THE DESIGN OF FLY-BY-WIRE FLIGHT CONTROL SYSTEMS

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Abstract

The design of an advanced Flight Control System (FCS) is a technically challenging task for which a range of engineering disciplines have to align their skills and efforts in order to achieve a successful system design. This paper presents an overview of some of the factors, which need to be considered, and is intended to serve as an introduction to this stimulating subject. Specific aspects covered are: flight dynamics and handling qualities, mechanical and fly-by-wire systems, control laws and air data systems, stores carriage, actuation systems, flight control computer implementation and flexible airframe dynamics. A comprehensive set of references are provided for further reading.

1. Introduction to Flight Control

When studying the mechanics of flight [1,2,3] it is common practice to assume that the aircraft can be represented as a rigid body, defined by a set of body axis co-ordinates as shown in Figure 1. The rigid body dynamics have six degrees-of-freedom, given by three translations along, and three rotations about, the axes. All forces and moments acting on the vehicle can be modelled within this framework.

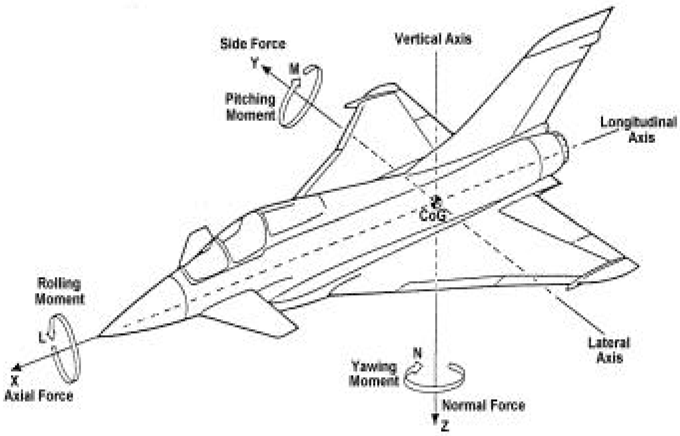


Figure 1 Body axis aircraft co-ordinate system

To achieve flight control we require the capability to control the forces and moments acting on the vehicle; if we can control these, then we have control of accelerations and hence velocities, translations and rotations. The FCS aims to achieve this via the aircraft's flight control surfaces, shown for the example in Figure 1: foreplane, trailing edge flaps and rudder. The thrust provided by the engines must also be taken into account, since this also produces forces and moments acting on the vehicle.

2. Mechanical and Fly-by-wire FCS

The early generations of flight control systems were mechanically-based, an example of which is shown in Figure 2 (single-seat Hawk aircraft).

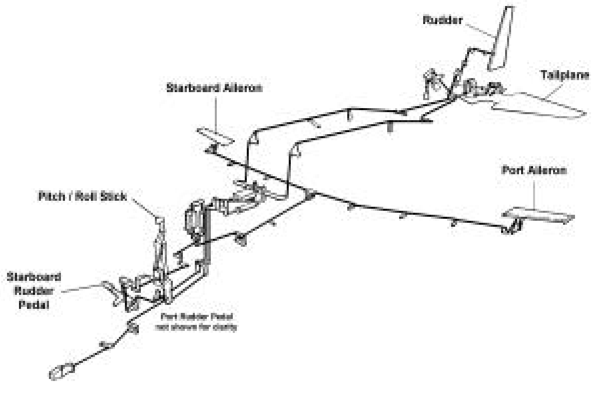


Figure 2 Mechanical flight control system

Direct mechanical linkages were used between the pilot's cockpit controls (pitch/roll stick and rudder pedals) and the control surfaces that manoeuvre the aircraft, which are for this example: tailplane, ailerons and rudder. This arrangement is inherently of high integrity, in terms of probability of loss of aircraft control, and provides us with a very visible baseline for explaining FCS developments.

