

# A Historical Overview of Research in Reconfigurable Flight Control

Marc Steinberg

Naval Air Systems Command, Patuxent River, MD 20670

## Abstract

This paper presents a historical overview of research in reconfigurable flight control with a focus on work done in the United States. For purposes of this paper, the term reconfigurable flight control is used to refer to software algorithms designed specifically to compensate for failures or damage of flight control effectors or lifting surfaces by using the remaining effectors to generate compensating forces and moments. This paper will discuss influences on the development of the concept of control reconfiguration and initial research and flight-testing of approaches based on explicit fault detection, isolation, and estimation as well as later approaches based on continuously adaptive and intelligent control algorithms. Also, approaches for trajectory reshaping of an impaired aircraft with reconfigurable inner loop control laws will be briefly discussed. Finally, there will be some discussion of current implementations of reconfigurable control to improve safety on production and flight test aircraft and remaining challenges to enable broader use of the technology such as the difficulties of flight certification of these types of approaches.

## I. Introduction

In the fall of 1998, an F-18E/F Super Hornet was in the midst of flutter testing when

“Uncommanded pitch oscillations occurred during an asymmetrical flutter sweep at 0.88M. The uncommanded oscillations continued for about 2 minutes with slightly increasing amplitude until finally the R/H [right hand] stabilator experienced a 4 channel failure and the motion ceased as the flight controls reconfigured. The pilot observed slightly sluggish, but precise, longitudinal and lateral response with PA1/2 [half-flap power approach] configuration. An uneventful full stop

landing was accomplished in a 13 kt crosswind with the airplane exhibiting level 1 flying qualities throughout the approach [1].”

On previous versions of the F/A-18, this failure would have triggered a reversion to a mechanical control mode that usually caused substantial transients and slightly degraded handling qualities. However, one of the upgrades on the E/F version was the replacement of this mechanical back-up system with a reconfigurable control law. A reconfigurable control law compensates for failures or damage of flight control effectors or lifting surfaces by using the remaining effectors to generate compensating forces and moments. For this particular failure, the left stabilator and rudder toe-in can be used to restore some of the lost pitching moment and the flaps, ailerons, and rudders can be used to compensate for coupling in the lateral/directional axis caused by asymmetric stabilator deflection as shown in Fig. 1. Though this control reconfiguration approach had been demonstrated with simulated failures in flight test, this was the first successful demonstration with an actual failure.

While this was a significant event, perhaps even more significant was the earlier design decision to replace a redundant hardware approach to maintain control of a primary flight control surface with a software-based reconfiguration scheme. For decades, the general approach had been to use physical hardware redundancy to design flight control systems to be tolerant to failures and damage [2]. The use of redundancy increased throughout the 1960's due to the introduction of new automatic capabilities that were required for safe operation. Examples of this include augmentation of aircraft with reduced stability, all-weather landing systems, and eventually fly-by-wire systems in which the pilot normally has no direct mechanical link to the control effectors. By the beginning of the

1970's, a variety of flight control architectures with three and four levels of redundancy had been introduced. Not surprisingly, the use of redundant hardware or other mechanical back-up approaches can add weight, volume, and cost penalties to the aircraft. Not as obviously, redundant architectures can also significantly decrease flight control maintenance reliability due to the increase in the number of parts and complexity. As a result, when digital computers started being used in the 1970's to perform redundancy management, there was also interest in using software algorithms to replace physical hardware redundancy.

Initially, there was a great deal of attention on sensor analytic redundancy approaches to enable the isolation of a failed sensor with only dual or simplex redundancy. Approaches developed to detect and isolate sensor failures were ultimately to become important parts of later control reconfiguration schemes to detect and isolate control effector failures. An example of this is the Sequential Probability Ratio Tests that were flight-tested on the F-8 Fly-by-Wire demonstrator in the late 1970's [3]. Digital computers also enabled far more advanced control laws, such as adaptive approaches and optimizing control allocation schemes that would also be important for future control reconfiguration systems. While there had been a large amount of research in adaptive flight control going back into the 1950's, it was limited by the available analog mechanization approaches [4]. It also had primarily focused on disturbance attenuation and eliminating the need for gain-scheduling over the flight envelope as opposed to dealing with damage or failure cases. More complex digital adaptive flight control laws were flight tested in the 1970's [3], but the results were mixed and there was still a great

deal of skepticism about adaptive control's suitability and value for flight control. For example, Gunter Stein, one of the developers of a digital adaptive control law that was flight tested on the F-8 in the late 1970's, ultimately concluded that this control law did not have advantages over conventional gain-scheduling for aircraft [5].

It is open to debate exactly where the idea of flight control reconfiguration originated. Anecdotal examples of control reconfiguration can be found in various cases throughout the history of flight in which pilots had manually been able to exploit the remaining control capability of a degraded aircraft. Stories of these became inspirations for later automatic reconfiguration systems. Some of the theoretical basis for control reconfiguration appeared in a 1971 dissertation by Beard that looked at the number of control effectors needed for controllability of a linear system for failure accommodation [6]. Beard also discussed a detection filter approach that could be used with linear time-invariant systems. Unrelated to that, studies in the 1970's looked at the idea of back-up flight control effectors that could compensate for the failure of a primary control surface. One of the motivations for this was the stabilator on the F-4 since there was not sufficient remaining control power to counteract the pitch moment of a failed actuator. While the idea of back-up control effectors is not exactly the same as reconfigurable control, many of the strategies considered for replacing a failed primary control effector are also relevant for reconfiguration. By the late 1970's, the idea of control reconfiguration was being discussed in some of the redundancy management literature. The earliest detailed study to show the value of control reconfiguration may have been one done by Grumman for the United States Air Force (USAF) on reconfigurable and dispersed flight control

published in 1978, which was followed by a study by the United States Navy (USN) published in 1980 [7]. The Grumman study showed both the value of reconfiguration and the importance of considering reconfiguration in the initial design process. One example from that study was a configuration that used a large stabilator for both primary pitch and roll. The roll moment caused by using only a single stabilator for pitch control could not be counteracted by the remaining effectors. However, Grumman suggested that a fairly minor redesign of the speedbrake could make the aircraft more suitable for reconfigurable control by allowing the speedbrake to also be used for pitch control. Another aircraft studied at this time was the F-16. This aircraft appeared very well suited for reconfiguration and would become a focus of later USAF studies

Research in flight control reconfiguration began in earnest in the 1980's and has remained a major area of study ever since. Given the enormous amount and variety of published research, a journal-length paper cannot comprehensively discuss or even reference all noteworthy work. As a result, this paper will provide only a representative overview of the history of reconfigurable flight control from its early origins to its most recent applications. The focus will be on approaches that have been demonstrated in flight or in high-fidelity simulation. This paper will not deal with approaches for accommodating sensor failures or for switching among redundant hardware, both of which are sometimes referred to as flight control reconfiguration. Recently, the U.S. National Aeronautics and Space Administration (NASA) has published several helpful books that describe the history of the major flight tests at Dryden under the Self-Repairing Flight Control System, Propulsion-Controlled Aircraft, and Intelligent Flight

Control programs as well as the F-8 FBW demonstrator that flight tested a number of technologies relevant to reconfigurable control [3,8-9]. These provide excellent and accessible overviews of important programs that culminated in flight-testing at Dryden. However, there is a great deal of research in reconfigurable control that is not covered in those books that will be briefly described in this paper.

## **II. Early Approaches based on Failure Detection, Isolation, and Estimation**

In September 1982, NASA sponsored a workshop on what was then called restructurable controls [7]. A definition of restructurable controls from a summary of the workshop was that it must have the following attributes:

- 1) A method to measure the effectiveness of the current control mode.
- 2) A technique to identify the control(s) which have been lost when the above measure exceeds a threshold
- 3) A means to determine the characteristics of the remaining controls
- 4) A routine that can redesign control laws for the remaining flight controls without the intervention of a controls engineer [10]

Reconfigurable control was defined as an alternative approach that had the first two attributes, but that implemented a predetermined response for each class of identifiable failures and did not need to have the third or fourth attribute. These definitions would be seen as too limiting by many researchers today, but they do clearly show the strong influence of redundancy management on how this problem was formulated in the 1980's. In contrast, there was quite a bit of skepticism at the workshop about the suitability of using continuously adaptive flight control to solve this problem without the first two or three attributes. For example, Michael Athans had referred to a study "which proved with a combination of analytical techniques and simulation results that all existing adaptive control algorithms are not worthwhile [7]."

