THE EVOLUTION OF FLY-BY-WIRE CONTROL TECHNIQUES IN THE UK

GL-04

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Abstract

The potential benefits of full-time feedback control have, until recently, been largely unrealised due to the problems of implementing control systems of sufficiently high reliability and integrity. A programme of research, including theoretical studies and flight trials, has been conducted in the UK with the ultimate aim of producing high integrity control systems with acceptably low overall cost penalties. This has led to the fitting of a full-time multiplex digital control system to a Jaguar aircraft. Parallel studies have explored some of the performance benefits which can be obtained by the application of these systems to military aircraft.

I. Introduction

Control is a fundamental part of the Aeronautical Sciences playing a necessary role in the design of all air-vehicles whether they are aircraft or balloons, missiles or kites. The early years of aircraft research were characterised by the amount of effort devoted to the control of the aircraft, and the shortcomings of early aircraft designs were frequently due to instability and to poor handling characteristics. Indeed the triumph of the Wright Brothers in 1903 when their first sustained powered flight was made at Kittyhawk was due as much to their mastery of the problems of control as to their work on aerodynamics, structure or powerplant, vital though these latter were.

There are inherently two ways of obtaining an aircraft design having the desired control characteristics, either by so designing the structure and the aerodynamics of the aircraft itself or by providing some 'artificial' or 'automatic' control to change its characteristics. The latter method uses the signal from some sensor in essentially the same way that the human being uses signals from his vestibular organs to stabilise himself, and the crane fly similarly stabilises his flight using signals from his halteres. The technique was tried even before 1903, and Sir Hiram Maxim in 1891 had produced a patent for an aircraft using a pendulous gyroscope for pitch stabilisation (Fig 1). For various reasons most of these early efforts were rather unsuccessful, and in the period up to World War II the principal advances in the science of aircraft stability and control came largely from the refinement of the basic aerodynamics of the vehicle.

In the years since World War II, and particularly in the last decade, there has been something of a reversal so that it can now be said that automatic flight control is one of the most exciting and rapidly advancing areas of aeronautics. The reasons for this are firstly that aircraft designers are striving for overall performance characteristics which can only be obtained at the expense of inherent stability and control characteristics, and secondly that progress in the development of automatic control technology has increased its potential for use in a wide range of applications. This increased potential is largely due to the fact that with modern electronic components and systems it at last appears possible to design feedback control systems which have very high integrity and reliability, of the same magnitude as that of other critical components of the total aircraft such as the airframe itself. I believe that this development of high integrity techniques has been the critical path in the realisation of full-time feedback control systems, and with the advent of such systems it appears that air craft designers will have a new degree of freedom which they are likely to explore in a variety of exciting ways.

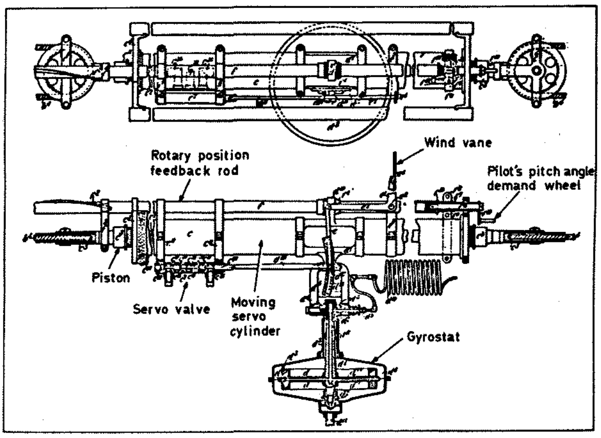


Fig 1 Maxim stabiliser

II. Integrity

It is of course impossible to design and build a practical control system which will never go wrong; what has to be done is to design one for which the statistical probability of going wrong is very small. Just how small is a matter for debate; the Civil Aviation Authority in the UK issued a draft technical note on the certification of fly-by-wire vehicles and called for the probability of a catastrophic failure of the control system to be not appreciably greater than 10^{-9} per hour. This is of course for a civil aircraft with perhaps 400 persons on board. For a military aircraft a rather less stringent figure, such as 10^{-7} per hour, appears to be regarded as a reasonable target for the control system failure rate.

For a single channel control system using electronic and electromechanical components these are impossibly small failure rate targets. The aircraft designer therefore has to arrange that the failure of such a single channel does not hazard the whole aircraft. In the past he has generally done this by limiting the authority of the electrical control system so that even if it sends the maximum fault signal to the actuator the resultant manoeuvre of the aircraft is not dangerous. He has also made provision for the channel to be switched out, in which case the aircraft must be able to fly safely without it. This in turn has led to compromises in the aircraft design because the reversionary mode was generally of lower performance than the initial mode using the electrical control system.

For a full-time feedback control system whose integrity is vital to the aircraft's safety, the system must be able to survive at least one failure and still be operative, and depending upon its complexity and on the overall failure-rate target it may well need to operate after two or three failures. The technique used to achieve this is redundancy, in other words having two or three or four control loops carrying out the same function in parallel.

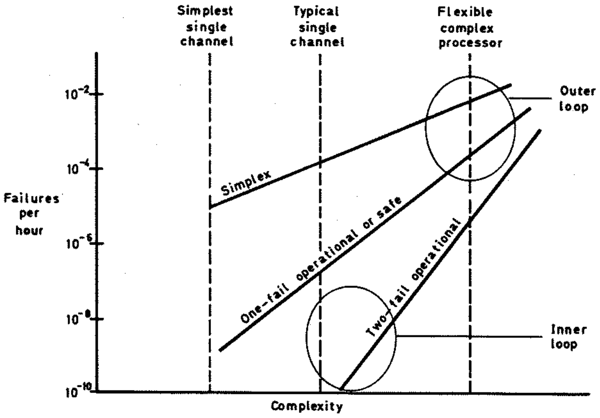


Fig 2 Failure probabilities

In Fig 2 is shown the broad shape of the relationship between failure rate and complexity for control systems of the type which might typically be installed in a modern aircraft. The failure rates increase as complexity increases since complexity is directly related to component count. Full authority inner-loop systems are generally two-fail operational as shown; by contrast most outer-loop autopilots have a considerable degree of complexity and flexibility and a fairly high failure rate probability is inescapable so that a simplex system is frequently sufficient.

