape modification to dramatically increase efficiency. Low-cost subscale vehicles are being used for early research and flight tests, primarily at the University of Minnesota. All design documents, software, and flight data are open source and available online at <http://paaw.net>.

**Looking ahead:** Armstrong's X-56A MUTT vehicle will be used for future large-scale testing.

### Benefits

- ▶ **Efficient:** Provides for reduced fuel consumption
- ▶ **Innovative:** Advances the state of the art for higher aspect ratio and efficient wings and enables future N+3 commercial aircraft concepts (i.e., three generations beyond the current commercial transport fleet)
- ▶ **High performance:** Contributes to enabling low-boom supersonic transport concepts

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## Real-Time Structural Overload Control via Control Allocation Optimization

This technology utilizes real-time measurements of vehicle structural load to actively respond to and protect against vehicle damage due to structural overload. The innovation uses control surfaces to actively constrain critical stresses measured by an array of strain gauges. The allocation algorithm optimally utilizes the control surfaces to control the aircraft motion while preventing overstresses in critical aircraft structure. This advanced allocation algorithm is implemented in a run-time assurance architecture that provides an additional layer of software protection and prevents algorithm/software errors from generating unsafe control commands. The complete technology effectively constrains the load at critical points while



producing the control response commanded by a pilot—all within a software assurance paradigm with high reliability.

**Work to date:** Using NASA's Full-Scale Advanced Systems Testbed (FAST) aircraft, the Armstrong team targeted the aileron hinge connection as a critical control point. A 2013 flight experiment using the FAST aircraft produced successful results in flight of a prototype of the optimal control allocation algorithm. A recent effort has focused on developing a real-time model of the structural response of the wing, which is being coupled with an optimal control strategy. All of the software elements have been incorporated with a run-time assurance algorithm to provide real-time software assurance.

**Looking ahead:** The aircraft simulation model is being reworked to incorporate additional structural elements. The FAST aircraft was decommissioned in 2013, and a new F/A-18 testbed is being instrumented to flight test this technology.

### Benefits

- ▶ **Effective:** Identifies the optimum control surface usage for a given maneuver for both performance and structural loading
- ▶ **Automated:** Monitors and alleviates stress on critical load points in real time
- ▶ **Assured:** Validates algorithm outputs in real time to improve software reliability

### Applications

- ▶ Jet aircraft
- ▶ Industrial robotics

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## APV-3 Testbed Aircraft

Armstrong's Fiber Optic Sensing System (FOSS) team is conducting flight tests with a remote-controlled APV-3 aircraft. This low-cost, low-risk efficient testbed is allowing the team to test advanced concepts without jeopardizing flight personnel or incurring costs associated with high-value aircraft, such as the Ikhana. Advancements in the miniaturization of the FOSS system have made its application on this small-scale aircraft possible. The team is also using the aircraft to not only gather strain data but also evaluate how FOSS can be used to provide sensory feedback to distributed control surfaces. These developments will enable the wing to adapt to varying maneuver loads by redistributing load along the wing. In this new research to extend FOSS capabilities, researchers are inputting real-time FOSS data to the flight control system to achieve improved vehicle control, with the ultimate goal of improving flight safety for aircraft and spacecraft.

**Work to date:** The team has instrumented the aircraft with the FOSS system and collected strain and deflection data during flight tests. The team has also demonstrated the use of FOSS in a feedback system to enable the wing structure to actively adapt to maneuver loads.

**Looking ahead:** Several projects involving shape- and load-sensing are planned for the summer of 2016. These new sensing capabilities can then be utilized by the flight computer to make better informed decisions on how to react to varying loads encountered in flight.

### Benefits

- ▶ **Cost effective:** Enables cutting-edge research to be conducted at low cost
- ▶ **Low risk:** Reduces greatly the potential risks associated with this flight research by using a small, inexpensive, and remotely piloted aircraft
- ▶ **Efficient:** Provides a platform where adjustments to equipment and instrumentation can be made quickly, enabling a greater volume of tests to be conducted in a shorter period of time

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## X-56A Multi-Utility Technology Testbed (MUTT) to Leverage FOSS Capabilities

The goal of NASA's X-56A project is to advance aeroservoelastic technology through flight research using a low-cost, modular, remotely pilot aircraft. The aircraft is being tested using flight profiles where flutter occurs in order to demonstrate that onboard instrumentation can not only accurately predict and sense the onset of wing flutter but also be used by the control system to actively suppress aeroelastic instabilities. Inputs from Armstrong's Fiber Optic Sensing System (FOSS) will be used for a variety of strain sensing and twist algorithms, including flutter suppression.

**Work to date:** With funding from NASA's Aeronautics Research Mission Directorate (ARMD), the team has instrumented an X-56A wing set with FOSS for testing in the Armstrong Flight Loads Laboratory. Results will help engineers characterize the system that will be used during flight experiments.

**Looking ahead:** Additionally, FOSS will be used for data collection during both static and dynamic loads testing. This research will also enable the FOSS team to characterize the performance of the sensor technology, as researchers are hoping to employ FOSS for feedback control during the X-56A flight testing.

### Benefits

- ▶ **Improved flutter control:** The high spatial resolution of FOSS, which can provide measurements every 0.5 inches, will enable a high degree of accuracy for understanding and controlling flutter.
- ▶ **Enhanced flight control:** The high sample rates, measurement density, and processing speed have the potential to greatly advance feedback control.

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## Active/Adaptive Flexible Motion Controls with Aeroservoelastic System Uncertainties

Most aeroservoelastic analyses of modern aircraft have uncertainties associated with model validity. Test-validated aeroservoelastic models can provide more reliable flutter speed. Tuning the aeroservoelastic model using measured data to minimize the modeling uncertainties is an essential procedure for the safety of flight. However, uncertainties still exist in aeroservoelastic analysis even with the test-validated model due to time-varying uncertain flight conditions, transient and nonlinear unsteady aerodynamics, and aeroelastic dynamic environments.

The primary objective of this research is to study the application of a digital adaptive controller to the flexible motion control problems by employing online parameter estimation together with online health monitoring.

The second objective of this research is to develop a simple methodology for minimizing uncertainties in an aeroservoelastic model.

**Work to date:** Research is progressing in three primary areas:

### Three-Dimensional (3D) Load Sensing from Measured Strain

This technology is a system and method for calculating wing deflection and slope over the entire surface of a 3D structure. The system integrates strain data measurements from discrete locations to compute out-of-plane deflection along fibers. It then uses a finite element model to interpolate and extrapolate all the deflections and slopes of the entire structure.

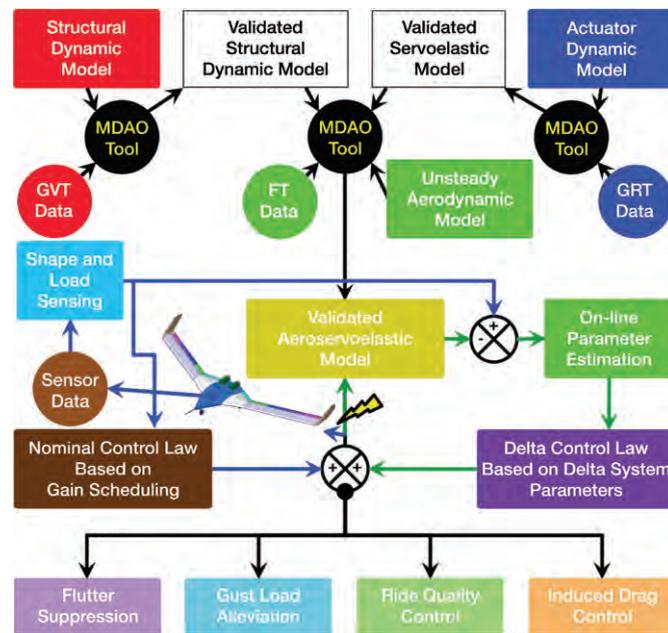
### Aeroservoelastically Tailored Wings and Aircrafts with Curvilinear Spars and Ribs (SparRibs)

For this project, a systematic multidisciplinary design, analysis, and optimization (MDAO) tool is employed to perform an optimization study and force the design flutter speeds back into the flight envelope. The approach combines an active control technique, aeroelastic control, and SparRibs to increase design stability.

### Test-Validated Aeroelastic Model of an Aircraft Using the Model Tuning Codes

This effort is seeking to reduce uncertainties in the unsteady aerodynamic model by employing a new flutter analysis procedure that uses the validated aeroelastic model. The research team has developed a technique to update unsteady aerodynamic models

by matching the measured and numerical aeroelastic frequencies of an aircraft structure. In defining the optimization problem to match the measured aeroelastic frequencies, researchers select the variation of an unsteady aerodynamic force as the design parameter. This unsteady aerodynamic force is a function of Mach number, reduced frequency, and dynamic pressure, and it can be obtained from any aerodynamic model.



**Looking ahead:** Work will aim to prove a tracking error convergence for the multi-input multi-output direct model reference adaptive control (MRAC) problem using a composite system construction with Lyapunov stability techniques. Performance of the proposed control design will be demonstrated through simulation of a linear version of an aircraft wing's aeroelastic pitch and plunge dynamics.

The surrogate tracking error MRAC design will be extended to accommodate uncertainty in the locations of the nonminimum phase zeros. It will be implemented on more complex versions of the X-56A models and

across a range of flight conditions to investigate its robustness. The delta control system design technique will also be applied to the cantilevered rectangular wing model.

**Partners:** Lockheed Martin Advanced Development Program (a.k.a. Skunk Works®) and U.S. Air Force Research Laboratory

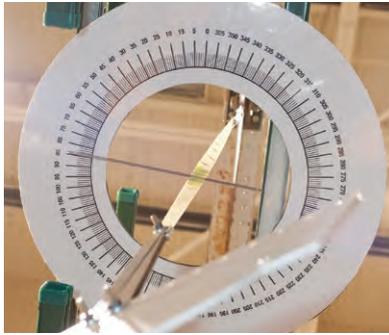
### Benefits

- ▶ **High performance:** Reduces uncertainties in the unsteady aerodynamic model of an aircraft to increase flight safety
- ▶ **Economical:** Enables high-precision simulation prior to expensive flight tests
- ▶ **Efficient:** Has the potential to improve fuel efficiency and ride quality

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## Active Control of Tailored Laminates

Part of a suite of technologies to enable a fully morphing seamless wing, this research effort focuses on tailoring composite materials to enhance structural response and generate out-of-plane deflections using in-plane forces.



Compass indicating degree of twist for test article

**Work to date:** An analytical feasibility study completed in 2013 determined that in-plane loading can generate significant out-of-plane displacement, effectively yielding wing twist. To create laminates with the largest displacement response, a laminate optimization tool was developed to generate ply schedules that produce the maximal desired  $b$ -matrix coefficient. Multiple laminates of differing ply thickness were analyzed using classic laminated plate theory and showed significant out-of-plane displacement given in-plane tension loading. Results were compared to finite element method (FEM) analysis and showed excellent correlation. These results provided the basis for determining the degree of structural interaction of stiffeners and migrating the suppression of structural response.

To validate model predictions, a series of composite test articles was fabricated and tested. Using the optimization tool, four laminates were created to maximize the  $b_{16}$  coefficient, which couples in-plane tension with panel twist. Tension loading each laminate revealed significant twisting response and provided a valuable anchor to the theory.

**Looking ahead:** Future work will concentrate on enabling continuous outer mold line structures that can change shape. This revolutionary new approach for aircraft design will improve performance and fuel efficiency in numerous ways, as seamless wings would reduce drag and would streamline and simplify an airplane's maneuverability. Immediate plans call for further examination of the design space. Variables to be examined include fiber type, matrix stiffness, and structural configurations.

### Benefits

- ▶ **Economical:** Increases fuel efficiency by reducing drag
- ▶ **Robust:** Features a simpler wing design without control surfaces that is easy to maintain and less likely to need repair

### Applications

- ▶ Commercial, general aviation, and military transport aircraft

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## Integrated Flight Dynamics and Aeroservoelastic Modeling and Control

This research effort is developing flight control systems and mathematical models that integrate both structural and flight dynamics. As modern aircraft become more flexible and these disciplines converge, conflicts arise between independently developed modeling methodologies. Because the structural and flight dynamics of the X-56A multi-utility technology testbed (MUTT) aircraft are acutely coupled, resulting models are capable of capturing the requirements of both disciplines.

**Work to date:** The Armstrong team generated linear models that were used to design flight controllers for the stiff wing flights. Stiff wing flight tests have been performed using the X-56A MUTT as a validation of the modeling approach.

**Looking ahead:** Planning has begun for a flexible wing flight test with unstable structural dynamics within the next year to further validate the integrated vehicle. The team is also developing a simulation capable of running in real time that would enable a pilot to evaluate the vehicle.

**Partner:** U.S. Air Force Flight Research Laboratory

### Benefits

- ▶ **More design freedom:** Enables the design of lighter, larger, and more flexible wing profiles
- ▶ **Economical:** Increases fuel efficiency
- ▶ **Safer flight:** Reduces likelihood of structural damage
- ▶ **Innovative:** Advances the state of the art for higher aspect ratio wing and efficient aircraft and enables future N+3 commercial aircraft concepts (i.e., three generations beyond the current commercial transport fleet)

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# Supersonic Technologies

## Key factors impacting sonic booms



Supersonic flight over land is currently severely restricted because sonic booms created by shock waves disturb people on the ground and can damage property. Armstrong innovators are working to solve this problem through a variety of innovative techniques that measure, characterize, and mitigate sonic booms. The Federal Aviation Administration (FAA) is carefully monitoring Armstrong's research efforts, and numerous industry partners are working with Armstrong to identify low-boom next-generation aircraft designs and other strategies that show promise for reducing sonic boom levels.