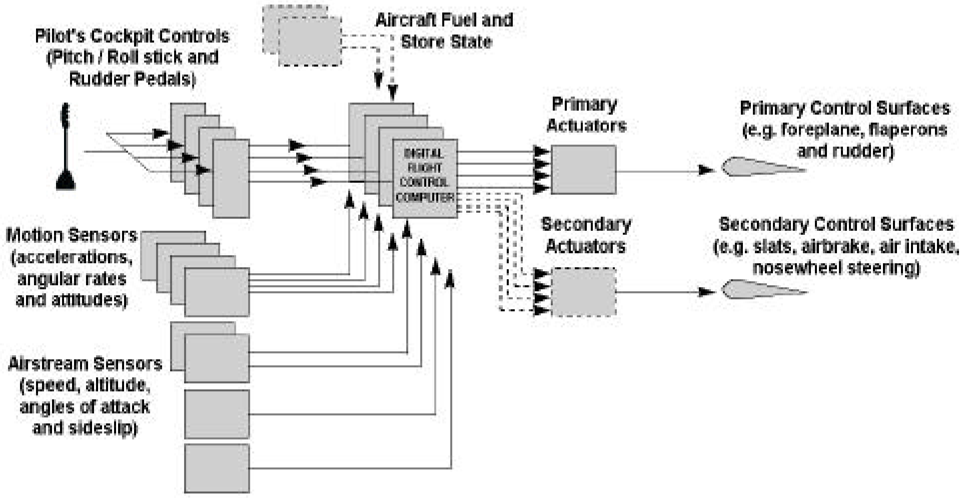


Figure 3 Digital fly-by-wire flight control system

Subsequent generations of FCS have been developed on programmes such as Tornado, Jaguar Fly-by-wire [4] and the Experimental Aircraft Programme [5], towards the current quadruplex digital fly-by-wire type, schematically shown in Figure 3 and used, for example, on Eurofighter Typhoon [6]. The main emphasis is now on digital computing with the use of inertial motion and air stream sensor units; the direct mechanical linkages between the cockpit controls and the control surfaces have been removed and replaced with electrical signalling with direct motion commands, hence the term 'fly-by-wire'. This arrangement provides a significant reduction in mechanical complexity.

In order to achieve the same level of integrity as that achieved with the earlier mechanical systems, multiple signal sources and several lanes of computing are necessary to provide redundancy, these being cross-monitored in order to isolate any failed equipment and to ensure safe operation. A comprehensive built-in-test capability is also included, to ensure that the system is 'safe to fly' prior to each flight and to identify and locate failures. The current military aircraft trend is towards triplex redundant architectures with reliance on both cross-lane and in-lane monitoring to achieve the required level of integrity, and hence the associated safety of system operation.

3. The Benefits of Fly-by-wire Technology

The major benefit of fly-by-wire is the ability to tailor the system's characteristics at each point in the aircraft's flight envelope. This is achieved by using 'control laws', which can be scheduled with flight condition. The introduction of digital computing for aircraft flight control has allowed complex algorithms to be implemented. These functions allow the performance benefits offered by Active Control Technology to be fully realised and include:

- 'Carefree Handling' by: (i) providing angle of attack control and angle of sideslip suppression, which lead to automatic protection against stall and departure; (ii) by the automatic limiting of normal acceleration and roll rate to avoid over-stressing of the airframe.
- Handling qualities optimised across the flight envelope, and for a wide range of aircraft stores.
- Aircraft agility, thereby providing a capability for rapid changes in fuselage aiming and / or velocity vector, to enhance both target capture and evasive manoeuvring.
- Aircraft performance benefits associated with controlling an unstable airframe, that is, improved lift / drag ratio and an increase in maximum lift capability, both leading to increased aircraft turning capability.
- The use of thrust vectoring to augment or replace aerodynamic control powers, in order to extend an aircraft's conventional flight envelope.
- Reduced drag due to optimised trim setting of controls, including thrust vectoring.

- Reconfiguration to allow mission continuation or safe recovery following system failures or battle damage.
- Advanced autopilots, providing significant reductions in pilot workload and weapon system performance benefits.
- Reduced maintenance costs, resulting from the reduction in mechanical complexity and the introduction of built-in-test.