A two-fail operational system can be mechanised by means of four data channels run in parallel - ie a 'quadruplex' system - with cross-comparison between the channels at suitable points to detect differences and eliminate the outputs from channels when these differences become excessive. Examples of such systems are those fitted to the UK Hunter and Jaguar experimental aircraft which I shall describe later, and similar approaches have been used elsewhere (eg Ref 7).

Redundancy implies complication and expense, as well as increased overall unreliability. It has become increasingly clear in recent years that digital data processors can make an important contribution to reducing these penalties. Specifically, digital computers have the following advantages over their analogue equivalents:

High reliability and availability
No drift
Comprehensive built-in-test capability
Relatively simple to change by software modifications
Simple realisation of nonlinearities and other complex control laws

The claim for no drift does require some further comment, because digital computers can in fact drift in their clock timing. To counteract this it is necessary to maintain synchronism between redundant parallel computers, and this is fairly readily carried out by the computers sending timing pulses to each other.

One of the advantages quoted above is that modification of the flight control laws should be relatively easy by software changes rather than the hardware changes which would be required with an analogue system, and this could have major advantages during the development phase of an aircraft. However such a process would have to be very carefully controlled because the integrity of the software itself must be proven to the same extent as that of the system hardware. This requirement to prove that the software is error-free is basic to the software design, and the most satisfactory approach to this appears to be modular software in which the overall package is built up from small modules each of which can be analysed completely rigorously.

Another problem in the use of digital computers arises from the very nature of digital processing itself. Because signals are represented in the processor by pulses, and because a pulse of a given size can represent any quantity from the smallest to the biggest, a random pulse picked up in error could have an effect at the output of almost any magnitude. Thus it is vitally important to shield against electro-magnetic interference, especially since interference could be picked up by parallel processors and could not be detected by cross-comparison. Shielding of computers is a well established technique and can protect them against such interference, but it is of critical importance that the links between all the sensors and computers which make up the total flight control system should have similar protection and integrity.

Conventional electrical wiring from point to point is the major data transmission currently used in aircraft. However, a more recent development is the use of fibre-optic light transmission systems terminated with light-emitting and light-detecting devices. These have obvious potential against electro-magnetic interference and extremely high capacity for data transmission. Because this is a relatively new development it is not easy to predict the extent of its ultimate use but it appears to offer real advantages for use in digital flight control systems.

This discussion of control system techniques has concentrated on the use of digital systems because their use is becoming a major factor in achieving the desired integrity levels. However one must not neglect the other parts of the system which are equally of vital importance.

These include the sensors and pickoffs which feed information into the system, the actuators, the electrical and hydraulic power supplies and so on. The degree of redundancy needed for these would depend ideally on their various failure probability rates, but in practice for the sensors and pickoffs it is generally most simple in a quadruplex system to include them in each of the quadruplex loops. For the actuators the degree of redundancy is largely determined by the number of independent hydraulic supplies fitted in the aircraft, which is generally two or three.

Failure rate calculations generally show that it is necessary to remain operational after the failure of both an electrical channel and a hydraulic power supply, and for safety reasons it is usually not permissible to switch hydraulic power supplies, so it becomes necessary to incorporate a rather complex interface between the computers and the actuators.

The technology of the prime sensors, which typically include gyroscopes, accelerometers and incidence sensors, is unlikely to change drastically in the near future. The gyroscope is perhaps the most critical and most expensive of the sensors, and if an aircraft is fitted with a three-axis system having quadruplex redundancy in each axis this totals twelve gyroscopes. In fact this number is really unnecessary because after two failures there are still ten gyroscopes available to provide signals in three axes, and it can be shown that by arranging the gyroscopes in non-orthogonal axes it is possible to reduce the number required to six. Similar arrangements can be used with accelerometers and other sensors in order to reduce system cost and perhaps improve reliability.

In the context of sensor failures, it should be mentioned that the calculated failure rates of the whole control system are generally based on the assumption that the incidence of failure in individual components is completely uncorrelated. This appears to be valid for a certain proportion of the failures of electronic components. For other components, particularly electromechanical components such as sensors, there is little doubt that external factors such as temperature, vibration and electromagnetic environment as well as operating life do provide a very powerful correlation between failure mechanisms in nominally independent components. At this time there appears to be no reliable data on which to base any studies of the effect of this on the overall system integrity calculations.

III. Evolution in the UK

At this point in the evolution of full time feedback control systems, when they are just beginning to be adopted for production aircraft, it is interesting and instructive to look back at their evolution. Within the UK there are several major flight experiments which can be identified(8), in addition to many parallel activities which contributed valuable experience and knowledge to the overall progress. Amongst these latter should be included the pioneering work on all-weather landing in which high integrity was a requirement for the automatic control systems of a number of trials and production aircraft, albeit for a few minutes only prior to touchdown.

The first British aircraft to fly with truly full-time feedback control appears to have been the Rolls-Royce Thrust Measuring Rig, better known as the 'Flying Bedstead', shown in Fig 3. This was also, as far as is known, the first jet-lift aircraft to fly anywhere in the world, and it was intended to demonstrate the practicability of controlling a jet-lift vertical take-off aircraft in hovering and low-speed flight. It flew at Hucknall, at RAE Farnborough and RAE Bedford, the trials at RAE being particularly concerned with investigations of the stabilisation system requirements for such an aircraft.

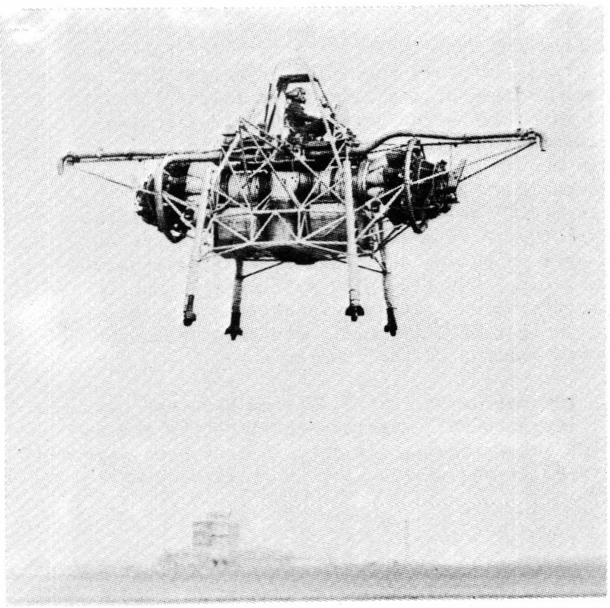


Fig 3 'Flying Bedstead'