## Investigating Laminar Flow

Researchers are collecting flight data about the extent and stability of laminar flow on highly swept wings at supersonic speeds. The **Swept Wing Laminar Flow** research project consists of testing articles first in a wind tunnel and then flying them beneath supersonic research aircraft, which enables characterization of the differences between the two types of tests while providing access to real-world conditions. The objective of this effort is to better understand boundary layer transition from laminar to turbulent caused by crossflow disturbances—the primary transition mechanism on highly swept wings—at supersonic speeds. Methods to mitigate crossflow and its effects on boundary layer transition will also be investigated. Experiment results can be used to help determine the viability of crossflow control mechanisms to delay boundary layer transition and their suitability for supersonic laminar flow wing designs, especially ones tailored toward future low-boom supersonic aircraft.

**Work to date:** The 65° swept wing model is due to complete wind tunnel testing at NASA's Langley Research Center in the near future. The design of the aircraft mounting hardware is in progress. Computational fluid dynamics (CFD) of the test article on the aircraft (F-15B) have also been completed.

**Looking ahead:** Work on the highly swept wings will continue, with a focus on developing a workable strategy to mitigate crossflow and its effects.

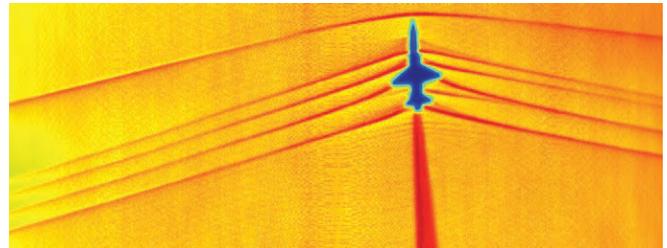
**Partner:** NASA's Langley Research Center

### Benefits

- ▶ **Informs wing design:** Data collected can help researchers understand key phenomena, which will impact supersonic laminar flow wing design.
- ▶ **Enables access to real flight conditions:** Flight testing allows data to be collected in conditions similar to what will be faced when wings are integrated into an aircraft design.

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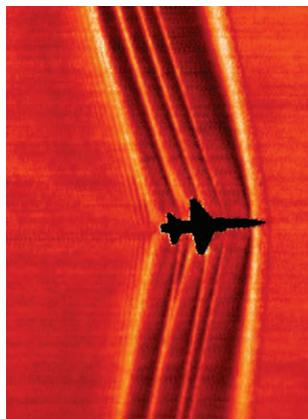
## Using Schlieren Techniques to Understand Sonic Booms

One of the most exciting advances at Armstrong involves the use of schlieren photography to capture images of shock waves emanating from aircraft in supersonic flight. Flow visualization is one of the fundamental tools of aeronautics research, and background-oriented schlieren can use a speckled background to visualize air density gradients caused by aerodynamic flow. Researchers have been using a technique called **Air-to-air Background Oriented Schlieren (AirBOS)**, which they most recently used in February 2015 to photograph a supersonic T-38 against a tumbleweed-studded desert backdrop using special cameras mounted on the underside of a subsonic King Air twin turboprop aircraft. Following each flight the AirBOS team used NASA-developed image processing software to remove the desert background and reveal rough shock wave images.

The team also demonstrated a ground-based method called **Background Oriented Schlieren using Celestial Objects (BOSCO)**. A subset of BOSCO is **Calcium-K Eclipse Background Oriented Schlieren (CaKEBOS)**.

Viewing the sun through a calcium-K filter provided a satisfactory speckled backdrop for the supersonic target aircraft and, once again, the patent-pending method for imaging shock waves was made possible through advanced image processing technology. Using a celestial object like the sun for a background has advantages because a second aircraft is not needed. Furthermore, with the imaging system on the ground, the target aircraft can be at any altitude as long as it is far enough away to be in focus.

**Looking ahead:** Armstrong researchers will continue to refine and integrate these schlieren techniques to further NASA's understanding of complex flow pattern of sonic shock waves. It is



hoped that these techniques can be used to validate and improve design models of future prototype and demonstrator low-boom aircraft, with the ultimate goal of enabling demonstration of overland supersonic flight with acceptable sonic boom impacts. Future work may also include imaging subsonic aircraft flow fields.

**Partners:** NASA's Ames Research Center; Spectabit Optics, LLC; and the U.S. Air Force Test Pilot School

### Benefits

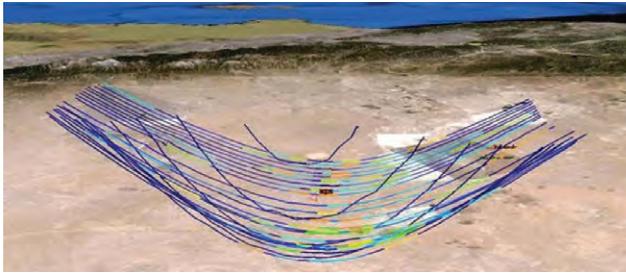
- ▶ **Real-world visualization:** Schlieren techniques enable visualization of shock wave geometry in the real atmosphere with real propulsion systems that cannot be duplicated in wind tunnels or computer simulations.
- ▶ **Improved data:** Studying life-sized aircraft flying through Earth's atmosphere provides better results than modeling and can help engineers design better and quieter supersonic airplanes.

### Applications

In addition to studying shock waves for aircraft, NASA's schlieren techniques have the potential to aid the understanding of a variety of flow phenomena and air density changes for several applications including:

- ▶ Wing tip vortices
- ▶ Engine plumes
- ▶ Wind turbines
- ▶ Subsonic aircraft
- ▶ Rotorcraft
- ▶ Highway traffic (e.g., trucks)
- ▶ Volcanic eruptions

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## Mitigating Sonic Booms

Armstrong innovators are advancing unique technology that will permit pilots to make in-flight adjustments to control the timing and location of sonic booms. The **Cockpit Interactive Sonic Boom Display Avionics (CISBoomDA)** is a revolutionary software system capable of displaying the location and intensity of shock waves caused by supersonic aircraft. The technology calculates an airplane's sonic boom footprint and provides real-time information, enabling pilots to make the necessary flight adjustments to control the impact of sonic booms on the ground. It can be integrated into cockpits and flight control rooms, enabling air traffic controllers to analyze flight plans for approval, monitor aircraft in flight, and review flight data to enforce regulations.

**Work to date:** The real-time cockpit system was tested in August 2015 during two supersonic flights on a NASA F/A-18, which compared computations with boom measurements on the ground. Two avionics companies, Honeywell and Rockwell-Collins, are integrating this software into their avionics systems for future low-boom aircraft.

**Looking ahead:** Further advancements on both the software and hardware are planned for 2016, with plans for inclusion on future low-boom aircraft.

### Benefits

- ▶ **Enables overland supersonic travel:** Because pilots can control the location and intensity of sonic booms, CISBoomDA may allow future-generation supersonic aircraft to fly over land.
- ▶ **Reduces noise pollution:** CISBoomDA allows for appropriate placement of booms, minimizing their effects on the ground.
- ▶ **Provides a tool for the FAA:** Software such as CISBoomDA could provide the FAA with the ability to approve flight plans, monitor flying aircraft, and review flight data to enforce regulations.

### Applications

- ▶ **In flight:** Enables pilots to avoid producing sonic booms or control their location and intensity
- ▶ **On the ground:** Allows the FAA to approve and monitor plans for supersonic flights

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## FOSS Aids Low-Boom Flight Demonstrator Project

Through its Low-Boom Flight Demonstrator Project, NASA is working to design an aircraft with a shape that will reduce its shock-wave signature. As part of this effort, researchers will need to precisely monitor the aircraft shape in order to determine its impact on the intensity of the sonic boom. With funding from NASA's Aeronautics Research Mission Directorate (ARMD), Armstrong's Fiber Optic Sensing System (FOSS) is being evaluated as a means to accurately determine the aircraft's shape during flight, with a particular focus on wing tip deflection and twist.

**Work to date:** Current efforts focus on determining the level of accuracy of the FOSS system as well as the degree of shape change expected for the vehicle. Early on, the technology will be used for model validation techniques.

**Looking ahead:** Depending on the shape and structure of the vehicle and the corresponding degree of shape change, FOSS may also be used to determine the shape of the aircraft so that researchers can compare the modeled response to the actual response. (For more information on Armstrong's FOSS technologies, see page 40.)

### Benefits

- ▶ **Model validation:** Enables researchers to determine if models accurately represent real-world shape changes, which in turn will impact aircraft design
- ▶ **Real-time monitoring:** Provides real-time shape data, allowing researchers to monitor shape during both wind tunnel and flight tests
- ▶ **High spatial resolution:** Enables measurements every 0.5 inches, providing significantly more data than other available measurement options
- ▶ **Easy application:** Small enough to be used on sensitive surfaces without affecting performance

### Applications

- ▶ Facilitating aircraft design that may ultimately enable overland supersonic flight

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## Quantifying and Measuring Sonic Booms

Because the FAA has not yet defined a maximum allowable boom loudness, Armstrong innovators are researching ways to identify a loudness level that is acceptable to both the FAA and the public. The Armstrong team and a number of industry, academic, and NASA partners have identified and validated several methods and techniques for capturing and measuring booms and their impacts. Activities range from collecting data above and below sonic booms via a sophisticated array of microphones to gathering information from remote sensors and Wi-Fi-controlled microphones strategically placed within communities.

**Work to date:** The **Farfield Investigation of No Boom Threshold (FaINT)** research project is characterizing evanescent waves, an acoustic phenomenon occurring at the very edges of the normal sonic boom envelope and sounding similar to distant thunder. During FaINT experiments, researchers collected data during a series of low-supersonic, high-altitude flights via a 1-mile stretch of microphones along the ground. Microphones were also placed more than 2,000 feet above ground, and another microphone was on a motorglider at altitudes around 10,000 feet.

The **Superboom Caustic Analysis and Measurement Program (SCAMP)** placed focused sonic booms on an array of prepositioned ground sensors spread over a 10,000-foot-long area. Researchers evaluated methods and computations used to place the focused booms on the array.

The Armstrong team and a number of industry and academic partners have also identified and validated several methods and techniques for capturing and measuring sonic booms. A notable method is the **Boom Amplitude and Direction Sensor (BADs)**, which employs six pressure transducers widely spaced on the vertices of an octahedron. The **Supersonic Pressure Instrumentation Kit Ensemble (SPIKE)** combines a high-quality microphone recording system and accurate time tagging in a solar-powered and rugged case to withstand the harsh desert environment where most of the tests are performed. Similarly, **Supersonic Notification of Over Pressure Instrumentation (SNOOPI)**, an all-weather pressure transducer system, records local sonic booms by date, time, and intensity 24 hours a day, 7 days a week. This test equipment is used to record sonic

booms generated through special piloting techniques specifically designed for sonic boom placement and mitigation. From these methods and techniques, the Armstrong team has collected test data from various projects to determine how F/A-18 dive maneuvers may create lower-level and focused booms.

**Looking ahead:** The Armstrong team is continuing to advance NASA's understanding of sonic boom phenomena via sonic boom tests. This includes **Sonic Booms in Atmospheric Turbulence (SonicBAT)**, which will develop analytical and numerical models of the effects of atmospheric turbulence on noise levels and then validate the models using research flights in both dry and humid climates. Planning is also underway for testing the community response to the quiet sounds of future supersonic aircraft. These activities will play a key role in the testing of an anticipated low-noise sonic boom flight demonstrator aircraft.

**Partners:** NASA's Langley Research Center; Wyle Laboratories, Inc.; Pennsylvania State University; The Boeing Company; Gulfstream Aerospace; and Eagle Aeronautics, Inc.

### Benefits

- ▶ **Advances sonic boom research:** These programs are producing valuable data to help characterize key elements of sonic booms (e.g., evanescent waves, sonic boom propagation effects, impact of flight maneuvers).
- ▶ **Informs aircraft design:** Data from these efforts will be critical for informing designs of future supersonic aircraft.
- ▶ **Quantifying perceptions:** Data from these programs includes public reaction, which will be critical as the FAA considers allowing overland supersonic flight.

### Applications

- ▶ Supersonic aircraft design
- ▶ Flight planning
- ▶ FAA approval of overland supersonic flight

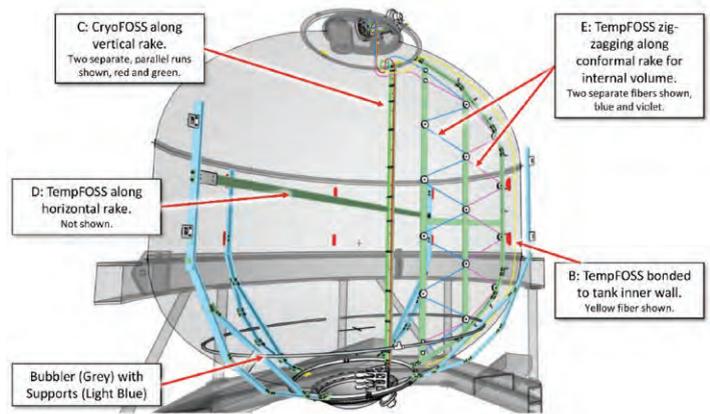
PIs: Larry Cliatt | 661-276-7617 | [Larry.J.Cliatt@nasa.gov](mailto:Larry.J.Cliatt@nasa.gov)  
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# Space and Hypersonics Technologies



A key objective of space research at Armstrong is to leverage our Center's expertise in aircraft flight testing, instrumentation, avionics development, simulation, and operations to assist NASA with space exploration. Our researchers are discovering innovative ways to use aircraft to develop new space capabilities and to test space technologies in a relevant environment.

