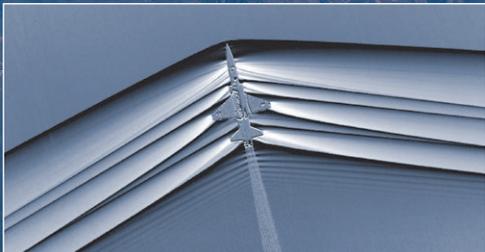




## Armstrong Flight Research Center



RESEARCH  
TECHNOLOGY &  
ENGINEERING **2017**





## **From the Director: Research and Engineering Directorate**

It's with great pride that I endorse the 2017 NASA's Armstrong Flight Research Center Research, Technology, and Engineering Report. We're entering an exciting new era of flight transportation, and the talented researchers, engineers, and scientists at Armstrong continue to create innovative solutions to address some of the challenges facing the aerospace community.

The center has long prided itself on its agility to develop and apply innovative tools, techniques, and technologies to the relevant aerospace problems of the day, and we're excited to continue that tradition on the cutting-edge projects of today and tomorrow. From imaging and documenting the 2017 total solar eclipse, to developing tools to validate quiet supersonic flight, to discovering and solving the real-world problems of electric flight, to addressing the challenges of space access, the work represented in this report highlights the ability of our research, engineering, and technical team to address diverse challenges across mission directorates.

As we support NASA's aerospace research and development missions, conveying news of this work to the public remains a priority. This report presents brief summaries of the technology work at Armstrong, along with 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 dedicated innovators possess a wealth of performance, safety, and technical capabilities spanning a wide variety of research areas involving aircraft, electronic sensors, instrumentation, environmental and earth science, celestial observations, and much more. They 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.

Armstrong's project teams have successfully accomplished many of the nation's most complex flight research projects by crafting creative solutions that advance emerging technologies from concept development and experimental formulation to final testing. 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 testing and validating 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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# Electric Propulsion Technologies



NASA will test new propulsion technology in 2018 using an experimental airplane designated the X-57 and nicknamed Maxwell. With 14 electric motors turning propellers and all of them integrated into a uniquely designed wing, researchers will use the X-57 to demonstrate that electric propulsion can make planes quieter, more efficient, and more environmentally friendly.

## Airvolt 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 enables evaluations of 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:** Researchers have used the Airvolt test stand to gather data from a Joby JM1 motor. Researchers are analyzing the data so that a motor model can be used for a hybrid electric hardware-in-the-loop simulation testbed. Accurate models are required in the simulation to reflect the true hardware configuration and provide an assessment tool for researchers.

**Looking ahead:** The Airvolt test stand will be used to test the cruise motors of the X-57 Maxwell experimental aircraft. A total of five motors will undergo endurance testing, each for 75 hours, as part of the acceptance program to ensure they can be used in flight. The test requirements are derived from a tailored version of Federal Aviation Regulations Part 33 airworthiness standards for aircraft engines.

### 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, and batteries as well as 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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X-57 Principal Investigator Sean Clarke flies the X-57 simulator at Armstrong, examining ideal maneuvers and reaction times for flight.

## X-57 Maxwell Experimental Aircraft

NASA will fly the X-57 experimental aircraft to validate and demonstrate the benefits that distributed electric propulsion may yield for future aviation. 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.

The project 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 compare the performance of the experimental aircraft with the original configuration to demonstrate the benefits of installing propellers at the wingtips to reduce vortex drag. They will also examine the improved powertrain efficiency that electric systems provide in comparison to reciprocating engines. The goal of the project is to demonstrate a 500 percent increase in high-speed cruise efficiency, zero in-flight carbon emissions, and flight that is much quieter for communities on the ground.

**Work to date:** Research collaborators recorded numerous significant milestones in 2016 and 2017:

- ▶ Collection of baseline data to compare to data that will be collected from the all-electric aircraft
- ▶ Arrival of the baseline fuselage at Empirical Systems Aerospace, the project's prime contractor
- ▶ Successful ground vibration testing of the fuselage to establish a baseline prior to planned modifications
- ▶ Transfer of the aircraft to Scaled Composites facilities at Mojave Air & Space Port for conversion into an electric airplane
- ▶ Development and operation of an X-57 simulator at Armstrong to prepare pilots for future flight tests
- ▶ Successful testing and validation of the battery system that will power the all-electric aircraft

**Looking ahead:** Integration of the electric systems into the X-57 aircraft is underway. When completed, the aircraft will

undergo ground taxi tests at Armstrong in 2018 to examine and validate the safety and functionality of the electric system. Flight tests will follow to validate the X-57's electric motors, battery, and instrumentation before integrating a new wing with a high aspect ratio. The planned final version will feature 12 small electric propellers along the new wing's leading edge and two larger electric cruise motors on the wing tips.

**Collaborators:** NASA's Langley Research Center, Glenn Research Center, Ames Research Center, Johnson Space Center, Empirical Systems Aerospace, Joby Aviation, Xperimental, Scaled Composites, Electric Power Systems, TMC Technologies, and Tecnam

### Benefits

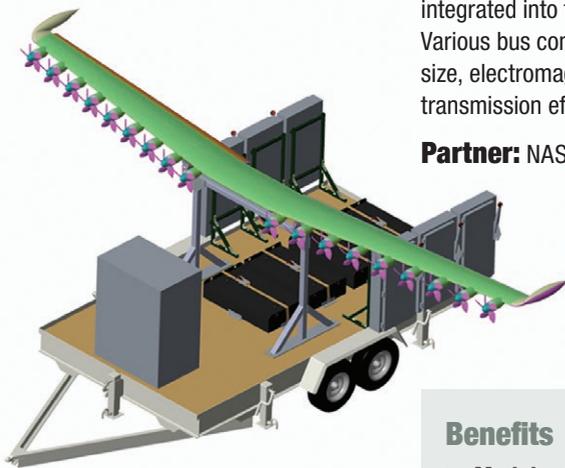
- ▶ **Enables cleaner flight:** Electric propulsion provides 5- to 10-factor reduction in greenhouse gas emissions with current forms of electricity generation and essentially zero emissions with renewable-based electricity.
- ▶ **Reduces lead emissions:** Electric propulsion provides a technology path 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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## Hybrid-Electric Integrated Systems Testbed (HEIST) Ironbird

The HEIST project is studying power management and transition complexities, modular architectures, and flight control laws for turbo-electric distributed propulsion technologies using representative hardware and piloted simulations. A primary focus is to study the system complexities of two power sources of which one is a turbo generator. The team is developing a simulator that can be used to investigate 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 designed 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 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, 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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The modified experimental wing with electric motors is prepared for mounting on a truck to measure lift, drag, pitching moment, and rolling moment.

# 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 novel test techniques that evaluate sensor suites and calibration systems, our researchers are finding unique solutions that increase efficiency.



## Calibration Research Wing (CREW)

Future aircraft will have high aspect ratio wings made of specially constructed composite materials optimized for structural and aerodynamic performance. These next-generation wings will also be lighter and more flexible than current wings. To prepare for testing these future advanced composite wings, Armstrong researchers designed a test using the high aspect ratio composite CREW as a testbed. CREW enables researchers to develop test techniques, evaluate suites of sensors, and develop a faster and more cost-effective approach for wing loads calibration testing. The CREW composite wing was instrumented with both conventional strain gauges for loads calibration testing and fiber optic strain sensors for determining wing shape and load distribution.

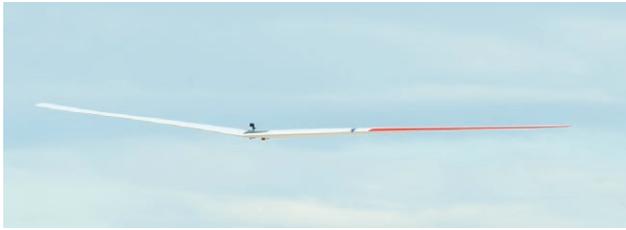
**Work to date:** Using the CREW, Armstrong researchers developed techniques for testing highly flexible composite wings as well as a cost-effective and faster approach for performing a wing loads calibration test using the Armstrong-developed Fiber Optic Sensing System (FOSS). Researchers also used the CREW for team member proficiency testing and for training personnel on the use of test systems.

**Looking ahead:** A follow-on test program is planned for 2018. Researchers will evaluate the performance of a passive aeroelastic tailored (PAT) wing with a series of loads tests. The uniquely designed composite PAT wing is lighter, flexible, and more structurally efficient than conventional wings. The team will also evaluate the performance of FOSS in determining wing shape and distributed load on a highly flexible composite wing. The outcome of the PAT wing testing will greatly advance NASA's understanding of the performance of advanced tailored composite high aspect ratio wings.

### Benefits

- ▶ **Innovative:** Enhances NASA's ability to meet the testing needs of future composite wing technology
- ▶ **Multi-purpose:** Enables testing of emerging approaches, instrumentation, test techniques, and algorithms
- ▶ **Efficient:** Provides a testbed for training personnel on test techniques and test systems

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## PRANDTL-D Flying Wing

Armstrong researchers are continuing to test 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. If the concept continues to prove its value, it could advance NASA's research goals to verify technologies leading to significant fuel economy and emissions reduction.

**Work to date:** The team has developed, demonstrated, and validated scale models of an improved PRANDTL-D wing, and their flight experiments have unequivocally established proverse yaw. The research has led to work on an autopiloted flying wing designed to land on Mars. In 2016, instrumentation was added to the model, the team published a technical paper, and the innovation was patented.

In 2017, the team completed test flights incorporating the Fiber Optic Sensing System (FOSS). This research demonstrated spanload in the expected range, as predicted in Prandtl's 1933 findings, and was the first evaluation of cleanly measured in-flight deflection of a PRANDTL-D wing.

**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 propeller systems (13 percent)
- ▶ **Economical:** Improves fuel efficiency by allowing aircraft to fly faster
- ▶ **Safer:** Reduces adverse yaw when correcting for roll

### Applications

- ▶ Mid-sized commercial aircraft
- ▶ Drones and unmanned aircraft
- ▶ Wind turbines
- ▶ Industrial fans
- ▶ Energy delivery systems

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## PRANDTL-M Airframe

Armstrong researchers are flight testing a subscale aircraft designed to fly in the Martian atmosphere, scouting terrain and collecting measurements. PRANDTL-M is derived from the PRANDTL-D glider and leverages the same aerodynamic design merits. The goal is for the aircraft to unfold and deploy from a CubeSat in the aeroshell of a future Mars rover. It then would fly over proposed landing sites and send detailed images and atmospheric measurements back to Earth. To prove the concept, researchers are validating the airframe and instrumentation and will be conducting flight tests up to 100,000 feet. The PRANDTL-M airframe also is the basis for the Armstrong-developed Weather Hazard Alert and Awareness Technology Radiation Radiosonde (WHAATRR) glider, which is collecting weather data on Earth.

**Work to date:** In 2017, supported by a large contingent of Armstrong interns, researchers confirmed PRANDTL-M's airframe, flew it autonomously for the first time, collected flight data, validated a telemetry system, reconfigured the battery system, and redesigned and integrated the electronics. PRANDTL-M is now a two-surface airplane with integrated instrumentation.

A key accomplishment was the development of a computer-controlled multi-axis cutting tool to enable rapid prototyping of new aircraft ideas. This new tool permits researchers to cut out new aircraft configurations in foam; then they can embed the electronics and conduct flight tests. Promising versions can then be selected for machining.

**Looking ahead:** The team will construct new airframes and perform parameter identification that will be used to develop a new control system and automated work flow. Tethered balloon flights up to 5,000 feet high will begin in 2018, with the goal being flights up to an altitude of 100,000 feet to simulate the Martian atmosphere.

### Benefits

- ▶ **Innovative:** Determines minimum viable Mars platform
- ▶ **High performance:** Enables forward progress in small unmanned aerial system prototyping via computer-controlled rapid prototyping and three-dimensional (3-D) printing
- ▶ **Advanced:** Permits high-altitude Earth monitoring

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## Adaptive Compliant Trailing Edge (ACTE) Flight Experiment

ACTE is an experimental flight research project that is a partnership between NASA and the U.S. Air Force Research Laboratory. Its purpose is to investigate 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 ACTE experiment was flown on NASA's Subsonic Research Aircraft Testbed (SCRAT), which is a Gulfstream III (G-III) aircraft converted into a testbed for flight research projects.

The experiment involved replacing the conventional Fowler flaps on the SCRAT with advanced shape-changing ACTE flaps that form continuous bendable surfaces. The ACTE flaps are manufactured by FlexSys, 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 was converted and instrumented into a test platform, and the first set of ACTE flight tests was completed in April 2015. Follow-on ACTE flights examining the flaps in a twisted configuration and at Mach 0.85 were completed in 2017.

### Benefits

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

### Applications

- ▶ Aircraft control surfaces and main landing gear
- ▶ Helicopter blades
- ▶ Wind turbines

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## Acoustic Research Measurement (ARM) Flight Experiment

The ARM flight experiment is examining noise reduction benefits of flexible wing flaps and also several landing gear noise reduction concepts developed by NASA's Langley Research Center. The experiment consists of flying NASA's Subsonic Research Aircraft Testbed (SCRAT) over an acoustic array set up on a lakebed at Edwards Air Force Base and measuring the noise signature of the aircraft in various configurations. The array was designed to identify those components of the aircraft that produce the highest levels of airframe noise, including elements that are deployed during the aircraft's approach and landing, such as the wing flaps and landing gear.

**Work to date:** The first phase of ARM flights occurred in fall 2016 and gathered information on the noise reduction benefits of the Adaptive Compliant Trailing Edge (ACTE) flexible wing flaps. Flight tests in October 2017 examined the benefits of various main landing gear noise reduction concepts.

**Looking ahead:** Researchers will analyze flight test data to determine how much airframe noise reduction resulted from the integrated technologies. A series of flights planned for spring 2018 will continue to examine benefits of the Langley noise reduction concepts, without the ACTE flaps installed.