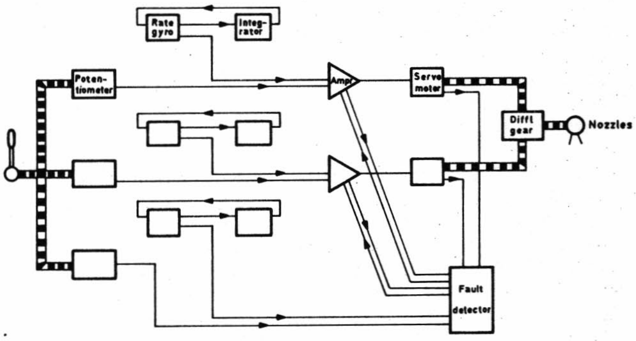


Fig 4 One axis of Bedstead control system

The aircraft was controlled by air jets at its extremities through which up to 9% of the mass flow of each engine could be passed. Control movements in pitch and roll were electrically signalled to butterfly control valves in the pipes leading to the corresponding nozzles so that in each case there was an increase in thrust from one nozzle and a reduction in thrust from its opposite so as to produce a control moment without affecting lift appreciably. The electrical link between stick and butterfly valve was as shown in Fig 4, and used dc electrical techniques typical of the period with potentiometers, servo motors and electric-spring rate gyros, partly duplex and partly triplex. Capacitors in series with the gyro coils had the effect of integrating the rate output to give an additional term proportional to aircraft attitude; this produced a problem characteristic of multiplexed integrator systems in which slight differences in gyro output signals were integrated up into large differences at the fault detector unit, so that leak resistors had to be put across the integrating capacitors.

With typical flight times of ten minutes, the duplex/triplex system was generally successful. It is worth quoting directly from the RAE report on the trials as follows. "The principal difficulties were matching of the components in the three lines and matching of the servos to avoid the frequent occurrence of spurious 'faults' while retaining a high enough sensitivity in the fault circuit to ensure that real faults would be rapidly detected." This has of course been one of the most persistent problems with all multiplex systems. However no potentially hazardous situations were experienced until a relay malfunctioned while the aircraft was operating on one lane only, hovering at a height of a few feet, and the consequent damage terminated the programme.

The follow-on to the 'Flying Bedstead' was the SC1 jet-lift VTOL aircraft developed by Shorts which was initially designed in 1954; two aircraft were built and flew during the period from 1957 to 1973.

It was intended to investigate the control of VTOL aircraft in the transition speed range down to the hover, primarily in the context of future Civil VTOL operation. Experience with the 'Bedstead' had pointed to the difficulty of piloting a VTOL aircraft in the hover without feedback control, and it was therefore decided that the SC1 should be fitted with an electrically signalled full-authority feedback control system which would remain operational after the occurrence of a single failure. A separate mechanical mode was also available, with no feedback, when the electrical control system was disconnected.

With a VTOL aircraft of the SC1 configuration there is a marked change in stability characteristics about all axes through the speed range down to the hover, during which the balance of aerodynamic and inertia forces is redistributed. Nevertheless it was demonstrated that relatively simple rate or attitude control systems could be designed both for pitch and roll which, when provided with gain scheduling with airspeed, gave good handling characteristics. The general arrangement of the control system is shown in Fig 6. Because the aircraft could operate from the hover up to full wing-borne flight, the control system operated both the nozzles, which were similar in principle to those of the 'Bedstead', and the conventional control surfaces.

Fig 5 Short SC1

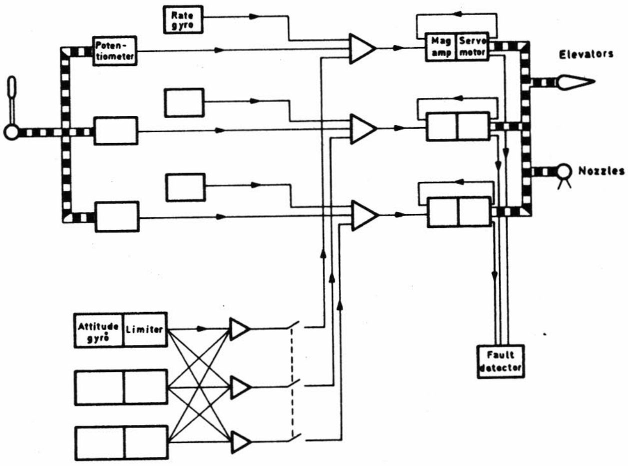


Fig 6 Pitch axis of SC1 control system

It was realised from the start of design of the SC1 that the solution of the stability problem was as much one of engineering the control system as of deciding in principle what was necessary. The aim therefore was to use engineering techniques which could be later applied to an operational aircraft without major modification. Although in many respects similar to the 'Bedstead' system the fault detector operated on ac signals from the triplex output servo and compared the three outputs magnetically. The output servo was very carefully engineered in order to minimise friction and lost motion in translating the electrical signal to mechanical movement.

Practical experience with the system showed that the main problem was caused by the drifts of the analogue components of the servo loops which were characteristic of the technology of the period; these drifts and the consequent problems of nuisance disconnects resulted in the use of signal consolidation of the attitude gyro signals as shown in Fig 6. Another consequence of component drift was that the maintenance of the system was a continuing and demanding task. However the system gave several years of valuable operation during which experiments were carried out both on the control characteristics and the evolution of display systems for VTOL transition and landing.

Contemporary with the SC1 was an experimental flight programme using as the test vehicle a small delta-winged research aircraft, the Avro 707C. This experiment was intended to explore the use of a redundant full-authority feedback system in a highly manoeuvrable aircraft, including an evaluation of a miniature controller to replace the conventional centre stick.