Much of the research in reconfigurable control in the 1980's would fit within the definitions provided above with a requirement for explicit Failure Detection, Isolation, and Estimation (FDIE). One important example of this type of approach was developed by General Electric (GE) Aircraft Controls in Binghamton. The USAF had begun funding GE in 1980 to determine a design concept for a reconfigurable control system that could compensate for failed actuators and damaged control surfaces. The initial design used a single extended Kalman estimator to perform all FDIE. Following FDIE, a pseudo-inverse approach based on a linearized model of the aircraft was used to determine control effector commands so that the degraded aircraft would generate the same accelerations as the nominal aircraft. The single Kalman estimator approach would turn out to be impractical, and most research efforts since have subdivided the FDIE problem to try to make it more feasible to solve. On the other hand, the pseudo-inverse approach would become a major focus of research with increasingly complex modifications to deal with practical issues such as the nonlinear flight envelope, actuator saturations, handling qualities, and axis prioritization. The GE design ultimately evolved to focus around three components as shown in Fig. 2 [11]: (1) A System Impairment Detection and Classification (SDIC) module to detect and isolate damage, (2) an Effector Gain Estimator (EGE) to determine the remaining capabilities of a partially damaged surface detected by the SIDC, and (3) a control mixer based on a pseudo-inverse approach to modify control surface commands initially generated by a conventional control law. There were a variety of other approaches examined in the early 1980's for control. Potts and D'Azzo looked at changing the closed loop poles of a system with

failures [12], Vander Velde looked at minimizing eigenvalue/eigenvector deviations [13], and Looze looked at maximizing a frequency domain performance metric to reallocate the controls [14]. A Command Generator/tracker approach was looked at by Ostroff and Hueshcn for a commercial aircraft with control surface failures under turbulence [15] and by Sadeghi for the A-7 aircraft [16].

In 1984, the USAF began the Self-Repairing Flight Control System (SRFCS) program. Recognizing that achieving the full potential of reconfigurable control might require incorporation in initial aircraft design, this effort initially focused on both the F-16 and a fictitious study aircraft called the Control Reconfigurable Combat Aircraft (CRCA) that would be designed by Grumman to have a wide variety of potential reconfiguration possibilities [17]. GE initially focused on the F-16 while studies were done on the CRCA that ultimately lead to a downselect of Lear Astronics to develop the control law and Charles River Analytics to develop the FDIE approach. Approaches by both GE and the CRCA team used a pseudo-inverse with a variety of modifications for performing reconfiguration following explicit FDIE. Both approaches to FDIE drew on work that had previously been done for sensor failure detection and isolation. GE chose an approach to developed by Alphatech for the SIDC that generated and filtered actuator and aircraft acceleration sensor residuals and then used a log-likelihood test to detect surface failures and a Sequential Probability Ratio Test (SPRT) to verify and classify a stuck or floating surface. The surface damage detection approach by CRA included a no-fail filter to generate residuals, a bank of filters to compensate the residuals based on partial surface loss estimates and expected modeling errors, a bank of likelihood ratios to

compute the likelihood of each surface damage hypothesis and a modified multiple hypothesis test to make detection and isolation decisions [18-19].

In 1985, limited flight-testing was done of the GE approach using the Total In-Flight Simulation (TIFS) aircraft, an NC-131H twin turboprop transport modified as a six degree-of-freedom in-flight simulator. The flight-testing included only a small number of simulated failure cases and the pseudo-inverse approach was not scheduled over the flight envelope. More extensive testing was done in 1986 using piloted high-fidelity simulation of the Advanced Fighter Technology Integration (AFTI) F-16 [20]. This testing did schedule the pseudo-inverse approach over the flight envelope, although the SIDC was designed for only a single flight condition. Results in simulation were positive for a wide variety of single and multiple surface failures including stuck, floating, and partial surface losses. However, several problems were noted including dealing with actuator saturations, pilot-vehicle coupling, and false detections. All remain significant challenges with reconfiguration approaches at the present. The pilots involved in the evaluation had also recommended the development of pilot alert displays. The idea of pilot alert displays had been examined previously, but was not then a major focus of the program.

In 1987 and 1989, the USAF performed additional limited flight-testing of a simple pseudo-inverse approach with detection of locked aileron and rudder cases [21]. This used the XBQM-106, a 200 lb. remotely piloted vehicle with a 12 foot wingspan and a pusher prop configuration. There were also a variety of other approaches being examined

for the flight control reconfiguration problem by the late 1980's in addition to those previously mentioned. For example, Huang and Stengel looked at implicit model-following [22] and Napolitano and Swaim looked at multiple model Kalman filtering [23]. FDIE for control reconfiguration had also become a major area of interest. Allen and Caglayan examined expert systems [24], Barron et al examined polynomial networks [25], Bonnice et al examined Orthogonal Series Generalized Likelihood Ratio tests [26], and Mayhew and Gleason examined other approaches based on analytic redundancy techniques [27].

By 1989, piloted simulation had been done of the CRCA approach [28] and extensive flight-testing of the GE approach began at NASA, Dryden in December. Piloted simulation on the CRCA focused on four diverse flight conditions and included significant complexity including structural modes, gusts, sensor noise, and sophisticated damage modeling. Flight-testing was done on a research F-15 with McDonnell Douglas as the prime integrator [29-30]. James Stewart was the NASA program manager and James Urnes, Sr. was the McDonnell Douglas lead. The flight test program covered twenty-five flights and allowed considerable evaluation of the system in some respects. However, it was only able to look at a small number of simulated failure and damage cases due to limitations of the on-board computer and flight safety concerns. Failure cases included both locked surfaces and a partially missing stabilator case that was simulated by moving the surface towards the local angle-of-attack. The results were mixed. A pilot alert display that showed the remaining maneuvering capability of the vehicle was rated highly and would ultimately become a great way to show the value of

reconfiguration to pilots. The program also provided considerable evidence that a pseudo-inverse approach could significantly restore flying qualities to an aircraft with severe damage or failures if they could be identified. Flying qualities were particularly improved in the most severe cases, such as with a locked stabilator at an unfavorable position. However, handling quality improvements were not universal. Further, both reconfiguration and pilot alert were dependent on reliable FDIE and that was the least successful part of the program. FDIE required substantial tuning of threshold parameters and it was difficult to get both fast detection and low false alarm rates. It was not uncommon for the pilot to need to put in large control inputs in order to trigger the FDIE in some of the simulated failure case.

The SRFCS program was followed by another important flight test program at Dryden for propulsion-only control of an aircraft that had suffered loss of all control surfaces due to a hydraulic failure [9,31]. Similar to SRFCS, James Stewart was the NASA program manager and James Urnes, Sr. was the McDonnell Douglas lead. The idea behind this program was developed by Burcham based on a Sioux City incident in 1989 in which the flight crew had remarkably succeeded in making a hard landing with a large commercial aircraft using thrust from the engines as the only control effectors. Unlike the SRFCS program, this used a switching approach in which a new conventional control law is used to replace the existing control law. The new control law enables the pilot to control heading and flight path angle and provides feedback to damp out the phugoid and dutch roll modes. This approach also may avoid the need for reliable FDIE since it would be possible to have a pilot perform the FDIE task and activate the system. In 1993, PCA

was demonstrated on the research F-15 with all control surfaces disabled and was able to perform a “firm but acceptable touchdown six feet left of the runway centerline [9].” Landing of an impaired aircraft in flight test had not been done previously under the SRFCS program. Successful flight-testing was also later done on an MD-11 and simulation evaluations were done with numerous other multi-engine aircraft.

By the beginning of the 1990’s, there was now a flight-tested set of techniques available that could be used to add limited reconfigurable control capability to otherwise conventional flight control laws for fixed wing aircraft. FDIE was the largest limiting factor and required complicated tuning based on known failure models, particularly for surface damage detection and isolation. However, there were a wide variety of actuator failures that could be reliably detected using actuator sensors, particularly if the actuators were initially designed with reconfiguration in mind. Similarly, the pseudo-inverse and related gain-switching approaches for modifying control laws could require quite a bit of design tuning to cover a full spectrum of failure cases and deal with issues such as actuator saturations, axis prioritization issues, handling qualities, and aircraft nonlinear dynamics and there was a lack of theoretical proofs of stability and robustness. However, these approaches could be very effective when optimized for a small number of failures cases. The pseudo-inverse could also be replaced by more advanced control allocation techniques that were being developed over the 1990’s and becoming feasible as on-board computational power increased [32]. Not unlike the related field of redundancy management, practice was moving ahead of theory.

### **III. Adaptive and Intelligent Control Approaches**

In the 1990's, there was an explosion in the number and variety of approaches applied to the reconfigurable flight control problem. Advances in computer technology and in control development software packages were making it much easier and cheaper to experiment with complex nonlinear approaches. At the beginning of the 1990's, many smaller research efforts in reconfigurable control were limited to partial implementation of their approach on simple linear models. By the end of the 1990's, it was not uncommon to see even small research projects demonstrating very complex nonlinear control laws on relatively high-fidelity six degree-of-freedom simulations. Further, throughout the 1980's there had been considerable theoretical advances in the areas of adaptive [33-34] and nonlinear control [35]. The late 1980's also saw a resurgence of interest in the use of emerging machine intelligence technologies such as neural networks and fuzzy logic for control [36]. These approaches might potentially improve FDIE or support the development of new architectures that did not use explicit FDIE at all. As a result, there were many potentially promising paths to pursue and the computer technology available to enable rapid experimentation. Yet, while adaptive, nonlinear, and intelligent approaches were becoming very popular among the research community, they remained controversial among the broader flight control community. For example, in 1991, an important journal paper on nonlinearities in flight control by Graham and McRuer concluded that "In connection with aircraft flight control, across modes (i.e., between system architectures), envelope restrictors, and in redundancy management, discreet nonlinearities are essential. Otherwise, nonlinearities are an abomination! [37]"

By the late 1980's and early 1990's researchers had begun experimenting with a variety of adaptive and intelligent techniques for flight control reconfiguration. Morse and Ossman looked at Model Reference Adaptive Control [38], Maybeck looked at Multiple Model Adaptive Control [39], Ahmed-Zaid et al looked at an LQR-based indirect adaptive control approach [40], Barron et al looked at applications of polynomial networks [25], and Huang et al and Calise et al looked at neural network control [41-42]. Initial results with limited fidelity simulation models were promising, but it was clear that much work would be needed to overcome many practical challenges with applying these types of approaches to the reconfigurable flight control problem. Some of the key concerns included ensuring stability and robustness despite the wide range of flight control inputs and nonlinear dynamics, providing sufficient design insight to allow tuning of control laws to meet a full set of qualitative and quantitative design criteria, avoiding excitation of aircraft structural modes, and maintaining acceptable pilot handling qualities. Throughout the 1990's, there were several adaptive and intelligent architectures that made considerable progress at addressing these concerns through broad research, simulation testing, and limited flight-testing. These involved the addition of adaptive or learning components to more conventional multivariable control laws.