Hypersonics research is important both for aeronautics and space research to enable extremely fast travel on Earth as well as for future space exploration. Armstrong has a long history of pioneering research in this area.



## Cryogenic Orbital Testbed (CRYOTE) to Use FOSS Technology

The CRYOTE provides an in-space environment where the unique properties and flow of cryogenic fluids can be demonstrated in micro- or zero-gravity. Sponsored by NASA's Launch Services Program and with partnerships across industry and NASA, the CRYOTE project provides a detailed concept of an in-flight core system that can accommodate a variety of experiments.

One goal of this effort is to better understand how cryogenic fluids transition from the liquid to gas phase. FOSS is being used to collect high-fidelity data along the liquid level boundary region to validate and inform the models for the region. Greater accuracy of the model will enable better control of the boundary region, which in turn allows the tanks to be filled to higher levels, resulting in improved efficiencies.

**Work to date:** In addition to providing these highly accurate liquid level measurements, FOSS is also being used to measure strain on the tank itself as well as provide temperature profiles throughout the tank. The use of FOSS for CRYOTE is not only providing invaluable information for the CRYOTE team, it is also advancing the capability of FOSS to provide liquid level measurements in applications where accurate determinations have previously been very challenging or even impossible.

**Partners:** NASA's Kennedy Space Center and Marshall Space Flight Center, United Launch Alliance, and NASA Launch Services



### Benefits

- ▶ **Precise:** Requires just one fiber optic strand and one metallic wire
- ▶ **Safe:** Is not susceptible to electromagnetic interference
- ▶ **Robust:** Can be used in corrosive or toxic liquids

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# Using FOSS to Improve Safety of Space Structures and Components

FOSS is being used to investigate a series of random failures of composite tanks and composite overwrapped pressure vessels (COPVs). With funding from NASA's Human Exploration and Operations (HEO) Mission Directorate, FOSS is one of several technologies being used to determine conditions in these tanks at the point of failure. The goal is to determine whether instrumentation exists that can predict imminent tank failure.

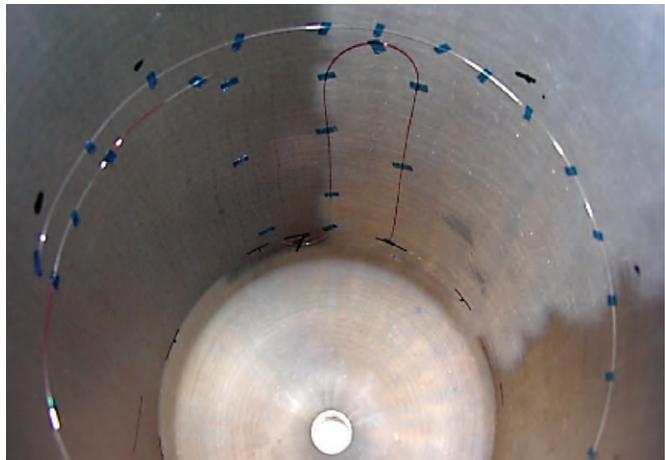
A separate effort, sponsored by the NASA Engineering and Safety Center (NESC) and the NASA Nondestructive Evaluation Working Group (NNWG), is seeking to identify specific failure mechanisms for COPV, specifically composite tanks constructed around a metal core. Investigation is focusing on how the core is fabricated and merged with the tank. Researchers are placing FOSS on that boundary layer between the metal and the composite to determine whether there are abnormalities that can be associated with the failure mechanism.

## Composite Shell Buckling Knockdown Factor

In a related effort also funded by NESC, FOSS is being used to obtain experimental validation of knockdown factor margins. Focused on large, panel-type structures where buckling is a common failure mechanism, researchers are evaluating design techniques as well as structural margins. FOSS is being used to gather performance data and validate models. These critical data could lead to the ability to reduce margins while still maintaining safety, which could enable significant weight savings for these large structures (e.g., tanks, rocket stages, space station components).

## Micrometeorite Impact Detection

FOSS is being used to more precisely determine the location and severity of micrometeorite impacts, which are a significant concern for space structures during long-duration missions. The research is contributing to the safety of the International Space Station, crew modules, and other high-value space assets. This research is funded by NESC.



Internal strain monitoring within a composite tank

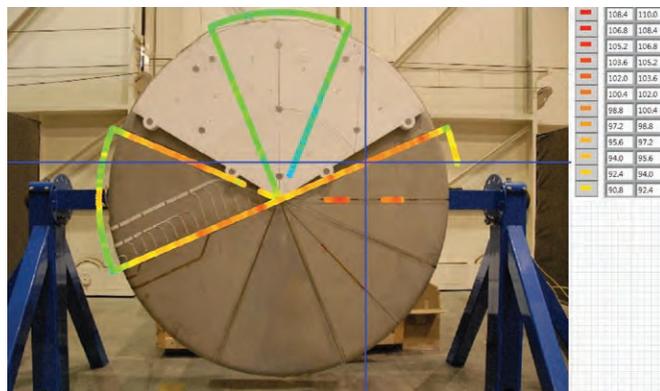
## Wire Bundle Validation Measurement

FOSS is being used as part of the instrumentation suite to validate a launch services provider's wire bundles. With NESC funding, FOSS temperature sensors are helping ensure the bundles comply with NASA safety standards.



## Thermal Protection System (TPS) Health Monitoring

In a joint effort with Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), FOSS was used to evaluate an innovative technique to monitor the TPS of a vehicle. Specifically, the FOSS strain and temperature data contributed to the evaluation process, in which much was learned about the technique and FOSS's ability to characterize it.



FOSS helps evaluate innovative technique to monitor vehicle TPS

## Benefits

- ▶ **Provides real-time data:** Enables measurements outside of test facilities and during operation
- ▶ **Accurate:** Improves accuracy of simplified structural models
- ▶ **Economical:** Provides similar spatial resolution to that obtained from more cumbersome, labor-intensive, and costly finite element analysis
- ▶ **High spatial resolution:** Enables measurements every 0.5 inches
- ▶ **Easy application:** Can be used on sensitive surfaces without affecting performance, due to its small size
- ▶ **High-temperature sensing:** Measures strain at much higher temperatures than conventional methods
- ▶ **Improves safety:** Provides validated structural design data, leading to lighter and more structurally efficient systems

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## Heavy-Lift Mid-Air Retrieval



Funded by the 2016 Armstrong Center Innovation Fund, this effort is investigating the feasibility of using the Third-Generation Mid-Air Retrieval

(MAR) system to retrieve valuable and relatively heavy space assets that return to Earth. Also known as 3G MAR, the system offers low-speed, low-g retrieval of payloads suspended under a parafoil. Mid-air retrieval offers a significant opportunity to reduce costs associated with rocket launches, as it enables the reuse of expensive components.

A key advantage of 3G MAR is that the capture system and maneuvers comply with federal regulations for helicopter long-line operations so does not have to be modified or reclassified as experimental to retrieve payloads. Another goal of this research is to investigate the feasibility of retrieving objects up to the lift capacity of the most capable heavy-lift helicopters. The 3G MAR system has been successfully performed with a 750-pound payload. Mid-air retrieval is a technology candidate within the Entry, Descent, and Landing technology of NASA's 2015 Technology Roadmaps.

**Work to date:** In 2015, 3G MAR was attempted on a 1,200-pound payload, utilizing an upgraded aero-grapple. Although the attempt was unsuccessful, several key lessons were learned about steering the guided parafoil.

The Armstrong research is a three-pronged effort:

1. Aero-mechanical system study
2. Reference mission concept of operations study
3. Guidance navigation and control (GN&C) and autonomy study

**Looking ahead:** The feasibility study will be completed in 2016. Results will be presented at industry conferences on responsive access to space.

**Partners:** Airborne Systems North America, Charles Stark Draper Laboratory, Inc., and Erickson, Inc.

### Benefits

- ▶ **Reduces costs:** Offers low-speed, low-g retrieval of expensive assets
- ▶ **Flexible:** Enables new missions through over-water recovery
- ▶ **Efficient:** Complies with federal regulations for helicopter long-line operations

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## Launch Vehicle Adaptive Control (LVAC) Flight Experiments

A series of LVAC flight experiments conducted at Armstrong successfully increased the technology readiness level (TRL) of an adaptive augmenting control (AAC) algorithm from 5 to 7. The AAC was developed to improve the performance and robustness of NASA's Space Launch System (SLS) during extreme, unanticipated events well outside the rocket's design envelope. The SLS is expected to produce more thrust and deliver more payload to orbit than any other launch vehicle, opening the way to new frontiers of space exploration.

**Work to date:** To validate the algorithm's effectiveness, researchers installed the prototype AAC flight software into Armstrong's Full-Scale Advanced Systems Testbed (FAST), giving it full authority control over the aircraft's aerodynamic effectors. Armstrong's FAST aircraft then simulated multiple failure scenarios the SLS may experience as it makes its way from the launch pad to booster separation. These tests provided valuable data that both proved the AAC technology and will aid its future development.

**Looking ahead:** The flight test data are being used to refine the AAC software and plans for future tests. The first flight of the SLS, with the AAC algorithm enabled, is scheduled for 2018.

**Partners:** NASA's Marshall Space Flight Center, Engineering and Safety Center, and Space Technology Mission Directorate's Game Changing Development Program

### Benefits

- ▶ **Cost effective:** Enabled the AAC to be evaluated in-flight without having to be launched into space
- ▶ **Unique:** Provided full-scale, high-performance piloted testbed with a proven research flight control system, extensive research instrumentation, data downlink for real-time experiment monitoring, and an experienced flight research team

### Applications

- ▶ Civilian, fly-by-wire transport, and high-performance military aircraft

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## Air Launch from a Towed Glider

This research effort is exploring the concept of launching a rocket from a glider that is towed by an aircraft. The idea is to build a relatively inexpensive remotely piloted glider that could be towed to altitude by a business jet or transport aircraft. The glider would carry a booster rocket capable of launching payloads into orbit. After rocket launch, the glider would return to its base to be used again. This approach could significantly reduce the cost and improve the efficiency of sending satellites into orbit.

**Work to date:** Three separate technical feasibility studies completed by independent contractors indicate the technique could achieve significant performance gains over vertical ground launches of similar-sized rockets and current approaches to air-launching rocket boosters. A technology transfer plan has been developed that involves a three-way partnership between NASA, the Department of Defense, and an industry collaborator. Over a 3-year span, NASA gains access to a towed-glider platform for conducting research, and the industry partner gains entry into the small satellite launch market at a reduced cost. In support of this plan, Aerospace Corporation has been contracted to conduct an economic and market analysis study relative to a towed glider launch.

**Looking ahead:** Future plans involve continuing work to assemble a one-third scale glider model with a 27-foot wingspan to obtain operational experience while under towed flight as well as performance and handling qualities data. Plans are underway to flight demonstrate a small rocket launch from the subscale model.

**Partner:** Whittinghill Aerospace

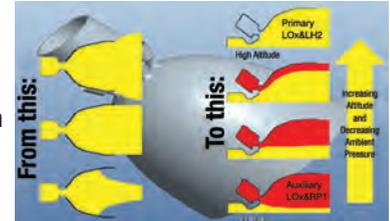
### Benefits

- ▶ **More economical:** Use of a simple remotely piloted glider, without the complex propulsion and life support systems required for a crewed, powered aircraft, provides an inexpensive air-launch platform.
- ▶ **Increased payload:** A towed glider can carry more than twice the payload compared to a modified, same size, direct-carry “conventional” aircraft.
- ▶ **Safer:** Remotely piloted gliders that are towed 1,000+ feet behind the tow plane offer a substantial safety perimeter from the high-energy systems inherent in rocket boosters (as compared to current crewed, direct-carry air-launch methodologies).

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## A Bi- or Tri-Propellant Rocket with Thrust-Augmented or Altitude-Compensating Nozzle

This research project is working to improve the efficiency of rocket-powered vehicles through altitude compensation techniques. The concept achieves altitude



compensation by burning multiple combustion chambers through a single nozzle, which allows for greater throttling capabilities without sacrificing efficiency. The technique enables continuous altitude compensation through a bell nozzle where multiple combustion chambers fire into a single combined nozzle. The proposed rocket engine would burn two or more propellants to produce variable levels of thrust and maintain an ideal expansion ratio throughout its flight envelope. Burning multiple fuels allows for higher thrust fuels to be used where desired (e.g., liftoff, low altitudes) and high-efficiency fuels to be used at altitudes where they are most beneficial (e.g., tri-propellant operations). The same fuel can be used in all chambers (i.e., bi-propellant operation). The concept provides better thrust and is more efficient than current designs, which operate with single-point design nozzles. This research has the potential to produce an engine and nozzle design that could increase payload to orbit by as much as 10 percent or more.

**Work to date:** The research group developed a one-dimensional engine simulation coupled with Program to Optimize Simulated Trajectories II (POST2) analysis quantifying the benefits of altitude compensation utilizing this multi-chambered design.

**Looking ahead:** Armstrong has contracted with Utah State University to build the nozzle for future testing, to be completed in 2016. Commercial partners have also expressed interest in this unique approach.

### Benefits

- ▶ **Improved engine efficiency:** Operating conditions for the engine can be adjusted throughout launch as altitude changes to achieve optimal performance.
- ▶ **Lower costs:** Improved efficiency decreases fuel usage, in turn decreasing the launch costs.
- ▶ **Increased payloads:** Improved efficiency could enable increases of payloads by 10 percent or more.