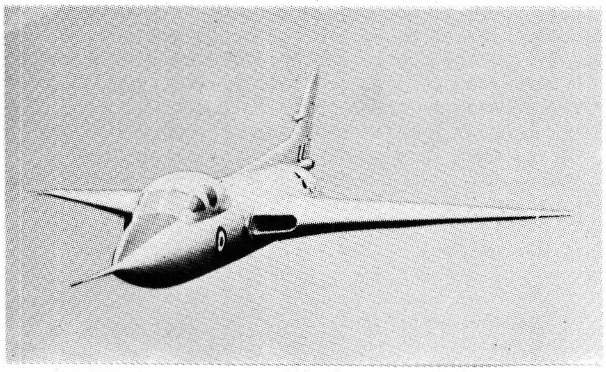


Fig 7 General view of Avro 707C

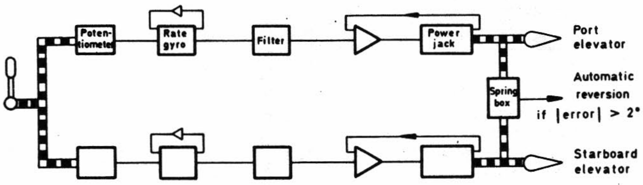


Fig 8 Pitch axis of 707C control system

The aircraft had a two seat side-by-side cockpit which enabled the experimental control system used by the right hand pilot to be largely isolated from a reversionary mechanical control system used by the left hand safety pilot. The arrangement of the pitch axis of the experimental system is shown in Fig 8, and it will be seen that it was duplex only with automatic reversion to the mechanical system in the event of a failure. The right hand pilot could use either the main stick or the miniature controller shown in Fig 9. The latter took the form of a finger-bar and was intended to minimise inertial coupling between the controller and aircraft's motion through the pilot's hand and arm. Test pilots found the use of this controller was very natural and soon manoeuvred the aircraft to the limits of the flight envelope.

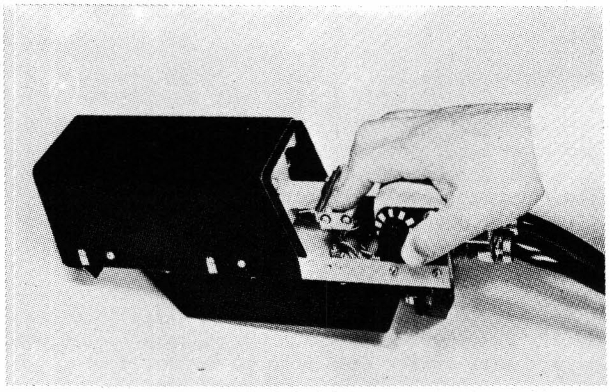


Fig 9 Avro 707C - Miniature stick

The loop gain of the control systems was quite high so that the overall characteristic approached an angular rate manoeuvre-demand type. The main advantage which was derived from the use of high gain in the feedback loop was the extent to which the disturbances caused by external effects such as gusting and ground effect could be reduced. In fact with the controller centered, several landings were made 'hands off', controlling the rate of descent with the throttle, which was particularly noteworthy since the aircraft's wing-tip design normally caused considerable roll disturbance at low speed. A further advantage was that the low frequency control system response was equalised over the whole flight envelope with a controller having constant force/deflection characteristics.

Contemporary with the Avro 707 experiment was the fitting of an electrically signalled control system to a Viscount aircraft which had two Tay jet engines. Again one pilot could operate the aircraft through this system, while the other retained the mechanical control. The electrical signalling and the hydraulic feeds were both duplex. The aircraft was first flown in 1957 and after some initial problems concerning the choice of system sensitivity, a series of satisfactory flights was made in which no failures occurred in flight and only one defect was found in pre-flight inspection. The programme unfortunately terminated in 1958, before the proposed extension of the trials to include motion feedback.

For the follow-on to the Avro 707 it was decided to use an improved system fitted to a two-seat Hunter aircraft. The arrangement was in many respects similar to that in the 707, having the experimental electrical feedback system operated by the right-hand pilot and a reversionary mechanical system operated by the left-hand pilot. The principal difference was in the design of the feedback system, which was intended to simulate as far as possible a two-fail operational capability appropriate to an in-service military aircraft, and having the capability to remain fully operational after failures in two lanes in the same axis. The Hunter aircraft was not an ideal vehicle for this exercise since it had a single engine and non-redundant hydraulic supplies which it was considered impractical to duplicate, and it was primarily for this reason that the mechanical controls were retained. However, all other problems associated with a double failure survival full-time full authority control system had to be solved. The system layout adopted is shown in Fig 11 and in functional form for the pitch axis in Fig 12. It was based on quadruplex redundancy in each axis with complete isolation between lanes and axes to reduce the chance of a failure in one lane causing a failure in another. This greatly simplified the system analysis and proving.