The first of these architectures to be flight-tested used a Receding Horizon Optimal Control Law with gains updated based on on-line parameter identification. On-line parameter ID is challenging for reconfiguration since it requires fast identification of abruptly changing parameters. This is problematic for a system, such as an aircraft, that does not always have sufficient excitation. Identification approaches that react rapidly

by using short data windows or discounting past data can suffer from numerical ill-conditioning or sensitivity to noise and may be unreliable for use on-line in a flight critical application. One approach towards mitigating this problem was to add constraints to the cost function of a least squares approach. Chandler, Pachter, and Mears developed an approach that constrains the problem by incorporating a priori knowledge of the relationships between aircraft stability and control parameters [43]. Another constraint-based approach penalized excessive parameter deviations over time. This was suggested by Bobrow and Murray [44] and eventually implemented by Ward et al [45]. Bodson later showed that this was equivalent to using an adaptive forgetting function that varies the size of the data window used by the identification algorithm based on the amount of excitation [46]. Barron Associates under the USAF Self-Designing Flight Control System program combined the two approaches in a Modified Sequential Least Squares (MSLS) algorithm [47]. In 1996, Barron Associates with support from Lockheed, flight-tested MSLS combined with a Receding Horizon Optimal Control Law on a research F-16 using the architecture shown in Fig. 3. While only five flights were done, a number of different failure cases were successfully demonstrated including landing with a simulated partially missing stabilator. The MSLS approach was also later applied within a more complex flight control law for reconfigurable control of a tail-less aircraft [48] and other applications.

Two other architectures to be flight-tested in the 1990's were based on neural network technology. In 1990, the USN had begun a program called Intelligent Flight Control to evaluate the potential of emerging machine intelligence technologies for a variety of

flight control functions including reconfiguration [49]. Some of the approaches examined under this program, such as learning, turned out to be impractical for flight control application at the time. However, important advances were made in several areas including the development of an adaptive neural network flight control law in Calise and Kim [42, 50-51]. It used two neural networks composed of sigma-pi and radial basis function neurons to invert the nonlinearities in a dynamic inversion control law. One neural network was trained off-line based on known data and remained static in flight. The second neural network adapted on-line to deal with uncertainties. The most important advance was the development of a Lyapunov-based proof of stability under mild assumptions on the inversion error. Eventually, the static neural network was replaced with a more conventional table look-up approach and variations of this approach were applied by Calise and his students to a wide variety of systems including missiles [52], a tilt-rotor aircraft [53], reusable launch vehicles [54], and munitions [55]. Several important theoretical advances were made in the course of this work including a stability proof for adaptive multi-layer sigmoidal neural networks in McFarland and Calise [52], and a pseudo-control hedging technique to allow adaptation to continue during actuator saturation in Johnson et al [54]. This adaptive neural network was also incorporated within a Boeing effort under the USAF RESTORE program, which made significant advances in practical application of the approach for a tail-less aircraft [56]. In late 1999, a joint program by the USAF, USN, NASA, and Boeing demonstrated the neuro-adaptive approach on the X-36, an unmanned subscale tailless aircraft [57]. The baseline X-36 controller was modified to become an explicit model following approach with the adaptive neural network as shown in Fig. 5 [58]. Unfortunately, only 2 flights of a

much more ambitious test matrix were completed due to problems with the vehicle that were unrelated to the reconfigurable control law. However, the results helped validate the previous positive simulation results and the testing included successful structural modes interactions testing. In addition, limited flight-testing of this approach was later also done on a munitions program and this approach was considered for use on the X-45, as will be discussed in Section V.

The other flight-tested neural network approach came out of an effort in Intelligent Flight Control begun by NASA Ames in 1994 with McDonnell Douglas [59]. This effort initially focused on the original Kim & Calise approach with both static and dynamic neural networks, but experimented with different types of neural networks to improve performance. Pre-trained NN accuracy was improved using a Levenberg-Marquardt Perceptron, a Dynamic Cell Structure neural network was investigated by Jorgensen to enable learning, and some aspects of the approach were demonstrated in F-15 simulation by Totah with a variety of damage cases [60]. Eventually, this evolved into a somewhat different architecture that was more comparable to an indirect adaptive control law as shown in Fig. 6. A Linear Quadratic Regulator approach developed by Washington University was used as the control method and gains were determined through an on-line Ricatti solver based on aircraft parameters stored in a static neural network. This was to be augmented by on-line parameter identification and a neural network that learned the errors in the aircraft model data stored in the static neural network. A version of this architecture without adaptation was flight tested in spring of 1999 on a research F-15 [61]. Fifteen flights were completed, making this a fairly large test program compared to

the other efforts described in this section. The parameter identification and dynamic neural network were also flight tested at this time, but were not included within the control loop due to safety concerns. Nonetheless, the flight tests did show the potential of using the on-line Ricatti solver to update gains even while performing maneuvers that caused rapid changes in flight condition. Also, flight-testing demonstrated the use of a static neural network to replace table look-ups with a checksum approach used to monitor the neural network performance. There was some degradation of handling qualities in pitch, but this has been linked to the use of out-of-date data to train the static neural network. More recently, analysis by Williams has shown that the dynamic neural network could have improved performance despite this modeling error [62]. Originally, plans were to follow this with flight tests with the dynamic neural network components in the control loop. However, currently it appears that NASA is moving to an architecture more comparable to the one that was flight tested on the X-36 for future flight tests.

Beyond the three approaches discussed above, there were a wide variety of other approaches to reconfiguration examined by the end of the 1990's. An additional limited flight test program was done by Deutsches Zentrum fur Luft und Raumfahrt (DLR) on a modified short-haul passenger aircraft. The approach used a control mixer combined with genetic algorithm optimization to adapt the feedforward parameters in an explicit model following control system [63]. Schtessel, Buffington, and Banda looked at a sliding mode control approach [64]. Steinberg and Page looked at an adaptive backstepping approach [65], which would later become more broadly studied and flight-tested to support trajectory reshaping of impaired aircraft as described in section IV.

Bodson and Pohlchuck looked at different methods of command limiting to address actuator rate saturation [66]. Balakrishnan and Biega looked at an adaptive critic approach [67] and Ho and Balakrishnan looked at a fuzzy logic approach [68]. The list of approaches here barely scratches the surface of the amount of published research. There were also attempts to apply reconfiguration to other types of aircraft configurations. A number of researchers such as Huang, Celi, and Shih looked at applying reconfiguration to rotary wing vehicles [69]. While rotorcraft degrade much less gracefully than fixed wing vehicles, specific configurations may have particular failure modes that can be compensated for using reconfiguration. However, whether any reconfiguration is possible is much more dependent on the specifics of the particular vehicle design than for conventional fixed wing aircraft. There were also advances towards aircraft with large numbers of distributed effectors. This type of system provides particular challenges towards performing on-line system identification and control allocation. A two-stage approach to parameter ID was developed by Buffington, Chandler, and Pachter to address this problem [70].

In the late 1990's, there were several studies that enabled a comparison between different approaches to this problem. One comparison study led by NASA, Marshall looked at a Reusable Launch Vehicle problem and had a variety of researchers applying their approaches to both reconfiguration and trajectory optimization of the X-33 [71]. For the inner loop, this included a sliding mode controller, an adaptive neural network approach, a robust dynamic inversion controller, a linear parametrically varying controller, and control design by trajectory linearization. Preliminary results showed that “the difference

in performance between most of the cases was a result of differences versus specific test criteria, where an algorithm did well or poorly for that criteria throughout the test cases.” Another comparison study was done by Steinberg and Page using medium and high-fidelity non-real-time F-18 simulations [72-73]. Approaches examined included adaptive neural network approaches, indirect adaptive approaches based on MSLS, fuzzy logic, adaptive backstepping, sliding mode control, and a baseline robust dynamic inversion control law. Results indicated that all of the control laws examined displayed features that might make them a good choice for certain types of design problems, but the best choice of which approach to use for any given design would be very dependent on the system configuration, designer preferences, and on requirements. Finally, Page and Steinberg compared a variety of advanced control allocation approaches including direct allocation, discrete time direct allocation, pseudo-inverse, and several variations of a weighted pseudo-inverse including a cascaded generalized inverse [32,74]. Results there were also less than conclusive in endorsing any particular approach.

