Subscale Flight Testing for Aircraft Loss of Control: Accomplishments and Future Directions

David E. Cox[1], Kevin Cunningham[2], and Thomas Jordan[3]
NASA Langley Research Center, Hampton, VA 23681, USA

Subscale flight-testing provides a means to validate both dynamic models and mitigation technologies in the high-risk flight conditions associated with aircraft loss of control. The Airborne Subscale Transport Aircraft Research (AirSTAR) facility was designed to be a flexible and efficient research facility to address this type of flight-testing. Over the last several years (2009-2011) it has been used to perform 58 research flights with an unmanned, remotely-piloted, dynamically-scaled airplane. This paper will present an overview of the facility and its architecture and summarize the experimental data collected. All flights to date have been conducted within visual range of a safety observer. Current plans for the facility include expanding the test volume to altitudes and distances well beyond visual range. The architecture and instrumentation changes associated with this upgrade will also be presented.

Nomenclature

ADS-B	= Automatic Dependent Surveillance Broadcast.
AirSTAR	= Airborne Subscale Transport Aircraft Research
ASROV	= Avionic System for Remotely Operated Vehicles
BVR	= Beyond Visual Range
FAA	= Federal Aviation Administration
FPGA	= Field Programmable Gate Array
GPS	= Global Positioning System
HDL	= Hardware Description Language
MOS	= Mobile Operations Station
NAV	= Navigation Display
NOSA	= NASA Open-Source Software Agreement
PFD	= Primary Flight Display
SHM	= System Health Monitor
UAS	= Unmanned Aerial Systems
UDP	= User Datagram Protocol

I. Introduction

AIRSTAR is a facility for subscale flight-research exploring flight dynamics and controls issues that are relevant to aviation safety. It has been designed and operated to perform experiments that, due to structural load constraints and uncertain outcomes, would incur too much risk for testing on a full-scale aircraft. Flight dynamic models for transport aircraft in unusual attitudes and conditions well outside the normal flight envelope benefit from validation through flight-testing. Although these post-stall dynamics don't play much of a role in traditional aircraft design trades, understanding these dynamics is important to building flight simulators of sufficient accuracy that they can be used for training pilots to recover from extreme upset conditions. Control algorithms also depend on accurate models, and the ability to validate control performance in extreme flight conditions or under conditions of system failure, is an important component of the research that has been conducted with AirSTAR.

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[1] Senior Research Engineer, Dynamic Systems and Controls Branch, MS-308.
[2] Senior Research Engineer, Flight Dynamics Branch, MS-308, AIAA Member
[3] Assistant Head, Aeronautics Systems Engineering Branch, MS-238.

The AirSTAR facility is composed of a piloted ground station, a set of subscale flight vehicles, and associated operations capability. Although it makes use of many Unmanned Aerial Systems (UAS) technologies, AirSTAR was designed with an emphasis on the requirements for remotely-piloted flight (vs. fully-autonomous flight), as well as efficiency in the execution of system identification and control experiments on a constrained test range. The core of the system is the Mobile Operations Station (MOS), shown in Figure 1 along with two of the research vehicles. The MOS serves as both a ground pilot station as well as an overall mission control center and a description of its early design can be found in Ref 1. The primary flight vehicle is a 5.5% scale model of a commercial transport aircraft. It was constructed to be both geometrically and dynamically scaled.[2] This means that the flight dynamics of the model scale to those of the full-scale vehicle. Being smaller, however, allows the vehicle to have much larger structural margins than are possible at full scale, and so it can perform more aggressive maneuvering without violating structural load constraints. These load margins, as well as the safety advantage of being unmanned, makes subscale flight-testing ideal for research in aircraft loss-of-control. The vehicle also has a history of wind-tunnel experiments, including forced-oscillation and free-spin testing.[3,4,5] The results of these tests were incorporated into a simulation of the vehicle that supported the ability for external partners to design experiments and prepare for flight-testing.

The MOS is discussed in Section II, with a description of its telemetry and display systems. The flight vehicle and its simulation are discussed in Section III. Section IV presents a summary of flight research conducted on AirSTAR over a three-year period, from 2009 to 2011. Finally in Section V a brief summary of the current development work is presented, which is focused on the infrastructure upgrades required to conduct remotely-piloted flight research beyond the visual range of a safety pilot.