### Benefits

- ▶ **Innovative:** Reduces aircraft noise by quieting the airframe and main landing gear
- ▶ **Adaptable:** Applies to different classes and sizes of aircraft

### Applications

- ▶ Aircraft control surfaces
- ▶ Aircraft main landing gear

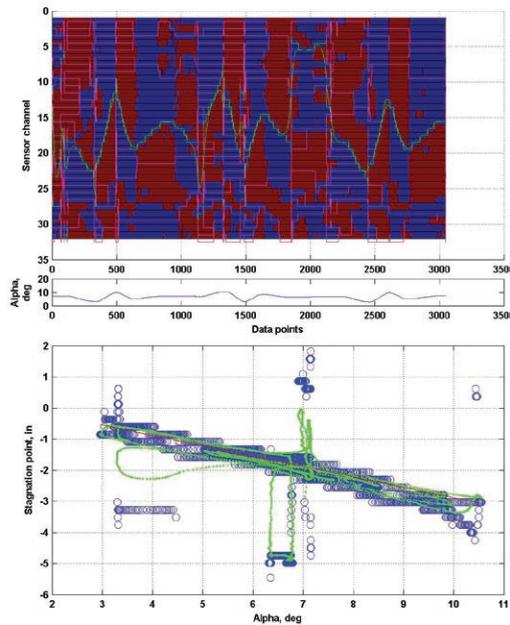
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## Determining Leading-Edge Stagnation Point Location with Sensors of Unknown Calibration

Armstrong researchers developed an algorithm to extract useful test data from a sensor array mounted on the wing of an aircraft testbed after the sensors stopped functioning as expected. NASA's Subsonic Research Aircraft Testbed (SCRAT) is a converted Gulfstream III aircraft outfitted with sensors to collect airworthiness and research data for a variety of flight projects. A self-calibrating hot-film sensor array was installed on the leading edge of one wing to track the stagnation point location throughout flight for varying flap deflections. When the array stopped functioning, Armstrong developed an algorithm to process the available system output and determine the stagnation point location. The innovation enabled useful data to be collected for more than 60 flights, enabling further research.

**Work to date:** As the flight test series progressed, the algorithm was modified several times to handle changing conditions and

failed sensor channels. The algorithm tracked the stagnation point through dynamic pitching maneuvers with a high degree of reliability. Armstrong presented a paper on this achievement at the American Institute of Aeronautics and Astronautics (AIAA) SciTech Forum in January 2017.



### Benefits

- ▶ **Effective:** Enabled extraction of useful test data from failed sensor array
- ▶ **Practical:** Advanced airworthiness aeronautics research

### Applications

- ▶ Aeronautics research

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Algorithm performance in a pitch maneuver



Ventura Coastline

NASA science team surveys California fires with high-altitude ER-2 aircraft.

# Control of Flexible Structures



## 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 advanced control 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:** In 2016–2017, researchers redesigned the landing gear and braking system to improve performance and mitigate problems discovered in earlier flight tests. In addition, they revised the flight controller, completed extensive analysis, and collected ground vibration data to update theoretical models to improve predictions on how the aircraft will fly. Armstrong engineers have developed a flight control system and advanced sensors to gather the information required to achieve project success.

**Looking ahead:** The team will continue to conduct flights that test new techniques to collect and analyze data and develop a methodology to confirm flutter suppression.

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

### Benefits

- ▶ **Advanced:** Enables construction of longer, lighter, more flexible wings for 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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Armstrong engineers continue to pioneer new research in aircraft design and modeling. Researchers are experimenting with revolutionary flexible wing 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 adaptive motion controls.

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.



## Spanwise Adaptive Wing Research

Researchers are investigating the feasibility of a system that will allow part of an aircraft’s wing to fold in flight, boosting efficiency and performance. A team of engineers are testing and evaluating the Spanwise Adaptive Wing (SAW) concept, which seeks to enhance aircraft performance by allowing the outboard portions of wings to adapt, or fold, according to various flight condition demands. A mechanical joint, acting as a hinge line for rotation, makes the freedom of movement possible. New advancements in shape memory alloy (SMA) actuators allow tighter packaging, allowing the folding of much smaller wing sections.

**Work to date:** To demonstrate SAW in flight, researchers designed an experiment to fly on the Prototype-Technology Evaluation and Research Aircraft (PTERA), developed by Area-I. Analysis showed that for a folding wing section on PTERA, the outer ailerons could achieve nearly 40 percent of total rudder authority in yaw. Flight hardware for the experiment has been installed and ground tested on the aircraft.

**Looking ahead:** SAW could be tested on the PTERA as early as spring 2018. Objectives include validating tools and vetting the system’s integration, evaluating control laws, and analyzing SAW’s airworthiness and potential benefits to in-flight efficiency. In addition, the team is working to develop large-scale actuators capable of folding full-scale wings in flight. An F/A-18 outer wing section was sent to NASA’s Glenn Research Center, where a large-scale SMA actuator will be mounted to the wing and tested in the lab.

**Partner:** NASA’s Langley Research Center and Glenn Research Center, The Boeing Company, and Area-I

### Benefits

- ▶ **Increased efficiency:** Increases aircraft stability and wing compression lift
- ▶ **Increased performance:** Augments yaw power and yaw stability
- ▶ **Adaptive:** Enables optimal wing position for all flight positions

### Applications

- ▶ Commercial, military, and general aviation aircraft

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## Modeling of X-56A Landing Gear

This research effort is modeling takeoff and landing behavior of flexible aircraft. The X-56A Multi-Utility Technology Testbed (MUTT) is a remotely piloted aircraft with a stiff body and flexible, detachable wings developed for testing technologies associated with flexible aircraft. Flight tests from an earlier campaign revealed detrimental landing characteristics, so researchers redesigned the landing gear and updated how they were modeling not only the gear but also the landing response of the vehicle. This work is enabling the development of techniques that will help pilots find ways to safely land flexible aircraft.

**Work to date:** Researchers created a method to simulate the X-56A aircraft during the takeoff and landing flight phases. Most notably, the simulation integrates for the first time aircraft structural dynamics, landing gear effects, and pilot inputs. Models were validated during August 2017 test flights that demonstrated that simulation predictions corresponded with flight results. These results boosted confidence in the takeoff and landing responses, further validating aircraft design updates.

**Looking ahead:** Tests flights scheduled for 2018 will focus on monitoring and gathering additional data to build confidence in these results.

### Benefits

- ▶ **Innovative:** Assesses the landing behavior of a flexible aircraft
- ▶ **Safer:** Allows pilots to assess and develop how to land a flexible aircraft

### Applications

- ▶ Flexible aircraft design
- ▶ Lightweight commercial aircraft

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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, even with the test-validated model, uncertainties still exist in aeroservoelastic analysis due to time-varying uncertain flight conditions, transient and non-linear 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:

## Distributed Aerostructural Sensing from Measured Strain Data

Researchers have developed a simple approach for computing unsteady aerodynamic loads from measured strain data. First, it computes deflection

and slope of the structure from the measured unsteady strain data using the two-step approach. It computes velocities and accelerations of the structure using the autoregressive-moving-average model, online parameter estimator, low-pass filter, and a least-squares curve-fitting method together with an analytical derivative with respect to time. Finally, it computes aerodynamic loads over the aircraft using modal aerodynamic influence coefficient matrices, a rational function approximation, and a time-marching algorithm.

## Aeroservoelastically Tailored Wings and Aircraft with Curvilinear Spars and Ribs (SpaRibs)

This project employs a systematic multi-disciplinary design, analysis, and optimization (MDAO) tool 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 SpaRibs to increase design stability. Researchers built two test articles to demonstrate the flutter-speed increase with curvilinear SpaRibs. They will update structural finite element models using the measured ground vibration test data.

## 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

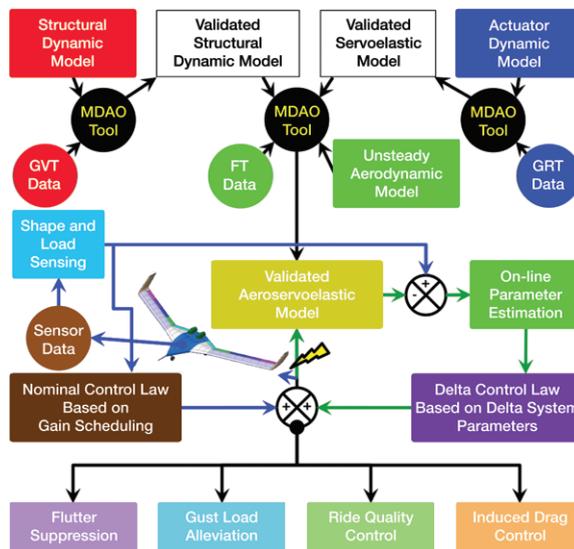
number, reduced frequency, and dynamic pressure, and it can be obtained from any aerodynamic model. This technique was successfully applied in 2017 to have a test-validated structural finite element model of the X-56A Multi-Utility Technology Testbed (MUTT).

**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.

Researchers will extend the surrogate tracking error MRAC design to accommodate uncertainty in the locations of the non-minimum phase zeros. They will implement it on more complex versions of the X-56A models and across a range of flight conditions to investigate its robustness. They will also apply the delta control system design technique to the cantilevered rectangular wing model.

**Partners:** NASA's Ames Research Center, Lockheed Martin Advanced Development Program (a.k.a. Skunk Works®), and U.S. Air Force Research Laboratory

Skunk Works is a registered trademark of Lockheed Martin Corporation.



## 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 Multi-Utility Technology Testbed (MUTT) experimental aircraft by commanding and controlling 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 the aircraft's sensor array, the wings will be instrumented with fiber optic sensors that can measure strain at thousands of locations. The controller will use these sensors in a feedback system to automatically manipulate the trailing edge control surfaces and body flaps to suppress flutter. 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 flutter-suppression controller using fiber optics is robust. Simulations have also shown that the shape controller can affect the global angle of attack and achieve drag changes. Engineers have installed the fiber optic sensors on the flexible wings of the X-56A. They experimentally derived the required fiber optic-based strain modes for both flutter suppression and shape control using loads data. They also experimentally verified and corrected the modes using dynamics, such as nose drop testing and frequency sweeps.

**Looking ahead:** Additional steps include completing 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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## 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 used to design flight controllers for the stiff-wing flights. The unsteady aerodynamic and structural data have been integrated with a non-linear piloted simulation. The piloted simulation allows for evaluation of the dynamics and development of pilot techniques in highly non-linear conditions, such as takeoff and landing. Stiff-wing flight tests have been performed using the X-56A MUTT as a validation of the modeling approach. The pilot techniques developed in the non-linear simulation were demonstrated to safely take off and land the X-56A with the flexible wings.

**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 at higher airspeeds.

**Partner:** U.S. Air Force 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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## System Identification for Flexible Aircraft

This research effort focuses on designing multi-sine programmed test inputs for use in flexible aircraft system identification situations. In this context, system identification is the process of exciting aircraft and control system dynamics, collecting flight data measurements, and constructing models from the data. For the X-56A Multi-Utility Technology Testbed (MUTT) aircraft, system identification is needed to refine and validate preflight aerodynamic and aeroelastic predictions and to verify robust stability of flight control laws. System identification as applied to the X-56A aircraft entails modeling the response to as many as 10 separate control surfaces and two engines.

The Armstrong team is applying optimization techniques to select excitation frequencies, amplitudes, and phases in order to efficiently generate data with a high signal-to-noise ratio across a wide frequency band, while maintaining a margin with respect to operating limitations. While this approach is tailored toward flexible aircraft, it is applicable to any complex system identification problem where manually tailoring the excitation is impractical. In addition to validating preflight predictions and control system design, the approach is also being used for computational fluid dynamics simulation to reduce expensive computation time.

**Work to date:** Researchers have collected baseline flight data using the X-56A in its stiff-wing configuration, using conventional programmed test inputs.

**Looking ahead:** New inputs designed using the advanced synthesis techniques will be tested during the next X-56A flexible wing flight test campaign, slated to begin early in 2018.

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

### Benefits

- ▶ **Powerful:** Generates high-quality flight data quickly and safely
- ▶ **Efficient:** Promotes real-time and onboard data reduction for control room monitoring

### Applications

- ▶ Fundamental research
- ▶ Control system requirements verification

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## Flight Research of Hyperelastic Materials

Hyperelastic material panel



The drive toward more efficient and lightweight aircraft structures requires the development of more efficient and lightweight materials. Hyperelastic materials have shown the potential to provide such a solution, as they are capable of increasing stiffness as a function of tension applied while contributing a fraction of the weight of metallic counterparts. However, the data required to prove their flight-worthiness and practical application are not readily available. This Armstrong research effort designed an experiment to acquire fundamental data on hyperelastic materials in flight and then assess the applicability of existing panel flutter criteria and analysis methods.

**Work to date:** With support from the Center Innovation Fund (CIF), a HyperFlutter flight experiment has been formulated and planned. In addition, CIF support provided resources for the Armstrong research team to design test articles as well as purchase the hyperelastic material to fabricate the test articles and the required accelerometers.

**Looking ahead:** The team is looking for the opportunity to integrate the hyperelastic experiment and perform supersonic flight tests on NASA's F-15 TN 836 aircraft.

### Benefits

- ▶ **Innovative:** Provides insight into the behavior of hyperelastic materials in flight that has not been previously explored
- ▶ **Effective:** Determines the accuracy of current panel flutter codes in predicting a panel-like instability
- ▶ **Advanced:** Enables morphing technologies for next-generation aircraft design

### Applications

- ▶ Aircraft and spacecraft control surfaces
- ▶ Passive flutter suppression systems
- ▶ Aircraft landing gear treatments
- ▶ Helicopter blades
- ▶ Motor vehicles, trains, and ships

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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. A paper published in November 2016 details research formulation and implementation along with preliminary results from a representative aerospace structure.

**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

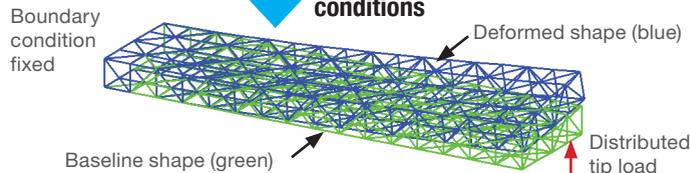
- ▶ Aircraft wing flaps
- ▶ Helicopter blades
- ▶ Wind turbines
- ▶ Motor vehicles
- ▶ Trains
- ▶ Ships and submersibles

### Aerospace structure

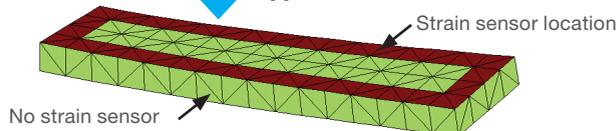


Installed strain sensors

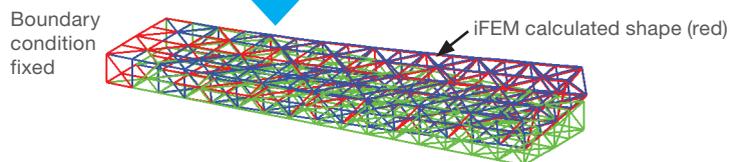
### Wing box FEM model of structure with representative boundary conditions



### Experimental or FEM strains applied to model



### iFEM formulation



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Load tests on Gulfstream III aircraft for Adaptive Compliant Trailing Edge (ACTE) Research

# Real-Time Structural Overload Control via Control Allocation Optimization

This technology uses 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 and prevent overstresses in critical aircraft structures. 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 F/A-18A Full-Scale Advanced Systems Testbed (FAST), the Armstrong team targeted the aileron hinge connection as a critical control point. A flight experiment using the FAST aircraft produced successful results 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. The team presented two research papers at the American Institute of Aeronautics and Astronautics (AIAA) SciTech Conference in January 2017.