By the end of the 1990's, continuously adaptive and intelligent control techniques had been flight-tested successfully for reconfigurable flight control. Progress had been made on many key areas such as stability proofs, dealing with actuator saturations, and integration with other flight control components. However, the flight testing had been fairly limited in many respects and concerns still remained about factors such as how to do flight certification to ensure safety, how to set design parameters that impact on adaptation, and how to incorporate all of the many qualitative and quantitative requirements that go into practical flight control design. While the potential benefits

were significant, control designers interested in using these approaches on production aircraft would still need to be cautious.

#### **IV. Beyond the Inner Loop**

The approaches described above focus on modifying the inner loop control system. Yet, an impaired aircraft may have significant restrictions on both its maneuvering capability and the flight envelope through which it can be safely controlled. Dealing with these types of issues has generally been the task of the human pilot, who has sometime developed very innovative strategies to control impaired aircraft. For example, a very skilled pilot could amazingly prevent departure with the previously mentioned F-4 stabilator case by repeatedly doing 180 deg. rolls with the aircraft. This is a technique beyond the adaptive capabilities of any of the reconfigurable control systems mentioned so far. Even much simpler trajectory following can be a challenge for impaired autonomous vehicles as well as for manned applications when there are severe constraints on the safe operating envelope or maneuvering capability. An approach for dealing with this is to automatically optimize or reshape the trajectory of the vehicle for particular tasks in a way that takes any impairment into account. One approach to this problem has been demonstrated on a high-fidelity unmanned combat air vehicle simulation under a joint USAF/USN effort by Barron Associates, the Massachusetts Institute of Technology, and Northrop Grumman. The approach combines a direct-adaptive backstepping controller that uses spatially-local models of the vehicle dynamics, a provably-stable approach to learning the structure of the underlying vehicle models online, and a finite automaton-based path planning approach that reshapes trajectories using pre-computed

maneuver and trim primitives [75]. While some progress has been made with this type of approach, there are still considerable technical challenges with performing on-line trajectory reshaping using this type of approach, particularly due to the curse-of-dimensionality problem [76].

This problem is also of great interest for reusable launch vehicles and a variety of different approaches has been examined [71]. Recently, Barron Associates flight-tested an approach for this on the Total In-Flight Simulator (TIFS) aircraft, which was being used to simulate an X-40 testbed [77]. The tested approach is shown in Fig. 8. It used a combination of a reconfigurable inner loop control law developed by the Air Force Research Laboratory [78] with an adaptive backstepping guidance approach. The gains of the guidance law were modified following detected effector failures based on the bandwidth of the reconfigured inner loop control law. There is also on-line trajectory reshaping using an Optimum Path-To-Go algorithm that uses polynomial networks to determine a path based on estimated vehicle capabilities after identification of upper and lower bounds of lift and drag. Forty evaluations of approach/landing (both actual landings and simulated landings at higher altitude) were demonstrated for 21 different failure cases with locked surfaces. Results were very promising and demonstrated the ability of the vehicle to perform landings with reasonable dispersion despite some significant failures.

A final area of reconfiguration that has not been discussed in this paper is approaches to compensate for changes in structural dynamics as a result of aircraft damage. This is a

very difficult problem for a number of reasons, including the challenges of real-time identification of structural modes and the difficulty in evaluating performance in simulation and flight-testing. There has been some work done in this area, but only a limited amount of progress has been made as yet [79].

## **V. Reconfigurable Flight Control in Practice**

By the 1990's, reconfigurable control had advanced sufficiently that simple forms of reconfiguration could be used to improve aircraft safety. To date, this has been done primarily to deal with a limited number of detectable actuator failure modes. The F/A-18E/F mentioned in the introduction was the first reported U.S. military production aircraft delivered with a reconfigurable control law in late 1999 [1]. The E/F uses reconfiguration only for a single stabilator actuator failure mode that is designed to fail to a locked neutral position. Even with this simple failure case, there were challenges with setting the threshold on failure detection in order to avoid nuisance failures, but still allow detection in a reasonable amount of time. Results in both flight-testing and practice have shown some slight pitch insensitivity, but roll/yaw compensation has been excellent and level 1 handling qualities are maintained. Another application of reconfigurable control has been to improve safety on flight test programs, particularly to deal with potential failure modes of electric actuation. There have been multiple examples of this, though the majority have not flown for one reason or another. One well-documented example was for the X-33 program [80]. Like the F/A-18E/F example, the X-33 design was a relatively simple system to deal with specific and detectable types of single actuator failures. Unlike much previous work, there were problems with using

a pseudo-inverse technique due to the limited control redundancy available on the vehicle. This was dealt with by using a constrained optimization approach based on Sequential Quadratic Programming (SQP). Because of the computational complexity involved, solutions were calculated off-line. A more advanced reconfigurable control law based on the one that flew on the X-36 as described in section III was part of the initial design proposed for the X-45 Unmanned Combat Air Vehicle (UCAV) demonstrator. However, Boeing was cautious about using the approach and included it only as an addition to a baseline control law that would be sufficient whether or not the adaptive approach was successfully implemented. More recently, Boeing has made the decision not to incorporate the adaptive approach on the aircraft, but are continuing to study it.

As can be seen, real-world applications have been largely limited so far other than for simple applications to deal with a small number of actuator failures. The latter are becoming increasingly common in flight control designs, but the more advanced adaptive and intelligent approaches are generally not used in practice. One reason for this has been the difficulty of certifying these approaches for safety of flight for anything more advanced than simple switching approaches similar to redundancy management techniques. This is particularly difficult due to the need for approaches to enable rapid re-certification following any changes made to a previously cleared control law. There has been some progress in developing tools for analyzing reconfigurable control laws such as the use of Linear Matrix Inequality techniques by Wise and Sedwick and by Chen, Patton, and Chen [81-82]. There has also been some progress in approaches for

more advanced control laws. Buffington et al describes a study of V&V techniques for adaptive and intelligent approaches [83]. However, there is still much progress that needs to be made before these types of approaches can be regularly used.

Another approach is to design adaptive reconfigurable control laws specifically to be easier to certify and implement. An early example of this by Wohletz [84] looked at summing the output of a direct adaptive component with a conventional control law. Another approach by Monaco and Ward under a USN program looked at adding the output of the adaptive element to the feedforward path as shown in Fig. 8 [85]. The adaptive element is an indirect adaptive approach that uses MSLS and receding horizon optimal control similar to the Self-Designing Control Law described in Section III. This avoids modifying any aspects of the inner loop such as structural limiters or filters and could potentially be treated more like an auto-pilot for certification purposes.. High-fidelity piloted simulation was done on an F-18, which found that a wide range of failure and damage cases could be dealt with without modifying the inner loop. A limited F-18 flight test program is planned to be performed in fall 2004 by Barron Associates and Boeing at the Naval Air Systems Command in Patuxent River, MD.

### **Conclusions**

The last few decades has seen substantial advances in flight control reconfiguration and an increasingly large number of approaches. Initial approaches were very heavily influenced by work in redundancy management and sensor analytic redundancy and focused on explicit failure detection, isolation, and estimation. These had some success, but were limited by the types of failures or damage that could be reliably detected and

isolated using existing aircraft sensors. In the 1990's, a much wider range of potential approaches were applied to the problem including adaptive and intelligent approaches. There has been some considerable success in addressing practical implementation issues and some limited flight-testing of these more complex nonlinear control laws, but these approaches still have a certain amount of risk involved with application. By the late 1990's, there started to be some applications of more limited reconfiguration systems to improve safety, particularly for a small number of actuator failure modes that could be reliably detected with sensors on the actuators. The largest remaining hurdle to broader use of reconfiguration is how to perform flight certification and how to readily incorporate the wide range of flight control design criteria within the more complicated nonlinear approaches. This includes the need for approaches to enable rapid re-certification following changes made to previously cleared control law.

## References

1. **Egbert, L, Halley, I.**, "Stabilator Reconfiguration Flight Testing on the F/A-18E/F," SAE Control and Guidance Meeting, March, 2001.
2. **Osder, S.**, "Practical View of Redundancy Management Application and Theory," *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 22, No. 1, Jan-Feb 1999, pp. 12-21.
3. **Tomayk, J.E.**, *Computers Take Flight: A History of NASA's Pioneering Digital Fly-By-Wire Project*, NASA SP-2000-4224, NASA, Washington, D.C., 2000.
4. **Ehlers, H.L., Smyth, R.K.**, "Survey of adaptive control applications to aerospace vehicles," AIAA Guidance, Control and Flight Dynamics Conference, AIAA-1968-970, 1968.
5. **Stein, G.**, "Adaptive Flight Control: A Pragmatic View," in *Application of Adaptive Control*, Monopoli, K.N. (ed.), Academic Press, New York, NY, 1980, pp. 291-312.
6. **Beard, R.V.**, "Failure Accommodation in Linear Systems through Self-Organization," PhD Dissertation, Dept. of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, Feb., 1971.
7. **Montoya, R.J., Howell, W.E., Bundick, W.T., Ostroff, A.J., Hueshen, R.M., Belcastro, C.M.**, "Restructurable Controls," NASA CP-2277, Sept., 1982.
8. **Tomayko, J.E., Gelzer, C.**, *The Story of Self-Repairing Flight Control Systems*, NASA, 2003
9. **Tucker, T.**, *Touchdown: The Development of Propulsion Control Aircraft at NASA Dryden*, NASA, Washington, D.C., 1999.
10. **Howell, W.E., Bundick, W.T., Hueschen, R.M., Ostroff, A.J.**, "Restructurable Controls for Aircraft," *Proceedings of the AIAA Guidance and Control Conference*, AIAA-1983-2255, New York, American Institute of Aeronautics and Astronautics, 1983, pp. 646-653.