Figure 1 Mobile Operations Station (MOS) at the NASA Wallops Flight Facility UAV runway with two 5.5% dynamically scaled vehicles (tail numbers T1 and T2) in the foreground.

II. Mobile Operations Station

The Mobile Operations Stations (MOS) serves as both a ground control station, as well as a flight test control room, as shown in Figure 2. It was designed to be fully field-deployable requiring no additional services in order to operate. The system is powered by a trailered 60 kW diesel generator, and contains a sufficient amount of uninterruptable power to continue to operate all computer and telemetry systems for 30 minutes, in the event of a generator failure. The MOS vehicle contains computer systems dedicated to rendering displays, a video distribution network, a data distribution network, and audio intercom system. It also contains the real-time flight computer system used to perform all experimental algorithm testing. The concept of leaving the flight computer on the ground reduces airframe weight and eliminates the need to reprogram experimental algorithms in an embedded system, and allows higher-performance processors to be used for implementing research algorithms. This has proven very beneficial in the ability to quickly implement control and identification algorithms prototyped on desktop systems into operational conditions. It also allows the facility to accommodate new flight vehicles, while retaining a well-tested system for critical flight control functions. It does, however, require that the telemetry system be highly reliable. As the vehicle contains no on-board computer even intermittent loss of telemetry will cause the vehicle to be uncontrolled.

In order to improve reliability of the telemetry system an actively pointed 50-inch parabolic antenna was mounted on the roof of the MOS, as pictured in Figure 3. This antenna system provides approximately 20db of gain, concentrating the power over a ±5 deg beam width. The antenna tracks the vehicle in flight using the downlinked GPS coordinates to compute azimuth and elevation pointing angles. A camera system is also mounted on the boresight of the antenna and used to provide "tower view" images of the vehicle in flight.

Inside the MOS a pilot station at the rear of the vehicle provides state-of-the-art environment for UAS flight-testing, as shown in Figure 4. The cockpit is equipped with a sidestick control effector, rudder pedals, and split throttle and flap levers. Actions required during flight are designed to keep the pilot hands-on the throttle and stick at all times. A trim hat on the stick is used to adjust longitudinal and lateral trim. Momentary buttons, also on the control stick, are used to disengage experimental control laws and to disengage failure emulation. Finally a trigger on the control stick will disengage both control laws and failures, and return the vehicle to a revisionary stick-to-surface direct control law. A momentary button on the throttle is used to engage wavetrain inputs, which perturb the control surfaces to provide a dynamic response for system identification.

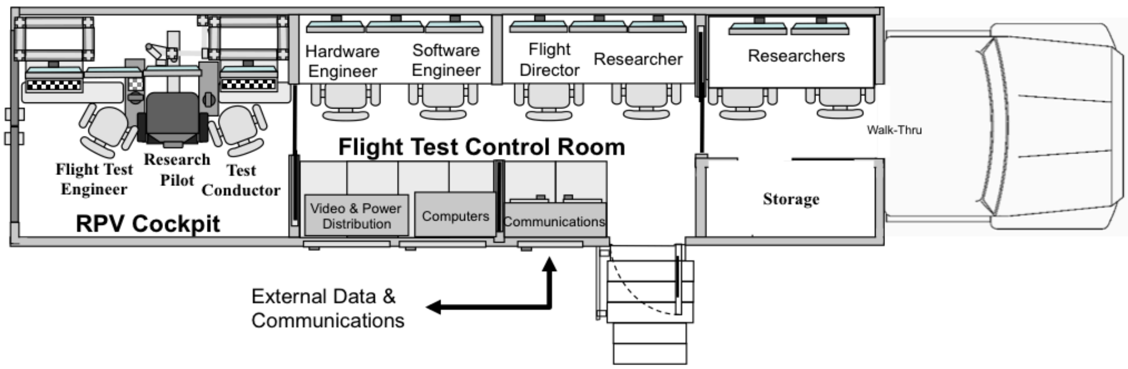


Figure 2: Mobile Operations Station interior layout with pilot cab, engineering and flight director monitors, and researcher stations.