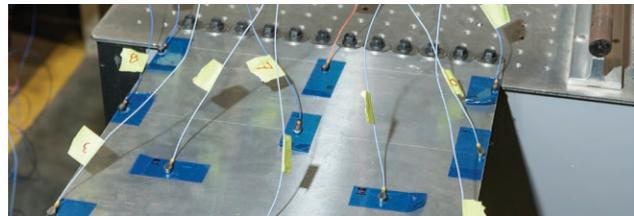
**Looking ahead:** The aircraft simulation model is being reworked to incorporate additional structural elements. Because the FAST aircraft has been decommissioned, a new F/A-18 testbed is being instrumented to flight test this technology.

## 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



# Flexible Matrix Composites for Passive Flutter Suppression

Armstrong researchers investigated the possibility of incorporating viscoelastic materials into the matrix of composites for wing structures. Viscoelastic materials have been used in helicopter blade design to dampen specific nuisance vibration frequencies, and aerospace researchers have considered the possibility that incorporating these materials into composite aircraft wings could lead to substantial weight savings and improved performance. With support from NASA's Center Innovation Fund (CIF), this team conducted basic research to explore incorporating flexible matrix composites (FMC) containing viscoelastic materials into aircraft wings.

**Work to date:** Researchers determined early on that stiffness considerations and temperature constraints associated with viscoelastic-based FMC materials meant that it was not feasible to design a wing test article by simply replacing matrix materials. After investigating traditional and non-traditional methods of layering viscoelastic materials, the team ultimately determined there was no reasonable design for a wing test article that would provide weight benefits, given stiffness and temperature sensitivities.

Researchers also designed and conducted an experiment to validate integrated modeling techniques by sandwiching a viscoelastic layer between two aluminum plates. The team built five model configurations that exhibited clear damping properties. Still, researchers determined that, due to the combined loss in stiffness and temperature sensitivity, FMC materials are not appropriate for wing designs at this time.

**Looking ahead:** This CIF project allowed for the exploration of the FMC material for wing design applications. Researchers gained experience working with viscoelastic materials and determined that, while not currently appropriate for wing designs, FMC material may still provide value in other aerospace applications where temperature variation and stiffness losses are better tolerated. Collaboration with research partners formed a basis for future mutually beneficial research efforts.

**Partners:** U.S. Air Force Research Laboratory, Pennsylvania State University, and UTC Aerospace Systems

## Benefits

This research contributed to the body of knowledge about the use of viscoelastic materials in aerospace applications.

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Above: ARTS computing platform

Left: View of the adaptive span on the PTERA

## Airborne Research Test System (ARTS) for Small Unmanned Aircraft

This research effort is evaluating the feasibility of the ARTS, acting as a flight controller, to command the outboard ailerons on movable-span sections of the Prototype-Technology Evaluation and Research Aircraft (PTERA) testbed. The ARTS is a hardware and software platform for testing advanced control and sensor concepts. It reduces the effort and cost of flight testing research by providing a flexible, reconfigurable computing platform for hosting research experiments.

This research is part of the Spanwise Adaptive Wing (SAW) project, which is investigating the use of control surfaces to allow the outboard portions of wings to adapt, or fold, to adjust to various flight condition demands. When the outboard portions of the wing are in a vertical configuration, the risk of Dutch roll (i.e., yaw-roll coupling) appears to be significant. As a first test of the ARTS, the outboard ailerons on the movable span will be used in this configuration to control the Dutch roll mode in lieu of the rudder. If successful, this could reduce the size of the rudder for future aircraft with wings that have movable spans.

**Work to date:** In 2017, the ARTS box was tested in full non-linear simulation, and the PTERA testbed and the ARTS successfully exchanged sensor information and control surface commands. The system was also successfully tested in hardware in the loop in a real-time operating environment. Three flight tests have been conducted to gather data that will be used to update the ARTS control laws.

**Looking ahead:** In late 2018, the Armstrong team will conduct a full experiment to suppress Dutch roll using the ARTS commanding the outboard ailerons in a vertical-span configuration.

Simulink is a registered trademark of MathWorks, Inc.

### Benefits

- ▶ **Compatible with Simulink® software:** Saves time and resources
- ▶ **Flexible:** Provides an array of options to test and implement advanced control concepts
- ▶ **Configurable:** Can be quickly customized for various experiments
- ▶ **Partitioned:** Separates research experiments from the core system

### Applications

- ▶ Operate as a flight controller
- ▶ Validate new flight control concepts
- ▶ Test aircraft limits

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Researchers prepare the X-56A for flight.

# Supersonic Technologies

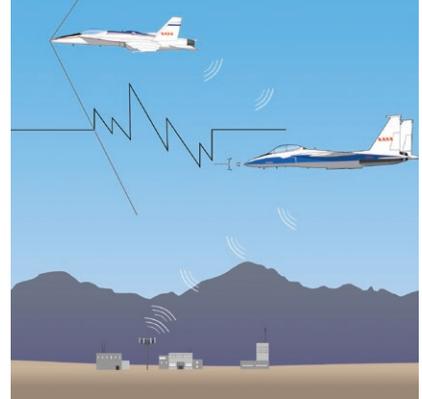


Supersonic flight over land is currently severely restricted because sonic booms created by shock waves disturb people on the ground and can damage property. Innovators at Armstrong are working to solve this problem through a variety of innovative techniques that measure, characterize, and mitigate sonic booms.

The development of a new experimental plane called the Low Boom Flight Demonstrator is advancing, with completion in 2017 of a preliminary design review. When the new X-plane arrives at Armstrong, our researchers will qualify and flight test it. It will help gauge how people respond to the lower intensity “thump” rather than the disruptive sonic boom in different areas of the United States. Determining a tolerable level of noise for supersonic flight is key to suggesting that the Federal Aviation Administration (FAA) amend its current rules for supersonic aircraft. Success could lead to opening a new market for next-generation aircraft.

## Shock-Sensing Probe to Study Sonic Booms

A new shock-sensing probe in development at Armstrong is expected to provide researchers with key information about sonic booms. NASA’s goal for sonic boom research is to find ways to control and lessen shock wave noise so that federal regulators will allow supersonic flight overland. The Armstrong probe will be mounted on the nose of an F-15 aircraft that will fly through the shock waves of another supersonic aircraft. In addition to measuring the static pressure change through the shock waves, the probe will measure the change



in Mach number and flow angularity. Researchers will compare these measurements to other data and potentially computational fluid dynamics models to verify those predictions. If successful, the probe will be used for the Low Boom Flight Demonstration experimental aircraft project.

**Work to date:** In 2016, an earlier version of the probe flew in a six-flight series on the F-15 test fixture, located underneath the aircraft. It measured the strength of shock waves generated from the aircraft itself. Fabrication of the new hardware is expected to be completed early in 2018.

**Looking ahead:** Integration onto the airplane and checkout should occur in early spring 2018, with flight tests slated for late spring and early summer. The nose-mounted shock-sensing probe will measure the shock wave signature generated by nearby supersonic aircraft.

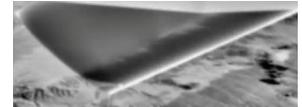
**Partner:** Eagle Aeronautics

### Benefits

- ▶ **High performance:** Measures flow speed, static pressure, and angularity
- ▶ **Efficient:** Allows for probing to be conducted at a higher closure rate, due to reduced pneumatic lag
- ▶ **Effective:** Contributes to NASA’s understanding and management of sonic booms

### Applications

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



NASA's F-15 research testbed will expose the swept wing laminar flow test article to speeds up to Mach 2, matching conditions presented during wind tunnel tests.

## 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 in a wind tunnel and then flying them beneath supersonic research aircraft. These activities enable 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. Highly swept wings are a typical design feature of supersonic aircraft.

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 to reduce drag. Data will also reveal the mechanisms' suitability for supersonic laminar flow wing designs, especially ones tailored toward future low-boom supersonic aircraft. This will ultimately lead to more efficient and environmentally friendly supersonic aircraft.

**Work to date:** The 65-degree swept wing model is currently being tested in flight on NASA's F-15B Research Testbed. It previously completed wind tunnel testing at NASA's Langley Research Center and computational fluid dynamics analysis of the test article on the F-15B aircraft. Results to date have improved the understanding of crossflow and how to reduce its effects.

**Looking ahead:** Work on 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



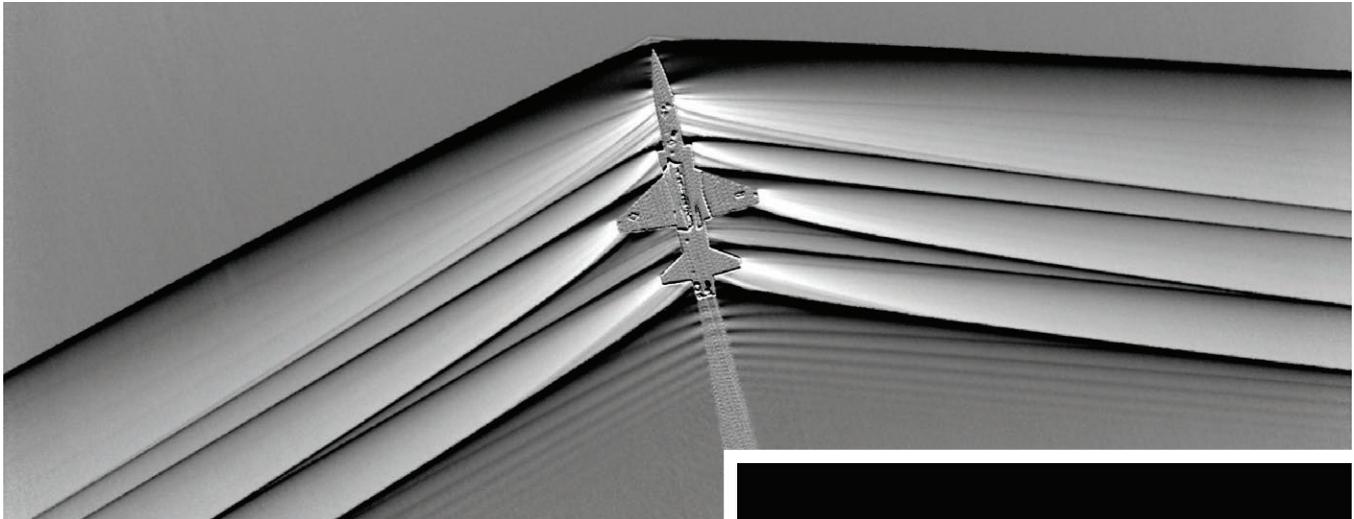
### Benefits

- ▶ **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.

### Applications

- ▶ This research is also applicable to transonic aircraft design as well as any design with moderate or higher leading-edge sweep angles where crossflow is a primary transition mechanism.

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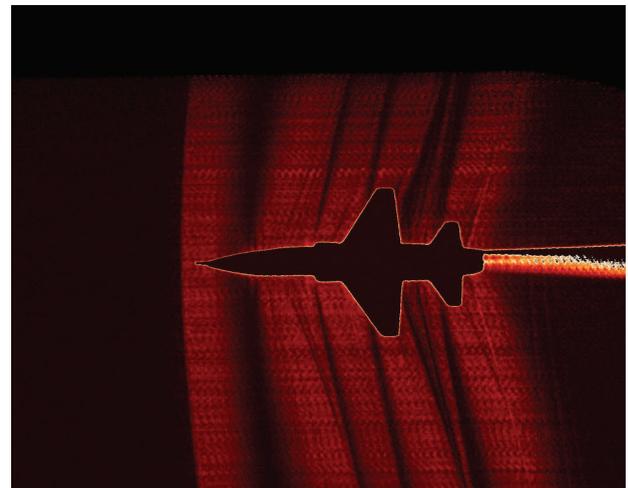
## Using Schlieren Techniques to Understand Sonic Booms

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 techniques use a speckled background to visualize air density gradients caused by aerodynamic flow.

**Work to date:** In April 2016, a flight series from Armstrong successfully demonstrated the Background Oriented Schlieren Using Celestial Objects (BOSCO) technology, which uses a celestial object, such as the sun, as a background to secure unique, measurable shock wave images previously attainable only in wind tunnels. The patented image-processing technology captures hundreds of observations with each shock wave, benefitting NASA engineers in their efforts to develop a supersonic aircraft that will produce a soft “thump” in place of a disruptive sonic boom. The 2016 flights at the U.S. Air Force Test Pilot School captured visual data of shock waves produced by a T-38 aircraft traveling at supersonic speeds.

**Looking ahead:** In addition to more BOSCO flights in 2018, Armstrong researchers are planning two additional flight campaigns for a complementary schlieren technology known as Air-to-Air Background Oriented Schlieren (AirBOS). This technique produces shock wave images using the desert floor as a speckled background. First demonstrated in 2011, AirBOS has undergone significant instrumentation upgrades. 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 also includes imaging subsonic aircraft flow fields.

**Partners:** NASA’s Ames Research Center 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, helping engineers design better and quieter supersonic airplanes.

### Applications

In addition to studying shock waves for supersonic and subsonic 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 and rotorcraft
- ▶ Highway traffic (e.g., trucks)
- ▶ Volcanic eruptions

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## Quantifying and Measuring Sonic Booms

Because the Federal Aviation Administration (FAA) has not yet defined a maximum allowable sonic 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 wireless network-controlled microphones strategically placed within communities.

**Work to date:** The Armstrong team is continuing to advance NASA's understanding of sonic boom phenomena via boom tests. This includes the **Sonic Booms in Atmospheric Turbulence (SonicBAT)** project, which is working to develop analytical and numerical models of the effects of atmospheric turbulence on noise levels and then validate the models using research flights. Flights were performed in the hot-dry climate of Edwards Air Force Base in California and the hot-wet climate of NASA's Kennedy Space Center in Florida to study the different effects of the two turbulence climates.

The **Waveforms and Sonic Boom Perception and Response (WSPR)** project is defining techniques and instrumentation required to perform sonic boom community response testing. Researchers are assessing possible recruitment, sampling, and surveying methods for effective sonic boom response. The project is also developing new instrumentation and analysis tools to correlate sonic boom noise levels with human responses across large communities. Recent exploratory research flights have been at Edwards Air Force Base.

The Armstrong team, along with industry and academic partners, has 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.

The team also utilizes the **Airborne Acoustic Measurement Platform (AAMP)**, a TG-14 motorglider with a high-quality microphone mounted on its wing, to measure sonic booms up to 12,000 feet above the ground. This test equipment is used to record sonic booms generated through special piloting techniques specifically designed for sonic boom placement and mitigation. Also in use is a unique F/A-18 dive maneuver called a "low boom dive" that simulates what future, quiet commercial supersonic airplanes may sound like.