In order to realise these benefits it is essential to establish an appropriate control law architecture. This is fundamental to the success of the system and will require good knowledge of systems equipment engineering and safety, flight dynamics and flight control. There is however, a significant cost associated with such performance benefits, in terms of system complexity, but usually, the performance and safety benefits that can be achieved, easily justify the necessary investment.

4. Flight Envelope and Gain Scheduling

An aircraft's flight envelope will usually be described in terms of Mach number, covering velocity and air compressibility effects, and altitude to cover air temperature and density effects. An example is shown in Figure 4 for a supersonic aircraft.

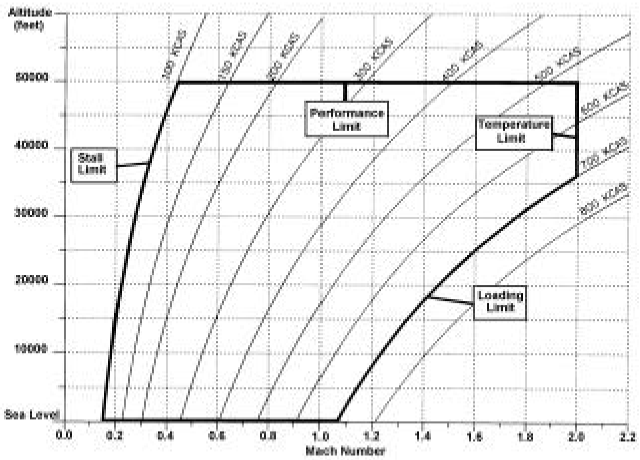


Figure 4 Supersonic aircraft's flight envelope

The boundaries of the flight envelope are associated with physical limits: the stall limit, at high incidence and low dynamic pressure, where the aircraft's wing lift is not sufficient to support the aircraft's weight; the performance limit, where the rarefaction of the atmosphere prevents a jet engine from sustaining its operation; the temperature limit due to the kinetic heating of the airframe by the viscous friction of the air; and the loading limit at high dynamic pressure, to provide a safe margin against excessive aerodynamic loads acting on the airframe.

In order to design control laws to cover such an envelope, it is necessary to select a grid of 'operating points' for which the design is to be carried out. This results in a set of localised controllers for the operating points. The number of design points can always be minimised by taking physical effects (such as dynamic pressure) into account, within the structure of the flight control laws.

As described so far, the design task is over a two-dimensional envelope, however, a third dimension covering an aircraft's angle of attack needs to be considered, in order to address the effects of aerodynamic non-linearity and control surface trimming capability. In addition, the effects of changes in mass, inertia and centre of gravity need to be considered. The localised controller designs need to be integrated together to cover the flight envelope. This can usually be satisfactorily achieved by using gain scheduling to produce a set of control laws. The information needed to schedule the flight control law gains is usually derived from the air data system, an example of which is shown in Figure 5. This includes a set of suitably located external probes for providing pitot and static pressures and local airflow measurements, in terms of speed and direction [7].

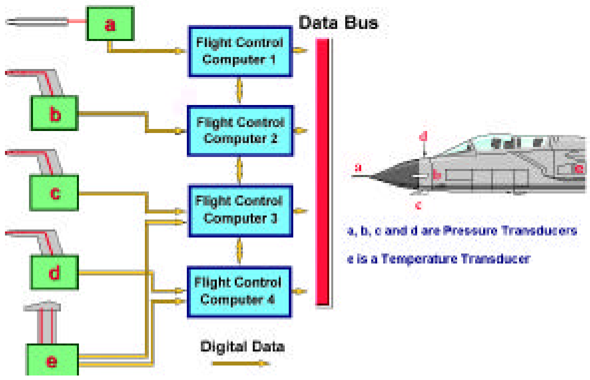


Figure 5 Distributed air data system

The locally derived probe measurements are used within the flight control computing in order to compute the true velocity vector of the aircraft, that is, its magnitude and direction, the latter being defined by the angles of attack and sideslip. These can then be used for gain scheduling and to provide feedback signals for stabilisation and flight envelope limiting purposes. The air data system is designed to provide high integrity information; for example, the arrangement in Figure 5 might provide triplex angles of attack and sideslip and quadruplex airspeed information. In practice, the quality and integrity of the air data will depend on the capabilities and locations of the individual sensors. For the arrangement shown in Figure 5, a is a pitot probe, and b, c and d would be multi-hole probes used to resolve local flow angles from pressure data. The air data information is complemented with information from the aircraft's inertial sensors.