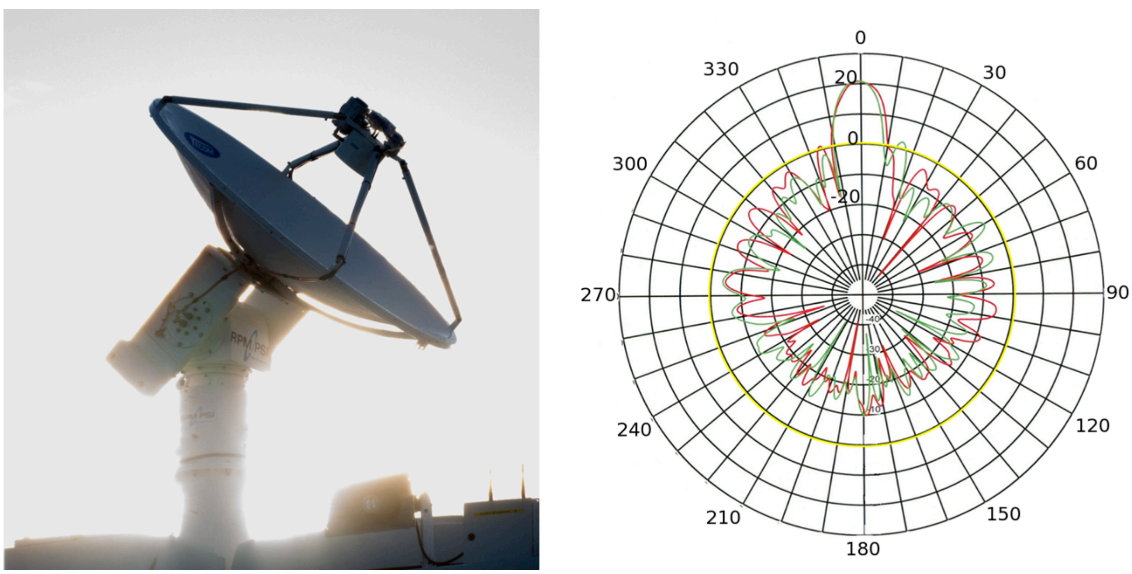


Figure 3: Active high-gain antenna on roof of MOS and experimental gain patterns for vertical (green) and horizontal (red) rotation, measured with L-band excitation.

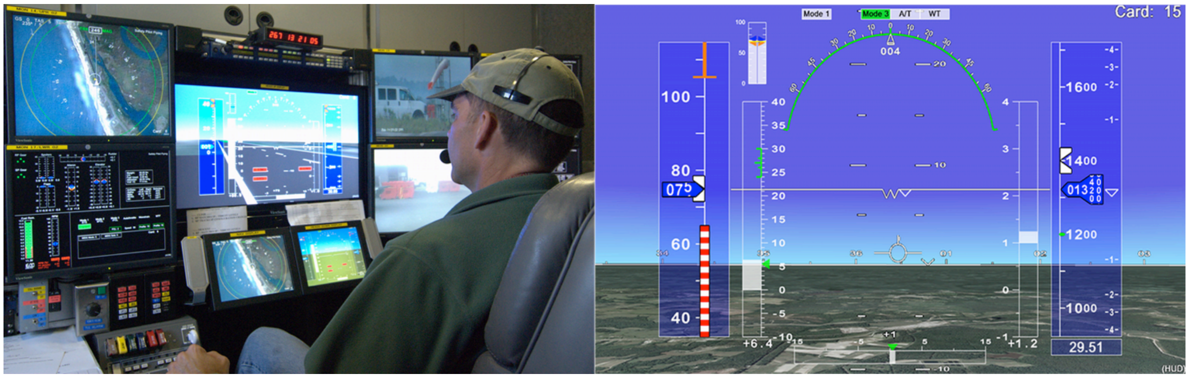


Figure 4: Pilot Station and Primary Flight Display (PFD). Green ranges on PFD indicate target conditions for current test card.

The pilot's Primary Flight Display (PFD) is a synthetic out-the-window view with an instrumentation overlay. Standard airspeed and altimeter tapes frame the terrain display, where a pitch ladder, bank angle and velocity vector indicators are overlaid. The display also includes angle-of-attack, angle-of-sideslip and g-load tapes to indicate current incidence angle and load conditions. Status of the system modes, are shown along the top of the display and indicate the arm and engage state of control algorithms, programmed test inputs, and failure conditions.