**Looking ahead:** Planning is underway for testing community response to the quiet sounds of future supersonic aircraft in an area where residents are unaccustomed to sonic booms. Recent sonic boom noise response efforts have focused on tools and methodology and were performed at small military locations that frequently experience sonic booms. Future projects will implement the newly developed strategies and technologies on large communities across the country that are representative of the national demographic. These activities will play a key role in testing an anticipated low noise sonic boom flight demonstrator aircraft.

**Partners:** NASA's Langley Research Center and Kennedy Space Center, KBRwyle, Pennsylvania State University, The Boeing Company, Gulfstream Aerospace, Lockheed Martin, Applied Physical Sciences Corp., Volpe National Transportation Systems Center, Eagle Aeronautics, Gaugler Associates, and Fidell Associates

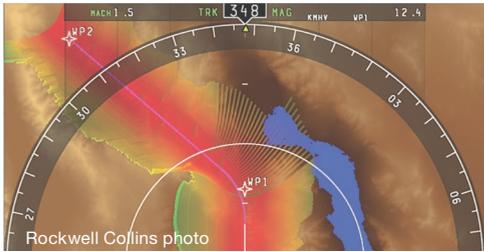
### Benefits

- ▶ **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.
- ▶ **Quantifies perceptions:** Data from these programs includes public reaction, which will be critical as the FAA considers allowing overland supersonic flight.

### Applications

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

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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 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, allowing 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 demonstrated in March 2017 during supersonic flights on an F/A-18, which compared computations with boom measurements on the ground. A collaboration with Rockwell Collins helped advance the system and implement the capability to utilize a worldwide terrain database to predict where and how a sonic boom will impact the

ground as well as at what sound pressure level. The system was integrated into NASA's Quiet Super Sonic Technology (QueSST) simulator at Armstrong.

**Looking ahead:** Next steps for the team are to implement a flight planning and guidance application and to define noise standards.

**Partner:** Rockwell Collins

### Benefits

- ▶ **Enables overland supersonic travel:** Because pilots can control the location and intensity of sonic booms, the system may allow future-generation supersonic aircraft to fly overland.
- ▶ **Provides a tool for the FAA:** Software such as CISBoomDA could provide the Federal Aviation Administration (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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Test pilots head for a mission debrief after flying a NASA F/A-18 to create sonic booms as part of the SonicBAT flight series at Armstrong.



## Flying Qualities for Low Boom Vehicles

Armstrong innovators are developing guidelines and evaluating stability and control characteristics for the planned supersonic Low Boom Flight Demonstration (LBFD) experimental airplane. NASA is working to develop aircraft that can fly at supersonic speeds and deliver a soft “thump” instead of the disruptive boom associated with supersonic flight today. In June 2017, NASA and Lockheed Martin completed the preliminary review of the unique aircraft’s initial design. In addition to stability and control evaluations, Armstrong researchers are anticipating the need to develop a supersonic cruise autopilot that maintains the desired flight path and conditions while minimizing perceived sonic boom noise levels on the ground.

**Work to date:** Armstrong researchers have developed a pilot-in-the-loop and batch non-linear simulation based on the initial models. The team has used the simulation to analyze vehicle stability, controllability, and handling qualities and to design trade studies on speed brakes, gear brakes, and approach and landing control system types.

**Looking ahead:** As design iterations continue, the Armstrong team will refine stability and control characteristics. In addition, the team anticipates developing a database for use in designing the supersonic autopilot that will factor in the perceived boom level on the ground due to the stabilator position on the aircraft.

**Partners:** NASA’s Langley Research Center and Lockheed Martin

### Benefits

- ▶ **Integrated research:** Enables NASA to become more aware of relevant issues, due to independent analysis of stability and control characteristics
- ▶ **Advanced:** Works to manage sonic boom noise levels through innovative autopilot design

### Applications

- ▶ LBFD support
- ▶ Subsequent commercial supersonic aircraft design



## CFD Study of Nozzle Plume Effect on Sonic Boom Signature

Armstrong researchers investigated the effects of nozzle exhaust jet plumes on the sonic boom signatures of supersonic aircraft. Supersonic flight over land is currently restricted because sonic booms created by shock waves disturb people on the ground and can damage property. To date, most research has concentrated on the external aerodynamic shape of the aircraft, without concern for the engine inside. This effort used computational fluid dynamics (CFD) to study nozzle exhaust plume effects. The results will be useful as NASA considers its Quiet Supersonic Transport (QueSST) design.

**Work to date:** The CFD study observed nozzle plume effects on the tail shock pressure signature of the NASA Lift and Nozzle Change Effects on Tail Shock (LaNCETS) NF-15B supersonic research aircraft. Solution sensitivities to CFD grid refinement, aircraft geometry details, aircraft inlet cowl positions, nozzle CFD in-flow boundary locations, and aircraft nozzle operating conditions were examined. Researchers found that an adaptive mesh refinement is a highly beneficial solution for capturing sharp shocks as well as complex flow and aircraft geometric features.

Researchers identified sources for the various shocks in the near-field and far-field sonic boom signatures of the aircraft. The engine nozzle’s location at the aft end of the airplane provides unique opportunities to shape the aircraft’s tail shock and lower the sonic boom signature. A higher nozzle exit pressure and downward nozzle thrust vectoring in pitch yielded smaller aircraft tail shocks, which is beneficial for low-boom aircraft designs. The beneficial effects were found to propagate all the way to the ground, resulting in a small but observable decrease in the aircraft’s tail shock strength.

Researchers produced and presented an analytical research paper at the Joint Army-Navy-NASA-Air Force (JANNAF) Propulsion Meeting in May 2016.

# 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.



## Towed Glider Air Launch System (TGALS)

TGALS is an innovative approach to launching satellites into space that significantly lowers costs and flight risks. The approach involves towing an inexpensive, reusable remotely piloted glider carrying a launch vehicle behind a conventional airplane. Once the proper altitude, direction, and speed are reached, the glider is released and maneuvered to the desired flight conditions to release the launch vehicle with its satellite or other science payload to boost it into orbit. The approach allows for increased payload weight, expanded launch windows, deployment of a wide range of launch vehicles with varying geometries, and reduced development costs associated with testing new rocket designs. This approach could significantly reduce the cost and improve the efficiency of sending satellites into orbit.

**Work to date:** The concept has undergone analysis, simulation, and design of a glider that can carry an 80,000-pound rocket. Successful flight tests involved towing a custom-made, twin-hulled sailplane model built primarily with commercial off-the-shelf components. The one-third scale, 27-foot-wingspan towed aircraft was released and glided to a perfect landing, confirming that a dual-fuselage glider could be used in this application.

**Looking ahead:** 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 direct-carry conventional aircraft of the same size.
- ▶ **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.

### Applications

- ▶ Weather monitoring/forecasting
- ▶ Hazard/Disaster monitoring
- ▶ Navigation
- ▶ Earth science and space weather research

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## Heavy-Lift Mid-Air Retrieval



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

(3G MAR) system to recover valuable and relatively heavy space assets that return to Earth. The 3G MAR 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 its maneuvers comply with federal regulations for helicopter long-line operations; therefore, it does not need to be modified or reclassified to retrieve payloads. Another goal of this research is to investigate the feasibility of retrieving objects that weigh the full lift capacity of the most capable heavy-lift helicopters. Mid-air retrieval is a candidate within the Entry, Descent, and Landing Systems Technology Area of NASA's 2015 Technology Roadmaps.

**Work to date:** On three separate occasions in 2016, the 3G MAR successfully retrieved a 1,100-pound payload. In addition, Airborne Systems performed an aeromechanical system study that determined that a stitched-textile load-limiting device (LLD) can protect a pickup helicopter during mid-air retrieval of up to 10,000-pound objects.

Results of a feasibility study were reported at the Commercial and Government Responsive Access to Space Technology Exchange in Westminster, Colorado, in June 2016.

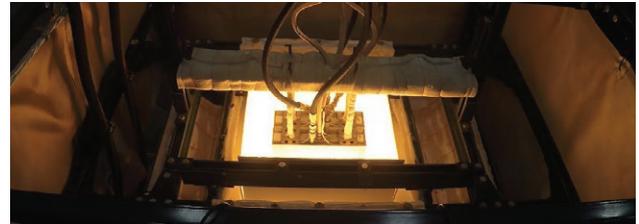
**Looking ahead:** Airborne Systems is developing a 10,000-pound-class textile LLD that will be ground tested to verify its load-limiting characteristics.

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

### Benefits

- ▶ **Reduced 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

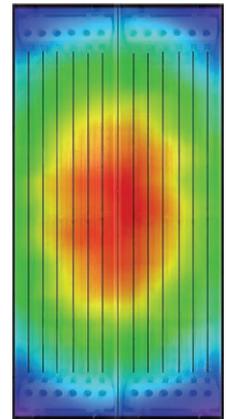
PI: John Kelly | 661-276-2308 | John.W.Kelly@nasa.gov



## Heat Flux Mapping System

Researchers at Armstrong have developed a technique to map the heat flux distribution of a radiant heating system. This technique is designed to generate data that will improve the correlation of measured thermal test data to analytical results of hot structure components. The Flight Loads Laboratory at Armstrong uses radiant heaters to simulate thermal loads imparted to vehicle structures during hypersonic flight. Researchers use various radiant heater layouts and boundary conditions to apply a specific heat flux to the test structure surface to match the predicted surface temperature-time history response.

This research effort involves developing a methodology for estimating the heat flux distribution provided by a defined heater array. To quantify the heat flux distribution of the heater array, the output of radiant heaters needs to be characterized in multiple configurations. The goal is to determine the relationship between the heat flux distribution and the radiant heater configuration, power level, heater height, and boundary conditions. Obtaining further insight into these relationships increases the accuracy with which the heat flux distribution of a heater array can be quantified, thus providing structural analysts with additional information for improved test-to-analysis correlation by factoring in the design of heater arrays.



**Work to date:** Testing occurred in spring and summer 2017. A student intern developed documentation that will be useful for future testing scenarios.

**Looking ahead:** Research will continue in February 2018. The team will test higher heat fluxes with varying heater arrays and boundary conditions.

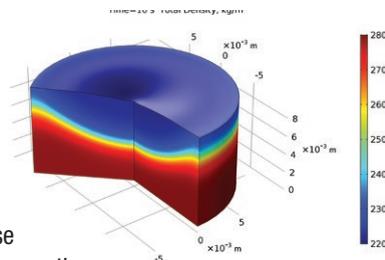
### Benefits

- ▶ **High performance:** Provides a two-dimensional map of the heat flux distribution as a function of the power level, height, and boundary conditions for a given configuration of radiant heaters
- ▶ **Effective:** Increases the accuracy with which the heat flux distribution of a heater array can be quantified for the purpose of improving the correlation between test data and analysis

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# Verification of Finite Element Models for Pyrolyzing Ablative Materials

This research effort is implementing the capability to model complex pyrolyzing ablation problems using commercial general-purpose software platforms. NASA currently uses customized in-house finite element analysis (FEA) tools to predict the thermal and ablative response of pyrolyzing materials. However, recent improvements in commercial FEA products offer the possibility of numerous benefits for ablation analysis, including versatility, usability, technical support, and more. NASA already uses commercial codes for much structural and computational fluid dynamics (CFD) analysis and design work. Adding ablation modeling and analysis to a commercial package that also offers structural and CFD fluid flow capabilities would establish an efficient and cost-effective modeling process.



**Work to date:** Researchers have computed and compared results for several test problems using the commercial COMSOL Multiphysics® and Abaqus® finite element codes. Results were verified using other well-validated computational tools, demonstrating that the general-purpose software platforms are suitable and advantageous for analyzing pyrolyzing ablators.

**Looking ahead:** Researchers will continue to investigate ways to incorporate ablation modeling and analysis into commercial packages that perform thermal, structural, and fluid modeling. In the case of the Abaqus tool, future work will investigate the feasibility of extending a proposed FEA procedure to two- and three-dimensional pyrolyzing ablation problems. Researchers will also investigate the effectiveness, limitations, and applicability of the proposed procedure for a broader range of ablation conditions.

COMSOL Multiphysics is a registered trademark of COMSOL, Inc. Abaqus is a registered trademark of Dassault Systèmes Simulia Corp.

## Benefits

- ▶ **Flexible:** Enables modifications and additions to ablation models to be incorporated into applications that model structural and other phenomena
- ▶ **Validated:** Offers a large user base that is essentially verifying the solution algorithms and accuracy of the code
- ▶ **Cost-effective:** Provides a dedicated support staff serving many users

## Applications

- ▶ Thermal protection systems
- ▶ Spacecraft systems

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## Motivation for Air Launch

This research effort examined the motivation for and application of air launch as a means of solving aeronautical and aerospace problems in military, civil, and commercial contexts throughout history and into the future. Air launch is defined as two or more air vehicles joined and working together that eventually separate in flight and that have a combined performance greater than the sum of the individual parts. These include airplanes, airships, blimps, balloons, space launch vehicles, and guided munitions, to name a few.

**Work to date:** The white paper identified the many uses of air launch:

- ▶ Lifting early gliders
- ▶ Demonstrating the aero-tow technique
- ▶ Augmenting air forces to move materiel and troops and to deliver munitions
- ▶ Extending flight distances for commercial transport
- ▶ Researching advanced aerodynamics and systems
- ▶ Enabling new military missions
- ▶ Launching satellites into space

The white paper produced by the effort was published in September 2017 by the American Institute of Aeronautics and Astronautics.

**Looking ahead:** Air launch is envisioned as a means of enabling future services, including delivering consumer goods, sending tourists above the Karman line (100 km/62 miles above sea level), and delivering satellites into orbit.

## Benefits

This white paper advances NASA's understanding of the benefits associated with using air launch to solve aeronautical and aerospace problems.

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# 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.



## Automatic Dependent Surveillance-Broadcast (ADS-B) System

Innovators at Armstrong and Vigilant Aerospace Systems collaborated for the flight test demonstration of an integrated ADS-B-based collision avoidance technology on a small unmanned aerial system (UAS) equipped with a micro ADS-B transceiver. The ADS-B Detect-and-Avoid (DAA) system is capable of providing small UAS with air-to-air collision avoidance against manned or unmanned vehicles.

NASA licensed its technology in 2016 to Vigilant Aerospace, and the company has commercialized it as part of its FlightHorizon™ product suite. Vigilant Aerospace joined unmanned aircraft response teams in Houston after Hurricane Harvey and used this technology to provide damage assessment and data collection services to the Federal Emergency Management Agency (FEMA) as it assessed flood damage in the greater Gulf Coast region.

**Work to date:** Armstrong and Vigilant Aerospace successfully flight tested the ADS-B DAA system in December 2016 on the DJI Phantom 4 quadrotor small UAS to further develop the technology in three key areas: flight beyond visual line of sight, collision avoidance, and autonomous operations. The system was also deployed in NASA's Sonic Booms in Atmospheric Turbulence (SonicBAT) research in August 2017.