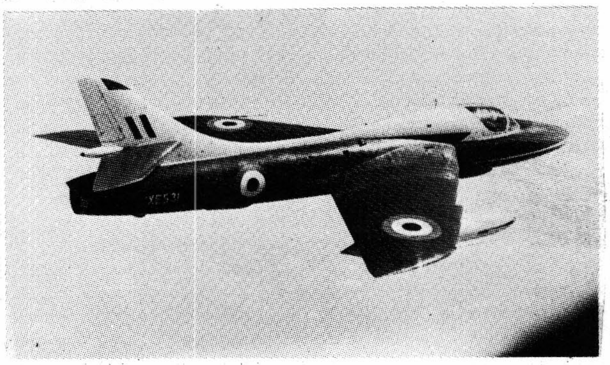


Fig 10 RAE Hunter T12

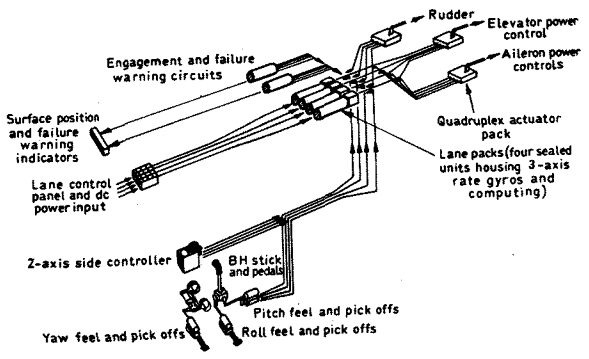


Fig 11 RAE Hunter T12
flight control systems schematic

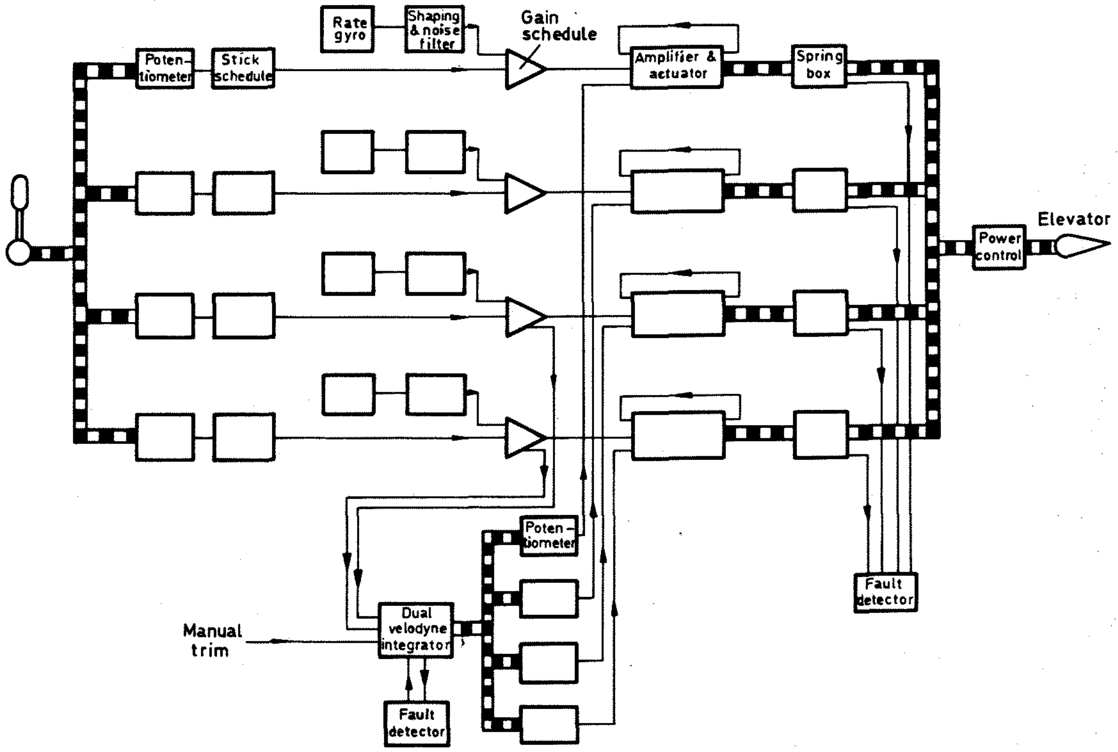


Fig 12 Pitch axis of Hunter control system

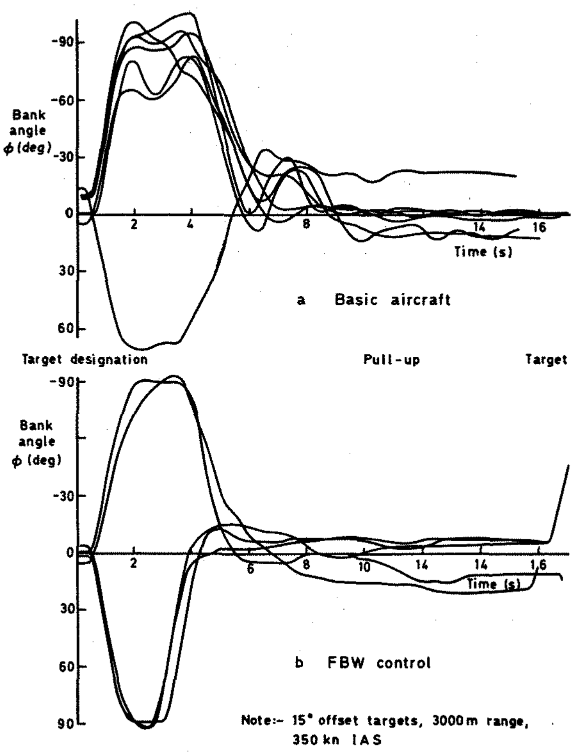
At the heart of the system are four lane packs, each of which contains one lane of pitch, roll and yaw computing, power supplies and a three axis gyro package. Pilot inputs are derived from quadruplex stick and rudder pick-off assemblies. Outputs from each of the four lane packs are fed to each of the three quadruplex electro-hydraulic assemblies, one each for elevator, aileron and rudder. Mechanical consolidation occurs at the output of each actuator pack, which functions as both the consolidation point and the error detector. Each pack consists of four individual actuators which are connected to a common output shaft. A microswitch detects misalignment between each piston and the output rod, and operates to warn and identify the faulty lane. Failure warnings are presented to the pilot who can manually disengage a faulty lane, converting from quadruplex to triplex by equalising the actuator pressures in that lane.

One of the principal problems found in the development of the Hunter system was that of lane equilisation. Because of the complete electrical isolation between lanes any difference in sensor or amplifier gain in the multiplexed lanes can result in differences in the actuator output. The technique of signal consolidation could have been used to ease this problem but would have led to possibilities of common-mode failure. However the use of an integral term in the pitch loop implied too high a gain to permit lane equilisation without consolidation, and after some experiments with an unconsolidated integrator this was replaced by a duplex integrator whose signals are consolidated before being applied to the four lanes of the basic system, and which can be switched out by the pilot if warned of error or failure.

Another practical problem was associated with the high bandwidth of the control system, the presence of gyro noise which was partially derived from structural motion, and the excitation of structural modes during ground runs and in buffet. Under these conditions bursts of unacceptably high noise were excited in the control system, and in spite of the most careful system design optimisation could only be brought down to acceptable values by redesigning the noise filters in the gyro signal path. As a result, the speed of response to either a pilot's input command or an external disturbance was decreased.

