Neural Adaptive Flight Control Testing on an Unmanned Experimental Aerial Vehicle

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Unmanned Aerial Vehicles have demonstrated potential as being effective platforms for supporting scientific and exploratory missions. They are capable of performing long endurance flights, and reaching remote areas that may be too dangerous for humans. As their role and types of missions expand, challenges are presented which require onboard systems to have increasingly higher levels of intelligence and adaptability. Missions requiring radical reconfiguration to carry mission-specific payloads, or operations under uncertain or unknown flight conditions, will require intelligent flight controllers that are capable of being deployed with minimal prior testing. This paper describes the testing of a neural adaptive flight controller that was designed to provide consistent handling qualities across flight conditions and for different aircraft configurations. The controller was flight tested on an unmanned experimental aerial vehicle, without the benefit of extensive gain tuning or explicit knowledge of the aircraft's aerodynamic characteristics. An overview of the neural adaptive flight controller is presented, along with a description of the experimental aerial vehicle test platform, and flight test results that demonstrate a dramatic improvement in handling qualities resulting from neural adaptation.

I. Introduction

THE Intelligent Flight Control (IFC) project at NASA Ames Research Center endeavors to investigate, maturate, and validate the next generation of intelligent flight controllers that exhibit higher levels of adaptability and autonomy than the current state of the art, reduce the costs associated with flight control law development, and can be applied to a wider-range of vehicle classes without significant development costs. The current IFC architecture is based on neural network augmentation, and is designed to enhance the handling qualities and response of a vehicle system subject to control surface failures or uncertainty in vehicle aerodynamic response resulting from structural damage, failures, or model inaccuracy. This technology has the promise to increase overall vehicle safety by adapting to changes in aircraft dynamics due to damage or failures, reduce cost associated with flight control law development by providing consistent handling qualities across flight regimes and variable aircraft configurations, and allow the application of generic control designs over a wide-range of vehicle classes, for example from commercial transports to high performance military aircraft and experimental concepts.

The process of validating experimental control technologies typically progresses from analytical analysis through testing using increasing levels of simulation fidelity to full-scale vehicle testing. Simulation testing has taken on increased importance over the past few decades. The rapid increase in computational power and tool sophistication available to researchers has allowed for more comprehensive testing and validation to be performed in the lab environment while providing results in a much timelier fashion. Analysis tools such as Matlab and Simulink integrate analysis tools with simulation capability seamlessly, and provide mechanisms for converting these designs directly to source code that can be quickly integrated into embedded flight vehicle control systems.

Despite the dramatic advances in computational technology, a crucial step in the maturation and validation of any research control technologies is real-world experimental flight testing on fully developed aircraft systems. The magnitude and severity of implementation-specific artifacts on a theoretical control construct may not be fully

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appreciated until testing of a control concept on a real-world vehicle system occurs. The degree to which unmodeled artifacts effect the overall performance of a vehicle system – for instance, noise and inaccuracy in sensor measurement of aircraft state, latency inherent in moving data between avionics subsystems, uncertainty in control system actuation, and unmodeled dynamics that can manifest in all aspects of vehicle subsystems – can have a devastating impact on performance. Identifying insufficiencies and flaws in a design during a full-scale flight testing phase can substantially increase the time and resource cost of a project well beyond initial estimates. Unfortunately, manned flight testing on full-scale aircraft is a challenging and expensive endeavor. The level of risk inherent in a manned flight program can propel the overall timeline and resource cost to several orders of magnitude beyond that required for simulation testing. The decision to test concepts on real vehicle platforms requires a major investment and development effort, and is often restricted to all but the most certain technologies which have the highest chances of succeeding – which unfortunately are often the most conservative.

The goal of the Experimental Aerial Vehicle (EAV) project at NASA Ames Research Center is to provide a rapid low cost aerial vehicle test-bed for research control technology experimentation and data analysis, without incurring the risks and costs of manned flight testing. The primary EAV vehicle platform is a small-scale fixed-wing unmanned aerial vehicle (UAV). The utilization of small-scale UAVs for the validation and testing of experimental flight technologies provides many advantages over larger scale UAV's or manned vehicles: small-scale UAVs are less costly to develop and operate, and small UAV projects can accept greater risk margins than conventional manned flight testing endeavors. For the researcher, these 'personal' small-scale platforms can provide vehicle test data for analysis with quick turn-around times; experimental concepts can be quickly integrated and rapidly flight tested.

The challenges associated with small-scale UAV testing, however, are not trivial. Vehicles at the scale of hobby-RC class aircraft systems have much higher response rates to disturbances and control input than their full-scale vehicle counterparts, requiring finer resolution from the aircraft sensors and better resolution in the control actuators. At the same time, significant weight, size, and cost constraints are forced into the avionics and actuator designs, resulting in less accurate state estimation and more uncertainty in control actuation. Avionics selection is often constrained to hobbyist-class components which can be orders of magnitude smaller, lighter, and less expensive than the commercial aviation technologies, but unfortunately suffer from lack of accuracy and precision when compared to their full-scale avionics counterparts.