- 11 Eslinger, R.A., Chandler, P.R.,** "Self-Repairing Flight Control System Program Overview," IEEE National Aerospace Electronics Conference, 1988, pp. 504-511.
- 12 Potts, D.W., D'Azzo, J.J.,** "Direct Digital Design Method for Reconfigurable Multivariable Control Laws for the A-7D DigitaC II Aircraft," Proceedings of the National Aerospace Electronics Conference, 1981, pp. 1284-1291.
- 13. Vander Velde, W.E.,** "Control System Reconfiguration," Proceedings of the American Control Conference, 1984, pp. 1741-1745.
- 14 Looze, D.,** "An Approach to Restructurable Control System Design," Proceedings of the IEEE Conference on Decision and Control, 1984, pp. 1392-1397.
  
- 15 Ostroff, A.J., Hueschen, R.M.,** "Investigation of Control Law Reconfigurations to Accomodate a Control Element Failure," Proceedings of the American Control Conference, 1984, pp. 1746-1754.
- 16 Sadeghi, T.,** "Redundant Command Generator Tracker Control Technique for Self-Repairing Flight Control System," Proceedings of the American Control Conference, 1984, pp. 653-655.
- 17. Weinstein, W., Posingies, W., Eslinger, R.A., Gross, H.N.,** "Control Reconfigurable Combat Aircraft Flight Control System Development," AIAA Guidance, Navigation, and Control Conference, 1986.
- 18. Caglayan, A.K., Allen, S.M., Wehmueller, K.,** "Evaluation of a Second Generation Reconfiguration Strategy for Aircraft Subjected to Actuator Failure/Surface Damage," IEEE National Aerospace Electronics Conference, May 1988.
- 19. Caglayan, A.K., Rahnamai, K., Allen, S.M.,** "Detection, Identification, and Estimation of Surface Damage/Actuator Failure for High Performance Aircraft," Proceedings of the American Control Conference, 1988.
- 20. Anderson, J., Clark, C., Madsen, P., Unfried, F.,** "Reconfigurable Flight Control System Simulation," Aerospace Simulation, 1988, pp. 89-101.
- 21. Mears, M. Pruett, S., Houtz, J.,** "URV Flight Test of an ADA Implemented Self-Repairing Flight Control System," WL-TR-92-3101, Aug 92
- 22. Huang, C.Y., Stengel, R.F.,** "Restructurable Control Using Proportional-Integral Implicit Model Following," Journal of Guidance, Control, and Dynamics, Vol. 13, No. 2, March-April 1990., pp. 303-309.
- 23. Napolitano, M.R., Swaim, R.L.,** "A New Technique for Aircraft Flight Control Reconfiguration," Proceedings of the AIAA Guidance, Navigation, and Control Conference, American Institute of Aeronautics and Astronautics, Washington, D.C., 1989.
- 24. Allen, S.M., Caglayan, A.K.,** "An Expert System Approach to Global Fault Detection and Isolation Design," USAF Report No. WL-TR-91-3007, Jan 1990.
- 25. Barron, R.L., Cellucci, P.R., Beam, N.E., Hess, P., Barron, A.R.,** "Applications of Polynomial Neural Networks to FDIE and Reconfigurable Flight Control," Proceedings of the IEEE National Aerospace Electronics Conference, 1990.
- 26. Bonnice, W.F., Motyka, P., Wagner, E., Hall, S.R.,** "Aircraft control surface failure detection and isolation using the OSGLR test," Proceedings of the AIAA Guidance, Navigation, and Control Conference, New York, American Institute of Aeronautics and Astronautics, 1986, p. 156-164.
- 27. Mayhew, E.R., Gleason, D.,** "Fault detection and isolation for reconfigurable flight control systems, , AIAA/IEEE Digital Avionics Systems Conference, Washington, DC, American Institute of Aeronautics and Astronautics, 1988, p. 48-55.
- 28 Mercadante et al,** "Control Reconfigurable Combat Aircraft Piloted Simulation Development," Proceedings of the IEEE National Aerospace Electronics Conference, 1998, pp. 512-519.
- 29 Urnes, J.M., Yeager, R.B.,** "Flight demonstration of the self-repairing flight control system in a NASA F-15 aircraft," AHS, and ASEE, Aircraft Design Systems and Operations Meeting, AIAA-1991-3106, 1991.
- 30 Stewart, J. F., Schuck. T.L.,** "Flight-testing of the self-repairing flight control system using the F-15 highly integrated digital electronic control flight research facility," SFTE, DGLR, and SETP, Biannual Flight Test Conference, AIAA-1990-1321, 1990.
- 31 Burcham, F.W., Pappas, D.,** "Development and flight test of an augmented thrust-only flight control system on an MD-11 transport airplane," Guidance, Navigation and Control Conference, AIAA-1996-3742, 1996
- 32 Page, A.B., Steinberg, M.L.,** "High-Fidelity Simulation Testing of Control Allocation Methods," AIAA Guidance, Navigation, and Control Conference, 2002.

- 33 Narendra, K.S., Annaswamy, A.M.,** *Stable Adaptive Systems*, Prentice Hall, 1989.
- 34 Astrom, K.J., Wittenmark, B.,** *Adaptive Control*, Addison Wesley, 1989.
- 35 Isidori, A.,** *Nonlinear Control Systems*, 2nd edition, Springer 1989.
- 36 Narendra, K.S., Parthasarathy, K.,** "Identification and Control of Dynamical Systems using Neural Networks," *IEEE Transactions on Neural Networks*, Vol. 1, No. 1, 1990, pp. 4-27.
- 37 Graham, D., Mcruer, D.,** "Retrospective essay on nonlinearities in aircraft flight control," *Journal of Guidance, Control, and Dynamics*, vol.14, no.6., 1991, pp. 1089-1099.
- 38 Morse, W.D., Ossman, K.A.,** "Model Following Reconfigurable Flight Control System for the AFTI/F-16, JGCD, Vol. 13, No. 6, Nov-Dec 1990, pp. 969-976
- 39 Maybeck, P.,** "Application of Multiple Model Adaptive Algorithms to Reconfigurable Flight Control," *IEEE Transactions on Aerospace Electronic Systems*," Vol. 27, No. 3, May 1991, pp. 470-480.
- 40 Ahmed-Zaid, F., Ioannou, P., Gousman, K., Rooney, R.,** "Accommodation of Failures on the F-16 Aircraft using Adaptive Control, *IEEE Control Systems Magazine*, Vol. 11, No. 1, pp. 73-8, Jan 1991,
- 41 Huang, C., Tylock, S., Engel, J., Eilbert, J.,** "Failure Accommodating Neural Network Flight Control," *AIAA GNC*, AIAA 92-4394, 2004.
- 42 Calise, A.J., Kim, B., Young, S., Kam, M., Azam, M.,** "Neural networks for feedback linearization in aircraft control," *AIAA Guidance, Navigation and Control Conference*, AIAA-1992-4391, Washington, D.C., American Institute of Aeronautics and Astronautics, 1992, p. 395-406.
- 43 Chandler, P.R., Pachter, M., Mears, M.,** "System Identification of Adaptive and Reconfigurable Control," *JGCD*, Vol. 18, No. 3, pp. 516-24, May-June 1995.
- 44 Bobrow, J.E., Murray, W.,** "An algorithm for RLS Identification of Parameters that Vary Quickly with Time," *IEEE Transactions on Automatic Control*, Vol. 38. No. 2, Feb. 1993.
- 45. Ward, D.G., Barron, R.L., Carley, M.P., Curtis, T.J.,** "Real-Time Parameter Identification for Self-Designing Flight Control," *NAECON*, 1994.
- 46. M. Bodson,** "An information-dependent data forgetting adaptive algorithm," *Proc. Amer. Control Conf.*, June 1995.
- 47. Monaco, J., Ward, D., Bird, R.,** "Implementation and Flight Test of an Adaptive Reconfigurable Flight Control System," *GNC*, AIAA-97-3738, 1997
- 48 Eberhardt, R.L., Ward, D.G.,** "Indirect adaptive flight control of a tailless fighter aircraft," *AIAA Guidance, Navigation, and Control Conference and Exhibit*, AIAA-1999-4042, 1999.
- 49 Steinberg, M.L.,** "An Initial Assessment of Neural Network and Fuzzy Logic for Flight Control, *Proceedings of the American Control Conference*, 1994.
- 50 Kim, B.S.,** "Nonlinear Flight Control using Neural Networks" PH.D. Thesis, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, Dec. 1993.
- 51 Kim, B.S., Calise, A.J.,** "Nonlinear Flight Control using Neural Networks," Vol. 20, No. 1, Jan-Feb 97, 26-33
- 52 McFarland, M.B., Calise, A.J.,** "Multilayer neural networks and adaptive nonlinear control of agile anti-air missiles," *AIAA Guidance, Navigation, and Control Conference*, AIAA-1997-3540, 1997.
- 53 Calise, A.J., Rysdyk, R.T.,** "Adaptive model inversion flight control for tiltrotor aircraft," *AIAA Guidance, Navigation, and Control Conference*, AIAA-1997-3758, 1997.
- 54 Johnson, E.N., Calise, A.J., El-Shirbiny, H.A., Rysdyk, R.T.,** "Feedback linearization with Neural Network augmentation applied to X-33 attitude control," *AIAA Guidance, Navigation, and Control Conference and Exhibit*, AIAA-2000-4157, 2000
- 55 Sharma, M., Calise, A.J., Corban, J.E.,** "Application of an adaptive autopilot design to a family of guided munitions," *AIAA Guidance, Navigation, and Control Conference and Exhibit*, AIAA-2000-3969, 2000
- 56 Brinker, J.S., Wise, K.A.,** "Reconfigurable flight control for a tailless advanced fighter aircraft," *AIAA Guidance, Navigation, and Control Conference and Exhibit*, AIAA-1998-4107, 1998.
- 57 Brinker, J.S., Wise, K.E.,** "Flight Testing of Reconfigurable Control Law on the X-36 Tailless Aircraft," *AIAA Journal of Guidance, Control, and Dynamics*, vol.24, no.5, 2001, pp. 903-909.
- 58 Calise, A.J.,** "Development of a reconfigurable flight control law for the X-36 tailless fighter aircraft," *AIAA Guidance, Navigation, and Control Conference*, AIAA-2000-3940, 2000
- 59. Jorgensen, C.,** "Feedback Linearized Aircraft Control using Dynamic Cell Structures," 1998.
- 60 Totah, J.J.,** "Simulation evaluation of a neural-based flight controller," *AIAA Flight Simulation Technologies Conference*, AIAA-1996-3503, 1996.