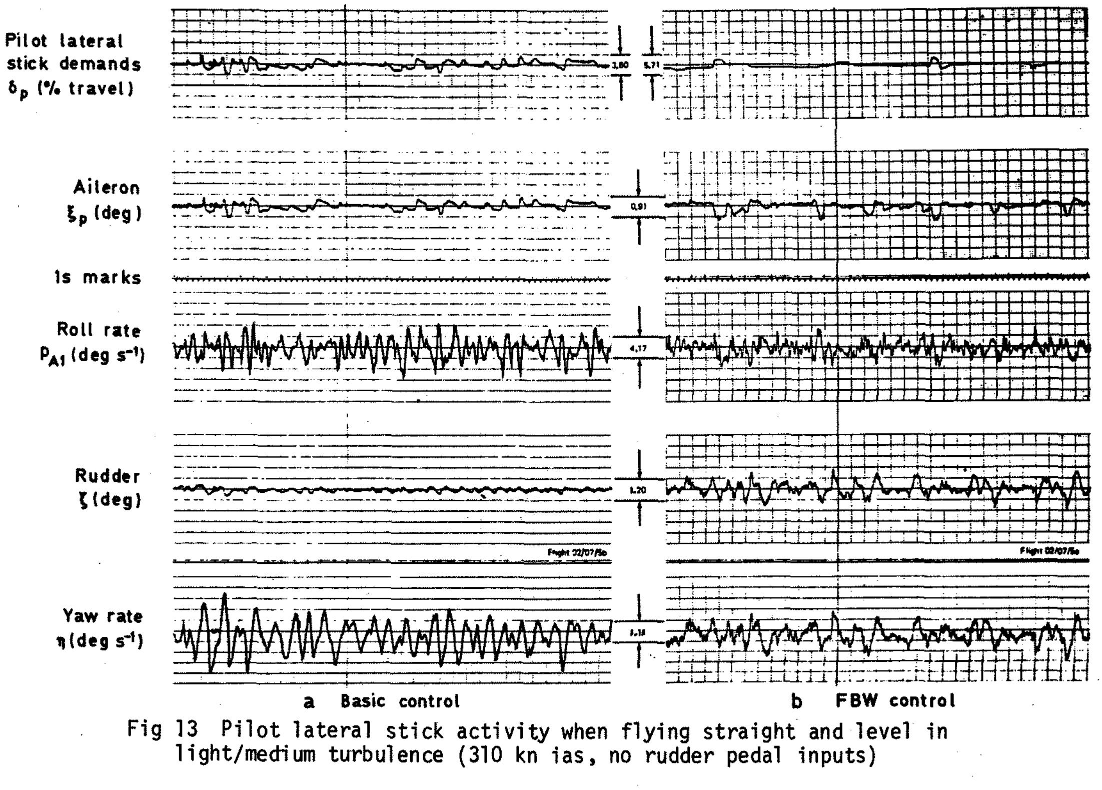
In mentioning these problems it should be made clear that the principal objective of the Hunter programme was clearly met and that the control system which was developed was proved in practice to be a practical and viable implementation of a double-failure survival system. Over 100 hours have now been flown with this aircraft with the control system engaged, and a wide flight envelope has been explored. Pilots have quickly established confidence in the system, and the bulk of the flying programme has been devoted to trials of the aircraft's dynamic handling characteristics.

Of the many handling characteristics explored, two are of particular interest. One is the reduction in pilot stick activity and in aircraft angular motion when flying in turbulence, which is illustrated in Fig 13. The second is the improved response to pilot command, which has been clearly demonstrated in the acquisition and tracking of ground targets. Fig 14 shows experimental traces of aircraft bank angle when acquiring offset targets and the increased precision of the manoeuvre with the feedback control system engaged is quite apparent.



Note:- 15° offset targets, 3000m range, 350 kn IAS

Fig 14 Offset target acquisition and tracking - bank angle traces



a Basic control b FBW control

Fig 13 Pilot lateral stick activity when flying straight and level in light/medium turbulence (310 kn ias, no rudder pedal inputs)

The potential advantages of digital control systems as compared with analogue have already been described, and in parallel with the Hunter development a number of rig experiments were carried out in the UK to explore the use of digital processors in multiplex control systems. By 1972 sufficient confidence had been gained to enable a contract to be placed for an experimental system to be used for flight trials. The vehicle chosen was an RAE Sea King helicopter, and the system itself was an auto-stabiliser of limited authority. As the first example in the UK of a multiplex digital system for airborne trials, its use in a relatively non-critical role was considered prudent, and it enabled the system to be tested and flown much more quickly than would have been possible with a full-authority application. To simplify the task the existing simplex actuators and power supplies were retained so that the digital auto-stabiliser was multiplexed to the extent of sensing and computation only. A further simplification was the use of triplex rather than quadruplex sensors and computers to provide single-failure capability only.

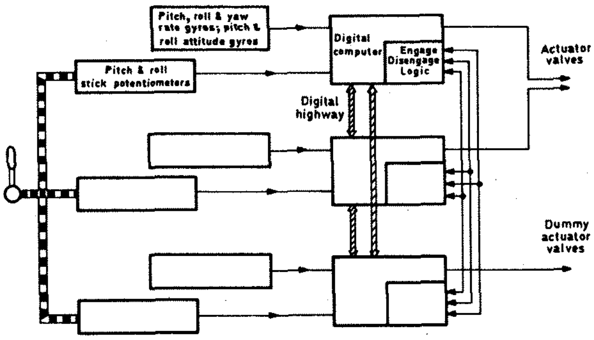


Fig 15 Sea King digital SAS

The arrangement of the triplex configuration is shown in Fig 15. An important difference from the Hunter system is that the signals from the rate gyro sensors and the stick pick-offs are consolidated immediately after the A/D converters; this ensures that the three digital computers are processing identical input information and consequently generating identical output data, thus making full use of the computational precision possible with digital computers. This in turn solves the integrator problem of the Hunter analogue system previously described. The disadvantage is that the consolidation process represents a mechanism for single-point failure and therefore has to be very carefully designed to ensure that single failures within the inter-lane connections cannot be misinterpreted by the system and cause the failure to be propagated through the system. The three digital computers were synchronised and the synchronisation mechanisation was similarly arranged to prevent the occurrence of single-point failures. A major advantage of digital systems is their capability for self-test, and an extensive pre-flight test routine was incorporated in the Sea King system, which checked both the digital processors and also much of the analogue parts of the system such as the stick pick-offs.

The control characteristics were designed to be very similar to those of the standard Sea King analogue autostabiliser, and flight and rig trials rapidly demonstrated good system performance in this respect. The main interest centered on the features of the system which were unique to the digital implementation. An immediate problem was the nearness of the iteration frequency of the processors (18 Hz) to a natural frequency of the control rod, swash plate and rotor blade system. This had been anticipated in the initial design modelling but the consequent control rod oscillations proved rather more serious than predicted, and were cured in practice by modifying the filters in the D/A converters. The system otherwise functioned extremely well, the self-test features in particular being very valuable both in the commissioning phase and in the routine flying programme.

By 1975, experience with the Sea King and with other rig and study exercises had demonstrated that a digital implementation of a full-authority fly-by-wire control system was realisable and should offer significant advantage over an analogue alternative. A decision was therefore made to proceed with detailed design studies of such a system, to be fitted into a Jaguar aircraft. Contracts were subsequently placed for the development and production of an experimental system which is due to be flight-tested in 1980.