This paper describes the Experimental Aerial Vehicle project at NASA Ames. The history of the Intelligent Flight Control program at NASA Ames Research Center is first presented. The EAV test vehicle platform is described in detail, followed by preliminary results from flight testing with the experimental IFC controller. Finally the conclusion discusses the overall results of this EAV project, and challenges that are faced in fielding small-scale UAVs for experimental purposes.

II. History of the Intelligent Flight Control System

The goal of the Intelligent Flight Control (IFC) project at NASA Ames Research Center is to investigate control systems that show adaptability in the face of failures, uncertainty, and system variability. The first phase of the IFC project - Gen 1 - investigated controller designs that required aerodynamic parameter identification, as reported in [1]. The second phase of development of the IFC - Gen 2 - investigated architectures that provide neural network augmentation to a model inversion controller (Figure 1), based on the work of Rysdyk and Calise [2]. This direct adaptive tracking controller integrates feedback linearization theory with both pre-trained and on-line learning neural networks; a Lyapunov stability proof guarantees boundedness of the tracking error and network weights [2]. The augmented structure provides adaptive control without explicit parameter identification, information on the nature or extent of the failure, knowledge of the control surface positions, or information on aerodynamic failure or unmodeled parameters [2-6]. The on-line direct adaptive neural algorithm drives the error between a reference model which defines the desired handling qualities and the commanded state to zero. Experimental investigations of the Gen 2 controller performed using six-degree-of-freedom (6DOF) simulation models under aerodynamic (A-matrix) failure and control surface (B-matrix) failure highlighted the ability of the Gen 2 neural augmentation design to improve handling qualities under failure [7]. Several neural network algorithms were also investigated, including the Extended Minimal Resource Allocating Networks (EMRAN) algorithm, the Single Hidden Layer (SHL) network, and the SigmaPi [8]. The positive results obtained from Gen-2 system simulation testing led to full scale testing on a NASA Dryden F-15 aircraft in 2006.

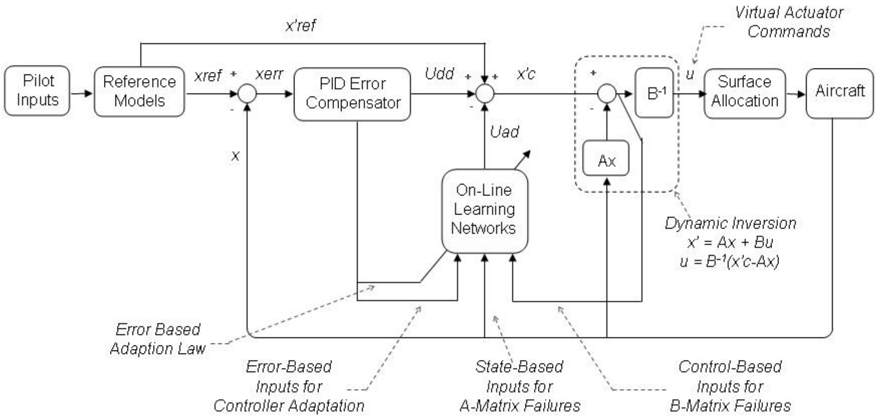

Figure 1. IFC Gen-2 Control Architecture

III. Experimental Aerial Vehicle (EAV): A Small Unmanned Aerial Vehicle Platform

During the development and testing of the IFC, a parallel effort was initiated at NASA Ames Research Center to develop in house capabilities for flight validation on a smaller scale, with the focus on reduced costs associated with performing flight test experiments on a real vehicle system. The EAV project currently fields three aircraft based on the Hanger 9 Cessna 182 Skylane 95" ARF platform, which is modeled after the 2000 version of a Cessna 182 at one quarter-scale. This particular model was chosen for two primary reasons: this model affords a large interior volume for installing flight avionics and systems, and vehicle data is readily available on the Cessna 182 full scale vehicle that can be scaled to give estimates on the performance and handling of the quarter-scale platform. The specifications for the EAV are shown in Table 1.

Table 1. Experimental Aerial Vehicle Specification

Airframe	Hanger 9 Cessna 182 Skylane 95" ARF
Wing Span	94.75 in (2406 mm)
Overall Length	76.75 in (1949 mm)
Wing Area	1246 sq in (80.39 dm^2)
Wing Loading	32.7 oz/sq ft
Flying Weight (Empty)	18.5 lb (8.22 kg)
Flying Weight (Full)	23.2 lb (10.52 kg)
Max Payload Weight	10 lbs
Cruise Speed	45 knots
Operations Ceiling	500 ft (flight field restrictions)
Engine Make/Model	Zenoah G-38
Engine Type	2-Stroke Gas/Oil
Engine Displacement	2.3 cu in (38 cc)
Actuation/Servomotors	Six (6) HiTec HS-5646MG DC Programmable Digital Ultra Torque Servos
Primary CPU	Diamond Athena 660MHz/128MB RAM
Secondary CPU (not yet flown)	Versalogic Cheetah M 1.6/512MB RAM
Embedded CPU	Motorola DSP56807
Sensor Suite	Athena GS111m INS/GPS Unit, provides full 6DOF state, WAAS-enabled GPS, angle of attack, sideslip, airspeed and pressure altitude
Sensors/Vision	Point Grey Dragonfly Cameras
Communication Links	• 72Mhz Receiver (Pilot/Safety Control) • 900Mhz Transceiver (Data Communications) • 2.4GHz Transmitter (Data/Video Downlink)

A. EAV Airframe and Modifications

The modified Hanger 9 Cessna aircraft has proven to be a reliable platform for flight testing. Several modifications were imparted to the vehicle to strengthen the airframe, provide access to the interior space, and provide mounting points for sensors and avionics.