**Looking ahead:** The team is working to develop an ADS-B ground station for NASA's Conformal Lightweight Antenna Structures project, which is developing antennas that enable beyond-line-of-sight command and control for UAS. The team is also working to demonstrate a similar system on Boeing F/A-18 and F-15 platforms for supersonic flight operations.

**Partner:** Vigilant Aerospace Systems

FlightHorizon is a trademark of Vigilant Aerospace Systems, Inc.

### Benefits

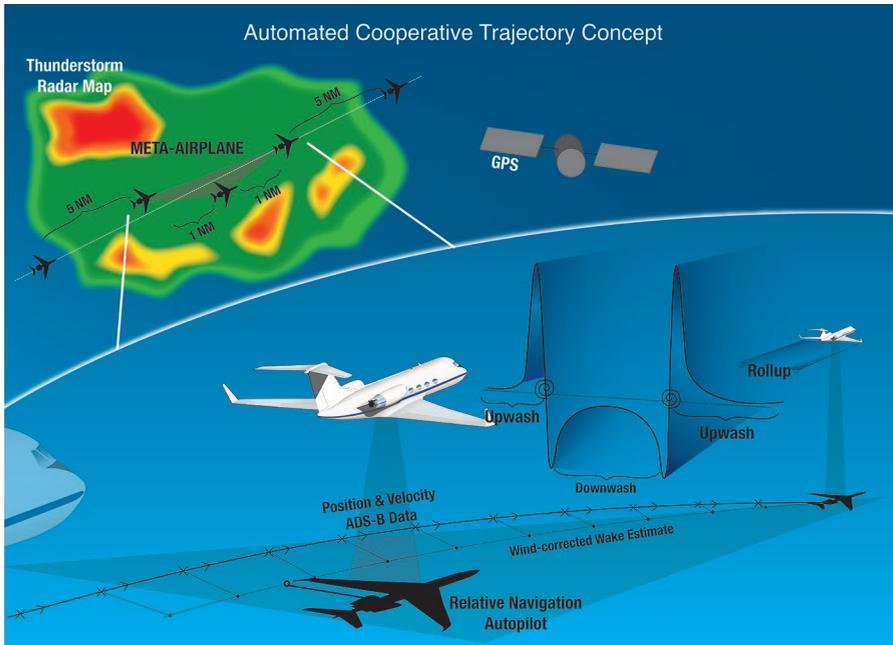
- ▶ **Improves safety:** Enhances detect-and-avoid capabilities to maintain self-separation for UAS
- ▶ **Highly accurate and fast:** Broadcasts position 120 miles in every direction, providing location data that are accurate to within 5.7 feet every 1 second

### Applications

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

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# Automated Cooperative Trajectories (ACT) Programmable Autopilot



Aircraft wakes contain 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 by retrimming at a lower angle of attack and power setting to maintain level flight and constant airspeed. Previous flight tests with military aircraft have shown that this procedure can reduce fuel burn by 7 to 10 percent, even at extended trailing distances of more than a nautical mile.

The main objective of the recent NASA ACT flight experiment was to demonstrate a similar benefit for civilian aircraft. Researchers also sought to evaluate the suitability of ADS-B for precise cooperative trajectory control applications such as wake surfing and characterize the

Armstrong conducted a series of research flights in 2016–2017 to better understand the challenges of aircraft wake surfing using civilian airplanes and avionics. Obstacles to the widespread adoption of aircraft wake surfing by civilian operators include the potential costs of avionics upgrades, impacts to passenger ride quality, and aircraft wear and tear. A primary goal of the NASA research flights was to ascertain whether significant fuel savings can be realized by a pair of aircraft engaged in ACT wake surfing using a civilian transport-like airframe and commercial off-the-shelf (COTS) avionics, including a 1,090 MHz automatic dependent surveillance-broadcast (ADS-B) data link.

NASA equipped a Gulfstream C-20A aircraft with an experimental programmable autopilot that contained wake-relative navigation algorithms and trajectory-tracking control laws. The programmable autopilot interfaced with a COTS “ADS-B In” receiver and controlled the airplane via localizer and glideslope commands to the production autopilot instrument landing system. The C-20A flew as the trailing airplane at multiple locations within the wake of a Gulfstream III aircraft.



impacts of wake surfing on passenger comfort. Eventually, NASA researchers hope to transition the benefits of this technology to commercial cargo and passenger operations.

**Work to date:** Milestones achieved to date include:

- ▶ The project completed a flight demonstration of ADS-B-enabled ACT operations with two aircraft.
- ▶ Researchers gathered in-flight measurements of performance benefits and ride-quality impacts of wake surfing.

**Looking ahead:** ACT project personnel are completing their analysis of the flight data and preparing technical reports. The flight research results will be shared with airframe and avionics manufacturers as well as cargo and passenger transport operators.

## 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 10 percent
- ▶ **Improved ATC workload:** Allows monitoring and directing of several aircraft at a time—as though they were a single entity—via active communication and coordination of flight paths



## 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. These systems will also 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 quadcopter and multi-rotor transition aircraft 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 an industry standard practice has been developed based on this concept. This standard is the first FAA-approved approach for a means of certifying an autonomous aircraft.

**Looking ahead:** The team will expand the scope and coverage of the safety-critical functions by integrating and tailoring them to a multi-rotor small unmanned aircraft for package delivery and a general aviation piloted aircraft.

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

### Benefits

- ▶ **Increased 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 aircraft
- ▶ Unmanned submersibles
- ▶ Autonomous rail transport
- ▶ Deep space exploration
- ▶ Driverless vehicles

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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 unmanned aircraft.

**Work to date:** Center Innovation Fund resources enabled Armstrong researchers to:

- ▶ Construct a stereo vision system
- ▶ Assemble and develop software tools for processing and analyzing stereo vision data
- ▶ Functionally verify that the stereo vision system works properly
- ▶ Conduct static testing of the stereo vision system to characterize its ability to range objects and terrain
- ▶ Determine design specifications for adapting a stereo vision system to an autonomous aircraft for NASA's Traveler project

**Looking ahead:** The team will expand the scope and coverage of the safety-critical functions by integrating and tailoring them to a multi-rotor package delivery small unmanned aircraft and a general aviation piloted aircraft.

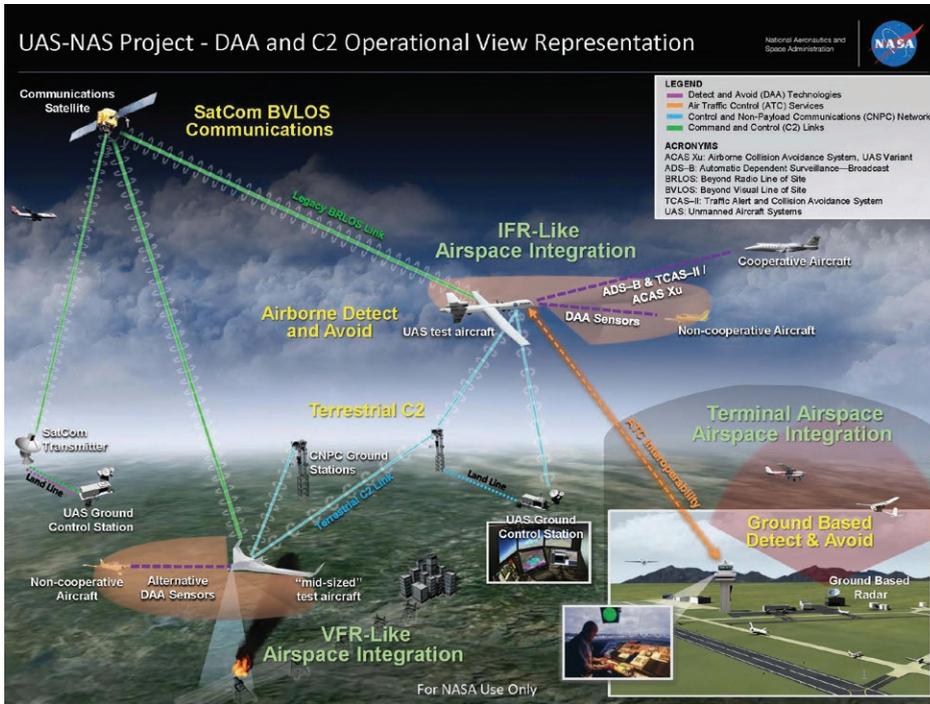
**Partners:** NASA's Jet Propulsion Laboratory and the University of Tulsa

### Applications

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

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



Development of these concepts and technologies is in support of standards to enable a broad range of UAS that have communication, navigation, and surveillance capabilities consistent with instrument flight rules.

**Work to date:** Successful completion of the first phase (2011–2016) research portfolio included:

- ▶ Executing multiple lab tests, batch and human-in-the-loop simulations, and flight tests
- ▶ Developing and implementing C2 radio and DAA alerting logic and maneuver guidance
- ▶ Providing an unmanned aircraft DAA system for Minimum Operational Performance Standards (MOPS) development and verification and validation (V&V)
- ▶ Providing a C2 radio system for MOPS development and V&V
- ▶ Technology transfer of all research findings

Armstrong is leading this multi-center research project that is developing technologies with industry to 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 (DAA) technologies and robust communications systems.

Providing critical data to such key stakeholders as the Federal Aviation Administration (FAA) and the RTCA Special Committee 228 (SC-228), the project is conducting system-level tests in a relevant test environment to address safety and operational challenges. The project falls under the Integrated Aviation Systems Program Office in NASA's Aeronautics Research Mission Directorate and is addressing two technical challenge areas:

- ▶ Develop DAA operational concepts and technologies to detect and avoid both manned and unmanned air traffic
- ▶ Develop satellite- and terrestrial-based command-and-control (C2) operational concepts and technologies to leverage allocated protected spectrum



Work began on the second phase (2017–2020) research portfolio and included the successful completion of a multi-partner flight test campaign of two prototype Airborne Collision Avoidance System – Xu (ACAS-Xu) units onboard the Ikhana unmanned aircraft. National and international stakeholders attended a VIP Day at Armstrong to commemorate the successful completion of the campaign.

**Looking ahead:** The second phase of the project continues. Researchers are utilizing simulation and flight tests in support of RCTA SC-228's Phase 2 MOPS and overall UAS integration needs. The plan is to demonstrate UAS operations in the NAS employing state-of-the-art DAA, C2, and other vehicle/airspace operations technologies that inform FAA UAS integration policies and operational procedures.

**Partners:** General Atomics Aeronautical Systems; Honeywell International; Rockwell Collins; Aviation Communications & Surveillance Systems; and NASA's Ames Research Center, Langley Research Center, and Glenn Research Center

## Benefits

- ▶ This DAA, C2, and vehicle-level 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 jet 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 have also been incorporated into an application for tablet or other handheld/mobile devices that can be used by pilots in the cockpit, enabling significantly safer general aviation. This feature will give pilots access to this lifesaving safety tool regardless of the aircraft type. The system can also be incorporated into electronic flight bags (EFBs) and avionics systems.

The payoff from implementing the system, which was designed to operate on a variety of aircraft (e.g., military jets, unmanned aircraft, general aviation airplanes) with minimal modifications, 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 collision threats, including satellites, automobiles, scientific research vehicles, and marine charting systems.

**Work to date:** This improved approach to ground collision avoidance has been demonstrated on small unmanned aircraft, a Cirrus SR22, and an experimental Cozy Mark IV aircraft while running the technology on a mobile device. These tests proved the feasibility of the mobile 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. In 2017, the system was integrated with a commercial glass cockpit system, and flight tests began late in the fiscal year.

**Looking ahead:** Future versions of the technology may employ a phone's wireless capabilities to connect it to an airplane's autopilot system. It could 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 iGCAS can be used for a wide variety of aircraft, including general aviation, helicopters, and UAVs. The technology has been incorporated into an application for tablets and other handheld/mobile devices.

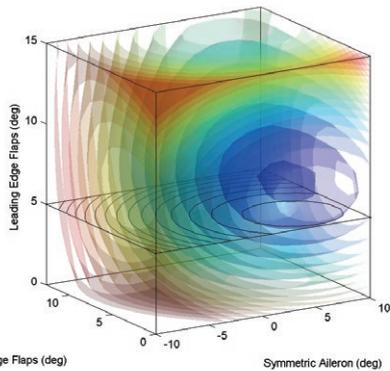
### Benefits

- ▶ **High-fidelity terrain mapping:** Armstrong's patented approach to digital terrain encoding enables the use of 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, unmanned aircraft, and fighter jets such as the General Dynamics F-16, 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 to avoid a collision, making it more appropriate for general aviation and unmanned aircraft.
- ▶ **Proven technology:** A follow-on to a system currently flown in F-16 test aircraft will be integrated into the aircraft's next generation for the U.S. Air Force's fleet.

### Applications

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

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## Peak-Seeking Control for Trim Optimization

Armstrong innovators have developed a peak-seeking algorithm that helps reduce drag and improve performance and fuel efficiency by enabling aircraft trim to be optimized 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 experiments on a modified Boeing F/A-18A and further refined it for implementation in the F/A-18E/F.

**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-18E/F military aircraft, and The Boeing Company is developing software for implementation in the aircraft's flight control computers.

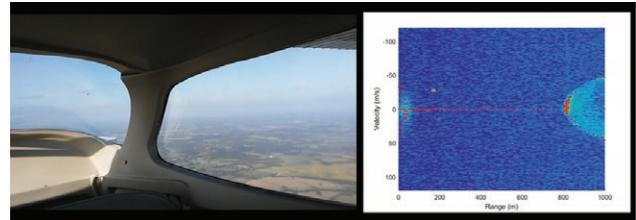
### Benefits

- ▶ **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
- ▶ Commercial airlines

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## Miniaturized Radar for Small Unmanned Aerial Systems (UAS)

Armstrong innovators are developing a miniature collision avoidance radar sensor for small UAS. Currently, commercial use of small UAS in the National Airspace System (NAS) is constrained by regulatory issues based on multiple safety concerns, some of which this technology addresses. This radar sensor is small, lightweight, and compact so that it can fit easily onto a drone. It is designed to determine the range, speed, and location of multiple hazards in real time and alert the drone to avoid a collision. The sensor operates day or night and in all weather conditions, detecting both cooperative and non-cooperative hazards. It can also transmit data to a ground station where operators can make flight decisions.

**Work to date:** In 2017, researchers completed a miniature prototype along with custom calibration setup and processing and real-time monitoring software. The team also successfully completed four manned aircraft flight tests, during which the radar successfully detected and tracked a Cessna-172.

**Looking ahead:** Next steps are to schedule unmanned flight tests, refine the sensor design, and integrate it with an autopilot or flight director. The team is also hoping to fly the technology on Armstrong's unmanned Prototype-Technology Evaluation and Research Aircraft (PTERA) testbed in 2018.