### Applications

- ▶ Orbital launch vehicles
- ▶ Suborbital launch and transport vehicles
- ▶ Rocket-based combined cycle systems
- ▶ Variable speed supersonic wind tunnels

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## Altitude Compensating Nozzle (ACN)

The ACN project is focused on advancing the technology readiness level (TRL) of the dual-bell rocket nozzle by demonstrating this technology in a relevant flight environment during captive-carried flight under a NASA Armstrong F-15 airplane. The dual-bell nozzle has been predicted to outperform the conventional-bell nozzle, both analytically and through static test data. The ACN project has two primary objectives: (1) to quantify the performance benefit of the dual-bell nozzle and (2) to demonstrate explicit control of the altitude-compensating capability.

**Work to date:** The project has completed several milestones, including: (1) completed a conceptual design of a dual-bell rocket nozzle system for use on an F-15 airplane, (2) developed a concept for actively controlling the dual-bell nozzle operating mode on a typical launch vehicle, and (3) completed a preliminary prediction of the F-15 external flow field with the dual-bell nozzle operating.

**Looking ahead:** A three-phase flight plan has been developed, ultimately leading to reacting-flow operation of a dual-bell nozzle during captive-carried flight on an F-15 airplane.

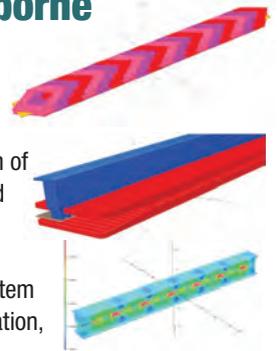
**NASA partner contributions:** Marshall Space Flight Center is developing all nozzle test articles, including nozzles used in flight. Armstrong is developing all systems required for operating the nozzle during flight, including system integration with the F-15 airplane. The Kennedy Space Center Launch Services Program is providing support for this project.

### Benefits

- ▶ **Performance:** The dual-bell nozzle is predicted to provide an increase in the payload mass to orbit for a launch vehicle.
- ▶ **Safety:** Active mode control is predicted to mitigate side loads on the engine.

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## Coreless Linear Induction Motor (LIM) for Spaceborne Electromagnetic Mass Driver Applications



This research effort focuses on the design of a coreless LIM that will enable high-speed electromagnetic (EM) spacefaring mass driver propulsion. This technology has the potential to revolutionize conventional system design for interplanetary space transportation, which focuses on chemical propulsion systems. While all-chemical propulsion systems can outperform many other space propulsion systems in the near term, they require high-maintenance purification and refining processes. In contrast, the mass driver system with a coreless LIM offers an alternative that achieves a high level of performance and is low maintenance, is self-sustaining, and has a low life-cycle cost.

**Work to date:** A coreless LIM was designed using three-dimensional motional EM finite element analysis (FEA) modeling software. Design features include a flat diamond coil design for low side leakage. A high-speed injector double-sided LIM (DSLIM) was also modeled to facilitate understanding of the magnetic field structure at the interface of the injector and the input of the coreless LIM.

**Looking ahead:** Preliminary designs have been completed. The successful creation of a coreless LIM design will provide insight into the critical aspects requiring additional testing. In addition, this design work will inform key specifications for future coreless LIM applications, including size, power requirements, and structures. These design and test data will feed into a proposal for the SpaceX Hyperloop Vehicle Design Competition being prepared as part of the NASA Aeronautics Research Mission Directorate's Convergent Aeronautics Solutions project.

**Partners:** Naval Air Weapons Station (NAWS) China Lake and NASA's Glenn Research Center

### Benefits

- ▶ **Low cost:** Offers the potential of self-sustaining, low life-cycle cost interplanetary space transportation
- ▶ **Low maintenance:** Reduces the need for manufacturing, refining, and processing chemical systems in space
- ▶ **Innovative:** Enables an alternative solution to chemical propulsion systems for asteroid redirect missions

### Applications

- ▶ Hyperloop high-speed, low-noise commercial passenger ground transportation
- ▶ Asteroid redirect
- ▶ Lunar launch

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## F-15 Aero Tow Vehicle Development

This research project demonstrated that the F-15 aircraft is an excellent candidate for use as a tow plane at medium and fast tow speeds. The aero tow concept calls for a powered aircraft to tow another aircraft or glider into the air with a long, robust towline. At a predetermined altitude, the towed aircraft separates from the tow plane and performs its mission. The concept dramatically reduces costs as well as risks to personnel associated with launching rockets and sending satellites into space. The results of this project paved the way for the start of ground testing and flight demonstrations using a representative tow train with a surrogate drag device. NASA's Aeronautics Research Mission Directorate has expressed a specific need for this kind of capability for the Towed X-Plane project.

**Work to date:** The Armstrong team evaluated available towline attach points on the F-15 aircraft as well as load path strength, tow performance, attachment hardware, towline design, and interaction with exhaust plumes. The team has:

- ▶ Produced the attachment hardware design and stress analysis
- ▶ Conducted a design review of the tow train hardware
- ▶ Procured tow rope (steel and Vectran®), tow rope fittings, explosive bolts, and firing circuit components for ground and flight tests of the tow train
- ▶ Fabricated towline attachment fittings and load-tested cable end fittings

**Looking ahead:** Future plans include:

- ▶ Additional component load testing
- ▶ Integrating system components into F-15 aircraft
- ▶ Assembly and ground load testing of a 1,000-foot tow train
- ▶ Ground-release testing
- ▶ Flight testing using a parachute to replicate drag load with release of tow train in a drop zone

### Benefits

This research project reestablishes NASA's capability to tow test aircraft to altitude for:

- ▶ Captive flight tests
- ▶ Release to independent-powered or gliding-flight tests

### Applications

- ▶ Towed X-Aircraft

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## Advanced Control Method for Hypersonic Vehicles

This research effort aims to develop software control algorithms that will correct for roll reversal before it happens. Roll reversal occurs when an aircraft is steered in one direction but rolls the opposite way due to aerodynamic conditions. The problem often compounds as a pilot attempts to correct for the motion by oversteering in the original direction, leading to uncontrollable roll. Unexpected yaw and subsequent roll reversal has caused the loss of high-speed, lifting body-like vehicles. The team has employed novel predictive software within adaptive controller technology to detect conditions likely to result in aircraft roll reversal and then automate compensating maneuvers to avoid catastrophic loss.

**Work to date:** The University of Michigan's retrospective cost model refinement (RCMR) control algorithm has been integrated into a flight simulator and tested with prerecorded, open source parameter data, which replicates the roll-reversal anomaly. A modified algorithm was provided to the Armstrong team, which integrated the RCMR algorithm into a six-degree-of-freedom simulation environment to test its ability to recover from unstable situations without having *a priori* knowledge of the instability. The control algorithm increased survivability by 12 percent.

**Looking ahead:** Potential next steps include evaluating testing techniques to improve control law design for other algorithms and asking the University of Michigan to further tune the algorithm for improved results.

**Partners:** University of Michigan, other government research agencies, and aerospace firms

### Benefits

- ▶ **Operates independently:** Unlike other standard control systems, this method allows for compensation and control of aircraft roll reversal without *a priori* knowledge of the dynamics.
- ▶ **Improves safety:** This technology is expected to prevent crashes that occur due to uncontrolled roll.
- ▶ **Increases envelope:** RCMR would enable planes to travel safely over a larger envelope.

### Applications

- ▶ Hypersonic jets
- ▶ Lifting body-type space vehicles and reentry vehicles

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## High-Altitude Atmospheric Reconstruction

Armstrong researchers are participating in an ongoing effort to model high-altitude atmospheric environments in order to improve flight planning designs for high-speed vehicles. The primary atmospheric conditions of interest include air density, temperatures, winds, pressure, and expected uncertainties. These conditions must be characterized and understood in order to ensure the safety of high-speed aircraft and the people inside them. Reliable upper-atmospheric models contribute to better flight parameter choices for speed and altitude, and they enable faster, safer, and higher flights for ultra-high-speed vehicles.

**Work to date:** Armstrong provided an atmospheric reconstruction of the flight regime or best-estimate atmosphere for NASA's Hyper-X scramjet demonstrator, DARPA's Hypersonic Technology Vehicle 2, the U.S. Army's Advanced Hypersonic Weapon launched glider, and the U.S. Air Force's X-51 hypersonic scramjet. Armstrong is assisting Michigan Aerospace Corporation in developing a high-altitude lidar capable of sampling the upper atmosphere to improve the quality of the observations and to reduce uncertainties in the atmospheric measurements.

**Looking ahead:** The team is currently working on several projects: (1) detecting and mitigating atmospheric turbulence to

improve aviation travel, (2) modeling the effects of radiation on pilots, (3) investigating how cosmic energies are affecting the atmosphere, and (4) developing sensors for *in situ* atmospheric measurements and transmitting these data to appropriate users.

**Partners:** U.S. Air Force, the Defense Advanced Research Projects Agency (DARPA), and U.S. Army

### Benefits

- ▶ **Increased efficiency:** Contributes to understanding of key parameters for ultra-high altitudes
- ▶ **Improved safety:** Helps designers and planners reduce risks associated with atmospheric reentry and radiation exposure

### Applications

- ▶ High-speed aircraft test flight research
- ▶ Weather prediction and climate change research
- ▶ Global Positioning System (GPS) performance research

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Armstrong's innovative Cockpit Interactive Sonic Boom Display Avionics (CISBooMDA) software system displays the location and intensity of shock waves caused by supersonic aircraft.

# Autonomous Systems



Armstrong is contributing to NASA's Roadmap for Robotics, Tele-Robotics, and Autonomous Systems through research in a wide range of areas, such as artificial intelligence, advanced flight control laws, new testing methods, collision avoidance technologies, and much more.

Armstrong's pioneering research into lifesaving collision avoidance technologies has the potential to be applied beyond aviation and could be adapted for use in any vehicle that has to avoid a collision threat, including aerospace satellites, automobiles, marine vehicles, and more.

NASA G-III/  
C-20A Research  
Testbed with  
a conceptual  
implementation  
of an AI Flight  
Advisor.



## Artificial Intelligence Flight Advisor

Recent advances in artificial intelligence (AI) promise the ability to manage unforeseen contingencies in manned and unmanned vehicles. Such systems may be able to provide real-time expert advice to pilots in situations where they have not had training, have forgotten their training, or training does not exist. This research is laying the groundwork to determine whether recent advances in AI can be leveraged to provide contingency management to autonomous systems.

**Work to date:** The flight advisor system is based on the IBM Watson™ cognitive computing system, which is already being used to help physicians develop treatments for cancer patients. In an unforeseen contingency management application, the cognitive system draws on aircraft manuals, close-call reports, accident reports, airport information, and other sources of relevant data to advise a pilot how best to execute mitigating actions with a high probability of improving the situation. Working with IBM, the Armstrong team developed an outline of system requirements for unforeseen contingency management applications. The team identified data sources to form the body of information, interviewed multiple potential end-users to understand the useful role the system would play, and developed multiple use cases in which the system can be applied.

**Looking ahead:** Longer range applications of this technology will be to autonomous systems. Cognitive computing systems will form a basis upon which autonomous systems will decide on a correct course of action in unforeseen contingencies. Multiple supporting technologies are required before such an application will be fully feasible.

**Partner:** IBM Corporation

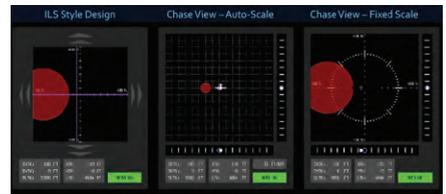
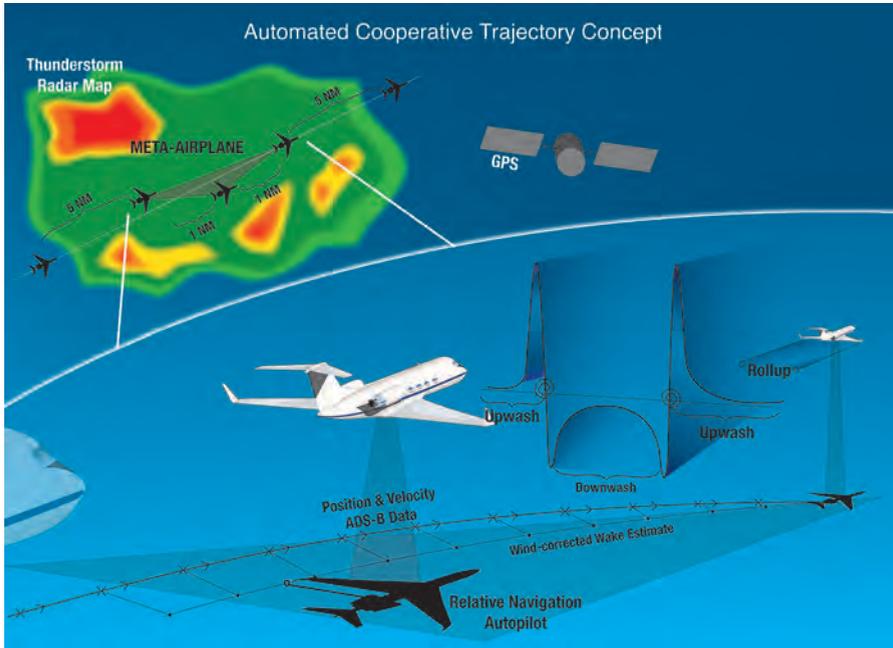
### Benefits

- ▶ **Improves safety:** Provides real-time decision-making support for pilots in emergency situations
- ▶ **Expands knowledge base:** Provides a building block upon which autonomous systems can be developed

### Applications

- ▶ Manned and unmanned aircraft systems
- ▶ Air traffic management
- ▶ Manned spacecraft systems
- ▶ Autonomous systems

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## Automated Cooperative Trajectories (ACT)

The ACT project is advancing Automatic Dependent Surveillance-Broadcast (ADS-B)-enabled autopilot capabilities to improve airspace throughput and vehicle efficiency. The concept leverages (1) meta-aircraft operations for safe, reduced separation and decreased air traffic control workload and (2) formation wake surfing for fuel savings. The concept proposes automated, distributed, multi-vehicle control using distributed knowledge of aircraft and wake locations by integrating ADS-B messages with autopilot systems.