5. Aerodynamics and Control

In terms of the aerodynamic design, there are a range of specialist activities, which need to be integrated and balanced for the satisfactory design and control of a combat aircraft [8]. As part of the overall design, the flight control system design, qualification and certification processes have to cover many aircraft configurations including the carriage of a wide range of aircraft stores [9,10].

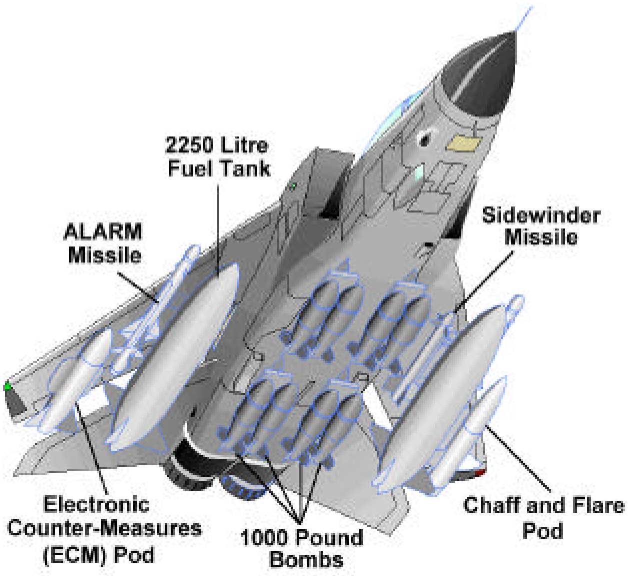


Figure 6 Stores carriage

It is usual to design the control system for a baseline configuration, such as the aircraft fitted with light stores. This involves using a nominal set of aerodynamic data, plus a set of parametric tolerances based on past project experience and uncertainties in the available wind tunnel data. If a range of significantly different stores are to be fitted to the aircraft, such as heavy under-wing or under-fuselage tanks, then it may be necessary to design control laws for each 'store group' to account for their differing inertial and aerodynamic properties.

Figure 6 shows a schematic of a Tornado aircraft carrying a heavy store load. The potential variation in aircraft mass, inertia and centre-of-gravity, due to the carriage and release of such stores is obvious. The aircraft and its flight control system have to be designed for carriage of a large range of such stores, including a very large number of possible symmetric and asymmetric combinations. Other significant factors that need to be taken into account in the design are: fuel state, high lift devices, airbrakes, wing-sweep (for Tornado), performance schedules, powerplant interface (or integration), reversionary modes, undercarriage operation and ground handling. All of these can have a significant effect on the design in terms of stability, handling and airframe loading. For all combinations of stores, the FCS can offer protection against over-stressing of the airframe and provide automatic stall and spin prevention.