Figure 2. Experimental Aerial Vehicle (EAV-2) and Flight Team

The major structural rework on this airframe has focused on the wing to body strut supports which have proven to be inadequate to support the aircraft with full avionics weight performing high-g maneuvers. Under heavy loading, the wing-to-body struts are a significant load-bearing member in the aircraft, providing structural integrity for the entire airframe. Several failures during early flight testing were encountered: the strut mounts in the wing failed (dislodging a section of the wing), the strut mounts on the fuselage failed (dislodging a portion of the fuselage), and the factory struts failed (snapping in two when both mounting points were reinforced). To address the wing-body strut failure issues, the aircraft struts were replaced with stronger custom built struts, the mounting points on the body and the wings were strengthened to support the additional stress to the aircraft, and larger bolts were used in the installation (Figure 3 center).

Figure 3. Airframe Modifications.
Access Hatch (Left), Wing Struts (Center), Pull-Pull Rudder System (Right)

The factory installed rudder mechanism was also problematic, providing less control and accuracy of the rudder control surface than was desired. The control assembly was replaced with a Du-Bro RC heavy-duty dual pull-pull system and a top-mounted servo (Figure 2 right). The factory provided landing nose gear was also not strong enough to handle the larger weight during landings, the factory struts were discarded in favor of a nose gear strut built by Robart Manufacturing specifically for the Hanger 9 Cessna aircraft.

During ground testing, avionics showed a propensity for overheating when ambient temperatures were high. In addition to installing an active cooling system in the avionics flight box, the front and rear windows panes on the aircraft were slotted with inlet and exit ducting to allow air to circulate in the fuselage while the aircraft is in flight. Additional modifications to the fuselage included cutting an access hatch on the rear of the fuselage for avionics insertion (Figure 2 left), and installing a vertically mounted antenna. Blind nuts were installed in a standard pattern on all aircraft to support installation of an avionics tray, which allows a tray to be moved between different aircraft, and also allows different avionics trays to be installed to support different configurations for flight testing.

Figure 4. Mounted Sensors.
Pan/Tilt Camera (left), Downward Facing Cameras (middle), Wing-Mount 5-Hole Air Data Probe (right)

The EAV aircraft can fly with three cameras. A pan-and-tilt camera assembly is mounted on the bottom of the aircraft, protruding through the bottom of the aircraft behind a plexiglass dome (Figure 4, left). A custom engine exhaust assembly was designed and installed which funnels oil exhaust from the two-stroke engine away from the camera dome during flight. The wings were modified to include a set of downward facing cameras (PointGrey Research Dragonfly IEEE-1394 cameras) to provide stereo-pair imaging (Figure 4, middle). A GPS antenna was mounted on the far left wing tip, and a five-hole air data probe from the American Sensors Corporation was installed on the left wing (Figure 4, right), which extends five inches beyond the leading edge of the wing, and provides airspeed, attack angle, and sideslip measurements.

B. Engine, Actuation, and Power

The EAV is powered by a single forward mount (puller configuration) Zenoah G38 2-stroke gasoline engine (38 cc, 2.3 cu in) driving an 18x10 propeller (18 inch tip to tip diameter, 10 inches of advancement per revolution) with a nominal rotation rate range from 7100 to 7400 rotations per minute at full throttle.

The power systems on the EAV are separated into two isolated systems: the avionics power and the actuator power. All onboard batteries use Lithium-Polymer chemistry and sold by Duralite Flight System, Inc. The actuator systems are powered by two 3S Li-Po packs, providing a total of 5000mAh at 11.1V nominal (9.0-12.3V). This power is regulated to 6V through two paralleled FMA Direct VRL12 linear regulators. These regulators power the DC servomotors which actuate the control surfaces.

The avionics system is powered by two 3S2P Li-Po packs which provide 10Ah at 11.1V nominal. All onboard avionics power is regulated by a Diamond Systems PC/104 power supply on the avionics CPU stack.

C. Avionics System

The avionics system is built around two processing boards; an Intel-based PC/104 processor and an embedded Motorola DSP. A list of avionics components used in the EAV is shown in Table 2 below. The PC/104 handles high level control and processing, while the Motorola DSP is responsible for all real-time processing. This allows the PC/104 computer system to run with commercial operating systems and relaxes the requirement for hard real-time processing, simplifying the development effort by tying the ground based simulation and analysis efforts with the flight computer environment.