An aircraft's wake contains stored energy in the form of twin wingtip vortices that persist in strength for several miles behind the generating airplane. An aircraft flying on the outer edges of one of these vortices can extract energy from the upwardly moving air, increasing lift. By re-trimming to maintain level flight, the aircraft is able to maintain airspeed with a lower throttle setting, thereby reducing fuel burn by as much as 15 percent. The ultimate goal of the ACT project is to demonstrate via formation flight experiments the feasibility of automatically coordinated flight paths and significant fuel savings and then to transition those benefits to commercial cargo and passenger operations.

**Work to date:** Armstrong is managing the ACT project to evaluate ADS-B data link technology to enable automated trajectory coordination, self-separation, and wake surfing. Milestones achieved to date include:

- ▶ ADS-B-enabled autopilot hardware-in-the-loop simulation
- ▶ Throttle and wake display piloted simulation evaluation
- ▶ G-III wake encounter structural analysis
- ▶ Flight test planning for 2016 research campaign

**Looking ahead:** In 2016, the project will gather data using two G-III test aircraft to better understand the suitability of ADS-B as a data link for meta-aircraft procedures. An ADS-B data link will be integrated with an aircraft's autopilot systems, and coordinated flight operations will be conducted. Additional wake surfing data will be gathered (contingent upon system performance and available resources) on passenger ride quality and performance benefits as well as to evaluate algorithms for wake prediction and estimation. This will be the first use of ADS-B as a data link for automated coordinated flight between two aircraft and the first demonstration of sustained wake surfing with a civilian business jet/transport airframe. For the first time, quantitative passenger ride quality data will be gathered during wake surfing operations.

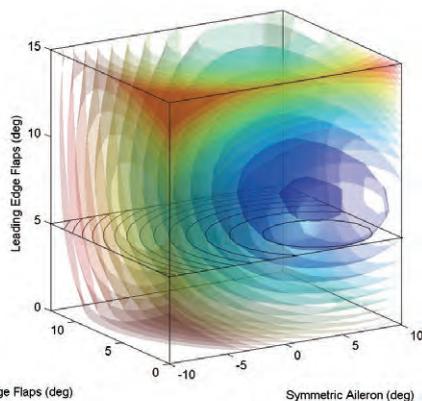
### Benefits

- ▶ **Increased throughput:** Reduces separation minimums between aircraft operating as a cooperative group, allowing them to safely occupy a smaller airspace footprint than under traditional flight rules
- ▶ **Increased efficiency:** Reduces fuel burn by as much as 15 percent
- ▶ **Improved ATC workload:** Allows controllers to monitor and direct several aircraft at a time—as though they were a single entity—via active communication and coordination of flight paths

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## Peak-Seeking Control for Trim Optimization

Innovators have developed a peak-seeking algorithm that can reduce drag and improve performance and fuel efficiency by optimizing aircraft trim in real time. The algorithm determines a unique trim position for an



aircraft by employing a time-varying Kalman filter to estimate the gradient of a performance function using in-flight measurements. Existing trim control systems preprogram position data into an aircraft's computer, based on knowledge gained from test flights and wind tunnel experiments. In contrast, this innovation determines in real time the most fuel-efficient trim surface position by taking into account actual flight conditions and an aircraft's physical condition. This customized approach results in maximum fuel efficiency for each particular aircraft.

**Work to date:** The Armstrong team has enhanced and validated the algorithm with a series of modified F/A-18A experiments and further refined it for implementation in the Super Hornet (F/A-18 E/F) military aircraft.

**Looking ahead:** Future flight research efforts will work to further mature the technology and transition it to other aircraft. In support of the U.S. Navy's Great Green Fleet Initiative, Armstrong is helping to plan a flight test campaign for the F/A-18 E/F military aircraft, and Boeing is developing software for implementation in the aircraft's flight control computers. A separate effort by Lockheed Martin is seeking to implement the algorithm in high-fidelity simulation software for the F-35C aircraft. The research team is also beginning a feasibility study for the U.S. Air Force focusing on the C-17 aircraft.

### Benefits

- ▶ **Efficient:** Reduces fuel consumption and extends the operating range of aircraft
- ▶ **Fast:** Determines and maintains the optimum trim surface position solution within 5 minutes, despite disturbances and other noise
- ▶ **Customized:** Determines unique trim position using in-flight measurements
- ▶ **Variable:** Works on multiple effectors in multiple axes simultaneously

### Applications

- ▶ Military jets and commercial airlines



## Expandable Variable Autonomy Architecture (EVAA)

Effective multi-level autonomous piloting systems require integration with safety-critical functions. Armstrong researchers are collaborating to develop a hierarchical autonomous system framework that will depend on deterministic systems with higher authority to protect against catastrophic piloting faults, faulty mission planning or execution, and inappropriate flight activities. They also will be designed to allow a lower-level certification for machine learning subsystems. The EVAA provides the framework for analytical systems that can learn, predict, and adapt to both routine and emergency situations.

**Work to date:** The hierarchical decision chain and framework, hardware, and embedded processing related to ground collision avoidance and dynamic rerouting in real time is in place for a subscale platform. Flight tests on a quad-copter demonstrated successful decision making when facing multiple imminent hazards while executing a mission plan. Findings have been presented to the Federal Aviation Administration (FAA), and planning to expand on the concept has begun. Plans are also being developed to communicate this approach as an industry best practice for creating a verifiable autonomous aircraft.

**Looking ahead:** The team is developing a full set of safety-critical functions for all aircraft and implementing this architecture for extensive flight evaluation on a small unmanned aerial system (UAS). Flight tests will begin in spring 2016 with demonstrations to follow in the fall.

**Partners:** The FAA UAS Integration Office and Small Airplane Office, the U.S. Air Force Research Laboratory, NASA's Langley Research Center, and the University of Tulsa

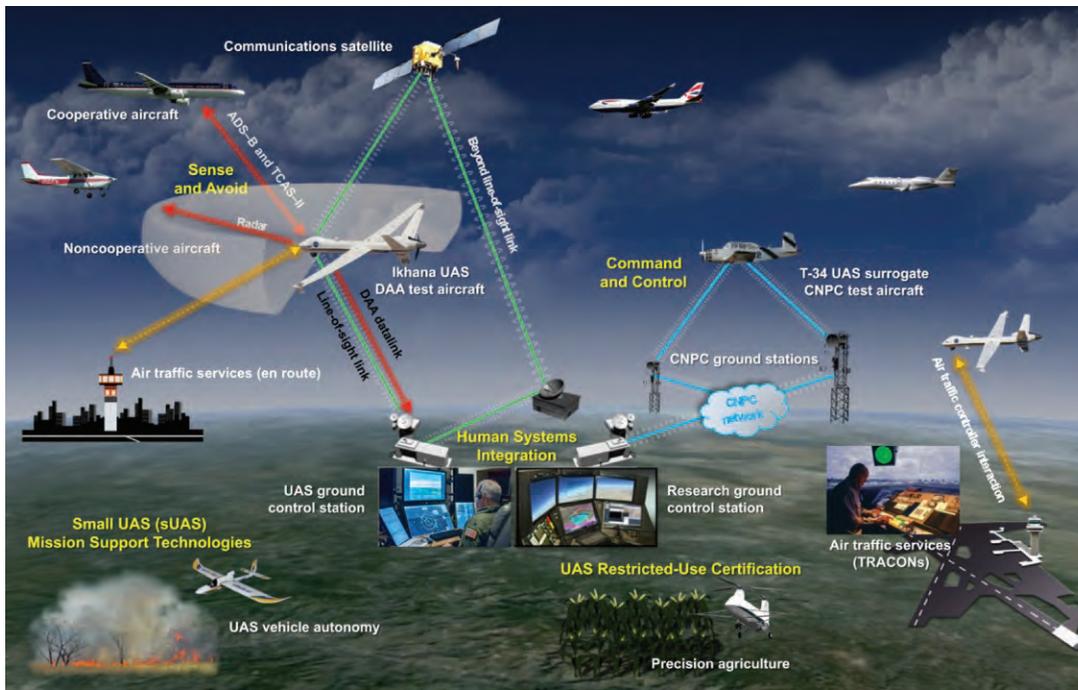
### Benefits

- ▶ **Increases safety:** Integration of safety-critical functions improves outcomes in emergency situations.
- ▶ **Certifiable:** Removal of safety-critical functions from the autonomous control enables adaptable processes to be certified to a lower level.

### Applications

- ▶ Unmanned aerial vehicles (UAVs)
- ▶ Unmanned submersibles
- ▶ Autonomous rail transport
- ▶ Deep space exploration
- ▶ Driverless vehicles

# Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) Project



## LEGEND

- Sense and Avoid (SAA/DAA Technologies)
- Air Traffic Services
- Control and Nonpayload Communications (CNPC) Network
- Legacy Command and Control (C2) Links

## ACRONYMS

- ADS-B: Automatic Dependent Surveillance-Broadcast
- DAA: Detect and Avoid
- TCAS-II: Traffic Alert and Collision Avoidance System
- TRACON: Terminal Radar Approach Control Facility

Armstrong is leading this multi-Center research project that is testing a system that would make it possible for unmanned aircraft to fly routine operations in U.S. airspace. Unmanned aircraft offer new ways of increasing efficiency, reducing costs, and enhancing safety. As new uses for these vehicles are considered, project partners are working to overcome safety-related and technical barriers associated with their use, such as a lack of detect-and-avoid technologies and robust communications systems.

The project is providing critical data to such key stakeholders as the Federal Aviation Administration (FAA) and the Radio Technical Commission for Aeronautics (RTCA) by conducting system-level tests in a relevant test environment to address safety and operational challenges. The project falls under the Integrated Systems Research Program Office in NASA's Aeronautics Research Mission Directorate (ARMD) and is addressing four technical challenge areas:

- ▶ Assuring safe separation of unmanned aircraft from manned aircraft in the NAS
- ▶ Establishing safety-critical command-and-control systems and radio frequencies to enable UAS safe operation
- ▶ Developing human systems integration guidelines for ground-control stations
- ▶ Integrating tests and evaluations that determine the viability of emerging UAS technologies

**Work to date:** The first comprehensive flight test series of all technologies developed thus far occurred at Armstrong in June 2015, and included multiple flight test configurations. The tests employed the Ikhana aircraft with an Engineering Development

Model Due Regard Radar, Automatic Dependent Surveillance-Broadcast (ADS-B), and Traffic Alert and Collision Avoidance System (TCAS II) systems to detect and resolve conflicts with proximate air traffic. Selected tests engaged the core air traffic infrastructure and supporting software components through a live and virtual environment to demonstrate how a UAS interacts with air traffic controllers and other air traffic.

**Looking ahead:** Plans for 2016 include more Ikhana flight tests that evaluate key algorithms and introduce two "intruder" aircraft. Additionally, the flight tests will include more complex geometries that stress the boundaries of well clear and examine TCAS II/DAA interoperability.



**Partners:** General Atomics Aeronautical Systems; Honeywell International, Inc., RTCA; and NASA's Ames Research Center, Langley Research Center, and Glenn Research Center

## Benefits

- ▶ This detect-and-avoid research will provide information to the FAA as it develops policies and procedures to integrate UAS into the NAS.

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## Improved Ground Collision Avoidance System (iGCAS)



Armstrong's iGCAS leverages leading-edge fighter safety technology, adapting it to civil aviation use as an advanced warning system. It offers higher fidelity terrain mapping, enhanced vehicle performance modeling, multi-directional avoidance techniques, more efficient data-handling methods, and user-friendly warning systems. The algorithms in Armstrong's technology also have been incorporated into an app for tablet or other handheld/mobile devices that can be used by pilots in the cockpit, enabling significantly safer general aviation. This will give pilots access to this lifesaving safety tool regardless of what type of aircraft they are flying. The system also can be incorporated into electronic flight bags (EFBs) and/or aircraft avionics systems.

The payoff from implementing the system, designed to operate with minimal modifications on a variety of aircraft (e.g., military jets, UAVs, general aviation) could be billions of dollars and hundreds of lives and aircraft saved. Furthermore, the technology has the potential to be applied beyond aviation and could be adapted for use in any vehicle that has to avoid a collision threat, including aerospace satellites, automobiles, scientific research vehicles, and marine charting systems.

**Work to date:** This improved approach to ground collision avoidance has been demonstrated on both small UAVs and a Cirrus SR22 while running the technology on a mobile device. These tests were performed to prove the feasibility of the app-based implementation. The testing also characterized the flight dynamics of the avoidance maneuvers for each platform, evaluated collision-avoidance protection, and analyzed nuisance potential (i.e., the tendency to issue false warnings when the pilot does not consider ground impact to be imminent). An extensive simulation evaluation of the system was conducted at AirVenture 2016, drawing on 25 pilots with a wide variety of backgrounds. All pilots said the system is easy to use and that they would like to see it made available.