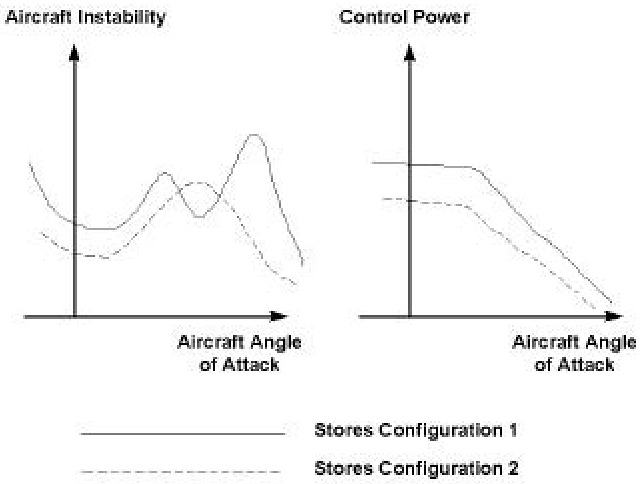


Figure 7 Aerodynamic non-linearities

Flight to high angle of attack leads to non-linear aerodynamic behaviour as flow separation occurs, wing and tail fin effectiveness are reduced and control surface power varies, often becoming very low. Such aerodynamic non-linearities are typified by Figure 7 where the left hand graph indicates how, for an unstable aircraft, pitch instability might vary with aircraft angle of attack, and the right hand graph illustrates how control surface effectiveness might reduce with increasing angle of attack. In addition, similar types of non-linearities are experienced in the lateral / directional axes, significantly affecting stability and control powers. The flight control system has to be designed to accommodate such effects. If the level of instability is too high or if there is insufficient control power available, then a satisfactory design will not be possible and flight envelope limitations will need to be applied, either manually observed by the pilot or automatically controlled by the system.

Significant aerodynamic non-linearities are also experienced as a function of Mach number, as an aircraft passes through the 'transonic region' from subsonic to supersonic flight. This is due to shock-induced flow separations and air compressibility effects causing the aircraft's aerodynamic centre to move aftwards.

6. System Implementation

For the FCS implementation, there are further specialist areas and inter-disciplinary activities, which are also essential for a satisfactory FCS design. Equipment specifications need to be established to unambiguously and completely define the required levels of functionality, performance and reliability, for the environment in which the equipment is required to operate. The equipment has to be designed and manufactured, and as part of the system qualification process, adequately tested to show compliance with its specification, as well as for validating the models assumed for the control laws design and clearance processes.

The FCS has to be designed to guarantee the necessary levels of reliability and integrity, by having a system architecture with the appropriate level of multiplexing and associated redundancy management, as well as comprehensive built-in-test capabilities. The system design is underpinned by a comprehensive safety analysis, covering both normal operation and failure modes.

The hardware necessary for the functioning of the FCS includes advanced sensors and actuation systems [11] such as that shown in Figure 8 (from the Experimental Aircraft Programme), and digital computing with its interfaces. All of these hardware components introduce lags and delays into the closed-loop system, which tend to reduce the aircraft's stability margins and impose physical limits on the aircraft performance that can be achieved. Additional lags are also usually present due to the structural dynamics filtering required to attenuate the flexible airframe response within the control loops. The FCS sensors measure (i) inertial data such as translational accelerations, angular rates and attitudes, (ii) air data, such as angles of attack and sideslip, and airspeed (as previously described).

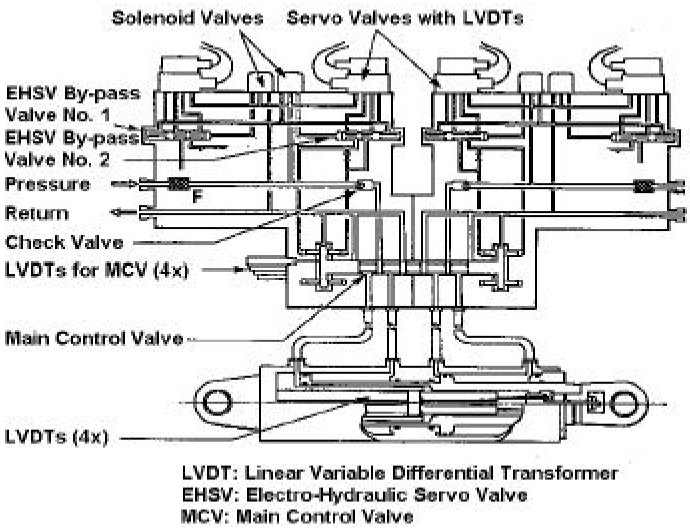
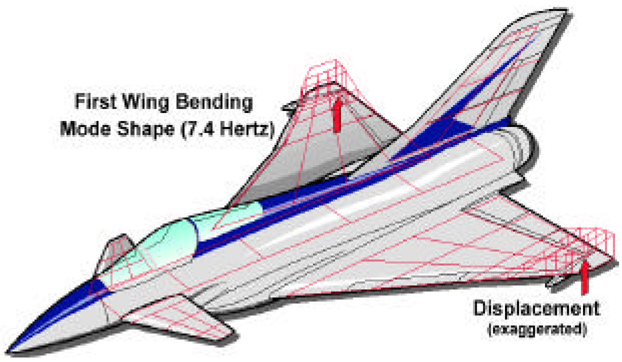