Adjacent to the pilot controls are a set of arm/engage switches and dials that provide a higher degree of configuration. Multiple test inputs, multiple control algorithms and multiple failure scenarios are compiled into the real-time code. Selection of which of these are to be activated by the pilot is set by the flight test engineer. A single "flight card" dial selects the nominal values of these parameters, as well as test condition targets on the primary flight display. The flight card default values maybe overridden by adjusting independent controls; however, once the system is armed, parameter values cannot be further adjusted without cycling the arming switch.

The small size of the 5.5% scale vehicle results in a constrained fuel load that limits the flight duration to approximately 15 minutes. The range of the system is limited to about a ½ mile radius by the visual range of the safety pilot. This range limitation causes current test execution to be highly compressed, with only 10-20 seconds of "on-condition flight" in each straight leg segment and about 15-20 seconds in course reversals. During a turn, the test conductor, seated adjacent to the pilot, would evaluate the previous maneuver, then decide on and review the next test card with the pilot and flight test engineer. This compressed time-frame required clear pre-established criteria for decision points and contingencies. A key to achieving the in-flight performance was having a realistic simulation environment for mission rehearsals. Mission rehearsals were conducted in the MOS, with the full team using the flight hardware, including intercom communication. Each test point or control algorithm was practiced and often adjusted to ensure range, loading, or altitude limits would not be violated. Emergency conditions were also tested thoroughly during mission rehearsals and any margins and "knock-it-off" criteria adjusted for each test card.

In addition to the PFD a number of other displays are available in the MOS, as outlined in Table 1. These displays can be shown on monitors at the pilot station, engineering stations, flight test director or researcher stations through a video distribution system. This provides configurability, particularly at the researcher stations, to allow monitoring of the test. In addition to the visual monitors, data being feed down from the vehicle is available as a real-time feed on the network. This allows researchers to bring laptops into the facility and run algorithms during the flight that monitor the live feed and give an indication if the data from the test maneuver meets expectations. The ability to make data-quality judgments during the flight, and if necessary, call for repeats or maneuvers with increased amplitude was found to be very useful to ensuring the data obtained meets the research goals set out for the flight test.

III. Research Vehicle and Simulation Environment

The primary AirSTAR vehicle is a 5.5% scale version of a commercial transport aircraft, with a wingspan of 6.8 ft and length of 8.5 ft, as shown in Figure 5. It is both geometrically and dynamically scaled, yielding a maximum takeoff weight of 58 lb including approximately 12 lb of fuel. Two turbine engines, each of which can produce 16 lb of thrust, power the vehicle. Instrumentation systems onboard the vehicle provide a full suite of inertial measurements, including rate, attitude and a GPS-enabled navigation solution. In addition, an airdata system provides angle of attack, sideslip, altitude and velocity estimates. More details of the flight vehicle and its instrumentation are available in Ref. 6. Prior to the flight model's construction, wind tunnel models were built at this same scale and used for both static and forced oscillation tunnel testing.[3,4,5] This data formed a baseline of information from which in-flight identification techniques could be evaluated. It also formed the basis for a high fidelity simulation model of the vehicle that was used for refinement of system identification experiments, design of control algorithms, pilot training and mission rehearsals.

