

# Adaptive Flight Control Research at NASA

Mark A. Motter  
NASA Langley Research Center  
Hampton, Virginia 23681  
Mark.A.Motter@nasa.gov

## Abstract

A broad overview of current adaptive flight control research efforts at NASA is presented, as well as some more detailed discussion of selected specific approaches. The stated objective of the Integrated Resilient Aircraft Control Project, one of NASA's Aviation Safety programs, is to advance the state-of-the-art of adaptive controls as a design option to provide enhanced stability and maneuverability margins for safe landing in the presence of adverse conditions such as actuator or sensor failures. Under this project, a number of adaptive control approaches are being pursued, including neural networks and multiple models. Validation of all the adaptive control approaches will use not only traditional methods such as simulation, wind tunnel testing and manned flight tests, but will be augmented with recently developed capabilities in unmanned flight testing.

## 1 Introduction

NASA's Aeronautics Research Mission Directorate is currently advancing several programs that have a vested interest in the broad advancement of adaptive control, ranging from the promotion of intellectual stewardship to the development of new experimental methods for validation of novel flight control concepts. These programs are: Fundamental Aeronautics; Airspace Systems; Aviation Safety; and the Aeronautics Test Program. Underlying these programs are several projects that are very specifically focused on the development, implementation and testing of adaptive flight control. In particular, the Aviation Safety Program's Integrated Resilient Aircraft Control Project, as well as Fundamental Aeronautics' Subsonic Fixed Wing and Hypersonics projects have substantial assets committed to research in adaptive, robust and optimal control, as well as experimental flight control testing on both full scale and sub-scale testbeds, in conjunction with more traditional simulation and wind tunnel testing.

A listing of some of the funding of external research projects through NASA research Announcements provides some insight into the efforts being pursued under these programs:

- 1) Adaptive Robust Control for Hypersonic Vehicles (ARCH)
- 2) Robust Composite Adaptive Control for Piloted Aircraft

- 3) Verifiable Adaptive Control: Analysis and Design
- 4) Experimental validation of metrics-driven enhanced-safety (ME) adaptive control
- 5) Flight Validation of Metrics-Based Adaptive Control Methods
- 6) Adaptive Control with a priori Guaranteed Performance Bounds and Robustness/Stability Margins
- 7) Using symbolic constraint solving techniques for analyzing stability properties of adaptive control systems
- 8) Adaptive Control with Stability Guarantee
- 9) Development of LMI Analysis Tools for Learning Algorithms
- 10) Minimal Modeling Direct Digital Adaptive Flight Control
- 11) Adaptive Control Techniques for Systems under Structural Uncertainties with Aircraft Control Applications
- 12) Flight Validation of Metrics Driven Adaptive Control

A number of these research projects will be reported on at the upcoming 2008 AIAA Guidance and Navigation Conference later this summer in a pair of sessions entitled "Adaptive Control under Anomaly – Theory and Design Methods, and "Adaptive Control Applications and Flight Validation," organized by Suresh Joshi and Nhan Nguyen of NASA. These two sessions include 16 papers by well-known researchers working in the forefront of this area, and will address adaptive control, particularly under anomaly, with a focus on theory and synthesis methods, as well as adaptive control implementation in test vehicles. Some of the topics will be covered in this workshop, but a summary is included for completeness and to give an overall context for the work.

## 2 Theory and Design Methods

Nguyen, Krishnakumar, and Boscovic [1] are working on a method that can achieve fast adaptation for a class of model-reference adaptive control. Fast adaptation is needed because of large uncertainties that can occur, for example, due to structural damage to an aircraft, resulting in large changes in its flight dynamic characteristics. It is known that

conventional model-reference adaptive control exhibits high-gain control behaviors when a large adaptive gain is used to achieve fast adaptation in order to reduce tracking error rapidly. High-gain control creates high-frequency oscillations that can excite unmodeled dynamics and can lead to instability. The fast adaptation approach is based on the minimization of the square of the tracking error, which is formulated as an optimal control problem. The necessary condition of optimality is used to derive an adaptive law using the gradient method. This adaptive law is shown to result in uniform boundedness of the tracking error by means of the Lyapunov's direct method. Furthermore, this adaptive law allows a large adaptive gain to be used without causing undesired high-gain control effects. Simulations demonstrate the effectiveness of the proposed method.