Figure 8 Typical aircraft actuation system (Courtesy of Dowty Aerospace, Wolverhampton)

With current technology, it is usual to implement control laws within a digital flight control computer, an approach which offers great flexibility and which allows highly complex functions to be implemented. The drawbacks are the inherent time delays, with their associated effect on closed-loop stability, and the clearance issues associated with safety-critical software. For digital control laws, the models used for the design and simulation must account for the digital processing effects, in order to be representative of the implementation, to avoid any unexpected results during ground or flight testing of the system. Anti-aliasing filters will be needed to limit the bandwidth of the input signals, in order to remove higher frequency components. A formal method of control law specification is required in order to capture the functionality and implementation requirements, including the ordering and timing of the control law elements.

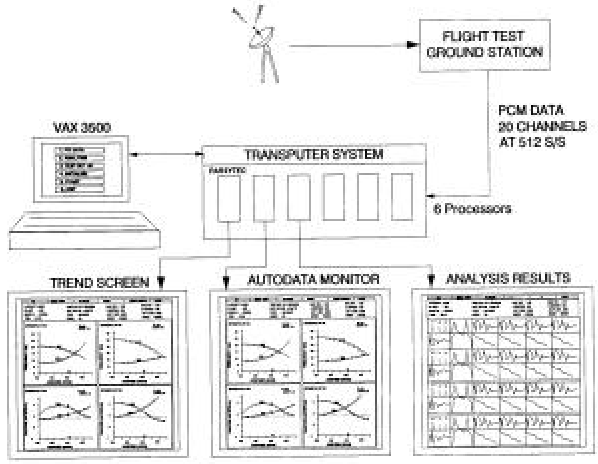
7. Handling Qualities and Pilot Interface

Flight control laws are designed to provide good aircraft handling qualities [12], a low pilot workload and a high degree of resistance to 'pilot-induced oscillations' (PIO). To establish a satisfactory design, appropriate design criteria are needed, firstly to establish a robust feedback design with good disturbance rejection, and secondly, to provide the desired handling characteristics. The PIO phenomenon, whereby the pilot's commands are (involuntarily) in anti-phase with the aircraft's response, has attracted much attention in the past decade and has recently been re-named 'Aircraft-Pilot Coupling' [13] or APC, to remove any suggestion that the pilot is to blame for the oscillation. The aircraft's handling qualities should be verified prior to flight, by a thorough programme combining theoretical analysis, off-line simulation and pilot-in-the-loop ground-based and/or in-flight simulation. Handling qualities and APC are the subject of ongoing research for both civil and military aircraft [14].



Finally, the control law algorithms and control strategy used must be realisable in terms of the aircraft's cockpit interface, including the inceptors, switches and displays; these must also be taken into account as part of the design and harmonised with the piloting control strategy used by the control laws.

8. Flexible Airframe Aspects



The FCS motion sensors for detecting the rigid body motion of the aircraft, also detect the higher frequency structural oscillations due to the flexible modes of the airframe, as indicated in Figure 9, which shows the first wing bending mode of the EAP aircraft.