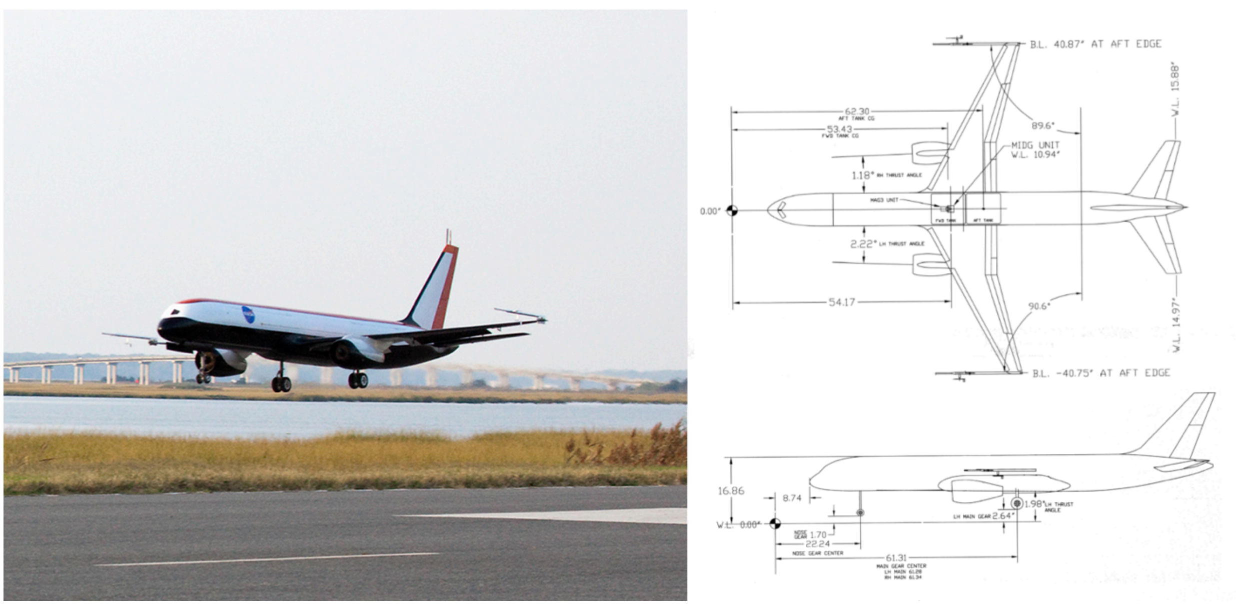


Figure 5: AirSTAR T2 model in flight at Wallops UAV runway, and schematic dimensions of the vehicle.

Three related pieces of software comprise the AirSTAR simulation and ground system: the GTM DesignSim, the AirSTARsim, and the GroundProcessing code. The GTM DesignSim is an open-source simulation based on an approximate aerodynamic model that includes high angle-of-attack and high angle-of-slideslip conditions, as well as dynamic data for predicting high rate maneuvers. This version of the simulation was released as open-source software, under the NASA Open-Source License Agreement (NOSA). It has been widely used in the design and evaluation of control algorithms, both for researchers targeting experimental validation on AirSTAR, as well as other more general studies. The GTM DesignSim was created to support control system analysis, and has efficient utilities for calculating trim points and generating linearized models about those trim conditions. The simulation includes many details that are specific to the hardware of the T2 vehicle. Actuators and sensor dynamics have non-linear models based on bench test results, including turbine engine models. The effect of fuel burn on the mass properties, which are significant over the course of a flight, are included as are some asymmetries associated with the as-built vehicle.

The AirSTARsim shares a codebase with the GTM DesignSim; however, it is configured to run in real-time (rather than batch) mode, has a high fidelity aerodynamic database, and includes additional sensor modeling and telemetry-system emulation. This simulation allows processor-in-the-loop (PIL) capabilities that were used extensively in the development of AirSTAR. The sensor models in the AirSTAR simulation take raw state information, and add to these physical effects of sensor placement, upwash and other installation errors, and signal conditioning circuitry present in the real system. These sensor outputs are then passed into a telemetry model, which takes into account the quantization of on-board ADC units and the conversion of this data into serial message streams. The simulation's input and output are a set of RS422 serial streams which exactly model the data stream sent through the telemetry system, including message headers, multiplexing logic, and latency inherent in the communication. This allows the AirSTARsim to be directly connected to the real-time dSpace® computer in place of the telemetry interface. Simulations run this way, with simulated hardware in the loop, provide a high degree of confidence in the real-time processing required during flight, and are used for all mission rehearsals and flight test profile planning.