Tao and Joshi [2], introduce the problems and methods of control of systems with failures and faults, and present an overview of recent work on direct adaptive control for compensation of uncertain actuator failures, which may be characterized by some unknown system inputs being stuck at some unknown (fixed or varying) values at unknown time instants that cannot be influenced by control signals. The key task of adaptive compensation is to design the control signals in such a manner that the remaining functional actuators can automatically and seamlessly take over for the failed ones, and achieve desired stability and asymptotic tracking. The challenge is to effectively use the available actuation redundancy to handle failures, without the knowledge of the failure patterns, parameters and time of occurrence. Their work addresses the key technical issues in adaptive actuator failure compensation and shows how state- and output-feedback adaptive control designs can be employed to effectively handle uncertain actuator failures, without explicit failure detection.

Annaswamy, Jang and Lavretsky [3], propose a new adaptive control approach for flight control. The adaptive architecture has the following properties: (i) the control design is based on a family of linearized models around multiple trim points, (ii) a nominal controller based on gain-scheduling is incorporated in the inner-loop, and (iii) an integral controller is included in order to ensure command following and disturbance rejection. The adaptive controller ensures (a) stability when state variables are accessible, (b) accommodates the presence of magnitude saturation, and (c) command following, when the desired trajectory varies slowly. The uncertainty addressed is assumed to occur due to actuator anomalies. This work will be covered in part at this workshop as well.

Kutay, Calise, and Johnson [4] are working on fault tolerant control approaches representing a selection of recent work in the literature. The value of these approaches has been demonstrated to various degrees through numerical simulations or in actual flight test. All these methods have certain benefits that make them suitable for certain types of problems, as well as some drawbacks that limit their usefulness in actual flight control system design. The objective of this paper is to test several key approaches on NASA's general transport model (GTM) simulation and compare their fault tolerance capabilities on a fair basis to provide insight on strengths and weaknesses of the available methods for future developments. .

Lavretsky, and Hovakimyan [5] are collaborating to the design of servomechanism controllers for uncertain multi-input systems, with *nonlinear-in-control dynamics*. Nonlinear flight dynamics can occur due to damage, failures, or other off-nominal conditions, therefore adaptive control of uncertain nonlinear systems is an important problem. Tracking controllers are developed using Hamilton's Principle, time-scale separation methods, and direct model reference adaptive control. Verifiable sufficient conditions are stated that guarantee closed-loop stability, bounded tracking, and uniform ultimate boundedness of all the signals.

Cao, Hovakimyan and Gregory [6] are working on an extension of the L1 adaptive output feedback controller to systems of unknown dimension in the presence of time-varying uncertainties without restricting the rate of their variation (for example, unmodeled or poorly modeled flexible modes with varying characteristics due to damage and other anomalies). A closed-loop reference system is defined, and its stability is proven using small-gain type argument. The performance bounds between the closed-loop reference system and closed-loop L1 adaptive system are computed and shown to be inversely proportional to the adaptive gain. As compared to earlier results in this direction, a novel adaptive law is proposed, which allows for controlling the systems in the presence of higher relative degree of the regulated output. Simulation, based on the wind tunnel data, of a highly flexible flying wing verifies the theoretical findings.

Santillo and Bernstein [7] are developing a novel, fully discrete-time adaptive control methodology that requires minimal modeling information. Continuous-time models provide physics insight needed to determine performance specifications as well as sensor/effector requirements. Complementary to these objectives is the need for discrete-time modeling and synthesis, which arises first and foremost from the realization that all obtainable data for system identification and on-line control are

discretized in time. Discrete-time identification and controller synthesis at operational sampling and reconstruction rates removes the need for controller discretization and the potential loss of gain and phase margin. Discrete-time controller synthesis also facilitates embedded controller encoding.