- 61 Urnes, J., Davidson, R., Jacobson, S.,** "A Damage Adaptive Flight Control System using Neural Network Technology," Proceedings of the American Control Conference, 2001, pp. 2907-2912.
- 62 Williams, P.S.,** Selected Flight Test Results for Online Learning Neural Network-Based Flight Control System, AIAA Intelligent Systems Conference, AIAA-2004-6263, 2004.
- 63 Buchholz, J.J., Heine, W., Baumgarten, G.,** "Genetic Algorithms for Reconfiguration," ZFW, Vol. 20, No. 3, June, 1996.
- 64 Shtessel, Y., Buffington, J., Banda, S.,** "Tailless aircraft flight control using multiple time scale reconfigurable sliding modes," AIAA Guidance, Navigation, and Control Conference, AIAA-1999-4136, 1999.
- 65 Steinberg, M. and Page, A.,** "Nonlinear Adaptive Flight Control with Genetic Algorithm Design Optimization," *International Journal of Robust and Nonlinear Control*, 9, Dec., 1999, pp. 1097-1115.
- 66 Bodson, M., Pohlchuck, W.A.,** "Command Limiting in Reconfigurable Flight Control," *Journal of Guidance, Control, and Dynamics*, Vol. 21, No. 4, Jul-Aug, 1998, pp. 639-646.
- 67 Balakrishnan, S N, Biega, V.,** "Adaptive critic based neural networks for aircraft control," AIAA Guidance, Navigation and Control Conference, AIAA-1995-3297, Washington, DC, American Institute of Aeronautics and Astronautics, 1995, p. 1126-1134.
- 68 Ho, H.S., Balakrishnan, S.N.,** "A hierarchical fuzzy logic controller with a velocity modifier for restructurable flight control systems," AIAA Guidance, Navigation and Control Conference, AIAA-1995-3228, Washington, DC, American Institute of Aeronautics and Astronautics, 1995, p. 505-515
- 69 Huang, C., Celi, R., and Shih, I.,** "Reconfigurable Flight Control System for a Tandem Rotor Helicopter," *Journal of the American Helicopter Society*, Vol. 44, No. 1, 1999, pp. 50-62.
- 70. Buffington, J., Chandler, P.R., Pachter, M.,** "On-Line System Identification for Aircraft with Distributed Control Effectors," AIAA GNC 1997.
- 71. Hanson, J. Jones, R.,** "Advanced Guidance and Control Methods for Reusable Launch Vehicles: Test Results," AIAA Guidance, Navigation and Control Conference, AIAA-2002-4561, 2002.
- 72. Steinberg, M.L.,** "Comparison of Intelligent, Adaptive, and Nonlinear Flight Control Laws," *Journal of Guidance, Control, and Dynamics*, vol.24, no.4, 2001, pp. 693-699.
- 73 Steinberg, M.L., Page, A.B.,** "High-Fidelity Simulation Testing of Intelligent and Adaptive Aircraft Control Laws," American Control Conference, 2002.
- 74. Page, A.B., Steinberg, M.L.,** "Effects of control allocation algorithms on a nonlinear adaptive design," AIAA Guidance, Navigation, and Control Conference AIAA-1999-4282, 1999.
- 75. Ward, D., Sharma, M., Richards, N., De Luca, J., Mears, M.,** "Intelligent Control of Unmanned Air Vehicles: Program Summary and Representative Results," AIAA "Unmanned Unlimited" Conf., AIAA-2003-6641, 2003
- 76. Valenti, M., Mettler, B., Schouwenaars, T., Feron, E., Paduano, J.,** "Trajectory Reconfiguration for an Unmanned Aircraft," AIAA Guidance, Navigation, and Control Conference, AIAA-2002-4674, 2002
- 77. Schierman, J., Gandhi, N., Hull, J., Ward, D.,** "Flight Test Results of an Adaptive Guidance System for Reusable Launch Vehicles," AIAA Guidance, Navigation, and Control Conference, AIAA-2004-4771, 2004.
- 78 Oppenheimer, M., Doman, D.,** "Reconfigurable Inner Loop Control of a Space Maneuvering Vehicle," AIAA-2003-5358, Proc. AIAA Guidance, Navigation, and Control Conf., 2003.
- 79. Nam, C., Chen, P.C., Urnes, J., Yurkovich, R.,** AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, AIAA-2001-1523, 2001
- 80. Cotting, M.C., Burken, J.J.,** "Reconfigurable control design for the full X-33 flight envelope," AIAA Guidance, Navigation, and Control Conference AIAA-2001-4379, 2001
- 81. Wise, K.A., Sedwick, J.L.,** Stability Analysis of Reconfigurable and Gain Scheduled Flight Control Systems Using LMI's," Proceedings of the AIAA Guidance, Navigation, and Control Conference, 1998, pp. 118-126.
- 82. Chen, J., Patton, R.J., Chen, Z.,** "An LMI Approach to Fault-Tolerant Control of Uncertain Systems," Proceedings of the 1998 IEEE ISIC/CIRA/ISAS Conference, 1998, pp. 175-180.
- 83. Buffington, J et al,** "Validation & Verification of Intelligent and Adaptive Control Systems," 2nd AIAA "Unmanned Unlimited" Conf., AIAA-2003-6603, 2003  
AIAA-2004-5254
- 84. Wohletz, J.M.,** "Retrofit Systems for Reconfiguration in Civil Aviation," Doctoral Dissertation, MIT, Feb, 2000.

**85. Monaco, J.F., Ward, D.G., Bateman, A.J.,** "A Retrofit Architecture for Model-Based Adaptive Flight Control AIAA 1st Intelligent Systems Technical Conference, 2004.