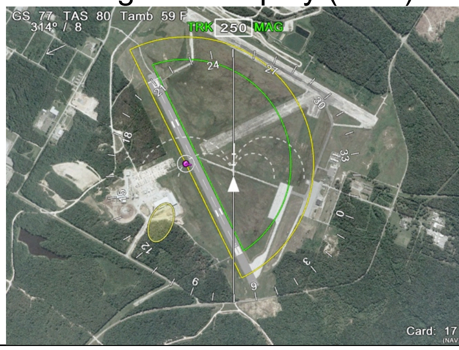
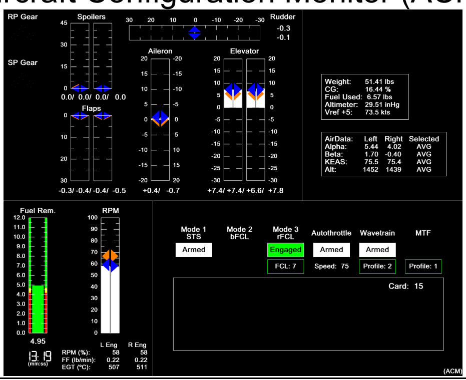
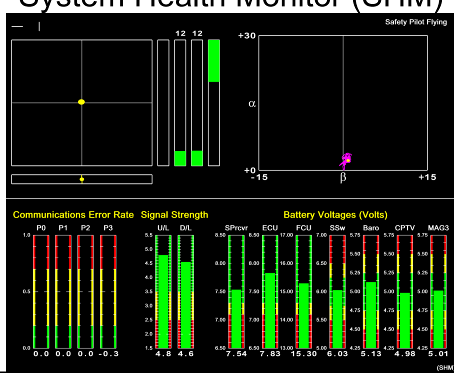
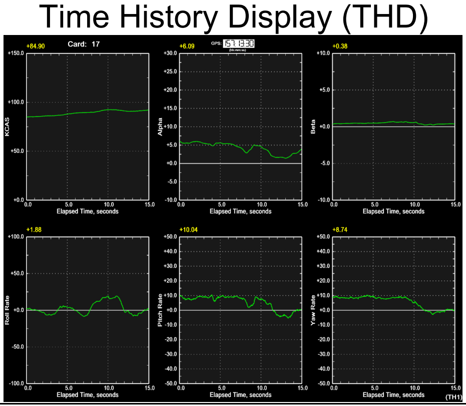
Display System	Key Parameters	Primary Function
Navigation Display (NAV) 	Top-view of aircraft location over terrain database, with range boundaries, winds aloft and turn radius prediction. Also includes sun-spot (yellow ellipse) to help ensure vehicle does not cross the sun from perspective of the safety pilot.	Primary display for Flight Test Director, responsible for calling turns and maneuver knock-off points due to range boundary.
Aircraft Configuration Monitor (ACM) 	Current state of aircraft research modes and algorithms, arm/engage status of test input, controller, or emulated failure conditions. Display shows the surface commands of both research and safety pilot. Caution and warnings messages and detailed textual messages are displayed.	Primary display for flight test engineer, used for selection of flight card, updates to target test conditions, selection of control algorithm or system identification experiment, monitoring of mission critical systems.
System Health Monitor (SHM) 	Status of key aircraft systems, battery voltages, and telemetry monitors. Upper left quadrant reflects pilot stick position. Upper right quadrant is a trailing time window flight condition over incidence angles (alpha and beta).	Primary display for hardware engineer, for in-flight monitoring of shipboard systems. Secondary display for flight test engineer
Time History Display (THD) 	A set of time history traces for key aircraft research parameters, e.g. angle of attack, side-slip, rotational rates, attitude, etc.	Primary display for research team to monitor maneuver and data quality.

Table 1: MOS Displays and their primary purpose

The ground processing software runs in real-time, using a dSpace® multi-processor system. This system is responsible for all the physical I/O in the Mobile Operations Station. A set of 32 analog channels, and 64 discrete channels, read all the pilot station inputs and scale these to produce aircraft commands and mode information for the control algorithms. All signal calibration, auxiliary variable calculations, caution and warning systems are computed in the ground processing code. The research control algorithms are hosted in dSpace® on an independent processor board that ensures the core ship systems remain operational even if an experimental algorithm faults. The ground processing software transmits commands to the aircraft through a telemetry link, and receives information from the vehicles sensors over the same link operating with a fixed message rate of 200 Hz. This information is distributed through the MOS in two UDP messages, one of which drives the displays generation while a second is available for researchers to use in monitoring the experiments. The architecture of this system is discussed in more detail in Ref. 7.

IV. Research History

Under five separate deployments from 2009-2011, 58 flights were conducted with the AirSTAR system using the dynamically-scaled T2 research vehicle, as detailed in Table 2. These flights covered a variety of experimental conditions supporting both system identification and control law experiments. The controls work supported a general objective of evaluating if adaptive control algorithms could respond to sudden and dramatic failures that degraded the vehicle stability and/or controllability, while maintaining robustness in normal (unfailed) flight conditions. The control law experiments conducted during 2010 culminated in a final piloted evaluation (deployment T2-2011.01) of a high-workload offset landing task under a simulated failure condition that destabilized the vehicle. This work involved the integration of adaptive flight control algorithms from several research organizations across the country, with eight independent control algorithms in the final evaluation. A summary of that evaluation task and the algorithms that provided damage-accommodating control is covered in Ref. 8.