**Looking ahead:** Future versions of the technology may employ a phone's wireless capabilities to connect it to an airplane's autopilot system. It might even one day exploit a phone's built-in location sensors to make a wireless or USB connection completely unnecessary. The Armstrong team is also working with avionics manufacturers to integrate iGCAS software into their systems.



Armstrong's technology has been incorporated into an app for tablet or other handheld/mobile devices.

### Benefits

- ▶ **High fidelity terrain mapping:** Armstrong's patented approach to digital terrain encoding enables the use of terrain maps with fidelity that is 2 to 3 orders of magnitude better than existing systems.
- ▶ **Flexible platforms:** This tool can be used with a variety of aircraft, including general aviation, helicopters, UAVs, and fighters such as F-16s, with the ability to incorporate the specific maneuvering performance for each aircraft type into the platform.
- ▶ **Nuisance-free warnings:** The iGCAS technology ensures that alarms will be triggered only in the event of an impending collision, reducing the risk of false alarms that may cause pilots to ignore the safety system.
- ▶ **Multi-directional maneuvers:** Unlike existing systems that recommend only vertical climbs, this innovation can recommend multi-directional turns, making it more appropriate for general aviation aircraft and UAVs.
- ▶ **Proven technology:** A follow-on to a system currently flown in F-16 operational test aircraft will be integrated into the next generation for the U.S. Air Force's F-16 fleet. It also has been tested on UAVs and a Cirrus SR22.

### Applications

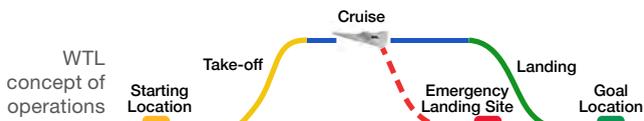
- ▶ General aviation
- ▶ Military aircraft
- ▶ UAVs/Drones
- ▶ Helicopters
- ▶ Digital autopilots

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## Determining Optimal Landing Locations in Emergency Situations

This research project is working to develop an automated navigation system that can land manned and unmanned vehicles in emergency situations, dubbed “Where to Land” (WTL). Building on an algorithm developed at the University of California at Berkeley, the system aims to mimic an expert pilot’s decision making by leveraging pre-computed trajectories using fault locations, maps, and reachable sets as well as real-time weather and vehicle occupancy data updates. The ultimate goal is to develop a system that can determine the optimal landing location that will minimize loss of life, property, and assets as well as the optimal trajectory required to reach this location.



**Work to date:** Researchers have performed hardware-in-the-loop simulations and developed flight software for embedded hardware platforms. The technology provides a reachable landing site “footprint” that is applied over a map, combining population density and terrain information. The system places this footprint over a “cost map” to determine the landing site that best minimizes loss of life and property damage and then generates a trajectory to that site.

**Looking ahead:** Flight tests with the algorithm implemented on an unmanned aerial vehicle (UAV) are planned for 2016. Researchers will examine how the system performs a fully autonomous emergency landing. Further work developing the third-generation WTL will incorporate the capability to handle more types of emergencies, expanded to multiple platforms and a dynamic cost map generated from real-time sensor data.

### Benefits

- ▶ **Improves safety:** Allows for off-field landings
- ▶ **Flexible:** Can be used as a support system for pilots and a fully automated system for UAVs
- ▶ **Fast:** Uses real-time updates

### Applications

- ▶ General aviation
- ▶ Commercial cargo and passenger vehicles
- ▶ UAVs

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## Stereo Vision for Collision Avoidance

This research project is evaluating the utility of stereo vision as an active sensor to support autonomous operations in a flight environment. Stereo vision utilizes two cameras with the same field of view to generate ranging data from a binocular image. Research findings indicate that the technology can detect hazards in rural and wilderness flight environments. Data from these research tests have enabled formulation of stereo vision requirements for Armstrong’s planned autonomous flight demonstrations. The research project has made a major contribution toward developing a completely autonomous UAV.

**Work to date:** Center Innovation Fund resources enabled the Armstrong researchers to: (1) construct a stereo vision system; (2) assemble and develop software tools for processing and analyzing stereo vision data; (3) functionally verify that the stereo vision system works properly; (4) conduct static testing of the stereo vision system to characterize its ability to range objects and terrain; and (5) determine design specifications for adapting a stereo vision system to a Traveler Project autonomous aircraft.

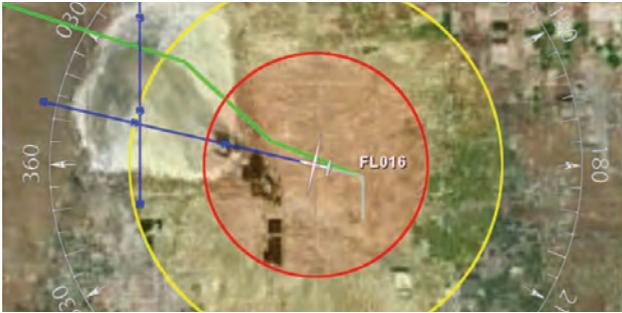
**Looking ahead:** The near-term goal is to extract information from point clouds that will enable just-received stereo input data to be compared to historic map data. A set subtraction of this information would provide information on obstacles and features in the stereo data that are not in the map data (e.g., obstacles, other vehicles, and humans in the system path). The goal is that, within a year, the technology will be mature enough to plug into EVAA and install on a vehicle to detect people, aircraft, and other obstacles.

**Partners:** NASA’s Jet Propulsion Laboratory and the University of Tulsa

### Applications

- ▶ Safe autonomous flight techniques
- ▶ Automatic collision avoidance technologies

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## Automatic Dependent Surveillance Broadcast (ADS-B) System for Traffic Situational Awareness

Armstrong innovators have developed an ADS-B system for unmanned aerial vehicles (UAVs). The system relies on highly accurate GPS signals to provide increased situational awareness and a self-separation assurance system to avoid accidents. This state-of-the-art technology automatically broadcasts a UAV's exact position 120 miles in every direction every 1 second, as opposed to legacy radar-based transponder systems that "sweep" for position every 12 seconds. Accurate to within 5.7 feet, this technology integrates commercial ADS-B hardware, radio data-link communications, software algorithms for real-time conflict detecting and alerting, and a display that employs a geobrowser for three-dimensional graphical representations. Some manned aircraft already have adopted ADS-B technology. The Armstrong team is the first to apply the system architecture to UAVs. Vigilant Aerospace Systems intends to commercialize this technology as part of its new FlightHorizon product suite and equip manned and unmanned aircraft with the hardware and software that provides synthetic cockpit views and detect-and-avoid commands.

**Work to date:** The team has developed, demonstrated, and validated an ADS-B system and integrated it into an unmanned aircraft system.

**Looking ahead:** Armstrong innovators have developed the methodology and metrics to verify and validate sense-and-avoid (SAA) alerting capability in a simulation and flight environment. The team will refine the SAA algorithm's conflict detection, trajectory estimation, and prediction capabilities using a miniaturized radar system for collision avoidance.

### Benefits

- ▶ **Improves safety:** Enhances sense-and-avoid capabilities to maintain self-separation for UAVs
- ▶ **Highly accurate and fast:** Provides location data that are accurate to within 5.7 feet every 1 second

### Applications

- ▶ Military missions and training
- ▶ Border surveillance
- ▶ Law enforcement
- ▶ Scientific research

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## Development and Flight Test of Resource Allocation for Multi-Agent Planning (ReMAP) System for Unmanned Vehicles

ReMAP is a multi-agent guidance and communications system designed to enable the safe operation and integration of multiple unmanned aircraft into the National Airspace System (NAS). ReMAP significantly reduces operator workload by providing a level of aircraft autonomy that allows operators to focus on mission management and data collection.

Initial flight testing in November and December 2015 with two aircraft (Mario and Luigi) demonstrated system feasibility and identified enhancements, some of which have been implemented and tested as part of the Phase 1 Small Business Innovation Research (SBIR) work.

**Looking ahead:** If selected for Phase 2 SBIR funding, Area-I, Inc., plans to fly up to 5 unmanned aerial vehicles (UAVs) and a general aviation aircraft to test ReMAP's ground- and collision-avoidance algorithms. Additionally, the team will test mission management of a larger number of vehicles. Area-I will also be working with a UAV manufacturer to commercialize this technology.

**Partner:** Area-I developed and flight tested the ReMAP system under the NASA SBIR program.

### Benefits

- ▶ **Effective:** Provides real-time mission-driven guidance capabilities to unmanned air vehicles
- ▶ **Flexible:** Features a system architecture that is platform and autopilot agnostic so can be used by a wide array of aircraft
- ▶ **Innovative:** Allows coordination of multiple aircraft due to use of a multi-agent planning and control algorithm
- ▶ **Improves safety:** Provides autonomous avoidance maneuvers and/or operator warnings
- ▶ **High performance:** Offers a mission planning toolbox that provides situational awareness and mission management either as a stand-alone system or integrated with existing planning tools

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# Avionics and Instrumentation Technologies



Armstrong innovators design and integrate data acquisition systems for research, support, and one-of-a-kind platforms. In many cases, these systems leverage commercial off-the-shelf parts to keep costs low and ease integration with legacy systems. At the same time, these cutting-edge data systems are finding innovative ways not only to collect data efficiently but also to flexibly configure collection parameters.



## Portable Data Acquisition System (PDAT)

Armstrong researchers have developed a PDAT that can be easily transported to and set up at remote locations to display and archive data in real time. The PDAT was developed to collect data from strain gauges and fiber optic sensors installed on a revolutionary wing flap while it was being constructed by NASA partner FlexSys Inc., as part of the Adaptive Compliant Trailing Edge (ACTE) project. The PDAT enabled the Armstrong team to monitor and analyze data during the construction process and provide vital feedback to designers onsite at FlexSys instead of having to wait until construction was completed and shipped to Armstrong's facility.

**Work to date:** This unique and flexible system has 64 channels for analog data, 32 channels for thermocouples, and the capability to collect 6,000 parameters of fiber optic Ethernet data. In 2015, PDAT was used to collect 12 hours of flight data during the first phase of testing on the Scalable Convergent Electric Propulsion Technology and Operations Research (SCEPTOR) project. The system enabled the SCEPTOR instrumentation team to rapidly develop a small data acquisition system in less than two months and meet all sensor data requirements, which included the collection of control surface, pilot yoke loads, aircraft vibration, and fuel flow data.

**Looking ahead:** The PDAT has been an integral part of two Armstrong flight projects and is versatile enough to become a successful component of many current and future NASA projects. The PDAT will be used again to evaluate more data acquisition cards required to support this year's ACTE II project.

### Benefits

- ▶ **Convenient:** Enables real-time analysis of data collected at remote locations
- ▶ **Portable:** Is easily reconfigurable and fits into a single small case for quick transport
- ▶ **Flexible:** Can be quickly reprogrammed to support various tests, and can display and archive data from both physical and virtual data streams

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## Upper-Atmospheric Space and Earth Weather Experiment (USEWX)

The USEWX project is monitoring, recording, and distributing atmospheric measurements of the radiation environment by installing a variety of dosimeters and other instrumentation on Armstrong aircraft. The goal is to routinely provide real-time in-flight radiation measurements to modelers and the space weather community. Radiation present in the upper atmosphere is harmful to humans and sensitive electronic equipment. Aviation is trending toward flying at higher altitudes and over polar routes, where radiation events are more likely to occur and obtaining radiation data using traditional means is more difficult. Real-time, broad spectral-based radiation measurements are needed to improve radiation forecasting and space weather understanding.

**Work to date:** The USEWX team has cross-calibrated two gold-standard HAWK Tissue Equivalent Proportional Counter (TEPC) dosimeters with the Airborne Radiation Measurements for Aviation Safety (ARMAS) Lite dosimeter in ground-based particle accelerators. The ARMAS Lite dosimeter has been used to collect data on approximately 100 flights of Armstrong's DC-8 and ER-2 aircraft. The USEWX-equipped ER-2 successfully supported the Radiation and Dosimetry Experiment (RaD-X) from NASA's Langley Research Center by taking radiation measurements at various aviation altitudes along with Columbia Scientific Balloon Facility's King Air beneath the RaD-X high-altitude balloon.