Figure 9 Flexible airframe modes

The high frequency components of the sensor outputs usually require attenuation to prevent driving the aircraft's flying control surfaces at these frequencies and further exciting the flexible modes [15]. This is achieved by introducing analogue or digital filters, for example notch (band-stop) filters, into the feedback paths. The major constraints on filter design are the need to meet specified stability requirements for the flexible modes, and the need to minimise the additional phase lag introduced by the filters at 'rigid aircraft' control frequencies, in order to minimise the impact on achievable aircraft handling. The effects of stores carriage, fuel state and flight condition on the flexible modes of the airframe, results in changes to the modal frequencies and response amplitudes; the structural mode filtering needs to be designed to accommodate such variations.

Initial structural mode filter designs are based on finite element modelling of the airframe. This is later updated, following a comprehensive ground test phase in which aircraft ground vibration and servo-elastic 'structural coupling' tests are carried out to identify the 'zero speed' characteristics of the airframe. This test data is then extended to include the theoretical effects of airspeed variation. Where verification of the aerodynamic effects on the aircraft's flexible modes is necessary, an 'In-Flight Structural Mode Excitation System' [16] is used, as shown in Figure 10.

Figure 10 In-flight structural mode excitation system

This system allows the pilot to input deterministic signals, such as swept frequency sine waves generated from the flight control computer, in order to stimulate the flying control surfaces and thus excite the airframe's flexible modes. Analysis can be carried out on-line and compared with predictions, as indicated. Similar techniques are used to identify the aircraft's 'rigid body' aerodynamics and for validation of control system stability margins.
Such advanced facilities allow flight envelope expansion to be carried out in a safe, efficient, and progressive manner.

9. Future developments in the Technology

The world's first fly-by-wire Advanced Short Take-off and Vertical Landing aircraft, that is intended for production, is being developed as part of the US Joint Strike Fighter Programme, with the Concept Demonstrator Aircraft being due to fly this year. For this class of aircraft, Active Control Technology has great potential in terms of pilot handling and accurate aircraft control. The UK's 'Vectored thrust Aircraft Advanced flight Control' (VAAC) programme [17, 18] is investigating and demonstrating advanced control strategies with low pilot workload, based on flight experiments in a modified Harrier. Complementary research is being carried out by BAE SYSTEMS to investigate aircraft handling qualities for jet-borne flight [19], in terms of evaluation tasks and desirable aircraft response characteristics. Under the UK's 'Integrated Flight and Powerplant Control Systems' (IFPCS) programme [20], the integration of the flight and powerplant controls is part of a wider development aimed at risk reduction of advanced technologies for application to future aircraft.

Whilst current applications have tended to integrate a limited number of systems, for example, flight control system and powerplant control system, the implementation of a total vehicle management system is seen to be a significant further development. Such a system might integrate the functionality of traditionally separate airframe systems, potentially providing systems performance improvements associated with efficient energy management, and a reduction in equipment space and mass requirements. In addition, such systems will make use of reconfiguration and advanced diagnostics/prognostics to improve reliability and maintainability, and to reduce the cost of ownership.

For future stealthy aircraft, advanced air data systems will be required, since external measurement devices need to be minimised and optical (laser-based) devices are being considered. The unusual shaping of such aircraft, for example due to faceting, and the need to reduce the number and size of control surfaces for low observability, the possible reliance on thrust vectoring, and the development of novel control methods such as nose suction / blowing, are likely to lead to highly non-linear aerodynamic characteristics. It is probable that for some missions, unmanned air vehicles will become the preferred weapons platform. The introduction of such technologies will present combat aircraft designers with interesting design challenges.

In terms of the overall technology, it is believed that most of the new developments will be dominated by the powerful computing facilities that are now readily available to both the system designers and the implementers. It is expected that greater emphasis will be placed on modelling the systems that interface with the flight control system, with an associated reduction in ground and flight testing. This has already started and is largely being driven by the need to reduce costs. The use of on-board aircraft and equipment models and 'articicial intelligence' will increase, with the models progressively increasing in complexity. Such models might be used for equipment performance monitoring, failure detection and for providing commands or data to the flight control system's inner control loops (an example of which is terrain-referenced navigation). Finally, many of the modelling, design and analysis techniques that have become mature for active flight control technology, will be increasingly applied to improve the performance of other flight systems, where passive control has already reached its limitations.

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