**Partner:** University of Kansas

### Benefits

- ▶ **Safety:** Enhances detect-and-avoid capabilities for small UAS, increasing safety for other aircraft as well as persons and property on the ground
- ▶ **Enabling:** Provides critical situational awareness for operation of UAS in the NAS
- ▶ **Robust:** Operates day or night; in rain, fog, and clouds; and more reliably than sensors based on cameras or lasers
- ▶ **Lightweight and compact:** Weighs just 32 ounces and measures 4x3x4 inches

### Applications

- ▶ Package delivery
- ▶ Search and rescue
- ▶ Surveillance
- ▶ 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 guidance and communication system designed to provide unmanned aircraft with autonomy in single- and multi-vehicle scenarios. Within the ReMAP framework, the operator's focus shifts away from agent task assignment to mission definition and observation, enabling a single operator to carry out safe operation and integration of multiple unmanned aircraft into the National Airspace System (NAS). Developed by Area-I via the Small Business Innovation Research (SBIR) program, the ReMAP system applies the concept of reducing operator workload and multi-vehicle teaming to real systems. Developers focused on using low-cost and low-computation-power hardware, increasing robustness to varying missions in real time, and enhancing functionality in a wide variety of missions and platforms.

**Work to date:** The system development has been highly coupled with testing, using hardware-in-the-loop simulation and actual flight testing of simultaneous unmanned aircraft. Initial flight tests demonstrated system feasibility and identified enhancements, some of which have been implemented and flight tested. Work now is focused on furthering the guidance and navigation module for more complex missions while increasing system robustness, culminating in manned and unmanned avoidance tests.

**Looking ahead:** Next steps are to continue flight tests and expand functionality to missions that include air, sea, and land agents.



**Partner:** Area-I

### Benefits

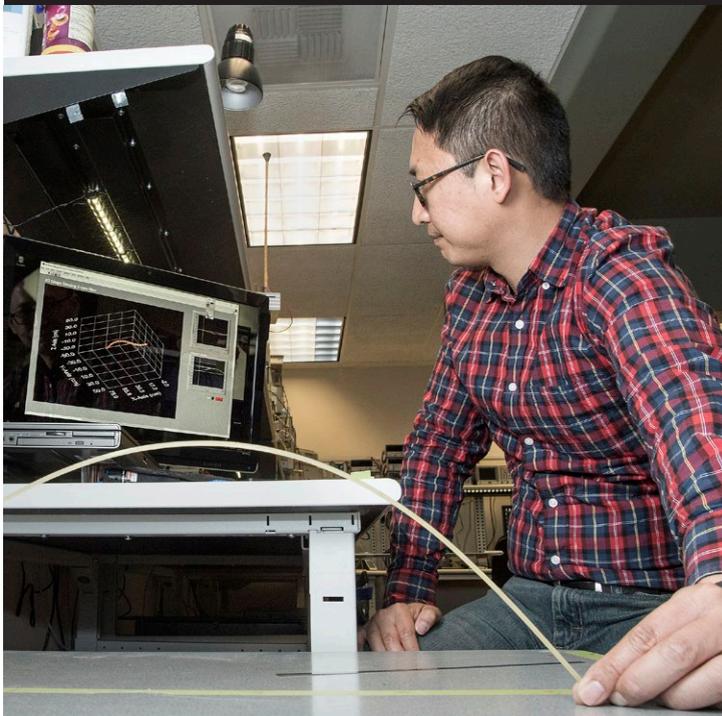
- ▶ **Effective:** Provides real-time guidance capabilities to unmanned aircraft
- ▶ **Flexible:** Features a system architecture that is platform and autopilot agnostic and therefore usable by a wide array of aircraft
- ▶ **Innovative:** Allows coordination of multiple aircraft due to use of a multi-agent planning and control algorithm
- ▶ **Improves safety:** Provides autonomous avoidance of manned and unmanned aircraft, generates safe routes around obstacles, and provides operator warnings to maximize situational awareness
- ▶ **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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NASA's C-20A, with Generation Orbit's hypersonic pod attached, undergoes flight test over Armstrong.

# 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.



## ARMED Flight Data Portal (AFDP)

Armstrong is taking the lead on a NASA-wide project in the Aeronautics Research Mission Directorate (ARMED) that will enhance flight research and test capabilities by improving the management of test data. The AFDP will replace the legacy Flight Data Archival System (FDAS), in place since 1980. An effective resource for its time, FDAS archives flight data but offers no corresponding analysis or related information. The new data portal will archive all test flight data for the four NASA centers involved in flight testing along with contextual information needed to understand and analyze the data: mission overviews, flight profiles, daily summaries, mission debriefs, and more. A robust search mechanism and intuitive graphical user interface (GUI) will further make the AFDP a meaningful flight test resource. Online and accessible to all with NASA credentials, the AFDP will increase collaboration across NASA centers.

**Work to date:** A 5-year project, work began in 2016 and is proceeding in three phases. Phase I involves the upfront work to build the portal, and Armstrong is leading this effort. The team is focusing on the X-57 experimental airplane project as a test case, including all flight data and contextual information to ensure the portal operates as intended. This phase will be operational in March 2019.

**Looking ahead:** Phase II will add all flight test projects from NASA's Langley Research Center, Glenn Research Center, and Ames Research Center and will be operational in January 2021. Phase III will be completed by August 2022.

### Benefits

- ▶ **Enhances research capabilities:** Enables rapid location of test flight, simulation, and loads test data along with corresponding contextual information
- ▶ **Increases collaboration:** Accessible to all NASA personnel via online system
- ▶ **Easy to use:** Features a user-friendly GUI and search mechanism

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USEWX-equipped aircraft supported research conducted in 2017 during the solar eclipse and over polar routes.

## 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 several 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 measurements are needed to improve radiation forecasting and space weather understanding.

**Work to date:** The USEWX team expanded flight experiments in 2016 and 2017. The Automated Radiation Measurements for Aerospace Safety (ARMAS) dosimeters collected data on 344 flights of these aircraft:

- ▶ Armstrong's Douglas DC-8, Gulfstream III (G-III), Stratospheric Observatory for Infrared Astronomy (SOFIA), and Lockheed ER-2 aircraft
- ▶ National Oceanic and Atmospheric Administration's Gulfstream IV
- ▶ National Science Foundation's Gulfstream V
- ▶ Federal Aviation Administration's Bombardier Global 5000
- ▶ Numerous commercial aircraft

The USEWX-equipped G-III supported research conducted during the August 21, 2017, solar eclipse by taking radiation measurements with the ARMAS FM5 and a thermal neutron detector. The G-III found space weather events that temporarily increased the radiation environment for part of the flight.

**Looking ahead:** Space Environment Technologies (SET) is moving into production with the ARMAS FM6, a commercial dosimeter designed for corporate jet fleet owners and operators. SET is also building an FM4 for a World View Enterprises high-

altitude balloon flight under NASA's Flight Opportunities program. In addition, plans are underway to:

- ▶ Upgrade the dosimeter used by the DC-8 aircraft
- ▶ Begin work on assimilating data from ARMAS into NASA's Langley Research Center's Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) model to achieve radiation weather forecasting
- ▶ Integrate a new dosimeter into the Armstrong high-altitude PRANDTL weather glider

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

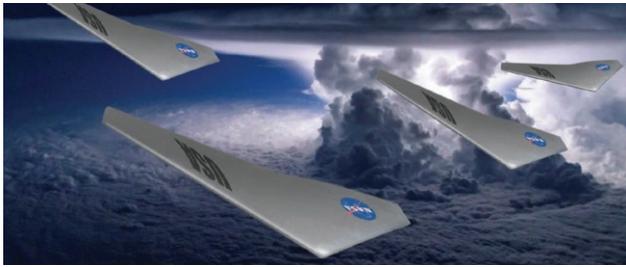
### Benefits

- ▶ **Provides access to critical data:** Provides radiation data for the purposes of guarding against human dosing, radio blackouts, 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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## Weather Hazard Alert and Awareness Technology Radiation Radiosonde (WHAATRR) Glider

An airborne science platform under development at Armstrong could one day provide weather scientists with more accurate, timely, and economical information on weather phenomena. Envisioned as a subscale aircraft jam-packed with sensors, instruments, and flight-control software, the WHAATRR glider is based on Armstrong's PRANDTL-M, a fixed-wing glider the center is developing to carry out low-altitude reconnaissance missions on Mars. Unlike when gathering data from weather balloons, scientists will be able to control the WHAATRR glider as it speeds through the skies collecting weather data. Armstrong researchers predict the glider will improve weather forecasting, saving the National Weather Service up to \$15 million a year and reducing costs incurred from unnecessary airline delays.

**Work to date:** A Center Innovation Fund award enabled the Armstrong team to complete a glider design that includes a small unmanned aircraft and state-of-the-art dosimeters and sensors. The glider will have a wingspan of about 3 feet and be constructed of double-ply carbon fiber. The project received a NASA Innovation Kick Start grant in 2016, which provided up to \$10,000 in startup funds.

**Looking ahead:** The next step will be an air launch from a weather balloon. The goal is to eventually drop the glider equipped with its instrumentation suite from 100,000 feet (a Mars-like atmospheric environment) and remotely pilot it to a predetermined location.

### Benefits

- ▶ **Reusable:** Detects aviation weather hazards then returns to its launch site for reuse
- ▶ **Improves safety:** Provides radiation data for purposes of guarding against human dosing while also measuring temperature, humidity, pressure, and wind speed
- ▶ **Saves money:** Provides faster and more reliable data compared to current collection methods

### Applications

- ▶ Data collection
- ▶ Weather modeling and research

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## Ethernet via Telemetry (EVTM)

This research effort is focused on developing a network-based telemetry system that transmits data between ground stations and research aircraft using less bandwidth than traditional telemetry methods. The EVTM system is an improvement over static, one-way pulse code modulation (PCM)-based systems that have crowded the frequency spectrum as research projects become more complex and involve larger amounts of data. The new system can move data at 40 megabits per second, 10 times faster than current systems Armstrong researchers are using. EVTM establishes a dynamic link between ground stations and research aircraft, enabling users to specify data rates and reallocate resources to free up space for other applications.

**Work to date:** In 2016, researchers successfully flight tested the system on a NASA 801 King Air aircraft equipped with a single EVTM antenna. The team also established a proof of concept for next-generation range capabilities that use higher level networking protocols and features. The team then evaluated those features across two advanced modulation techniques.

**Looking ahead:** With resources from NASA's Center Innovation Fund, the team is investigating how to use EVTM to advance flight test data acquisition capabilities.

### Benefits

- ▶ **High performance:** Features direct Ethernet network compatibility and provides bidirectional communication
- ▶ **Efficient:** Allows for real-time ground-based experiment control while using less bandwidth
- ▶ **Advanced:** Offers reconfigurable downlink data architecture
- ▶ **Convenient:** Allows frequency spectrum reallocation

### Applications

- ▶ Flight research
- ▶ Aircraft-to-ground and aircraft-to-aircraft data communication

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## Fiber Optic Sensing System (FOSS)

Developed for aeronautics research at Armstrong, FOSS is solving technical instrumentation challenges within the agency and beyond. What started as a table-sized collection of fiber optics and sensor mechanisms now is a simpler and lighter solution the size of a shoebox. It is being widely used throughout NASA to support research projects as varied as investigating techniques for quieting sonic booms, measuring wing displacement and twist, and examining composite tank failures. FOSS is also being actively considered for use in a wide range of applications beyond NASA by the aerospace, engineering, automotive, medical, and energy sectors.

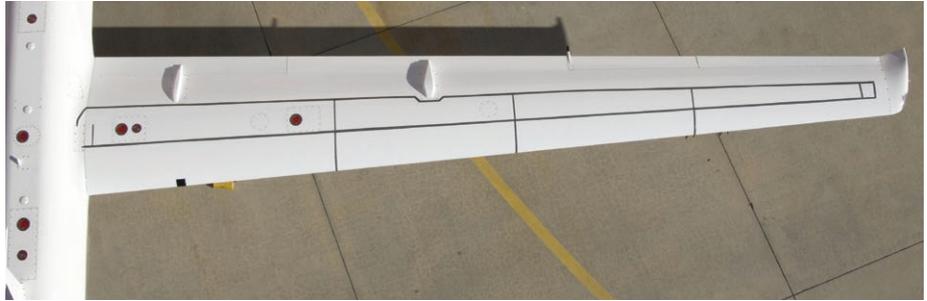
The state-of-the-art sensor system measures in real time a variety of critical parameters, including strain, shape deformation, temperature, liquid level, and operational loads. Each of the up to eight 40-foot hair-like optical fibers provides up to 2,000 data points with adjustable spatial resolution for a total of 16,000 sensors per system. To achieve these 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 the WDM sensors can be sampled at rates up to 35,000 times per second for highly dynamic applications.

Here are just a few of the current ways the FOSS team is supporting NASA projects.

**X-56A Multi-Utility Technology Testbed (MUTT):** FOSS will collect real-time strain data to enable researchers to see dynamic changes on the wings that could result in flutter.

**Low Boom Flight Demonstration (Lbfd) aircraft:** The FOSS team is working on two fronts to advance NASA's efforts to prepare for the Lbfd experimental aircraft. One effort is validating the algorithms that would be used to ensure the system can provide required twist measurements. The other is integrating the avionics and sensors so that the FOSS system will be NASA-qualified to fly in the research aircraft.

**Safety-critical certification:** Multiple research projects at Armstrong would like to use FOSS for real-time calls in the control room related to structural monitoring and/or flight control. The team is working to ensure that software is written and implemented in a way that allows it to be certified as



safety critical to meet NASA flight requirements. The hardware is also being reworked to ensure that it is robust enough for flight.

**Fiber optic augmented reality system:** This effort is working to visualize the individual measurements FOSS provides in a way that helps engineers understand how to view and analyze the (at times overwhelming amount of) data provided by the system.

**NASA Launch Services Program's investigation of composite tank failures:** NASA Engineering Services Center has asked the FOSS team to provide instrumentation and support for test articles as well as the models under development.

**Looking ahead:** The team continues to refine the FOSS algorithms as needed to support additional applications. This work is advancing achievements in strain sensing as well as algorithms related to determining twist, displacement, and more.

### Benefits

- ▶ **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, enabling precise, high-resolution measurements in locations where conventional strain gauges will not fit (e.g., within bolted joints, in composite structures).

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## Fiber Optic Augmented Reality System (FOARS)

This research effort is working to visualize the individual measurements Armstrong's Fiber Optic Sensing System (FOSS) provides in a way that helps users understand how to view and analyze the data. FOARS is a mobile data visualization application that receives FOSS data via a wireless connection and then creates a three-dimensional (3-D) augmented version, superimposed over a target image. Currently, users must review and analyze FOSS data via conventional methods such as with the Excel® spreadsheet software or LabVIEW® programming, which require on-site computers. In contrast, the stand-alone FOARS app can be downloaded onto any mobile device for easy, portable use. The goal is for customers to be able to use the app without support from the FOSS team.

**Work to date:** Work began in 2016. Resources from NASA's Center Innovation Fund provided a license for 3-D gaming software and time to complete the work. The app is now fully functional. In addition to real-time data visualization and analysis, the technology is useful for pretest assessments to ensure that fibers are in place and functioning correctly.