IV. Future Trends in Fly-by-wire Technology

Although the Jaguar system has not yet flown, it represents today's technology and is broadly of similar type to other systems being developed elsewhere(7). Already it is possible to predict the evolution of full-time fly-by-wire systems beyond the Jaguar type. Reasonable assumptions are that digital processing will continue to be used, and that systems for military combat aircraft will have to be largely two-fail operational. However within the range of possibilities of two-fail operational digital systems the Jaguar represents one extreme of very simple architecture (minimum cross-comparisons and other inter-lane connections) but considerable hardware complication (quadruplex sensors in all axes, etc). A trade-off is possible in which architectural simplicity can be sacrificed to achieve hardware simplicity, and as knowledge is gained of the techniques for designing and proving the systems airworthiness, this trade-off will become increasingly attractive. The self-test capability of digital computers, which is not fully used in-flight in the Jaguar, will also feature in future systems.

Other trends for the future are likely to be the use of electrical first-stage actuators to achieve an improved processor/power actuator redundancy match, and adaptive systems to reduce the number of sensor and discrete signals required to allow for a wide flight envelope and a range of store configurations.

V. The Design Benefits of Fly-by-wire

In parallel with the practical developments and trials already described, there has been carried out in the UK a programme of studies to explore the benefits which can be derived from the adoption of full-time fly-by-wire control systems. The first and most obvious benefits of the application of fly-by-wire control are in improved handling and control of the aircraft. These have already been mentioned in the case of the flight trials of the Hunter aircraft, and in control systems such as the Hunter's high feedback loop gain will have a very pronounced effect on the handling as compared with the basic aircraft. Such handling improvements can be achieved by feedback control systems whether or not there is mechanical reversion capability in the event of failure, and such systems are used in many modern combat aircraft.

Within the general range of handling improvements can be mentioned 'carefree manoeuvring' which describes the concept of using the control system to automatically limit the excursions of the aircraft to those which are safe, and releasing the pilot from the task of monitoring his approach to forbidden boundaries. Moreover the boundaries may well be extended since the control system can provide stability over a wider range of flight parameters, eg up to higher angles of incidence.

A wider range of benefits can be derived from a full-time fly-by-wire control system when the possibility of mechanical reversion is rejected from the beginning. This allows some important constraints in the overall aircraft design to be relaxed and opens up a range of possibilities of which only the following are considered below:

Artificial longitudinal stability
Automatic configuration management
Manoeuvre load control
Direct force control
Ride control
Flutter control
Miniature control stick

In the following description it will become clear that these applications can be very interrelated. They are illustrated in the context of application to military combat aircraft, since studies in the UK have largely concentrated on the military applications. Nevertheless it must be mentioned that full-time fly-by-wire techniques also have considerable potential for application to civil aircraft although the safety requirements for civil application may delay their adoption as compared with the military field.

Artificial Longitudinal Stability

In an aircraft not fitted with a feedback control system, static longitudinal stability must be obtained by having the neutral point behind the centre of gravity. This implies that the tail provides a downward force or negative lift, so that the wing lift must be greater than it would otherwise need to be, with consequent penalties in drag. The situation is made worse as the aircraft goes from subsonic to supersonic, since the neutral point and the wing lift both move backward and the downward tail force has to be increased. Thus for a supersonic combat aircraft the centre of gravity has to be ahead of the subsonic neutral point, so that when the aircraft is supersonic the static margin is very large and the aircraft response becomes relatively sluggish.

A fly-by-wire control system can profoundly alter this, for by feeding back control signals to the elevators to provide suitable pitching moments the longitudinal stability characteristics can be completely changed. In particular it is no longer necessary to insist that the centre of gravity lies ahead of the neutral point in subsonic flight.

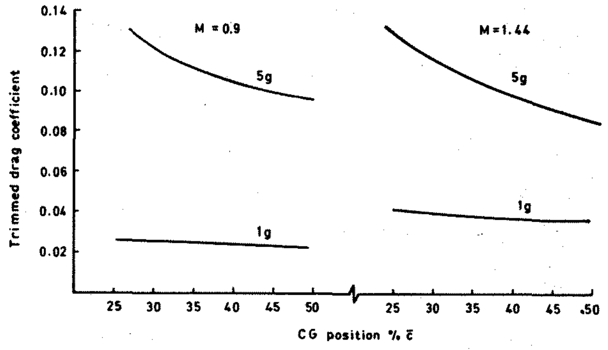


Fig 16 Drag coefficient as a function of CG position

The effect of moving the relative positions of CG and neutral point is shown in Fig 16 for both subsonic and supersonic speeds. In each case the saving in drag is most noticeable when the aircraft is being accelerated normally, ie the wings are being loaded, although even at 1 g the effect is significant. The reduced drag in a combat situation results in a significant increase in specific excess power which could be of the greatest importance in a combat fighter. From Fig 16 it appears that the greatest performance gain is obtained as the CG is moved progressively aft; the limit to this is set by the requirement that in the most aft CG position the control system must be capable of providing adequate dynamic and static control response, and this in turn will be limited by elevator size and frequency response.

Automatic Configuration Management

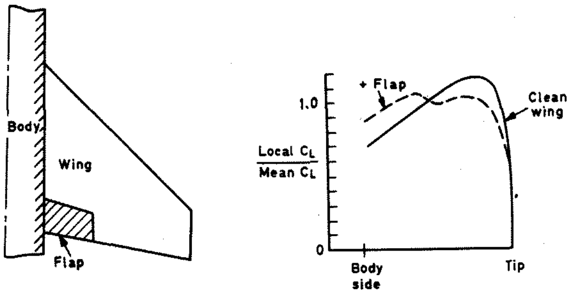
Combat aircraft operating in high-g conditions can obtain a useful reduction in drag by increasing with incidence the downward deflection of leading-edge slats or flaps and of trailing-edge flaps. This improves both thrust-limited and lift-limited manoeuvrability. With these high-lift devices programmed to operate automatically as a function of incidence and speed, the large uploads on the tail to trim at high incidence can be reduced, so reducing the drag still further. Another benefit of automatic management of flap position is the reduction of pilot's workload, which can be particularly beneficial in air combat because any task which diverts the pilot's attention from the main job of engaging or avoiding his enemy is unacceptable. Thus automatic management can overcome the disadvantage that manual high-lift devices are likely to be in the wrong position for much of the time with consequent loss in aircraft performance.