Table 2. List of Avionics and Sensor Components

Component	Manufacturer	Model	Details
PC/104 CPU	Diamond Systems	Athena 660-128	Via Eden 660Mhz 128MB
PC/104 CPU	Versalogic	Cheetah EPM-32c	Pentium M 1.6GHz
PC/104 Power Supply	Diamond Systems	Jupiter MM-SIO	50W DC/DC Power Supply
Embedded CPU Board	New Micros/Motorola	USBServopod/DSP56807	Processor Board
Flash Drives	San Disk	Extreme III CF, 8GB	Two (2x) 8GB CF Cards
PC/104 FireWire Card	Parvus	COM-1461	PC/104-Plus 3-Port IEEE-1394b FireWire Controller
Sensors/INS/GPS	Athena Controls	GS111m Guidestar	Digital IMU/INS/GPS Sensor Suite
Radio Modem	Microhard Systems	MHX-910	ISM Band 900Mhz RF Radio Modem
Fan	(Unknown)	(Unknown)	Cooling Fan
2.4Ghz Video System	(Unknown)	(Unknown)	Video camera and transmitter
Firewire Camera	Point Grey Research	Dragonfly	IEEE-1394 Digital Camera

The component block diagram for a typical flight configuration is shown in Figure 5. Depending on the configuration, the EAV avionics and actuator systems consumes around 26W of power total during nominal operations.

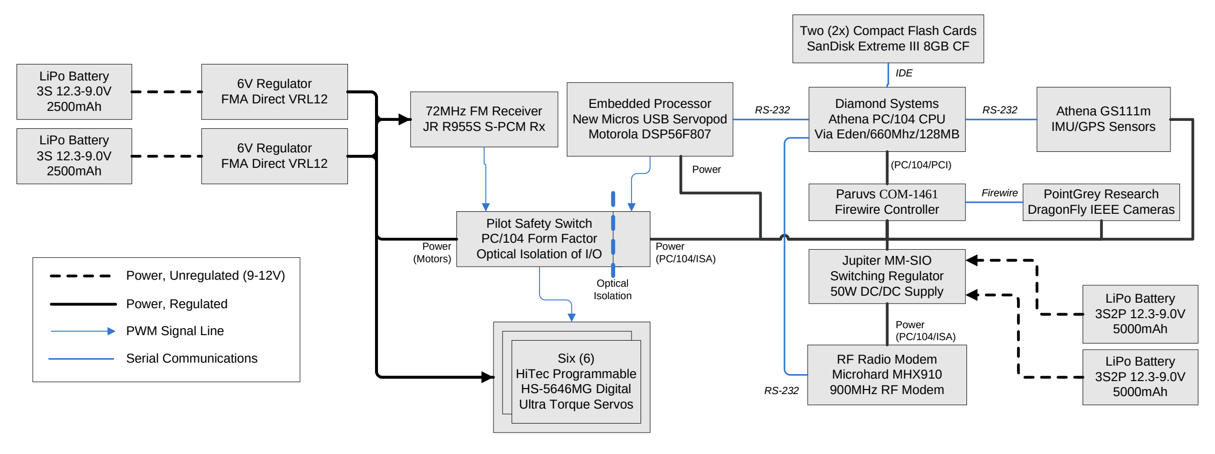

Figure 5. EAV-2/3 Avionics Components Diagram

The sensor suite is built around an integrated unit provided the Athena Technologies, Inc. The GS111m Guidestar unit provides a complete integrated sensor suite, providing full state information at 100Hz to the central PC/104 processor. The GS111m provides complete air data sensor information (airspeed, altitude, angle-of-attack, sideslip), inertial measurement with three-axis gyros and accelerometers, three-axis magnetometers, WAAS enabled GPS, and an extended Kalman filter to tie the information together. The GS111m unit is only used on the EAV for sensor data information; this unit also provides a complete navigation and control suite, but this functionality is not being used on the EAV.

D. Pilot Safety Switch

The EAV flight system has two control links to the ground: a 72MHz link and a 900Mhz link. The primary pilot controls the aircraft through a JR XP8103 radio transmitter, which broadcasts a 72Mhz S-PCM signal to the onboard receiver (JR R955S S-PCM receiver). The receiver sends signals to the pilot safety switch, which relays the signals to the servos. The pilot safety switch operates in two modes: pilot in control (PIC) or computer in control (CIC). One channel from the primary pilot is used to select which mode is active, and the primary pilot has the option of allowing the computer to take control of the EAV, or taking direct control from the computer.