**Looking ahead:** Researchers are working to make the app more user friendly, dynamic, and robust. Estimates are that work will be complete by the end of 2018.

Excel is a registered trademark of Microsoft Corporation. LabVIEW is a registered trademark of National Instruments Corporation.

### Benefits

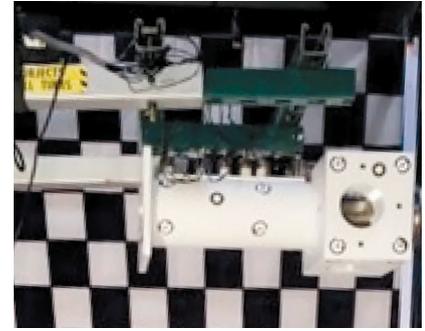
- ▶ **Real-time visualization:** Enables users to quickly interpret FOSS data
- ▶ **Automated:** Creates color 3-D augmented model with upload of target image files
- ▶ **Portable:** Works on a mobile device, without the need for a computer

### Applications

- ▶ Aerospace
- ▶ Energy
- ▶ Transportation
- ▶ Infrastructure
- ▶ Medical

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## New Flight Data Acquisition Techniques for Store Separation



Ground test rig for store separation data acquisition system testing

Armstrong researchers have developed and are investigating the effectiveness of an innovative store separation instrumentation system. Such systems record transient position and attitude of a store (e.g., rocket, ordnance) as a function of time to mitigate hazards, improve prediction capabilities, and monitor and control in-flight separation events either manually or autonomously. Armstrong's three-dimensional flash light detection and ranging (3-D flash lidar) technology uses an array of laser emitters to provide a real-time video of a store together with direct laser ranging data for each of the pixels in each video frame. This direct data makes the 3-D flash lidar system the only system to provide direct measurement of store position and attitude. Legacy methods in use today—photogrammetry and telemetry—do not provide direct ranging data and instead derive a store's linear and angular positions from videos and accelerometers/gyroscopes, which have limitations.

**Work to date:** Resources from NASA's Center Innovation Fund enabled the research team to begin investigating the feasibility of the new technique. The team designed and developed a small-scale ground test rig and an instrumented small-scale drop test article and began evaluating the performance of the instrumentation systems.

**Looking ahead:** The team will continue to evaluate and test the 3-D flash lidar technique. Specific goals include characterizing accuracies for known basic shapes at various locations and for reflected intensity using neutral density filters of various strengths.

### Benefits

- ▶ **High performance:** Enables quick-turnaround evaluation of future store separation data acquisition techniques
- ▶ **Advances understanding:** Contributes to NASA's body of knowledge involving store separation

### Applications

- ▶ Store separation data acquisition for aircraft and spacecraft
- ▶ Docking and close formation flight controls for aircraft and spacecraft
- ▶ Real-time shape sensing for aircraft and spacecraft structures (e.g., wings, pylons)

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Getty Image

## Advanced Wireless Flight Sensor System

Researchers at Armstrong are developing a wireless flight sensor system that eases integration of wireless sensors into existing avionics. Key to the innovation is a software-defined radio device that implements into software the capability of individual wireless protocols and systems. Currently, adding wireless sensors to avionics systems is time consuming and expensive due to integration requirements. This innovation streamlines that process, eliminating the need to overhaul preexisting avionics systems to integrate new sensors. If implemented throughout the aviation industry, this system would open a clear transition path from experiment to practical implementation.

**Work to date:** Benefitting from the NASA Center Innovation Fund, researchers purchased software-defined radio devices and created a preliminary architecture. In addition, the team demonstrated in the laboratory the capability to communicate with dissimilar wireless devices with no hardware modifications.

**Looking ahead:** Next steps are to test the technology in aircraft. The team is working with two small businesses to test their unique wireless technology on Armstrong aircraft.

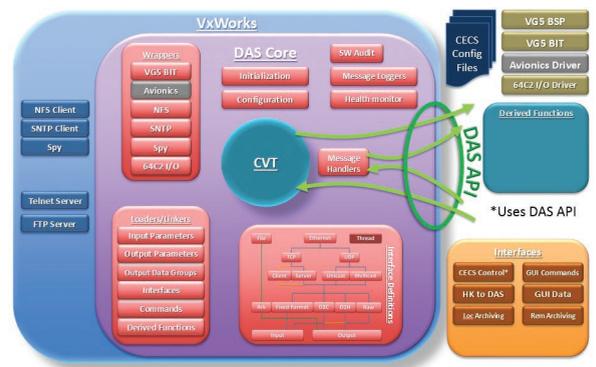
### Benefits

- ▶ **Saves time:** Streamlines testing and implementation of wireless technology
- ▶ **Efficient:** Adds new mechanisms and capabilities to aircraft
- ▶ **Cost-effective:** Reduces costs associated with integrating wireless sensors

### Applications

- ▶ Avionics
- ▶ Instrumentation systems
- ▶ Health monitoring

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## SOFIA Cavity Environmental Control System (CECS)

During descent and landing of the Stratospheric Observatory for Infrared Astronomy (SOFIA) aircraft, the CECS provides the telescope assembly cavity with clean, dry air to protect the optics from dust contamination and to prevent condensation from forming on the cold optics and electronic equipment. After landing, the CECS warms the telescope assembly to allow personnel to enter the cavity without introducing condensation. A new CECS controller is under development that will offer better maintainability, reliability, and functionality.

**Work to date:** Researchers have completed the requirements and design phases and are now in the development stage. The team has adapted the core software architecture of the SOFIA Data Acquisition Subsystem (DAS) to leverage previous coding, testing, and more than 350 flights of successful mission operation. Further, the new CECS will use the same flight chassis, circuit boards, and disk drives as the DAS and other subsystems to enable reuse of parts and hardware as well as benefits from previous efforts to ruggedize flight hardware. The core software architecture will be extended to include new required features, such as support for analog and digital inputs and outputs as well as resistive thermocouple devices.

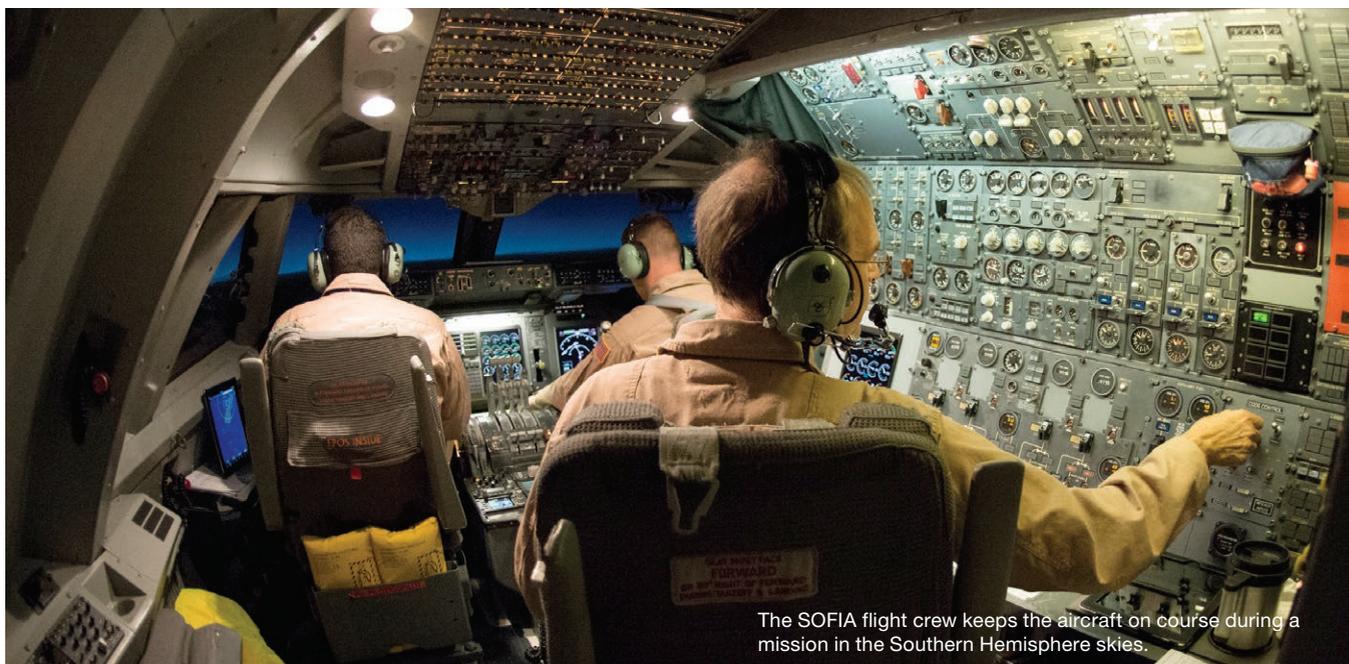
**Looking ahead:** The new CECS controller is projected to be operational, installed, and tested on SOFIA by the end of summer 2018.

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

### Benefits

- ▶ **Robust:** Increases reliability and maintainability
- ▶ **Elegant implementation:** Refines and expands the DAS core software, which then can be the basis for supporting future embedded systems at Armstrong

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The SOFIA flight crew keeps the aircraft on course during a mission in the Southern Hemisphere skies.

## SOFIA Data Acquisition Subsystem (DAS)

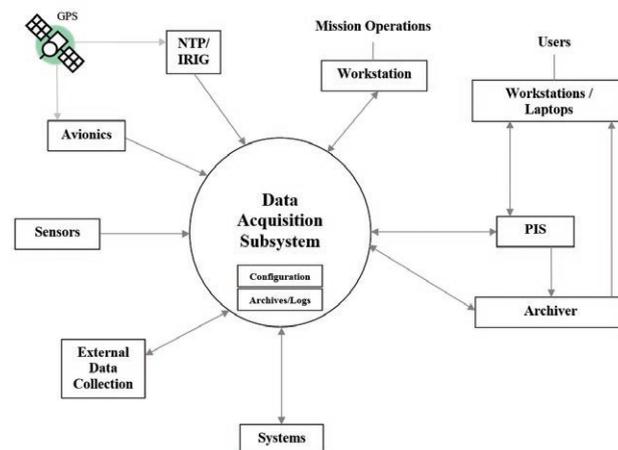
Developed for the Stratospheric Observatory for Infrared Astronomy (SOFIA) aircraft to facilitate in-flight observations, the DAS provides avionics and instrumentation data to other aircraft subsystems. A custom solution—including commercial off-the-shelf (COTS) hardware, a real-time operating system, and application—was implemented based on concept-of-operations and system requirements compiled with stakeholder input and review. The DAS has satisfied its role in enabling SOFIA science missions for more than 5 years without delaying a flight or causing any lost science time.

**Work to date:** The DAS software development complies with NASA Procedural Requirement 7150.2B and includes approximately 12,000 source lines of code written in-house. COTS software reliance was minimized to reduce system complexity, improve performance, and reduce verification and validation efforts. Software includes the VxWorks® operating system, a board support package and built-in test library, an avionics library, and an Extensible Markup Language (XML) library.

An application programming interface (API) has been part of the DAS software architecture and was utilized after the initial software release to add new features without the need to modify the core software. The new features can be built independently from the DAS source code and dynamically loaded into the system on boot-up through configuration files. Examples of API use include: a FalconView® moving map interface over Ethernet, filtering of avionics data, and embedded GPS timestamps for determining aircraft position with maximum accuracy.

**Looking ahead:** Next steps for the development team include (1) adding engine parameters through a new interface with the instrumentation system, (2) recording high-rate accelerometer data to eliminate the need for a standalone system, (3) utilizing

DAS core software for a new Cavity Environmental Control System controller, and (4) evaluating the applicability of the DAS core software to the Fiber Optic Sensing System (FOSS).



**Partners:** NASA's Ames Research Center and the German SOFIA Institute (DSI)

VxWorks is a registered trademark of Wind River Systems, Inc.

FalconView is a registered trademark of Georgia Tech Research Corporation.

### Benefits

- ▶ **Extensible:** Allows for easy addition of new interfaces without the need to modify source code
- ▶ **Streamlined:** Improves performance while reducing complexity

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## Real-Time Parameter Identification

Armstrong researchers have implemented a technique for real-time, control room–based estimating of the aerodynamic parameters that describe an aircraft’s stability and control characteristics. Oftentimes, aerodynamic modeling is performed on recorded data after test flights and then used in simulations. The drawback with this approach is that, if the collected data are not complete or of high quality, additional and costly flight tests must be scheduled. In this innovative approach, Armstrong’s real-time parameter estimation automates the process and runs during flight, enabling researchers in the control room to evaluate and adjust flight maneuvers to ensure data quality. The technology increases the efficiency and productivity of flight tests, as researchers can determine during the tests if they have collected the data needed for specific modeling simulations.

**Work to date:** The system successfully evaluated data from the Gulfstream III aircraft as part of the Adaptive Compliant Trailing Edge (ACTE) project and is currently being used in Armstrong control rooms to evaluate data collected during test flights and in-flight maneuvers. Researchers have continued to improve the system display and refine the way that results are presented.

**Looking ahead:** A capability to compare the estimated parameters to preflight-predicted values is being added, which will make it possible to evaluate the aerodynamic effects of aircraft modifications. The system is expected to become part of Armstrong’s control room toolset for use with upcoming X-planes and other projects.

### Benefits

- ▶ **Automates data collection:** Estimates in real time the parameters for aircraft stability and control
- ▶ **Improves data quality:** Enables adjustments during flight tests to ensure correct data acquisition
- ▶ **Saves time and resources:** Decreases the duration and number of flight tests

### Applications

- ▶ Aerodynamic modeling

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Armstrong’s internship program offers students a unique hands-on research experience.

# Flight and Ground Experimental Test Technologies



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.



## Fixed Base Modes Method for Ground Vibration Testing

Armstrong and industry partner ATA Engineering, Inc., are testing and validating a method to extract fixed base modes of a wing mounted on the wing loads test fixture (WLTF) during ground vibration tests (GVT). The partners tested the method during the Calibration Research Wing (CREW) project, which sought to reduce test setup time by conducting the GVT with the same boundary condition in the WLTF as used for load testing on large composite aircraft structures. The method calls for employing multiple electromagnetic shakers simultaneously, rather than the usual one or two shakers used in conventional GVT. Connection stiffness of boundary conditions greatly changes modal response, so the goal is to decouple the wing modes from the test fixture, enabling a comparison of wing test results to a wing finite element model.

**Work to date:** Successful validation tests were conducted in spring and summer 2017 as part of the CREW testing. These tests demonstrated that the method can successfully acquire decoupled wing modes.

**Looking ahead:** Next steps are conducting tests on the passive aeroelastic tailored (PAT) wing, slated to begin in spring 2018.