**Looking ahead:** Space Environment Technologies (SET) is moving into production with the ARMAS Lite FM-5, a commercial dosimeter designed for private and corporate jet fleet owners and operators. In addition, plans are underway to:

- ▶ Install dosimeters on numerous Armstrong aircraft that fly in the upper atmosphere, including SOFIA, Gulfstream-III, C-20, F-18, and F-15 aircraft

- ▶ Continue to partner, develop, and fly instruments for the space weather community
- ▶ Integrate new dosimeters into radiosondes, rocketsondes, the Armstrong PRANDTL-D Mars Glider, and high-altitude PRANDTL Weather Glider

**Partners:** SET; Honeywell International, Inc.; Prairie View A&M University; the German Aerospace Center (DLR); and NASA's Langley Research Center, Goddard Space Flight Center, Johnson Space Center, and Marshall Space Flight Center

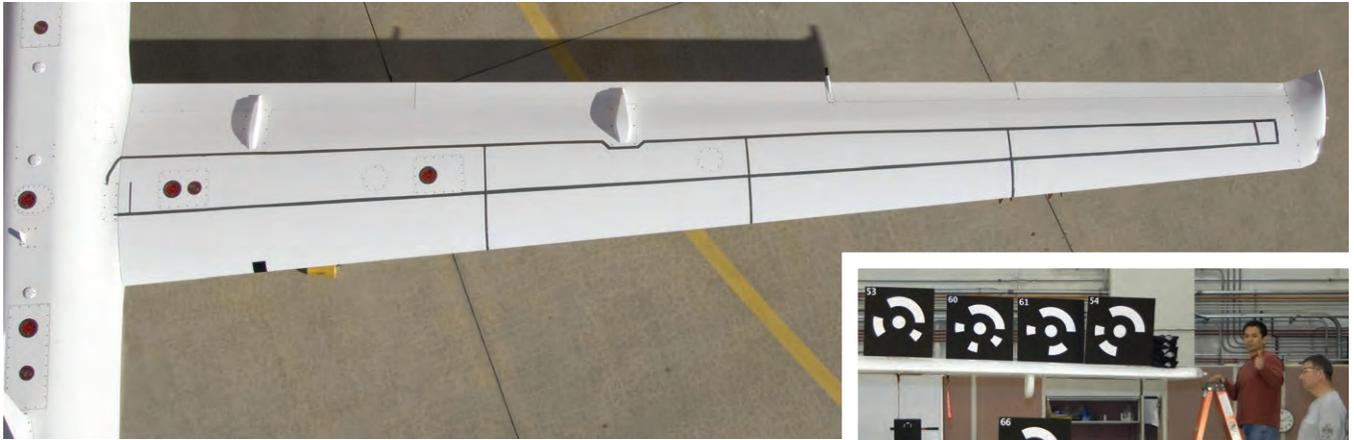
### Benefits

- ▶ **Provides access to critical data:** Provides radiation data for the purposes of guarding against human dosing, radio blackouts, Global Positioning System (GPS) navigation errors, and single event effects (SEEs) for sensitive instrumentation
- ▶ **Improves safety:** Identifies radiation limits for humans and instrumentation
- ▶ **Enables improved modeling:** Facilitates radiation forecasts for human dosing and instrumentation SEEs

### Applications

- ▶ In-flight radiation exposure monitoring to enable real-time flight plan changes to reduce risk to crew and passengers
- ▶ Radiation shielding materials for space exploration missions
- ▶ Real-time SEE monitoring

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Ground validation testing with fiber optic sensors that led to validation flights on the Ikhana aircraft.

## Fiber Optic Sensing System (FOSS)

Armstrong’s portfolio of FOSS technologies offers unparalleled options for high-resolution sensing in applications that require a unique combination of high-powered processing and lightweight, flexible, and robust sensors. FOSS is being widely used throughout NASA to support research projects as varied as investigating techniques for quieting sonic booms, monitoring cryogenic fuel levels in launch vehicles, and improving the safety of space structures. It also is being actively considered for use in a wide range of applications beyond NASA by the aerospace, engineering, automotive, medical, and energy sectors.

This state-of-the-art sensor system measures in real time a variety of critical parameters, including strain, shape deformation, temperature, liquid level, strength, and operational loads. FOSS offers unprecedented levels of spatial density, as each of the eight 40-foot hair-like optical fibers provides up to 2,000 data points with adjustable spatial resolution for a total of 16,000 sensors per system. To achieve these revolutionary capabilities, FOSS employs fiber Bragg grating (FBG) sensors and a combination of optical frequency domain reflectometry (OFDR) for high spatial resolution and wavelength division multiplexing (WDM) for high acquisition speed. FOSS’s interferometer technique can simultaneously interrogate thousands of FBG sensors in a single fiber. Each of the 16,000 OFDR sensors can be sampled up to 100 times per second, while several dozen of these sensors can be sampled at rates up to 35,000 times per second for highly dynamic applications.

**Looking ahead:** The FOSS team continues to refine the algorithms and pursue additional applications. Funding from the Transformative Test Techniques (TTT) Project within NASA’s Aeronautics Research Mission Directorate (ARMD) has enabled significant breakthroughs in size and cost reductions of the FOSS system while also enabling performance improvements. At the conclusion of 2016, it is projected that the FOSS system will be less than half of its current size and cost one-quarter of the previous generation. This work has also led to advancements in strain sensing as well as algorithms related to determining twist and displacement.

In addition, the team continues to work with groups across NASA to identify additional projects for which FOSS can provide critical data in applications where it has previously been challenging or impossible to measure key parameters. A variety of projects employing FOSS are highlighted throughout this report in critical areas, ranging from monitoring the safety of key space-related structures to facilitating development and model validation for supersonic and remotely piloted aircraft.

### Benefits

- ▶ **Highly accurate:** With up to 2,000 sensors per fiber and scanning 8 channels simultaneously, the multiplexing system can calculate 16,000 measurements at once.
- ▶ **Powerful:** Ultra-efficient algorithms and a high-speed processing platform allow for rapid processing of data, enabling real-time analysis.
- ▶ **Ultra-fast:** FOSS processes information up to 100 samples/sec (OFDR) and 35,000 samples/sec (WDM).
- ▶ **Lightweight:** The system currently weighs just 10 pounds and operates on 16 to 30 volts of DC power or 120 volts of 60-Hz AC power, with further advancements underway.
- ▶ **Non-intrusive:** With thousands of sensors on a single fiber, sensors can be placed at 1/4-inch intervals (e.g., within bolted joints and in composite structures), enabling precise, high-resolution measurements in locations where conventional strain gauges will not fit.

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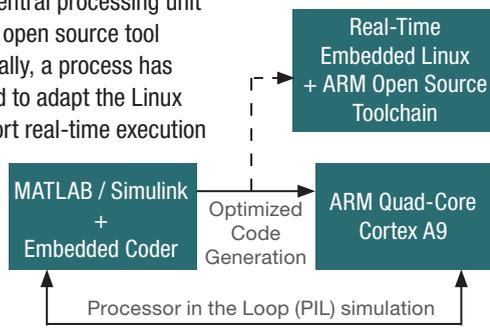
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## Autocode from Simulink to Real-Time Embedded Linux

Armstrong has a history of autocoding algorithms developed in MATLAB® Simulink® software for use in flight applications. Many flight projects benefit from Armstrong’s streamlined approach for implementing various flight control and guidance algorithms on aircraft flight hardware. The purpose of this research is to evaluate extending this capability to an embedded Linux® target with an ARM® processor. This capability will allow support of increasingly complex control algorithms without incurring the expense of the proprietary tool chain. The ARM processor core provides the advantage of high-performance multi-core processors with low power, size, and cost running on an open source embedded Linux system. Decreasing the time and costs associated with evaluating complex algorithms in the research environment will ultimately lead to faster commercialization of these algorithms.

**Work to date:** Researchers have developed a methodology for autocoding from Simulink software to an embedded Linux target with an ARM central processing unit (CPU) using an open source tool chain. Additionally, a process has been developed to adapt the Linux kernel to support real-time execution and remove unnecessary kernel functions. The team has demonstrated processor-in-the-loop (PIL) capability to tune the algorithm on the target hardware while running the model in Simulink software.

**Looking ahead:** Follow-on work will build on the effort to execute RTLinux on Raspberry Pi® firmware. This will enable more complex algorithms to be autcoded to the ARM target and comparisons to be made between real-time and non-real-time execution.



### Benefits

- ▶ **High performance:** Decreases time and costs associated with evaluating complex algorithms
- ▶ **Efficient:** Enables faster commercialization of algorithms used in flight applications

### Applications

- ▶ Research projects currently using autocode techniques with older, underperforming hardware targets
- ▶ Projects with complex algorithms requiring high-performance hardware

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## Next-Generation Post-Flight Processing Software

Aircraft flight test projects generate large amounts of instrumentation data that are used to monitor performance and safety. A single vehicle flight typically generates gigabytes of data, and one project could involve several hundred flights. Multiple active projects could be in progress at a major research center, requiring management of terabytes of data. Armstrong researchers continue to employ the OMEGA Data Environment (ODE) software tool from Smartronix® to achieve rapid access to test vehicle data. This commercial off-the-shelf (COTS) data-mining tool is allowing researchers to find data needles in haystacks—bits within terabytes—both during flight and through post-flight data analysis.

**Work to date:** Armstrong researchers have increased the ODE post-flight data management warehouse by collecting an additional 2.7 TB of bulk data through numerous active projects that support aviation safety, engine prognostic health management, new emerging testbeds for distributed electric propulsion, and subscale unmanned aircraft systems. Another analytics approach toward flight test data management uses OMEGA NEXt, a powerful real-time telemetry data processing software tool that provides engineering unit conversion, data distribution, real-time displays, and Chapter 10-compliant data recording.

**Looking ahead:** Armstrong is leading the drive toward all NASA Centers’ using ODE as a cloud-based analytics and data-mining tool under the Agency domain. Using ODE for examining near-real-time publishing in conjunction with the OMEGA NEXt software implementation will allow flight data to be available quickly and used collaboratively across the Agency.

### Benefits

- ▶ **Fast:** Permits rapid data searches by inspection via visualization feature
- ▶ **Easy to use:** Allows practical searching through terabytes of post-flight data

### Applications

- ▶ Real-time and post-flight data analysis
- ▶ Records management

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## Networked Instrumentation

Armstrong researchers developed a networked instrumentation system that connects modern experimental payloads to existing analog and digital communications infrastructures. This work led to the development of a commercial product that improves on the data rate and modulation capabilities of the original research system. In airborne applications, this system enables a cost-effective, long-range, line-of-sight network link over the S and L frequency bands that support data rates up to 40 megabits per second (Mbps) and a practically unlimited number of independent data streams. The resulting real-time payload link allows researchers to make in-flight adjustments to experimental parameters, increasing overall data quality and eliminating the need to repeat flights. Additionally this can allow for a reduction in total frequency needed for a mission, as at

each test point the desired parameters can be commanded to telemeter at the maximum rate, while less important parameters are throttled or disabled.

**Work to date:** The Armstrong team developed and flight-tested a 10 Mbps bidirectional aircraft-to-ground line-of-sight network that was further refined into a more operational system that provided the Airborne Research Test System (ARTS) access to thousands of parameters from the heavily instrumented aircraft. The team worked closely with the vendor of the new commercial product to resolve performance concerns and is pushing for flight tests of the new system this year.

**Looking ahead:** Work has begun to design the architecture for a network-based data acquisition system to allow for reconfigurable data streams and live commanding during a flight test.

### Benefits

- ▶ **Flexible:** Expands the utility of existing airborne platforms with legacy communications systems by supporting state-of-the-art payloads that leverage current network technology
- ▶ **Economical:** Achieves a bidirectional line-of-sight network without the need to replace existing communications infrastructure
- ▶ **Flight efficient:** Reduces the need for repeat flights by offering real-time control of experimental parameters

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## Distributed Aerostructural Sensing and Control



Armstrong researchers are investigating ways to increase aircraft maneuverability, safety, and fuel efficiency by applying networks of smart sensors distributed across an aircraft. This “fly-by-feel” concept could enable a vehicle to autonomously react to changes in aerodynamic and structural conditions. Distributed pliable membrane sensors obtain real-time information and convert it into aerodynamic information that can be used for adaptive flight control. In comparison with conventional sensing technologies, which measure aerodynamic parameters from only an aircraft’s fuselage, these smart sensors enable localized measurements at nearly any surface on an aircraft structure. The ultimate goal is to feed real-time sensor information into a control scheme such that the aircraft can autonomously control the position of a surface appropriately for active aeroelastic wing control.

**Work to date:** The team has conducted sensing and analysis work with hot-film sensors installed on Gulfstream III, F/A-18, and X-56A aircraft.

**Looking ahead:** Next steps involve more investigative work with the X-56A aircraft, specifically hot-film sensors combined with fiber optic strain sensing and associated data fusion algorithms to address distributed sensing and control applications.

**Partners:** Texas A&M University, California Institute of Technology, Illinois Institute of Technology, University of Minnesota, U.S. Air Force Materiel Command, U.S. Air Force

### Benefits

- ▶ **High performance:** Offers certifiable performance and stability guarantees and aerostructural efficiency
- ▶ **Improved safety:** Provides localized data, enabling engineers to be more confident that design specifications offer appropriate safety margins

### Applications

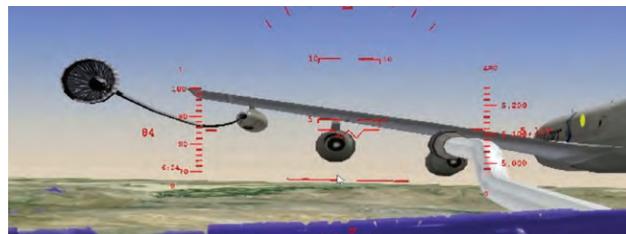
- ▶ Aircraft testing and design
- ▶ Improved drag reduction and increased lift performance
- ▶ Active aeroelastic control of flexible structures

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Stratospheric Observatory for Infrared Astronomy (SOFIA)

# Flight and Ground Experimental Test Technologies



## Fused Reality for Enhanced Training and Flight Research

An updated, advanced head-mounted display is providing test pilots with unprecedented analysis and evaluation capabilities for aircraft and pilot performance—tasks that until now have been largely evaluated subjectively. The Fused Reality system combines real-world images from a video camera with computer-generated virtual images to create a highly immersive environment for complex tasks, such as approach and landing, formation flying, and aerial refueling. Originally developed under a NASA Small Business Innovation Research (SBIR) project, the tool has been significantly improved and is now a portable, standalone system that can be easily integrated on virtually any aircraft.

**Work to date:** Improvements were evaluated in-flight in collaboration with the National Test Pilot School on the school's Gippsland GA-8 Airvan research aircraft as well as four evaluation flights with Armstrong test pilots. A paper on the flight test program was given at the 2015 Society of Flight Test Engineers (SFTE) conference and received the Best Paper Award.

**Looking ahead:** The team is preparing for a March 2016 flight test in collaboration with the U.S. Air Force (USAF) Test Pilot School. Team partner Systems Technology, Inc., is pursuing interest shown by some companies as a result of the flight testing and SFTE conference paper. The Armstrong team is working with researchers at other NASA Centers to identify ways Fused Reality can support space exploration.