Bosovic, Jackson, and Nguyen [8] are addressing controller synthesis based on the Multiple Models, Switching and Tuning (MMST) approach to approach to fault-tolerant control. It presents the design method as well as implementation in a hardware-in-the-loop (HWIL) simulation of Delta Clipper Experimental (DC-X) dynamics. The DC-X is a scale prototype for a proposed vertical take-off and landing (VTOL) reusable launch vehicle capable of single stage to orbit (SSTO) and is characterized by large control input redundancy. The failures considered include loss-of-effectiveness, lock-in-place, and hard-over failures of the flight control effectors. Several simulations results indicate excellent performance over a large range of single and multiple faults and failures. This topic will also be covered in part during the workshop.

### 3 Applications and Validation

Kaneshige and Burken [9], are developing enhancements to a neural network based approach for directly adapting to aerodynamic changes resulting from damage or failures. This is a follow-on effort to flight tests performed on the NASA F-15 aircraft, as part of the Intelligent Flight Control System research effort. Previous results demonstrated the potential for improving performance under simulated damage conditions. However, little improvement was provided under simulated control surface failures, and the adaptive system tended to be prone to pilot induced oscillations. They present an analysis of the previous flight tests and propose an alternate input selection criterion, a technique for improving robustness through normalized learning rates, and a method for adaptively retrofitting a classical yaw damping controller. Simulation results demonstrate significant improvement in performance and robustness over the neural network implementation used in the previous flight tests.

Bosworth [10] presents flight test results that show closed-loop stability margins with and without neural net adaptation. The direct adaptive system was engaged with these same simulated destabilization failures. Flight results show that the adaptive system provided higher stability margins. A comparison of the stabilator open loop frequency response is made with and without adaptation for the canard multiplier of -1.5. Without adaptation the simulated failure reduced the stability margin to about 1.6 dB. The

adaptation weights increased the stabilator loop gain and resulted in a stability margin of about 4.8 dB. A comparison is made between the flight-measured closed loop frequency response and the frequency response of the reference model. Limitations of the existing system are discussed. Comparisons will be made with the simulation predictions.

Johnson, Calise, and De Blauwe [11] are collaborating on a flight validation process for several existing and underdevelopment metrics-driven adaptive flight control methods. This is key element in the larger NASA Intelligent Resilient Aircraft (IRAC) program, which seeks to increase overall aircraft safety through dramatic improvements in stability, maneuverability, and probability of safe landing under adverse conditions – including aircraft damage. This project enables innovations in adaptive control approaches to be validated in flight tests that include simulated and actual damage as part of the fundamental research elements of the IRAC program. It also enables lessons learned from early flight experiments to aid this same fundamental research. The process consists of three major parts. First, suitable metric-driven adaptive controls will be analyzed. The focus will be on the one hand on existing methods and on the other hand on new and under-development methods. Second, flight control software will be developed based on methods using Georgia Tech UAV Simulation Tool (GUST). Third, flight testing of multiple methods performed using inexpensive flight vehicles that can be easily modified to simulate damage.

Urnes, Reichenbach, and Smith [12] have proposed a three year research program to be conducted by the Boeing Phantom Works, the Dynamic Flight Envelope Assessment and Prediction system, that will provide NASA with flight safety enhancements through a process to identify fault damage anomalies for a damaged air vehicle, and measure changes in structure dynamics mode shapes due to the damage. The system also provides adaptive control to maintain the aircraft within allowable structure limits and suppress any adverse structure dynamic mode interaction with the flight control system. The primary focus is on Control-Centric Modeling, combining rigid body models with dynamic flexible structure and loads models to provide the basis for on-line adaptive control of the structure properties of the aircraft. Products will be algorithms and processes that can provide control of structures properties for tactical and transport aircraft. This system addresses system anomalies caused by battle damage to military aircraft and structure failures to civil aircraft caused by incidents

such as fatigue, composite structure delamination, corrosion, mid-air collisions, or improper maintenance procedures. The development approach builds on the NASA Intelligent Flight Control System technology, already demonstrated on a research F-15 for adaptive control of the aerodynamic capability of a damaged aircraft. The significance of this program is to add a control capability to prevent excessive structure loads or dynamic interaction on an aircraft that experiences failures to structure elements, thereby increasing the safety and survivability of air vehicles.

