Request for Information Appendix A and Appendix B in 'Flight Validation of Adaptive Control to Prevent Loss-of-Control Events'

Appendix A – Flight Test facilities

For the experimental flight test program, the IRAC project has access to: NASA's F/A-18, a full-scale testbed, and NASA's AirSTAR facility, a sub-scale testbed (additional information is available upon request).

I. F/A-18 Testbed

The F/A-18 tail number 853 testbed is capable of hosting a wide variety of multi-disciplinary, state-of-the-art adaptive control experiments. Full-scale flight testing of these technologies on the F/A-18 IRAC testbed provides the capability for piloted evaluations and for the exploration of unanticipated interactions involving non-linear and higher-order effects that are often difficult or impossible to model in simulation. Implementation of these technologies on a real-world platform gives designers the opportunity to explicitly address constraints such as measurement noise, time delays, asynchronous and multi-rate systems, and redundant architectures.

The F/A-18 testbed is capable of simulating a variety of damage and failure conditions, thereby facilitating the testing of experimental adaptive control technologies. Flight within a limited envelope gives the research systems the capability to fully reconfigure the F/A-18's control surfaces in novel combinations, while maintaining adequate structural margin. Direct control of the throttles allows for integrated propulsion control experiments. Special structural instrumentation allows for real-time monitoring of loads and eventually for integration with experimental control laws or integrated vehicle health-monitoring algorithms. The F/A-18 testbed system also includes capabilities for experiment development, including dynamics and structural design models, 6-DOF piloted simulation and hardware-in-the-loop test facilities. Researchers can work with engineers at NASA DFRC to evaluate their control laws in the simulator and, if necessary, fine tune them. Pilots can evaluate control laws in the simulation to study adaptive controller/pilot interface issues as well.

The capabilities of the F/A-18 testbed are summarized in the table below.

Capabilities	F/A-18 Full-Scale Testbed
Platform	
Altitude	15,000-33,000 ft
Speed	0.2-0.7 Mach, < 250 knots
Typical flight test time	1 hour, in-flight refueling is available to support longer duration tests
Test location	NASA Dryden Flight Research Center
Control effectors	Stabilators, ailerons, rudders, leading- & trailing-edge flaps, dual engines (individually controlled via throttle servos)
Research Computing	

Flight control computer	Research flight control system (RFCS) – quad redundant production flight control computers augmented with additional processor in each channel. The RFCS hosts "replication" F/A-18 production control laws, an on-board excitation system for parameter ID and logic for simulating damage and failures. The RFCS accepts both outer-loop and control surface commands from the dual Airborne Research Test System (ARTS).
Additional processing power, memory, & external I/O	Dual redundant ARTS computers. Each computer houses three 1 GHz processors. Up to eight experiments can be loaded and tested on a given flight, and experiments are highly configurable by the pilot. The ARTS supports Simulink and C based experiments with all-software and hardware-in-the-loop testing available.
Experimental	
Surface failures	Up to and including all aerodynamic surfaces for engine-only control testing.
Scenarios	Several damaged wing scenarios, with additional scenarios programmable within the ARTS for both "A" matrix and "B" matrix simulated failures.
Maneuvers (preprogrammed)	Doublets and frequency sweeps, with additional maneuvers programmable within the ARTS.
Maneuvers (Pilot-in-the-loop)	Doublets, frequency sweeps, attitude captures, windup turns, formation station-keeping, air-to-air tracking.
Data Capture	
Telemetry	Over 1600 instrumented parameters, including loads, dynamics & aerodynamic parameters, data from production flight control systems & on-board experiments, real-time video of heads-up display, fuel tank quantities.
On-board sensors	Nose boom provides angle of attack, angle of sideslip, total pressure and static pressure measurements, 40 pressure sensors on wings, 200 strain gages on wings, flight deflection measurement system for left wing, 50 accelerometers in wing, fuselage, and empennage, control deflection measurements.
Flight dynamics	Inertial data from inertial navigation system, global positioning system data.

II. AirSTAR Testbed

The AirSTAR testbed includes: a remotely piloted 5.5% dynamically scaled, turbine powered unmanned aerial vehicle, and a Mobile Operations Station (MOS) from which the Generic Transport Model (GTM) is flown. The AirSTAR system is designed to conduct control system

experiments relevant to large transport category airplanes. The mass properties and geometry of the flight vehicle are based on a commercial transport airplane so that key dynamic characteristics are representative of the full-scale vehicle.