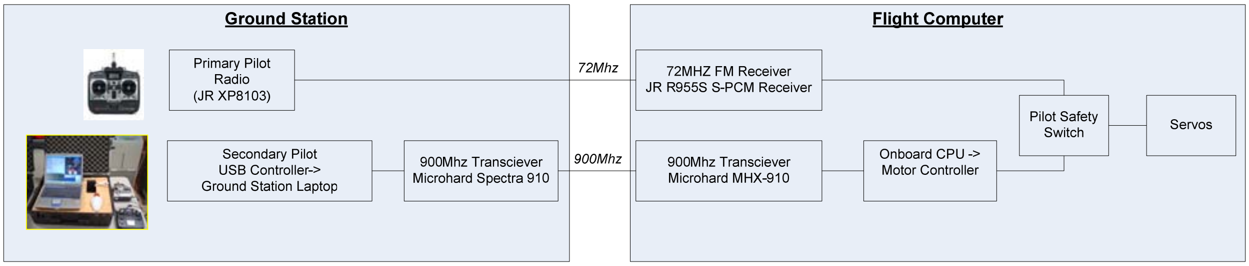

Figure 6. Primary and Secondary Links

A backup pilot is always on standby on the 900Mhz link. Should the primary pilot's 72Mhz link be lost, the CIC mode is automatically engaged. The secondary pilot controls the EAV through a USB controller connected to the primary ground station. The ground station sends commands through a long range 900Mhz radio modem system to the onboard system (Microhard Spectra 910/MHX-910). These controls are sent through the onboard CPU to the pilot safety switch. In the event of a primary 72Mhz communications loss, the onboard CPU will allow the secondary pilot to control the aircraft. In the event of a 72Mhz and a 900Mhz communications loss, the CPU triggers a failsafe controller mode, which is a slow circling descent mode that commands pitch and roll angle to a specified hold-value, and sets the throttle to an idle setting: should connection never be reestablished, this mode will bring the aircraft down within the confines of the approved operations area.

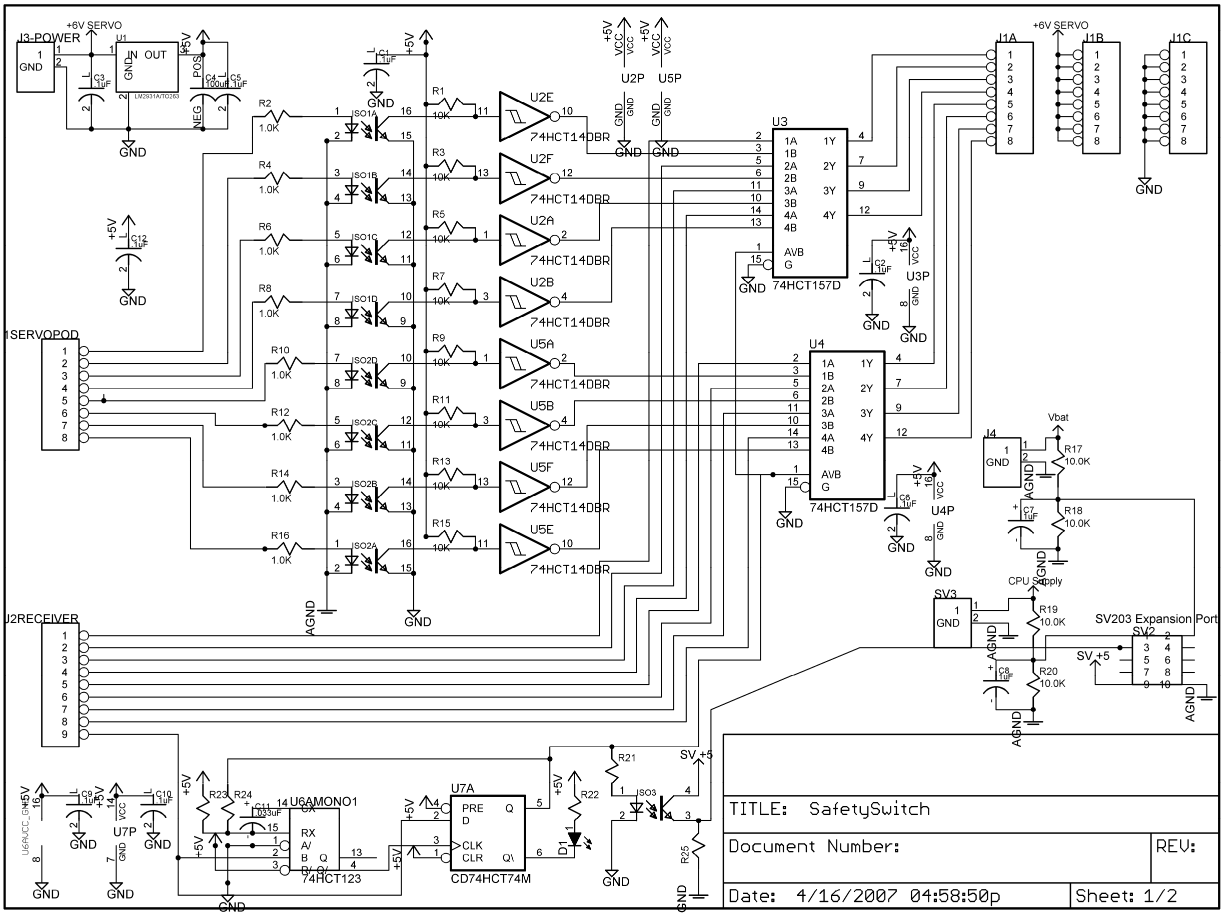

Figure 7. Safety Switch Circuit.