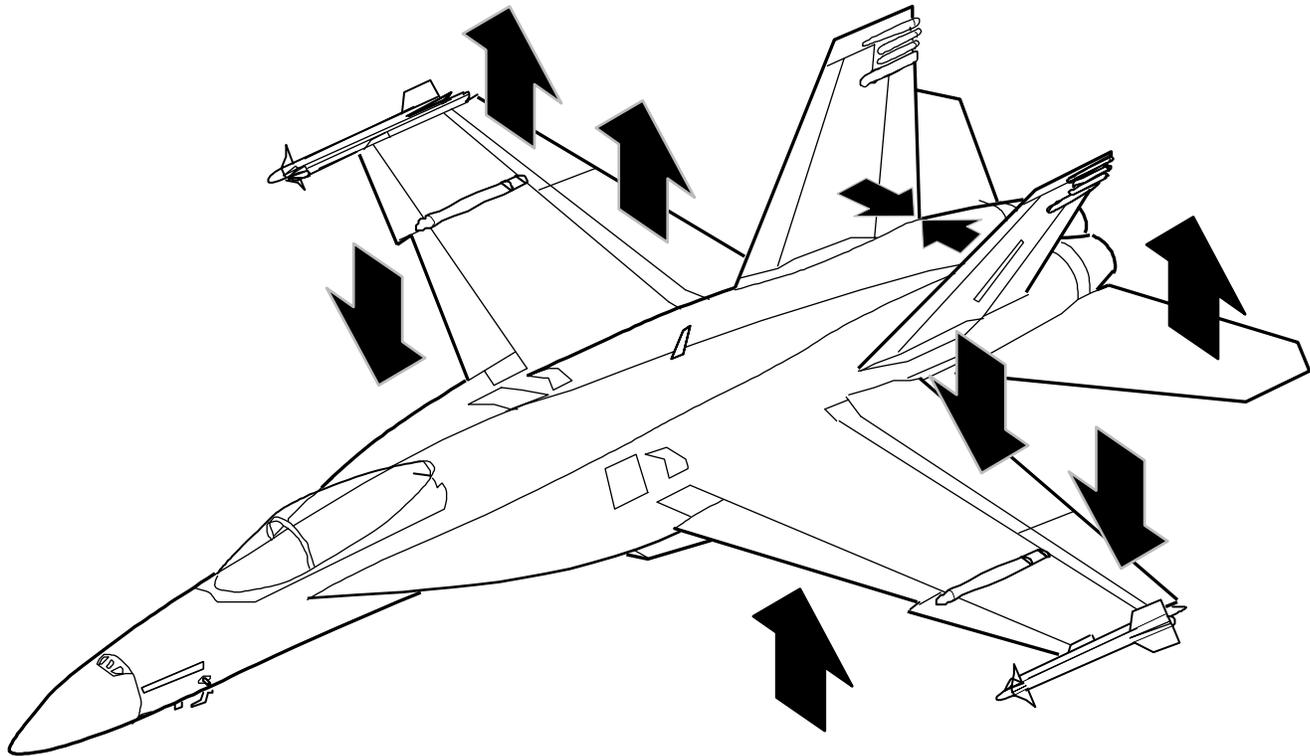


Fig. 1 – Reconfiguration of F/A-18E/F

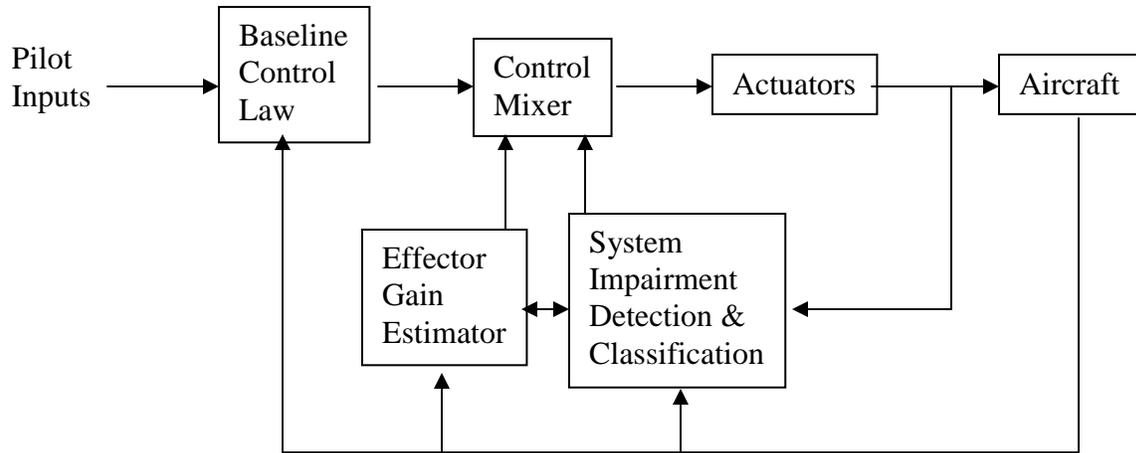


Fig. 2 Self-Repairing Flight Control System Architecture

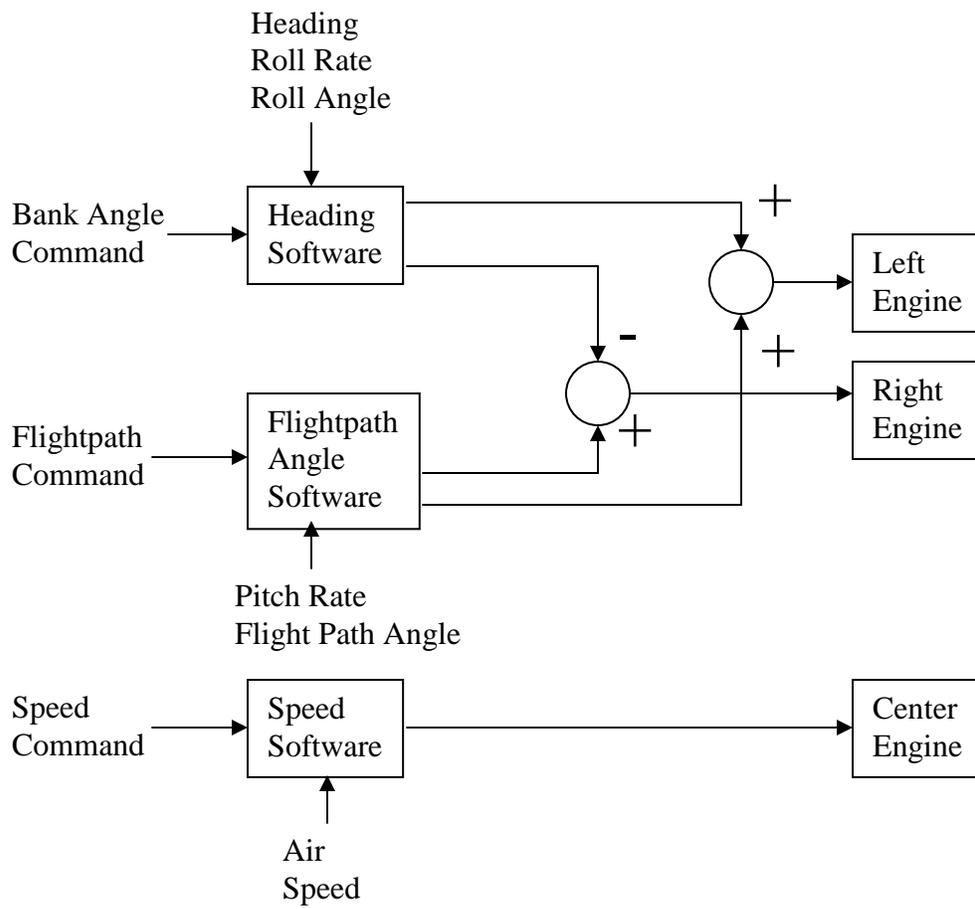


Fig. 3 Propulsion Controlled Aircraft – MD –11 Design

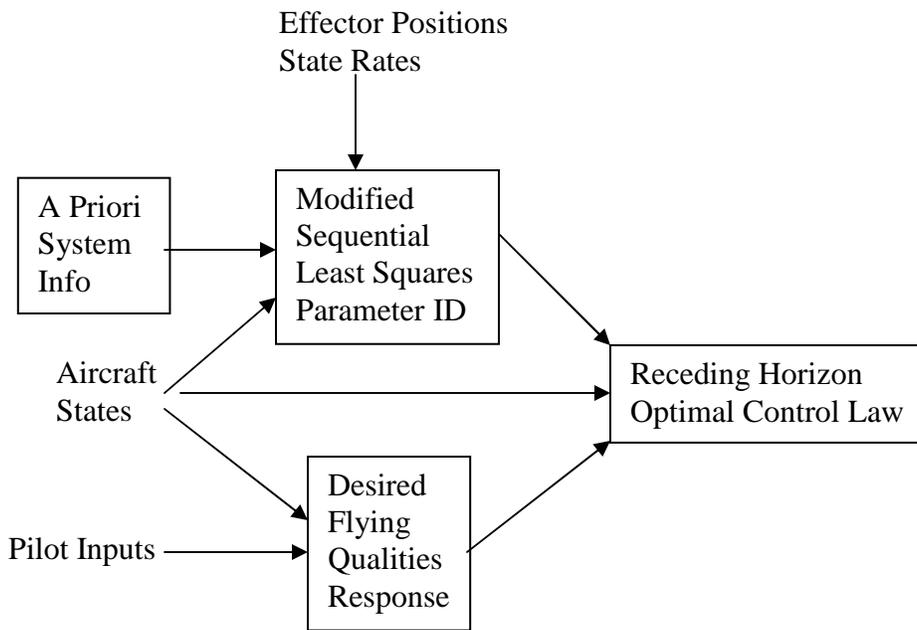


Fig. 4 Self-Designing Flight Control System