System identification and aerodynamic modeling studies have also been an important part of the research conducted with AirSTAR. The capability to determine flight dynamics in real-time through simultaneous multi-axis excitation has been a part of the test matrix in each of the T2 deployments. Through a combination of excitation design and recursive frequency domain processing, real-time system identification techniques have been developed and validated on AirSTAR.[9,10,11] These techniques have been refined to provide an aerodynamic database using only a small amount of flight data and minimal perturbations from normal trimmed conditions. Therefore, these techniques can provide flight-dynamics models over extended envelopes, where test data is scarce. Also, since they compute aerodynamic information in real time, in the future these algorithms could serve as the basis for automated systems that monitor vehicle health in flight.

The AirSTAR UAS system was also used to develop an innovative method for pitot-static calibration.[12] The method uses a global error method and GPS data to efficiently and accurately perform in-flight pitot-static system calibration. Real-time winds-aloft monitoring, provided by a tethered aerostat, was used to aid in the validation of this method. This method was also shown to have application to aviation safety as a tool to provide pitot tube fault detection.

Table 2: Summary of AirSTAR deployments with the T2 vehicle supporting Aviation Safety with model identification under upset conditions, and control law evaluation under failures.

Deployment	Location	Date	Number of Flights	Test Time (hh:mm)	Test Cards Executed	Number of Test Points	Data Archived
T2-2009.01	Wallops Island	Sept. 2009	12	3:24	48	48	2.31 GB
T2-2010.01	Fort Pickett	March 2010	6	1:49	44	74	1.96 GB
T2-2010.02	Fort Pickett	June 2010	9	2:50	68	99	2.39 GB
T2-2010.03	Fort Pickett	Sept. 2010	21	6:16	115	207	5.28 GB
T2-2011.01	Fort Pickett	May 2011	10	3:03	47	101	2.77 GB
			58	16:22	322	529	14.71 GB

V. Future Directions – Beyond Visual Range

For the takeoff and landing phases of the flight the AirSTAR T2 vehicle was flown as a model aircraft from a traditional Radio Controlled (RC) model perspective. Operationally the RC pilot, referred to as the safety pilot, was the pilot-in-command for the entire flight and was able to take control of the vehicle at any time or if necessary engage a flight termination system that set fixed commands to the throttle and control surfaces. This not only relieved the complex display and telemetry systems in the MOS of a safety-critical role, but also provided the necessary see-and-avoid function required for flight operations outside restricted airspace under a Certificate of Authorization (COA) issued by the FAA.

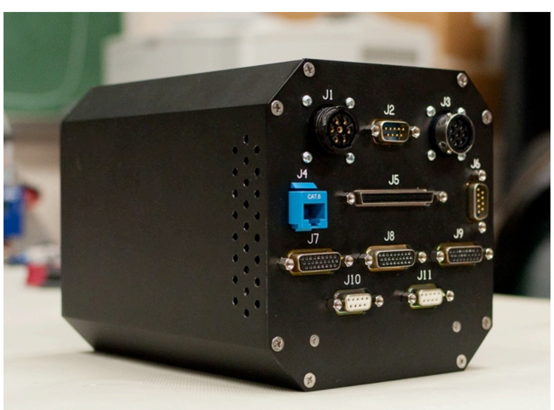
Although a large number of experiments were possible with the AirSTAR concept of operations described above, the limitation to visual range of a safety pilot was always an operational challenge and eliminated some interesting types of research. The straight leg of a flight pattern was generally only about 20-30 seconds long in which the pilot had to re-establish trim conditions coming out of a turn and execute a parameter identification or control evaluation maneuver before heading into the next turn. Approximately 40% of the flight time was spent in turns, and these consumed an even larger fraction of the available fuel. Some experiments, such as a fully-developed spin or any work integrating with outer-loop guidance, were simply not possible within visual range.

In order to overcome these limitations the flight test volume needs to be expanded. A study was conducted looking at potential future applications and the requirements these would impose on a subscale system. It was found that going Beyond-Visual-Range (BVR) of the ground station, but within direct RF line-of-sight, was the best operational concept for this work. It would allow the low-latency links to a ground station for piloted studies, but would greatly increase the time on-condition and vertical altitude available for research flights. The system upgrades are being designed to operate a research vehicle over a test range of 10 nautical miles, with altitudes up to 15,000 ft. AGL.