Typically, simulations of aircraft are based on wind-tunnel-derived aerodynamic data that are modeled for use in the equations of motion. However, accurate modeling in regions of the flight envelope expected in upset conditions, which are characterized by high wind angles, high angular rates, and separated flow, is a formidable challenge. Additionally, the literature on modeling large transport airplanes in upset conditions is very limited. Since wind-tunnel-based data would not completely emulate full-scale flight characteristics in upset conditions, the AirSTAR vehicle allows evaluation and validation of simulations that are critical for accurate control system development and demonstration. An important advantage of this test vehicle is that it allows flight investigations in regions of the flight envelope that are not safe to test on the full-scale manned vehicle. An additional advantage of this testbed is the significantly reduced cost to perform experiments compared to flying the full-scale vehicle.

The capabilities of the AirSTAR testbed are summarized in the table below.

Capabilities	AirSTAR Sub-Scale Testbed
Platform	
Altitude	600-2000 ft
Speed	60-120 knots
Scale	5.5%
Typical flight test time	20 minutes
Test location	NASA Wallops Flight Facility
Control effectors	Ailerons, Flaps, Split-Spoilers(4), Split-rudders(2), Split elevators(4), dual engines.
Research Computing	
Flight control computer	Ground based flight control via dual-processor dSpace real-time computer. This architecture also supports Simulink based flight control systems with desktop-emulation, hardware-in-the-loop testing, and piloted simulation. Multiple experimental flight control laws can be pre-loaded and selected in-flight so that back-to-back comparisons can be performed.
Additional processing power, memory, & external I/O	Real-time monitoring of control system and on-board instrumentation available through network connection in MOS. An interface between real-time data stream and analysis tools running on experimenters' laptops is provided.
Experimental	
Surface failures	Single & multiple surfaces, fully programmable for all surfaces.
Scenarios	Full and partial hydraulic failures. Impaired and inoperative engine(s). Reduced static and dynamic

	stability through in-flight simulation ("A" matrix failures).
Maneuvers (preprogrammed)	Frequency sweeps, generic wavetrain inputs.
Maneuvers (Pilot-in-the-loop)	Offset landings, precision capture tasks (Nz, attitudes, altitudes, etc), doublets, windup turns, upset recoveries, approach to stall, stall and departure, post-stall gyrations/spins.
Data Capture	
Telemetry	540 channels of data plus video from the downlink, 32 channels from the control command uplink. Recording of all intercom and cockpit audio, cockpit video, display video, and ground tracking cameras.
On-board sensors	Left and right wing-tip mounted alpha/beta vanes and pressure probes with static and dynamic pressure measurements. Outside air temperature. Analog IMU with angular rates and accelerometers. Surface positions measurements. Engine RPM, exhaust gas temperature and fuel flow.
Flight dynamics	Inertial data from INS system with GPS position data.

Appendix B – Initial Set of Potential Experiments for the F/A-18

The IRAC project has identified three broad objectives for the experimental flight test program. These objectives are subject to change based on the responses received as a result of this RFI and subsequent discussions with interested parties.

The three objectives and a brief outline of the experiments supporting these objectives are presented next:

Objective 1: To validate adaptive control technology using manned flight experiments. Experiments that address (See section B.1):

- The biggest barriers to implementing adaptive control on commercial, manned aircraft
    - Experiment with various stability metrics, adaptive control architectures, and features
- Challenges that can only be answered with manned flight research using representative avionics (e.g., quad redundant) and control actuations (e.g., engines).
    - Adaptive Propulsion Controlled Aircraft (PCA)
    - Redundancy management of faults
- Sufficiently large (or meaningful) failures to hinder pilot recovery
    - Upset/failure scenarios
    - Simulated damage scenarios

Objective 2: To examine the benefits of manned vs autonomous recovery (see Section B.2). Experiments that address:

- Types of pilot inputs to the system
  - Attitude rate commands via stick and rudder
  - Autopilot commands (target heading & altitude, for example)
- Choices of separate, backup system, or primary flight control system (in this case should it always be adaptive or should that be a 'mode'?)
  - Autonomous vs Semi-autonomous recovery
- Interactive adaptation
  - Pilot controls on/off, freeze, reset options