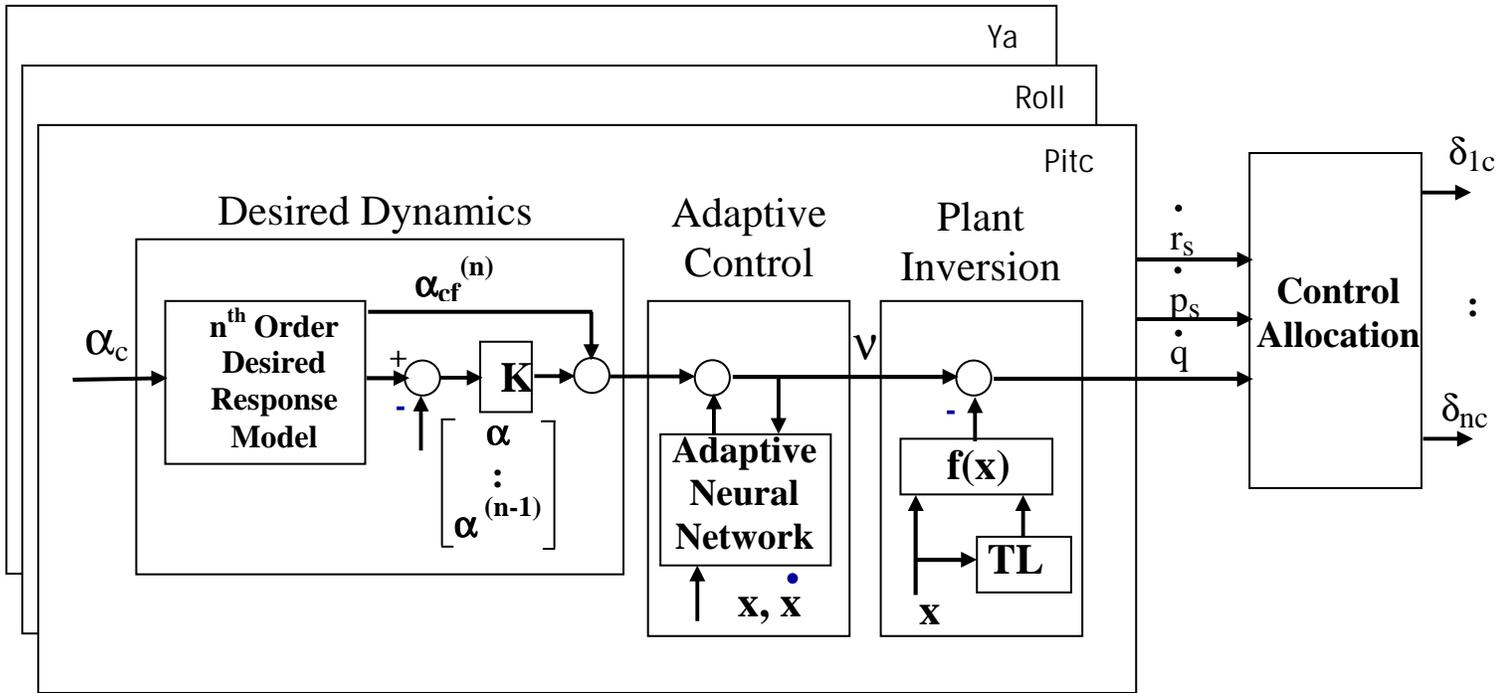


Fig. 5 Adaptive Neural Network Flight Tested on X-36

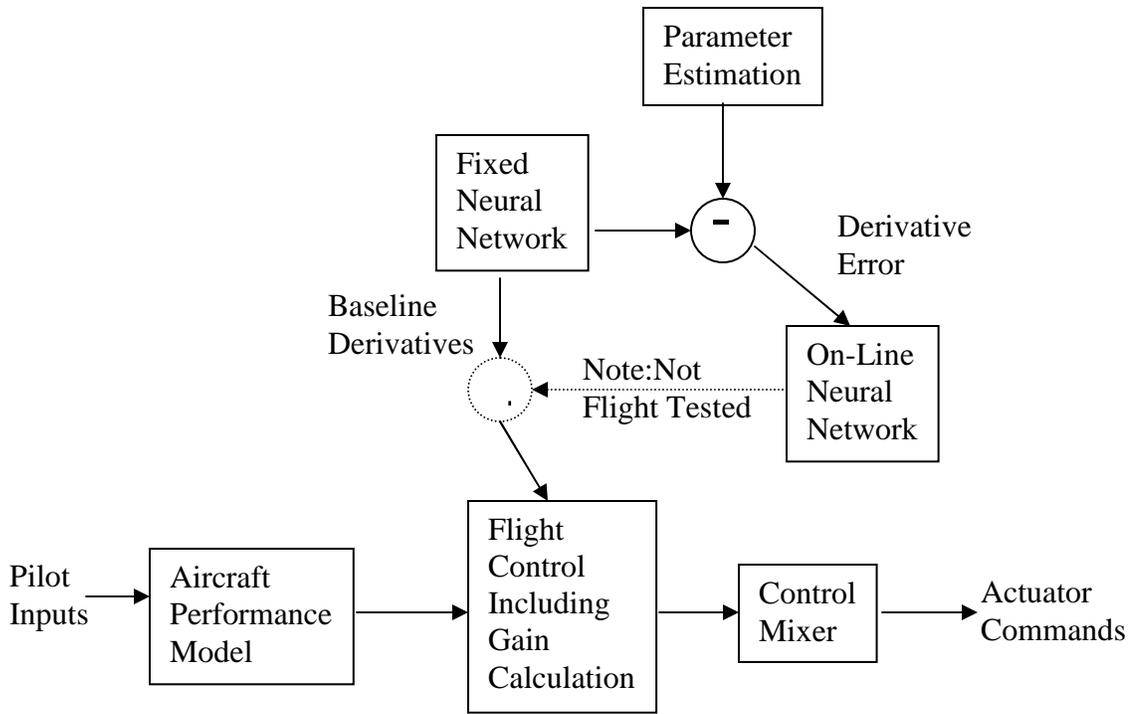


Fig. 6 – NASA Intelligent Flight Control Law

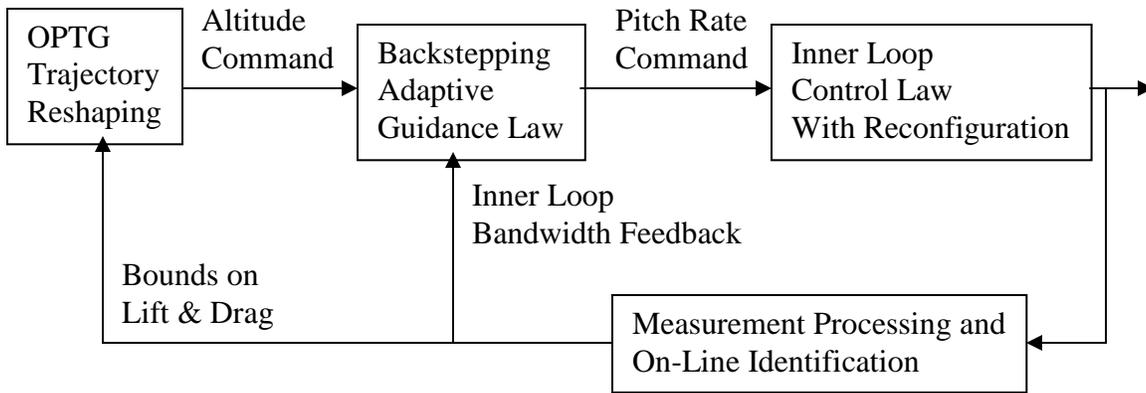


Fig. 7 Trajectory Reshaping for Reusable Launch Vehicle

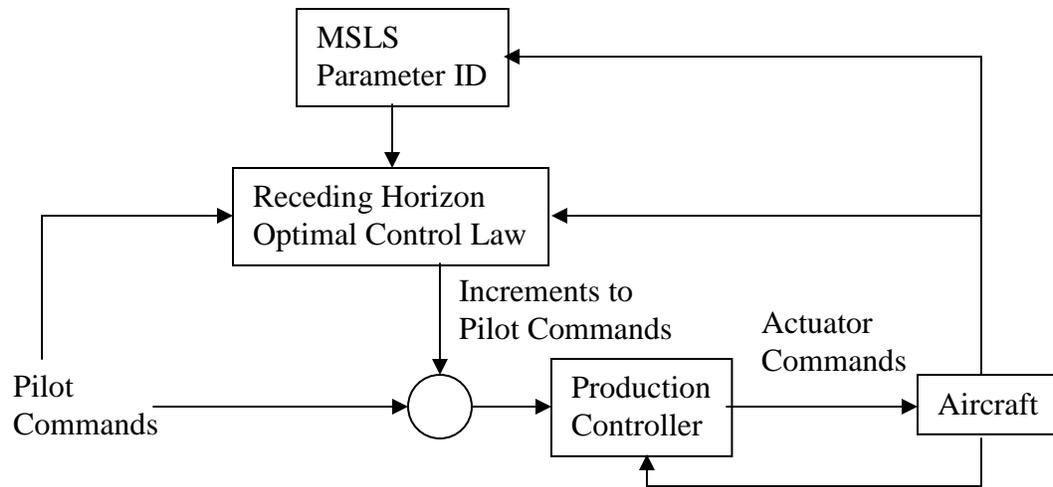


Fig. 8 Retrofit Reconfigurable Control Law for the F-18