**Partner:** ATA Engineering

### Benefits

- ▶ **High performance:** Provides decoupled data from a test fixture
- ▶ **Efficient:** Enables comparison of test results to an analytical model

### Applications

- ▶ Ground vibration testing

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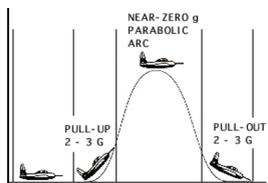


## Unmanned Aerial System (UAS) for Microgravity Research



Armstrong researchers are investigating the feasibility of using a high-performance UAS as a flexible, accurate, and cost-effective solution for microgravity testing and research. Microgravity research covers a broad spectrum of research disciplines, ranging from medicine to materials development to manufacture of electronic components, to name a few. Further, testing of spacecraft components in a microgravity environment will be critical in reducing risks for future space missions to Mars and beyond. Currently, there are three options for microgravity testing: zero-gravity drop towers, reusable rockets and balloons, and converted passenger aircraft that fly parabolic profiles. All of these options are complex and expensive.

The Armstrong concept involves using a high-performance unmanned aircraft to autonomously fly a microgravity profile for up to 20 seconds using a five-phase flight path. The preprogrammed UAS could fly not only zero-gravity trajectories but also trajectories to simulate the gravity conditions on other planets, a feature not available on drop towers. Such a platform would be particularly useful for initial testing of CubeSats, sensors, and computers before tests on more expensive platforms or on the International Space Station.



**Work to date:** The Armstrong team has received a concept test vehicle from NASA's Johnson Space Center, has completed simulations, and is working on programming flight control computers.

**Looking ahead:** With funding, the team could begin test flights in 2018.

**Partner:** NASA's Johnson Space Center

### Benefits

- ▶ **Economical:** Provides a significantly lower cost alternative to existing microgravity platforms
- ▶ **Flexible:** Offers opportunities for deployment closer to customers
- ▶ **Efficient:** Offers quick turnaround and the opportunity to fly experiments several times a day

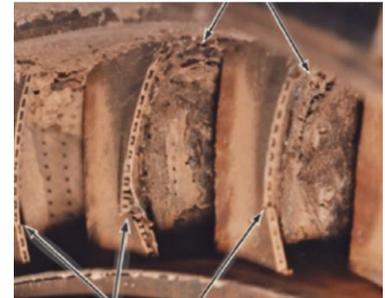
### Applications

- ▶ Microgravity research
- ▶ Spacecraft component testing

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## Acoustic Detection of Aircraft Turbine Cooling Hole Clogging

Very heavy deposits on pressure surface.



Break-through in vane.

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 Douglas 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 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. When implemented via commercial off-the-shelf (COTS) acoustic instrumentation in an engine, the system could 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.

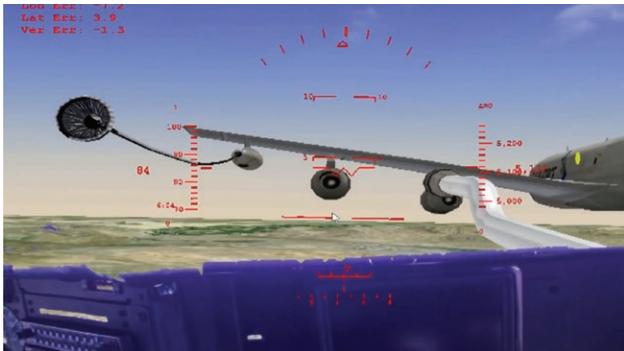
**Looking ahead:** Following successful characterization of single microjets, linear single- and multi-row arrays will be studied. These arrays will be configured to represent those of typical turbine vanes and blades. This will allow for an understanding of the influence of jet-jet interactions on the 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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## 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, stand-alone 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 GippsAero GA8 Airvan research aircraft as well as evaluation flights with Armstrong test pilots.

**Looking ahead:** Team partner Systems Technology, Inc. (STI), is pursuing interest shown by some companies as a result of flight test results. The Armstrong team is working with researchers at other NASA centers to identify ways Fused Reality can support space exploration, in particular astronaut training on the Station Manipulator Arm Augmented Reality Trainer (SMAART).

**Partners:** STI, National Test Pilot School, and U.S. Air Force Test Pilot School

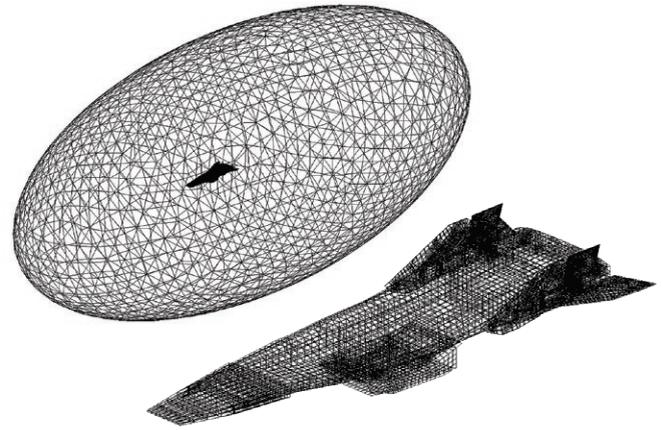
### Benefits

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

### Applications

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

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## Aerothermoelastic-Acoustics Simulation of Flight Vehicles

Researchers have developed a novel method for simulating aerothermoelastic-acoustics problems in aerospace flight vehicles. The finite element computational fluid dynamics (CFD)-based methodology enables the use of unsteady aerodynamics generated from the interaction of flexible structures with fluid flow to derive acoustic data. At high speeds, flight vehicles are subject to acoustic resonance issues that could damage sensitive instrumentation. Earlier research resulted in the development of an analysis method and software for simulating complex problems involving the interaction of elastic structures with air. This new research extends simulation capability to include thermal effects and is a unique implementation involving large-scale computations.

**Work to date:** Researchers employed a finite element idealization that fully accounts for thermal effects for both fluid and structure domains. The team verified the accuracies of fluid and structure capabilities with ground- and flight-test data.

In a white paper, two example problems demonstrate the capability of the methodology and associated code to produce accurate and economical simulations. The first relates to a cantilever wing that at high-speed flow shows aerothermoelastic-acoustics instability. The second involves the hypersonic X-43A test vehicle. In both examples, natural frequencies are recalculated for each time step if a large variation of temperature occurs in subsequent time steps. The associated code is freely available for public use.

The white paper was published in January 2017 by the American Institute of Aeronautics and Astronautics (AIAA).

### Benefits

- ▶ The procedure and the resulting code can be conveniently utilized for the accurate and economical solution of complex problems (such as a flight vehicle) of any geometry and in any Mach regime.

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## Risk and Complexity Considerations for Midsized X-Planes

A comparison of potential manned and unmanned flight demonstration aircraft designs for NASA's X-planes showed that manned aircraft configurations are expected to minimize risk and complexity issues, according to a study authored by researchers at Armstrong and NASA's Ames Research Center. Undertaken at the request of the Aeronautics Research Mission Directorate (ARM D), the study compared risk and complexity topics between manned and unmanned piloting options associated with developing and testing new low-cost, medium-sized X-planes. Data indicated significantly fewer risk and complexity issues associated with manned flight options, particularly in areas such as stability and control, airworthiness, and sense-and-avoid capabilities. Similarly, the study found that autonomous functions for unmanned options would likely distract from the fundamental flight experiment and/or increase costs and schedule.

**Work to date:** The study collected evaluations from a diverse set of subject matter experts—pilots, engineers, and experts in other disciplines at ARM D centers—regarding more than 50 aircraft and system topics. Group evaluations were completed for each topic to provide qualitative and quantitative analyses, where the quantitative values summarized and supported qualitative results. All the X-plane vehicles considered were medium-sized, approximately the size of a Gulfstream III aircraft, with the ability to sustain flight conditions appropriate for subsonic and transonic air transport research operations.

The study also identified an Edwards Air Force Base instruction document that mitigates risk by requiring new or low flight number vehicles to systematically perform sorties and pass numerous review boards during testing before being granted further

operational flexibilities. Serving as a key resource for the study, this document also clearly describes the maturation process and restrictions for unmanned systems. The study was published in June 2017 by the American Institute of Aeronautics and Astronautics (AIAA) and in October 2017 by NASA.

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



### Benefits

- ▶ **Practical:** Enhances flight research efficiency
- ▶ **Cost-effective:** Reduces flight test costs

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## Electric Propulsion Technologies

### Airvolt Single Propulsor Test Stand

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### X-57 Maxwell Experimental Aircraft

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

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## Improving Aerospace Vehicle Efficiency

### Calibration Research Wing (CREW)

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### PRANDTL-D Flying Wing

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#### ADDITIONAL INFORMATION:

- Bowers, Albion H; Oscar J. Murillo; Robert Jensen; Brian Eslinger; Christian Gelzer; "On Wings of the Minimum Induced Drag: Spanload Implications for Aircraft and Birds," NASA TP 219072, March 2016.
- NASA has received a patent for this technology (U.S. Patent 9,382,000, July 2016).

### PRANDTL-M Airframe

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

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### Acoustic Research Measurement (ARM) Flight Experiment

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### Determining Leading-Edge Stagnation Point Location with Sensors of Unknown Calibration

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#### ADDITIONAL INFORMATION:

- Ellsworth, Joel C., "Dynamic Leading-Edge Stagnation Point Determination Utilizing an Array of Hot-Film Sensors With Unknown Calibration," American Institute of Aeronautics and Astronautics, January 2017.

## Control of Flexible Structures

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

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### Modeling of X-56A Landing Gear

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

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

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### Integrated Flight Dynamics and Aeroservoelastic Modeling and Control

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### System Identification for Flexible Aircraft

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### Flight Research of Hyperelastic Materials

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

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#### ADDITIONAL INFORMATION:

- Eric J. Miller; Russel Manalo; Alexander Tessler; "Full-Field Reconstruction of Structural Deformations and Loads From Measured Strain Data on a Wing Test Article Using the Inverse Finite Element Method," NASA TM 219407, 2016.

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

Chris Miller: 661-276-2902 | Chris.J.Miller@nasa.gov

#### ADDITIONAL INFORMATION:

- Miller, Christopher J. and Dan Goodrick; "Optimal Control Allocation With Load Sensor Feedback for Active Load Suppression, Flight-Test Performance," American Institute of Aeronautics and Astronautics, January 2017.

## Flexible Matrix Composites for Passive Flutter Suppression

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## Airborne Research Test System (ARTS) for Small Unmanned Aircraft

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## Supersonic Technologies

### Shock-Sensing Probe to Study Sonic Booms

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### Investigating Laminar Flow

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### Using Schlieren Techniques to Understand Sonic Booms

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#### ADDITIONAL INFORMATION:

- NASA has received a patent for this technology (U.S. Patent 9,599,497, March 2017)

### Quantifying and Measuring Sonic Booms

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### Mitigating Sonic Booms

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### Flying Qualities for Low Boom Vehicles

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### CFD Study of Nozzle Plume Effect on Sonic Boom Signature

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#### ADDITIONAL INFORMATION:

- Bui, Trong T., "CFD Analysis of Nozzle Jet Plume Effects on Sonic Boom Signature," NASA TM 214650, September 2009.

## Space and Hypersonics Technologies

### Towed Glider Air Launch System (TGALS)

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#### ADDITIONAL INFORMATION:

- NASA has applied for a patent for this technology.

### Heavy-Lift Mid-Air Retrieval

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### Heat Flux Mapping System

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### Verification of Finite Element Models for Pyrolyzing Ablative Materials

Timothy Risch: 661-276-6720 | Timothy.K.Risch@nasa.gov

#### ADDITIONAL INFORMATION:

- Risch, Timothy K., "Verification of a Finite Element Model for Pyrolyzing Ablative Materials," American Institute of Aeronautics and Astronautics, date?
- Wang, Yeqing; Timothy K. Risch; Crystal L. Pasilliao; "Modeling of Pyrolyzing Ablation Problem with ABAQUS: A One-Dimensional Test Case," American Institute of Aeronautics and Astronautics, date?

### Motivation for Air Launch

John Kelly: 661-276-2308 | John.W.Kelly@nasa.gov

#### ADDITIONAL INFORMATION:

- Kelly, John W.; Charles E. Rogers; Gregory T. Brierly; J. Campbell Martin; Marshall G. Murphy; "Motivation for Air-Launch: Past, Present, and Future," American Institute of Aeronautics and Astronautics, September 2017.

## Autonomous Systems

### Automatic Dependent Surveillance Broadcast (ADS-B) System

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### Automated Cooperative Trajectories (ACT) Programmable Autopilot

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### Expandable Variable Autonomy Architecture (EVAA)

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### Stereo Vision for Collision Avoidance

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

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### Improved Ground Collision Avoidance System (iGCAS)

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### Peak-Seeking Control for Trim Optimization

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## Miniaturized Radar for Small Unmanned Aerial Systems (UAS)

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

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## Avionics and Instrumentation Technologies

### ARMD Flight Data Portal (AFDP)

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

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### Weather Hazard Alert and Awareness Technology Radiation Radiosonde (WHAATRR) Glider

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### Ethernet via Telemetry (EVTM)

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### Fiber Optic Sensing Technologies (FOSS)

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#### ADDITIONAL INFORMATION:

- NASA has received six patents for this technology (U.S. Patent 7,715,994, U.S. Patent 7,520,176, U.S. Patent 8,909,040, U.S. Patent 8,700,358, U.S. Patent 9,074,921 and U.S. Patent 9,664,506) and is pursuing patent protection for several additional innovations within the fiber optic sensor portfolio.

### Fiber Optics Augmented Reality System (FOARS)

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### New Flight Data Acquisition Techniques for Store Separation

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### Advanced Wireless Flight Sensor System

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### SOFIA Cavity Environmental Control System (CECS)

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### SOFIA Data Acquisition Subsystem (DAS)

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### Real-Time Parameter Identification

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## Flight and Ground Experimental Test Technologies

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### Acoustic Detection of Aircraft Turbine Cooling Hole Clogging

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### Fused Reality for Enhanced Training and Flight Research

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### Aerothermoelastic-Acoustics Simulation of Flight Vehicles

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#### ADDITIONAL INFORMATION:

- Gupta, K.K.; S.B. Choi, S.F. Lung; A. Ibrahim; "Aerothermoelastic-Acoustics Simulation of Flight Vehicles," American Institute of Aeronautics and Astronautics, January 2017.

### Risk and Complexity Considerations for Midsized X-Planes

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#### ADDITIONAL INFORMATION:

- Lechniak, Jason A and John E. Melton; "Manned Versus Unmanned Risk and Complexity Considerations for Future Midsized X-Planes," American Institute of Aeronautics and Astronautics, June 2017, NASA TM 219541, October 2017.

All photos and illustrations by NASA unless otherwise noted.

Caption for front/back cover image:

NASA science team surveys California fires in fall 2017 from ER-2 aircraft based at Armstrong.



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NASA/TM-2018-219871