Manoeuvre Load Control

The structure of a combat aircraft tends to be dictated by manoeuvre loads, and the redistribution of these aerodynamic loads by manoeuvre load control can therefore have a significant effect upon the structural design. An example of this is shown in Fig 17, where deflection of the inboard trailing-edge flap on a swept wing is seen to redistribute the lift towards the aircraft centreline, thus reducing the wing-root bending moment by about 10%. As with the leading- and trailing-edge flaps previously mentioned, this bending moment reduction can be achieved automatically by suitable scheduling of the flap deflection. A further development of this technique is to prevent overstressing by limiting the manoeuvres of the aircraft, which can be mechanised by feeding back signals derived either from flight parameters or from structural strain sensors. This forms another part of the 'carefree manoeuvring' concept in which the pilot is prevented from executing a range of potentially dangerous manoeuvres by such feedback techniques.

Direct Force Control

Because a conventional fixed-wing aircraft has only four independent degrees of freedom it cannot



Wing and flap geometry

Showing distribution of C_L

Fig 17 Manoeuvre load control

directly accelerate itself laterally or normally, but must first rotate to give a change in wing angle-of-attack and thence a change in wing lift. For some critical tasks such as target acquisition and weapon release, the ability to rapidly generate direct forces perpendicular to the flight path could be very useful. Techniques to generate direct lift forces are canards, flaps and spoilers, and to generate direct side forces both horizontal and vertical canards can be used.

As an example, suppose that two horizontal canards are rotated differentially. This gives a rolling moment which can be opposed by an opposite moment from the ailerons. In addition it has been shown that the canards produce an unbalanced pressure distribution between the two sides of the aircraft, which in turn produces a sideforce whose magnitude can be up to 1 g or 2 g. Simulator trials have shown this to be useful in speeding up a target acquisition task, especially in turbulence. Before these advantages can be fully exploited, much more work will have to be done in studying how best the pilot can cope with the control of an additional degree of freedom, and it is likely that a form of blending using a fly-by-wire control system will be adopted in practice.

Ride Control

In the discussion of the RAE Hunter experiments it has already been shown how the use of a high gain feedback system can reduce the effect of turbulence and gusts on the motion of the aircraft. The extent to which the response can be reduced in this way is very much limited in aircraft such as the Hunter by the lack of independent control surfaces to enable lifting and pitching motions to be decoupled. If substantial improvements in ride control are required, then additional direct force control is necessary.

At first sight it would seem that by using direct lift, large reductions in ride-bumpiness or gust response should be possible, but in practice this turns out to be very difficult to achieve. Practical loop gains are limited by frequency responses of the sensors, filters and actuators, and by the structural resonances of the aircraft. Within these limits it is then found that as the loop gain is increased, although the power spectral density of normal acceleration can be reduced, that of rate-of-change of acceleration is actually increased, resulting in a rather harsh or 'cobblestone' ride characteristic. The trade-off between frequency content and magnitude of normal acceleration therefore needs further study in terms of pilot tolerance and performance characteristics before the real value of direct lift ride-control can be properly assessed.

Flutter Control

It should be possible by applying active flutter suppression systems to relax structural stiffness requirements and hence reduce the total aircraft weight, and further potential advantages are increased speed clearances and a wider range of external stores, due to reduced sensitivity to aircraft mass distribution. However such benefits appear unlikely to justify the fitting of additional control systems to a military combat aircraft and it seems more likely that the existing sensors, actuators and control surfaces might be used to achieve a measure of flutter suppression. One of the principal problems will be the high bandwidth which will be required, which will create particular difficulties in the design of the actuators, particularly in terms of their frequency response under load conditions. This is likely to prevent adoption of active flutter control in the next generation of aircraft. Indeed, it will be very important to ensure that the adoption of feedback control of lower bandwidth for other purposes does not in practice degrade the flutter characteristics.

Miniature Control Stick

The use of the full-time electrical control allows almost complete freedom in the choice of pilot's input mechanisation. Because of the established acceptability of the conventional control stick for pitch and roll inputs, it is likely that this will continue to be favoured for many future aircraft. However the alternative of a miniaturised stick has three important characteristics which may lead to its general adoption. These are:

1. It can be situated in positions where it does not obstruct the pilot's view of his instrument panel.
2. It is better suited to reclined seats which may be used to provide greater 'g' tolerance.
3. The inertial coupling of the pilot's forearms which is transmitted to the control stick can be reduced by anchoring the arms.

Flight trials with the Avro 707 and the Hunter, simulator trials, and many experiments elsewhere have demonstrated the general acceptability of miniature control sticks. Much more work on the human factors aspects of their use will be required before there is general acceptance of the control characteristics appropriate to a wide range of uses.

VI. Conclusions

Although the description of the performance advantages of using feedback control has been given in terms of separate identifiable subsystems, these will interact between themselves and with the basic aircraft design. By considering these capabilities from the start of an aircraft design, it is possible to achieve several of the improvements from one integrated control system; thus although it may not be necessary for systems such as ride control to use full-time high integrity technology, it may be simpler and more economical to incorporate this into an overall full-time fly-by-wire system than to provide a separate system. Moreover the pilot workload implicit in managing these complex controls also suggests that an integrated system will be necessary.

It is very difficult to quantify the benefits available from the use of advanced controls because an aircraft designed to incorporate them will not be exactly comparable with a more conventional design and the results obtained from parametric studies are very dependent on the constraints laid down. As an example, if performance requirements are held constant, then by use of artificial longitudinal stability an empty weight saving approaching 10% can probably be achieved. On the other hand, by keeping weight constant an improvement in Lift/Drag ratio of up to 50% appears possible. These are impressive figures, but on the other side of the balance sheet are the penalties associated with high integrity control systems, the first cost, the in-service cost and the potential problems of additional maintenance and down-time resulting from the use of very sophisticated technology. This paper has traced how the technology of full-time fly-by-wire has been developed in the UK with the ultimate aim of producing high performance, high integrity designs in which these penalties are not too severe. With the technology of multiplex digital control systems now firmly established it is becoming increasingly probable that the balance of advantage for many future aircraft designs will lie with the adoption of full-time feedback control.

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