Operating BVR, however, levies new requirements on the research systems in terms of onboard computing, enhanced telemetry, and fail-safe systems. An on-board computer has been designed with the goal of preserving the software flexibility the current AirSTAR system has, while adding a degree of autonomy and reliability required for autonomous operations. The resulting system, Avionics for Subscale Remotely Operated Vehicles (ASROV), is built using the PC104 computer form factor and includes a blend of field-programmable gate array (FPGA) and microprocessor-based computing.[13] The FPGA card handles timing, analog drivers, and all digital I/O, including serial, Ethernet, and Pulse-Width-Modulation signals. Within the FPGA chip is a PowerPC core running real-time Linux that manages the physical I/O and communications. This microprocessor is the primary flight computer and is responsible for detecting a lost-link situation and invoking a return-to-base autopilot. Code for the FPGA and primary flight computer is relatively static, implemented in C and Hardware Description Language (HDL) and is expected to endure a large amount of testing prior to use in flight.

The research code, however, will be hosted on a secondary card in the PC104 stack. This card is a standard X86-based CPU board, running an Intel Atom processor. All code executing on the secondary processors, except for a small communication wrapper, is written in Simulink and autocoded for onboard implementation. This system will perform the calibration, auxiliary variable calculations, mode switching, test input excitation, and control law implementations currently implemented in the ground processing software on the MOS. As a research system this code is not assumed to be reliable, and the primary processor, which can operate in a revisionary flight mode independent of the research processor, monitors deviations from expected behavior.

A fall back to the primary on-board processor, however, with its ability to stabilize the vehicle and command a trajectory, increases the risk of an errant flight extending beyond the restricted area and into unrestricted airspace. Such a situation brings with it the risk of injury or property damage, and is more serious than losing the vehicle in a crash within a predefined hazard area. Therefore, a flight termination system (FTS) is being added to safeguard against errant actions of the onboard computer. This system provides a secondary, highly reliable RF link to the vehicle, with a command set limited to cutting thrust and engaging pro-spin controls. Position information from the vehicle will be obtained through ADS-B transmission, and this will update a multi-function display in the MOS set to show all nearby ADS-B equipped aircraft in a navigation mode display. This design makes the safety-critical subsystem of FTS uplink telemetry and ADS-B downlink telemetry independent of the ASROV or other research systems, and composed entirely of commercial available components. A range-safety officer within the MOS will monitor this system and have the authority to engage flight termination if required.



- 16-bit Analog to Digital Input, 32 Channels
- Programmable Antialiasing Filters, 32 Channels
- Pulse Width Modulation Input, 16 Channels
- Pulse Width Modulation Output, 32 Channels
- Digital Input/Output, 4 Channels
- RS-232 Serial Ports, 4 Channels
- RS-422 Serial Ports, 2 Channels
- 100 Base-T Ethernet Ports, 2 Channels
- PowerPC-440 microprocessor (primary)
- Intel Atom Z530 microprocessor (secondary)

Figure 5: Avionics for Subscale Remotely Operated Vehicles (ASROV) flight computer

The T2 vehicle, dynamically scaled at 5.5% of a commercial transport, has been the flight vehicle for nearly all the research done with the AirSTAR system. Much data exist on the post-stall and departure characteristics of this vehicle, and work continues on the use of this data to validate class-representative models for post-stall flight. The next stage of research, however, will look at aircraft with T-tail configurations, which have different departure characteristics and the potential for deep stall. Studies are being conducted to determine a design for a modular and configurable vehicle that will support loss-of-control research on T-tail type transports. The vehicle will likely be designed at larger scale than 5.5% in order to increase the volume for instrumentation systems and more significantly increase the payload mass margin to achieve dynamic scaling results.

VI. Summary

The AirSTAR system has been developed to provide a flexible, research-oriented facility for flight-dynamics and control algorithm testing. With its focus on aviation safety, AirSTAR has been used to conduct a series of high-risk flights exploring the post-stall regime, and has successfully allowed piloted recovery from these conditions without incident. Under these conditions tests have been conducted that advanced the state of the art in parameter identification techniques, pushed the development of new flight test techniques and evaluated the performance of novel adaptive control algorithms. Current efforts in development of the AirSTAR system are looking to increase the operation volume beyond the visual range of an observer to take full advantage of UAS technology for flight research.

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