The pilot safety switch is a custom-designed hardware that has gone through several design cycles and modifications. Originally designed on a 1.75"x2" form factor, a new PC/104 size has also been assembled for placement on the avionics stack, minimizing vibration issues and simplifying assembly. The safety switch is the sole bridge between the engine/actuation and aviation systems, electrically isolating the two with separate grounds and power and transmitting commands between the two over optical couplers. It is powered by the +6V regulators for the servos. A monostable multivibrator and D-flip-flop set controls the output of the multiplexer as PIC or CIC, triggering and holding a constant output based on the pulse code modulated input on channel 9 of the 72 MHz receiver.

E. System Identification

The major lateral and longitudinal modes of the aircraft were identified through a series of flight tests. The pilots provided lateral and longitudinal inputs using a number of maneuvers such as 3-2-1-1, 2-1-1, pulses, and doubles, to excite the aircraft modes. The results were post-processed with a least-squares regression in frequency domain to identify the system. The major modes are shown in Figure 8 and Table 3.

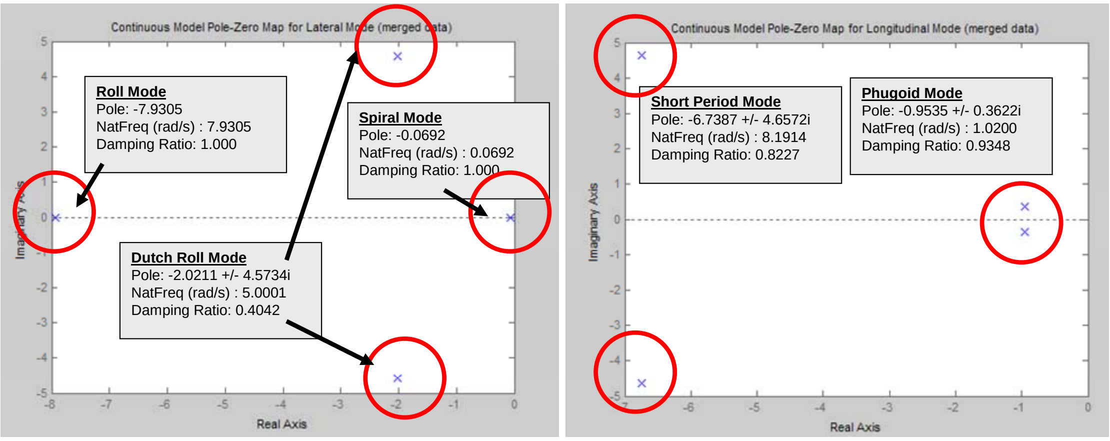

Figure 8. Pole-Zero Plots of the Lateral and Longitudinal Modes

Table 3. Mode Characteristics of the Identified Longitudinal and Lateral Dynamics

Mode	Pole	Frequency (rad/s)	Damping (ξ)
Roll Mode	-7.9305	7.9305	1.0000
Dutch Roll Mode	-0.0692	5.0001	0.4042
Spiral Mode	-0.0692	0.0692	1.0000
Short Period Mode	-6.7387 +/- 4.65721i	8.1914	0.8227
Phugoid Mode	-0.9535 +/- 0.36220i	1.0200	0.9348

IV. Methodology for Development

The Reflection Architecture [9] is a component-based software architecture for embedded systems development. This architecture was created to provide the EAV project with capability for rigorous and rapid hardware in the loop simulation and testing. Reflection provides the communication layer for the computer systems used during ground testing and flight testing, including the ground-based simulation environment, the ground stations that monitor the aircraft in flight, and the onboard flight computer systems. This architecture provides rapid reconfigurability of components, allowing experimental components to be thoroughly tested in various configurations with hardware and simulation in the loop. Utilizing rapid configuration allows a formalized methodology to be developed for fielding research control systems. Flight software and control system development proceeds through four development phases.

Phase 1 development occurs on workstation computers, using low to moderate-fidelity simulation, where the focus is on developing the capabilities of the controller component. Various fidelity simulation configurations can be swapped into and out of the simulation to allow testing at the appropriate level of fidelity.

Phase 2 development moves the experimental component into a series of hardware in the loop simulation. A number of intermediate configurations are created where simulation components are replaced with hardware interfaces.

Phase 3 development transitions the software component to the flight computer, where a series of ground tests are performed on the fully assembled EAV. Configurations are typically run with most of the actual flight hardware in the loop, except sensor data is replaced with the flight data generated simulation models. Complete simulations of the planned flight test experiments can be performed, from taxi, takeoff, controller activation, to final landing. A series of ground tests are also performed during Phase 3, which includes communication range testing, vibration testing, and system endurance testing.

Phase 4 is the final fight testing phase. All simulation components are removed from the configuration, and all hardware is in the loop. All flight tests are performed at NASA Ames Research Center on Moffett Federal Airfield. An extensive set of checklists and procedures have been established to ensure proper flight setup and operation, including emergency and flight termination procedures.