Neidhoefer, Gibson, Kulkarni, and Al-Ali [13], are initiating work toward the development of two methods for Real Time Estimation of Stability Margins (RTESM). The first is intended for use with single input single output systems (SISO RTESM), and the second is intended for use with multiple input multiple output systems (MIMO RTESM). In addition, these methods are being used to develop Metrics-driven, Enhanced-safety (ME) adaptive control algorithms. Finally, efforts are underway to experimentally validate these techniques and their robustness to various types of uncertainties including aerodynamic, mass/inertial, aeroelastic, and wing damage in actual flight conditions.

Murch and Huschen [14] at NASA Langley Research Center report on the design and performance of a Remote Piloted Vehicle (RPV) flight control system architecture developed for the Airborne Subscale Transport Aircraft Research (AirSTAR) flight test facility. The primary purpose of AirSTAR is to test the performance of research control systems designed to accommodate failures of aircraft sensors, control effectors, and structural components. The AirSTAR facility will be used as a test bed for validating adaptive control development under the IRAC project. The AirSTAR facility consists of a RPV test article, the Mobile Operations Station (MOS), which is a control room/ground station that houses most of the test team, a safety pilot, and a research pilot. The safety pilot performs takeoffs, landings, and can take over control in the event of an emergency. The safety pilot transfers control to the research pilot, who is located inside the MOS. Using a suite of synthetic displays and air and ground video feeds, the research pilot flies the research maneuvers for each flight. The Flight Control System (FCS) is engaged while the research pilot has control. The MOS contains a dSPACE real-time computer that hosts the FCS software, in addition to telemetry and data processing software.

Kitsios, et al. [15] are investigating flight testing of metrics driven adaptive L1 control systems. In

particular, they addresses 1) definition of appropriate control driven metrics that account for the presence of failures; 2) tailoring the recently developed L1 adaptive controller to the design of adaptive flight control systems that explicitly address these metrics in the presence of failures and dynamic changes under adverse flight conditions; 3) development of a flight control system for implementation of the resulting algorithms on both NPS and NASA UAVs; and 4) conducting a comprehensive flight test program that demonstrates performance of the developed adaptive control algorithms in the presence of failures, including engine failure.

Jacklin [16] is examining what might be done to close the gaps or differences between what standard methods of airborne software certification can currently provide and what additional capability is required for adaptive software certification.

## 4 Experimental Testbeds

A number of experimental testbeds, both manned and unmanned are available for flight testing. The leading manned testbed is the Intelligent Flight Control System (IFCS), a highly modified F-15. The stated goal of the IFCS project is to develop and demonstrate a direct adaptive neural-network-based flight control system. The most recent tests used a modified angle-of-attack feedback to create a destabilizing condition which was compensated by the adaptive neural networks.



Figure 1. Intelligent Flight Control System F-15

Several unmanned testbeds are available for flight testing of experimental control concepts. The AirSTAR testbed, is a remotely piloted, dynamically scaled, 5.5% transport aircraft, where the experimental flight controls are used in conjunction with input from a research pilot seated in control room on the ground.



Figure 2. AirSTAR subscale transport testbed

The Flying Controls Testbed (FLiC) and its jet-powered version (J-FLiC) are fully autonomous unmanned testbeds initially developed under Langley Research Center's Creativity and Innovation initiative and further developed for experimental controller testing under the Subsonic Fixed Wing Program's Experimental Capabilities discipline.

The Flying Controls Testbed (FLiC) proposed to conceive, develop, implement, and flight test highly experimental and perhaps even controversial flight control technologies in a relatively low cost and low risk platform. Early efforts in the program focused on developing an inexpensive, small, relatively slow test platform controlled by a commercially available autopilot capable of stabilizing, navigating, and recording flight data. On June 27<sup>th</sup>, 2005, the FLiC performed a fully autonomous flight test demo at the Association for Unmanned Systems International (AUVSI) UAV Demo 2005, held at Naval Auxiliary Landing Field, Webster Field, MD. J-FLiC essentially has the same avionics as its prop-powered predecessor. The fundamental differences are in the airframe, engine and autopilot control gains and settings. J-FLiC was demonstrated at the AUVSI UAV Demo 2007.