Objective 3: To test and validate system-level reasoning for flight control reconfiguration (see Section B.3). Experiments that address:

- Detection, diagnosis, prognosis, and isolation technologies for control reconfiguration and envelope limiting controls
  - Sensor fault (surface actuator, etc.)
  - Surface actuator fault (stuck on/stuck off, sluggish)

<u>B.1 Experiments that lead to Objective 1</u>

Experiment with various stability metrics, adaptive control architectures, and features

- Time delay issues
  - Protocol for introducing time delay for unified testing
  - Change actuator rate to small value to simulate time scale separation & rate limiting
- Adaptation rate
  - Fast adaptation by increasing sampling rate in between clock cycles
  - The frequency limits for the adaptive control signal
- Stability issues
  - PE (persistent excitation) effects on adaptation
  - Run-time monitoring experiment
  - Long duration flight test of adaptive algorithm
  - Examine parameters convergence/divergence with extended use due to measurement noise
  - Verify long duration controller performance at constant failure condition
- Architectures
  - Retrofit adaptive control law
  - Indirect adaptive control with forced excitation
  - Hybrid or composite direct-indirect adaptive architecture
- Online stability analysis
  - Adaptive control of stability margin through forced excitation measurement and feedback
  - Metrics-driven adaptation by changing gain online to maintain appropriate time or phase delay margin
  - Online stability analysis with adaptation

- Handling Qualities metric
    - Flight validation of cross-coupling handling qualities metric for use as a design and evaluation tool of adaptive controls

Experiment with various aspects of Adaptive PCA:

- Engine only
    - Experiment with simulated vertical tail loss
    - Experiment with differential thrust levels with engine lags for testing controllers with time-delay
- Integrated Flight Propulsion Control System (IFPCS)
    - Blended test of fast engine response research in flight. Flight condition, "high speed flight idle".
    - Demonstrate the capability of using engine as an extra set of actuators and design the flight controller with this redundant set of actuators during normal operation and emergency operation
    - Blend aero and propulsive control in lat/dir axis in response to pitch/lateral failures
    - IFPCS with full tail failure (horizontal & vertical)
    - Integrated aero/propulsion control – vary rate limit on throttle with daisy chain mixer

Experiment with various aspects of upsets, failures, and damage scenarios

- <u>Upsets</u>: with unusual attitude, high alpha
- <u>Failures</u>: sensors, actuators (e.g., stuck surface, floating surface)
- Simulate failure of all surfaces on one side of vehicle. Guide vehicle to specific point (simulated approach) using aero/propulsion control remaining
- Use structural instrumentation to compute local load margin. Simulate failure and adapt while staying within local loads –on ground.
- <u>Simulated Damage</u>
    - Unsteady aero experiment--damage (stuck surface, etc) asymmetric loads-high drag stores; real time System ID
    - Identification of "failures" using nontraditional surfaces (speed brake, rudder, toe-in) in combination with other failures.

<u>B.2 Experiments that lead to Objective 2</u>

Experiment with pilot interaction with adaptive control

- Choice of pilot inputs
    - Rate command
    - Autopilot commands
- Interactive adaptation – pilot controls on/off, freeze, reset
- Study pilot interaction issues w/ adaptive control by changing adaptive gains using same pilots. Obtain pilot model (if possible).
- Pilot awareness vs. no awareness

<u>B.3 Experiments that lead to Objective 3</u>

Experiment with on-line Integrated Vehicle Health Management (IVHM) technologies

- Detect, diagnose, and predict sensor faults
- Detect, diagnose, and predict surface actuator faults (stuck on/stuck off and sluggish actuation)
- Real-time updating of a dynamic vehicle systems reliability model using flight measured information

Experiment with off-line Integrated Vehicle Health Management (IVHM) technologies

- Data mining to validate algorithms against historical SHM (structural HM) data
- System-level reasoning and validate results using hardware-in-the-loop and flight tests
- Evaluate physics-based + data driven prognostics systems for SHM
    - Combine monitoring & anomaly detection of aircraft subsystems
    - Leverage existing sensors and data streams