V. Preliminary Flight Testing Results

The first phase of flight testing has been conducted to test the inner-loop control adaptation with rate-command and attitude-command modes. The EAV flights at Moffett Field are approved up to a maximum flight ceiling 500 ft AGL, and not to extend past the confines of the airfield. The typical flight pattern establishes a race-track pattern roughly 2500ft in length, as shown in Figure 9. The flight systems were configured to pass the secondary pilot's stick positions through the ground station (over 900Mhz) to the flight computer and into the inner-loop control system as real-time command inputs – either rate commands or attitude commands. The secondary pilot also had the ability to engage or disengage the neural network augmentation.

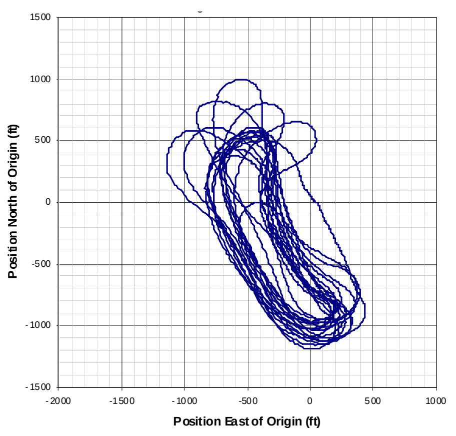

Figure 9. Flight Test Ground Track.

The baseline controller with dynamic inversion was not tuned for the EAV aircraft so the baseline controller performance was expected to be initially poor. The goal of the flight tests was to allow the neural network augmentation system to adapt for the mismatch in the dynamic model and improve the handling qualities of the inner-loop controller. A handoff protocol was established to switch between the primary and secondary pilot, either to start the experiment, or to terminate the experiment if the controller proved to be unstable.

The following figures show flight test results of command tracking in both pitch and roll for an attitude command configuration. Figure 10 shows the baseline controller without augmentation of the neural network. As expected, the roll and pitch responses showed poor tracking with the commanded input from the pilot. The secondary pilot was never able to maintain control of the aircraft for an extended period of time without neural augmentation, and often required the primary pilot to recover control from unusual attitudes.

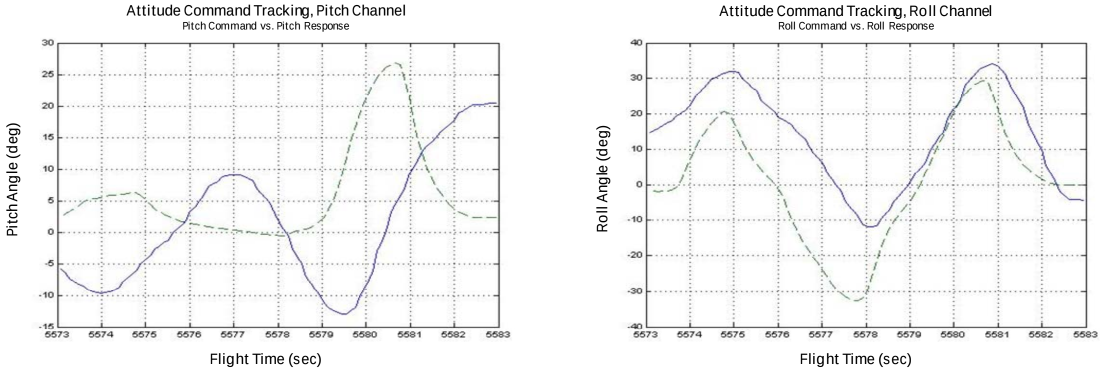

Figure 10. Baseline Controller Response, Attitude Command Mode.

The charts in Figure 11 show the results of the adaptive control system after the neural network was engaged, and given time to learn and adapt. In this final series of flight tests, the neural network provided sufficient handling to allow the secondary pilot to control the aircraft and maintain the desired test pattern over an extended period of time.

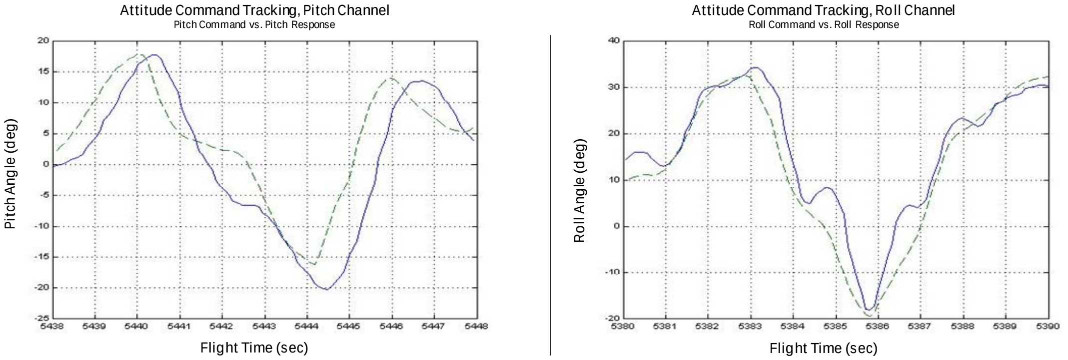

Figure 11. Controller Response with Neural Network Augmentation, Attitude Command Mode.