Figure 3. J-FLiC unmanned testbed

## REFERENCES

1. Nguyen, N., Krishnakumar, K., and Boscovic, J., "An Optimal Control Modification to Model Reference Adaptive Control for Fast Adaptation," Proceedings of the 2008 AIAA GNC conference, Aug 2008.
2. Tao, G., Joshi, S., "Direct Adaptive Control in the Presence of Actuator Failures- State of the Art and Continuing Challenges," Proceedings of the 2008 AIAA GNC conference, Aug 2008.
3. Annaswamy, A., Jang, J., and Lavretsky, E., "Adaptive Gain-Scheduled Controllers in the Presence of Actuator Anomalies," Proceedings of the 2008 AIAA GNC conference, Aug 2008.
4. Kutay, A., Calise, A., and Johnson, E., "A Comparison of Methods for Adaptive Control under Actuator Failure Accommodation," Proceedings of the 2008 AIAA GNC conference, Aug 2008.
5. Lavretsky, E., and Hovakimyan, N. "Control of Uncertain Systems with Nonaffine Dynamics using Hamilton's Principle and Time-Scale Separation," Proceedings of the 2008 AIAA GNC conference, Aug 2008.
6. Cao, C., Hovakimyan, and Gregory, I., "L1 Adaptive Output Feedback Controller for Flexible Wing Application," Proceedings of the 2008 AIAA GNC conference, Aug 2008.
7. Santillo, M., and Bernstein, D., "Inherent Robustness of Minimal Modeling Discrete-Time Adaptive Control to Flight Anomalies," Proceedings of the 2008 AIAA GNC conference, Aug 2008.
8. Boskovic, J., Jackson, J., and Nguyen, N., "Multiple Model-based Adaptive Fault-Tolerant Control of Delta Clipper Experimental (DC-X) Planetary Lander," Proceedings of the 2008 AIAA GNC conference, Aug 2008.
9. Kaneshige, J., and Burken, J., "Enhancements to a Neural Adaptive Flight Control System for a Modified F-15 Aircraft," Proceedings of the 2008 AIAA GNC conference, Aug 2008.
10. Bosworth, J., "Flight Results of the NF-15B Intelligent Flight Control System (IFCS) with Adaptation to a Simulated Destabilization Failure," Proceedings of the 2008 AIAA GNC conference, Aug 2008.
11. Johnson, E. N., Calise, A. J., and De Blauwe, H., "In Flight Validation of Adaptive Flight Control Methods," Proceedings of the 2008 AIAA GNC conference, Aug 2008.
12. Urnes, Sr., J., Reichenbach, E., and Smith, T., "Dynamic Flight Envelope Assessment and Prediction," Proceedings of the 2008 AIAA GNC conference, Aug 2008.

13. Neidhoefer, J. and Gibson, C., Kulkarni, N., and Al-Ali, K., "Experimental Validation of Metrics-Driven Enhanced-Safety (ME) Adaptive Control," Proceedings of the 2008 AIAA GNC conference, Aug 2008.
14. Murch, A. and Heuschen, R., "A Remote Piloted Vehicle (RPV) Flight Control System for the AirSTAR Flight Test Facility," Proceedings of the 2008 AIAA GNC conference, Aug 2008.
15. Kitsios, I., Dobrokhodov, V., Kaminer, I., Lizarraga, M., Cao, C., Hovakimyan, N, and Gregory, I., "Flight Validation of Metrics Driven L1 Adaptive Control," Proceedings of the 2008 AIAA GNC conference, Aug 2008.
16. Jacklin, S., "Closing the Certification Gaps in Adaptive Flight Control Software," Proceedings of the 2008 AIAA GNC conference, Aug 2008.