**Partners:** Systems Technology, Inc.; National Test Pilot School; and USAF Test Pilot School

Armstrong conducts innovative flight research that continues to expand its world-class capabilities, with special expertise in research and testbed platforms, science platforms, and support aircraft. Researchers place particular emphasis on providing accurate flight data for research aimed at designing next-generation flight vehicles.

Described here are research projects that are seeking to increase safety, reduce costs, and dramatically decrease testing and approval times.

### Benefits

- ▶ **Portable:** Can be quickly installed on any aircraft, allowing pilots to train in their own aircraft
- ▶ **Realistic:** Provides higher fidelity training than ground-based simulators
- ▶ **Safe:** Allows pilots to learn difficult flying tasks such as landing and formation flight without damaging training aircraft and other assets

### Applications

- ▶ Pilot, astronaut, and in-flight aircraft carrier landing training
- ▶ Enhancement of unmanned aircraft system ground stations for improved operator situational awareness

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## Vehicle Integrated Propulsion Research (VIPR)



A major aspect of NASA's propulsion health management development work is demonstrating and evaluating emerging technologies on operational engines. Harsh environment conditions within an engine present significant challenges for the integration and application of aircraft health management technologies. VIPR is a program for developing real-world tests to evaluate such emerging technologies.

**Work to date:** The VIPR I tests occurred in 2011 at Armstrong and involved model-based performance estimation and diagnostic work. In 2013, follow-on VIPR II tests evaluated additional engine health management sensors and algorithms under nominal and faulted engine operating scenarios. VIPR III tests, completed in the summer of 2015, evaluated a suite of health management technologies in nominal and faulted engine conditions, including the controlled degradation of the engine through volcanic ash ingestion.

**Looking ahead:** The VIPR project ended with the completion of VIPR III test activity and associated reporting. Additional investigations in the realm of fuel efficiency (associated with the technologies tested in the VIPR activity) and engine degradation associated with foreign particulate ingestion have been proposed.

**Partners:** U.S. Air Force, Federal Aviation Administration, U.S. Geological Survey, Pratt & Whitney, GE Aviation, Rolls-Royce, The Boeing Company, Makel Engineering, and academia

### Benefits

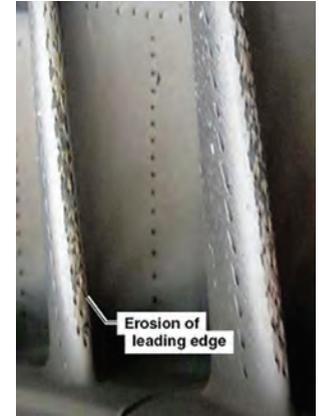
- ▶ **Advances research:** Accelerates the technology readiness level for aviation safety innovations
- ▶ **Increases safety:** Enhances safety features implemented on aircraft to handle a wide variety of potentially dangerous conditions and situations
- ▶ **Increases efficiency:** Provides new data for decision makers to determine airspace utilization in the presence of low concentration volcanic ash

### Applications

- ▶ Detecting and diagnosing engine faults
- ▶ Testing health management technologies
- ▶ Designing fault-tolerant engines

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## Acoustic Detection of Aircraft Turbine Cooling Hole Clogging



Volcanic ash presents a relevant danger to all sorts of aviation in all parts of the world. This image shows how a deposition of ash on the first-stage turbine blades of a NASA DC-8 aircraft partially clogged the cooling holes and changed the airfoil shape, irreparably damaging the engines. This research effort is seeking to determine whether microjet noise may reveal a capability to detect anomalies in the high-pressure turbine (HPT) component cooling holes, which would allow pilots to shut down an unhealthy engine or report a maintenance concern.

The goal is to characterize the changes in turbine cooling hole noise when clogging and erosions occur as a consequence of exposure to volcanic ash or calcium magnesium aluminosilicate (CMAS) materials. The outcome should be the practical implementation of commercial off-the-shelf (COTS) acoustic instrumentation into an engine and the evaluation methods to detect component failures in the HPT before they reach critical points.

**Work to date:** This work was performed at Armstrong periodically over the course of several months as part of a build-up effort to understand microjet noise in simpler geometries before studying film cooling hole noise on turbine airfoils. Research revealed trends with microjet noise that indicate similar behavior to larger subsonic jets in terms of the characteristic single-broadband peak in the frequency domain, albeit centered on much higher frequencies well into the ultrasonic domain. There is also a clear inverse relationship between peak frequencies produced by the jet and the diameter of the nozzle.

**Looking ahead:** Following successful characterization of single microjets, linear single- and multi-row arrays will be studied. These arrays will be configured to represent those of typical turbine vanes and blades. This will allow for an understanding of the influence of jet-jet interactions on the ultrasonic noise produced by these microjets. Additionally, single- and multi-row angled jets will be studied to evaluate the influence of jet-surface interactions.

### Applications

Detecting volcanic ash encounters or excessive and detrimental sand ingestion in:

- ▶ Aircraft installations
- ▶ Land-based turbines

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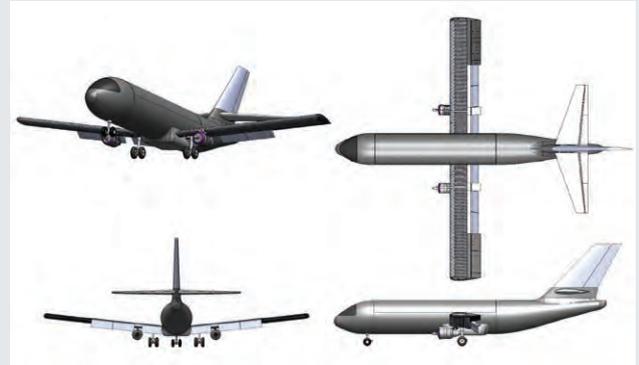
## First Flight of the NASA Armstrong PTERA

The Prototype Test Evaluation Research Aircraft (PTERA) successfully flew for the first time at Armstrong in October 2015. Developed for NASA by Area-I, Inc., the PTERA is a highly reconfigurable unmanned flight research testbed that bridges the gap between wind tunnel and manned flight testing. It allows for evaluation of numerous advanced aerodynamic configurations, research control laws, and circulation control systems. Non-structural and replaceable leading/trailing-edge flaps permit flight evaluation of various research high-lift and drag-reduction technologies. Any UAV autopilot and flight control computer can be integrated into the platform.

The October flight test provided insight into PTERA operation, which will allow Armstrong flight engineers to operate the testbed aircraft safely and efficiently for future research flights. (For more information on PTERA operation, see <https://youtu.be/IAEYX8NT1fA>)

The PTERA testbed is currently the focus of three NASA Aeronautics Research Mission Directorate (ARMD) Convergent Aeronautical Solutions (CAS) proposals and a NASA Kennedy Space Center Innovation Fund (CIF) proposal.

**Partner:** Area-I, Inc., developed the PTERA testbed under the NASA Small Business Innovation Research (SBIR) program.



### Benefits

- ▶ **Accessible:** Allows testing of unconventional designs that might otherwise be too dangerous or expensive to test with a full-scale, crewed aircraft
- ▶ **Economical:** Provides cost-effective options for developing a wide range of cutting-edge aviation and space technologies

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## Electric Propulsion Technologies

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### Scalable Convergent Electric Propulsion Technology and Operations Research (SCEPTOR)

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## Improving Aerospace Vehicle Efficiency

### PRANDTL Flying Wing

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#### ADDITIONAL INFORMATION:

- Putch, A., "What Does Flight Mean To You?" YouTube video, <https://www.youtube.com/watch?v=y8QWnvxwdHA>, 2013.
- NASA has applied for a patent for this technology.

### Adaptive Compliant Trailing Edge (ACTE) Flight Experiment

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### ACTE Flight Experiment to Leverage FOSS

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### FOSS to Support Calibration Research Wing (CReW) Validation

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### Real-Time Wing Deflection Measurement System

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### Using Shape Memory Alloys (SMAs) to Morph Aircraft Structures

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### Electromagnetic Flow Control to Enable Natural Laminar Flow Wings

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### Robust Virtual Deformation Control of the X-56A Model

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### Fundamental Research into Hyperelastic Materials for Flight Applications

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#### ADDITIONAL INFORMATION:

- Streett, C. L.; Casper, J. H.; Lockard, D. P.; Khorrami, M. R.; Stoker, R.W.; Elkoby, R.; Wenneman W. F.; Underbrink, J. R.; "Aerodynamic Noise Reduction for High-Lift Devices on a Swept Wing Model," 44th AIAA Aerospace Science Meeting and Exhibit, Reno Nevada, AIAA 2006-212, 2006.

### Inverse Finite Element Method (iFEM) Investigation for Aerospace Structures

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#### ADDITIONAL INFORMATION:

- Tessler A.: Structural analysis methods for structural health management of future aerospace vehicles. NASA/TM-2007-214871 (2007).

### Lightweight Adaptive Aeroelastic Wing

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### Real-Time Structural Overload Control via Control Allocation Optimization

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### APV-3 Testbed Aircraft

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### Active/Adaptive Flexible Motion Controls with Aeroservoelastic System Uncertainties

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#### ADDITIONAL INFORMATION:

- Skunk Works is a registered trademark owned by Lockheed Martin Corporation.

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### Mitigating Sonic Booms

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### FOSS Aids Low-Boom Flight Demonstrator Project

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### Quantifying and Measuring Sonic Booms

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## Space and Hypersonics Technologies

### Cryogenic Orbital Testbed (CRYOTE) to Use FOSS Technology

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### Using FOSS to Improve Safety of Space Structures and Components

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### Heavy-Lift Mid-Air Retrieval

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### Launch Vehicle Adaptive Control (LVAC) Flight Experiments

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### Air Launch from a Towed Glider

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#### ADDITIONAL INFORMATION:

- NASA has applied for a patent for this technology (Patent Application 13/573,920, "System and Method for an Air Launch from a Towed Aircraft," March 2013).
- Wilhite, Alan, "Value Proposition of a Towed-Glider Launch System," National Institute of Aerospace, October 2012.
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- Gliding to Space: A novel means of launching space satellites," Aerotech News and Review, March 2013.

## A Bi- or Tri-Propellant Rocket with Thrust-Augmented or Altitude-Compensating Nozzle

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### Altitude-Compensating Nozzle

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#### ADDITIONAL INFORMATION:

- Jones, Daniel S.; Trong T. Bui; and Joseph H. Ruf; "Altitude-Compensating Nozzle (ACN) Project: Planning for Dual-Bell Rocket Nozzle Flight Testing on the NASA F-15B," Report Number DFRC-E-DAA-TN7508, January 2013.
- Jones, Daniel S.; Trong T. Bui; and Joseph H. Ruf; "Proposed Flight Research of a Dual-Bell Rocket Nozzle Using the NASA F-15 Airplane," AIAA 2013-3954, July 2013.
- Jones, Daniel S.; Joseph H. Ruf; Trong T. Bui; Martel Martinez; and Clinton W. St. John; "Conceptual Design for a Dual-Bell Rocket Nozzle System Using a NASA F-15 Airplane as the Flight Testbed," AIAA 2014-3956, July 2014.

## Coreless Linear Induction Motor (LIM) for Spaceborne Electromagnetic Mass Driver Applications

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## F-15 Aero Tow Vehicle Development

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#### ADDITIONAL INFORMATION:

- Vectran is a registered trademark of Kuraray Co., Ltd.

## Advanced Control Method for Hypersonic Vehicles

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#### ADDITIONAL INFORMATION:

- Nguyen, Luat T.; William P. Gilbert; and Marilyn E. Ogburn; "Control-System, Techniques for Improved Departure Spin Resistance for Fighter Aircraft," NASA TP 1689, August 1980.
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## High-Altitude Atmospheric Reconstruction

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## Improved Ground Collision Avoidance System (iGCAS)

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## Determining Optimal Landing Locations in Emergency Situations

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## Stereo Vision for Collision Avoidance

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## Automatic Dependent Surveillance Broadcast (ADS-B) System for Traffic Situational Awareness

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## ENGINEERING SUCCESS: Resource Allocation for Multi-Agent Planning (ReMAP) for Unmanned Vehicles

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## Avionics and Instrumentation Technologies

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#### ADDITIONAL INFORMATION:

- NASA has three patents issued for this technology portfolio (U.S. Patent 7,715,994, U.S. Patent 7,520,176, and U.S. Patent 8,700,358).
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## Autocode from Simulink to Real-Time Embedded Linux

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#### ADDITIONAL INFORMATION:

- Simulink and MATLAB are registered trademarks of The MathWorks, Inc.
- Linux is the registered trademark of Linus Torvalds in the U.S. and other countries.
- ARM is a registered trademark of ARM Limited (or its subsidiaries) in the EU and/or elsewhere. All rights reserved.
- Raspberry Pi is a registered trademark of Raspberry Pi Foundation.

## Next-Generation Post-Flight Processing Software

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### Vehicle Integrated Propulsion Research (VIPR)

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## ENGINEERING SUCCESS: First Flight of the NASA Armstrong Prototype Test Evaluation Research Aircraft (PTERA)

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All photos and illustrations by NASA unless otherwise noted.

Caption for front cover main image: NASA Armstrong's X-56A Multi-Utility Technology Tested (MUTT) is being used to pioneer new research in aircraft design and modeling.

Caption for back cover main image: This DC-8 aircraft, based at Armstrong, supports NASA's Airborne Science Program. In May 2015, it began a series of flights in Iceland aimed at studying Arctic polar winds.



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