Despite the promising results with an attitude control system, the performance results of the IFC during EAV flight testing were not as positive as the results from simulation. The rate control autopilot has not been as successful and is currently undergoing continued EAV flight testing. Several possible contributing factors have hindered progress with successful rate-command testing on this system. The rate command system requires faster response than the attitude command systems with tighter phase and gain margins. Time-delays in the transport of data between systems were not negligible, and a late development effort was undertaken to redesign the avionics to help minimize transport delay. The dynamic inversion computes control from angular rates using a simplified aerodynamic model, but mismatch between the model and the real-world vehicle behavior may be contributing to performance degradation. Noise and latency in the off-the-shelf sensors and uncertainty and slop in the actuator mechanisms may also be playing a role. The neural network had the propensity to increase the overall gain of the controller, impart very large forces on the vehicle system that exacerbated the structural problems of the off-the-shelf vehicle platform. Additionally, several pilots were used during flight testing; unfortunately the difference in pilot control tendency has a noticeable effect on the IFC controller performance. Interestingly, the flight testing initiative of the IFC controller on a full-scale piloted F15 uncovered many of the same issues related to the controller that the EAV program uncovered; tests utilizing the small-scale EAV platforms could have been used to further refine the controller technology before initiating the larger effort. However, the issues encountered during EAV testing that concern deficiencies in the vehicle platform could be considered a function of the novelty of the platform and are addressed as they are uncovered, so the platform issues become less frequent as the vehicle platform matures, allowing future technologies developed to undergo EAV testing with the distinct advantage of a mature vehicle platform.

Conclusion

Small-scale UAV vehicle platforms are becoming an increasingly common tool in research programs for experimental control systems technology. These platforms can be assembled quickly and rapidly utilizing low cost commercial off the shelf products. The EAV flight tests have provided valuable data and feedback about the IFC controller design. Several lessons were learned from frequent fielding of the EAV flight system. Simulation in the loop testing is an invaluable tool in identifying problems in the lab that can be time consuming to fix in the field. Establishing and constantly refining formal procedures and checklists is of paramount importance in the ability to conduct test flight consistently and expeditiously, ensuring quick turnaround times and reducing the amount of time wasted in the field. Redundancy must be established throughout all systems, including onboard avionics and ground systems. Electronics noise and interference caused by poor grounding and subsystem separation was a major problem during the inception of the project; these issues should be considered and addressed early in the project. Utilizing off-the-shelf components where possible provides major savings in terms of time and development effort, though in certain situations it is necessary to build custom hardware and software for higher performance or functionality geared to the application. Despite the differences between full-scale manned vehicles and small-scale vehicles such as the EAV, experimental test of the IFC on a small-scale vehicle provided many of the same results as the full-scale manned vehicle testing. These results provide support to the hypothesis that the investment in a low-cost small-scale platform such as the EAV can provide tremendous benefit to research programs where technologies are developed with the goal of application in full-scale manned vehicle systems.

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References

[1.] Peggy S. Williams-Hayes, *Selected Flight Test Results for Online Learning Neural Network-Based Flight Control System*, NASA/TM-2004-212857, 2004

[2.] Rolf T. Rysdyk, and Anthony J. Calise, “Fault Tolerant Flight Control Via Adaptive Neural Network Augmentation,” AIAA-98-4483, Aug. 1998.

[3.] Peggy S. Williams-Hayes, *Flight Test Implementation of a Second Generation Intelligent Flight Control System*, NASA/TM-2005-213669, 2005.

[4.] A. J. Calise, S. Lee, and M. Sharma, “Direct Adaptive Reconfigurable Control of a Tailless Fighter Aircraft,” AIAA-98-4108, Aug. 1998.

[5.] Mario G. Perhinschi, Marcello R. Napolitano, Giampiero Campa, Brad Seanor, Srikanth Gururajan, and Gu Yu, “Design and Flight Testing of Intelligent Flight Control Laws for the WVU YF-22 Model Aircraft,” AIAA-2005-6445, Aug. 2005.

[6.] John Kaneshige, John Bull, and Joseph J. Totah, “Generic Neural Flight Control and Autopilot System,” AIAA-2000-4281, Aug. 2000.

[7.] John Burken, Peggy Williams-Hayes, John Kaneshige, and Susan Stachowiak, “Adaptive Control Using Neural Network Augmentation for a Modified F-15 Aircraft”, ISBN: 0-9786720-0-3, IEEE 14th Mediterranean Conference on Control and Automation, June 2006.

[8.] M.G. Perhinschi', J. Burken', M.R. Napolitano', G. Campa', M. L. Fravolini, “Performance Comparison of Different Neural Augmentation for the NASA Gen - 2 IFCS F-15 Control Laws”, Proceeding of the 2004 American Control Conference, Boston, MA, 2004

[9.] C. Ippolito, G. Pisanich, and K. Al-Ali, “Component-Based Plug-and-Play Methodologies for Rapid Embedded Technology Development”, AIAA-2005-7122, Infotech@Aerospace, Arlington, Virginia, Sep. 26-29, 2005